CONF-800420--1

Biological Ramifications of the Subseabed Disposal of High-level Nuclear Waste

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ABSTRACT

The primary goal of the U.S. Subseabed Disposal Program (SDP) is to assess the technical and environmental feasibility of disposing of high-level nuclear waste in deep-sea sediments. The subseabed biology program is charged with assessing possible ecosystem effects of radionuclides as well as possible health effects to man from radionuclides which may be released in the deep sea and transported to the ocean surface. Current biological investigations are attempting to determine benthic community structure; benthic community metabolism; the biology of deep-sea mobile scavengers; the faunal composition of midwater nekton; rates of microbial processes; and the radiation sensitivity of deep-sea organisms. Existing models of the dispersal of radionuclides in the deep sea have not considered many of the possible biological mechanisms which may influence the movement of radionuclides. Therefore, a multi-compartment foodweb model is being developed which considers both biological and physical influences on radionuclide transport. This model will allow parametric studies to be made of the impact on the ocean environment and on man of potential releases of radionuclides.

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Biological Ramifications of the Subseabed Disposal of High-level Nuclear Waste

Introduction

The ultimate disposal of high-level nuclear wastes is one of the prime concerns in deciding whether or not nuclear power should be relied upon as a major energy source. At present several land disposal options are being investigated by the U.S. Department of Energy (DOE) (McElroy and Burns, 1979). In addition, a program was begun in 1973 by the DOE (then the Atomic Energy Commission) to assess the feasibility of using geologic formations beneath the world oceans for the disposal of appropriately packaged and solidified high-level nuclear wastes. The U.S. Subseabed Disposal Program (SDP) is currently conducting research in the areas of site selection, multiple barrier identification, canister emplacement techniques, high-level nuclear waste transportation, socio-political aspects, risk/safety analyses, economics, and environmental impact. The subseabed biology program, which is to contribute to environmental impact evaluation, is charged with assessing possible ecosystem effects and human health effects from radionuclides which may be released in the deep sea and transported through the water column to the ocean surface.

In order to evaluate the feasibility of subseabed nuclear waste disposal, it is necessary to consider the results of leakage or accidental failure to emplace the nuclear waste canister within the deep-sea sediments. Accidental release is possible for any nuclear waste disposal option, and the risks associated with each option must be evaluated so that comparisons among options can be made. Therefore, it is necessary to be able to understand the migration of escaped radionuclides from the canister emplacement site within the sediments (or possibly elsewhere for various accidents) through the sediments, water column and ecosystem to man. Only in this way can the environmental impact of subseabed nuclear waste disposal be quantitatively evaluated.

Present studies focus on the abyssal hill regions of the deep sea floors in the middle of tectonic plates and under the major surface current gyres. Anderson (1979) discusses the characteristics used to select generic study sites.

Marine Trophic Structure

The marine biomass of the world oceans has been estimated at 10 billion tons (Menzies et al., 1973). Over half of this (6.7 billion tons) can be assigned to the benthos. About 5.5 billion tons is distributed in the shoal waters of the continental shelves, and only 56 million tons remain on the abyssal sea floor at depths greater than 3000 meters. Thus, these depths generally have a low biomass comparable to that of terrestrial deserts. Nevertheless, representatives of many of the groups of organisms which are commonly found in shallow seas are also found in the deep sea (Hessler, 1974). Figure 1 is a simplified spatial frame of reference for the ocean with some representative marine organisms.

If the deep sea is defined as starting at a depth of 1000 meters, it represents about three quarters of the biosphere (Jannasch, 1978). In the deep sea there is no light (other than bioluminescence) and the temperature is a few degrees above zero degrees Celsius. Hydrostatic pressure increases by about one atmosphere with every 10 meters of depth. For all organisms in the deep sea nutrition becomes a most important problem.

Primary production in the euphotic region (the upper 200 meters) of the ocean is a principal source of food (the most limiting resource) for deep-sea benthic communities (Dayton and Hessler, 1972). In the waters of the central gyres such primary production is low (Hessler and Jumars, 1977). Furthermore, nutrients from land runoff are insignificant because the mid-gyres are remote from land, and because of prevailing oceanic currents. Great water depth combines with these other factors to maintain a lower nutrient supply to the deep ocean bottom than at any other place in the ocean (Hessler and Jumars, 1977). As a result, high species diversity and low standing crop are characteristics of deep-sea faunas (Sanders and Hessler, 1969).

