UNITED NATIONS	UNITED NATIONS ENVIRONMENT PROGRAMME	FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS	UNITED NATIONS EDUCATIONAL SCIENTIFIC AND CULTURAL ORGANIZATION	WORLD HEALTH ORGANIZATION	WORLD METEOROLOGICAL ORGANIZATION	INTER-GOVERNMENTAL MARITIME CONSULTATIVE ORGANIZATION	INTERNATIONAL ATOMIC ENERGY AGENCY
NEW YORK	NAIROBI	ROME	PARIS	GENEVA	GENEVA	LONDON	VIENNA

IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP
JOINT GROUP OF EXPERTS ON THE SCIENTIFIC ASPECTS OF MARINE POLLUTION
- GESAMP -

REPORTS AND STUDIES

No. 16

Scientific Criteria for the Selection of Waste Disposal Sites at Sea

INTER-GOVERNMENTAL MARITIME CONSULTATIVE ORGANIZATION

Report and Studies No. 16

IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP)

SCIENTIFIC CRITERIA FOR THE SELECTION OF WASTE DISPOSAL SITES AT SEA

IMCO, 1982

NOTES

1 GESAMP is an advisory body consisting of specialized experts nominated by the Sponsoring Agencies (IMCO, FAO, UNESCO, WMO, WHO, IAEA, UN, UNEP). Its principal task is to provide scientific advice on marine pollution problems to the Sponsoring Agencies and to the Intergovernmental Oceanographic Commission (IOC).

2 This report is available in English from any of the Sponsoring Agencies.

3 The report contains views expressed by members of GESAMP who act in their individual capacities; their views may not necessarily correspond with those of the Sponsoring Agencies.

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Definition of Marine Pollution by GESAMP

"POLLUTION MEANS THE 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."

* * *

For bibliographic purposes, this document may be cited as:

IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP).

Scientific criteria for the selection of waste disposal sites at sea. Rep. Stud. GESAMP (16).

EXPLANATORY NOTE

This document, which appears in English only, is the edited and approved report of the GESAMP Working Group on Sea Disposal Studies. The Working Group met at the headquarters of the Inter-Governmental Maritime Consultative Organization (IMCO)* in London from 30 September to 29 October 1980 and from 27 to 30 April 1981 with the following members participating:

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Financial support for the Working Group's activities was provided by the United Nations Environment Programme (UNEP).

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* During the preparation of this report the name of the Organization has been changed to the International Maritime Organization (IMO). Throughout the text of this publication reference is made to the original name only.

SCIENTIFIC CRITERIA FOR THE SELECTION OF WASTE DISPOSAL SITES AT SEA

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ABSTRACT

The main concern with waste disposal at sea arises from possible adverse effects on living resources. Effects on human uses are chiefly associated with the accumulation of substances by marine organisms, tainting of sea food, interference with fishing and reduction of amenities by discoloration, turbidity and floating materials. The wastes of greatest concern are therefore those which are toxic (particularly at low concentrations), accumulate in organisms, reach the sea in large amounts, and persist there for long periods.

Disposal of those materials permitted under the Dumping Conventions should be done in such a way as to avoid adverse effects. Rapid and widespread dispersion is a principal objective particularly for liquid wastes. This can be done by ensuring maximum initial dilution through an appropriate means of disposal and by selecting areas where the dispersive processes of transport and mixing are active. On the other hand, in some circumstances it may be desirable to confine waste to a limited area of sea. This can be done by selecting more quiescent sites, by containerization, or by capping and burial.

Some wastes are amenable to incineration at sea. The problems associated with this method of disposal, including effects and site selection, are discussed.

The report takes a positive approach by identifying sites suitable for waste disposal, but this involves recognizing that some types of location are unsuitable. In all operations it is desirable to identify and avoid particularly sensitive areas.

Field observations are required at disposal sites at both the pre- and post- discharge stages. Physical observations should be directed mainly at evaluating dispersion characteristics and should include observations of wind, vertical density distribution, currents and bottom properties. Measurements of light penetration may also be relevant. Chemical measurements appropriate to the disposal material are required from wastes, sediments and benthos. Appropriate biological observations include data on primary production, zooplankton and benthic populations and on the commercial resources. For an adequate assessment, the field observations should be supplemented with experimental work designed to detect and evaluate effects.

At appropriate points in the report, attention is drawn to the need for greater research emphasis, or for new studies.

1 INTRODUCTION

A GESAMP Working Group met during 1974 to consider the scientific criteria for the selection of sites for dumping of wastes into the sea, and its conclusions were published in 1975 as GESAMP Reports and Studies No. 3. Since that publication, there have been international discussions on how to identify sea areas which might be particularly sensitive to marine disposal of waste, and partly arising from this concern a new Working Group was established by GESAMP in 1980. The terms of reference of the Working Group as set out in the Report of the Eleventh Session of GESAMP (Rep.Stud.GESAMP (10), paragraph 11.3) were as follows:

> "To review and update Rep.Stud.GESAMP(3) - Scientific Criteria for the Selection of Sites for Dumping of Wastes into the Sea - and compile a bibliography of relevant material."

The Working Group met on two occasions in 1980/81, and conducted an extensive examination of the existing report. In the five years since its publication there had clearly been advances in scientific research, significant changes in the pattern of dumping activities, and new thinking on the approach to waste disposal. However, the Working Group considered that much of the content of the report was still valid and that the general presentation could hardly be improved. It was therefore agreed to retain as much as possible of the original report, but to amend or expand those sections which required updating and to inject new material where necessary. In following this approach, the words of the original report have in many places been repeated unaltered, and the overall framework for the most part remains intact. During intersessional periods the members of the Working Group prepared a number of short case studies and working papers designed to assist its deliberations. The subjects covered were: acid iron wastes, sewage sludge, dredged material, capping and burial of contaminated solid wastes, processed ore wastes, biological effects, plankton blooms, bulky wastes, experimental techniques, fish migrations, and deep sea benthos. These papers can be made available by the IMCO Technical Secretary of GESAMP upon request.

Finally, the Working Group, in response to the terms of reference, considered the preparation of a comprehensive bibliography of relevant material. The Working Group recognized that a fully comprehensive compilation of all relevant material would, however, be a major task and one more appropriate to an abstracting or indexing service*. It was therefore considered more useful to produce a selective list containing mainly recent references which were judged to be of particular importance. A copy of that list is also available through the IMCO Technical Secretary of GESAMP on application.

1.1 General considerations

Dumping can be defined as any deliberate disposal at sea of wastes or other matter from vessels, aircraft, platforms or other man-made structures. The international and multilateral Conventions on the Prevention of Marine Pollution by Dumping (Dumping Conventions) which are currently in force** do, however, explicitly exclude in their definition the disposal of wastes or other matter derived from the normal operations of vessels, aircraft, platforms or other man-made structures at sea. The disposal of wastes or other matter arising from or related to the exploration and exploitation of sea-bed mineral resources is also excluded.

It should be recognized that dumping of wastes at sea is only one of several methods of disposal, and that all disposal operations merely move material from one part of the environment to another. Ideally, the only entirely safe way of dealing with a waste is to avoid disposal altogether by recovering and utilizing the various constituents. In practice this seems an

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* See also Champ, M.A. and P. Kilho Park: Global Marine Pollution Bibliography: for Ocean Dumping and Industrial Wastes, in press (Plenum Press, New York. 1982)

** Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (London Dumping Convention); Convention for the Prevention of Marine Pollution by Dumping from Ships and Aircraft, 1972 (Oslo Convention); Convention on the Protection of the Marine Environment of the Baltic Sea Area 1974 (Helsinki Convention); Protocol for the Prevention of Pollution of the Mediterranean Sea by Dumping from Ships and Aircraft, 1976 (Barcelona Dumping Protocol).

unrealisable goal because costs and benefits are usually considered inequable. However, there is scope for the introduction of changes to industrial processes which, for example, either avoid the creation of wastes containing potentially harmful substances or which substantially reduce their concentration. Additionally, a number of processes are available by which wastes can be treated to render them less harmful, e.g. by degrading harmful constituents chemically or biologically, or by altering their physical or chemical state. Such processes may open up alternative disposal options.

For certain wastes, and under particular circumstances, the financial cost of operating disposal at sea may be less than that of the alternatives, such as disposal on land or recycling, but the cost must be assessed against the possible damage to marine resources, so that low operating costs should be viewed in the light of any environmental impact. It must also be recognized that the environment is not divisible into neat compartments. Consideration should be given to the costs and consequences of waste disposal in a variety of alternative ways. The Group did not examine cost-benefit analysis, and did not consider the alternatives to sea disposal, although it agreed these must be taken into account in determining the most appropriate procedure in each case. The purpose of this report is to consider what scientific principles are involved in the selection of dumping sites at sea, and how effects of ocean waste disposal can be assessed and reduced to a minimum. Matters related to pretreatment of wastes (dewatering, removal of trace metals, etc.) will obviously affect the development and application of criteria for site selection.

The Group agreed that the disposal of waste at sea can be scientifically discussed without attempting to justify the operation. The concept of a capacity of the oceans to receive waste has long been accepted and utilized by mankind, though the criteria of assimilative capacity have not been static. Early criteria tended to be based on visual or aesthetic factors, but the recognition of the eutrophic effects of nutrients resulted in a more quantitative approach tied to responses of organisms. More recently the potential effects of persistent and toxic wastes on the health and stability of the ecosystem and on its human uses have been highlighted. In accepting that the marine environment has a capacity to receive wastes, it must be recognized that this is often largely related to the great volume of the oceans; that the self-purification and buffering capacity of the water is limited, and that the sea-bed will not act as an effective sink for all materials or for infinite amounts. Given these facts, the particular conditions existing in any area proposed for dumping should be examined and suitable criteria relevant to the area's assimilative capacity should be developed. One basic decision is whether the dumped material should be quickly and widely dispersed, or whether it should be allowed to accumulate in a restricted area. There are different sorts of effects associated with either option, and these are discussed in the report.

The assessment of the probable effects of waste disposal at sea involves several disciplines, including physical oceanography, chemistry, sedimentology and marine biology, all of which are interdependent and none of which is adequate by itself in making an assessment. In a report of this scope it has been necessary to identify those matters of primary importance for predicting the behaviour and effects of materials dumped at sea. Having done this, an attempt has been made to specify subject areas where knowledge is reasonably precise and also those where it is lacking.

Detrimental effects of marine pollution include harm to living organisms, hazards to human health, hindrance to maritime activities and reduction of amenities. The Group noted the desirability of maintaining an overall balance and diversity in the marine ecosystem. The exploitation of living resources, one of the important uses of the sea, is closely related to this, and could be affected by the disposal of wastes. The young stages of many organisms are particularly vulnerable to changes in water quality, and certain areas of the marine environment, although not at present supporting commercial resources, may have potential value in this respect. In considering human health aspects possible contamination of food resources is important.

Activities which may require special attention include aquaculture, water abstraction for drinking or industrial purposes, recreation, preservation of endangered species and exploitation of mineral resources on or under the sea-bed.

The effects of marine waste disposal operations may be assessed by a calculation of waste dispersion, biological uptake, absorption and deposition on the sea floor or on suspended particles, and re-release or re-suspension. Most calculations of this kind are based on a mass balance approach; they attempt to account for the fate of the total waste released, since it is only by knowing where the waste or its component chemicals are distributed and in what quantities, that it is possible to predict environmental effects. The frequency of disposal, and the coupling between this frequency and the natural variability in ecosystems is of particular relevance to such studies.

