United States
Environmental Protection
Agency

Office of
Radiation Programs
Washington DC 20460

EPA 520/1-89-019
August 1989

Radiation

EPA

A Review and Evaluation of Principles Used in the Estimation of Radiation Doses Associated with Deep sea Disposal of Low-Level Radioactive Waste

Printed on Recycled Paper

EPA 520/1-89-019

A REVIEW AND EVALUATION OF PRINCIPLES USED IN THE ESTIMATION OF RADIATION DOSES ASSOCIATED WITH DEEPSEA DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE

D. A. Baker
W. L. Templeton
J. K. Soldat

Battelle-Pacific Northwest Laboratory
Richland, Washington 99352

Prepared Under
Interagency Agreement DE-AC06-76RLO 1830

Project Officer

Robert S. Dyer
Office of Radiation Programs
U.S. Environmental Protection Agency
Washington, DC 20460

FOREWORD

In 1972 the Congress enacted Public Law 92-532, the Marine Protection, Research and Sanctuaries Act (MPRSA), which authorized the Environmental Protection Agency (EPA) to regulate any future ocean disposal of waste materials, including low-level radioactive waste (LLW). In response, the EPA Office of Radiation Programs (ORP) initiated studies at ocean sites previously used for disposal of LLW.

These studies were initiated: (1) to determine the condition of LLW containers after disposal and prolonged exposure to the marine environment; (2) to assess whether previous ocean disposals of LLW were adversely affecting human health or the marine environment; and (3) to obtain data to develop and support criteria for regulating any future ocean disposal of LLW.

In 1983 the Congress enacted Public Law 97-424, the Surface Transportation Assistance Act. Section 424 of that Act pertains to ocean dumping and amends the MPRSA to require a Radioactive Materials Disposal Impact Assessment (RMDIA) as part of a disposal permit application. The RMDIA must include consideration of any potential adverse environmental effects from ocean disposal of LLW.

Thus, the ORP, as part of an interagency agreement with the Department of Energy (DOE), tasked the DOE's Battelle-Pacific Northwest Laboratory to review and evaluate the principles used to estimate radiation doses from deep ocean disposal of LLW.

This report summarizes dose limitation data, as recommended by various national and international radiation protection organizations. It also discusses available pathway dose models and identifies problems in assessing ocean disposal as a waste management option for LLW.

The Agency invites all readers of this report to send comments or suggestions to Mr. David E. Janes, Director, Analysis and Support Division (ANR-461), Office of Radiation Programs, Environmental Protection Agency, Washington, DC 20460.

Richard J. Guimond, Director
Office of Radiation Programs

SUMMARY

This report presents information obtained from reviewing relevant guidance for estimating radiation doses applicable to deepsea disposal of low-level radioactive wastes (LLW). The review was requested by the Environmental Protection Agency's (EPA) Office of Radiation Programs (ORP) via an interagency agreement with the Department of Energy's (DOE) Battelle-Pacific Northwest Laboratory (B-PNL) to determine whether a specific, acceptable methodology exists for assessing risks from ocean disposal of LLW.

The report includes discussions of: (1) dose categories and recommended dose limits; (2) the radiation protection philosophy of the International Commission on Radiological Protection (ICRP); (3) physical and biological pathways by which radiation from disposals of LLW in the marine environment could also reach man; (4) three types of existing pathway models that can be used to estimate dose to man; (5) oceanographic and radiological components of existing assessment models; (6) proposed models; and, (7) problems related to assessing risk from ocean disposal of LLW.

The report concludes that existing models, if improved as additional environmental and risk assessment data becomes available, should provide adequate information for regulatory determination of risk from any future ocean disposals of LLW. The existing models identified in this report should be able to indicate whether maximum individual exposure limits are likely to be exceeded.

ACKNOWLEDGMENTS

We wish to express our gratitude to Robert S. Dyer, Office of Radiation Programs, Environmental Protection Agency, for his ideas, support, discussion, and assistance in this work.

We also wish to thank John E. Till for his pertinent and helpful advice.

TABLE OF CONTENTS

		Page
FOREWORD		iii
SUMMARY		v
ACKNOWLEDGMENTS		vii
LIST OF FIGURES AND TABLES		xi
1	INTRODUCTION	1
2	DOSE LIMITATIONS RECOMMENDED BY VARIOUS ORGANIZATIONS	2
2.1	DOSE CATEGORIES	2
2.2	INTERNATIONAL COUNCIL ON RADIATION PROTECTION (ICRP)	3
2.3	NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS (NCRP)	4
2.4	WORLD HEALTH ORGANIZATION (WHO)	5
2.5	U.S. GOVERNMENT	5
2.5.1	Federal Radiation Council (FRC)	5
2.5.2	Environmental Protection Agency (EPA)	6
3	ICRP RADIATION PROTECTION PHILOSOPHY	6
3.1	JUSTIFICATION	6
3.2	OPTIMIZATION	7
4	PATHWAY DOSE MODELING	9
4.1	STEADY-STATE MODELING	10
4.2	TRANSIENT MODELING	12
4.3	SPECIFIC ACTIVITY MODELING	15
4.4	MODELING CONSIDERATIONS	15
4.5	SELECTION AND IDENTIFICATION OF PARAMETER VALUES	16
4.5.1	Nature of the Released Radioactivity	17
4.5.2	Concentration Factors	17
4.5.3	Consumption Rates and Occupancy Factors	18

TABLE OF CONTENTS (Continued)

		Page
5	THE BASIS FOR DEEP OCEAN DISPOSAL	18
	5.1 LONDON DUMPING CONVENTION (LDC) RECOMMENDATIONS	18
	5.2 RADIOLOGICAL EVALUATION OF OCEAN DISPOSAL PRACTICES	20
	5.2.1 Need for Modeling	20
	5.2.2 Need for Research	21
	5.3 NUCLEAR ENERGY AGENCY (NEA) MODEL	21
	5.3.1 Release Model	22
	5.3.2 Marine Model	22
	5.3.3 Pathway Model	22
	5.4 INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA) MODEL	23
	5.4.1 Oceanographic Component	23
	5.4.2 Radiological Component	27
6	PROBLEMS IN THE ASSESSMENT OF OCEAN DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE (LLW)	31
	6.1 COLLECTIVE DOSE	31
	6.2 CHOICE OF A RADIOLOGICAL PROTECTION SYSTEM	32
7	CONCLUSIONS	36
8	REFERENCES	37
9	GLOSSARY	42

LIST OF FIGURES AND TABLES

		Page
FIGURE 1	Theoretical Relationships Between Costs and Collective Dose Showing Optimum Collective Dose, S_o, at Optimum Cost, C_o	8
FIGURE 2	Simple Compartment Model	14
TABLE 1	Current NCRP Dose Limits for Members of the Public or Occasionally Exposed Individuals	4
TABLE 2	Pathways and Mode of Exposure in the IAEA Radiological Component	28
TABLE 3	Pathways and Usages Proposed by the IAEA	30
TABLE 4	Comparison of Allowable Intake by Individual Members of the Public for Selected Radionuclides	34

1. INTRODUCTION

The selection of a specific methodology for the assessment of the risks of ocean disposal of other than high-level radioactive waste (OTHLW) must be preceeded by an examination of the need for this mode of waste disposal. Assuming that such disposal would be permitted and licensed by a governmental agency, some limitation must be placed on the quantities to be disposed, the location of the disposal site, the waste matrix material, the kinds of monitoring to be performed, and the types of containers. In the United States, the agency assigned the responsibility for developing such limitations and guidance is the Environmental Protection Agency (EPA). However, any regulations and criteria the EPA promulgates should be at least as restrictive as the recommendations of international bodies such as the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA). They should also be in accord with provisions contained in the London Dumping Convention (LDC) that cover the practice of ocean disposal of wastes, including those that are radioactive.

The U.S. guidance must address the sea disposal of wastes by any commercial or governmental entity within the U.S. territorial waters and Exclusive Economic Zone (out to 200 miles from the coast line) to ensure protection of the U.S. population and of the contiguous marine environment. In addition, the U.S. guidance must cover disposal by U.S. entities in international waters, since the United States is a signatory to the LDC.

In this report we discuss the radiological protection considerations necessary for the disposal of low-level radioactive waste (LLW) that could detrimentally affect populations worldwide. The applicable dose limitations, recommended for various disposal practices by the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the EPA are identified. Some recent conclusions from the World Health Organization (WHO) concerning waste disposal are summarized.

This report primarily considers the current ICRP-IAEA philosophy concerning dose assessment, and the modeling of dose pathways to individuals and populations, from any release of LLW in the deep ocean. The present IAEA release rate limits for ocean disposal of LLW are discussed, as are the models proposed by NEA and IAEA. Finally, some of the inadequacies of the recent ICRP methodology for calculating dose are presented.

2. DOSE LIMITATIONS AS RECOMMENDED BY VARIOUS ORGANIZATIONS

This section provides a summary of dose categories and presents pertinent radiation guidance developed by various national and international bodies. It concentrates primarily on the radiation standards set for the general population; standards for radiation workers are not covered.

2.1 DOSE CATEGORIES

Radiation doses [a] can be calculated for individuals in a "critical group" and for populations. In order to assess the dose received by an exposed population in dose equivalent terms, use is made of the collective dose equivalent. This collective dose can be obtained by integration of the ranges of dose rates within the population or the population group. In actual practice, this collective dose is usually derived by multiplying the average or per capita dose equivalent by the number of subgroup individuals in the population. In some instances, assessment of collective dose can be simplified, often avoiding the need to identify and assess the separate individual doses. For example, in a food-chain pathway it is sufficient to know only the total collective consumption of marine organisms - not the individual consumption rates. However, in a geographically extensive pathway, such as fish consumption, it will be necessary to group the total catches and to weight them according to their concentrations of radioactivity. The latter will generally vary with distance from the point of release.

