Considerations on the Disposal of Radioactive Wastes From Nuclear-Powered Ships Into the Marine Environment (1959)

Pages
74

Size
6 x 9

ISBN
0309302935

Committee on Effects of Atomic Radiation on Oceanography and Fisheries; National Research Council

The map on the front cover is reproduced from a bathymetric chart of the North Atlantic Basin published in "Instructions and Sailing Directions to Accompany the Wind and Current Charts," 7th Edition of 1855. The chart was compiled by Lieutenant Matthew Fontain Maury when he was Superintendent of the U.S. Naval Observatory and Hydrographic Office. The cooperation of the U.S. Navy Hydrographic Office in making this chart available is gratefully acknowledged.

Considerations on the Disposal of Radioactive Wastes from Nuclear-Powered Ships into The Marine Environment

A report of the Committee on the Effects of Atomic Radiation on Oceanography and Fisheries of the National Academy of Sciences' Study of the Biological Effects of Atomic Radiation

Publication 658

National Academy of Sciences—National Research Council
Washington, D.C.
1959

Library of Congress catalog card number: 59-60054

COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION ON OCEANOGRAPHY AND FISHERIES

Roger Revelle, Chairman, Scripps Institution of Oceanography

Howard Boroughs
Hawaii Marine Laboratory

Dayton E. Carritt
The Johns Hopkins University

Walter A. Chipman
U. S. Fish and Wildlife Service

Lauren R. Donaldson
University of Washington

Richard F. Foster
General Electric Company

Edward D. Goldberg
Scripps Institution of Oceanography

Richard H. Fleming
University of Washington

John H. Harley
U. S. Atomic Energy Commission

Bostwick Ketchum
Woods Hole Oceanographic Institution

Louis A. Krumholz
University of Louisville

Charles E. Renn
The Johns Hopkins University

Milner B. Schaeffer
Inter-American Tropical Tuna Commission

Allyn C. Vine
Woods Hole Oceanographic Institution

Lionel A. Walford
U. S. Fish and Wildlife Service

Warren S. Wooster
Scripps Institution of Oceanography

Working Group on Disposal of Radioactive Wastes from Nuclear-Powered Ships

Donald W. Pritchard, Chairman, The Johns Hopkins University

Edward D. Goldberg
Scripps Institution of Oceanography

Milner B. Schaefer
Inter-American Tropical Tuna Commission

James M. Smith, Jr.
General Electric Company

Thomas T. Sugihara
Clark University

Lionel A. Walford
U. S. Fish and Wildlife Service

Warren S. Wooster
Scripps Institution of Oceanography

CONSULTANTS

Arnold B. Joseph
U. S. Atomic Energy Commission

Ralph K. Longaker
Maritime Administration

DeCourcey Martin, Jr.
Scripps Institution of Oceanography

FOREWORD

In June 1958, the Atomic Energy Commission requested the Committee on Oceanography of the National Academy of Sciences - National Research Council to consider the problem of disposal of radioactive wastes from nuclear-powered ships. The Committee on Oceanography asked the Academy's Committee on the Biological Effects of Atomic Radiation on Oceanography and Fisheries to undertake this study. As chairman of the latter Committee, I appointed a special working group under the leadership of Donald Pritchard.

Following the first meeting of the working group in September 1958, drafts of sections of this report were written by individual members. In December, at the second meeting, the drafts were reviewed. Professor Pritchard then consolidated these contributions into a single document. The report was discussed in detail and approved for publication by the Committee on the Biological Effects of Atomic Radiation on Oceanography and Fisheries in March 1959.

The report gives a series of detailed and specific recommendations concerning the amounts of different types of radioactive wastes that can be released safely into the sea by nuclear-powered ships. Separate rules are given for each zone of the marine environment. These rules are most restrictive for the innermost zone of harbors, estuaries and coastal waters, and least restrictive for the open sea outside of fishing areas, more than twelve miles from shore, and where the bottom depth is greater than 200 fathoms.

The working group has attempted to make its recommendations as precise as possible within the limits of our present knowledge of the physics, chemistry, and biology of the oceans. Where uncertainties exist because of inadequate knowledge, a conservative position has been chosen - that is, the calculations underlying the recommendations may err on the side of safety. Each assumption and each step in the calculations is fully described, however, so that the reader may make an independent evaluation of the degree of conservatism of the recommended rules. It is sometimes said that biologists and oceanographers, when considering the introduction of artificial radioactive materials into the sea, tend to pile safety factors upon safety factors to arrive at a quite unrealistic result. I am convinced that any careful reader will conclude this is not true of the present report.

One of the most important conclusions of the report concerns the necessity for monitoring and maintaining records of the amount and location of radioactive waste disposal by nuclear ships. This will involve not only action by each maritime country, but also international agreement and collaboration.

Roger Revelle

TABLE OF CONTENTS

SUMMARY AND RECOMMENDATIONS

This report is an evaluation of:

(1) The nature and amount of radioactive waste materials which would conceivably be introduced into the sea through normal operations of nuclear-powered ships. No conclusions are reached concerning the safety of operating nuclear-powered ships in tideless, fresh water bodies.

(2) The routes by which such introduced activity would return to man from the sea.

(3) The portion of the maximum permissible dose to man, allotted to the peaceful uses of nuclear energy, which should be permitted to originate from waste disposal operations from nuclear-powered ships.

(4) The concentration by marine organisms of the various significant isotopes in the wastes.

(5) The processes of dispersion of the wastes within the various subdivisions of the marine environment.

(6) The permissible rate of introduction of the subject waste materials into the various subdivisions of the marine environment.

This report deals specifically with the wastes which would originate from a water cooled reactor. Other types of reactors will undoubtedly be used in future nuclear-powered ships; the character and amount of wastes which might be introduced to the marine environment from such future designs cannot now be stated accurately. It is believed, however, that the general conclusions of this working panel can be utilized in formulating design criteria and operating doctrine, with respect to waste disposal into the marine environment, for such future types of marine reactors.

In the present report it is assumed that the bulk of the fission products remain contained in the spent fuel elements and are removed from the ship with these elements at time of refueling. The two principal types of radioactive waste which could enter the marine environment through the normal operation of nuclear-powered ships are: (a) a low level liquid effluent originating, for the most part, in the primary coolant system; and (b) spent ion exchange resins, used in the by-pass clean-up system for the primary coolant. Other possible sources include

contaminated expendable tools, glassware, etc., which would be packaged before discharge. The liquid effluent will contain low concentrations of radioactive corrosion products together with very much lower concentrations of fission products. The ion exchange resins will contain considerably higher activities of these same materials.

The following subdivisions of the marine environment are considered:

(1) harbors, estuaries, and coastal waters out to two miles from the shoreline;

(2) the coastal area between 2 miles and 12 miles from the coastline;

(3) the outer continental shelf, extending from 12 miles offshore outward to the 200 fathom depth contour;

(4) the open sea, here considered to comprise those ocean areas more than 12 miles from shore having depths greater than 200 fathoms.

For the last two categories, a further distinction is made between fishing areas and areas which do not contribute materially or directly to the commercial harvest of sea food.

On the basis of reports dealing with the U.S.S. NAUTILUS and the proposed N.S. SAVANNAH, a list is made of isotopes with half lives longer than 6 hours which are likely to occur in significant quantities in the primary coolant and the ion exchange resins of marine pressurized water reactors. For each of these isotopes the partial permissible concentrations (ppc's) in seafood and in the marine environment are determined for each of the above listed subdivisions of the environment. Assuming that the relative proportions of the various significant isotopes in the wastes do not vary greatly, a weighted mean ppc value for the various subdivisions of the marine environment, for each type of waste, is determined. The relative compositions of the wastes predicted for the SAVANNAH and observed for the NAUTILUS differ somewhat, and hence a different weighted mean ppc value is determined for the primary coolant and for the ion exchange resins, for each of these two types of ship.

The predicted nature and quantity of the potential wastes from the SAVANNAH, and the observed nature and quantity of the wastes from the NAUTILUS, are utilized in arriving at the conclusions and recommendations presented here. A similar evaluation can be made for any potential waste of known relative composition, by use of the appropriate weighted

mean partial permissible concentration (ppc) values for that waste. If M_i represents the activity in the waste resulting from a given isotope, i, and $(ppc)_i$ represents the partial permissible concentration for the subject environment for that isotope, then the weighted mean ppc value for the environment, for that waste, is given by

$$\overline{ppc} = \frac{\Sigma M_i}{\Sigma \left\{ M_{i/(ppc)_i} \right\}} .$$

The weighted mean ppc value is utilized with the gross activity resulting from the isotope mix. It has the advantage of providing a convenient means of including the additive effect of the various isotopes contained in the wastes.

The maximum number of discharges, N, which may be made into a representative segment of each of the subdivisions of the marine environment during any one month period is determined as a function of (a) the total activity in a single such discharge and (b) the environmental ppc value. These determinations are based on an evaluation of the rates of dispersion and exchange in the marine environment. The limitations to our present knowledge of these phenomena require us to use conservative interpretations of the results. If the permissible number of discharges, for a given activity, into a representative segment of the marine environment is computed to be less than one per month, that environment is considered to be unsuitable as a receiver of that particular waste.

Our conclusions and resulting recommendations for each of the environmental subdivisions are as follows:

Harbors, estuaries, and coastal waters out to two miles from the shoreline (Zone 1):

The considerable variation in the physical processes of dispersion within, and exchange between, segments of this marine environment, as well as local variations in the biological and geochemical processes of importance to our problem, makes it impossible to present a completely general conclusion regarding waste disposal into harbors, estuaries and other inshore areas. Since these are areas of high human activity, it is evident that solid wastes should not be introduced into such waters. Because of the poor dispersion characterizing tideless harbors which are separated from the sea by locks, it is questionable whether any radioactive wastes should be introduced into such waterways from nuclear-powered ships.

An evaluation is made of a "typical" harbor of poor flushing characteristics. The results are summarized in the following table, which gives the maximum permissible total activity for a single discharge, as a function of selected values of the ppc value for the environment and the maximum permissible number of discharges per month.

ppc value for the environment (μc/ml)	Permissible Activity in a Single Discharge For 1 discharge per month (curies)	For 30 discharges per month (curies)
10^{-9}	2.5×10^{-2}	2.5×10^{-3}
10^{-8}	2.5×10^{-1}	2.5×10^{-2}
10^{-7}	2.5	2.5×10^{-1}

The weighted mean ppc value for the inshore environment computed for the primary coolant of the SAVANNAH is 2×10^{-8} μc/ml, and the predicted gross activity which would be contained in the warm-up expansion volume from this primary coolant is 6.8×10^{-1} curies. Hence this "typical" harbor would be unsuitable as a receiver of warm-up expansion volume wastes from nuclear-powered ships having the activity characteristics predicted for the SAVANNAH.

The weighted mean ppc value for this marine environment computed for the primary coolant of the NAUTILUS is 4×10^{-8} μc/ml, and the observed average activity due to the significant isotopes contained in the normal warm-up expansion volume of 500 gal is 1.4×10^{-2} curies. Hence apparently this "typical" harbor could receive a maximum of over 10 discharges per day of warm-up expansion volume wastes from nuclear-powered ships having the activity characteristics observed for the NAUTILUS.

While relatively poor flushing characteristics were chosen for the harbor used in these sample computations, they do not represent the most restrictive conditions which might be encountered in marine harbors. Also, because of lack of adequate data, it was not possible to include the potential effect on bottom-living animals and plants, of concentration by the bottom sediments. For these reasons the recommendations which follow are somewhat more conservative than might otherwise be drawn from the above numerical results.

Since the total activities on the spent ion exchange resins, as predicted for the SAVANNAH and observed on the NAUTILUS, are 100 to

400 curies, and 12.5 curies, respectively, it is evident that wastes from ion exchange beds cannot be discharged into harbors and other inshore waters.

Our recommendations pertaining to harbors, estuaries, and other inshore environments (Zone 1) are as follows:

Recommendation 1: No solid radioactive wastes or spent ion exchange resins should be discharged into harbors or estuaries, or into coastal waters within 2 miles of the shoreline, from nuclear-powered ships.

Recommendation 2: Nuclear-powered surface ships should be equipped with tanks capable of containing any liquid wastes which accumulate during the time such ships are in harbors, estuaries and other inshore waters, and such wastes should not be discharged until the ship has reached the open waters of the continental shelf. (Restrictions on discharges in this latter environment are treated later in this summary.) Other means of restricting the introduction of such wastes into the inshore environment would also be allowable.

Recommendation 3: For certain special types of nuclear-powered ships, other than surface ships, for which Recommendation 2 would result in significant operational disadvantages, the requirements of that recommendation may be relaxed providing that:

(a) Detailed evaluation of each specific major port of call and harbor base for such vessels be carried out using the general approach outlined in this report, such evaluation serving to establish the permissible activity and frequency of discharge. Actual discharges should be maintained well below the maximum permissible number and activity until the results of detailed environmental monitoring are available, and in any case should be maintained as much below the maximum permissible as is technically feasible.

(b) A detailed monitoring program be maintained, on a continuing basis, in the vicinity of each nuclear ship base and major port of call. (See also Recommendation 11.)

The coastal area, between 2 miles and 12 miles from the shoreline (Zone 2):

A 10 mile wide segment of this subdivision, extending from the inshore edge to the offshore boundary and considered as a ship traffic route, was employed in the sample computations for the inner continental

shelf. Because of the possibility of accidental recovery, no solid wastes should be introduced into this environment. The results of the evaluation for the liquid effluent are summarized in the following table, which gives the maximum permissible total activity for a single discharge as a function of selected values of the ppc value for the environment and the maximum permissible number of discharges (N) per month.

ppc value for the environment (μc/ml)	Permissible Activity in a Single Discharge For 1 discharge per month (curies)	For 30 discharges per month (curies)
10^{-9}	5.2×10^{-1}	5.3×10^{-2}
10^{-8}	5.2	5.3×10^{-1}
10^{-7}	52	5.3

The weighted mean ppc value for the coastal area, for the primary coolant of the SAVANNAH, is 2×10^{-8} μc/ml and the predicted gross activity which would be contained in the warm-up expansion volume of some 2200 gallons is 6.8×10^{-1} curies. Thus, considering that it would be unlikely that more than 30 nuclear-powered ships per month would pass, outbound, through any such 10-mile wide stretch of the coastal area, this environment appears suitable to receive the low level liquid wastes which would be stored in tanks as a result of restrictions placed on the release of such wastes in harbors.

This zone does not appear suitable, however, to receive the 10 to 400 curie amounts of activity which might be released with the spent ion exchange resins.

Our recommendations pertaining to the coastal area, between 2 and 12 miles offshore (Zone 2), follow:

Recommendation 4: Spent ion exchange resins should not be discharged from nuclear-powered ships into the waters of the coastal area, between 2 and 12 miles offshore. Except under very exceptional circumstances there should be no discharge of packaged solid wastes from nuclear-powered ships into these waters, and any such exceptional discharge should conform to recommendations contained in the National Academy of Science's report "Radioactive Waste Disposal in the Atlantic and Gulf Coast" (NAS-NRC Pub. 655, 1959).

Recommendation 5: Low level liquid effluent may be discharged into the waters of the coastal area, between 2 and 12 miles from shore, providing that the total activity contained in any single discharge does not exceed 5×10^{-1} curies resulting from isotopes with half-lives of more than 6 hours.

The outer continental shelf, from 12 miles offshore to the 200 fathom depth contour (Zones 3a and 3b):

The continental shelf off the east coast of the United States was employed in the sample computation for the outer continental shelf. The results of the evaluation for a liquid effluent or for the discharge of ion exchange resins are summarized in the following table, which gives the maximum permissible total activity for a single discharge as a function of selected values of the ppc value for the environment and the maximum permissible number of such discharges per month.

ppc value for the environment (μc/ml)	Permissible Activity in a Single Discharge For 1 discharge per month (curies)	For 30 discharges per month (curies)
10^{-9}	23	2.4
10^{-8}	2.3×10^{2}	24
10^{-7}	2.3×10^{3}	2.4×10^{2}

This region has a much greater capacity for receiving waste materials than the coastal area, and the release of low level liquid wastes from nuclear-powered ships into waters of the outer continental shelf apparently presents no serious problem.

For fishing areas of the outer continental shelf (Zone 3a), the weighted mean ppc value for the spent ion exchange resins of the SAVANNAH is 2×10^{-8} μc/ml. Since as many as 30 discharges per month onto the continental shelf of the eastern United States could conceivably result from the activity of 300 nuclear-powered ships, the maximum permissible activity per discharge would be about 50 curies. Since the predicted activity on the spent ion exchange resins of the SAVANNAH will be 100 to 400 curies, it is evident that no release of such resins into fishing areas of the outer continental shelf should be allowed.