At present, the rates at which essential nutrients are recycled in the benthos are largely unknown, as are the rates of growth, metabolism, and reproduction of deep-sea organisms (Jannasch, 1978). There are also few data available on population densities, food webs or vertical and horizontal migrations with which to evaluate radionuclide uptake, accumulation, and transport through the deep-sea ecosystem. Because deep benthic communities are the first that would be exposed to released radionuclides, much of the research in the subseabed biology program has focused on deep-sea ecology.

The influence of biological pathways on the potential transport of radionuclides from the deep-sea sediments to the ocean surface is of prime importance (Hessler and Jumars, 1979). The infauna in a benthic community could mediate radionuclide transport by moving sediment and by moving pore water in and out of the sediments. Roving megafauna may also contribute to bioturbation. Radionuclides that would otherwise remain sorbed on deep-sea sediments may then be transported by currents to areas of low radionuclide concentration. Feeding and excretion can transfer radionuclides through the seas. Since coprophagy, the ingestion of feces, is an important nutritional source in a wide range of marine animals (Frankenberg and Smith, 1967), it may be an important factor in the transfer of radionuclides that have been brought into surface waters. Some benthic invertebrates have pelagic eggs or larvae that may disperse horizontally. This mode of reproduction, which is a usual breeding pattern among shallow water marine communities (Menzies <u>et al.</u>, 1973) may contribute to radionuclide transport. Vertical migrations in the water column may range from a diel pattern over hundreds of meters (Longhurst, 1976) to the ontogenetic migrations of rattail fish that can extend a few thousand meters up from the bottom (Merrett, 1978). Marine mammals and birds may also transport radionuclides by their annual horizontal migrations of thousands of miles. Many species of fish of commercial interest to man have dramatic anadromous migrations. Some commercial fish reproduce with pelagic eggs which may be transported horizontally for many miles (Russell, 1976). These and other biological interactions are influenced by an assortment of physical processes such as wind-driven currents, eddies, upwellings and thermohaline circulation. All are potentially important in radionuclide transport.

Nuclide Migration Model Development

Existing models of the dispersal of radionuclides in the deep sea have not considered many of the possible biological mechanisms which may influence the movement of such radionuclides. Therefore, a multi-compartment model is being developed that considers both biological and physical influences on radionuclide transport. This model will allow parametric studies to be made of the impact on the environment and on man of potential releases of radionuclides into the sea. This paper will concentrate on the biological influences of foodweb model development with minimal consideration of the physical influences.

The nuclide migration model is directed towards answering two questions. What is the effect of radionuclides which may be released in the deep sea upon the marine environment, and what is the effect of such a release upon man? These questions require an ability to predict the levels of radioactivity in the marine biota and the ultimate radiation dose to man.

The present model (Fig. 2) is made up of several modules: near-field transport with heat effects, far-field transport through the sediments, water column and biological transport, human dosimetry, affected human populations and human health effects.

The marine ecosystem has been compartmentalized after a scheme reported by Wishner (1977) for the SDP biology program. A compartment represents a functional grouping of many species in the biota. The species within a compartment are assumed to behave similarly in their relationships with the environment as well as in the ways they may transport radionuclides. Group bounds on the standing crop and metabolic rates may then be assigned to each compartment by considering characteristics of the group. The benthic boundary layer model(s) extends from the lower limit of biological activity in the sediments through the lower 20-50 meters of the water column. Above the benthic boundary layer are one or more midwater models. The upper part of the water column (euphotic zone) is represented by another model. These models are shown schematically in Fig. 3.

Transport between biological compartments and physical compartments is complex. Radionuclides may be transported by predator-prey interactions, excretion, mortality, adsorption, migration, reproduction and molting. In addition, sediments (organic and inorganic) and particulate materials may be consumed. Radionuclides may also be taken up directly from the water column and from interstitial water. Various transport mechanisms must be considered, such as, association-dissociation in the sediments and water column, erosion-sedimentation, vertical and horizontal water dispersion, bioturbation, horizontal migration of benthic megafauna, vertical migration of midwater organisms, and the dispersion of host particulate matter. These forms of radionuclide transports, which are depicted as arrows between the boxes in Fig. 3, are being or will be carefully examined.