The collective dose rate will vary as a function of time. The total collective dose equivalent commitment from a particular source can be obtained by integrating the collective dose equivalent rate. This collective dose equivalent commitment is required for the justification or optimization of different choices of waste management practices. The collective quantities are frequently expressed as man-rem (or man-Sv) to distinguish them from individual doses.

---

[a] The term "dose" in this report should be interpreted to mean the sum of the internal and external dose equivalents unless otherwise indicated.

2.2 INTERNATIONAL COUNCIL ON RADIATION PROTECTION (ICRP)

The ICRP has recommended radiation protection standards for consideration by its member countries. The first standard, issued in 1959 [ICRP 1959], as well as a later one issued in 1965 [ICRP 1965], set the dose-rate limit to the whole body of a member of the public at 0.5 rem/yr (5 mSv/yr). This same limit was also stipulated for gonads and red bone marrow. A dose-rate limit of 3 rem/yr (30 mSv/yr) was stipulated for skin, bone and the thryoid. However, the limit was set at 1.5 rem/yr (15 mSv/yr) for thryroids in children up to age 16. Later, in 1977, the ICRP revised their dose recommendations on the basis of a new concept of (weighted) effective whole-body dose [ICRP 1977].

Recommendations were made for "stochastic" and "nonstochastic" effects. Stochastic effects were defined as those for which the probability of an effect occurring, rather than its severity, is regarded as a function of dose without threshold. On the other hand, nonstochastic effects were defined as those for which the severity of the effect varies with dose and for which a threshold may occur.

The ICRP regards hereditary effects and somatic effects, primarily cancer, as stochastic. Nonstochastic effects are specific to particular tissues, such as lens cataracts, nonmalignant skin damage, depletion of bone marrow, and gonadal cell damage, which may cause infertility.

In their 1977 recommendations, the ICRP went on to define two types of members of the general population: critical groups and average members of the population. A typical member of the critical group would closely resemble the "maximum individual" as used in the United States. The average member of the population would correspond to the U.S. nomenclature "average individual," or the European term "per caput." The 1977 ICRP whole-body dose recommendations (pp. 23-25) are as follows:

Stochastic:

Critical groups	0.5 rem/yr (5 mSv/yr)

Nonstochastic:

Any member of public	5 rem/yr (50 mSv/yr)

The stochastic limit of 0.5 rem/yr (5 mSv/yr) to individual members of the public is likely to result in average dose equivalents of less than 50 mrem/yr (0.5 mSv/yr) provided that disposal practices exposing the public are few and cause little exposure outside of the critical group.

2.3 NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS (NCRP)

In 1975, the NCRP issued limits for maximum radiological dose in the United States. Their recommended annual dose limit for an occasionally exposed individual member of the general public was set at 0.5 rem/yr (5 mSv/yr). The NCRP established an average annual dose limit of 0.17 rem/yr (1.7 mSv/yr) for the general public. This limit applied to both genetic and somatic doses.

TABLE 1

Current NCRP dose limits for members of the public or occasionally exposed individuals [NCRP 1975, p.34]

Individual Dose Limits		
Occasionally Exposed Public	0.5	rem in any one year
Students	0.1	rem in any one year
Population Dose Limits	0.17	rem average per year
Emergency (Lifesaving) Dose Limits		
Individual (over age 45, if possible)	100	rem
Hands and Forearms	200	additional rem (300 rem total)
Emergency (Less Urgent) Dose Limits		
Individual	25	rem
Hands and Forearms	100	rem total
Family of Radioactive Patients		
Individual (under age 45)	0.5	rem in any one year
Individual (over age 45)	5	rem in any one year

2.4 WORLD HEALTH ORGANIZATION (WHO)

Historically, the WHO has accepted the ICRP dose limits and philosophy. A 1978 WHO working group agreed that the basic principle to be used in formulating radiation protection regulations is the ICRP recommendation that all radiation exposures should be kept as low as readily [sic] achievable, with economic and social considerations taken into account. With regard to the dumping of wastes into the oceans, the working group recognized that current dumping levels represent only a minute fraction of the maximum amounts permitted by the IAEA [IAEA 1975]. Accordingly, the WHO working group recommended that studies of sea disposal, as well as other waste disposal methods, be continued; and they called upon the IAEA to accelerate the acceptance by member states of the IAEA recommendations and procedures, as specified in the LDC [WHO 1978, p. 33]. The WHO working group also stressed that attention should be given to the various exposure routes to humans rather than to possible effects on aquatic populations. Although they observed no evidence that previous releases into the sea have been harmful to anyone, the group cautioned that prudence dictates that the exposure paths leading to man and to accumulation in marine organisms should be closely monitored [WHO 1978, p. 34].

2.5 UNITED STATES GOVERNMENT

2.5.1 Federal Radiation Council (FRC)

The FRC was established in 1960 to provide guidance to the President in radiation matters. It established and promulgated radiation standards that were not to be exceeded (without formal justification) by Federal Agencies. In its first report, the Council set limits for external exposure of the total body; viz., 0.5 rem/yr (5 mSv/yr) to the individual and 5 rem (50 mSv) per 30 year (equal to 0.17 rem/yr or 1.7 mSv/yr) to the average individual of suitable sample of the exposed population [FRC 1960]. In its second report, the Council recommended that exposure of bone and thyroid from internally deposited radionuclides should be limited to 1.5 rem/yr (15 mSv/yr) for the individual and 0.5 rem/yr (5 mSv/yr) for a suitable sample of the population [FRC 1961].

By authority of the President, FRC authority was transferred in 1970 to the newly-formed EPA.

2.5.2 Environmental Protection Agency (EPA)

The EPA has promulgated dose limits for any member of the general public from the uranium fuel cycle, as given in 40 CFR 190, and from geologic disposal of high-level radioactive wastes (HLW), as stated in 40 CFR 191.

EPA states that the total annual dose to the whole body from all aspects of the uranium fuel cycle shall not be greater than 25 mrem (0.25 mSv), and that the annual dose to the thyroid and any other body organ shall not exceed 75 mrem (0.75 mSv) and 25 mrem (0.25 mSv), respectively.

It should be noted that doses received from mining operations, waste disposal and associated transportation to support mining and disposal activities, are not included when determining compliance to the EPA dose limits. Doses from Radon daughter nuclides are not included in the above limits, but are to be addressed separately.

3 ICRP RADIATION PROTECTION PHILOSOPHY

The ICRP radiation protection philosophy is based upon three primary guiding principles (justification, optimization, and compliance) which together, constitute its dose-limitation system [ICRP 1973 and 1977].

3.1 JUSTIFICATION

This principle states that no practice or operation (i.e, nuclear power production, military or civilian isotopic research, development or manufacturing activities) shall be adopted unless a positive net benefit to society is produced.

The ICRP does not consider this principle to be amenable to formal analysis since many broad issues must be considered and assessed to determine whether "net benefit(s)" are produced from a particular practice/operation. The issues are likely to include economic, social, military, scientific and political factors.

3.2 OPTIMIZATION

This prinicple states that all exposures shall be kept as low as reasonably achievable (ALARA), upon consideration of economic and social factors.

The ICRP recommendation that all exposures be kept "as low as practicable" or "as low as reasonably achievable" is also supported in the U.S. by the NCRP, the EPA and the Nuclear Regulatory Commission (NRC).

The ICRP first addressed the practical implications of this recommendation in 1973. In 1977, the ICRP further stated that optimization would be achieved when the level of exposure is such that any increase in the cost of protection per unit dose equivalent is balanced by a reduction of detriment per unit dose equivalent. The ICRP methodology that can be used to assist in determining optimization is given by the following equations.

$$B = V - (P + X + Y) \qquad (1)$$

where V = gross benefit of operation or practice
P = basic production costs
X = cost of achieving a selected level of protection
Y = cost of the detriment involved in the operation or practice

Thus, optimization is achieved when the net benefit is maximized with respect to the costs associated with the level of radiation protection. Let X and Y be functions of the collective dose, S, and assume that the gross benefit, V, and production costs, P, are independent of S. Then on differentiating Equation (1) with respect to S, we arrive at

$$(dX/dS)_{S_o} + (dY/dS)_{S_o} = 0 \qquad (2)$$

where S_o = optimum level of collective dose ($dB/dS_o = 0$). Figure 1 shows this relationship.

Since it is not usually practical to consider infinitesimal changes in costs and collective doses, Equation (2) may be written in terms of finite increments.

$$(\Delta X/\Delta S)_{S_o} + (\Delta Y/\Delta S)_{S_o} = 0 \qquad (3)$$

Then by cancelling the ΔS in the denominators of Equation (3), we can write:

$$\Delta X + \Delta Y = 0 \qquad (4)$$

The result can be obtained by a simple inspection of tables of cost values, but with discrete options it is very unlikely that the incremental costs can be exactly matched. The optimum control option will be defined when $\Delta X + \Delta Y$ is closest to zero for a set of options. It should be emphasized that while it is relatively easy to mathematically specify a procedure for optimization, it is exceedingly difficult to apply this formalism in practice. One may find examples of applying these equations in IAEA Proceedings 1979b.