For this zone, the weighted mean ppc value for the wastes from the spent ion exchange resins of the NAUTILUS is computed to be 6×10^{-9} μc/ml. The above table then indicates that the gross activity per discharge for such wastes should not exceed about 14 curies, at the rate of 30 discharges per month spread over the entire continental shelf of the eastern United States. This 14 curies is approximately equal to the observed gross activity on the spent ion exchange resins of the NAUTILUS.

For non-fishing areas of the outer continental shelf (Zone 3b), the ppc value for the wastes from the spent ion exchange resins on the NAUTILUS is 3×10^{-8} μc/ml. Thus the gross activity per discharge for such wastes introduced into this environment should not exceed about 70 curies per discharge, for a maximum of 30 such discharges per month randomly distributed over the outer continental shelf off the east coast of the United States. This is approximately equivalent to one discharge per month in any 100 mile wide slice of this shelf.

The continental shelf region selected for the sample calculation may not be the most restrictive segment of the continental shelf of the world ocean, from the standpoint of radioactive waste disposal. Therefore the recommendations which follow are somewhat more conservative than would be drawn from a strict application of the numerical results.

Recommendations for the outer continental shelf, from 12 miles offshore to the 200 fathom depth contour (Zones 3a and 3b), follow.

Recommendation 6: No discharge of spent ion exchange resins from nuclear-powered ships should be made into known fishing areas of the outer continental shelf, from 12 miles offshore to the 200 fathom contour line. Except under very exceptional circumstances there should be no discharge of packaged solid wastes from nuclear-powered ships into these waters, and any such exceptional discharge should conform to recommendations contained in the National Academy of Sciences' report "Radioactive Waste Disposal in the Atlantic and Gulf Coast" (NAS-NRC Pub. 655, 1959).

Recommendation 7: If denser than sea water, spent ion exchange resins from nuclear-powered ships may be discharged into non-fishing areas of the outer continental shelf, from 12 miles offshore to the 200 fathom contour, provided that the activity in any single discharge shall not exceed 50 curies, and also provided that such discharges be restricted to ships which could not, without appreciable loss in efficiency, limit such discharges to waters of the open sea having depths exceeding 200 fathoms. Thus ships inbound from an ocean passage should schedule discharges,

which might actually become due during transit of the continental shelf, while still in waters exceeding 200 fathoms in depth. Ships outbound for an ocean passage should delay discharges, where practical, until after having passed into waters of over 200 fathoms in depth. Discharge may be made only when the ship is under way and more than 3 miles from a neighboring vessel.

Recommendation 8: No restriction need be placed on the discharge of low level liquid effluent from nuclear-powered ships into waters of the outer continental shelf, provided that the composition and amount of activity in such wastes are of the same general character as that predicted for the primary coolant of the SAVANNAH or observed for the primary coolant of the NAUTILUS.

The open sea, more than 12 miles from any shore, and having depths greater than 200 fathoms (Zones 4a and 4b):

This segment of the marine environment has a greater capacity for receiving radioactive wastes than any of the other subdivisions considered in this report. The area of the open sea which is employed in this sample computation consists of the North Atlantic trade route from New York to London. The results of the evaluation for this environment are summarized in the following table, which gives the maximum permissible activity for a single discharge as a function of selected values of the ppc for the environment and the maximum permissible number of such discharges per month.

ppc value for the environment (μc/ml)	Permissible Activity in a Single Discharge For 30 discharges per month (curies)	For 300 discharges per month (curies)
10^{-9}	9.5×10	2×10
10^{-8}	9.5×10^{2}	2×10^{2}
10^{-7}	9.5×10^{3}	2×10^{3}

For fishing areas of the open sea (Zone 4a), the weighted mean ppc value for the spent ion exchange resins of the NAUTILUS is 1×10^{-8} μc/ml, and for non-fishing areas (Zone 4b), 7×10^{-8} μc/ml. The corresponding values for the SAVANNAH are slightly higher. If 300 nuclear-powered ships should each discharge spent ion exchange resins 6 times a year, there would be on the average 150 such discharges per month. If all these

CONSIDERATIONS ON THE DISPOSAL OF RADIOACTIVE WASTES FROM NUCLEAR-POWERED SHIPS INTO THE MARINE ENVIRONMENT

PURPOSE

An unavoidable consequence of the operation of any fission reactor, whether located on land or aboard a nuclear-powered ship, is the production of unwanted radioactive wastes. The two general methods of treating these wastes are: (1) containment, coupled with isolation from man's environment; and (2) dispersion, so that the probability of return to man is extremely small. In some cases complete containment and isolation are not technically feasible. In other cases such containment and isolation are conceivably feasible, but at high cost.

The purpose of this report is to provide an evaluation of the potential capacity of the marine environment to receive certain radioactive wastes originating from normal operations of nuclear-powered ships. Basically, this report is an evaluation of the potential risks involved in utilizing the marine environment in dispersion of these wastes so that the probability of return to any segment of the human population would be small. The conclusions of this working panel can then be employed in weighing these risks against the costs and the risks of alternate methods of waste treatment. Such a comparative evaluation can finally be utilized in the formulation of design criteria and operating doctrine for nuclear-powered ships.

SCOPE

Our considerations have been limited to the marine environment. No conclusions are reached concerning the safety of operating nuclear-powered ships in tideless, fresh water bodies. We would assume that before any nuclear-powered ship operated on such waterways, special consideration would be given to the problems peculiar to that environment by scientists competent in physical, chemical, and biological limnology.

Separate evaluations are made for (a) the inshore area, including harbors and estuaries; (b) the coastal area, which is here considered as the area between 2 miles and 12 miles offshore; (c) the outer continental shelf, which is here considered as the area seaward of a line 12 miles from shore and extending to the 200 fathom depth contour; and (d) the open sea, here considered as those oceanic areas more than 12 miles from shore with depths exceeding 200 fathoms.

BRIEF DESCRIPTION OF A NUCLEAR SHIP REACTOR AND ITS OPERATION

In this report, consideration has been given primarily to current American practice in the design and operation of water-cooled nuclear reactor systems. There is to date considerable actual operating experience with systems of both the pressurized water and the boiling water type. (Descriptions of these are given in technical manuals covering the Shippingport Atomic Power Station, Shippingport, Pennsylvania, the Army Package Power Reactor at Fort Belvoir, Virginia, the Experimental Boiling Water Reactor at the Argonne National Laboratory, Lemont, Illinois, and the Vallecitos Boiling Water Reactor, Vallecitos, California.)

Design and operation: A nuclear reactor for ship propulsion replaces conventional boilers fired by fossil fuel. Thermal energy removed by the reactor coolant serves to form steam, either directly or indirectly, to drive the ship's propulsion equipment. Most of the other principal and auxiliary equipment associated with the power cycle is very similar to that used in the conventional marine power system.

In the typical reactor, light water serves as a neutron moderating medium, as well as the heat transfer fluid. The uranium is fabricated in the form of plates or pins, within a cladding, and assembled as conveniently handled fuel elements to form the reactor core. At start-up the excess volume created by thermal expansion of water in some types of systems is displaced as the reactor is brought up to operating temperature. This volume must necessarily be replaced when the reactor is shut down, to assure that the system will be completely filled.

This excess volume from thermal expansion is one of the types of waste with which this report is concerned. As later described, this water contains relatively low concentrations of radioactive corrosion products and may, under some circumstances, also contain a certain variable concentration of fission products. The removal of these materials is generally accomplished by the use of a by-pass purification system through which a portion of the primary coolant is continuously circulated.

Additional sources of liquid radioactive wastes include: operational leakage from various components of the primary and auxiliary systems; sampling and laboratory wastes, and those due to equipment decontamination; and shower and laundry wastes associated with the reactor plant. The effluents are collected into holding tanks for storage, decay, and analysis before being either transferred to shore facilities, treated aboard ship, or directly disposed of through controlled discharge overboard.

Shipboard reactors are generally designed to operate continuously for two to three years on a single loading of fuel ranging up to several thousand kilograms of uranium, depending on the degree of its enrichment. Refueling will be programmed insofar as possible to coincide

with conventional hull and machinery inspection and maintenance schedules. Liquid wastes associated with refueling will generally include drainage from the primary system, together with effluents from decontamination of reactor components and fuel handling facilities.

As additional experience is obtained in the operation of both land-based and shipboard reactor systems, changes will undoubtedly be made in design criteria, selection of materials, and other factors influencing the character and volume of wastes. Other types of reactors will undoubtedly be used in some future nuclear-powered ship designs. Thus there are now in progress several feasibility studies of the use of organic-moderated and gas-cooled nuclear reactors. The character and amount of wastes which might be introduced to the marine environment from such future designs cannot be stated accurately now. It is believed that these general conclusions can be utilized in formulating design criteria and operating doctrine, with respect to waste disposal into the marine environment, for such future types of marine reactors. The specific considerations presented here are primarily directed towards the presently planned water-cooled marine reactors.

DEFINITION OF THE TERM "WASTES"

In the normal operation of a nuclear-powered ship, as with any conventionally powered ship, liquid effluent will originate from a number of sources. Thus considerable quantities of sea water are circulated through the steam condenser, and discharged back to the marine environment. Sanitary wastes and water used to wash down the decks and for similar normal operating purposes are usually discharged overboard. These liquid effluents would not normally contain any radioactivity resulting from the operation of the nuclear power plant, though it is conceivable that some human or mechanical failure could alter this.

It therefore is desirable, from a practical standpoint, to state some criteria serving to clarify, within the scope of this report, whether a particular effluent could be considered as a radioactive waste or not. For this purpose the following working definition is proposed:

A liquid effluent shall be classed as a radioactive waste if the activity of the undiluted effluent exceeds the mpc values for drinking water for the general public as given in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed).

Solid materials such as trash and garbage are normally discharged overboard from ships at sea. Such material would not be expected to have any activity originating from the operation of the nuclear power plant. In order to cover any eventuality, this working panel suggests that:

Solid materials discharged to the ocean shall be classed as radioactive wastes if the total activity of any whole solid segment exceeds the total activity which would be contained by an equal volume of water having mpc values for drinking water for the occupational worker as

given in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed).

POTENTIAL SOURCES OF RADIOACTIVE WASTES

Of all the unwanted radioactive byproducts, or wastes, produced in the operation of a nuclear reactor, the fission products comprise the bulk. Under present and contemplated design, these fission products would be contained largely in the spent fuel elements. Additional wastes result from the induced activity of corrosion products in the primary coolant, together with small amounts of fission products which may be transferred to the primary coolant as a result of minor failures in the cladding of the fuel elements. The amount of radioactive materials in the primary coolant is maintained at relatively low levels by use of a bypass purification system resulting in the accumulation on ion exchange resins of corrosion product activity, and a considerably smaller amount of fission product activity.

The greater part of the fission products is removed from the ship in the spent fuel elements at the time of refueling. The possible ultimate fate of such high level wastes is beyond the scope of this report. It is, however, our basic assumption that these high level wastes do not enter the marine environment through normal operation of a nuclear-powered ship. Only in the case of a highly improbable maximum credible accident could any portion of these materials enter the marine environment.

The potential sources of radioactive wastes which might be discharged to the marine environment from nuclear-powered ships are, then: (a) the expansion volume of primary coolant during warm-up of a pressurized water reactor; (b) operational leakage from various components of the primary and auxiliary systems, and wastes from the laboratory, from sampling, from equipment decontamination, and shower and laundry wastes associated with the reactor plant; (c) ion exchange resins which remove corrosion products from the primary coolant; and (d) contaminated solid materials.

AMOUNT AND COMPOSITION OF WASTES

The amount and composition of radioactive wastes cannot be predicted accurately for all potential marine reactors. In order to have some reasonable basis for evaluation, data for the proposed N.S. SAVANNAH, obtained from the report of the Maritime Administration entitled "Waste Disposal Considerations in the Nuclear-Powered Merchant Ship Program" (January, 1959), have been employed as representative of the composition and amount of "typical" potential radioactive wastes from a nuclear-powered merchant ship.

In addition, actual operating data from the nuclear-powered submarine NAUTILUS have been made available in the report "Radioactive Waste Disposal from U. S. Naval Nuclear-Powered Ships" (January, 1959) presented for inclusion in the record of the public hearings on

industrial radioactive waste disposal held by the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, 27 January to 3 February, 1959. These data also have been utilized by this working panel.

The major source of potential liquid waste is the primary coolant. For the SAVANNAH,* after 50 days of operation during which a single ion exchange bed has been utilized for by-pass clean-up, and assuming 1530 grams of exposed fuel, it is estimated that the concentration of activity of the significant isotopes in the primary coolant will be about 8×10^{-2} μc/ml, of which the greatest amount will be Cr 51, Co 60, Fe 55, and Ta 182. Strontium 90 is estimated to have a concentration in the primary coolant water of 1.4×10^{-7} μc/ml.

The expansion volume during reactor warm-up is estimated to amount to 290 ft^3, or 8.2×10^6 ml. Thus during each warm-up a total release of about 6.8×10^{-1} curies would occur. Cr 51 would contribute about 0.4 curies, while Co 60, Fe 55 and Ta 182 would contribute about 0.1 curie each, and Sr 90 would contribute about 1×10^{-6} curies per warm-up to the potential liquid effluent. Leakage and other minor sources of liquid waste might contribute 100 gals/day, or 3.8×10^5 ml, of liquid effluent of about the same activity as the warm-up water. This would be equivalent to a total activity per day of 3.0×10^{-2} curies.

Assuming that each vessel had an average of two warm-ups per month, the total potential activity in the liquid wastes from one ship during one year's operation would be 16 curies from warm-up and 11 curies from leakage and other minor sources.

The ion exchange resins used in the by-pass clean-up of the primary coolant would contain far greater activity than that present in the primary coolant itself. It is estimated that in the present merchant ship design these resins, after 50 days of operation, would contain a total activity of about 400 curies, with Cr 51, Ta 182, Co 60, and Fe 55 each contributing about 100 curies. Assuming a change of resin every 50 days, the total activity released per ship per year from this source would be 2900 curies.

It is estimated in a later section of this report that 300 nuclear-powered ships of all nations will be in service by 1975. These 300 ships would then potentially release to the marine environment approximately 2500 curies per year from expansion water, some 3400 curies per year from leakage and other minor sources of liquid wastes, and some 9×10^5 curies per year from the ion exchange beds.

---

*Since completion of this report, subsequent re-evaluation of the probable character and activity of the primary coolant and the ion exchange resins has been issued by the Oak Ridge National Laboratory (1959). While this ORNL report includes somewhat different values for the activity in these potential wastes, the general conclusions arrived at here remain unchanged.

According to the report "Radioactive Waste Disposal from U. S. Naval Nuclear-Powered Ships", the actual operating results of the U. S. S. NAUTILUS and the U. S. S. SKATE have produced radioactive wastes considerably less, both in intensity of activity and in amount, than those predicted in the Maritime Administration's report for the SAVANNAH. The average gross activity of the primary coolant of the NAUTILUS, 15 minutes after sampling, was 5×10^{-2} μc/ml. However, the bulk of this activity was associated with Mn 56 (2.5 hr half life) and F 18 (1.9 hr half life). The gross activity 120 hours after sampling has averaged 3×10^{-3} μc/ml. The measured activity of Co 60, Fe 59, and Ta 182 has averaged 5.7×10^{-6}, 1.5×10^{-4}, and 7.3×10^{-3} μc/ml respectively. Fe 55 apparently does not occur in measurable quantities in the primary coolant of the NAUTILUS.

The expansion volume on warm-up for the NAUTILUS is much less than that predicted for the SAVANNAH, averaging about 500 gals (67 cubic feet). The maximum activity on the spent ion exchange resins in the NAUTILUS, and the rate at which these resin beds require replacement, are likewise much less than the corresponding figures for the SAVANNAH. The total activity on the spent resin beds is reported to be no more than 12.5 curies, with the bulk of the activity (some 10 curies) resulting from Co 60. The beds have required replacement about once every six months.

During each warm-up involving the average discharge of 67 ft^3 or 1.9×10^6 ml, the NAUTILUS then releases approximately 9.5×10^{-2} curies (measured 15 minutes after sampling). Co 60, Fe 59, and Ta 182 would contribute 1.1×10^{-5} curies, 2.9×10^{-4} curies, and 1.4×10^{-2} curies, respectively. Assuming two warm-ups per month, the total activity in the expansion volume liquid wastes from the NAUTILUS during one year would be about 2.3 curies measured 15 minutes after sampling and 0.14 curie measured 100 hours after sampling.