A simplified variant of this approach is to focus on the most sensitive or vulnerable species. This "critical path" method is widely applied in the field of radioactive waste disposal, and although there have been problems in adapting it to other waste disposal problems, it may be useful under certain circumstances.

The principal physical processes involved in marine waste disposal are transport and mixing ("dispersion"), the analytical or numerical modelling of which may be done with reasonable success for short periods (around 100 hours) following release (Fischer et al. 1979). Dispersion calculations for time periods of several weeks to several months, or more complete mass balance calculations involving, for example, biological uptake, cannot at present be done with confidence, because several key parameters required in such calculations are not well known.

There is reason to hope that more complete assessment models will be developed in the near future for many coastal ocean applications. Within the last decade or so the knowledge of coastal ocean physics has increased dramatically (Csanady, 1981) and, if exploited, should materially improve chances of success in modelling. This requires, however, the development of an intellectual framework for pollution assessment in unsteady, non-uniform flow, a research problem of high priority. Equally important is the field verification of such models. Complex computer models, in particular, should not be relied upon without thorough observational checks.

The report considers the various properties of a waste which should be known in order to understand the way it will behave in the marine environment, and examines how its behaviour may be affected according to the disposal method used. The methods considered include release from hopper barges, discharges into the wake of a vessel, disposal of containerized or other bulky wastes, burial and capping, and incineration. It is important to ensure that conditions of licences are observed, especially in relation to site and method of disposal. It is also important, in the context of control, that adequate records are kept of all dumping operations (e.g. amounts, locations, methods of containment etc.).

The Group did not discuss the disposal of radioactive waste into the sea, as this has been covered elsewhere (IAEA, 1978 a and b). It is also relevant that GESAMP at its eleventh session (25-29 February 1980) established a Working Group to advise on the present knowledge of pathways by which substances might be transferred from a deep ocean dumping area to man.

The Group, noting that under the Dumping Conventions the disposal of wastes at sea directly arising from the exploration and exploitation of sea-bed minerals is not considered as "dumping", did not include in its consideration these sources of marine pollution. Reference is however made to GESAMP Reports and Studies No.7 (GESAMP 1977) describing scientific aspects of pollution arising from the exploration and exploitation of the sea-bed.

Attention is also drawn to the fact that many of the considerations made in preparing this report are not only relevant to the disposal at sea of wastes loaded on board ships for the purpose of dumping, but also include aspects which have to be taken into account when considering the discharges of wastes through pipes into coastal sea areas. These particular problems have also been addressed by GESAMP when discussing marine pollution implications of coastal area development (GESAMP 1980a).

It should be stressed that this report should not be thought of as replacing the criteria and conditions set out in the Dumping Conventions, of which note must always be taken. Rather, the report may serve to amplify and clarify the items listed in the Conventions. It deals in sequence with the following questions:

(1) What are the physical, chemical and biological characteristics of the waste and possible effects of the waste in the marine environment?

(2) How can the effects be minimized by appropriate selection of the method of disposal or by appropriate pre-dumping treatment of the waste?

(3) How can the effects be minimized by appropriate selection of the site for disposal and by alternative methods at sea?

Rather than structuring the report in terms of various zones of the oceans, the Group preferred to adopt a more general approach, citing specific examples as illustrations. Throughout the document, reference is made where appropriate to needs for new or additional research.

2 CHARACTERISTICS AND POSSIBLE EFFECTS OF WASTES

The characteristics of a waste may be discussed in terms of physical, chemical and biological properties. All three have a bearing on effects in the marine environment. Different wastes require different considerations, depending on the lifetime of the wastes or their components in the sea, and on factors such as the degree of toxicity of the substances and the turbidity resulting from their disposal. All these factors might influence the selection of dumping sites.

2.1 Physical characteristics and effects

The dispersal of liquid wastes miscible in sea water is influenced by their density, but this applies mostly in the initial period. After dilution with a thousandfold volume or more of sea water the density excess or deficiency usually becomes too small to matter. Thus liquid wastes discharged into the wake of a barge often disperse following rapid dilution as if they were coloured sea water (Ketchum et al, 1981), in contrast to domestic waste released from a submarine outfall which usually "boils" to the surface on account of its significantly lower density even after initial mixing. When the densities of overlying layers of water and diluted waste differ significantly (by one part in one thousand or so), mixing is suppressed at the interface.

Miscible or immiscible low density wastes which float on the sea surface often pose a particularly difficult disposal problem. They are confined to a two- instead of a three-dimensional medium and disperse much less effectively. Furthermore, surface convergences concentrate floating waste and may cause their reaccumulation rather than dispersal. Floatable wastes (including persistent plastics, ropes and netting) can interfere with fisheries, shipping and amenities, and if released near shore may be washed up on beaches. Such wastes, whether on beaches or at sea, are highly undesirable (Myers, 1981) and their dumping is prohibited by the Conventions.

Wastes of particulate form disperse according to their settling velocity. The median settling velocity of particulate material in sewage, for example, is very slow, some 10^{-3} cm s^{-1}. The reason is not so much that the particles are small, but that their density is close to that of sea water. On settling through progressively denser, deeper oceanic layers such particles may lose their negative buoyancy altogether and collect along isopycnal surfaces, at least until thermal and chemical equilibrium with surrounding sea water is re-established.

Deposition of particulate waste on the sea floor is affected by the density of the waste cloud and by the properties of the bottom surface. Under simple quiescent conditions the deposition rate is a function of settling velocity and concentration. Under the turbulent conditions prevailing in tidal waters, or over some continental shelves, the probability of permanent deposition for waste particles becomes very small (or, put another way, the probability of their resuspension becomes very high). Natural organic particles are normally not deposited permanently in locations where near-bottom velocities regularly exceed about 0.15 m s^{-1}. Over open continental shelves near-bottom velocities are usually greater than this.

Quantitatively, the vertical distribution of particulate waste depends mainly on the ratio of the vertical mixing coefficient (which is a measure of the vigorousness of mixing) to the settling velocity. The physical dimension of this ratio is length, and it indicates the layer depth over which vertical mixing tends to distribute the waste. Over continental shelves in well mixed conditions the mixing coefficient is of the order of 100 cm^2 s^{-1}, so that a waste with a settling velocity of 10^{-3} cm s^{-1} tends to be distributed evenly in the vertical over a layer up to a kilometre deep, i.e. over the entire available water depth. It should be noted, however, that in the varying physical situations of continental shelves such well-mixed conditions occur only periodically.

An important aspect of the behaviour of particulate waste is that individual particles are not necessarily permanent - they may aggregate, be enriched by flocculation or reduced by scavenging, and further complications may arise following their arrival on the sea-bed where they may be subject to chemical and biological processes different from those acting in the water column.

In view of these considerations it is necessary to know whether the waste is liquid, solid, or a solid in suspension, to know the density of the waste as a whole, and of any solids it may contain, since these properties will influence initial dilution as well as subsequent dispersion and settlement.

Particulate material can influence the marine environment in several ways. Adding particulate matter to the natural suspended particle load will increase turbidity and may cause discoloration of the water with possible adverse effects on fisheries and recreational interests. Light penetration may also be reduced, with consequent effects on photosynthesis. Certain forms of particulate waste may clog gill surfaces of marine fish and invertebrates. Also, particles settling in large amounts in a confined area will alter the composition of the sediment, and thus affect benthic organisms.

If the solids are organic, anoxic conditions may develop in the sediment and overlying water, which will lead to a reduction in the suitability of the habitat for spawning, shelter or feeding. The International Council for the Exploration of the Sea warned of the possible adverse ecological effects of altering marine sediment grain size and consistency through dumping of wastes (ICES, 1978). It was pointed out that gravel beds required by spawning fishes, such as herring, and the habitats of lobsters, could be adversely altered by particulate wastes, even at considerable distances from the dump site. Sediment changes following sewage sludge disposal have also been documented and shown to affect the structure of benthic animal communities (Topping & McIntyre, 1972). Coral habitats, which because of their complexity harbour a great diversity of specialized animals, are particularly sensitive and dumping of particulate matter in the vicinity of a coral reef could modify the structure of the habitat with subsequent reduction in productivity. When a reef community is damaged, it cannot be assumed that it will ever renew itself (Johannes, 1975).

Important fisheries may be adversely affected where sediment changes prevent burrowing or other activities. Thus, sewage sludge dumping on a Norway lobster (Nephrops norvegicus) fishing ground resulted in physical changes due to the accumulation of dumped material which made the sediment unsuitable for burrowing over an area of 10 km^2 (McIntyre and Johnston, 1975).

2.2 Chemical characteristics and effects

An appreciation of the chemical composition of a waste is necessary to assess its potential effects on water quality and on biota. This does not mean that every waste should be subjected to exhaustive chemical analysis to establish the concentration of a standard wide-ranging list of chemical elements or compounds. Knowledge of the raw materials and production processes used will often provide a key to the probable composition of the waste. A selective analysis may then be sufficient for a preliminary assessment.

Wastes can modify the chemistry of the marine environment in a number of ways. For example, they can lead to a change in the concentrations and distribution of chemicals already present in the water either directly through addition or by modifying the ionic balance leading to de-gassing or precipitation of otherwise soluble materials, or wastes may introduce new and alien compounds to the environment. There are often associated biological changes.

Under calm or quiescent conditions, as in lagoons or fjords, wastes with a high chemical oxygen demand (COD) and/or biochemical oxygen demand (BOD) can lead to deoxygenation of the water or the sediment. Examples of such wastes are the ferrous sulphate waste from titanium dioxide production, sewage and sewage sludge, pulpmill and food processing wastes. Where rapid dilution occurs, deoxygenation of the water column as a result of chemical oxygen demand alone is unlikely to affect marine life. Similarly deoxygenation of the water column as a direct consequence of disposal at sea of highly organic wastes is unlikely to occur where dumping takes place in well mixed waters. However, the decomposition of such wastes can release large amounts of plant nutrients, phosphate, nitrate and silicate, which can lead to massive blooms of algae. Deoxygenation often follows such blooms either because of the respiratory activity of the large biomass or because of the death and decay of the algae. In certain circumstances the effect can be extensive enough to result in fish and shellfish mortalities. The fact that deoxygenation can have significant effects even in open waters was demonstrated by the events off the north east coast of America in 1976 (Swanson and Sindermann, 1979). The algal blooms may be composed of species normally considered undesirable, e.g. those associated with red tides, toxin formation or unsightly foams and scums. Apart from these effects of nutrients, there may be situations where the injection of some other "limiting" substance such as a trace metal, may stimulate local production with potentially similar consequences.

If solid organic material (as in sewage sludges and food processing wastes), is dumped in an area with low velocity currents or closed loop currents, an anaerobic organic rich sediment may accumulate. A change in sediment composition could affect the structure of the benthic communities and lead to a decrease in species diversity, an initial increase in standing stock and eventually, in severe cases, to a decrease in total biomass (Pearce et al, 1976; McIntyre, 1977). Such effects, and those mentioned earlier in relation to the water column, may be avoided by selection of disposal areas with dispersive water movements.

Sea water has a considerable buffering capacity for acids and alkalies and this property can be an advantage if disposal methods and sites that give adequate dilution are used. Most marine organisms are acutely affected by pH outside the range 6 to 10 but smaller changes in the pH of sea water can be detrimental in the longer term through, for example, effects on the partial pressure of carbon dioxide. Care must also be taken to ensure that adverse effects do not arise as a result of the presence of the other constituents of acid and alkaline waste, for example, the acid wastes from titanium dioxide manufacture contain high concentrations of ferrous or ferric iron (depending on the process used) which will precipitate as floccular ferric hydroxide. Several other metals may also be present at lower concentrations. The acid waste from methacrylate manufacture contains many synthetic organic chemicals and the longer-term effects of these must be considered. Alkaline wastes which arise from various scrubbing processes, e.g. wool scouring and refinery gas emissions, usually contain organic or mineral constituents.