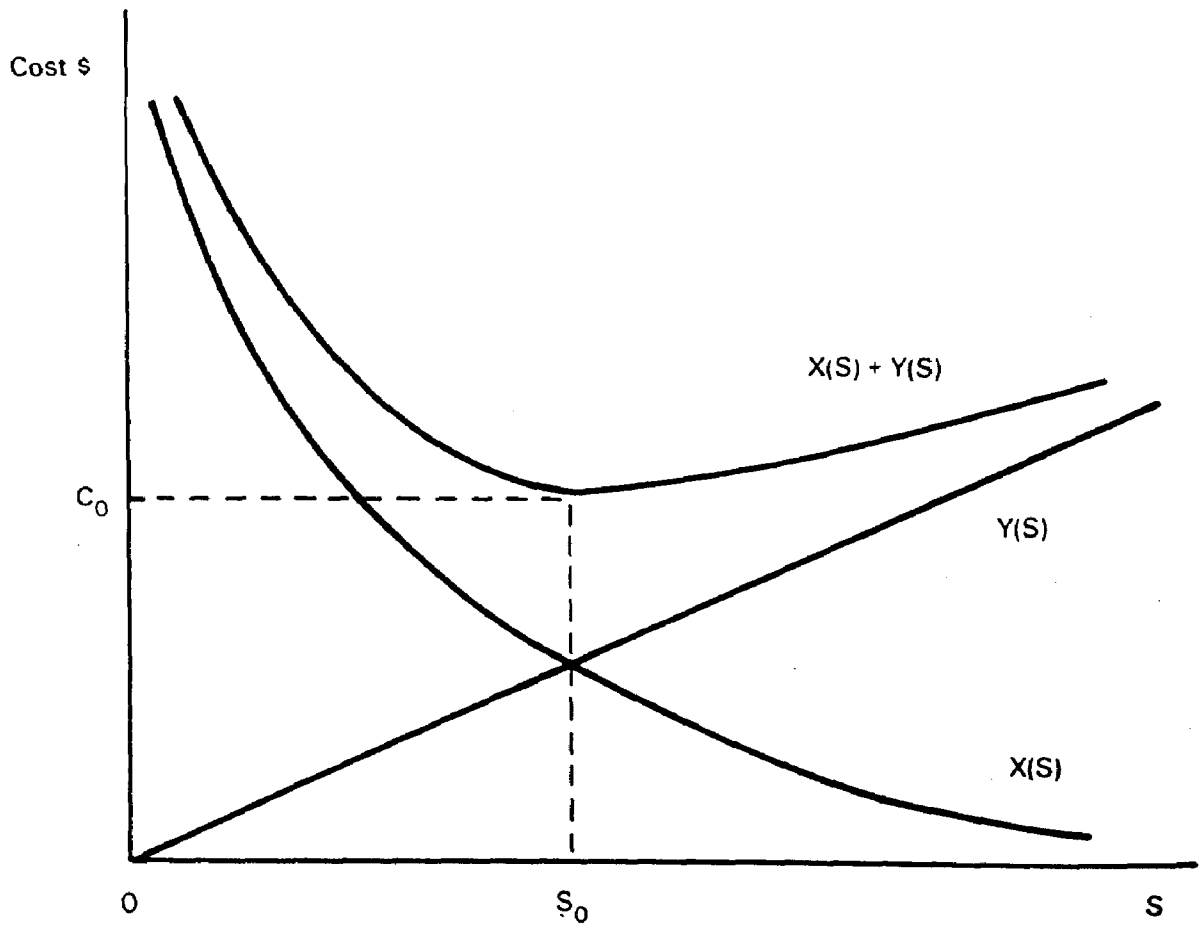

FIGURE 1. Theoretical relationship between costs and collective dose showing optimum collective dose, S_o, at optimum cost, C_o

4 PATHWAY DOSE MODELING

To determine the appropriate release limit to set for a specific practice or operation, you must analyze the various pathways leading to man in order to determine those that could lead to doses exceeding the limit or that lead to the highest exposure. These are often referred to as critical pathways and the group of persons so exposed are called critical groups. As used here, "critical" denotes the sense of importance relative to other pathways and groups and identifies the pathway(s) that will have to be limited to control the dose.

For any given site, only one or a few pathways will prove to be limiting. If the total dose to the public via these limiting pathways is kept below the ICRP recommended dose limits, then the total dose from all pathways combined may be less than the recommended limit. In addition, although a large number of radionuclides may be released, only a few may contribute significantly to the total dose.

Webb (1980) listed the items to consider in the analysis of a general pathway model for ocean dumping of radioactive waste, as follows:

- release of radionuclides from the package (container and waste form)
- local mixing with water and adsorption onto sediments
- local biological uptake processes
- physical transport of dissolved or resuspended radionuclides via the water column
- biological transport of radionuclides
- sediment transport
- reconcentration of dissolved radionuclides by biota after transport in water to location of harvest
- exposure of man via ingestion, inhalation, and direct irradiation

The estimation of dose to man from ocean disposal of radioactive waste may be carried out using mathematical models describing either transient or steady-state conditions. A third

method based upon specific activity is the simplest; however, it can only be applied to those radionuclides having stable analogs. The steady-state or concentration-factor approach is only slightly more complex, but it necessitates that the user assume the system is at equilibrium. On the other hand, the transient or compartmental model methodology, which describes a transient condition produced from a variable source function, is usually more complex and time consuming. Also a knowledge of a great many transfer rates between the various compartments making up the model is required. In most instances the concentration-factor models are used unless the dynamics or time variations of radionuclides in various compartments is important [ICRP 1980b].

4.1 STEADY-STATE MODELING

The steady-state or concentration factor (CF) model contains multiplicative parameters called transfer or concentration factors, F_{ij}, defined as:

$$F_{ij} = M_j(t)/M_i(t) \qquad (5)$$

where F_{ij} = the factor relating concentrations in media i and j

$M_i(t)$ = activity concentration in compartment i at time t

$M_j(t)$ = activity concentration in compartment j at time t

The factors, F_{ij}, are expressed in terms of the units of the M_j and M_i. For example, the concentration factor in SI units that relates fish concentration to that of its surrounding water is in units of Bq/kg per Bq/m^3 or m^3/kg.

For equilibrium conditions, the concentrations attain constant values so that we can write:

$$M_{j,e} = M_{i,e} F_{ij} \qquad (6)$$

where the $M_{j,e}$ and $M_{i,e}$ are equilibrium concentrations.

Dose usually cannot be measured directly because it is lower than the natural background. Accordingly, the limits are often set for either the radioactive discharge of the practice or the resulting concentrations in air or water. These limits are called "derived limits." When the limits are placed on discharge rate, they must be calculated from the dose limits using any of the modeling techniques and the full critical path. When the limits

are placed on environmental concentrations, multiple pathways need not be considered because they were considered in the setting of the concentration standards.

As mentioned above, for systems that have come to equilibrium or for dynamic systems that may be approximated by a steady-state approach, the use of the concentration-factor model is usually justified. An example of this methodology is presented for calculating the dose, H, (either annual or committed) from the consumption of seafood harvested in waters containing a radionuclide that has been transported from a waste container leaking at a constant rate:

$$H = R\ P\ B\ U\ DF \quad \text{rem (Sv)} \tag{7}$$

where H = annual dose, or committed dose over 50 years rem (Sv)
R = leak rate (Ci/yr) or (Bq/yr) of a radionuclide from the waste container
P = hydrospheric dispersion factor $(Ci/m^3)/(Ci/yr)$ or $(Bq/m^3)/(Bq/yr)$
B = bioaccumulation factor for seafood $(Ci/kg)/(Ci/m^3)$ or $(Bq/kg)/(Bq/m^3)$
U = consumption rate of seafood (kg/yr)
DF = dose factor (rem/Ci) or Sv/Bq.

The calculated dose, H, may be either an annual dose or a committed dose over a 50 year period. The annual dose is calculated in determining compliance with the ICRP dose limits. The dose factor, DF, is dependent upon the radionuclide involved and the age of the consumer. The collective dose is usually calculated by assuming the population is made up entirely of average adults. This is probably satisfactory for calculating collective dose from seafood consumpiton since, in most countries, infants and younger children do not consume as much seafood as adults.

In selecting a disposal site, it is necessary to determine the maximum release rate of radionuclides that would not lead to radiation exposures in excess of the ICRP limits. Equation (7) may be rearranged to give a release rate, R*, that should not be exceeded, as follows:

$$R^* = \frac{H^*}{P\ B\ U\ DF} \tag{8}$$

where H* = the relevant dose limit.

In application, R is usually kept much smaller than R* for any particular nuclide or practice so that the dose limit, H*, will not be exceeded if the individual is subject to exposure from radionuclides resulting from practices or operations other than ocean disposal.

4.2 TRANSIENT MODELING

A system that is not in equilibrium may, with appropriate approximation, be modeled using concentration factors; however, a more rigorous method is to use a multicompartmental model coupled together by linear first-order equations. This technique, sometimes called the system analysis (SA) method, has been used for the analysis of tracer kinetics in living organisms [Whicker and Schultz, 1982 and Finkelstein and Carson, 1979]. It can be extended to dynamically simulate the movement of radionuclides through various environmental media. These compartments are then connected by various rate constants which determine the relative movement of a radionuclide throughout the system.