In order to develop a realistic data base with which to exercise the model, deep and shallow-water biological data have been compiled from the literature. In addition, algorithms for computing transfer rates between compartments have been developed (Jackson, 1979).

The compilation of model input data is described very briefly below.

a) Mass Density Parameters:

Mass density is defined in the model as kilograms wet weight mass per square or cubic meter of sediment-water interface or water volume, respectively. The mass density of organisms (biomass) is compiled from the literature in several forms: direct biomass determinations, direct counts of organisms with an estimate of mean individual weight, direct measurement of a biochemical parameter (pigments, adenosine triphosphate, etc.) coupled with appropriate conversion factors, and indirect estimate of the biomass density in one compartment based on a direct measurement of density in another, e.g., in one study "the mass of herbivorous and omnivorous zooplankton is approximately 40% of the phytoplankton standing crop" (Mullin and Evans, 1974). Mass densities for abiotic compartments are taken from reported measurements of suspended particulates, sediment densities, etc.

b) Transport Parameters:

Transport of radionuclide-carrying material between compartments is described by uptake times and transfer rates for transports involving biotic and abiotic receiver compartments, respectively. A receiver compartment is a state variable or compartment into which energy or matter is added, while a donor compartment is a state variable or compartment from which energy or matter is removed (Forrester, 1968). Uptake times are defined in the model as the time required, in years, for a given biotic receiver compartment to take up the fraction α (α=0.50) of its biomass from a given biotic or abiotic donor compartment. Transfer rates are described in terms of physical parameters such as distribution coefficients, erodibility constants, particulate fall velocities, critical shear for deposition or erosion, probabilities of an erosional or depositional event, characteristic lengths, and diffusivities.

Future modification of the model will focus on improving estimates of possible doses to man as well as possible environmental effects of radionuclides in the deep sea. The model will evolve through careful parameter study to its simplest possible form, and all assumptions will be made conservatively with respect to a particular environmental effect or dose to man. Modifications will be evaluated according to their significance with respect to the estimation of environmental effects and dose to man.

This initial version of the SDP biotransport model can be viewed as an ecosystem pump designed expressly for moving radionuclides from sediment, through the water column and marine biota to man. Operation of this pump is governed by our assumptions regarding modes of radionuclide uptake and transport in the marine ecosystem.

Existing human dosimetric codes will be used to calculate human exposure from released radionuclides from the deep sea. Fisheries consumption data are being compiled to interface with the internal dosimetry model(s) in order to calculate dose to man.

SDP Biology Program

1) Benthic Biological Studies

The SDP biology program is in the process of characterizing the fauna present in and on the sediment in the central North Pacific gyre, including the microbiota, meiofauna, macrofauna and abysscpelagic scavengers (Hessler and Jumars, 1974; Hessler and Jumars, 1977; Burnett, 1977; Hessler et al., 1978). These studies are focusing on the potential of these various biotic components to disperse or to concentrate any leaked radioactive wastes.

A characterization of the distribution and density of the macro-infauna is fairly complete, but relatively little is known of the meiofauna and even less about the microbiota. These are important because they are the most abundant portions of the infauna and are at the base of the food web.

Of the mobile scavengers present focus has been placed on amphipods, since they are a large component of the abyssal benthic community and are highly mobile cosmopolitan organisms. Aspects of their generalized life-style suggest that they may be very important in potential mobilization of radionuclides. They appear to feed on the bottom which could allow direct incorporation of radionuclides present in the sediments, and their mobility allows direct biological transport. Because amphipods live in the water column, their waste products are especially susceptible to physical transport. Thus they may constitute an important early step in a pathway leading ultimately to man.