Certain chemicals, e.g. organophosphorus compounds, cyanides, complex phenols, strong acids or alkalies and even simple inorganic radicals such as chlorine and ammonia, can be acutely toxic to marine life. Acids and alkalies have already been discussed; certain cyanide wastes provide another example. Heat treatment wastes contain barium and unspent cyanide and have been disposed of as solids in drums in deep water areas. Eventually the drums corrode and the salts slowly leach out. The cyanide is hydrolysed to formic acid and ammonia and the barium precipitates as barium sulphate. The rate of leaching, the rate of hydrolysis of cyanide and the degree of mixing will determine the extent of any toxic zone around the drums. Chlorine is readily reduced to chloride and many of the highly toxic organophosphorus compounds are hydrolysed in sea water, although in some cases their half-life may be of the order of months and the effect of some of the degradation products is poorly understood. Not all chemicals discharged to the sea are readily rendered harmless by dilution or degradation. Certain groups, e.g. some of the halogenated organic chemicals, are relatively resistant to biochemical degradation and can persist in the environment for many years.

The organisms which decompose organic compounds are generally more numerous in coastal waters and act more rapidly at higher temperatures. As a consequence, organic wastes are more likely to decompose readily if discharged to warm or temperate coastal or shelf waters than if they are disposed of in deep water. This does not necessarily imply that synthetic organic wastes should not be disposed of in deeper waters. As a general rule it is probably safest to regard most synthetic organic compounds as being at least moderately persistent and to assume that longer-term effects have to be taken into account.

Living organisms can accumulate some substances within their tissues to a concentration greater than that found in water or sediments; heavy metals can combine with proteins, and petroleum and chlorinated hydrocarbons accumulate in lipid components. The process is usually reversible, but in many cases the rate of uptake by the organisms is substantially higher than the rate of excretion or degradation, thus resulting in bioaccumulation. The concentration factor (the ratio of the concentration within the organism to that in the ambient water or its food) may reach several orders of magnitude, and as a result predators including man may ingest larger quantities of a contaminant than they would otherwise receive. It should be pointed out that bioaccumulation per se is not necessarily harmful, and in some cases may even be beneficial, since it may represent a mechanism by which the organisms counteract the elevated levels and potentially toxic effects of certain contaminants. However, where synthetic organic substances are involved bioaccumulation is undesirable, and is more likely to be dangerous to the individual animal or in the food web context.

A particular form of bioaccumulation is that which involves contamination of the flesh of fish and shellfish through tainting, making it unacceptable for human consumption because of an acquired taste or smell. This can arise even though the substance concerned is present in the water in very low concentrations (10^{-5} mg per l). The best known tainting substances are chlorophenols and certain constituents of oils, although both of these would probably be prohibited from dumping under the terms of the Conventions.

Many metals are accumulated by marine organisms and may have a detrimental effect either on the organisms or on their predators. Because metals, being elements, are indestructible, particular attention must be paid to their concentration and quantity in a waste. The special problems posed to human health by mercury and cadmium and their compounds are well known and their disposal at sea is prohibited by all the Dumping Conventions.

Wastes containing contaminants such as lead, copper, zinc and arsenic, may be licensed for disposal only with special care. There is an increasing volume of data on the relationship between concentrations in water and those found in the tissues of organisms so that estimates can be made of acceptable levels in water and therefore acceptable inputs of materials to a given area. Much less data are available on the significance of contaminated sediments as a source of metals for benthic organisms.

The importance of the chemical state of a substance should be noted; in insoluble form, and sometimes also in complexed form, the acute toxicity of lead, zinc and copper is much reduced. In anoxic areas of the sea - as in many sediments below the top few centimetres, where hydrogen sulphide occurs - heavy metals can be virtually eliminated from the water by formation of very insoluble metal sulphides. An exception is iron, which as ferrous sulphide is more soluble in sea water than in the form of ferric hydroxide, which is the normal form under oxygenated conditions. It should also be noted that under anoxic conditions mercury sulphide is more soluble in sea water than would be expected from its solubility product (IAEA, 1971).

Certain metals and organic compounds are readily and strongly adsorbed on to and/or absorbed into, particulate matter such as clay, metal hydroxides and organic particles. There is some evidence that in this state they are much less readily available to marine organisms, so the risk of bioaccumulation or toxic effects is reduced. Extensive investigations on the bio-availability of metals and organic contaminants contained in dredge spoils have revealed very little evidence of uptake, although there is some evidence of uptake from highly polluted anoxic sediments. Similar effects may also be created by the formation of organic complexes, e.g. metals with humic substances, but the extent of biological inactivity involved is then very dependent on the stability of the complex formed. Where solubilization does occur it is probable that benthic organisms will accumulate metals through their contact with interstitial or pore water. Finally, in relation to the toxicity of metals it should be noted that valency state is important; hexavalent chromium is more toxic than trivalent chromium and pentavalent arsenic is more toxic than trivalent arsenic. Arsenic, in contrast to mercury, appears to be inactivated by biological action and, although quite high concentrations of arsenic (up to 100 mg kg^{-1}) are found in many species of marine organisms, the element is present in a highly complex "organo" form which appears to have no harmful effect on either the organism concerned or its predators.

2.3 Biological characteristics and effects

Wastes can have a biological impact in two ways. They may add biological material, especially micro-organisms, or they may modify the physical and chemical environments, thus affecting existing flora and fauna.

Sewage sludges, polluted dredge spoils and certain industrial wastes introduce organisms into the sea that are largely foreign to the marine environment. For the most part the survival of these organisms in the water column of the alien environment will be short, but elevated levels of both total and faecal coliforms have been found in surface waters after sewage discharge (Verber, 1976). In the sediments the picture is likely to be different. Micro-organisms attached to particles can exist as aggregates and the sedimentary environment could have a stabilizing effect on their viability. There is also the question of the transfer of virulence, and of resistance to antibiotics, from one group to another, or from introduced to indigenous bacteria. Studies of these aspects are becoming available (Stewart and Koditschek, 1980). It is also of concern that parasitic worms, pathogenic bacteria and viruses, protozoans, yeasts and fungi may be present in the waste in concentrations well above the minimum infective dose for humans. From the public health point of view, it is clearly important to ensure that waste contaminated with these organisms is disposed of in such a way as to prevent relatively high concentrations of pathogens returning to man via the water in recreational areas such as bathing beaches or via his food, especially shell-fish, which tend to concentrate micro-organisms and which may be eaten raw or without sterilization by cooking. The numbers and kinds of pathogenic organisms present in sludges are very variable, depending primarily on the health of the community from which the sludge is generated. Variability also occurs because the excretion of enteroviruses and pathogenic entero-bacteria is occasional and quantitatively inconsistent. It is caused not only by infection rates in the community at any given time, but also by the hour of the day, the season of the year, the ratio of industrial to domestic waste, the degree or type of treatment, and the extent of sewage dilution from seepage or surface run-off into the sewer system. However, there are usually sufficient pathogenic organisms present in raw sludges to warrant public health concern that disposal is appropriately carried out. Despite much study the exact health risk of viral pathogens has not yet been quantified. Anaerobic digestion does inactivate bacteria such as salmonellas, shigellas, vibrios and also many viral particles. Cysts of Entamoeba histolytica are killed by anaerobic digestion, even at relatively low temperatures, but the eggs or ova of the nematode Ascaris lumbricoides have been shown to survive. Lime treatment of sludge also inactivates bacteria. Generally, it is preferable to dump digested sludge rather than raw sludge, not only because of potential microbiological contamination but also because of odour and other aesthetic problems.

Turning from public health to more general ecological considerations in relation to sea disposal of micro-organisms, there is now considerable evidence that the incidence of bacterial and viral diseases of fish and shellfish can be much higher in areas receiving wastes such as sewage sludge rich in potentially pathogenic organisms. It is not known to what extent the increase of disease in marine organisms is due to the direct infection by introduced pathogens or results from a general reduction in the quality of the habitat (see Sindermann 1976 for general discussion). There is no evidence that such diseased fish present a health risk to man but their marketability is greatly reduced. The direct and indirect effects of introduced pathogens on the viability of fish and shellfish populations are difficult to quantify and require further study (Rosenfield, 1976). Nonetheless, it is clearly advisable to dispose of "biologically active" wastes in areas remote from commercial fishing grounds.

Apart from the results, discussed above, of introducing biological material into the sea, wastes can have biological effects related to one or more of the following characteristics. They may be toxic to marine organisms; they may be accumulated within organisms to a concentration substantially greater than in the environment; they may reach the environment in large amounts; they may persist for long periods of time. Some groups of chemicals are considered to be particularly hazardous to the marine environment or its resources; these are included in the so-called "black lists" annexed to the Dumping Conventions. The disposal of such chemicals is not permitted unless the compound concerned is such that it is "rapidly rendered harmless" after dumping or is present in "trace quantities" in otherwise acceptable wastes. Contracting Parties to the Dumping Conventions adopted guidelines or procedures for the interpretation of "rapidly rendered harmless" and "trace quantities". In the case of the London Dumping Convention these guidelines include biological tests and, where appropriate, also consultation procedures (LDC/IMCO, 1978)

In general terms, the biological effects of a substance introduced into the sea are dependent on the interaction of four factors - the biological system involved; the chemical (or physical) nature of the substance; its concentration; and the length of time for which an enhanced concentration persists.

It is a special feature of biological systems that because different species have different susceptibilities to a poison, and may be affected in different ways, the spectrum of possible consequences is very wide indeed. Also, it is worth noting that the species affected and the extent of the effect have different significance to the biological community and to fishable resources. It is difficult to generalise about the relative sensitivities of different groups since this depends very much on the substance involved, crustaceans for example being particularly sensitive to most organic insecticides, and algae to substances containing available copper. However, within a species the young stages tend to be more susceptible to injury than adults.

The chemical nature of the substance is of primary importance in determining how a biological system is affected. Certain chemicals (e.g. nitrogen and phosphorus) are fundamental to the existence of life, and biological production is often limited by the amount of these substances naturally available in marine waters. The effects of increasing them have been discussed in the previous section. On the other hand, the introduction of chemicals which are foreign to the marine environment or which lead to unnatural concentrations presents a potential threat through their toxicity to plants and animals. Chemicals can be very specific in their action at the biochemical level (e.g. on nerve impulse conduction or transmission, on calcium metabolism) and at the species or genus level, affecting one group but not another. Substances which produce their effects as a result of their physical as opposed to their chemical nature tend to be less specific, as discussed in the section on physical characteristics and effects.

Some chemicals are biologically active at very low concentration (e.g. trace metals, organochlorine insecticides) whilst others exert detrimental effects only at very high concentration (e.g. sulphate, carbonate). Some chemicals can produce their effects within seconds (e.g. cyanide) whilst for others much longer exposure may be necessary. Generally, it is the relationship between concentration and time that is critical. Thus on the one hand there is a minimum time to produce an effect even at the highest concentration and on the other hand there is a concentration below which the chemical will not produce an effect even after prolonged exposure. Between these two extremes time and concentration are related in a more or less straightforward way. In theory therefore it should be possible to specify for a given area the discharge conditions necessary to achieve the concentration versus time configuration that will avoid a particular biological effect occurring. In practice this involves first identifying the particular biological system to be protected and second determining the relationship between time and concentration which gives rise to an undesirable effect on the system.