The compartments may be highly conceptual, such as the world's surface water or vegetation, or they may be specific subunits, such as the portion of the sea in a small geographic location. The quantity (activity) of a radionuclide is calculated for each compartment at a certain time, and then the whole set of equations governing the system is incremented in units of time (e.g. day, week, month or year), depending on the rates in that system. Thus, the activity in each compartment will change with each time increment. It is assumed in this type of analysis that, after each iteration, the activity in each compartment is homogenously and instantaneously distributed through the compartment such that its concentration is constant throughout the compartment. This assumption becomes more uncertain or questionable as the size of the compartment is increased and the time increment is decreased. A great many calculations must be made, depending on the number of compartments and time iterations involved.

The general formula for the set of differential equations describing a system of connected compartments with radiological decay is given by:

$$\frac{dy_j}{dt} = \sum_{\substack{i=1 \\ i \neq j}}^{n} K_{ij} Y_i + P_j - Y_j \left[\sum_{\substack{i=1 \\ i \neq j}}^{n} K_{ji} + \lambda_j \right] \quad (j=1,2,3,\ldots n) \quad (9)$$

where $_j$ = compartment of reference
$_i$ = all other compartments
K_{ij} and K_{ji} = transfer coefficients between compartments having activity inventories of Y_i and Y_j.

The first two terms after the equal sign in Equation (9) represent all the activity entering compartment $_j$ from all other compartments $_i$ and from outside the system P_j. The terms in brackets represent all the activity leaving compartment $_j$ and going to all other compartments $_i$ (K_{ji}) and being removed from the system entirely (λ_j). The P_j includes the source term and ingrowth of daughter radionuclides. The λ_j includes the radioactive decay constant along with any other removal of concern.

As an example, consider an idealized three-compartment system of a fish existing in a body of water in which radioactive wastes are being released (see Figure 2). It is required to estimate the activity in the fish when activity is being released into the sediment and surrounding water from the waste container at the rates indicated. Here (Figure 2), Y_i represents activity levels in the $_i^{th}$ compartment and K_{ij} is the constant fractional rate of activity flow in units of reciprocal time from compartment $_i$ to compartment $_j$. The following set of system equations may then be written for this example:

<u>Compartment 1, Water</u>

$$dY_1/dt = K_{21}Y_2 + K_{31}Y_3 + P_1 - Y_1(K_{12} + K_{13} + \lambda_r) \quad (10)$$

<u>Compartment 2, Sediment</u>

$$dY_2/dt = K_{12}Y_1 + K_{32}Y_3 + P_2 - Y_2(K_{21} + K_{23} + \lambda_r) \quad (11)$$

<u>Compartment 3, Fish</u>

$$dY_3/dt = K_{13}Y_1 + K_{23}Y_2 - Y_3(K_{31} + K_{32} + \lambda_r) \quad (12)$$

Here, P_1 and P_2 represent the release rate from the waste containers to the water and sediment, respectively. The term for removal from the system is the radiological decay term λ_r).

This set of equations (10, 11 and 12) may be solved analytically [Whicker and Schultz, 1982]; however, for more than about four equations, numerical methods must be used. By converting these equations to difference equations so that a finite change in t will produce a finite change in Y_i such that by adding each ΔY_i to each Y_i and then repeating this process for all the equations, the system may be iterated through time until equilibrium is reached ($dY_i/dt = 0$).

The resulting compartment activities, Y_i, may be divided by their respective volumes or masses to determine the concentration of activity in each compartment after any given time period. By decreasing the time increments, Δt, any degree of precision may be achieved, but only at the cost of increased computational time. However, the degree of numerical precision of the results should never be more than that of the input parameters.

Discussions of compartmental modeling are given in many publications. Good discussions with examples are presented in ICRP Publication 29 [1980b] and in a 1980 Organization for Economic Cooperation and Development (OECD)/ Nuclear Energy Agecy (NEA) publication. Methods for solving these models are summarized in a publication for microcomputer users [Hicks, 1981].

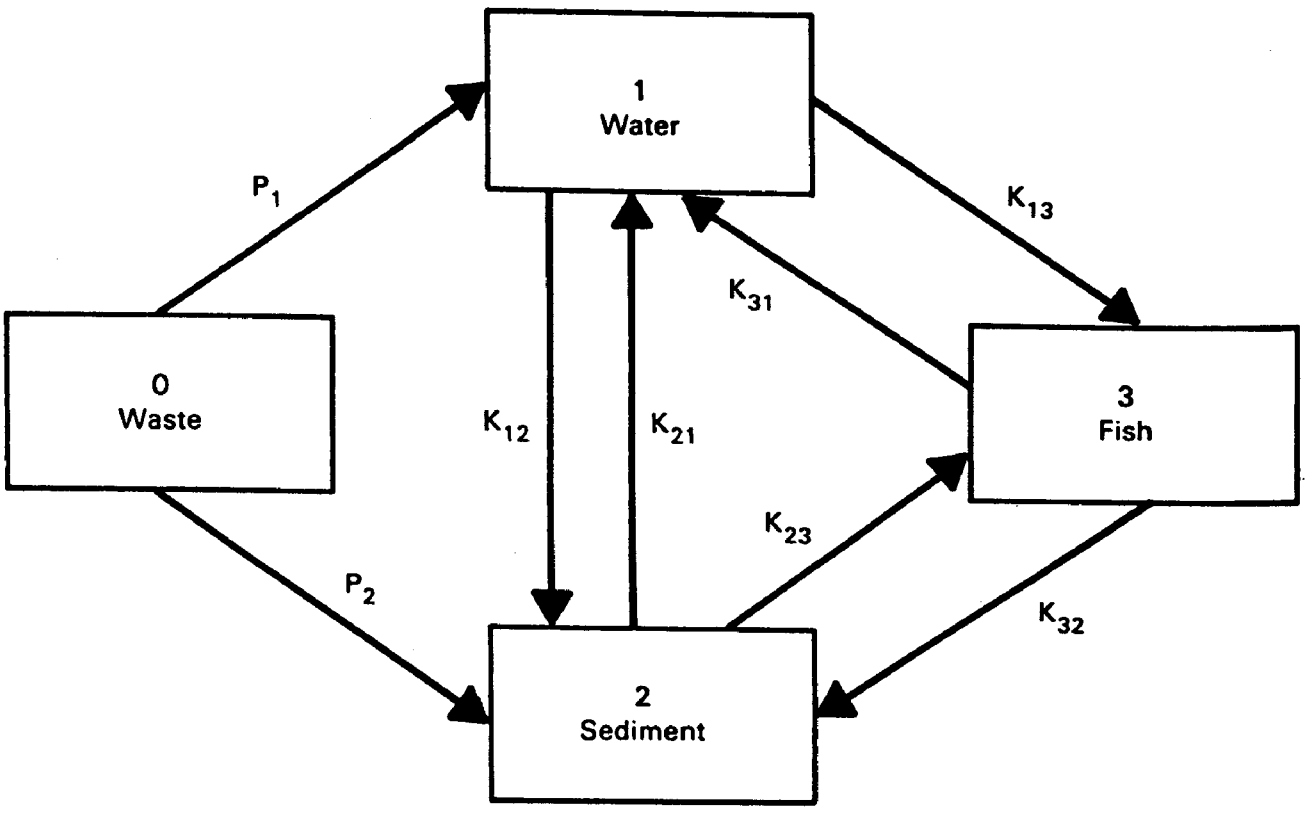

FIGURE 2. Simple Compartment Model

4.3 SPECIFIC ACTIVITY MODELING

Whereas the previous two modeling methods are concerned with various pathways, especially the critical pathway, the specific-activity approach is independent of any pathway. The basic assumption in this method is that the specific activity (the ratio of the concentration of a radioactive isotope to its stable analog) remains constant throughout all environmental media. Thus, by limiting the release of various radionuclides, the specific activity of a recipient medium (e.g. sea water) is kept below a fixed value. Thus, the specific activity cannot be exceeded at any point in the food chain or in a critical organ in humans (NAS/NRC, 1962; IAEA, 1978a; and, Foster, Ophel and Preston, 1971). The advantage to this approach is that the requirement for various dilution factors, concentration factors, transfer coefficients, etc. is eliminated. The disadvantages are: some of the radionuclides (e.g. americium and curium) do not have stable analogs; the chemical form of a released radionuclide may differ from its stable analog; and, calculating GI-tract dose is not applicable since exposure is produced by food passing through the gut rather than from tissue deposition. However, this approach is useful for some radionuclides (e.g. carbon-14, tritium, iodine-131, and strontium-90). It should be noted, however, that this approach is not compatible with the methodology in ICRP Publication 26 [ICRP, 1977], since the ICRP equations and parameters are based on the intake of the radionuclides irrespective of stable element intake.

4.4 MODELING CONSIDERATIONS

Following the stage of dilution into the immediate receiving water mass, allowances must be made for factors that influence the amount of a radionuclide actually transferred through successive model compartments. It is important, for example, to consider are distribution coefficients (K_ds) between the water and seabed or between the water and sedimentary materials in suspension, as sediment 'contaminated' by water-borne radionuclides may be a direct pathway of exposure to man via occupational exposure from the use of bottom-fishing equipment or via recreational exposure on beaches. Radionuclide transport from sediment to water is also important to consider for any disposal of radioactive wastes under the surface of the seabed.

Modeling of food-chain pathways results in calculated concentrations of radionuclides in food products that are consumed by humans. One these concentrations are predicted, the intake of radionuclides can be determined from the consumption rates of the food products.