To date the inaccessibility of the deep ocean environment and the associated pressure and temperature constraints have permitted only a limited glimpse into the functional aspects of this ecosystem. An instrument, a free vehicle grab respirometer (FVGR), has been designed and built to elucidate the *in situ* activity rates of the benthic community including oxygen uptake and nutrient exchange (Smith, *et al*., 1979a). Total oxygen uptake and nutrient exchange have been measured *in situ* in the eastern North Pacific at two stations. Both stations underlie the eutrophic California Current system. There was no significant difference in total oxygen uptake between stations, but the values were significantly higher than previous measurements made at comparable depths from the more oligotrophic northwest Atlantic (Smith, 1978).

The FVGR will also be used to conduct *in situ* experiments on the effects and fate of injected low-level radiolabelled compounds on transfer rates in the deep-sea benthic community. The data obtained from these experiments will be of great value in improving the data base for the SDP foodweb model.

Since microorganisms are ubiquitous in ocean water, they offer ideal experimental possibilities for studying many of the biological phenomena of interest to the subseabed program under the special deep-sea conditions of extreme food limitation, high pressure and low temperature.

The need for a greater understanding of microbiological processes in the deep sea is widely recognized. For example, can microbiological activities affect (adversely or favorably) the canister, the waste form or the sediment-radionuclide interactions at planned emplacement depths (30 to 100 meters into the sediments)?

A substantial effort has been devoted to evaluating the use of the ATP (adenosine triphosphate) method for assessing the microbial composition of deep-sea sediments. An important recent finding has been that the physiological state of deep-sea bacteria is a significant determinant of their ATP content, which can be increased up to thirty times that normally present by placing the cell at a hydrostatic pressure which is inhibitory to its growth (Yayanos, 1979). This means that the ATP content of a deep-sea sample may overestimate the number of cells capable of functioning at the depth of the sample. We have shown that the inhibition of cell division by both excessively low as well as excessively high pressures leads to the accumulation of ATP.

Microscopic techniques are presently inadequate for determining microbial standing stock in the marine environment because of their inability to distinguish live from dead bacteria. Autoradiographic and fluorescent labeling techniques have been used by many laboratories to overcome this difficulty. We are using image analysis instrumentation to develop these fluorescent and autoradiographic techniques, and are using the techniques to study large numbers of spatially and temporally collected microbial samples.

In addition to the indirect methods of microbial detection discussed above, techniques for the cultivation of deep-sea microbes are being explored. Several deep-sea microbes have been successfully isolated (Dietz and Yayanos, 1978; Yayanos, Dietz and Van Boxtel, 1979). One of the many isolates (designated CNPT-3, originating in the central North Pacific Ocean) is being studied to determine which of the many cultivation variables are significant. Cultivation at atmospheric pressure has been avoided to eliminate or reduce the chance of contamination with shallow water microbes which continuously enter the deep sea.

Spores of bacteria that grow at high temperatures (thermophiles) have been found in deep-sea sediments (Bartholemew and Paik, 1966). The ability of these spores to germinate in the presence of heat from emplaced high-level nuclear waste canisters should be determined. Evidence to date from the bacterium CNPT-3 and a few other isolates suggests that the deep-sea microbial population will stop functioning above 15°C at 580 bars, indicating that in the 100°C regions surrounding nuclear waste canisters, only spores of thermophilic bacteria could be viable.

2) Water Column Studies

According to Smith et al., (1979a) the open ocean water column can be viewed simplistically as a stack of horizontal layers, each inhabited by a discrete faunal assemblage and bounded by the air-water and sediment-water interfaces. This view is complicated by the many animals that transcend these layers while undergoing vertical migrations (diurnal, seasonal or ontogenetic). The upper layers of the ocean have received the most study because of their accessibility and the basic premise that the whole water column ecosystem is driven by the food energy fixed in the surface waters by the autotrophs.

Food energy exchange through the water column can be viewed as either active or passive. The passive mode of nutrient transport involves the sinking of particulate organic matter controlled primarily by gravitational forces (Wiebe et al., 1976; Honjo, 1978). The active mode of nutrient transport is the flux mediated by organism transport, and has been equated to a ladder of plankton with overlapping migrational depths of various animals in a food web down to the abyssal floor (Vinogradov, 1968). Evidence exists on the vertical migration of mesopelagic animals justifying such a hypothesis, but the evidence for active exchange in deeper waters, including the sediment-water interface, is tenuous. Benthopelagic fishes have been caught in midwater (Haedrich, 1974; Pearcy, 1976; Merrett, 1978) giving credence to this exchange. All of the above work was performed with towed nets, and the primary ecological interest was to estimate the downward flux of material.