Disposal will normally be planned so as to avoid or minimize lethal effects on marine biota, but sub-lethal effects might also be important, particularly if they alter migration patterns (avoidance, attraction), or change the competitive ability of a species, for example through its breeding success or feeding efficiency. The conventional method for determining the quantitative relationship between effect, time and concentration is by toxicity tests which help to assess directly the interaction of the many chemicals that might be present in a waste. One approach to determining toxicity is the establishment of a response curve using a local species over a relatively short time (often 96 hours) and with mortality as the criterion of effect. The relationship determined by these bioassay observations is then modified in various empirical ways to provide some margin of safety for species more sensitive than the one tested and for effects more sensitive than mortality. These so-called application factors usually produce an "acceptable" concentration which is one or two orders of magnitude less than that determined in the test. In most cases the conditions of exposure in the toxicity test (near constant concentration over time) are unrealistic in comparison to practical situations (declining concentration over time) but this is usually accepted as providing an additional, if not readily quantifiable, factor of safety. This approach is suitable for dealing with the acute phase of exposure but not necessarily the long-term phase for which bio-accumulation, either from water or sediment, is likely to be the most significant aspect. There is an increasing number of sub-acute tests now available which can add valuable information on the "no effect" levels indicated by acute tests.

These sub-acute tests may focus for example on biochemical or physiological processes or on alterations to the structure or behaviour of individual organisms. A wide range of possible techniques was discussed at an ICES Workshop (McIntyre and Pearce, 1980) and it was concluded that for biological effects to be identified and assessed adequately a suite of varied procedures was desirable. A recent GESAMP working group examined these techniques, graded them according to a number of appropriate criteria (specificity, sensitivity, response time, cost, etc.) and attempted to develop a strategy for their application which could be adapted to study effects in different circumstances (GESAMP, 1980b). While many of these tests are suitable for laboratory or small-scale situations, it is often desirable to continue the exposure for long periods, to study groups of species or microcosms rather than single individuals, or to examine for the effects of interactions of chemicals, e.g. synergisms, antagonisms, potentiation. In these contexts the development of studies in large enclosed systems, either in the water column or on the bottom, is relevant (Davies et al, 1980).

3 METHOD OF DISPOSAL

In considering the methods used for the dumping of wastes into the sea, it is pertinent to distinguish between:

(1) waste confined in containers, or in the form of compacted bales, and/or bulky scrap materials; and

(2) uncontained waste in bulk cargo.

3.1 Confined wastes

Wastes of a heterogeneous type can be handled much more readily in contained form than in a bulk, unincorporated state. Municipal solid wastes can, by high pressure compaction, be transformed into stable bales suitable for transportation. The primary requirements for the containers and bales are that they meet the appropriate transport regulations and retain their contents during the descent to the sea-bed, or to some pre-determined intermediate depth. In a situation where prolonged confinement is required, the containers should not break owing to the increased pressure. Their overall density should exceed 1.2 g/cm^3.

Depending on the shape, size, integrity and weight of containers, and the character of the sea bottom where they are dropped, they may behave in one of the following ways:

(1) sink intact into the bottom ooze without disintegration;

(2) sink into the bottom ooze and disintegrate;

(3) remain intact and sealed indefinitely on the bottom without significant penetration;

(4) rupture on impact accidentally, or having been deliberately charged to do so, releasing their contents on to the ocean floor and into the overlying water;

(5) implode under the high pressure, or gradually disintegrate on the bottom, releasing their contents to the surroundings.

If the container and contents sink into the bottom ooze, without disintegration, they will, in effect, be interred. Provided the bottom is not disturbed later by mining or dredging activities, the effect on the bottom water and sediment will be minimal. Disintegration after penetrating the sediments would lead to local sediment contamination. If the container explodes or implodes, because of pressure, impact or explosive, the contents will be suddenly dispersed and diluted, and if the container is so designed, its disintegration can take place as required in the water column or the sediment.

For the transport of certain packaged or containerized wastes the provisions of the International Maritime Dangerous Goods Code (IMDG Code)* must be observed. The provisions of the IMDG Code, aimed to prevent injury to persons or damage to the ship, include requirements on the safe packing, marking and labelling as well as the stowage of specific dangerous goods or categories of dangerous goods on board ships.

3.2 Bulk cargo wastes: Release techniques

Various types and sizes of disposal vessels are used for the dumping of bulk cargo wastes, but the two main types are self-propelled ships and towed barges. The discharge is either by pumping or by gravitation. On some towed barges the dumping is accomplished by remote control from the towing vessel. In larger dredging operations very often hopper dredges are used - large self-propelled vessels which dredge while in motion and which contain the dredged materials on board for subsequent disposal elsewhere. Dumping of material derived from smaller dredging operations is mainly carried out with bottom releasing hopper barges. Sewage sludge is usually discharged from hopper barges, using gravity alone or in combination with low pressure air. In some cases the discharge is made by pumping the sewage through pipes at depths of several metres below the water surface.

3.2.1 Initial dilution of cargo waste

Industrial wastes are discharged from motor vessels or from large barges towed by ocean-going tugs. The discharge is usually through pipes with diameters in the range 10-80 cm, into the wake of the moving vessel. In most cases the objective is to ensure a certain initial dilution in the wake of the vessel. The initial dilution is accomplished by turbulent eddies, which

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* The IMDG Code was prepared by the Inter-Governmental Maritime Consultative Organization (IMCO) within the framework of the International Convention for the Safety of Life at Sea, 1960 (SOLAS Convention).

distribute the waste laid down per unit length of track (travel) over the wake cross-section (Ketchum et al, 1981).

The cross-sectional area of the wake is more or less fixed by the vessel's dimensions. Thus the degree of initial dilution is controlled by the amount of waste released per unit track: at the same release rate (per unit time) a faster vessel releases less waste per unit track length than a slower one.

An example of how initial dilution can be calculated is given by the use of the empirical discharge formula* (Tromp, 1976):

$$D = C.V^{1.4}.L^{1.6}.t^{0.4}.Q_d^{-1}$$

in which D = dilution

C = constant: 0.0030 for single discharge pipe; 0.0045 for multiple discharge located symmetrically with respect to the centre line of the ship and forward of 0.2L from the rudder stock

V = speed of the vessel (m/s)

L = length of the vessel (m)

t = time after discharge (s)

Q_d = discharge rate (m^3/s)

Note: Application of this formula is limited to 3 Vt/L 40

On the basis of this equation for a vessel of 50 m, a speed of 8 knots and a discharge rate of 385 m^3/h the dilution after 5 minutes would be approximately 1000 if liquid wastes are discharged through one pipe into the wake of the moving vessel.

Density differences between waste and receiving sea water are considerably reduced by the initial dilution in the wake of the vessel, to the point where the mixture behaves as sea water. This applies to the usual initial density

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* This formula was originally developed for the calculation of the dilution of discharges of tank washings and tank residues from chemical tankers into the sea (IMCO document MEPC III/7 of 27 May 1975).

differences of the order of 10% and initial dilution by a factor of 1,000-10,000. Wastes with an average density much higher than sea water, such as wastes containing a high percentage of particulate matter, dumped in bulk and over short periods of time from an almost stationary vessel, experience little dilution on entry into the water, and sink. In such cases "initial" dilution is controlled by the dynamics of a descending heavy plume. A heavy plume behaves much as an inverted buoyant plume and entrains ambient water until its density becomes equal to that of its local environment, or until it hits bottom.

In the descending plume phase entrainment of ambient water reduces the concentration of waste. On approaching the sea floor, diluted waste that is still appreciably heavier than sea water spreads out laterally, much as a buoyant liquid spreads out at the surface. If, however, waste dilution during the descending plume phase is rapid enough to eliminate the density excess of the waste, the diluted material spreads out at the level where its density is equal to that of ambient sea water. This often occurs in strongly stratified conditions, when most of the water diluting the waste is drawn from relatively light surface layers. The mixture of waste and surface water can then easily become the same as the density of some deeper-lying layer of denser sea water.

In the descending plume phase, the dilution that can be reached depends on the depth of the water column, or more accurately, the ratio of plume diameter to water depth (Fischer et al, 1979). Generally, it is difficult to achieve dilution much in excess of 1:100 in this manner (Bokuniewicz, 1978), although under certain conditions dilution of 1:500 has been observed (Crickmore, 1972; Kullenberg, 1974). By contrast, initial dilution in the wake of a fast moving vessel has been reported as high as 1:1000 - 1:5000 in the first 5-10 minutes after discharge (Abraham et al, 1971; Ketchum, 1974; Weichart, 1977) without undue delay of the dumping operation. As already explained, the reason is that waste is then efficiently distributed along the vessel track and over the wake cross-section, i.e. over a relatively large volume.

3.2.2 Long-term transport and dispersion of cargo waste

Following initial dilution, the waste/sea water mixture moves with the ocean currents and is slowly diluted further by turbulent mixing, especially in connexion with the distortion of the waste cloud due to non-uniform current velocity ("shear"). Observations on cargo waste dilution following the initial phase have been carried out only for periods of the order of 100 hours. In this period a further dilution by a factor of 10 to 100 is usually reached. However, under calm, stratified conditions the rate of still further dilution can be very slow. In a deep mixed layer cooled from above (i.e. in autumn and winter) mixing by turbulence is rather more efficient. It should be noted, however, that there is no evidence on the long-term fate of cargo waste, especially when the release takes place in deep water. In the deep ocean a vast volume of sea water is available for dilution, but it is not known at what rate waste enters the deeper layers.

Dispersed particulates will settle according to their size, relative density, the current velocity and the turbulence in the water column. In areas with strong currents - such as tidal zones - newly deposited material can be stirred up and gradually transported away in the direction of the residual current until final deposition. Sediments with little cohesion may be more susceptible to re-entrainment than other sediments. Compensation currents in estuarine zones can cause transport of sediments back inshore.

The disposal technique and the waste characteristics can to a certain extent be adjusted to achieve the conditions for a minimum impact on the marine environment.

It can be concluded that when rapid dilution is required the waste material should be discharged into the boundary layer or the wake of the discharging vessel travelling at maximum speed. Sufficient water depth, good mixing characteristics of the discharge area and a good exchange rate with neighbouring water bodies will contribute significantly to good long-term dispersion.

3.3 Capping and burial of contaminated solid wastes

The use of relatively clean or uncontaminated sediments to cap or overlay contaminated sediments or dumped dredged material has been considered seriously for only about two decades. Recent studies indicate that under certain conditions an overlay of 2 m of clean sand can contain in place material contaminated with toxic substances (Morton, 1980, a and b), and scientists have begun to consider whether it is feasible to backfill depressions or pits, which result from aggregate extraction processes in estuarine and coastal habitats, with dredged materials containing toxic substances: once filled, such pits would be capped with clean sediments to prevent escape of toxic substances. Success in placing such caps, and keeping them in place, primarily depends upon navigational control, the geometry of the disposal mound, the physical nature of the materials, the ratio of the volume of cap material to mound material, and the physical oceanography at the dump site. Success has varied considerably. Burial in holes excavated into the sea floor followed by capping with clean material offers a more permanent solution than covering unconfined deposits on the level sea floor. The strategy of combining sand or gravel mining with disposal of contaminated dredged material and other solid wastes in borrow pits calls for permanent sacrifice of portions of the sub-bottom and temporary sacrifice of the surface of the bottom-sea floor.

Many questions must be addressed before this disposal alternative can be considered feasible and environmentally safe. Can contaminated dredged material be placed in the pit accurately? How much of the original mass will be lost during the disposal operation? What is the total volume of contaminated sediments which can be placed efficiently in a pit? Will it remain there until it can be capped? Can it be capped by conventional techniques? How thick must the cap be in order to isolate the contaminants in the sediment? How effective will the cap be and will it be mechanically stable?