The inverse ratio of the dose (calculated using such models) to the appropriate annual limits of intake (ALI) and external exposure rates recommended by ICRP gives an estimate of the maximum permissible daily discharge rate. The major difference between this method and the "specific activity" approach is that estimates are required for the degree of contamination of environmental materials, and for detailed information about eating, working, and leisure habits of local and distant populations subject to exposure.

Determining equilibrium concentrations in environmental media and marine organims, using the above pathway approaches, provides the starting point for calculating dose according to methods given in IAEA publications [IAEA, 1976 and 1979a].

To ensure that no member of the general public is exposed beyond the recommended dose limit, individuals or individual groups having exceptional habits that could lead to such exposure must be identified. Estimated average exposures for these critical individuals/groups provides a basis for ultimately determining permissible release rates.

4.5 SELECTION AND IDENTIFICATION OF PARAMETER VALUES

The availability of parameter values (data) that support models used to predict transfer of radionuclides along environmental pathways is an important factor in determining the complexity or realism that can be represented by pathway models. It is also a major factor in deciding whether to apply the more fundamentally rigorous transient (systems analysis) method, or the more simplified steady state (concentration factor) method.

For the transient method, transfer functions are required between compartments that are both time and spatially dependent. For the steady state method, only the ratio of concentrations (or the time concentration integral) is needed between interacting compartments (e.g. fish and seawater) since it is assumed that equilibrium conditions exist. Although the nature of the parameter values used in each modeling method are different, the data needs in the final stage of converting an intake rate of a food-chain material (with a calculated concentration or measured dose rate associated with a nonfood-chain pathway) to dose are similar. For strict application of the transient method, time dependence should be built in. Alternatively, time-averaged values are generally adopted over a one-year period to be consistent with the ICRP dose limits time base.

Values chosen will depend on the type of dose calculation (individual or collective) and, for individual dose, will generally characterize those people most likely to be highly exposed through the pathway under analysis. IAEA Safety Series publication number 45 addresses this topic in detail [IAEA, 1978a].

4.5.1 Nature of the Released Radioactivity

To assess the affects of radioactivity released into the environment, it is important to know daily or annual quantities released, the radionuclide(s), and the physical and chemical forms of that radionuclide at the time of release. The behavior of plutonium, for example, differs according to chemical state or isotopic number [Beasley and Fowler, 1976]. Additionally, the discharge of some radionuclides in combination with certain nonradioactive wastes may result in complexation or adsorption before mixing with seawater - which could affect subsequent transport or availability to biological systems. It is also important to know the proposed method of release (e.g. continuous, pulsed, or a combination of both) since the method could help to determine whether the steady state or transient modeling approach for dose estimation is more appropriate.

4.5.2 Concentration Factors

When calculating dose, it is obvious that concentration factors (CF) or ratios (CR) for aquatic organisms are required. A recommended list of CF values is not readily available, however, because such values are only applicable to specific materials at any one time or place, and are subject to continuous revision. Thus, technically sound judgement should be exercised when applying apparently relevant data, from the scientific literature, to one disposal site. Note too that, if the radionuclide composition of the waste is known in detail, it may be possible to assess the expected CF values in different materials by stable element analyses obtained from the appropriate literature. Environmentally derived data is generally more applicable because of the varied use made of such terms as "concentration ratio" or "concentration factor" in experimental studies. Attention should also be paid to whether the seawater values used as a denominator in any CF are based on total water samples (water plus suspended material) or on filtrate water only, and the analytical method by which they were determined.

It is also necessary to consider the degree of accuracy required for parameter values relative to the calculations being made. A greater accuracy is clearly required for those materials included in pathway-type calculations used to ensure that individual dose limits are not exceeded. For calculating collective dose, greater latitude can be tolerated in view of the uncertainties in population size and exposure pathways.

4.5.3 Consumption Rates and Occupancy Factors

In applying the ICRP and national dose limits, it is necessary to definitely establish that the dose to the most highly exposed individuals be within those dose limits. In this case, identification of the working, eating and recreational habits of the local population and, in certain instances, a population at some distance from the site may be essential. For example, this might include estimates of seafood ingested and the area from which it came, hours spent on the beach at work or in recreation, and hours spent handling fishing gear on the beach or at sea. Consumption rates and occupancy factors, derived from surveys of the habits of the identified critical group, will be extremely variable. ICRP considers that these sources of variability may appropriately be dealt with by the consideration of dose limits to individuals in this group rather than of an overall dose to the whole group (population dose).

When important pathways cannot be fully identified, potential pathways suspected to be most important, such as consumption of any marine fish species or occupancy of the beach at low tide, should be selected. Following the start of disposal operations, radioactive materials in these assumed pathways should be monitored to provide the basis for their control.

5 THE BASIS FOR DEEP-OCEAN DISPOSAL

5.1 LONDON DUMPING CONVENTION RECOMMENDATIONS

In contrast to the disposal of liquid wastes to coastal waters, which is under national control, the dumping of packaged radioactive wastes in the deep ocean is specifically governed by the 1970 International Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, known as the London Dumping Convention [IAEA, 1974]. This Convention, which embraces all types of wastes, divides radioactive wastes into two categories: high-level (Annex I) wastes (HLW), which are considered unsuitable for dumping in the oceans; and other radioactive wastes (Annex II), which may be dumped under a national permit.

The Convention requires the IAEA to define radioactive material that is unsuitable for dumping and to make recommendations that should be considered when issuing national permits. The IAEA has prepared a provisional definition for Annex I waste, and has issued recommendations for disposal of Annex II wastes [IAEA, 1975]. This document was subsequently reviewed, revised, and adopted [IAEA, 1978d]. IAEA also has issued two key supporting documents - "The Oceanographic Basis" [1978b] and "The Radiological Basis" [1978c].

The IAEA definition of HLW took the form of specific activities, which were in turn based on release rate limits; i.e., upper values of release rates for various radionuclides, which, under a series of generally pessimistic pathway parameter values, might give rise to critical group exposure at the ICRP recommended dose limit to the public of 5 mSv (500 mrem). From these studies a revised definition was adopted [IAEA, 1978d), which states:

> For the purpose of Annex I to the Convention, high-level radioactive wastes or other high-level radioactive matter unsuitable for dumping at sea means any waste or other matter with an activity per unit gross mass (in tonnes) exceeding:
>
> (a) 1 Curie (Ci)/tonne (t) for alpha-emiiters but limited to 10^{-1} Ci/t for ^{226}Ra and supported ^{210}Po;
>
> (b) 10^{2} Ci/t for beta/gamma-emitters with half-lives of at least 0.5 years (excluding tritium) and beta/gamma-emitters of unknown half-lives; and,
>
> (c) 10^{6} Ci/t for tritium and beta/gamma-emitters with half-lives of less than 0.5 years.
>
> The above activity concentrations shall be averaged over a gross mass not exceeding 1000 tonnes.

In a footnote, the IAEA further defines the upper limits to ocean disposal. The definition is based on:

> (1) An assumed upper limit to the mass dumping rate of 100,000 t/year (yr) at a single dumping site: and,
>
> (2) Calculated upper limits to activity release rates from all (other than natural) sources of
>
> (a) 10^{5} Ci/yr for alpha-emitters but limited to 10^{4} Ci/yr for ^{226}Ra and supported ^{210}Po,
>
> (b) 10^{7} Ci/yr for beta/gamma-emitters with half-lives of at least 0.5 years (excluding tritium) and beta/gamma-emitters of unknown half-lives, and
>
> (c) 10^{11} Ci/yr for tritium and beta/gamma-emitters with half-lives of less than 0.5 years
>
> at a single dumping site and also, for alpha-emitters, when released to an ocean basin of not less than $10^{17} m^{3}$.

In 1985 the IAEA proposed a new definition of HLW that includes the irradiated reactor fuel and the liquid wastes from chemical porcessing of such fuel through the first solvent extraction cycle. The new definition also included other wastes having activity levels, per unit mass, exceeding:

> 5×10^{-5} Tera-Becquerels (TBq)/kilogram (kg) (1×10^{-3} Ci/kg) for alpha-emitters
>
> 2×10^{-2} TBq/kg (0.5 Ci/kg) for beta/gamma-emitters with half-lives greater than 1 year (excluding tritium); and,
>
> 3 TBq/kg (80 Ci/kg) for tritium and beta/gamma-emitters with half-lives of 1 year or less.

It is assumed in the definition that the following conditions are satisfied: activity concentrations specified shall be averaged over a gross mass not greater than 1000 tonnes; disposal takes place in an ocean-basin volume of $10^{17} m^3$; average water depth of a site is 4000m; rate of disposal is 10^8 kg/yr; disposal continues for 1000 years; and, annual dose to critical group members shall not exceed 1 mSv (100 mrem).

When the activity levels per unit mass given in the proposed definition are multiplied by the 10^8 kg/yr disposal rate, there is only about a 40 percent increase in the alpha-emitters allowed for disposal within a year. Also, there is no special reduction for radium-226 and polonium-210. The allowable limit for beta/gamma-emitters has increased 5-fold for those having a long half-life, excluding tritium, and decreased 10-fold for those with a short half-life, including tritium. The cut-off point between short and long half-life has been increased from 1/2 year to 1 year. Thus, in general, the basis for the revised (1985) definition of HLW is less restrictive than it was previously.

5.2 RADIOLOGICAL EVALUATION OF OCEAN DISPOSAL PRACTICES

5.2.1 Need for Modeling

The application of the basic IAEA site selection criteria [IAEA, 1978d] effectively minimizes the interaction of the radionuclides from the disposal material with man's activities. This poses a problem for both predicting the potential exposure of populations before the disposal operation and for confirming the estimated exposure following initiation of disposal operations. Additionally, the quantity of radionuclides relative to the size of the receiving environment, together with such factors as the degree of containment and the time scales involved in transport from the deep ocean, will most likely result in lower concentrations of potentially critical materials than can be measured.