Recently a free vehicle midwater gill net and baited trap-hook array (FVMNT) has been extensively used to characterize the abyssopelagic fauna (Smith _et al.,_ 1979b). Sampling of the abyssopelagic zone was prompted by limited knowledge of the deep midwater fauna and its significance in the food energy flow through the open ocean ecosystem. Fish and amphipods which are widely regarded as benthic organisms have been captured with the FVMNT up to 730 meters above the abyssal sea floor (Smith _et al.,_ 1979b). The presence of these "benthic" animals in the abyssopelagic zone reinforces the idea that there exists a mechanism for actively transporting material upwards from the sea floor.

A giant conical net (GCN) is currently being developed. The GCN, which is 100 meters in diameter and 200 meters long, will be used to help characterize the abyssopelagic fauna by capturing pelagic animals that elude capture with either smaller towed nets or with the FVMNT array.

Estimates of the population density of deep-sea benthic organisms have been made using techniques such as grabs, dredges, trawls and camera surveys. However, the densities of the more mobile abyssopelagic animals cannot be accurately determined using these techniques. So, a free vehicle for acoustically assessing abyssopelagic animal population sizes and mobility rates is being developed. This acoustical array will monitor for long periods of time (months) the movements of abyssopelagic populations within a water column 1.9 kilometers in diameter by 100 meters high immediately above the abyssal sediment surface.

These water column studies, as well as the benthic biological studies will provide many of the parameters that are required to exercise the SDP foodweb radionuclide transport model.

3) Radiation Biology Studies

A. Marine Biota

Marine organisms have always been exposed to radiation from natural sources, and estimates of the absorbed dose rate from natural background sources have been used to assess the biological significance of any dose rate increment contributed by man's activities. Blaylock and Trabalka (1978) have reviewed the effects of ionizing radiation on aquatic organisms; however, as far as we know, the radiosensitivity of any deep-sea organism has not yet been determined. Until radiation sensitivity studies can be performed on deep-sea organisms, the data available on the radiosensitivity of shallow-water organisms will be used in estimating any impacts of released radionuclides on deep-sea organisms. As part of the SDP Biology Program an extensive bibliography has been prepared on the effects of ionizing radiation on aquatic organisms (Schultz, 1980).

In an effort to acquire data on the radiosensitivity of deep-sea organisms, we plan to determine the radiation sensitivity of deep-sea bacteria which can now be cultivated under deep-sea conditions in the laboratory, and to determine the radiation sensitivity of deep-sea amphipods, since these can also be recovered alive and maintained in the laboratory under deep-sea conditions (Yayanos, 1978). These initial radiation sensitivity studies will be lethality experiments; however, additional endpoints will be used in later studies to investigate radiobiological impact on deep-sea organisms. Bacq and Alexander (1961) show that radiosensitivity increases with increasing complexity in living organisms. We will, therefore, compare the radiosensitivity of deep-sea organisms with that of similar shallow-water organisms, in order to determine whether or not marine organisms which occupy equivalent phylogenetic positions are equally radiosensitive or if there are conditions peculiar to the deep sea which may modify (increase or decrease) radiosensitivity. For example, do the pelagic eggs of rattail fishes become more or less radiosensitive because of the vertical ontogenetic migration they undergo which exposes them to pressure changes of several hundred atmospheres and possibly to temperature changes if the eggs penetrate the thermocline? This kind of information on radiosensitivity in the deep sea will allow an estimate of the validity of using the data obtained from shallow water studies to assess radiobiological impact in the deep sea.

Due to the lack of bioenvironmental data for many radionuclides in the marine environment, we have constructed three "metabolic equivalence classes" of radionuclides (plutonium class, strontium class, cesium class) in order to model the radiological effects of radionuclides in the high-level nuclear waste inventory which may be important contributors to the radiation dose to man and to the environment. The assignment of a radionuclide to a specific class is based upon human dosimetric considerations. The plutonium class consists of bone-seeking, alpha-emitting radionuclides whose Maximum Permissible Body Burdens (MPBBs) are less than one microcurie. The strontium class consists of beta- or gamma-emitting, bone-seeking radionuclides with MPBBs greater than one microcurie. The cesium class consists of beta- or gamma-emitting nuclides which are "soft-tissue" seekers. The MPBBs for radionuclides in this class are greater than ten microcuries.