In comparison with these amounts, the activity in the fission products contained in the spent fuel elements is quite large. Thus the fission products in the fuel elements from a 60 MW reactor which had been in service for one year on a nuclear-powered ship would amount to over 10^7 curies.

It has been stated that the vast majority of the fission product wastes will be stored on land, after chemical separation from unused fuel and useful by-products. However, even a small fraction of this activity could be significant if released in coastal areas. Release of activity to the coastal environment by land based nuclear installations, particularly chemical processing plants, may be difficult to avoid. Thus, under a carefully controlled program designed to limit the return of activity to man to a safe level, the Windscale Works in England is authorized to release over 10^5 curies per year into the coastal waters of the Irish Sea. The major part of the safe capacity of these inshore areas should then be reserved for land based operations, since nuclear-powered ships could conceivably delay discharge of wastes until outside such areas.

Nuclear-powered ships will spend a part of their time in areas well removed from man, where perhaps the disposal of limited amounts of wastes would not result in ready return to man through the food chain. These ships will also spend part of their time in regions of high human activity, such as harbors and harbor approaches. The release of even very small amounts of radioactive materials in these latter environments might result in the return to man, through the food chain, of undesirable amounts of activity. For this reason even the relatively small amount of activity present in the primary coolant is considered deserving of consideration.

PREDICTED NUMBER OF NUCLEAR-POWERED SHIPS

In order to evaluate properly the capacity of the various parts of the marine environment to receive radioactive wastes from nuclear-powered ships, it is necessary to have a reasonably correct prediction of the number of such ships which will be operating on the world oceans within the next several decades. Efforts to obtain such an evaluation have not resulted in consistent estimates, within even an order of magnitude. For this reason the evaluation presented herein is based on an arbitrary number of 300 nuclear-powered ships of the 60 MW class. It is believed that this figure should safely apply to the next ten to fifteen years. Thus, adequate time is available to revise the conclusions made here on the basis of more dependable estimates of the probable number of nuclear-powered ships which will, in the foreseeable future, operate on the world oceans. Undoubtedly, better information than is now available on the allowable exposure of man to radiation, and on the processes of dispersion, uptake, and concentration in the marine environment, will become available over the next ten years, making such a re-evaluation desirable in any case.

GENERAL APPROACH TO THE PROBLEM

The fate of radioactive material introduced into the marine environment is dependent upon the following considerations:

1. The physical and chemical form in which the material occurs at time of introduction, together with any relatively rapid changes in the physical and chemical character of the introduced material which occur when it is brought into contact with sea water. The subsequent dispersion by physical processes and re-concentration by the biota and bottom materials will be greatly affected by the physical and chemical form in which the wastes occur in sea water.

2. Initial mechanical dilution of the wastes by the receiving waters, which will depend upon the manner of introduction. Thus a liquid waste will be subject to greater initial mechanical dilution if introduced as a strong jet into the body of the receiving waters, than if introduced as a gently flowing stream on the surface. Large initial mechanical dilution is important in reducing the density difference between the initial contaminated volume and the surrounding receiving waters. This reduction in turn favors subsequent turbulent diffusion.

3. Advection of the waste material away from the source region, and simultaneous turbulent diffusion, which lead to reduced concentrations of the radioactive components in the water.

4. Uptake of the activity onto suspended silt and bottom sediments, which removes some of the radioactive materials from the water, and restricts further dispersion. In deep water such removal would be favorable since material incorporated with the bottom sediments there would be unlikely to return to man's environment. In shallow coastal areas containing bottom living shellfish and bottom feeding commercial fin fish, concentration of radioactivity on the bottom may be unfavorable since these detritus and filter feeders may further concentrate the activity from the bottom material.

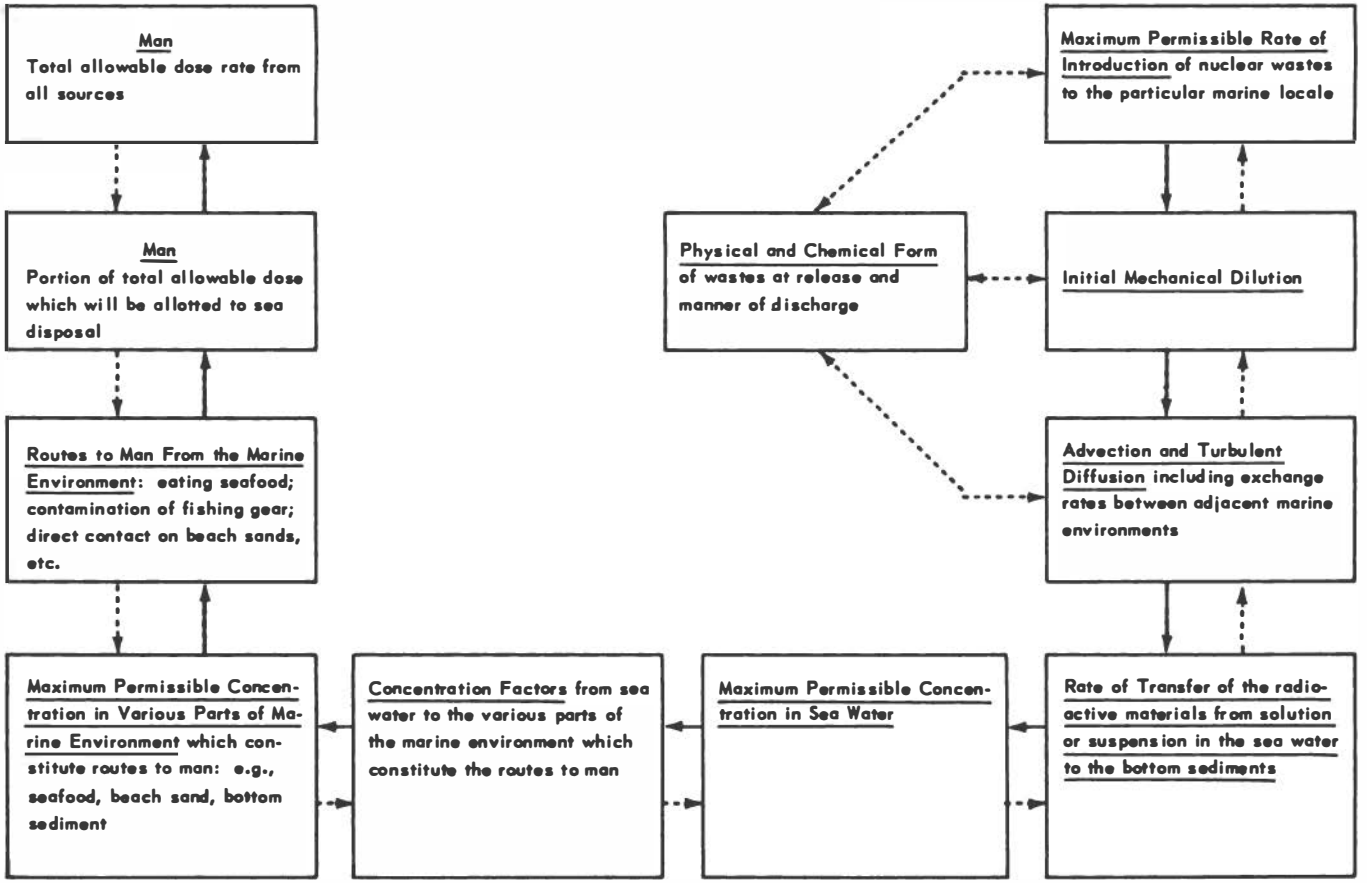
5. Concentration of activity by various parts of the biota, including shellfish and fin fish important to man as a source of food. Some important fission products and corrosion products are concentrated by marine organisms by factors of 100 to 10,000 over the concentrations of these isotopes in the water.

The evaluation of the suitability of any particular marine locality as a receiver of nuclear wastes ideally involves the precise, step by step consideration of all factors affecting the possible return of radioactive material to man. The general procedure is the same whether the evaluation concerns: (a) the selection of suitable disposal areas for packaged wastes; (b) the selection of the position of an outfall discharging low level liquid effluent from a chemical processing plant; (c) the consideration of the suitability of a given harbor or harbor approach to receive low level liquid wastes from nuclear powered ships; or (d) the determination of the suitability of the mixed layer of the open ocean to receive wastes from the ion exchange resins on nuclear powered ships. Understanding of many of the physical and biological processes involved is, however, far from adequate, and further research is recommended to provide a more adequate foundation for the determination of the capacity of any particular marine locale to receive nuclear waste materials without undue risks to man.

Figure 1 presents in schematic form such a step by step procedure. The solid arrows between blocks on the diagram indicate the route taken by the radioactive material in returning to man, while the dashed arrows indicate the reverse course taken in the evaluation. The starting point in the evaluation is man. In order to make any evaluation of the problem at all, some maximum permissible rate of exposure must be adopted. The usual basis for the selection of such a maximum rate would be national (or international) published statements of the maximum permissible ingestion rate for the various isotopes, for the general population. At the outset it should be recognized that such a maximum permissible rate of exposure is not the most desirable rate. The latter, where technical and economic feasibility allow, should be as close to zero as possible. Thus in making this evaluation, some real, though admittedly extremely slight, risk to the general public is assumed.

FIGURE 1

Schematic Presentation of the Step-by-Step Considerations which Should be made in Evaluating the Suitability of Any Marine Locale as a Receiver of Nuclear Wastes



Considerable care should be taken in any evaluation that the potential additive effect of exposure to radiation from various sources is given due consideration. The second step in the evaluation is then a consideration of all sources of radiation exposure to the particular segment of the population which would also be potentially affected by the waste disposal operations. On the basis of such consideration a portion of the maximum permissible dose is assigned to sea disposal.

The next step is the consideration of the various routes which the radioactivity can take in reaching man from the marine environment. Here an evaluation of the uses man makes of the marine environment is required. The possible danger of direct radiation, the harvest of seafood, possible contamination of fishing gear and of beach sand are some of the items which should be considered at this stage of the study.

The determination of the maximum permissible concentrations of the various significant isotopes in those parts of the marine environment (seafood, bottom sediments, and shore material), which constitute the routes by which radioactivity may return to man from the sea, then follows as the next step in the process. From a consideration of the known factors by which the biota and the sediment concentrate the various radioactive isotopes from the sea water, it is then possible to arrive at the maximum permissible concentration of the various isotopes in the sea water.

The final steps involve evaluating the changes in the concentration and distribution of radioactivity which may be brought about by

(a) exchange between bottom sediment and suspended or dissolved material in sea water;

(b) advection and turbulent diffusion, both within a given marine environment and between adjacent environments;

(c) initial mechanical dilution, influenced by manner of discharge; and

(d) physical and chemical form of the wastes at time of release.

The end result is an estimate of the maximum rate of introduction of radioactive material which will not exceed the maximum permissible concentration in sea water.

In the present problem of waste disposal from nuclear-powered ships, some modification of this ideal step-wise procedure must be made since we are not dealing with a fixed region of the marine or coastal environment. For this reason it has been necessary for this working group to take a conservative (safe) assumption at each step of the evaluation. Thus, for inshore and coastal environments, when considering the return route to man of radio-isotopes through seafood, the assumption used here is that man receives all his protein requirement from seafood, and that the highest known concentration factor for

the particular isotope to the edible marine biota is applicable. Any specific evaluation of a particular marine locale, such as a harbor in which nuclear ship testing and servicing are carried out, or which serves as a primary port for nuclear powered vessels, can be based on the study presented here, taking into account the actual utilization of that particular marine environment by man.

BIOLOGICAL SIGNIFICANCE OF THE VARIOUS PARTS OF THE MARINE ENVIRONMENT

With respect to the various physical and biological processes leading to contamination of man's food from the sea, the marine environment may be subdivided in the following manner:

1. The nearshore areas, including the intertidal zone of the open coast and the areas which are partially enclosed by land, i.e., harbors, bays, estuaries, lagoons, and passages separated from the open sea by fringing islands.

2. The continental shelf, and overlying waters. The continental shelf is the submarine rim of a land mass. It extends from the beach seaward and ends at a depth of about 200 meters with a slope descending more or less precipitously into the deep sea. It may be only a few miles wide, as it is along the coast of California, or it may reach out over 100 miles into the ocean, as it does off the North Atlantic coast of North America.

3. The deep sea beyond the continental shelf.

An important further subdivision of the deep sea and the outer continental shelf must be recognized for our purpose. The upper 100 meters (more or less) from the shore outward is a layer in which the water is mixed by various processes brought about by wind and seasonal changes of temperature. A sharp density gradient of considerable thickness separates this mixed layer from the water below, which is generally more stable; the density gradient constitutes a barrier which impedes exchange between the deeper water and the mixed layer.

The nearshore environment is the habitat of commercially important oysters and clams; it is a principal habitat of some highly valued game fishes; it is an essential nursery ground for other commercial species. Seaweed industries gather their raw material in this area. It is the only part of the sea that can be cultivated like farmland; and it provides exceedingly important fishing grounds for thousands of men, most of them working with small craft.

Upon the continental shelf live many commercially important invertebrates and fish, together with plants and animals of indirect economic value as food for the species utilized by man. Centers of fish population concentration shift diurnally and seasonally. There are few unpopulated areas. Certain commercial species range freely both within and below the mixed layer, over the continental shelf and the

deep ocean. We cannot specify any of the marine environments from the land out to the deeper parts of the slopes of the continental shelf which are absolutely devoid of exploited or exploitable food resources, especially as world populations and food needs continue to expand.

GENERAL CONSIDERATIONS ON CRITERIA OF ACCEPTABILITY

The International Commission on Radiological Protection and the U. S. National Committee on Radiation Protection have estimated the maximum permissible total body burden of various radio-isotopes and the corresponding maximum permissible concentrations in drinking water. These have been published by the U. S. National Committee in Handbook 52 of the National Bureau of Standards (1953). A revision by the International Commission on Radiological Protection is under preparation; data from this forthcoming revision have been utilized by AEC in preparing tables contained in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed).

Permissible concentrations in the marine environment are usually calculated on the basis of these maximum permissible body burdens or maximum permissible concentrations in drinking water by: (1) assuming a factor relating maximum permissible exposure of the general population to the maximum permissible exposure as an occupational hazard (Dunster, 1956, for example, used a factor of 1/10; Carritt, et al., 1958, use the mpc's in Handbook 52); (2) calculating, from reasonable and conservative assumptions, the quantity of radionuclides that will reach man from given quantities in the environment. By further considering the relationship between the rate of introduction of a nuclide and the resulting concentration in the environment, there can finally be estimated the maximum permissible rate of discharge into the environment.

This is a reasonable procedure and is similar to the one that we have followed. However, it should not be assumed that the maximum permissible rate of discharge of nuclides into the environment is the sole criterion for determining the acceptable rate of discharge. The acceptable discharge should be that quantity, less than the maximum permissible, which is reasonable, taking into account the cost of reducing the quantity. In some cases where the cost of alternatives is low and the advantages to be gained by such alternatives are great, the acceptable discharge of radioactive wastes may be zero. This is emphasized because, although it has been repeatedly pointed out by other committees dealing with such problems, it has often been ignored.

Both the International Commission on Radiological Protection (1950) and the U. S. National Committee on Radiation Protection (1953) have recommended that exposure to any type of radiation be kept to the lowest level deemed possible or practicable. Evidence that there may be no threshold value for radiation damage, either somatic or genetic, led the U. N. Scientific Committee on the Effects of Atomic Radiation (1958) to the conclusion that any amount of radiation, no matter how small, may be harmful in some degree.

On the other hand, this same U. N. Committee (1958) stated that "the possibility cannot be excluded that our present estimates exaggerate the hazards of chronic exposure to low levels of radiation". There is obviously need for much intensive research on all aspects of the problem. For the present, it is evident that the only proper course to pursue, in regard to exposure of man to radiation, is a cautious one.

It should be noted that the maximum permissible concentrations in drinking water tabulated in Handbook 52, and in similar publications, are calculated on the assumption that this is the only source of man's intake of an isotope. If a man is ingesting quantities from several sources, the total intake should not exceed the intake corresponding to the mpc for drinking water times 2,200 (the daily water intake, in milliliters, assumed in Handbook 52). Therefore, in estimating the maximum permissible level in any particular source (such as in food from the sea), account must be taken of all other sources.

On the other hand, care must also be taken to appreciate the full significance of the terms "maximum permissible exposure" and "maximum permissible concentration". These terms, as used here, are based on the effects of continuous exposure to a large human population over the average life span. Thus local, short term conditions in which concentrations of radionuclides exceed the mpc values may be permissible, provided that the total exposure over a relatively long period of time remains below the required average for that period.