Some of these questions can already be answered with confidence. For example, the technology is available to place dredged material accurately on a pit floor and it is considered feasible to deposit more than 95% of total materials in a pit using scows or hopper dredges and normal procedures. Calculations suggest that walls of pits are effective barriers to the spread of dredged sediment during discharge. Other problems still remain to be during storms. The hydrodynamic conditions in many borrow pits favour the deposition of fine-grained sediment, and such pits and therefore likely to be long-term containment sites for dredged mud. The task remains, however, to evaluate the instantaneous effects of storm waves and to answer the questions concerning the stability of the proposed sediment cap.

3.4 Incineration

The report so far has considered methods by which wastes are added directly to the water. Incineration at sea*, which comes within the scope of the Dumping Conventions, is a relatively new approach by which certain types of waste are disposed of by burning on ships at sea, with the initial impact being on the atmosphere. Rather than fragment the discussion by referring to incineration under appropriate headings throughout the whole report, the various aspects are considered together in the sub-sections below.

3.4.1 General

Many organic wastes can be destroyed by incineration. On land, this technique is applied to materials ranging from wood and domestic wastes to complex solid and liquid chemicals. Depending on the composition of the wastes, the gases produced during combustion can contain noxious or toxic substances, in which case scrubbing of the gases may be necessary. Incineration of chlorinated wastes of industrial origin for example will lead to high concentrations of hydrogen chloride in the combustion gases, and scrubbing of these corrosive gases is technically difficult and costly. To overcome this problem, incineration at sea of such wastes was started in open ovens in 1967, and flue-gases from the combustion were discharged directly into the marine atmosphere. It was expected that the sea would quickly absorb and neutralise the gases and that no adverse effects on the marine environment would occur. Since then experimental and full-scale incineration installations for the destruction of chlorinated wastes on land have come into operation, but in the meantime it has been demonstrated that incineration of chlorinated wastes at sea is safe if the process is technically well controlled.

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* A bibliography on incineration a sea has been prepared by the IMCO Secretariat and can be made available upon request.

3.4.2 The wastes

Wastes currently incinerated at sea are mixtures of liquid halogenated - usually chlorinated - compounds of industrial origin (e.g. PVC production, pharmaceutical industry, manufacture of pesticides). Many of these compounds are very persistent in the marine environment, can be extremely toxic at low concentrations both acutely and in the longer term, and are likely to be accumulated in many organisms. Dumping them at sea is not permitted by the Conventions.

Generally these wastes are suitable for incineration depending on their calorific value, overall composition (not too high chlorine content and the absence of elements which are likely to damage the incinerator) and acceptable homogeneity. Incineration of wastes which only partly fulfil these criteria is in many cases possible with addition of fuel during combustion. Incineration of solid wastes has in the past not proved successful in the type of incinerators currently used at sea.

3.4.3 The incineration process

The completeness of the combustion process is determined by incineration temperature, residence time, presence of sufficient oxygen during the combustion and by homogeneous conditions in the combustion chambers. Standards for these parameters have been set in the "Regulations for the Control of Incineration of Wastes and Other Matter at Sea" agreed as addendum to Annex I of the London Dumping Convention and the "Guidelines" belonging to those regulations. Under those regulations and guidelines for incineration of organohalogen wastes, combustion and destruction efficiencies of 99.9% can normally be achieved by a flame temperature of 1250^{o}C, a minimum residence time of approximately 1 second and a surplus of more than 3% oxygen. For a given combustion chamber these conditions can be reached by adjusting the supply of air, waste and fuel to the combustion chamber. Residence time is given by the geometry of the combustion chamber and the supply of air and waste and is thus also a design factor. Geometry is also important for ensuring the homogeneous conditions in the combustion chamber: a well-chosen geometry eliminates negative wind influences and makes better control possible.

Good incineration requires controlled injection of the wastes to achieve rapid vaporization and subsequently a homogeneous combustion. During the destruction process waste components are transformed into inorganic components: CO_2, H_2O and HCl. Other components like NO_x and SO_2 will be present in minor quantities reflecting the composition of the waste. Depending on the chlorine content of the waste the HCl content in the stack gases can reach values up to 105 g/m^3 (Lützke et al, 1979).The presence of carbon monoxide in high quantities in the combustion gases indicates incompleteness of combustion. The CO/CO_2 ratio is therefore used as a routine control parameter for determining combustion efficiency. Metals, usually present in small quantities in the wastes, will be emitted as small particulates.

Tests carried out on land-based incinerators and on board incinerator vessels (Ackerman et al, 1978; Lützke et al, 1979; Rijkswaterstaat, 1979) show that wastes can be incinerated with a destruction efficiency of more than the 99.9% required by the London Dumping Convention. Incompletely destroyed or newly formed chlorinated compounds can however be present in detectable quantities. In fact a wide range of compounds can be found some of which belong to the types of organochlorines which are commonly present in the atmosphere. The number of individual compounds tested is however limited, and for compounds which are extremely stable at high temperatures (e.g. PCBs) or are very toxic in low concentrations, further research is desirable. In this respect it is noteworthy that incineration at sea of Herbicide Orange containing tetrachlorodibenzo-dioxins has proved successful. No information is available on the efficiency of incineration at sea of organohalogens other than chlorinated and fluorinated compounds.

3.4.4 Plume transport

The flue gases produced during the incineration process are emitted into the atmosphere, where they rise to considerable heights due to their high temperature. Further transport of the combustion plume will depend on the meteorological conditions of the site (such as wind, atmospheric turbulence and the height of the mixed layer) and will follow a distribution pattern generally as described by Pasquill (1974).

Most information on the distribution of pollutants in atmospheric plumes relates to overland situations. Physical conditions in the marine atmosphere can be significantly different (Roll, 1965; Krause, 1977). The typical differences are:

(1) wind speeds at sea are generally higher than over land;

(2) the surface roughness of water is generally lower than that of land surfaces;

(3) the stability of the atmosphere above the sea is generally greater than over land (at mid-latitudes).

The last two factors have the consequence that the turbulence level in the marine atmosphere is lower than above land. Further, low surface roughness and absence of pronounced vertical air movements generally favour inversions at lower altitudes than over land.

The effect of these differences on the behaviour of smoke plumes over water is complex. A lower turbulence level reduces the rate of plume growth where this is no longer due to the initial buoyancy of the plume. Another aspect of some concern is that a plume, once trapped in an inversion, may travel very long distances virtually without further dispersion (beyond that which is reached by the time the plume arrives at the inversion). On reaching land, the plume may be broken up by turbulence originating at ground level and intermittently cause high ground level concentrations ("fumigation").

Field observations on plume rise and dispersion over the sea are few and this constitutes a serious obstacle to the evaluation of the distant consequences of marine incineration. Remote concentration measurements of hydrochloric acid in the plume of incineration ships with a shipbound so-called lidar system which uses the technique of differential absorption and scattering of short pulses of laser radiation indicated concentrations up to 15 ppm in the centre of the plume, and suggested the decrease of HCl concentration down-wind from the incineration ship was quite slow, with 1 ppm at a distance of 15 nautical miles (Weitkamp et al, 1981). On other occasions concentrations of about 1 ppm have been measured at relatively short distances from the ship (Wastler et al (1975)). On the other hand, it is known that relatively undiluted combustion gases can be carried over great distances under stable conditions, e.g. satellite images show plume transport over distances of more than 100 km. Though no causal relationship with incineration could be assessed in coastal areas, a slightly irritating atmosphere has been noted at distances of approximately 50 km in the direction of the prevailing wind (Oslo Commission, 1977).

Hydrochloric acid in the combustion plume will to a large extent be absorbed by the condensation nuclei in the plume, which as a result may show a tendency to grow to precipitable sizes. Under stable conditions of relatively low humidity it may however be expected that absorption of HCl by the sea surface is unlikely within approximately 100 km from the ship. On the other hand, showers will wash the HCl quickly into the sea. Particulates emitted by the oven on the ship (metals etc.) will as a result of their weight fall out into the sea at short distances from the ship.

3.4.5 Effects on the environment

When incineration is carried out with the required efficiency, organohalogenated substances are present in the combustion gases only as traces. Effects on the environment may be expected from the hydrochloric acid, organohalogenated substances and particulate metals as potential pollutants present in the combustion plume. The contribution of other components such as SO_2 is considered to be negligible. Field surveys designed to quantify the effect of absorption of HCl by the sea surface detected no significant lowering of the pH of sea water where the combustion plume touched the ocean surface (Wastler et al, 1975). The same surveys could not detect an increase of the content of toxic metals and organochlorines of the sea water, nor measure any change in the composition of the plankton. Toxicological studies on combustion gases (Rijkswaterstaat, 1979; E.P.A., 1979) indicate that toxicological effects which do occur are localized and temporary. Birds may be attracted by the combustion plume or the incinerator vessel. Gulls have been observed to pass through the combustion plume without any visible effect but smaller migrating birds with rapid wing movement show respiratory disturbances.

3.4.6 Site selection

Because the process of incineration and the subsequent dispersion of the combustion products differ from ocean dumping, there are additional factors which should be considered in the selection of an appropriate incineration site.

Although ecological effects of incineration have either not been demonstrated or have shown to be transitory, one would tend not to select for incineration operations locations such as fish breeding or nursery grounds or areas with high productivity or important fish stocks. Sites with good oceanic dispersion characteristics would be more favourable than those with little current or turbulence. Incineration vessels attract sea-birds and also migrating birds. In selecting an incineration site, migratory routes particularly of birds but also of mammals and other organisms should be avoided.

The atmospheric dispersal characteristics of a proposed area are of particular interest. Information on wind speeds, air and sea water temperatures, frequency and altitude of inversions will be needed for an evaluation of atmospheric stability. Long-range transport of combustion gases under stable atmospheric conditions may lead to situations in which the atmosphere in coastal areas is experienced as slightly irritating. The geographical situation, particularly the distance to inhabited or recreational areas, and the prevailing wind direction, should therefore be given due attention.

Furthermore, a number of technical considerations should be noted. Incineration of a waste load will generally take a few days, depending on the capacity of the vessel. Spells of bad weather may force interruption of the incineration process and may under certain conditions involve an increased risk for the incineration vessel. High sea states which make incineration impossible are related to high wind speeds, water depth and wind fetch. Bottom topography, water depth and the presence of submarine cables and pipelines may be relevant in the selection of anchoring sites.

Finally, incineration should not hinder other uses of the sea. The presence of a combustion plume close to intensively used shipping lanes or areas with oil or gas exploration and exploitation is likely to be undesirable. Also the tolerance of the other activities like fishing and sand and gravel extraction should be considered.

4 SITE SELECTION

The selection of dumping sites should be made in such a way as to minimize interference with other present and potential uses of the sea. These other uses include fishing, aquaculture, mining and drilling for minerals, recreation, transportation and national defence. In addition, sea water is used for processing and desalination, cables of various kinds are laid on the sea floor, and a range of energy-generating programmes in the marine environment are under present investigation. Many of these uses can be adversely affected by the material dumped or may not be compatible with the disposal operation. Dumping and incineration sites should be selected to minimize also the environmental impact of the waste. The assessment of the environmental impact is therefore one of basis of site selection. In this connexion, the presence of other dumping sites or other sources of input in the vicinity of a proposed site must be taken into account, since this could influence considerations of amounts and types of wastes dumped at a site and the frequency of dumping operations.