If site-specific radiological assessments are required either before the operation is authorized or at intervals thereafter, the lack of confirming data makes validation of the dose exposure estimate from deep ocean disposal exceeding difficult. This is in contrast to coastal discharges, where validation of quite simple models can be conducted almost immediately following the initiation of the disposal operations. For the reasons given above, the assessment of deep ocean disposal will have to rely heavily on mathematical modeling techniques.

Thus, the use of models is central to the assessment of radiation doses from ocean disposal operations. Models provide the primary means of integrating and interpreting the information gained from other investigations.

5.2.2 Need for Research

To apply models, additional deep ocean scientific research and monitoring will be required to provide realistic parameters that correctly represent the major oceanographic and biological processes of the area in question. However, in view of the ICRP requirement for optimization of radiological protection, which involves considerations of costs and benefits, the research requirements must focus on the needs of the pathway analysis rather than on acquiring a detailed understanding of all the pysical and biological transport processes involved within the system.

It should be noted that the term "site specific" does not mean that all investigations must be undertaken at and in the vicinity of a proposed site. It is possible that the released radionuclides will be transported away from the site, especially the long-lived radionuclides whose half-lives exceed the residence times in the oceans. It is therefore necessary to obtain data on basin-wide circulations, as well as on mixing within the ocean basin. In addition, there is a need to examine those processes that occur on the margins of basins, which have the potential to mix or conduct water from the deep ocean into biologically productive zones.

Four distinct areas of research are required for a coordinated effort: physical transport processes, geochemistry, biological pathways anlysis, and model development.

5.3 NEA MODEL

The conceptual framework proposed by OECD/NEA in 1981 for evaluation of ocean disposal of radioactive wastes may be represented by a general model that we will call the "NEA Model."

The general form of the model is designed to aid in focusing research work and to assist in incorporating the results of research directly relevant to the preparation of a site-specific assessment of doses resulting from deep ocean disposal.

The general model envisaged for overall assessment purposes may be divided into three essentially distinct parts: release, marine, and pathway.

5.3.1 Release Model

This model describes the release of radionuclides from waste packages; its input is the rate of disposal of wastes, and its output is the release rate of various radionuclides from the packages to sea water or the sediments.

Past assessments have assumed that disposal of all radionuclides in the ocean are released instantaneously . This is probably a reasonable assumption (except for radionuclides with very short half-lives, e.g., those less than 10 years), and only a small elaboration of this part of the model would be appropriate. A suitable next step might be to use a single compartment model with a flushing time that depends on leach rate from the package, the radionuclide involved and its chemical form.

5.3.2 Marine Model

This model describes the dispersion and reconcentration of radionuclides throughout the marine environment. Its inputs are the release rates of the various radionuclides; its outputs are the time-dependent concentrations of the various radionuclides throughout the water column, in the sediments and in marine biota.

The model includes both geochemical (e.g., sediment/water interactions) and biological (e.g., scavenging and bioturbation) processes that can significantly affect the mass transport of radionuclides and, therefore, their overall concentrations in the marine environment. The calculated concentrations may be long-term averages, or they may include short-term fluctuations.

5.3.3 Pathway Model

This model describes the transport of radioactivity through food chains and other direct pathways to man (e.g. external exposure from sediments). Its input is the concentrations of radionuclides in edible marine organsims or other materials; its output is dose to man derived from the marine biota and other data.

The transports may be very small in mass transport terms (i.e., they do not significantly perturb the overall concentrations

of radioactivity), but they are crucial because they lead directly to man. The food chains may contain several links and may begin with the sedentary biota in either deep or shallow water. The concentrations of radionuclides in marine biota are calculated as part of the marine and pathway models and, thus, may be used to evaluate doses to both the organisms themselves and to man.

5.4 IAEA MODEL

The model developed by IAEA contains two parts:

(a) an oceanographic component that predicts the relationship between water concentration and release rate at a given ocean location, appropriate to potential or existing pathways [IAEA, 1987b]; and,

(b) a radiological component that uses the oceanographic component prediction results and combines that data with data on (assumed) environmental exposure pathways, and ICRP data, to relate human radionuclide intake rates to dose [IAEA, 1978c].

Since the IAEA model was first proposed, work has been carried out by an international Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) to provide advice for more suitable modeling techniques. GESAMP, comprised of representatives from IMO, FAO, UNESCO, WMO, WHO, IAEA, UN, and UNEP, studied various models which were thought to reasonably estimate doses to humans and biota from ocean disposal of radioactive waste [IAEA, 1983]. Based upon the GESAMP study, the IAEA summarized the models and parameter values thought to provide an approach to the definition of wastes that are unsuitable for disposal at sea, but that would not exceed recommended limits [IAEA, 1984]. The following sections discuss the original IAEA oceanographic and radiological components and modifications recommended in 1983 and 1984 by GESAMP and IAEA.

5.4.1 Oceanographic Component

5.4.1.1 Original Model

The model adopted by IAEA in 1978 was a hybrid of several fairly simple calculations. It was based partly on conclusions from previous (1976) work by Shepherd, but it also included considerations of possible effects from short-term processes and unusual events. These are particularly important insofar as they may "short-circuit" the steady and progressive deep ocean dispersion allowed for in Shepherd's model.

The Shephered model was developed to calculate theoretical equilibrium concentrations in the ocean, both at the surface and in vertical profile, from a continuous release of material on the bottom of the deep ocean. Application of the model showed that, except under rather extreme conditions, the given surface concentrations would not exceed the long-term average value that would arise if all the activity released were eventually distributed over the whole ocean. To overcome the possibility that some biological pathways might short-circuit the most obvious pathway to man (via dispersion of activity in the water mass and then via the consumption by man of fish from the surface layer of the continental shelf fishing grounds), the IAEA based its radiological assessment on bottom concentrations as if the (normally higher) bottom concentrations were present in the surface waters. A considerably slower vertical diffusivity (1 cm^2/s) was used, corresponding to a 4000-year vertical mixing time in the Shepherd model. It was also assumed that release would continue for a period of 40,000 years, which is comparable with the mean lifetime of plutonium-239.

These results provided concentrations applicable to an ocean volume of $10^{17} m^3$ (which is slightly smaller than the volume of the North Atlantic), irrespective of whether a single site or multiple sites are used for disposal. While Shepherd's model provided concentrations that could arise from long-term, large-scale dispersions from a disposal site, it did not include the possibility of physical, chemical or biological processes which, on time-scales of decades or less, might result in high concentrations in pathways leading to man. The IAEA oceanographic basis included estimates of such processes that could short-circuit long-term dispersion processes. These were based on the possibility of an advective, year-long plume reaching a fishing zone in deep water (e.g., a long-line fishery operation) and deep convective mixing of the type that has been observed down to about 2000 m in the Mediterranean Sea and in the polar deep-water formation regions. Calculations for these areas indicated that the short-term concentrations in a single site might be on the order of 10^{-6} Ci/m^3 per Ci/s released, and this value was therefore used as a more restrictive limit for single sites, except for the longer-lived nuclides, where the whole ocean limit becomes more restrictive.

The oceanographic model also describes disposal of waste in an area where the depths are normally greater than 4000 m. The assumption is usually made that radionuclides are continuously released as soon as the waste container reaches the ocean floor. However, any delay in the release of activity from the container once it has reached bottom, would actually reduce the activity that

could be released later because of the radioactive decay process, but that factor is not included in the model. The model also assumes a transit time of 3 years between any release from the container and arrival at the nearest possible place of interaction with man, and it also assumes that continuous release rates prevail.

The oceanographic basis, therefore, depends on fairly elementary calculations and makes use of several rather sweeping simplifications, principally that: (1) the concentrations appropriate for input to food chains in the surface waters are the (higher) concentrations of deep ocean waters; (2) although sediments are assumed to come to equilibrium with concentrations in water, no activity is actually depleted from the water column onto/into the sediments; and (3) there is an appreciable chance that fluctuations will dominate concentrations in a critical pathway.

These simplifying assumptions are intended to err on the side of conservatism (tending to overestimate dose). They are in general particularly pessimistic for short-lived radionuclides. For long-lived alpha-emitting wastes (such as plutonium-239), which are of particular concern, the degree of conservatism is not large, perhaps one or, at most, two orders of magnitude. The IAEA advisory group, who drew up the revised definition, attempted to estimate the possible degree of conservatism and it was stated when the radiological basis was published [IAEA, 1978c].

5.4.1.2 Revised Models

The newer, GESAMP, models are somewhat more sophisticated than the older Shepherd model. The philosophy, however, is still that the sophistication level of models should match what is actually known about natural processes. The following processes were considered by IAEA in 1984:

(a) movement and mixing of water within an ocean basin;

(b) radioactive decay or chemical degradation of contaminants;

(c) interaction of contaminats with particles of various types, both within the water column and on the sea bottom; and,

(d) mixing and diffusion, including that due to bioturbation, in and out of surface sediments.

The GESAMP stressed that the interactions of contaminants with inorganic and organic particles was important in the resulting activity contributed to water.

Three distance ranges from a source were considerd for calculation of activity concentrations: an extreme near-field, an intermediate near-field, and a far-field (see the Glossary section for definitions of these terms). The IAEA subsequently chose to use the models discussed in Appendices VI and VII of the GESAMP report [IAEA, 1983].