PROCESSES DETERMINING THE CONCENTRATION OF NUCLIDES IN THE MARINE ENVIRONMENT AND IN SEA FOOD

The physical, chemical, and biological processes affecting the distribution of radio-isotopes in the sea have been considered in some detail by Revelle, et al. (1957), and the processes in coastal waters particularly have been reviewed by Carritt, et al. (1958). It is, however, desirable to consider some of these matters here, with particular reference to the problems of disposal of wastes from nuclear-powered ships.

Physical effects: The oceans are stratified in approximately a two layer system, with an upper, mixed layer about 100 meters thick, separated from the deeper waters by a region of rapid increase in density, which acts as a barrier to vertical mixing. In partially enclosed basins (harbors and estuaries) interchange between the waters thereof and the waters of the upper mixed layer of the open sea is often inhibited, so that the rate of dilution of pollutant in the water of the basin is a great deal less than the rate of dilution due to eddy diffusion in the open sea. Where the basin has a shallow entrance, there usually will be developed in the basin below the entrance depth a body of water which stagnates seasonally or permanently, and in which there can be a considerable accumulation of elements which fall out as particles from the upper layer. The interchange of water from partially enclosed basins with the open sea depends on a number of factors including (1) the topography of the basin, (2) the amount of fresh water runoff into the

basin, (3) the rate of evaporation from the surface, and (4) the tidal and other currents in the waters of the basin. The flushing time (mean residence time of a water particle) is highly variable among estuaries, from a few days to a year or more.

Geochemical effects: Several things can happen to radioactive materials introduced into the sea as liquid wastes. They may remain in solution or be precipitated out, depending on whether or not the solubility product of the least soluble compound in seawater has been exceeded. Dissolved substances may also be precipitated by coprecipitation with other elements or by sorption on organic or inorganic particles already present in the sea. Both particles and dissolved materials may also be taken up by organisms and enter into biochemical cycles.

Krumholz, Goldberg and Boroughs (1957) point out that the elements of Groups I, II, V, VI, and VII usually occur as ionic forms in seawater (these include Cs, Sr, Ba, Zr, Cu, Zn, and I) while the other elements, except the rare gases, occur as solid phases (e. g. Y, Fe, Co, and Ru). These authors also tabulate, from Greendale and Ballou (1954), the physical states of elements following detonation of an atomic bomb, which probably also indicates the physical states resulting from waste products introduced into the sea. The material is reproduced here in Table 1.

TABLE 1

PHYSICAL STATES OF ELEMENTS IN SEAWATER
(from Greendale and Ballou, 1954)

	Percentage in given physical state		
Element	Ionic	Colloidal	Particulate
Cesium	70	7	23
Iodine	90	8	2
Strontium	87	3	10
Antimony	73	15	12
Tellurium	45	43	12
Molybdenum	30	10	60
Ruthenium	0	5	95
Cerium	2	4	94
Zirconium	1	3	96
Yttrium	0	4	96
Niobium	0	0	100

Gravity effects on particulate matter in the sea will tend to remove from the seawater radio-isotopes incorporated in such particles, which eventually settle to the sea bottom. In the deep sea such sedimentation will remove radio-isotopes from the domain of harvested marine organisms. In the nearshore and continental shelf waters,

however, it may tend to concentrate them in the bottom sediments from which they may be returned to the water or taken up by bottom-living food organisms.

Biological effects: A number of elements are concentrated in the bodies of organisms by several orders of magnitude over their abundance in natural waters. Radio-isotopes of such elements are, therefore, concentrated in man's aquatic foods. As pointed out by Ketchum (1957), the concentration of certain elements by organisms, subsequent migration of these organisms, and gravitational effects on their excreta and remains, all combine to produce a circulation of these elements which differs from the circulation of the water. This is of particular importance in inshore and estuarine waters where, as shown by Ketchum, there may result an accumulation of an element greater than that in the source waters. Revelle and Schaefer (1957) have noted also that "The time required for removal of radioactive materials from estuaries will, in general, be much greater than the flushing time of substances that are not absorbed by organisms or taken up by bottom sediments".

MAXIMUM PERMISSIBLE CONCENTRATIONS IN SEA FOOD

As we have noted above, the maximum permissible body burdens of various radio-isotopes and the corresponding maximum permissible concentrations in drinking water as applicable to the general public (calculated under the assumption that this is the only source of the ingested isotope) have been tabulated in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed). These are recapitulated in Table 2 for a number of isotopes, including the more important corrosion products and fission products which may occur in wastes from shipborne reactors.

Two additional considerations are required in arriving at the maximum permissible concentrations in seafood which would be permitted to originate from waste disposal operations of nuclear-powered ships. The first of these involves estimation of the amount of seafood which would be ingested, per unit of time, by a segment of the population. The second involves allocating to ship waste disposal a certain share of the maximum permissible dose which man may receive from the utilization of atomic energy. As has been pointed out earlier, food from the sea is not the only source of ingestion of radio-isotopes, and nuclear-powered ships are not the only potential source of introduction of radioactive material to the sea. Therefore, it is necessary to decide how much of the maximum permissible intake shall be allocated to the results of waste disposal from nuclear-powered ships.

Since the maximum permissible concentrations so determined apply only to that activity originating from nuclear ship operation, they are actually partial permissible concentrations (ppc's) and are so designated in this report.

The evaluation of how much of the maximum permissible intake should be allocated to the results of waste disposal from nuclear-

TABLE 2

DATA ON CERTAIN RADIOISOTOPES WHICH MAY BE PRESENT IN WASTE FROM NUCLEAR POWERED SHIP REACTORS

Isotope	Half Life	Maximum* Permissible Total Body Burden (μc)	mpc in Drinking** Water (μc/ml)	Partial Permissible Concentration in Marine Food for Cases (see footnotes): (1) (μc/g)	(2) (μc/g)	(3) (μc/g)	(4) (μc/g)	(5) (μc/g)
Cobalt 60	5.2 y	10	3×10^{-5}	3×10^{-5}	6×10^{-5}	3×10^{-4}	1×10^{-4}	7×10^{-4}
Iron 55	2.9 y	1×10^{3}	8×10^{-4}	8×10^{-4}	2×10^{-3}	8×10^{-3}	4×10^{-3}	2×10^{-2}
Iron 59	45 d	20	5×10^{-5}	5×10^{-5}	1×10^{-4}	5×10^{-4}	2×10^{-4}	1×10^{-3}
Chromium 51	27 d	800	2×10^{-3}	2×10^{-3}	4×10^{-3}	2×10^{-2}	1×10^{-2}	5×10^{-2}
Copper 64	12.8 y	10	2×10^{-4}	2×10^{-4}	4×10^{-4}	2×10^{-3}	1×10^{-3}	5×10^{-3}
Tantalum 182	112 d	7	4×10^{-5}	4×10^{-5}	8×10^{-5}	4×10^{-4}	2×10^{-4}	1×10^{-3}
Zinc 65	250 d	60	1×10^{-4}	1×10^{-4}	2×10^{-4}	1×10^{-3}	5×10^{-4}	2×10^{-3}
Cesium 137	33 y	30	2×10^{-5}	2×10^{-5}	4×10^{-5}	2×10^{-4}	1×10^{-4}	5×10^{-4}
Strontium 90	28 y	2	1×10^{-7}	1×10^{-7}	2×10^{-7}	1×10^{-6}	5×10^{-7}	2×10^{-6}
Zirconium 95	65 d	20	6×10^{-5}	6×10^{-5}	1×10^{-4}	6×10^{-4}	3×10^{-4}	1×10^{-3}
Niobium 95	36 d	40	1×10^{-4}	1×10^{-4}	2×10^{-4}	1×10^{-3}	5×10^{-4}	2×10^{-3}
Ruthenium 106	1 y	3	1×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-4}	5×10^{-5}	2×10^{-4}
Cerium 144	280 d	5	1×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-4}	5×10^{-5}	2×10^{-4}
Iodine 131	8 d	7×10^{-1}	3×10^{-6}	3×10^{-6}	6×10^{-6}	3×10^{-5}	2×10^{-5}	7×10^{-5}

Isotope	Concentration Factor*** Sea Water to: Invertebrates (edible parts)	Fish (soft parts)	Fish (skeleton)	Partial Permissible Concentration in Sea Water for Cases (see footnotes): (1) (μc/ml)	(2) (μc/ml)	(3) (μc/ml)	(4) (μc/ml)	(5) (μc/ml)
Cobalt 60	10^{4}			3×10^{-9}	6×10^{-9}	3×10^{-8}	1×10^{-8}	7×10^{-8}
Iron 55	10^{4}	10^{3}	5×10^{3}	8×10^{-8}	2×10^{-7}	8×10^{-7}	4×10^{-7}	2×10^{-6}
Iron 59	10^{4}	10^{3}	5×10^{3}	5×10^{-9}	1×10^{-8}	5×10^{-8}	2×10^{-8}	1×10^{-7}
Chromium 51	10^{3} (6)			2×10^{-6}	4×10^{-6}	2×10^{-5}	1×10^{-5}	5×10^{-5}
Copper 64	5×10^{3}	10^{3}	10^{3}	4×10^{-8}	8×10^{-8}	4×10^{-7}	2×10^{-7}	1×10^{-6}
Tantalum 182	10^{3} (6)			4×10^{-8}	8×10^{-8}	4×10^{-7}	2×10^{-7}	1×10^{-6}
Zinc 65	5×10^{3}	10^{3}	3×10^{4}	2×10^{-8}	4×10^{-8}	2×10^{-7}	1×10^{-7}	5×10^{-7}
Cesium 137	50	10		4×10^{-7}	8×10^{-7}	4×10^{-6}	2×10^{-6}	1×10^{-5}
Strontium 90	10	1	200	5×10^{-9}	1×10^{-8}	5×10^{-8}	2×10^{-8}	1×10^{-7}
Zirconium 95	2×10^{3} (7)			3×10^{-8}	6×10^{-8}	3×10^{-7}	1×10^{-7}	7×10^{-7}
Niobium 95	200	100		5×10^{-7}	1×10^{-6}	5×10^{-6}	2×10^{-6}	1×10^{-5}
Ruthenium 106	10^{3} (7)			1×10^{-8}	2×10^{-8}	1×10^{-7}	5×10^{-8}	2×10^{-7}
Cerium 144	8×10^{3} (7)	12 (8)		1×10^{-9}	2×10^{-9}	1×10^{-8}	5×10^{-9}	2×10^{-8}
Iodine 131	100	10		3×10^{-8}	6×10^{-8}	3×10^{-7}	1×10^{-7}	7×10^{-7}

* From Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised, 1959 (proposed).

** From Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised, 1959 (proposed), for the general public. Same as 1/10th the values given in Handbook 52, Revised, 1959 (proposed).

*** Data from Revelle et al. (1957); Ketchum and Chipman (1958); except as otherwise noted below.

(1) Harbors, estuaries, and inshore waters within 12 miles of the coast line (Zone 1 and Zone 2).

(2) The outer continental shelf, beyond 12 miles from the share line, in known fishing areas (Zone 3a).

(3) The outer continental shelf, beyond 12 miles from the share line, in regions not designated as known fishing areas (Zone 3b).

(4) The open sea, in known fishing areas (Zone 4a).

(5) The open sea, in regions not designated as known fishing areas (Zone 4b).

(6) No experimental data. Values approximated on basis of experimental data on biologically similar elements.

(7) Calculated from Martin (1957).

(8) Dunster (1956).

powered ships can be considered in two parts. The first involves an allocation to sea disposal in general. Essentially there are three environments from which man might receive radioactivity; these are the atmosphere, the land (including food and water from the land), and the sea. It is assumed here that sea disposal from all potential sources should be limited to a contribution to a selected portion of the population of no more than one-third of the maximum permissible intake for such a selected portion of the population. This allocation is not intended to specify the manner of subdividing the remaining two-thirds between land and atmosphere.

The evaluation of the remaining factors is somewhat different for each of the major subdivisions of the marine environment. In the following paragraphs the special considerations which apply to the inshore areas, to the continental shelf, and to the open sea are presented.

Special considerations related to harbors, estuaries and other inshore waters and to the continental shelf: An extremely conservative approach is warranted for these waters for the following reasons.

1. Most of the harvest of food from the sea comes from these waters, including the entire harvest of some sedentary forms, such as oysters, scallops, clams and seaweed, which concentrate certain elements by very large factors. Some large segments of the world population receive the bulk of their protein requirements from this part of the sea.

2. With the continuing development of atomic power, there will inevitably occur a requirement for some introduction of radionuclides into the inshore waters from land based establishments; the cost of avoiding this may be prohibitively high. Thus only a portion of the total potential receiving capacity of these waters is available for waste disposal from nuclear-powered ships.

3. In the case of a nuclear war, one of the least contaminated sources of food will be the sea. It is, therefore, desirable to keep the radioisotope contamination prior to this as far below the maximum permissible level as possible.

Some areas of the continental shelf do not contribute materially to the commercial fisheries, and hence some subdivision of this environment might be considered on the basis of known fishing areas. However, it should be remembered that the migratory species travel throughout the waters of the shelf, even though they may not be readily exploitable in some areas. Also some segments of the continental shelf are not now classed as known fishing areas simply because, for one reason or another, they have not yet been exploited. Hence no region of the shelf can be considered as completely devoid of biological significance.

The possible introduction of radioactive wastes into the sea from land based operations will result, for the most part, in contamination of harbors, estuaries, and coastal waters. Hence it may be appropriate

to consider waters within an arbitrary twelve miles from the coastline in a different category from the waters of the outer continental shelf. It must be pointed out, however, that this outer continental shelf will very likely be utilized in the disposal of packaged waste material. Hence nuclear-powered ships are not the only potential source of radioactive material for these waters.

Considerations relative to the open sea: Ocean areas more than 12 miles from shore and in which depths exceed 200 fathoms are here considered as open sea. In the open sea there are large areas which do not contribute materially to the commercial fisheries. There are, however, other large areas within which important oceanic fisheries operate, for example the Pacific tuna fishery. The open sea is now being utilized for the disposal of packaged waste material, though these wastes sink to the bottom and the possibility of any significant activity reaching the productive surface layers is slight. Under present doctrine regarding the containment of high level wastes on land, it appears that waste disposal from nuclear-powered ships will be the major source of radioactive wastes introduced into the surface layers of the open sea.

Subdivision of the Marine Environment: On the basis of the above considerations the sea has been divided into six zones, which differ one from another either in terms of potential contribution to the food supply of a selected portion of the population, or in terms of importance as a potential receiver of wastes from sources other than nuclear-powered ships, or in terms of the restrictions placed on dispersal within the zone due to physical boundaries. These zones, together with the assumptions required for computation of the partial permissible concentration in seafood in each of the zones, resulting from the operation of nuclear-powered ships, are listed below:

Zone 1. Harbors, estuaries, and inshore waters within 2 miles of the coastline. For this zone the assumption is made that a selected portion of the population receives all its protein requirement from seafood harvested from these waters. It is further assumed that 30 percent of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear ships in these waters.

Zone 2. The coastal area, between 2 and 12 miles from the shoreline. For this zone the same assumptions are made as for Zone 1. This zone differs from Zone 1 in that the dispersion is less restricted by physical boundaries.

Zone 3a. The outer continental shelf, beyond 12 miles from shoreline, having depths less than 200 fathoms, in known fishing areas. For this zone the assumption is made again that a selected portion of the population receives all its protein requirement from seafood harvested in these waters. It is further assumed that three-fifths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear-powered ships in these waters.

Zone 3b. Those areas of the outer continental shelf which are not classified as known fisheries areas. For this zone the assumption is made that these areas contribute, either directly or indirectly through migratory fish, 20% of the protein requirement of a selected portion of the population. It is also assumed that three-fifths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear-powered ships in these waters.

Zone 4a. The open sea, more than 12 miles from shore and having depths greater than 200 fathoms, in known fishing areas. For this zone the assumption is made that a selected portion of the population receives 50% of its protein requirement from seafood harvested in these waters, and that three-fourths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear-powered ships in these waters.

Zone 4b. Those areas of the open sea which are not classified as known fishing areas. For this zone the assumption is made that these areas contribute, either directly or indirectly through migratory fish, 10% of the protein requirement of a selected portion of the population, and that three-fourths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear-powered ships in these waters.