Before starting the assessment of possible effects the requirements of the Dumping Conventions must be studied carefully since these may contain specific criteria for selecting sites for the dumping of certain wastes, e.g. sites for the disposal of containerized wastes and scrap metal have to be situated outside given distances from the nearest coast and at minimum water depths.

With these remarks in mind, a number of considerations relevant to site selection are set out in the following paragraphs under headings referring to physical, sedimentological and biological considerations.

4.1 Physical considerations

Given that site selection should be based, among other practical criteria, on a rational assessment of nuisance or hazard likely to result from waste disposal, then the questions of importance from a physical point of view are how frequently (more precisely, with what probability) certain critical regions, such as bathing beaches and biologically sensitive areas, are reached by waste clouds; how dilute waste clouds are when this happens; and how long they tend to stay there.

The spreading of a pollutant injected at sea is governed by two different processes:

(1) advection, caused by relatively large-scale water movements transporting a given property and thus effecting a local change in concentrations; and

(2) diffusion, caused by comparatively small-scale random and irregular movements giving rise to a local exchange of a given property without causing any net transport of water. In this context the effects of diffusion are also called "mixing".

In contrast to advection by currents, which may be well defined as to direction and velocity, diffusion is omni-directional and statistical. It can be described by formulas and parameters similar to those of molecular diffusion, but this well-known physical process has only a very small effect in the sea compared with turbulent diffusion or shear diffusion described in sections 4.1.2 and 4.1.3 below.

It is not always easy to decide precisely if a process has to be considered as diffusion or as advection, since the definitions are much dependent upon time and space scales. To avoid any confusion reference in the following paragraphs, wherever appropriate, has been made to transport and mixing which are caused by advective motions and by diffusion, rather than to the processes themselves.

In assessing the effects of wastes dumped into a marine system some calculations are required of (a) transport and (b) mixing processes, with additional consideration of chemical reactions, biological cycles, deposition or reentrainment at the sea floor and transfer at the sea surface, all of which may be significant from certain points of view. The sections below highlight some of the more important physical components involved in transport and mixing.

4.1.1 The oceanic flow environment

Key flow properties governing the fate of wastes injected into the coastal and open ocean are the intensity of turbulence and shear (i.e. velocity gradient) (Csanady, 1973). Several classes of motion, characterized by widely different time scales, contribute significantly to turbulence and/or shear levels. These include surface waves, tidal and inertial oscillations, wind driven surface currents, and the circulation of the ocean interior.

From the point of view of transport and mixing processes, the most important feature of the oceanic environment is "stratification", i.e. the stable arrangement of layers of slightly different density on top of one another. The lightest layer occurs at the surface and is more or less homogeneous (of constant temperature, salinity and density) to a depth ranging typically from 10 to 100 metres. Below the surface mixed layer is found a layer of relatively rapid density change, known as the pycnocline, within which the density increases downward by something like one or two parts per thousand. Beneath the pycnocline density change with depth is weaker, but still significant. Near the sea floor, a second mixed layer ("benthic boundary layer") is present.

The importance of stratification arises from its effect on the hydrodynamic stability of the flow, i.e. the suppression of turbulence and hence of vertical mixing. As a consequence, overlying layers in the interior of the deep ocean generally slide over one another with little exchange of materials. The principal exceptions are the surface and bottom mixed layers. In shallow seas (of about 100 m depth or less) in winter the mixed layer extends over the entire water column. In summer, however, even waters as shallow as 10 to 30 m may become stratified.

Surface waves, especially storm waves, are an important source of turbulence and they also enhance certain transfer processes at the air-sea interface and at the sea floor in shallow water. Turbulence accompanies waves near the surface where smaller waves break, forming whitecaps and sea spray, as well as near the sea floor, where an oscillating turbulent boundary layer develops in shallow water. The resulting enhanced bottom stress causes resuspension of particulate wastes.

In many coastal locations tidal <u>oscillations</u> contribute most of the kinetic energy of observable motions. Shallow water tides are long waves propagating shoreward from the edge of the continental shelf and they occur with great regularity. The typical velocity of tidal motion over broad flat shelves is 0.2 - 1 m s^{-1}. During a full tidal cycle, individual particles experience elliptical displacements, the major axis of the tidal excursion ellipse being typically some kilometres long. For example, as the coastal waters move bodily past a continuously discharging waste outfall in the course of their tidal oscillations, the waste is distributed over a considerable water mass, much as if the waters stood still and the outfall moved over an elliptical path, several kilometres long and wide, in the opposite direction to tidal motion. A comparable situation exists with a discharging vessel.

Tides are also responsible for much of the turbulence and shear of a coastal region. Considerable shear is associated with the bottom boundary layer of a strong tidal current, which leads to a large horizontal shear diffusivity (cf. later).

Inertial oscillations are prominent especially in non-tidal shallow seas such as the Baltic Sea. In many respects their physical effects on transport and mixing processes are similar to those of tides, although inertial oscillations are not continuously present: they are excited by sudden wind impulses.

<u>Wind-driven surface currents</u> dominate the flow field of coastlines with negligible tidal motions. They are generally of the same amplitude as typical tidal currents (about 0.3 m s^{-1}) but occur much less regularly, according to the passage of weather cycles. The shear in such currents is generally intense, at least near the surface, because the wind rarely blows exactly parallel to the deep current.

In wind-driven currents the Coriolis force due to the rotation of the earth plays an important role because these currents generally persist for a day or two, long enough for such effects to become prominent. Effects of earth rotation further enhance shear, and make it complex with both the magnitude and direction of horizontal velocity varying along the vertical.

Simple frictional models of near-shore flow (so-called Ekman models) show considerable circulation in a cross-shore transect even when driven by longshore directed wind.

Interior oceanic circulation, away from surface, bottom and coastal boundary layers, is also often driven by winds, although indirectly, through a piling up or depletion of water in the surface layers. Other driving mechanisms are thermo-dynamic, such as differential heating or cooling of water masses, evaporation and the influx of fresh water from land. Typical interior velocities range from a few centimetres per second in quiescent deep regions to several metres per second in narrow, intense currents. The ocean interior is stratified and only sporadically turbulent in most places, and suspended particles move with little mixing along constant density surfaces (isopycnals). The topography of these surfaces therefore generally determines which way a waste cloud will be advected. Although mixing is slow across the isopycnals, there may be considerable shear diffusivity along isopycnal surfaces because of the generally strong shear between adjacent isopycnals. Thus waste clouds moving in the ocean interior may cover long distances along isopycnal surfaces, and become stretched out over a similarly long range of these surfaces, while their vertical extent remains quite limited.

The isopycnal surfaces are generally close to their horizontal static equilibrium position, their inclination being mostly 1:1000 or even 1:10,000 and rarely as high as 1:100. Nevertheless, as a waste cloud may travel many hundreds of kilometres along such a surface, it can suffer vertical displacements measured in kilometres. This is especially the case in so-called "frontal" zones, where gently inclined isopycnals intersect the sea surface and evidence is often found for substantial particle movements downward along some isopycnal surfaces, upward along others.

As already noted, a benthic boundary layer forms on the sea floor, in which turbulence is vigorous and mixing efficient. The mean flow velocity varies with distance from the sea floor, both in magnitude and direction, under the influence of the earth's rotation. Transport in this layer may be in a direction quite different from the current a few tens of metres above the sea floor. There is also generally strong shear induced diffusion due to the variable velocity. Quantitative knowledge of the benthic boundary layer in the deep sea is sparse.

4.1.2 Turbulent diffusion

In a turbulent environment, such as is found in surface, bottom or coastal boundary layers of the ocean, the primary physical factor distributing waste over a larger region of space than occupied initially is random spreading by turbulent eddies. A waste cloud is most efficiently distorted and made larger by eddies similar in size to the cloud. The net effects may be quantified by means of a mixing coefficient which is proportional to the product of an eddy length scale and a velocity scale, much as molecular diffusivity is the mean free path times molecular velocity. The eddy velocity scale is a measure of the intensity of turbulence. The effective length scale is either the size of the waste cloud or the size of the principal eddies, whichever is smaller. Thus while a cloud is small, so is the eddy diffusivity quantifying its growth rate, but once the cloud is as large as the eddies, a larger diffusivity applies which no longer increases with cloud size.

Turbulent eddies are usually characterized by a length scale and a velocity scale. In the surface and bottom boundary layers or in the coastal ocean these scales are typically a few tens of meters and 1 cm s^{-1} respectively and the corresponding eddy diffusivities applying to large clouds are of the order of 100 $cm^2\ s^{-1}$. In a well mixed water column without significant velocity shear this applies to vertical or horizontal diffusion. However, stratification reduces vertical mixing rates, while once a waste cloud has spread vertically over a layer of fluid within which the horizontal velocity varies significantly from top to bottom, a composite process known as "shear induced diffusion" takes over as the principal mechanism of horizontal spread.

4.1.3 Shear induced diffusion

A layer of fluid with significant shear from top to bottom advects adjacent laminae of a waste cloud at different velocities, leading eventually to large horizontal distortion and to a considerable increase in the contact surface between waste and ambient fluid. Vertical mixing between faster and slower moving laminae greatly increases cloud size at all levels. The net result is horizontal cloud growth at a rate greatly in excess of that produced by simple turbulent diffusion. This rate may be quantified by a shear diffusivity. Shear induced diffusion is an important mixing process for time scales up to several weeks. Over continental shelves typical shear diffusivities are up to 10^6 cm^2 s^{-1} or four orders of magnitude greater than typical turbulent diffusivity. Such a diffusivity applies to a cloud which has spread vertically to the entire available depth.

In the interior of the ocean a similar process operates along isopycnal surfaces and leads to the stretching out of clouds along these surfaces. However, the shear diffusivity applying to this process is different in character, because it depends on the cross-isopycnal spread of the waste cloud. The greater this spread, the larger (in general) the velocity difference available to stretch the cloud along the isopycnals.

Whether over continental shelves or in the ocean interior, quasi-horizontal mixing can often be quantified in terms of a "diffusion velocity" as defined by Joseph and Sendner (1958). The diffusion velocity in the surface layer is in the range of 0.5 to 1.5 cm s^{-1} and in the interior of the water column diffusion velocities in the range of 0.01 to 0.1 cm s^{-1} have been observed over time scales of hours to weeks.

4.1.4 Vertical mixing

Vertical mixing (cross-isopycnal mixing in the ocean interior) is everywhere in the ocean more intense than mixing caused by molecular diffusion. Turbulent vertical mixing in coastal, surface, and bottom waters has already been described. In the ocean interior sporadic turbulence due to intermittent hydrodynamic instability is still an important cause of mixing. It is supplemented by the breaking of internal wavelets on otherwise stable density interfaces and also by so-called "double diffusive convective" motions caused by differences in the rates of heat and salt transfer. Typical vertical mixing coefficients quoted in the literature for the interior of the water column, beneath a pycnocline or the main oceanic thermocline, are in the range of 0.05-1.0 cm^2 s^{-1}, depending on the intensity of the various processes involved.

4.1.5 Modelling of transport and mixing in the ocean

Any set of calculations, however simplistic or crude, aimed at the quantitative assessment of the factors discussed above, may be thought of as a "model". The most complex models are three-dimensional numerical models yielding appropriate probability distributions of concentrations, exposure time, etc. These are not necessarily the most useful because their very complexity may hide important factors of waste cloud behaviour. Also, the sophistication of the model actually used should be commensurate with the knowledge of quantitative parameters affecting transport and mixing phenomena. There is little point in carrying out elaborate calculations when the key quantitative data used in them are crude guesses.