We are well aware that any grouping of a large number of radionuclides into three metabolic equivalence classes is subject to error because of the wide range of chemical characteristics of those nuclides. Therefore, since we are concerned with radiation effects we have assumed that since each class contains a radionuclide (^{239}Pu, ^{90}Sr, ^{137}Cs) for which significant bioenvironmental data are available, these nuclides can be used to model the other nuclides of the class. Also, since the radiobiological effects of the principal radionuclide of each class are better known than the radiobiological effects of other members of each class, we felt we could, in general, conservatively model the radiobiological effects of each class of radionuclides by using the data available for the principal nuclide of each class. This scheme will be revised as more data become available.

Ultimately a determination of the effects of released radionuclides on a deep-sea community may require an <u>in situ</u> radiobiology experiment.

B. <u>Man</u>

The basic responsibility for providing guidance in matters of human radiation safety has been assumed by the International Commission on Radiological Protection (ICRP), which was established as the International X-ray and Radium Protection Commission in 1928.

For the purpose of setting maximum allowable exposure limits, the most sensitive radiation induced change was assumed to be genetic damage. It was further assumed that there is no threshold dose for this effect, that the dose-response curve is linear down to zero dose and that the effect is independent of dose rate, that is, only the total dose is of biological significance. Since this means that every increment of dose increases the likelihood of an adverse effect, and because the benefits to man of the use of nuclear energy are many, the problem is to limit exposure to a level that results in an acceptable risk to the individual and to the population. On the basis of this "acceptable risk concept", the ICRP (1959) defined the maximum permissible dose for an individual as "That dose, accumulated over a long period of time or resulting from a single exposure which, in the light of present knowledge, carries a negligible probability of severe somatic or genetic injuries; furthermore, it is such a dose that any effects that ensue more frequently are limited to those of a minor nature that would not be considered unacceptable by the exposed individual and by competent medical authorities". The ICRP (1977) later determined that the absorbed dose is insufficient by itself to allow the prediction of either the severity or the probability of deleterious effects on health resulting from irradiation under unspecified conditions. Therefore, they introduced a quantity called "dose equivalent" that correlates better with the more important deleterious effects of exposure to radiation, especially with the delayed stochastic effects. Dose equivalent is the absorbed dose weighted by specific modifying factors as defined by the ICRP (1977). Although upper exposure limits have been recommended, the basic philosophy of radiation protection, which is being followed by the Subseabed Disposal Program, is to keep exposure as low as practicable.

As indicated in the section on Model Development, existing human dosimetric codes coupled with the foodweb transport model will be used to calculate human exposure from released radionuclides from the deep sea.

Final Comments

The task of the SDP biological research program is to provide an adequate long-term data base to assess the environmental feasibility of a program to emplace appropriately packaged nuclear waste in deep-sea sediments. Should subseabed emplacement become a reality long-term biological monitoring by sampling key marine species as indicators of radionuclide migration will be necessary.

Since the disposal of nuclear waste is an international concern, cooperation among marine biologists of many nations is being encouraged. International cooperation is needed since no single nation should be expected to perform all of the required long-term research.

Nevertheless, we believe that the tasks of the SDP Biology Program, while formidable, can be accomplished at an acceptable cost over the next decade or so.