Computation of ppc Values for Seafood: A human population which obtained all its protein food from marine sources would eat about 1.5kg per week per person of fish or marine invertebrates. If this food is contaminated with a radioisotope, and if this is the only source of ingestion of the isotope, we can calculate the maximum permissible concentration in food corresponding to the maximum permissible concentration in drinking water by multiplying the latter by the ratio (water ingested per week) / (food ingested per week) =

$$\frac{2200 \times 7}{1500} \doteq 10.$$

Designate this factor as N_{wf}. Further, for each of the subdivisions of the marine environment, designate by N_p that fraction of the protein requirement which a selected portion of the population receives from seafood harvested there; designate by N_D that fraction of the maximum permissible dose for this population which can be allotted to waste disposal into the sea, and by N_s that fraction of the allotment to the sea which may be utilized for nuclear-powered ships within the particular marine subdivision. Then the partial permissible concentration in seafood which can result from the operation of nuclear-powered ships, for each of the subdivisions of the marine environment, is obtained by multiplying the maximum permissible concentration for drinking water for the general public by the factor N_m, which is given by

$$N_m = N_{wf} \times \frac{1}{N_p} \times N_D \times N_s .$$

These factors are, for each of the subdivisions of the marine environment:

(1) Zones 1 and 2: harbors, estuaries, inshore waters, and coastal areas within 12 miles of the coastline.

$$N_m = 10 \times 1 \times 1/3 \times 3/10 = 1$$

(2) Zone 3a: the outer continental shelf, beyond 12 miles from the shoreline, with depths less than 200 fathoms, in known fishing areas.

$$N_m = 10 \times 1 \times 1/3 \times 3/5 = 2$$

(3) Zone 3b: the outer continental shelf, beyond 12 miles from the shoreline, with depths less than 200 fathoms, in regions not designated as known fishing areas.

$$N_m = 10 \times 5 \times 1/3 \times 3/5 = 10$$

(4) Zone 4a: the open sea, in known fishing areas.

$$N_m = 10 \times 2 \times 1/3 \times 3/4 = 5$$

(5) Zone 4b: the open sea, in regions not designated as known fishing areas.

$$N_m = 10 \times 10 \times 1/3 \times 3/4 = 25$$

The partial permissible concentration in marine foods which may be allowed to result from the disposal of radioactive wastes from nuclear-powered ships is tabulated in Table 2 for each subdivision of the marine environment. As noted in a footnote to Table 2, these calculations have been made on the basis of the mpc's for the general public. These values are lower by a factor of 10 than the occupational values for mpc's given in Handbook 52, and they also include certain revisions which are to appear in the forthcoming new ICRP and NCRP tables.

RESTRICTIONS ON THE APPLICATION OF PPC VALUES IN SEAFOOD AND IN THE MARINE ENVIRONMENT

In applying these ppc values for seafood in the following computation of the ppc's for the various marine environments, and the

subsequent use of these latter values in the determination of the safe rate of discharge of nuclides into the various marine environments, the following considerations must be taken into account. The ultimate major source of dilution water for the most restrictive environment (harbors, estuaries, and inshore waters) is the next most restrictive environment, the waters of the continental shelf. Likewise, the ability of the waters of the continental shelf to receive wastes depends, in part, upon the rate of exchange of these waters with the waters of the open sea. These dilution waters must have, in each case, significantly lower average concentrations than the ppc values of the neighboring more inshore environment. The environmental ppc values computed below thus cannot be considered to represent the average permissible concentration throughout the entire volume of each of the subject marine environments. While these ppc values may apply to substantial areas of each environment in an absolute sense, such areas must be only a relatively small fraction of the entire area of the respective marine subdivision. The manner in which this condition is satisfied is presented in a later section of this report entitled "Basis for Evaluating Safe Discharge Rates".

PARTIAL PERMISSIBLE CONCENTRATIONS IN THE ENVIRONMENT

Having estimated ppc's in marine food organisms, we can estimate ppc's in the environment if we know the factor by which the food organisms concentrate the isotope in question in their bodies from their environment. Concentration factors from seawater to the edible parts of marine invertebrates and marine fishes have been estimated by the authors noted in the footnotes to Table 2. Values are tabulated here for soft (edible) parts of marine invertebrates and for the soft parts and the bones of fish. The latter have been included because some fish (especially canned fish, such as salmon, mackerel, and sardines) are often eaten bones and all. Where the fish bones are eaten, it seems appropriate to use 1/10 of the concentration factor for fish bone (since that is roughly the ratio of bone to whole fish) in obtaining a weighted average concentration factor to use in further computations.

Based on whichever of the concentration factors (that for invertebrates or that for fish) is the higher for each isotope, we have calculated and tabulated the ppc in the environment according to the relation

$$\text{ppc (environment)} = \frac{\text{ppc (food)}}{\text{concentration factor}} .$$

The resulting ppc's in the various subdivisions of the marine environment are tabulated in the last five columns of Table 2.

Some investigators have questioned this method of computing ppc values for the marine environment since certain pertinent features of human body chemistry are not evidently included. For the case of strontium 90, an alternate method of computation is based on the so-called "sunshine unit". This computation does not explicitly include the concept of "concentration factors" used in the above evaluation.

On the basis of the allowable body burden in man of strontium 90 and of the total amount of body calcium, it has been shown that, for the population as a whole, the ratio of strontium 90 to total body calcium must not exceed 0.1 μc per kg, i. e.

$$\text{Sr 90 / Ca} \leq 0.1\ \mu\text{c Sr 90 / kg body Ca.}$$

Man apparently discriminates against strontium in the uptake of calcium and strontium by a factor of 8:1. Therefore, if man receives his total protein requirements from fish, and the fish contain strontium 90, we must have in the fish:

$$\text{Sr 90 / Ca} \leq 0.8\ \mu\text{c Sr 90 / kg Ca.}$$

Assuming that fish do not discriminate against strontium in the uptake of calcium and strontium (probably a conservative assumption), the above limiting relation must also hold for the ratio of strontium 90 to calcium in sea water. The calcium concentration in sea water of 34‰ salinity is approximately 400 ppm, or 0.40 g of calcium per kg of sea water. Therefore, there must be less than 0.8 μc of strontium 90 per 2,500 kg of sea water. Hence the maximum permissible value for strontium 90 in the marine environment, assuming that man receives all his protein requirement from fish harvested from that environment, and assuming that this is man's only source of ingestion of radioactive materials, would be 3.2×10^{-7} μc/ml. Since for the coastal environment we have assigned only one-tenth the maximum permissible dose to the effects of wastes from nuclear-powered ships, the ppc value for coastal water would be 3.2×10^{-8} μc/ml.

It is seen that this value differs from the corresponding value given in Table 2 by a factor of only about 6.5. The two methods of computation would agree if a concentration factor of about 3, rather than 20, had been used in obtaining the ppc value for the marine environment, for strontium 90, given in Table 2. Thus there is some evidence that slightly conservative values of the concentration factors were employed in computation of the ppc values for the marine environment given in the Table.

It is not readily seen how the concept of the "sunshine unit" can be applied to all the radioisotopes with which we are concerned. Also, in view of the many uncertainties involved, conservative estimates must be made at this time. Hence, for our further computations, the approach used to obtain Table 2 is employed in this report.

The values thus calculated for ppc's in the environment are probably fairly reliable guides where the "environment" is the water and the food organisms are obtaining their nutrients from the water. This will apply where there is no uptake by organisms of isotopes from bottom sediments.

For food organisms which obtain all or part of their food by ingestion of detritus which has settled on to the bottom (for example the mullet, and some pelecypods and crustacea), we should take account of the concentration factors from bottom sediments to these organisms. Unfortunately, there are no data on this. However, a conservative assumption would seem to be that the concentration factor from bottom sediments to marine food organisms is the same as from water to organisms. Under this assumption, the maximum permissible concentrations in the bottom sediments, for estuarine and inshore waters which support bottom-feeding organisms used as food for man, will be the same as those tabulated for "environment" in Table 2. Since certain of the radioisotopes with which we have to deal, especially those which occur in particulate form in seawater, may be heavily concentrated in the bottom sediments, this may prove restrictive on the maximum permissible quantities which may be introduced into the superjacent waters.

WASTES FROM NUCLEAR-POWERED SHIPS

The Maritime Administration's report (1959) gives data on the expected quantities of various nuclides in the primary cooling water and in the ion-exchangers of N. S. SAVANNAH*. In Table 3 pertinent data extracted from this report are tabulated for those isotopes in the primary system which present the greatest potential hazard through ingestion in marine food organisms. For the corrosion product nuclides, the report gives the concentration in the system. From this and from the volume of the system (3.9×10^7 ml) the total quantity in the primary coolant has been calculated and tabulated. For the fission products (assuming 1,530 grams of exposed fuel, 100 days operation, and normal purification) the report gives the total quantity of each isotope in the system. These also are tabulated, with the corresponding calculated concentrations in the system.

Since according to the Maritime Administration's report there will be 290 ft^3 of discharge water due to expansion at each start-up, it is possible to compute the resulting total amounts of each of the important isotopes which could be displaced per start-up. These values are tabulated in Table 3. They may be used together with data from Table 2 to compute minimum necessary dilution volumes. With discharge in an environment (such as the open sea) where the accumulation would be negligible, the minimum necessary dilution volume will be obtained by dividing the partial permissible concentration for the particular subdivision of the marine environment into the amount discharged per start-up. For the discharge into a restricted segment of the sea having only slow exchange with the open ocean waters, more complex procedures, discussed later, must be followed.

*Since completion of this report, subsequent re-evaluation of the probable character and activity of the primary coolant and the ion exchange resins has been issued by the Oak Ridge National Laboratory (1959). While the ORNL report includes somewhat different values for the activity in these potential wastes, the general conclusions arrived at here remain unchanged.

TABLE 3

IMPORTANT ISOTOPES IN REACTOR COOLANT WATER, N. S. SAVANNAH
(based on estimates made in the Maritime Administration's report, 1959)

Isotope	ppc value for coastal waters (μc/ml)	Concentration in primary coolant (μc/ml)	Total amount in primary coolant (curies)	Amount displaced per start-up* (curies)
Corrosion Products				
Co 60	3×10^{-9}	1.2×10^{-2}	4.6×10^{-1}	9.8×10^{-2}
Fe 55	8×10^{-8}	1.1×10^{-2}	4.3×10^{-1}	8.9×10^{-2}
Fe 59	5×10^{-9}	5.5×10^{-4}	2.1×10^{-2}	4.5×10^{-3}
Ta 182	4×10^{-8}	1.7×10^{-2}	6.7×10^{-1}	1.4×10^{-1}
Cr 51	2×10^{-6}	4.0×10^{-2}	1.6	3.4×10^{-1}
Fission Products**				
Sr 90	5×10^{-9}	1.4×10^{-7}	$.52 \times 10^{-5}$	1.2×10^{-6}
Zr 95	3×10^{-8}	1.4×10^{-6}	$.52 \times 10^{-4}$	1.2×10^{-5}
Ru 106	1×10^{-8}	0.9×10^{-5}	$.34 \times 10^{-3}$	7.2×10^{-5}
Cs 137	4×10^{-7}	1.5×10^{-4}	$.56 \times 10^{-2}$	1.2×10^{-3}
Nb 95	5×10^{-7}	1.3×10^{-6}	$.52 \times 10^{-4}$	1.1×10^{-5}
Ce 144	1×10^{-9}	0.8×10^{-6}	$.31 \times 10^{-4}$	6.5×10^{-6}
Weighted ppc value and gross activity for above listed isotopes	2×10^{-8}	8×10^{-2}	3.6	6.8×10^{-1}

* From expansion volume of 290 ft^3 = 8.2×10^6 ml.

** After 100 days operation, 1,530 grams fuel exposure, with normal purification.

In Table 4 are recapitulated from the Maritime Administration's report the corrosion products expected to be present in the ion exchange resins of the SAVANNAH at time of their discharge. If these are disposed of in the open sea far from known fishing areas, and if the probability of two such discharges occurring in the same vicinity within a period of several days is negligible, the minimum necessary dilution

TABLE 4

IMPORTANT CORROSION ISOTOPES IN DEMINERALIZER AFTER 50 DAYS OF OPERATION, N. S. SAVANNAH

Isotope	ppc value for open sea (non-fishing) (μc/ml)	Total activity in resin (curies)	Required dilution vol. in m^3 *
Fe 59	1×10^{-7}	3.8	3.8×10^{7}
Fe 55	2×10^{-6}	75.0	3.8×10^{7}
Co 60	7×10^{-8}	75.0	1.1×10^{9}
Ta 182	1×10^{-6}	103	1.0×10^{8}
Cr 51	5×10^{-5}	148	3.0×10^{6}
Weighted ppc value (for open sea, non-fishing areas) and gross activity for above listed isotopes	3×10^{-7}	405	1.4×10^{9}

* For disposal in open sea, in regions not designated as known fishing areas (Zone 4b).

volumes can be calculated by dividing the total activity by the ppc value for the open sea, for regions not designated as known fishing areas. This has been done for the corrosion product isotopes for which data are available.

The report "Radioactive Waste Disposal from U. S. Naval Nuclear-Powered Ships" gives information on the actual observed concentrations of the various radioisotopes in the primary coolant and on the spent ion exchange resins for the U.S.S. NAUTILUS. These data are reproduced for the significant isotopes in Tables 5 and 6.

The evaluation of permissible rates of discharge of nuclear wastes is complicated by the fact that the potential effluents from nuclear-powered ships are composed of a mix of isotopes which may have additive effects on man. In order to include this feature in later computations, it is convenient to determine a weighted mean ppc value for the isotope

TABLE 5

IMPORTANT ISOTOPES IN REACTOR COOLANT WATER, U.S.S. NAUTILUS
(average)

Corrosion Products	ppc value for coastal waters (μc/ml)	Concentration in primary coolant (μc/ml)	Amount displaced per warm-up * (curies)
Co 60	3×10^{-9}	5.7×10^{-6}	1.1×10^{-5}
Fe 59	5×10^{-9}	1.5×10^{-4}	2.9×10^{-4}
Cr 51	2×10^{-6}	1.0×10^{-5}	1.9×10^{-5}
Ta 182	4×10^{-8}	7.3×10^{-3}	1.4×10^{-2}
Cu 64	4×10^{-8}	1.5×10^{-5}	2.9×10^{-5}
Fission Products			
I 131	3×10^{-8}	1×10^{-5}	1.9×10^{-5}
Sr 90	5×10^{-9}	5×10^{-8}	9.5×10^{-8}
Ce 144	1×10^{-9}	1×10^{-7}	1.9×10^{-7}
Cs 137	4×10^{-7}	1×10^{-8}	1.9×10^{-8}
Weighted ppc value and gross activity for above listed isotopes	4×10^{-8}	7.5×10^{-3}	1.4×10^{-2}

* From average expansion volume of 500 gals = 1.9×10^{6} ml.

TABLE 6

IMPORTANT CORROSION ISOTOPES IN SPENT DEMINERALIZER, U.S.S. NAUTILUS

Isotope	ppc value for open sea (non-fishing) (μc/ml)	Total activity in resin (curies)	Required dilution vol. in m^3 *
Co 60	7×10^{-8}	10	1.4×10^{8}
Co 58		0.5	
Fe 59	1×10^{-7}	0.5	5.0×10^{6}
Cr 51	5×10^{-5}	0.3	6.0×10^{3}
Mn 54		0.2	
Hf 175		1.0	
Weighted ppc value (for open sea, non-fishing areas) and gross activity for above listed isotopes	7×10^{-8}	12.5	1.8×10^{8}

* For disposal in open sea, in regions not designated as known fishing areas (Zone 4b).

mix in the primary coolant. This weighted mean ppc value can then be compared with the gross activity resulting from the mix of the significant isotopes listed. In computing the weighted mean ppc value for coastal waters, and the gross activity, which are included in Table 3 for the SAVANNAH primary coolant and in Table 5 for the NAUTILUS primary coolant, only the isotopes listed in these Tables have been considered. Very short lived isotopes are not included in the calculation.

BASIS FOR EVALUATING SAFE DISCHARGE RATES

The partial permissible concentrations in the various subdivisions of the marine environment given in Table 2, and utilized by this working panel in the computations which follow, are based on long time exposure of a selected segment of the population. After release of a given volume of liquid wastes or of spent ion exchange resin to the sea water, processes of diffusion will continually reduce the concentration of activity in the water. There will occur a certain period of time during which the activity in a restricted volume of the sea water may possibly exceed the environmental limits which are based on long term exposure. The purpose of the following development is to provide criteria which would insure that no significant volume of a given marine locale would have an average activity exceeding the ppc value for that locale over a significant period of time.

Let A designate the area of a particular marine region within which N discharges of radioactive materials are made during the time period T. Further, designate by $t_{1/2}$ the time interval required to replace 50% of the water in the area A with "new" water from an adjacent, uncontaminated area. The area A must be chosen such that the N contaminated volumes are randomly distributed throughout the area, as a result both of variations in the discharge site and of the movement of the contaminated volumes by currents. The time period T must be short compared to a man's lifetime, but long compared to the time required for the maximum concentration of activity from a point source discharge to be reduced by processes of dispersion to less than ppc values for the environment.