Modelling the transport and mixing or diffusion of a waste cloud is possible in principle using equations containing representative variables which describe adequately the behaviour of the systems involved. In practice the enterprise is difficult on account of the random variability of ocean currents. State-of-the-art models generally pre-suppose steady conditions and predict much more regular behaviour than observed.

In coastal waters, one common method is to calculate waste concentrations in a steady state model based on a long-term mean velocity as measured by a current meter anchored at a fixed point. In fact a low long-term mean velocity is often the end result of strong episodes of opposing flow, during each of which the waste is rapidly flushed away. In the steady state model this is not simulated and excessively high concentrations are predicted. Model predictions of this kind should be very carefully verified before any credence is placed upon them.

The engineering science of waste behaviour prediction in randomly varying currents is in its infancy, and investment of effort in this field might pay dividends.

4.2 Sedimentology

Marine sediments and suspended particulates have a high potential sorption capacity for many types of inorganic and organic waste substances. Pollutant distribution coefficients (defined as the ratio of the pollutant concentration in the sediments to that in water) are often as high as 10^5-10^6 and attest to the ability of sediments to remove effectively these elements from surrounding sea water. The higher distribution coefficients are typically found in the fine grained sediments which exhibit a greater specific surface area for sorption. Organic matter content, clay mineralogy, lithology and metal oxide hydration potential are other factors which affect the sorption capacity of sediments. In some cases, much of the contaminant can be virtually immobilized by the sediment through a very strong adsorption process (Stanners and Aston, in press). Despite strong sorption of some substances to sediments, the process is not totally irreversible and following a change in concentration gradient, contaminants may leach back into the water column suggesting that sediments can act as a source of these materials as well as a sink.

In high energy regions sediment dispersion will occur and resuspended sediments with their associated pollutants may be transported substantial distances horizontally and vertically. Movement of contaminants away from the sediments is governed by the partitioning of a given pollutant between suspended particulate and aqueous phases and the rates of vertical mixing in the overlying water column. Furthermore, through the filtering activities of benthic fauna, contaminants on suspended sediments can enter the food chain or be recycled to the sediments via biodeposition.

When liquid or dissolved wastes are present in the overlying waters, in the absence of turbulence relatively little of the contaminants will become fixed to the bottom sediments. That which is sorbed by undisturbed sediments usually occurs in the upper surface layer of the sediments. Penetration of the contaminant into the deeper layers solely by pore water diffusion is slow, for example 10^{-12} cm^2 s^{-1} for plutonium (Aston and Stanners, 1981); however, bioturbative processes may rapidly carry surface sediments contaminated with pollutants down to several tens of centimetres.Sediment re-working activities of infauna and epifauna do not result only in downward transport; materials ingested at depth are also deposited at the surface of burrows as faeces and pseudofaeces. Furthermore infauna pump a significant amount of water into and through the sediment, a process which can substantially enhance the transport of material from sediment to overlying waters and vice versa (Aller, 1978). Owing to relative biomass distributions throughout the ocean, bioturbation ought to be greater in shelf and slope areas than in the abyss. Biological mixing rates are extremely difficult to measure but have been estimated to range between roughly 10^{-8}-10^{-11} cm^2 s^{-1} at abyssal depths and 10^{-5}-10^{-8} cm^2 s^{-1} in coastal sediments (Guinasso and Schink, 1975; Dayal et al, 1979).

In areas where larger amounts of organic materials reach the sea bottom, either by high productivity or by dumping, the consumption of oxygen by decomposition reactions may exceed the rate of oxygen supply. A series of secondary oxidizers will be utilized by the bacteria leading to the production of hydrogen sulphide, the depletion of sulphate ions, and the production of methane. These processes influence the redox potential (Eh) and the pH values of the upper sediments and, in certain areas, of the overlying water. The redox conditions and the pH values at and in the sediments influence the behaviour, remobilization and even toxicity of many contaminants.

The increasing weight of overlying sediment tends to compact the deeper layers and slightly reduce the pore water fraction causing some upward movement of pore waters.

Sediment stability is another factor which must be taken into account in any waste disposal site assessment. Submarine mass movements can involve enormous volumes of sediment. These occur as slumps, slides, debris flows and turbidity currents which are activated by a number of factors including tectonic events, sediment overloading, erosion and changes in sediment compaction. Continental margins are most prone to these disturbances and some mass movements have been known to occur on slope angles of as little as 0.5°. In deep sea floor regions small-scale effects of mass movement such as creep may also be important.

4.3 Biological considerations

An evaluation of the biological sensitivity of a potential dumping area should be made either by a study of existing data or if necessary by new surveys. Several of the relevant criteria have already been discussed, and the main considerations (usually associated with the use to which particular areas are put) are summarized below:

Fishing grounds and aquaculture sites Dumping in active fishing areas can affect the living resources of the sea and may interfere with fishing vessels. Some kinds of waste may damage or foul fishing gear.

Breeding and nursery grounds Certain grounds although not in use for fishing may be important to fish stocks as spawning, nursery or feeding areas, and the effects of dumping on these grounds should be considered.

Migration routes Migrating species use their acute senses for orientation to their native region or for movement from one area to another. Dumped materials may disrupt the physiological processes used by the fish for detection, and may mask natural characteristics of sea water or tributary streams, thus confusing migrating species which consequently lose their direction, go unspawned or fail to find food.

Areas of high productivity or other special interest Some sea areas may be judged as requiring particular attention because of unusually high biological productivity. This may be related to features such as estuarine export, cyclonic gyres, upwelling, boundary currents or ocean fronts producing conditions conducive to high nutrient supplies with resulting plant production and zooplankton concentrations on which fish and other marine life depend. Dumping of toxic substances in such areas could reduce production while the addition of wastes containing nutrients, whether organic or inorganic, may augment primary production and result in eutrophication, especially in estuaries and coastal waters. In addition, the effects which dumping could have on the habitats of rare, vulnerable or endangered species should be recognized. Some such habitats are formally designated as protected areas, for example under national jurisdiction, but it is not always practicable to manage some threatened species of high mobility even within protected areas.

Depending upon the characteristics of waste materials, certain general precautions may be observed in planning the disposal operations. If the waste contains toxic materials, the dilution achieved during disposal and the subsequent mixing with sea water will determine whether the concentrations are such as to damage the marine biota. For substances that settle to the bottom the avoidance of areas of high benthic productivity will help to reduce impact but the sacrifice of part of the benthic population may be regarded as acceptable and assessed as a component of the real "cost" of disposal.

5 INVESTIGATIONS AT THE SITE AND ASSOCIATED EXPERIMENTAL WORK

The observations required at the site of disposal fall into two basic categories: pre-disposal investigations designed to assist in the selection of the site or to confirm that the one selected is suitable, and post-disposal studies to check that the effects are as predicted. Whether at the pre- or post-discharge stage, the observations will be concerned with physical, chemical and biological characteristics. Ideally, initial observations should extend over at least one year to detect seasonal variations, but post-disposal monitoring may be reduced either in scope or frequency in the light of data from the early phases. The observations will need to be carried out both in and around the disposal site and it must be accepted that it may prove necessary at any stage to change the position of the site in the light of the observations made. With regard to post-disposal monitoring it must be recognized that long-term variations arise as a result of purely natural causes and it may be difficult to distinguish such changes from those which are induced artificially, particularly in relation to populations of organisms.

Most of the approaches discussed involve in situ observations sometimes with associated laboratory measurements. Other data-collecting techniques such as remote sensing are rapidly developing and may provide valuable additional information. Attention is therefore paid also to those techniques below.

5.1 Physical observations

The physical characteristics of the ocean environment which influence the transport and dispersion of waste vary within broad limits from place to place. When a given location is first under consideration as a candidate dumping site, the main characteristics are usually not known in sufficient detail or accurately enough for reliable modelling of waste effects. While much can be inferred from an analogy with locations broadly similar to the candidate site, final selection of a site for major dumping operations should be preceded by a comprehensive series of observations designed to quantify the key transport and mixing properties of the sea area in the neighbourhood of the site.

Generally these observations should consist of at least the following:

(1) Hydrographic surveys elucidating water mass properties (temperature, salinity, density) over the entire water column and extending horizontally over the entire region likely to be affected by the waste. The precise horizontal extent of the region to be surveyed will depend on the nature of the dumping and will vary from one oceanic domain to another: in shallow seas the survey area may need to extend only about 10 to 100 km round the site, while in the deep ocean the hydrography of a much wider region needs to be explored, at least as to its gross features, extending perhaps even up to 1,000 km from the site.

An important aspect of hydrography is seasonal variability, which mainly affects the top 100 m or so of the water column. At mid latitudes, summer conditions are often characterized by strong stability (stratification), while in autumn and winter convective overturn takes place near the surface, extending in shallow seas right to the bottom. The seasonal progress of stratification should be documented in detail for the proposed site area.

(2) Moored current meter observations at least at the proposed site, at a number of levels, especially where initial waste spreading is likely to occur (e.g. near the surface if initial dispersion is to be within the mixed layer). A time series (usually one year) of current observations is necessary to obtain statistical measures such as mean square current speed, autocorrelation of the time series, and long-term simulated particle trajectories (progressive vector diagrams). The deployment of several moorings in the site area is desirable to give some indication of horizontal variability, as well as a back-up device, to ensure that adequate evidence on current climatology is available for all seasons at all important levels.

(3) Meteorological data collection. For the proper interpretation of oceanographic observations it is necessary to have recourse to weather maps of the region under study and to know local surface weather, such as wind speed, direction, air temperature and humidity. It is desirable to deploy a meteorological buoy to collect direct over-water observations, since extrapolation from land stations can be somewhat inaccurate.

In addition to the above categories of observation, which are included in the routine programmes of meteorologists and oceanographers, it may be thought desirable to conduct special studies of dispersion using what are known as "Lagrangian tracers": e.g. fluorescent dye, radioactive or microbiological tracers, drogues and sea-bed drifters. Furthermore, remotely sensed data (from aircraft or satellite) are useful in determining the horizontal distribution of surface temperature, surface drift of coloured patches of material, or any boundaries ("fronts") between different water masses. All these observations provide further important clues to water movements and mixing processes.

If the waste can cause discolouration or if it contains solid materials which will increase the load of suspended matter or which will fall to the sea-bed, then pre-disposal measurements should also include:

(1) an assessment of the normal range of turbidity and suspended solids content of the water column; and

(2) an assessment of the nature of the bottom and geological conditions in the area (e.g. sediment type; presence of outcrops, trenches, ridges).

Useful tools in the conduct of such observations are turbidity meters, grab and core samplers, underwater TV cameras and side-scan sonar. The sea-bed samples will need to be analysed for particle size distribution and chemical constituents which may be affected by the waste.

Once disposal has commenced, similar observations will need to be made to establish the scale of any effects that may occur as a result of the solids content of the waste; these may be coupled with chemical observations.

5.2 Chemical observations

As with certain of the physical observations the chemical observations conducted in and around the site of disposal should be related to the type of waste(s) involved. Although in principle chemical analyses can be easy and many different determinations can be performed on a single sample, they can be expensive, in terms of manpower and facilities. Consequently, as with all observations, they should be conducted only if there is a clear objective. Thus if the waste is dispersed on the surface waters, there will generally be no need to characterize the sea-bed chemically unless the waste contains constituents which could reach the sea-bed by sedimentation. Similarly if the principal constituents of the waste are solids the number of observations required in the water column will be limited unless the input is more or less continuous. The range of chemical constituents can also be adjusted depending on the expected chemical composition of the waste to be dumped.