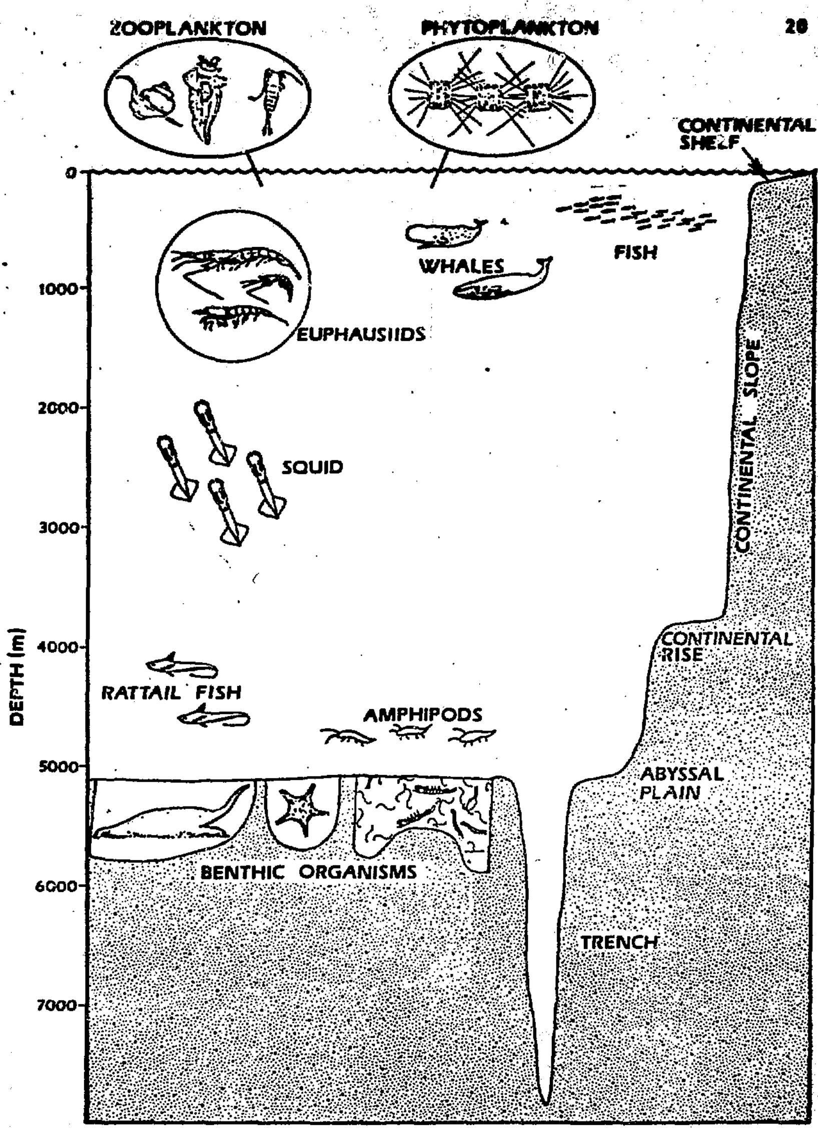

FIGURE 1. REPRESENTATIVE MARINE BIOTA (NOT DRAWN TO SCALE)