The concentration of activity at a given position and a given time which results from a single discharge is designated by s, and the increment of area within which the concentration varies from $s - 1/2\ ds$ to to $s + 1/2\ ds$ during the increment of time dt is designated by dA. Further, let the total area within which the concentration at any time t exceeds the ppc values for the environment be designated by A_{ppc}, and let the time required to reduce the concentrations everywhere in the area to less than ppc values be designated by t_{ppc}.

The double integral

$$\int_0^{t_{ppc}} \int_0^{A_{ppc}} sdAdt$$

then represents the total activity, per unit of depth, which occurs in the area having concentrations exceeding ppc values, times the time interval during which the concentration exceeds that critical value. The area of "new" water available for dilution each time period T is given by

$$\frac{AT}{2\ t_{1/2}}$$

Hence the relationship

$$\frac{2\ N\ t_{1/2}}{A \times T^2} \int_0^{t_{ppc}} \int_0^{A_{ppc}} sdAdt$$

then defines a mean concentration for the total area A during the time period T, resulting from N discharges, each having the same amount of activity. This relationship serves to establish the criteria for evaluating the suitability of any particular marine area as a receiver of radioactive wastes from nuclear-powered ships.

If the distribution of contaminated volumes within the area were truly random at all times, and if the processes of biological concentration of radioisotopes were instantly reversible, then a suitable criterion for safe discharge to the marine environment would be the requirement that the mean concentration defined by the above relationship be less than the ppc value (here designated as s_{ppc}) for that environment. Unfortunately, marine organisms which take up radioisotopes when in contact with sea water of a given concentration of activity, do not reach a new equilibrium readily when exposed to water of much lower activity. Also, it would be difficult to assure a completely uniform distribution of the contaminated volumes within the subject area. Finally, and perhaps most important, the condition discussed in the previous section entitled "Restrictions on the Application of ppc Values in Seafood and in the Marine Environment" must be satisfied. Therefore, the criterion employed here is that the mean concentration defined by the above relationship be 1/100th of the ppc value for the environment; that is, the number of releases N in the area A during the time period T must satisfy the relationship

$$N \leq \frac{AT^2 s_{ppc}}{200\, t_{1/2} \int_0^{t_{ppc}} \int_0^{A_{ppc}} sdAdt} \quad (1)$$

This relationship is utilized in subsequent sections of this report to determine the limits of activity which may be introduced into the various segments of the marine environment without undue risk to man.

EVALUATION OF HARBORS, ESTUARIES, AND OTHER INSHORE ENVIRONMENTS (ZONE 1)

In this section the question of whether harbors, estuaries, and other inshore environments may serve as suitable receivers of any radioactive wastes from nuclear-powered ships is investigated. For the present purpose, inshore areas are those coastal regions within two miles of the shore.

Harbors, estuaries, and other inshore environments are regions of high human waterborne activity. This fact, coupled with the normal relatively shallow depths in such environments, argues for a relatively high probability of accidental recovery of any solid wastes introduced there. It is therefore concluded that no solid wastes, packaged or otherwise, should be released in harbors or other nearshore environments. Our attention is then confined to liquid wastes which might be discharged in such waters.

The potential sources of low level liquid wastes which would occur under normal operation of a nuclear-powered ship using a water cooled reactor have been described in an earlier section of this report. The fate of such wastes introduced into the marine environment will depend upon the following three processes:

(1) Initial dilution, resulting from the mechanical mixture of the effluent with the receiving waters. This initial mixing depends upon the manner in which the effluent is introduced into the receiving waters. Thus a strong jet of effluent introduced below the surface of the receiving waters would result in a mechanical entrainment of the diluting waters until the energy of the jet was dissipated. A gentle flow of effluent at the surface of the receiving waters would result in relatively little initial dilution.

(2) Advection of the effluent with the currents in the harbor or harbor approach and simultaneous turbulent diffusion leading to further reduction in concentration.

(3) Concentration of activity from the water to the suspended silt, the bottom sediments, and the biota.

There is no way that man can directly influence the processes of advection, turbulent diffusion, and concentration in a given environment. Man can, however, influence the degree of initial mechanical dilution through proper design of the discharge assembly. Since the rate of dispersion through turbulent processes is scale dependent, man can then influence indirectly the natural diffusion of the wastes by increasing the degree of initial mechanical dilution. Also, initial mechanical dilution reduces the density difference between effluent and receiving waters, and hence aids diffusion. Considering the volumes of liquid effluent involved (a maximum of approximately 300 ft^3), the incorporation of a discharge assembly capable of supplying an initial mechanical dilution of 100:1 should be no problem.

Factors such as current velocity, depth, density stratification, wind velocity and fetch, and density difference between effluent and receiving waters all influence the process of turbulent diffusion. Since these factors differ so markedly from one harbor environment to another, it is virtually impossible to make any precise general statement regarding the subsequent fate of liquid wastes discharged into harbor environments. The degree to which harbors, harbor approaches and other inshore environments might be utilized as receivers of liquid radioactive effluent from nuclear-powered ships must ultimately be determined through an evaluation of each specific location involved.

We can, however, consider the general characteristics of certain types of harbors, with the purpose of determining whether there is any possibility of utilization of any considerable fraction of the harbor environments as receivers of liquid effluent from nuclear ships. Thus some important world harbors are approached through locks which limit exchange with the open coastal waters. In most cases such harbors contain fresh water or water of very low salinity. The absence of tidal currents limits the turbulent diffusion within such harbors, and the lack of free exchange with the open coastal waters would result in accumulation within the harbor of any waste disposed therein. It therefore appears unlikely that harbors located in tideless basins, connected to the sea by a system of locks, can be utilized as receivers of any effluent from nuclear-powered ships.

Another group of harbors are located well up estuaries of major river systems, and are characterized by fresh water, though tidal currents of significant magnitude may occur. Possible restriction on the use of such harbors as potential receivers of liquid effluent from nuclear ships is not so much due to the lack of a mechanism (such as tidal currents) to induce appreciable turbulent diffusion within the harbor, but rather due to the much larger concentration factors to the biota which occur in fresh water as compared to sea water.

The majority of harbors throughout the world are, however, located in the lower reaches of tidal estuaries or in coastal embayments. The waters of these harbors are normally characterized by salinities of from one-quarter to three-quarters that of full sea water; they are influenced to some degree by tidal currents and wind induced motion;

and these harbor waters exchange, to a greater or lesser degree, with the adjacent coastal waters.

Consider such a harbor having a volume V and an exchange coefficient of γ (per day). The exchange coefficient is the fraction of the volume of the water in the harbor which is renewed each day by exchange with the adjacent coastal waters, and by inflow of land drainage. γ is thus comparable to the radioactive decay coefficient, and a "half-life" for the harbor water can be defined in the same way as radioactive half-life.

The $t_{1/2}$ in equation 1 is then the half-life of the area, and is related to γ by

$$t_{1/2} = \frac{0.693}{\gamma} .$$

Further, consider a particular discharge of effluent into the harbor. Following the initial mechanical dilution, turbulent diffusion will lead to further dilution at approximately an exponential rate, at least during the early stages of diffusion when contaminated volume is small compared to the volume of the harbor.

A major part of the analysis of the problem of disposal of nuclear wastes into the sea and coastal waters requires sufficient knowledge of the rates of mixing so that the dilution of any introduced liquid can be estimated correctly.

The diffusion model employed in this analysis: It has always been difficult to make such an estimate because of the lack of a satisfactory general theory of diffusion in the sea; rates of diffusion (the so-called eddy diffusivity coefficients) required by existing theory were known adequately only for certain special cases where direct measurements had been made. Recently, however, Joseph and Sender (1958) have proposed a horizontal diffusion equation which seems to permit a useful statistical description of the time change of concentration of a diffusing substance. The following paragraphs discuss the application of this diffusion equation to the problem of waste disposal from nuclear-powered ships.

Joseph and Sender consider the introduction at time t = 0 of an amount M of a substance into a small area either of the sea surface or at some deeper level. This small area is regarded as the "point" source for isotropic horizontal diffusion along a thin homogeneous and isentropic layer. After time t the distribution is described by concentric isopleths around the point of maximum concentration. This point is not fixed but moves downstream with the prevailing current. It is further postulated that the velocity of a diffusing particle is independent of distance from the origin, but that the mean dispersion increases in linear fashion with increasing distance.

The following diffusion equation was derived:

$$(1) \qquad \frac{\partial s}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[Pr^2 \frac{\partial s}{\partial r} \right]$$

where s is the concentration, r the distance from the origin, and P the constant mean velocity of diffusion. Solution of this equation gives:

$$(2) \qquad s = \frac{M}{2\pi(Pt)^2} \exp \left[- \frac{r}{Pt} \right]$$

where s and M refer to the concentration and total amount of a given isotope introduced. Note that concentration in this equation has the dimensions ML^{-2}; in applying the equation, volume concentrations can be obtained by using an estimated layer thickness D as the third dimension.

The diffusion velocity P of this equation is related to the Fickian coefficient of eddy diffusivity A by the equation

$$A = \frac{Pr}{2} .$$

Joseph and Sender examined quantitative descriptions of diffusion in a variety of situations in the ocean and found P to be relatively constant with a value of about 1 cm/sec.

This equation applies to a region of unrestricted horizontal dimensions. In restricted waterways, or near shore, the boundaries would limit diffusion. The principle of reflection of the solution obtained by Joseph and Sender, so that the angular range within which diffusion can occur is limited in accordance with the existence of a boundary, can be employed to obtain an approximate equation for use in harbors and other restricted waterways. Thus diffusion of a substance released near an open shoreline would be limited to an arc of 180°. In such a case the reflection of the solution given by equation 2 would produce exactly the same equation, except that the right side would be multiplied by a factor of 2. In an elongated, restricted waterway in which the boundaries restrict diffusion to an arc of, say, 30° in the up-channel and 30° in the down-channel direction the approximate equation for the concentration of a diffusing substance released as a point source would be obtained simply by multiplying the right side of equation 2 by the factor 360°/2 x 30° = 6. Thus:

$$(3) \qquad s(r,t) = \frac{6M}{2\pi(Pt)^2} \exp \left[- \frac{r}{Pt} \right] .$$

If θ_n designates the arc within which diffusion is constrained by the boundaries, then, letting

$$n = \frac{360^\circ}{\theta_n} \tag{4}$$

we have in general

$$s(r,t) = \frac{nM}{2\pi D(Pt)^2} \exp\left[-\frac{r}{Pt}\right] \tag{5}$$

where s(r, t) is here concentration per unit volume, since the factor 1/D has been entered into the right side of the equation.

The maximum concentration occurs at the center of the diffusing volume, and is given by

$$s_o(t) = \frac{nM}{2\pi D(Pt)^2} . \tag{6}$$

At the center the concentration decreases continually with time.

At any distance r from the center, the concentration first rises to a maximum value, and thereafter decreases with time. Thus, assuming that the introduction is truly a point source (i. e. , neglecting initial mechanical dilution), there will be, for any finite amount of radioactive wastes introduced, an area within which the concentration exceeds, for a time, the ppc values for the environment. This area will at first increase in size to a maximum value, and thereafter will decrease in size until a time is reached at which the concentration is everywhere less than ppc values. This time can be obtained from equation 6 by setting $s_o(t)$ equal to the ppc value for the particular isotope in question. Thus

$$t_{ppc} = \sqrt{\frac{N}{2\pi DP^2}} \sqrt{\frac{M}{s_{ppc}}} \tag{7}$$

where t_{ppc} is the time after which the concentration everywhere is less than the ppc concentration, which is here designated by s_{ppc} .

Equation 5 can be solved for the distance, at any time t, at which the concentration has just reached ppc values, by setting s(r, t) equal to s_{ppc} . Thus

$$r_{ppc} = Pt \ln \frac{nM}{2\pi D(Pt)^2 s_{ppc}} . \tag{8}$$

The increment of area which, during the time interval t to t + dt, has a concentration varying from s - 1/2 ds to s + 1/2 ds, if given by:

$$\frac{2\pi r dr}{n}$$

and hence the integral which appears in equation 1 is given by

$$\int_0^{t_{ppc}} \int_0^{A_{ppc}} s dA dt = \int_0^{t_{ppc}} \int_0^{r_{ppc}} s \frac{2\pi r dr}{n} dt = \int_0^{t_{ppc}} \int_0^{r_{ppc}} \frac{Mr}{D(Pt)^2} e^{-r/Pt} dr dt .$$

This integral can be evaluated using equations 5, 7, and 8. The solution is given by

$$(9) \qquad \int_0^{t_{ppc}} \int_0^{A_{ppc}} s dA dt = \frac{4}{9} \frac{M}{D} t_{ppc} .$$

The criterion for establishing the number of discharges, N, each of strength M, which may be made into a marine locale of area A during the time interval T is then, from equation 1

$$(10) \qquad N \leq \frac{9\ DAT^2 s_{ppc}}{800\ t_{1/2}\ Mt_{ppc}} .$$

The time period T, which must be short compared to a man's life span but long compared to the time required to reduce the maximum concentration resulting from a single release to below ppc values, is here taken as 30 days.

Now consider a harbor having relatively poor mixing characteristics and a low rate of exchange with adjacent coastal waters. A review of available data indicates that most marine harbors of the United States have a half life of 30 days or less. Joseph and Sender (1958) found that for a number of phenomena of varying scale in the open sea the diffusion velocity P was nearly constant at 1 cm/sec. A conservative estimate of this parameter for inshore tidal waters is taken at 0.5 cm/sec. Further, assume that in this "typical" harbor the depth interval within which vertical mixing occurs is at least 6 meters. The boundaries of the harbor are considered to constrain diffusion to within an arc of 30°, both up-channel and down-channel; hence n = 6.

We take for the volume and surface area of this "typical" small harbor the values 3×10^8 m^3 and 5.4×10^7 m^2 respectively. Letting D = 6 meters, $t_{1/2}$ = 30 days, and T = 30 days, then for this sample

computation in a "typical" harbor of poor flushing characteristics, equations 6, 7, and 10 become

$$(11) \qquad s_o(t) = 6.4 \times 10^3 \frac{M}{t^2}$$

$$(12) \qquad t_{ppc} = 0.80 \times 10^2 \sqrt{\frac{M}{s_{ppc}}}$$

$$(13) \qquad N \leq \frac{9.5 \times 10^{12}}{\frac{M}{s_{ppc}} \times t_{ppc}} = \frac{1.2 \times 10^{11}}{\left(\frac{M}{s_{ppc}}\right)^{3/2}}$$

where s_{ppc} and $s_o(t)$ are expressed in μc/ml, $\underline{M}$ in curies, $\underline{t}$ and $\underline{t_{ppc}}$ in secs, and $\underline{N}$ in discharges per month.

An inspection of Tables 3 and 5 reveals that most of the significant isotopes in the primary coolant have ppc values for coastal water between the values 10^{-7} μc/ml and 10^{-9} μc/ml. Table 7 presents, for this range of ppc values, some sample computations of the time ($\underline{t_{ppc}}$) for the maximum concentration resulting from a single discharge of $\underline{M}$ curies to be reduced to the ppc value for the environment, and the permissible number of such discharges, $\underline{N}$, per month, for the "typical" harbor described above. The marine locale is considered unsuitable as a receiver of any discharge for which the value of $\underline{N}$ is less than 1.0 per month. Thus, for this sample situation, it would be considered unsafe to introduce a single discharge in which the ratio M/s_{ppc}

TABLE 7

Sample computations for a "typical" small harbor of poor flushing characteristics, giving the time (t_{ppc}) for the maximum concentration resulting from a single discharge of M curies to be reduced to the ppc value for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml.

				M, in curies for		
M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	$s_{ppc} = 10^{-9}$	$s_{ppc} = 10^{-8}$	$s_{ppc} = 10^{-7}$
10^4	8.0×10^3	9.3×10^{-2}	1.2×10^5	10^{-5}	10^{-4}	10^{-3}
10^5	2.6×10^4	3.0×10^{-1}	3.7×10^3	10^{-4}	10^{-3}	10^{-2}
10^6	8.0×10^4	9.3×10^{-1}	1.2×10^2	10^{-3}	10^{-2}	10^{-1}
10^7	2.6×10^5	3.0	3.7	10^{-2}	10^{-1}	1
10^8	8.0×10^5	9.3	1.2×10^{-1}	10^{-1}	1	10

(curies per μc/ml) was 10^8 or greater. Slightly less than four discharges per month could be made without undue risk for this ratio equal to 10^7 curies per μc/ml.