Model VII is a simple three-dimensional, ocean-diffusion model modified for finite source size and scavenging, whereas model VI is a one-dimensional model. Model VII should be used for most near-field distance ranges, unless it gives a smaller concentration than model VI. In such instances, model VI should be used. For the extreme near-field ranges, model VII should be used.

The Appendix VII (near-field and extreme near-field) model is summarized below. The radionuclide activity concentration (C) is given by:

$$C = C' \frac{Q}{\pi r_s \quad K_H K_V} \qquad (13)$$

where Q = the rate of release,

r_s = the radius of the source,

K_H, K_V = the horizontal and vertical eddy diffusivity in the water column, respectively,

C' = three complex functions of parameters which depend on the distance from the source.

Although the above model is intended primarily for near-field and extreme near-field calculations, it may also be used for some far-field calculations.

The Appendix VI model (far-field) is a simplified equilibrium version of a more complex model found in Appendix IX of the GESAMP report. This one-dimensional model includes diffusion, boundary and interior scavenging, and up/down water movement. The formula for radionuclide activity concentration (C) is given by:

$$C = ae^{r_1 z} + be^{r_2 z} \qquad (14)$$

where z = the vertical distance from the ocean bottom,

r_1, r_2 = the roots of a quadratic equation with coefficients being functions of various oceanographic parameters,

a,b = involved functions determined by the surface and bottom boundary conditions.

This model should be used for far-field calculations, and for near-field calculations when the results obtained are higher than the Appendix VII model.

5.4.2 Radiological Component

5.4.2.1 Original Model

For the radiological component, the IAEA [1978c] considered doses to critical groups via 12 pathways (see Table 2). Release-rate limits were derived by first calculating the dose to man in each pathway arising from a unit release rate. The method used for this calculation was conventional, combining an estimate of water concentration (from the oceanographic basis), a concentration factor, a consumption or occupancy rate, and the appropriate maximum permissible annual intake for ingestion or inhalant pathways (see Equation (7) for an example). The release rate which would lead to the ICRP dose limit was then derived. Additivity due to the possibility of exposure via more than one pathway was admitted in appropriate cases. The lowest of the release-rate limits for the different critical groups was then adopted as the overall release-rate limit for each radionuclide.

Some of the pathway parameter values adopted (e.g., seaweed consumption rate) were unrealistically high. Because of these maximizing assumptions and others in both the oceanographic and radiological components, the doses that would result from release rates at the limits calculated would, in practice, probably be very much less than the dose limit (e.g., 5 mSv (500 mrem)) for

TABLE 2

Pathways and mode of exposure in the IAEA radiological component [IAEA, 1978c]

Pathway	Mode of Exposure	Ingestion Rates (kg/yr) or Occupancy Rates (hr/yr)
Fish consumption	Ingestion	220
Crustacea consumption	Ingestion	37
Mollusc consumption	Ingestion	37
Seaweed consumption	Ingestion	110
Plankton consumption	Ingestion	11
Exposure from shore sediments	External irradiation	1000
Exposure from fishing equipment	External irradiation	300
Suspension of sediments	Inhalation	Continuous
Evaporation of sea water	Inhalation	Continuous
Desalinated water consumption	Ingestion	730
Sea salt consumption	Ingestion	1
Swimming	External irradiation	300

the whole body. This is confirmed in the case of radium-226, for example. The release-rate limit for radium-226 is of the same order as the natural production rate, while the natural dose rates from marine radium-226 are known to be much less than the ICRP dose limit [Mitchell and Shepherd, 1981].

It should be recognized that the mathematical modeling from which the current IAEA definition was derived is generic in nature. As such, it provides a means by which upper limit dose values may be estimated. It thus is more likely to lead to overestimates of dose than is one tailored to a specific location or set of conditions.

5.4.2.2 Revised Model

The primary changes to the radiological component of the original model were a reduction of the disposal period from 400,000 to 1,000 years, and changes in pathways and usage rates [IAEA, 1984].

The disposal period was changed to 1,000 years because it more nearly represents a fraction of well-recorded political and social history but only a minute fraction of geological history. Thus, it was thought that no major social or geological changes would have taken place over this time period to invalidate the pathway and usage assumptions.

The new pathway and usage assumptions (see Table 3) reflect concerns for future ocean activities, thus additional pathways (e.g., deep ocean mining activities, consumption of deep ocean fish, plankton consumption) were incorporated. The IAEA cautioned, however, that the latter two examples were hypothetical and should not be included in the calculation of disposal-rate limits with "careful consideration."

Release-rate limits were then derived, as previously, using the appropriate annual limit of intake and dose limit for internal and external exposures, respectively.

Except for mid-depth fishing and deep ocean mining activities, surface-water concentrations should be used for pathway calculations. A depth of 100 m was recommended for mid-depth fishing calculations. In addition, a sensitivity analysis should be performed to ascertain the importance of the various parameters and assumptions.

Dose to marine organisms should be calculated separately, including both internal and external doses from the spatial distribution of activity predicted by the models - including that from sediments. An assessment of the combination of effects from these doses on the ecological populations should then be made.

TABLE 3

Pathways and usages proposed by the IAEA in 1984

Pathway	Usage
ACTUAL	
Ingestion	
Surface fish	300 g/d
Mid-depth fish	300 g/d
Crustacean	100 g/d
Mollusc	100 g/d
Salt	3 g/d
Desalinated sea water	2 kg/d
Inhalation	
Suspended airborne sediments	23 m^3/d
Marine aerosols	23 m^3/d
External irradiation	
Boating	5000 hr/yr
Swimming	300 hr/yr
Beach sediments	2000 hr/yr
Deep-sea mining [a]	500 hr/yr
HYPOTHETICAL	
Ingestion	
Deep-sea fish	60 g/d
Plankton	3 g/d

[a] = also inhalation at 23 m^3/d

6 PROBLEMS IN THE ASSESSMENT OF OCEAN DISPOSAL FOR LLW

6.1 COLLECTIVE DOSE

In principle, the acceptable risk level associated with a practice such as ocean disposal should be examined through a cost/benefit analysis, based on the principle of optimization (ALARA). The detriments from the use of nuclear energy are best expressed a collective dose equivalent in order to permit a meaningful cost/benefit analysis to be performed. An optimization derived from a cost/benefit analysis should be translatable to guidance on allowable disposal rates, although resulting regulations may or may not define limitations on the collective committed dose.

At present, there are not specific U.S. regulations that address quantitative limitations on collective dose. Regulations to establish limitations for populations near light-water reactors were previously considered by the former Atomic Energy Commission (AEC), but never issued. The EPA regulations for geologic disposal of HLW (40 CFR 191) do contain limits on releases of radionuclides from a repository to the "accessible environment" that were derived from a consideration of the potential health effects to the population exposed to such a release. These health effects were considered to be proportional to collective dose in the EPA system of radiological assessment, which uses a linear, nonthreshold assumption approach.

Regardless of whether the best approach is to define the basic limits in terms of collective dose or nuclide releases, limits must be translated usable terms such as: allowable quantities of radionuclides per waste container, allowable annual quantity to be disposed, and/or total allowable quantity for disposal per site.

Granted that the calculation of some type of collective dose is warranted, the question remains as to what type should be calculated. It is possible to evaluate a "collective committed dose," wherein an acute or chronic external exposure and radionuclide intake are used to derive a total dose accrued over some time longer than the standard IAEA exposure period of 50 years.

It is also possible to evaluate the "collective dose commitment," accrued by one or several generations of people, resulting from long-term exposure to radionuclides in the environment, due to ocean disposals, over the entire exposure period. This is preferred because it provides an indication of the total potential detriment from disposal practices; not just the detriment possible from a single release or an annual release.

The collective dose commitment was used by the EPA in the calculation of its "environmental dose" and potential health effects from nuclear power facilities [EPA, 1974]. A further decision is needed on the length of time over which the population detriment should be evaluated: hundreds, thousands, or tens of thousands of years.

6.2 CHOICE OF A RADIOLOGICAL PROTECTION SYSTEM

Because a potential detriment to the U.S. (or to the world) population could arise from wastes disposed by more than one national authority, the systems of radiological assessment used by each nation should be compatible. Compatibility would allow for a common basis in summarizing and comparing potential effects from ocean disposals.

Several radiological guidance systems are available for calculating dose. The U.S., for example, previously used the equations in ICRP Publication #2 (1959) to first calculate organ or whole-body dose, and then to apply that data to a population group. The ICRP has developed improvements to its equations over the years, including multiple exponential radionuclide retention in the body and in individual organs (1968) and the task group lung model (1972).

The advantages of the system described in ICRP Publication 2 include simplicity of the dosimetry equations, as compared to those in ICRP Publication 26 (1977), and familiarity of those in the health physics profession with its application and interpretation. In addition, the maximum permissible concentrations (MPC) in air and water, derived within this system, were incorporated into U.S. regulations (10 CFR 20), and those of several other countries. This may be a disadvantage, however, as changes and improvements to metabolic parameter data that enter into dose calculations are not usually reflected in a convenient and timely manner in the above MPC values.

Collective doses can also be calculated using the radiological protection system defined in ICRP Publication #26 (1977), wherein an "effective" (weighted) whole-body dose is calculated. This system is based on a desire to limit total risk from a health detriment to all exposed body organs. It attempts to arrive at a single weighted value for an "effective" whole-body dose. One advantage of this system is that it obviates the need to compound potential health effects in each of several organs <u>after</u> the individual doses are calculated.