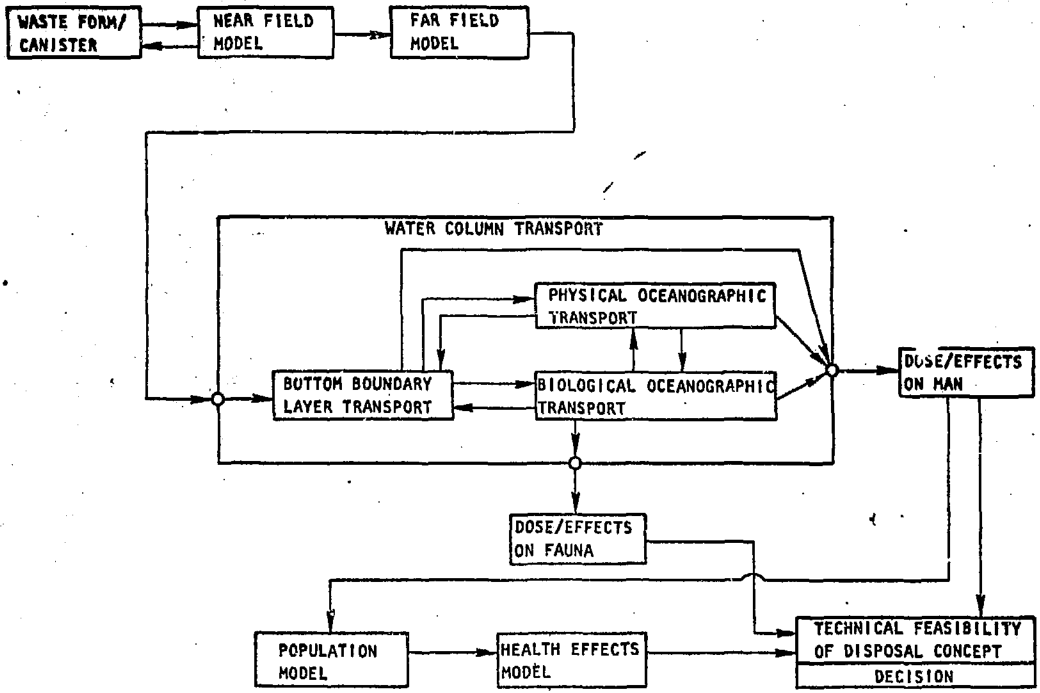

FIGURE 2. ION TRANSPORT ANALYSIS MODEL

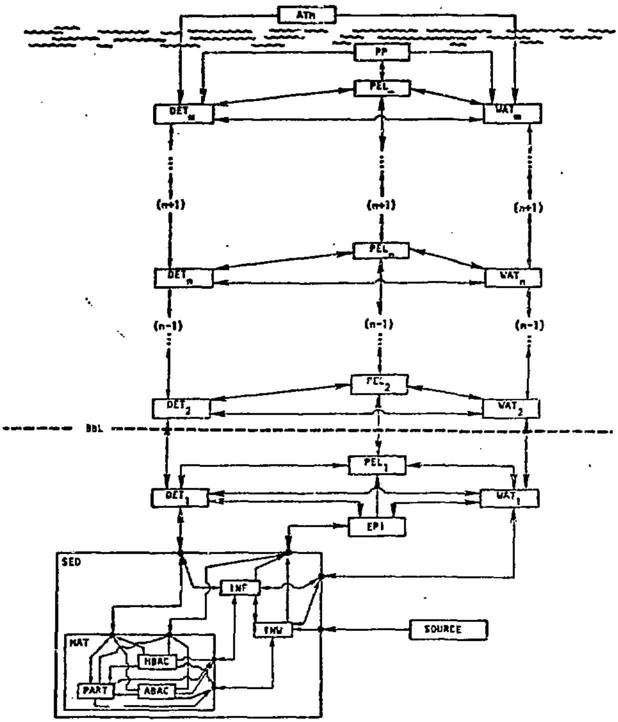

FIGURE 3. MULTICOMPARTMENTAL FOODWEB MODEL

Definitions of Compartments in Foodweb Model

ABAC: Autotrophic Bacteria found in the bioturbation zone.

ATM: Atmosphere

DET_1: Suspended Particulates. Suspended labile and refractory organic-inorganic complexes (of all sizes) and associated bacteria and microbiota in the first depth interval, autotrophic bacteria.

DET_n: Suspended particulates in the n^{th} depth interval.

EPI: Epibenthic Fauna. Carnivores and deposit-feeding animals living on or near the bottom, but never traveling far from the sediment-water interface.

HBAC: Heterotrophic Bacteria and associated detritus found in the bioturbation zone.

INF: Eukaryotic Benthic Infauna. Deposit feeding (sometimes suspension feeding) and carnivorous animals living beneath the sediment-water interface.

INW: Interstitial Water. Water and dissolved constituents beneath the sediment-water interface.

MAT: Solid Matrix. Labile and refractory organic-inorganic complexes and associated heterotrophic bacteria and microbiota, autotrophic bacteria.

PART: Solid Inorganic Particulates. The remaining solid matrix in the bioturbation zone.

PEL_1: Pelagic Fauna. Zooplankton and nekton in the first depth interval.

PEL_n: Pelagic fauna in the n^{th} depth interval.

PP: Primary Producers. Phytoplankton confined to the upper 200 meters of the water column (euphotic zone).

SED: Sediment Particulates, bulk sediment material including interstitial waters found within the bioturbation zone.

WAT_1: Water and dissolved constituents in the first depth interval (above the sediment-water interface).

WAT_n: Water and dissolved constituents in the n^{th} depth interval.

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