These data are presented in graphical form in Figure 2, from which the values of the ratio M/s_{ppc} for $\underline{N}$ equal to one per month, one per day, and 10 per day have been obtained. Using these ratios, the maximum permissible activities which can be discharged in any single release in this "typical" harbor for the various important isotopes, listed in Tables 3 and 5 for the primary coolant of the SAVANNAH and the NAUTILUS, have been calculated for these three rates of discharge. The results are presented in Table 8.

This computation applies to the hypothetical case in which the discharge is composed of only a single isotope. For the actual situation the additive effect of the combination of isotopes present must be considered. Assuming that the relative composition of the isotopes in the primary coolant remains fairly constant (a condition which has been shown to exist for the NAUTILUS), then the weighted mean ppc value for the isotope mix may be utilized in computing a permissible gross activity, which can be compared to the gross activity in the actual discharge resulting from the listed isotopes. This has been done for the isotope mix in the primary coolant for both the SAVANNAH and the NAUTILUS.

A comparison of the permissible activities given in Table 8 with the activities which have been predicted to exist in the warm-up volume discharge from the SAVANNAH, as given in Table 3, indicates that the predicted gross activity due to the listed isotopes exceeds the computed permissible activity even for only a single release per month. Also the predicted activity for Co 60 and Ta 182 both exceed the computed permissible activities for these individual isotopes. It would thus appear undesirable to have a general operating doctrine which would allow liquid effluents of the volume and activity predicted for the warm-up volume of primary coolant from the SAVANNAH to be discharged into harbors and estuaries. It should again be pointed out that the basis of this conclusion involves the most conservative (safe) assumptions regarding the eating habits of a selected segment of the population, and also regarding biological uptake of the radioisotopes. Such assumptions are not unduly conservative for a country such as Japan, where the bulk of the protein requirement is supplied from seafood. The assumptions may well be overly conservative for the coast of the United States. However, recommendations on general operating doctrine for nuclear-powered merchant ships must envision these ships operating in areas in which the most restrictive conditions as to waste discharge would apply.

A comparison of the figures in Table 8 with the average measured activities in the primary coolant expansion volumes for the NAUTILUS as given in Table 5 suggests quite a different conclusion. The observed activities for each isotope, as well as the computed gross activity assuming an isotope mix with the observed activities for the listed isotopes,

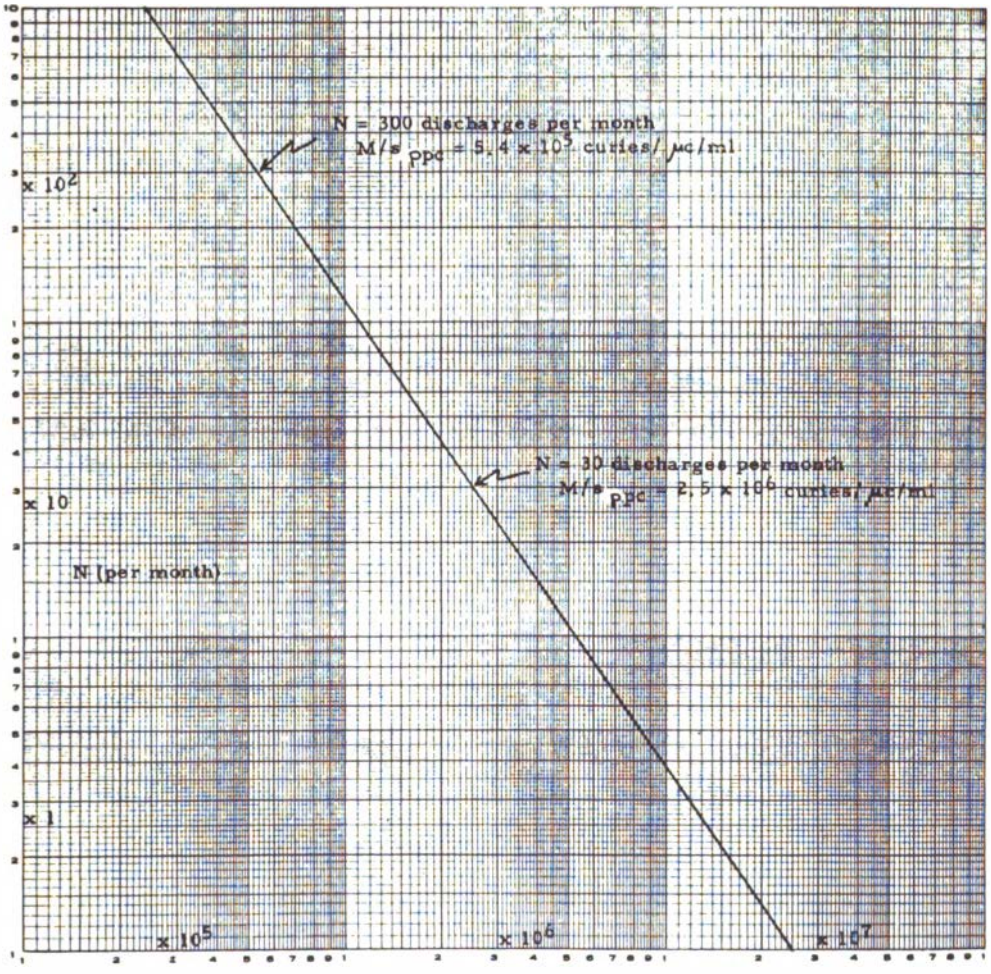


FIGURE 2

The permissible number (N) of discharges of primary coolant which can be made, per month, into a "typical" harbor, as a function of the ratio of total activity per discharge, M, in curies, to the ppc values for coastal waters in μc/ml.

TABLE 8

Tabulation, for the discharge of primary coolant expansion volumes into a "typical" harbor of low flushing rate (see text for assumed conditions), of the permissible total activity, for each isotope, per discharge, assuming the discharge contains only that single isotope, and the permissible gross activity for the isotope mix in the primary coolant of the SAVANNAH* and the NAUTILUS*.

Isotope	ppc for coastal waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
Co 60	3×10^{-9}	7.5×10^{-2}	7.5×10^{-3}	1.6×10^{-3}
Fe 55	8×10^{-8}	2.0	2.0×10^{-1}	4.3×10^{-2}
Fe 59	5×10^{-9}	1.2×10^{-1}	1.2×10^{-2}	2.7×10^{-3}
Cr 51	2×10^{-6}	5.0×10	5.0	1.1
Ta 182	4×10^{-8}	1.0	1.0×10^{-1}	2.2×10^{-2}
Cu 64	4×10^{-8}	1.0	1.0×10^{-1}	2.2×10^{-2}
Sr 90	5×10^{-9}	1.2×10^{-1}	1.2×10^{-2}	2.7×10^{-3}
Ce 144	1×10^{-9}	2.5×10^{-2}	2.5×10^{-3}	5.4×10^{-4}
Cs 137	4×10^{-7}	1.0×10	1.0	2.2×10^{-1}
Ru 106	1×10^{-8}	2.5×10^{-1}	2.5×10^{-2}	5.4×10^{-3}
I 131	3×10^{-8}	7.5×10^{-1}	7.5×10^{-2}	1.6×10^{-2}
Primary Coolant SAVANNAH	* 2×10^{-8}	2.2×10^{-1}	2.2×10^{-2}	4.7×10^{-3}
Primary Coolant NAUTILUS	* 4×10^{-8}	8.8×10^{-1}	8.8×10^{-2}	1.9×10^{-2}

* Assuming that the isotope mix in the primary coolant is composed of only the isotopes listed in Table 3 for the SAVANNAH and Table 5 for the NAUTILUS. Operational experience on the NAUTILUS shows that due to the presence of very short lived isotopes, the measured gross activity of the primary coolant, 15 minutes after sampling, is about 3.5 times the gross activity resulting only from the isotopes listed in Table 5.

are all lower than the computed maximum permissible activity, even for ten discharges per day. It therefore appears that discharges of liquid effluent in the quantities and activities similar to the warm-up volume of primary coolant from the NAUTILUS may be made into the majority of inshore areas without introducing undue risk to man. However, it should be pointed out that the "typical" harbor used in this evaluation, while representing an area of rather poor flushing characteristics, does not represent the worst inshore area from this standpoint.

It is therefore necessary that specific evaluation be made of any harbor or inshore waterway which is to be utilized as a base or as a major port of call for nuclear-powered ships. Such an evaluation should include a study of the routes by which activity introduced into the particular harbor or waterway may return to man; of the principal marine products harvested from the area; of the concentration factors to these food products both from the water and from the bottom sediments; and of the physical processes of movement, mixing and exchange of the waters of the particular marine locale.

A similar comparison of the computed permissible activity of a single discharge, with either the predicted activity for the spent ion exchange resins from the SAVANNAH, or the observed activity on the resins from the NAUTILUS, contained in Tables 4 and 6, leads to the definite conclusion that spent ion exchange resins should not be discharged in harbors or other restricted coastal waterways.

EVALUATION OF THE COASTAL AREA (ZONE 2)

For this coastal area from 2 to 12 miles offshore, equations 1 through 8 in the previous sections may be utilized, setting $\theta_n = 180^\circ$ and $n = 2$, to take into account the possible limits placed on diffusion by the coastline. A conservative mixed layer depth of 10 meters is taken for this computation. The diffusion velocity $\underline{P}$ is assumed to be equal to 1.0 cm/sec, which is the value found by Joseph and Sender (1958) for a number of phenomena of varying scale in the open sea.

Releases of wastes from nuclear-powered ships in this regime will probably occur primarily in areas off major ports, with rather definite approach routes. The size of the representative area, $\underline{A}$, to be utilized in equation 1 is obtained by considering a 10 mile wide slice extending seaward from two miles offshore to 12 miles offshore. A current parallel to the coastline of velocity less than one mile per day would provide for essentially complete replacement of the volume under consideration during the representative time period of one month. The value of $\underline{A}$ is then 3.8×10^8 m^2, and $t_{1/2}$ equals 15 days.

The pertinent equations, using the symbols introduced in the last section, then are:

(14) $$s_o(t) = 3.2 \times 10^2 \frac{M}{t^2}$$

(15) $$t_{ppc} = 0.18 \times 10^2 \sqrt{\frac{M}{s_{ppc}}}$$

(16) $$N \leq \frac{2.2 \times 10^{14}}{\frac{M}{s_{ppc}} \cdot t_{ppc}} = \frac{1.2 \times 10^{13}}{\left(\frac{M}{s_{ppc}}\right)^{3/2}},$$

Tables 9 and 10 present the pertinent computations. The probability is extremely small that there will be, on the average, more than 30 of the potential 300 nuclear-powered ships outbound through a single such harbor approach per month. Since the weighted mean ppc, for coastal waters, for the isotope mix in the primary coolant is approximately 10^{-8}, it is evident from a comparison of Table 10 with Tables 3 and 5 that this segment of the continental shelf can safely receive the discharge of warm-up expansion volumes which may have been stored in tanks aboard ship, due to restrictions on the release of this waste into the inshore environment.

Since it is considered undesirable to average over a period longer than one month, the maximum permissible amount of activity in a single discharge, even if less than one such discharge were to be made into the subject area per month, is about 5 curies. An inspection of Tables 4 and 6 then indicates that this segment of the continental shelf would be unsuitable as a receiver of spent ion exchange resins.

EVALUATION OF THE OUTER CONTINENTAL SHELF (ZONES 3a AND 3b)

For the region of the shelf from 12 miles seaward to the 200 fathom line, diffusion on a pertinent scale would be unrestricted by horizontal boundaries. Within this area a mixing layer depth of 40 meters may be assumed. Though there are significant areas of this shelf region which are not fished commercially, migratory fish traverse the whole of the continental shelf, and it is not possible to assume that any segment is biologically unimportant, though some parts of the shelf contribute significantly less to the total fisheries than others.

The continental shelf off the east coast of the United States is utilized here as the subject area for our computations of the safe rate of discharge of radioactive wastes from nuclear-powered ships into this type of marine environment. The region of this shelf from 12 miles seaward to the 200 fathom line averages about 100 miles in width over

TABLE 9

Sample computations for a section of the continental shelf 10 miles long extending seaward from 2 miles offshore to 12 miles offshore, giving the time (t_{ppc}) for the maximum concentration resulting from a single release of M curies to be reduced to ppc values for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml.

M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	M, in curies, for $s_{ppc} = 10^{-9}$	$s_{ppc} = 10^{-8}$	$s_{ppc} = 10^{-7}$
10^6	1.8×10^4	2.1×10^{-1}	1.2×10^4	10^{-2}	10^{-1}	1
10^7	5.8×10^4	6.7×10^{-1}	3.7×10^2	10^{-1}	1	10
10^8	1.8×10^5	2.1	12	1	10	10^2
10^9	5.8×10^5	6.7	3.7×10^{-1}	10	10^2	10^3

TABLE 10

Permissible total activity per discharge into a section of the continental shelf 10 miles long extending seaward from 2 miles offshore to 12 miles offshore, as a function of the number of such discharges per month and the partial permissible concentration for the coastal waters.

ppc for coastal waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
10^{-9}	5.2×10^{-1}	5.3×10^{-2}	1.2×10^{-2}
10^{-8}	5.2	5.3×10^{-1}	1.2×10^{-1}
10^{-7}	52	5.3	1.2

the 1,200 mile length of the Atlantic seaboard of the United States. It has been estimated that the average retention time for waters on this shelf is about one year. Hence a conservative estimate of the "new" water area available each month is 1/10th of the total area, or 4×10^{10} m^2.

For unrestricted horizontal mixing, the value of n in equations 5 through 8 is 1.0. The value of the diffusion velocity is taken as 1.0cm/sec, as found by Joseph and Sender (1958). The pertinent equations for the required computations then become

(17) $$s_o(t) = 0.40 \times 10^2 \frac{M}{t^2}$$

(18) $$t_{ppc} = 6.3 \sqrt{\frac{M}{s_{ppc}}}$$

(19) $$N \leq \frac{2.3 \times 10^{16}}{\frac{M}{s_{ppc}} \cdot t_{ppc}} = \frac{3.6 \times 10^{15}}{\left(\frac{M}{s_{ppc}}\right)^{3/2}} .$$

Tables 11 and 12 present the pertinent computations. A comparison of the predicted activities in the primary coolant for the SAVANNAH, given in Table 3, with permissible total activity per discharge, given in Table 11, indicates that no undue risk to man would result from the discharge of several thousand gallons of such effluent as a single release into the waters of the continental shelf seaward of a line 12 miles from the coast. In fact, if each of the potential 300 nuclear-powered ships were to make one such release per month into the waters of the continental shelf off the east coast of the United States, the permissible environmental levels would still not be exceeded.

Table 4 shows that the total activity on the spent ion exchange resins of the SAVANNAH is predicted to be about 400 curies after 50 days of operation. Since the ppc value for continental shelf waters, in known fishing areas, for the mix of isotopes shown in Table 4, is about 2×10^{-8} μc/ml, it is evident that not even one such discharge per month into known fishing areas of the continental shelf would be suitable. Even for those areas of the shelf which do not contribute materially to fisheries, and where a weighted mean ppc value of 1×10^{-7} μc/ml applies, the discharge of 400 curies at one time is not advisable.

On the other hand, Table 6 shows that the total activity on the spent ion exchange resins on the NAUTILUS amounts to about 12.5 curies. The ppc value for fishing areas on the continental shelf for the isotope mix listed in Table 6 is about 6×10^{-9} μc/ml. Setting M equal to 12.5 curies and s_{ppc} equal to 6×10^{-9} μc/ml in equation 19 gives a maximum permissible number of releases per month of 36, or about

TABLE 11

Sample computations for the segment of the continental shelf extending seaward from 12 miles offshore to the 200 fathom depth contour, giving the time (t_{ppc}) for the maximum concentration from a single release of M curies to be reduced to ppc values for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml.

				M, in curies, for		
M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	$s_{ppc} = 10^{-9}$	$s_{ppc} = 10^{-8}$	$s_{ppc} = 10^{-7}$
10^{8}	6.3×10^{4}	7.3×10^{-1}	3.6×10^{3}	10^{1}	1	10
10^{9}	2.0×10^{5}	2.3	1.1×10^{2}	1	10	10^{2}
10^{10}	6.3×10^{5}	7.3	3.6	10	10^{2}	10^{3}
10^{11}	2.0×10^{6}	23	1.1×10^{-1}	10^{2}	10^{3}	10^{4}

TABLE 12

Permissible total activity per discharge into the segment of the continental shelf extending seaward from 12 miles offshore to the 200 fathom depth contour, as a function of the number of such discharges per month and the partial permissible concentration for the coastal waters.

ppc for coastal waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
10^{-9}	23	2.4	5.1×10^{-1}
10^{-8}	2.3×10^{2}	24	5.1
10^{-7}	2.3×10^{3}	2.4×10^{2}	51

one per day. In non-fishing areas of the continental shelf, where the environmental ppc value for the isotope mix on the ion exchange resins is about 3×10^{-8} μc/ml, the permissible number of releases of ion exchange resins having the activity reported for the NAUTILUS is computed to be about 20 per day.