Since the objective of the post-disposal observations will be to establish the scale of any effect, the observations carried out can be tailored to the expected effects. Thus, attention should be paid to an assessment of the distribution (in the water column or on the sea-bed as appropriate) of any major chemical constituent in the waste, which may range from simple suspended solids or nutrients to measurements of pH or more complex observations and general characteristics such as organic carbon content. These measurements will serve to map the distribution of the waste after disposal and provide a useful check on the distribution pattern predicted by a knowledge of the physical characteristics of the area. They will also serve to check that the expected initial dilution patterns, which may be critical if the waste has a high acute toxicity (e.g. as from pH effects) are being observed. In this context it should be noted that a wide range of chemicals - e.g. metals and oil soluble substances - tend to accumulate in the surface microlayer. As this is an extremely active zone biologically, attention should be given to analysis of the surface layer and assessment of the biological implications. This will, however, require the use or development of routinely deployable sampling devices.

Attention must also be paid to those substances which, although perhaps not present in the waste in major quantities or concentrations, may, because of their persistent nature, accumulate either on the sea-bed or in biota. It is unlikely that such substances would accumulate to a detectable extent in the water column. Although disposal at sea of substances such as mercury, cadmium, organochlorine pesticides and PCBs is prohibited under the terms of the Dumping Conventions it should be noted that they may be present in trace concentrations in wastes such as dredge spoil and sewage sludge, as well as certain industrial wastes. If they are found it may be necessary to monitor their presence in sediments and biota to establish whether accumulation is occurring.

Several of the substances mentioned in the so-called "grey lists" of the Dumping Conventions with a view to demanding special care if proposed for dumping are persistent, e.g. zinc, copper, lead and arsenic. Thus although such elements are naturally present in the environment, they should be measured both pre- and post-disposal if they are present in the waste in appreciable concentrations. Again the main emphasis should be on the sediments and biota, especially benthic biota. Sufficient analyses should be done to allow the detection of changes against the background of variation due to size, age and sex of organisms.

Although the substances cited above are all mentioned in the Annexes to the Conventions it should not be assumed that this is an exclusive listing. There is a wide variety of chemicals, any one of which may be worth consideration either as a tracer or because it has potential to accumulate. Nor should the list be taken as an indication that all the chemical observations are specific to a particular determinant. There are a number of less specific analyses which may be useful, e.g. analysis of the water column for pH, or total nitrogen, or the analysis of sediments for the presence of organic carbon.

5.3 Biological observations

As with physical and chemical observations, the frequency and intensity of pre- and post-dumping monitoring of biological variables should be compatible with the scale of the disposal operation and the degree of risk to potential resources. Pre-monitoring surveys should be sufficiently extensive to cover the whole of the area potentially at risk, and critical variables may be identified which should be monitored frequently in preference to a larger number of variables that require less regular attention.

An assessment of the phytoplankton and zooplankton biomass and productivity before disposal establishes a general picture of the area, but these parameters are so variable in space and time that they are of limited use for monitoring unless carried out very frequently and this is usually impractical. Observations of the plankton immediately following disposal can help to determine if acute effects are occurring but again problems of temporal and spatial patchiness interfere with interpretation. An alternative way of examining for effects in the water column is by the use of bio-assays whereby the biological quality of the water is measured directly according to a standard procedure. Examples of this technique are given by Stebbing (1980).

Monitoring of the benthic and epibenthic flora and fauna is likely to be more informative because they will be subjected to not only the influence of the overlying water column and any changes that occur within it, but also to changes in the sediments brought about by solids in the waste. Pre-discharge observations are taken to provide a baseline or bench mark by which to judge subsequent data so that they should concentrate on variables which are likely to respond more specifically to pollution than to natural phenomena. A description of the benthic and epibenthic communities should be accompanied by information on the sediment structure and bottom topography. Particular attention should be given to measuring the community by quantitative methods as some potentially useful techniques for identifying pollution stress in communities rely on measures of the numbers and diversity of organisms (Gray, 1980). There is also a number of variables that can be measured readily at the level of the individual and which can be indicative of stress (Bayne, 1980). They probably offer a more sensitive method for indicating that a change has occurred after disposal (see GESAMP, 1980b), and they may be utilized initially to supplement data gained from the community survey.

Information on the resources, particularly fisheries, of the area is important. Data should include density and diversity, seasonality, size distribution, and body burdens of pathogens and potentially harmful substances.

5.4 Remote sensing

Information on a number of phenomena, processes and parameters to be measured in both pre-dumping and post-dumping monitoring phases can be acquired using remote sensing techniques. These techniques use primarily optical and electronic sensors carried on fixed wing aircraft or satellites but also include the use of telemetry drogue buoys (Kerut and Haas, 1979) and acoustical detection systems (Proni, 1980) to study the fate of ocean dumped wastes. Further development of this relatively new approach is necessary, but it has already shown its usefulness as a research and monitoring tool providing a synoptic and detailed picture of large sea areas which otherwise could only be made with an immense effort by in situ measurements. It must be recognized, however, that certain ground meaurements for interpretation of the images will also remain necessary. Some examples of application of the approach in relation to ocean dumping are:

(1) detecting coastal frontal systems which can be of importance because toxic metals can be associated with them (Szekielda et al, 1972);

(2) Detecting warm core rings (anticyclonic Gulf Stream eddies) which may carry dumped wastes over considerable distances (Bisagni, 1976);

(3) surveying transport of floating materials (e.g. oil) with currents or frontal systems (Klemas, 1980);

(4) establishing productivity patterns in the sea (e.g. by chlorophyll distributions);

(5) establishing mixing patterns in estuaries.

6 CONCLUSIONS AND SUMMARY

The foregoing pages suggest that by considering the nature and effects of any given waste from the physical, chemical and biological points of view; by conducting appropriate field investigations, laboratory experiments and model studies; and by recognizing other uses of the marine environment, it is possible to make rational practical decisions on whether and where the waste may be disposed of in the sea, and to quantify the degree of risk to other users associated with the disposal. A basic initial question will be whether to opt for a site offering vigorous and extensive dispersion and dilution immediately after release, or whether to prefer a location where the waste will be relatively confined in the area of the dumping site.

In principle, the first option is attractive for wastes of limited life-time, which are eventually rendered harmless by natural oceanic processes. Such wastes, with a lifetime of the order of days once released into the sea, are of concern only if they are discharged so close to the coast that they can reach the shoreline before degradation. Sewage sludge can cause more lasting effects by introducing a substantial volume of oxygen-demanding material together with various plant nutrients and microorganisms. If dumped in a region subject to only slow or inefficent flushing, the effects of sewage sludge are detectable on the local benthic environment, as shown by observation in such places as the outer Clyde estuary and New York Bight. However, a site flushed by vigorous currents transporting an adequate volume of water for mixing with the wastes can effectively take care of a considerable quantity of domestic waste as experience in California has shown (Brooks, 1980), and this type of site would now probably be considered the most acceptable.

The situation is different with wastes of essentially permanent toxicity, if they are not readily incorporated into immobile sediments. Continuous release of such wastes, if no economic method can be found to render them harmless, would result in their accumulation in the world's oceans - a situation which is unacceptable, as recognized by the prohibitions in the Conventions.

The second option, a location where the waste will be relatively confined at least on the time-scale of human generations, offers the prospect of restricting the (albeit severe) effects to a definable area. This will be the most satisfactory disposal strategy for wastes such as dredge spoils, which consist of heterogeneous aggregations of largely inorganic material, impacting mainly on the sea-bed, often by physical blanketing. This approach is implied for example in capping and burial operations, and if such a disposal strategy is adopted the possible interference with other activities, particularly fishing, must be recognized in selecting a site.

In considering effects, an important difficulty arises because almost any disposal site selected is likely to be influenced by extraneous contaminants, whether from other disposal operations or from a range of less controllable sources such as land run-off, river drainage and atmospheric fall-out. There is thus a problem in defining the effect of any given waste on its own, and this problem is greater for the far-field effects, when low concentrations are involved. Compounding the problem is the fact that low-level, far-field effects of most wastes would be difficult to quantify or detect even in the ideal situation where the waste in question was the only contaminant present. In the complex real world, subtle effects are masked by more pronounced signals from nearby sources. However, reports of DDT, PCB and petroleum hydrocarbons in fish and other organisms taken hundreds of kilometres from any dumping site or specific input suggest work must continue on contaminants which are subject to accumulation in the environment, to identify the pathways and processes and to evaluate the effects. The history of DDT in the terrestrial field cautions against the automatic assumption that contaminants at concentrations difficult to detect may safely be ignored. A waste may be best regarded as one contributor to the complex contamination pattern of the ocean region in question, and the pattern should be thought of as having a time as well as a space dimension. It is against this background that the concept of assimilative capacity must be viewed.

This report elaborates the criteria which are relevant to the disposal at sea of various wastes and the toxic substances associated with them. The criteria for the selection of sites are important not only in the context of current disposal patterns, but also in the planning of future dumping operations, and for establishing sensitive areas or sanctuaries which should remain as far as possible free of disposal activities. One rational approach to the licensing or prohibition of ocean dumping, which has recently gained ground, is to quantify the economic value of the oceanic resources destroyed or made useless by dumping (including for example the aesthetic value of an unpolluted marine zone) and to compare this with the benefits derived from using the dumping option for disposal. One approach to this quantification is through the use of models of the effects of the waste - physical, chemical and biological. In this context, we have already noted that there is a tendency to respect the results of the application of composite numerical models beyond their intrinsic value. Although the computational techniques may be well advanced, often the knowledge and formulation of the physics of the modelled processes and particularly the availability of the modelled parameter values do not support the confidence which the results are accorded. Both scientists and administrators should be aware of this possible misuse of computer modelling. However, where numerical computer models are consistent with a particular situation and are judiciously applied, they may be of major value. For example, a suitable hydrodynamic model may provide valuable output guiding the placement and data specification for ocean current measurements, and in using the measurement data to provide parametric values for the model utilization in an interactive manner with the measured data.

Finally, in a field of activity like that of waste disposal at sea, the problems will vary continuously as industrial processes change and develop, and the greater the amount of information on the marine environment the better will be the forecasts of waste behaviour and effects. In such circumstances, an open-ended list of research requirements could be generated, but this paragraph summarizes only those aspects which have been noted in the text as requiring further research. The value of analytical or numerical models has been mentioned, and the need, in calculating dispersion, to extend them to times of more than about 100 hours after disposal; to adapt them to cover pollution assessment in coastal situations, and to conduct adequate field tests. In particular, the need to develop models to predict waste behaviour in randomly varying currents could usefully be pursued. In the deep sea, attention is drawn to the scarcity of quantitative knowledge, physical and biological, of the benthic boundary layer, a zone of great relevance in certain dumping contexts. At the other extreme, information is also inadequate on the surface microlayer of the ocean, and the significance of contaminants concentrated in this layer should be evaluated, requiring the development of appropriate sampling devices. The consequences of reduced water quality and increased stress on the disease status of fish and shellfish are little known and studies of the effects of disease on the levels of exploited populations should be encouraged. On the public health side, further information is required on the survival of pathogens introduced to the sea by dumping, and on the development of resistant populations of microorganisms. Apart from these topics, several items specific to particular disposal procedures have been highlighted. Thus for incineration, further tests are desirable on the efficiency of destruction of many substances, especially organohalogens other than chlorinated compounds, and additional knowledge is needed on plume rise and dispersion over the sea before a fully adequate assessment can be made of far-field effects. Finally, the procedures of capping and burial are still developing and further work is needed, particularly on the remobilization of heavy metal compounds under anaerobic conditions, the stability of caps, and on the resuspension of material.

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