According to the report "Radioactive Waste Disposal from U. S. Naval Nuclear-Powered Ships", the ion exchange resins in the NAUTILUS require replacement about once each six months. Thus, if each of the potential 300 nuclear-powered ships were to discharge their spent ion exchange resins twice each year, in a random spatial distribution over the continental shelf of the eastern United States, the environmental limits for this area would not be exceeded, provided that the total activity on the spent ion exchange resins for each ship would not exceed 50 curies.

EVALUATION OF THE OPEN SEA (ZONES 4a AND 4b)

For the purposes of this report, the open sea is considered to consist of those regions of the oceans which are more than 12 miles from any land and which have depths greater than 200 fathoms. The open sea undoubtedly has greater capacity to safely receive radioactive wastes than any of the marine environments previously considered. Since the waters of the outer continental shelf are suitable receivers of the low level liquid effluent from nuclear-powered ships, it is evident that no restriction need be placed on the discharge of low level liquid effluent from nuclear-powered ships into the open sea. This statement is valid so long as the activities in the liquid effluent are similar to those observed on the NAUTILUS and predicted for the SAVANNAH.

The major source of potential wastes for marine disposal on nuclear-powered ships are the spent ion exchange resins. According to the report "Radioactive Waste Disposal from U. S. Naval Nuclear-Powered Ships", these resins sink in sea water and also rapidly give up the attached active isotopes to the sea water. It is a basic requirement for the application of the findings of this study that in all cases these resins must sink when released into the sea.

In the evaluation of the dispersal of an inoculant in the open sea, using the equations developed by Joseph and Sender, a layer depth of 100 meters is assumed. Since no boundaries exist to restrict horizontal diffusion, at least on the scale of concern here, n in equations 5 through 8 would be equal to unity. The value of P, the diffusion velocity, is taken as 1 cm/sec.

In determining the total area A to be used in evaluating the criteria expressed by equation 1, it is conservatively assumed that all 300 potential nuclear-powered ships operate in the New York-London route. The area of this route is estimated at 6×10^5 km^2 (6000 km x 100 km). The length of the significant time period T is, as in the evaluations for the inshore and continental shelf areas, taken as 1 month, and $t_{1/2}$ is taken as 15 days.

Equations 6, 7 and 10 then become

(20) $$s_o(t) = 16 \frac{M}{t^2}$$

(21) $$t_{ppc} = 4 \sqrt{\frac{M}{s_{ppc}}}$$

(22) $$N \leq \frac{3.5 \times 10^{18}}{\frac{M}{s_{ppc}} \cdot t_{ppc}}$$

The resulting computations are summarized in Tables 13 and 14. Table 3 shows that the predicted activity on the spent ion exchange resins for the SAVANNAH* is about 400 curies. The weighted mean ppc value for fishing areas of the open sea, for the isotope mix on the ion exchange resins of the SAVANNAH, is about 5×10^{-8}. Applying this value to the subject open sea area, equation 22 gives a limiting value of over 10^3 for the permissible number of releases, per month, of 400 curies each. This corresponds to about 30 such discharges per day. In those large areas of the open sea which do not contribute materially to the commercial fishery harvest, the appropriate value for the corresponding environmental ppc is 3×10^{-7}. The permissible number of releases into the subject open sea area would for this case be over 10^4 per month, or 300 per day. Thus, if each of the 300 potential nuclear-powered ships should discharge spent ion exchange resins, containing 400 curies each, into the subject open sea area once each 2 months, the permissible limit of radioactivity in the environment would not be exceeded.

CONSERVATIVE AND NON-CONSERVATIVE ESTIMATES USED IN THIS REPORT

As a result of the many gaps in our basic knowledge of the pertinent phenomena in the sea which enter into the problem evaluated in this report, it has been necessary for the working panel to include many estimated parameters in the evaluation. Because we are treating a problem which is potentially very dangerous to man and to man's utilization of the natural environment, we have in general made conservative (safe) estimates of the uncertain factors. An additional reason for making conservative approximations is that the nuclear ship

*Since completion of this report, subsequent re-evaluation of the probable character and activity of the primary coolant and the ion exchange resins has been issued by the Oak Ridge National Laboratory (1959). While this ORNL report includes somewhat different values for the activity in these potential wastes, the general conclusions arrived at here remain unchanged.

TABLE 13

Sample computations for a selected trade route area of the open sea, giving the time (t_{ppc}) for the maximum concentration resulting from a single release of M curies to be reduced to ppc values for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml.

M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	M, in curies, for $s_{ppc} = 10^{-9}$	M, in curies, for $s_{ppc} = 10^{-8}$	M, in curies, for $s_{ppc} = 10^{-7}$
10^9	1.3×10^5	1.5	2.7×10^4	1	10	10^2
10^{10}	4×10^5	4.6	8.8×10^2	10	10^2	10^3
10^{11}	1.3×10^6	15	2.7×10	10^2	10^3	10^4
10^{12}	4×10^6	46	8.8×10^{-1}	10^3	10^4	10^5

TABLE 14

Permissible total activity per discharge into a selected trade route area of the open sea, as a function of the number of such discharges per month and the partial permissible concentration for the open sea.

ppc for open sea waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
10^{-9}	9.4×10^2	9.5×10	2.0×10
10^{-8}	9.4×10^3	9.5×10^2	2.0×10^2
10^{-7}	9.4×10^4	9.5×10^3	2.0×10^3

is not fixed and may travel into marine waters which are most restrictive from the standpoint of dispersion, exchange and biological uptake, as well as being heavily utilized by man.

The following summarizes the conservative approximations made in this evaluation.

1. It is assumed, for coastal areas and fishing areas of the continental shelf, that a selected segment of the population receives all its protein requirement from seafood harvested from the marine area subject to waste disposal. This assumption is not overly cautious for a country such as Japan, but is quite conservative for the United States. This restrictive assumption is relaxed when considering those areas of the outer continental shelf and open sea which contribute little to the fisheries harvest.

2. In computing the distribution of activity with time resulting from a given discharge, the radioactive decay was not included.

3. In computing the effect of discharge of spent ion exchange resins, it was assumed that all the activity was immediately released by the resin to the sea water. This is a conservative assumption only if the resins sink.

4. The effect of initial mechanical dilution on the distribution of activity after release to the marine environment was not included in the computations. This factor would be significant only during the very early stages of dispersion, since the point source solution and the finite source solution to the diffusion equations converge with increasing time. The major importance of initial mechanical dilution would be the reduction of any density difference between the effluent and the receiving waters. The assumption is made that no such density difference exists; hence the major effect of initial mechanical dilution is in fact indirectly included in the evaluation.

5. In the computations for the outer continental shelf and for the open sea, the possible transport of activity out of the surface layer by settling of particulate material was not included. In inshore waters it is possible that this process would be detrimental, since activity could be concentrated onto bottoms where important shellfish and bottom feeding fin fish occur.

6. The highest measured concentration factors for the uptake of a specific isotope by the biota were employed in the calculations, except that where concentration in the skeleton was important, one-tenth of the concentration factor from sea water to bone was used, since bone makes up about one-tenth of the edible portion.

Possible non-conservative features of our estimates include the following.

1. The equations of Joseph and Sender (1958), which were employed in computing the dispersion of radioactive wastes due to turbulent diffusion, are based on a statistical concept which provides a smoothed space and time distribution. A time record of the concentration at any given point, or the spatial record of the concentration at any given time resulting from a single actual point source, would differ in a random manner from the smoothed distribution predicted by the equations of Joseph and Sender. There would thus occur, from any single discharge, periods of time during which the concentration over small areas would be higher than that predicted. Since there would also occur corresponding times and locations with concentrations less than predicted, and since our concern is, at least in part, with the integrated effect of a number of such releases over time and space, this departure of the actual distribution from the predicted distribution does not introduce serious error in the final computations.

2. In the evaluation of the open sea environment, a 100 meter thick stirred layer was assumed. In some ocean areas this may be too large. In the case of a 10 meter stirred layer, the estimates of the time, t_{ppc}, required for the concentration to be reduced to environmental ppc levels would be increased by a factor equal to $\sqrt{10}$, or approximately 3.2; the corresponding value of N, the allowable number of discharges per month, would be decreased by $\sqrt{10^3}$, or approximately by a factor of 32. Such a small value of the layer depth for the open sea would be very unusual; any real overestimation of this factor is most probably compensated for by the neglect of transport of any activity to the deeper water.

3. In the computations for coastal waters, the possible concentration of activity on the bottom, due to uptake by suspended silts and subsequent settling, was not included. While this would be a conservative factor for those organisms which spend most of their time swimming or drifting in the water, it may well be quite detrimental to bottom living forms, particularly detritus and filter feeders. Data are not available to evaluate adequately the significance of this phenomenon. It is primarily for this reason that our final recommendations relative to inshore waters are more conservative than might otherwise be warranted from a strict application of our numerical results.

MONITORING AND RECORD KEEPING

It is essential that a systematic monitoring program be initiated as soon as possible to determine the consequences of the release of radioactive wastes from nuclear-powered vessels, both civilian and military*. This program is required in order to protect public health and property, to modify regulations in the light of new knowledge, and to prepare for intelligent action if and when nuclear disasters occur in inshore environments.

*A monitoring program has also been recommended by the Committee on Oceanography of the National Academy of Sciences - National Research Council (in its report entitled "Oceanography 1960-1970").

This program should be carried out by a single agency of the Federal government apart from that having regulatory authority. Since the work requires development of techniques for detecting low level radioactivity and for sampling a wide variety of habitats and organisms, and since the nature of the problem will be continually changing with changing technologies of atomic power, the program must have a core of excellent scientists capable of backing a dynamic directorate. In order to attract such people (which is in itself a difficult problem), provision should be made to allow them wide latitude for independent research related to the subject.

The monitoring should cover all harbors in the United States and its territories entered by nuclear vessels to the extent required by such use. It should be flexible enough to encompass, when circumstances require, all marine environments where organisms are exploited by man. It should be directed towards the detection of the radioactive isotopes produced in both corrosion and fission processes, distinguishing the quantities originating from fallout, from land based reactors and from nuclear vessels.

Although those engaged in the program must be given wide latitude in its execution, the panel suggests that the following are sensible subjects for observation: commercially useful organisms; certain other organisms that have high concentration factors for any of the radioactive elements; the water and its suspended solids; and the sediments.

In this regard it is recognized that the permissible concentrations recommended for the coastal waters are quite small from the standpoint of detection, and would require special counting techniques to determine. It is, however, not the concentration in the water phase of the environment, but rather the activity in the marine organisms, which is the controlling factor. The determination of environmental ppc values has been primarily an intermediate step to provide the necessary means of getting from the ppc value for the edible portions of marine organisms to the permissible rate of introduction of radionuclides to the environment. An inspection of Table 2 shows that the ppc values in the marine organisms are generally several orders of magnitude above the corresponding ppc value for coastal water. It is thus obvious that the most profitable method of monitoring the effects of the introduction of nuclear wastes into the marine environment is through measurements on the biota.

All nuclear-powered vessels should be required to maintain a record of all discharges of liquid waste effluent, of ion exchange resins, or of any other materials which, by the definitions used in this report, are classed as radioactive wastes. Such records should give information as to the location and time of each discharge; the concentration, total volume and total activity of each discharge (within the accuracies of available practical techniques for estimating these quantities); as well as an estimate of the isotopic composition of the discharge, with estimates of the amount of activity associated with each of the major constituents. Copies of such records should be transmitted at regular

intervals to the appropriate national agency, which will, in turn, supply condensations of these records to any international organization which may, by mutual agreement between governments, assume responsibility on an international basis for the monitoring and registry of nuclear waste disposal into the ocean.

Provision should be included for the prompt reporting and dissemination of information relative to the emergency or accidental release of radioactive materials in amounts exceeding those recommended in this report.

REFERENCES

Alco Products, Inc. (1955)
Description of the Army package power reactor. AECD-3731, October, 1955.

Argonne National Laboratory, University of Chicago (1957)
The experimental boiling water reactor. ANL-5607, May, 1957.

Carritt, Dayton E., et al. (1958)
The feasibility of the disposal of low level radioactive wastes into inshore waters of the Atlantic and Gulf coasts of the United States. Mimeographed report to the National Academy of Sciences - National Research Council Committee on Oceanography, 36 pp., plus 10 appendices separately paged.

(1959)
Radioactive Waste Disposal into Atlantic and Gulf Coastal Waters. National Academy of Sciences - National Research Council, Pub. 655, 36 pp.

Congress of the United States (1959)
Code of Federal Regulations, Title 10, Chapter 1, Part 20, revised 1959 (proposed).

Craig, Harmon (1957)
Disposal of radioactive wastes in the ocean: the fission product spectrum in the sea as a function of time and mixing characteristics, in Revelle, et al. (1957), p. 34-42.

Department of the Navy (1959)
Radioactive waste disposal from U. S. naval nuclear-powered ships. Nuclear Propulsion Division, Bureau of Ships; Iltis, T. J., and Miles, M. E. Mimeographed, presented for the record at the public hearings on industrial radioactive waste disposal, held by the Special Subcommittee on Radiation, of the Joint Committee on Atomic Energy, Congress of the United States, 27 January to 3 February, 1959.

Dunster, H. J. (1956)
The discharge of radioactive wastes into the Irish Sea, Pt. 2, the preliminary estimate of the safe daily discharge of radioactive effluent. Proc. Int. Conf. on Peaceful Uses of Atomic Energy, Geneva, 1955, Vol. 9, p. 712-715.

General Electric Corporation (1957)
The General Electric developmental boiling water reactor. SG-SVAL-1, Vallecitos Atomic Laboratory, L. Kornblith, Jr., L. Welsh, and E. Strain. February, 1957.

Greendale, A. E., and Ballou, N. E. (1954)
Physical state of fission product elements following their vaporization in distilled water and seawater. USNRDL Doc. 436, p. 1-28.

International Commission on Radiological Protection (1950)
Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units. U. S. Dept. of Commerce, Nat. Bur. Standards Handbook 47.

Joseph, J., and Sender, H. (1958)
Horizontal diffusion in the sea. Deut. Hydrog. Zeit. 11 (2), p. 49 - 77.

Ketchum, Bostwick H. (1957)
The effects of the ecological system on the transport of elements in the sea, in Revelle, et al. (1957), p. 52-59.

and Chipman, Walter A. (1958)
Permissible sea water concentration - monitoring of disposal areas. Appendix VI of Carritt, et al. (1958), 9 pp.

Krumholz, Louis A., Goldberg, Edward D., and Boroughs, Howard A. (1957)
Ecological factors involved in the uptake, accumulation, and loss of radionuclides by aquatic organisms, in Revelle, et al. (1957), p. 69-79.

Maritime Administration (1959)
Waste disposal considerations in the nuclear-powered merchant ship program. Mimeographed, presented for the record at the public hearings on industrial radioactive waste disposal, held by the Special Subcommittee on Radiation, of the Joint Committee on Atomic Energy, Congress of the United States, 27 January to 3 February, 1959.

Martin, DeCourcey, Jr. (1957)
The uptake of radioactive wastes by benthic organisms. 9th Pacific Science Congress, November, 1957.

National Committee on Radiation Protection, Subcommittee on Permissible Internal Doses (1953)
Maximum permissible amounts of radioisotopes in the human body and maximum permissible concentrations in air and water. U. S. Dept. of Commerce, Nat. Bur. Standards Handbook 52, 45 pp.

Oak Ridge National Laboratory (1959)
Maritime Reactor Project, Annual Progress Report for Period Ending November 30, 1958. ORNL-2657. TID-4500 (14th edition).

Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (1958)
U. N. Gen. Assembly, Official Records, 13th session, suppl. 17 (A 13838), 228 pp.

Revelle, Roger, and Shaefer, Milner B. (1957)
General considerations concerning the ocean as a receptacle for artificially radioactive materials, in Revelle, et al. (1957), p. 1-25.

Revelle, Roger, et al. (1957)
The effects of atomic radiation on oceanography and fisheries, report of the Committee on Effects of Atomic Radiation on Oceanography and Fisheries, of the National Academy of Sciences Study of the Biological Effects of Atomic Radiation. Nat. Acad. Sci. - Nat. Res. Council Pub. 551, 137 pp.

Technical Information Service, U. S. Atomic Energy Commission (1958)
The pressurized water reactor forum, December 2, 1955, held at Mellon Institute, Pittsburgh. TID-8010, February, 1956.