Considerable discussions have occurred on the problems of implementing the "ICRP-26" system. Those problems may not be apparent to those not readily familiar with internal dosimetry calculations and the metabolic parameters needed to use the "effective" whole-body dose concept [Thompson, 1979].

A principal problem is that uptake and elimination parameters for most radionuclides are available for only a few of the organs for which ICRP has assigned weighting fraction (W_T) values. In addition, such data are generally only available for those organs that tend to have the highest concentrations and for the whole body. Thus, it was to simply assume that those radionuclides not having deposition parameters are uniformly distributed throughout the remainder of the body mass. The mass, in this case, is the difference between 70 kg and the mass of those organs having a known deposition. This approach was considered to be the most feasible to use since the only other alternative seemed to be delaying implemention of the system for years until the data needed was identified and obtained.

Another disadvantage of the method in ICRP-26, at least in theory, is that the correct intake limits, which are based on a "weighted" whole-body dose for each nuclide, should not be calculated independently of the other nuclides present in a mixture. Since the formula involves terms for summing dose to the "next five highest" exposed organs, the sum of dose to all organs from all nuclides present should be calculated before it is determined which five organs receive the highest exposure.

In addition, the technique of spreading the "remaining" body activity over the "remaining" body mass tends to create effective dose factors that are heavily dependent on the few "known" organs (or is some cases a single critical organ). Thus, the major difference between radionuclide intake limits in ICRP-2 (1959) and ICRP-26 (1977) often result from revisions to metabolic parameters.

Potential differences from using different radiation protection systems to derive guidance for ocean disposal of radioactive wastes were compared for nine radionuclides of interest. The comparisons were actually made between maximum permissible rates of intake (MPRI) by ingestion, based on the methodology in ICRP-2 and variations thereof, and the annual limit of intake (ALI) methodology, derived from ICRP-26, as described in ICRP Publication 30 and supplements [1979a, 1979b, 1980a, 1981a, 1981b, 1982a, and 1982b]. The calculated MPRI and ALI values were expressed as those assumed to be appropriate for an individual adult member of the general public (i.e., one-tenth of the values for persons occupationally exposed for 168 hours/week). The results of this comparison are given in Table 4.

TABLE 4

Comparison of allowable intake by individual members of the public for selected radionuclides

	MPRI (Bq/yr)			ALI[i] (Bq/yr)	Ratio ALI/MPRI		
	ICRP-2[a]	10CRF20[a]	FRC Dose Limits[b]	ICRP-30	ICRP-2	10CRF20	FRC
^{3}H	3E8[c]	9E7[d]	3E8	3E8	1	3	1
^{60}Co	1.5E6	1.5E6	1.4E6	7E5	0.5	0.5	0.5
^{90}Sr	1E4	9E3	6E3	1E5	10	10	20
^{106}Ru	3E5	3E5	3E5	7E5	2	2	2
^{129}I	1E4	2E3[e]	8E3	2E4	2	10	3
^{137}Cs	6E5	6E5	3E5	4E5	0.7	0.7	1
^{144}Ce	3E6	3E5	3E5	8E5	3	3	3
^{226}Ra	3E2	9E2	8E1	7E3	20	8	80
^{239}Pu	2E5[f] 2E5[g]	2E5	7E4[f] 1E5[h]	2E4	0.1 (0.1)	0.1 (0.2)	0.3

(a) Calculated by multiplying most restrictive 168 hr MPC_w (public) by annual water intake

(b) Calculated by dividing the FRC dose limits for individual organs by the corresponding values of dose per unit intake [Hoenes and Soldat, 1977] with metabolic parameters from ICRP-19

(c) Calculated for whole body and Q = 1.0

(d) Based on body water and Q = 1.7

(e) MPC values for I in 10CFR20, based on a 2 g thryroid, 1 L/d fluid intake and 1.5 rem/yr (15 mSv/yr) annual dose limit

(f) Based on parameters in ICRP-2, with bone as critical organ

(g) Based on parameters in ICRP-19, with liver as critical organ

(h) Based on parameters in ICRP-19, with bone as critical organ

(i) Values listed are 1/10 of the most restrictive occupational ALI for the corresponding nuclide

As evidenced by the many footnotes in Table 4, the comparisons are not completely straightforward in all cases. Besides changing the basis for deriving values for ALI, as compared to former MPRI (MPC) values, there have been several changes in metabolic models and parameters, and in values for quality factors (Q). The results of those changes can be seen in the ALI/MPRI ratios that are the furthest from a value of 1.

The metabolic model for ^{90}Sr, for example, has changed since ICRP-2 from a single to a multiple exponential and then to a combination of a multiple exponential and a power function. In the process, the value of parameter (f_1), for uptake from the GI-LLI to blood, has been changed and the value of the biological half-life recommended for the single exponential model has also been changed. The ratio of ALI to the FRC's MPRI is 20, rather than 10, because the FRC dose limit is 1.5 rem/yr (15 mSv/yr) to bone - as opposed to a 3.0 rem/yr (30 mSv/yr) dose limit recommended in ICRP-2, and used as the basis for the MPC values in 10CFR20.

The ratios for ^{239}Pu are complicated by the change in the value of Q for alpha emitters from 10 in ICRP-2 to 20 in ICRP-30. In addition, the introduction of new values for distribution of Pu in the body (ICRP-19) changed the critical organ from bone to liver. For the ICRP-2 corrected values (see footnote [g], Table 4), this also meant a shift from a dose limit of 3 rem/yr (30 mSv/yr) to bone, to a dose limit of 1.5 rem/yr (15 mSv/Yr) to liver. The net result was that no significant difference appeared in the MPRI calculations via ICRP-2 methodology, whether based on the ICRP-2 parameters for bone or the ICRP-19 parameters for liver. The values listed for FRC dose limits for ^{239}Pu are lower than ICRP-2 and 10CFR20 because of the lower FRC bone limit of 1.5 rem/yr (15 mSv/yr).

The purpose of this discussion is to illustrate both the extreme complexity involved in the different systems of radiation protection, and the problems involved in comparing calculated doses or ALI in one system to those calculated in another system.

7 CONCLUSIONS

Until essential data on key oceanographic and biological processes are available, assessing the impact of ocean disposals will be based on applying simplistic and intentionally conservative assumptions. Accordingly, such assessments will provide upper-limit or pessimistic values instead of more realistic dose calculations. It will not be possible to determine more realistic values for radiation doses until the concentrations of radionuclides in critical pathways are determined. Nevertheless, existing models, which should continue to be improved as more data becomes available, are adequate for regulators to use in deciding whether disposals should be authorized because they can indicate whether maximum individual (critical group) exposure limits are likely to be exceeded.

To implement the ICRP optimization principle, the collective dose commitment (total dose to an exposed population) must be estimated. The method usually involves a step-by-step summation of a series of calculated committed doses. For long-lived radionuclides, the assumption of a well-mixed ocean requires that all or some of the global population be considered the exposed population. It is then relatively straightforward, given the total annual production of foods from all or portions of the oceans, to estimate the collective amount of activity ingested and to estimate dose. For shorter-lived nuclides, the oceanographic dispersion models do not presently provide sufficient spatial resolution to identify the geographical radionuclide distributions needed to successfuly identify an exposed population. Because any values derived are likely to be over-estimates, perhaps by several orders of magnitude, the models can only provide a less than precise assessment of collective dose commitments. Optimization will, therefore, still be qualitative, based on value judgements.

Newer models and information, however, are continuouly being developed by the international community to assess and compare land and ocean disposal of radioactive wastes, in general and on a site-specific basis. It is apparent that future site characterizations, for both land and ocean, will employ modeling techniques. Thus, the newly developed models must include data to define exposure pathways and calculate conservative, yet realistic, dose scenarios.

8 REFERENCES

Beasley, T.M. and Fowler, S.W.
Plutonium and Americium Uptake from Sediment by Polychaete Worms IAEA-187, IAEA, Monaco, 1976.

Finkelstein, L. and Carson, E.R.
Mathematical Modeling of Dynamic Biological Systems
Research Studies Press, Forrest Grove, OR, 1979.

Foster, R.F., et al.
"Evaluation of Human Radiation Exposure" in Radioactivity in the Marine Environment
National Academy of Sciences, Washington, DC, 1971.

Hicks, R.E.
"Mathematical Modeling: A BASIC Program to Simulate Real World Systems" in BYTE, vol. 6, no. 6
McGraw Hill, Peterborough, NH, June 1981.

Hoenes, G.R. and Soldat, J.K.
Age-Specific Radiation Dose Commitment Factors for a One-Year Chronic Intake NUREG-0172
US Nuclear Regulatory Commission, Washington, DC, 1977

International Atomic Energy Agency (IAEA)

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
INFCIRC/205, IAEA, Vienna, 1974

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. The Definition Required by Annex I, Paragraph 6, to the Convention, and the Recommendations Required by Annex II, Section D
INFCIRC/205/Add 1, IAEA, Vienna, 1975

Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems
Technical Report Series No. 172, IAEA, Vienna, 1976

Principles for Establishing Limits for the Release of Radioactive Materials into the Environment
Safety Series No. 45, IAEA, Vienna, 1978a

The Oceanographic Basis of the IAEA Revised Definition and Recommendations Concerning High-Level Radioactive Waste Unsuitable for Dumping at Sea
IAEA-TECDOC-210, IAEA, Vienna, 1978b

The Radiological Basis of the IAEA Revised Definition and Recommendations Concerning High-Level Radioactive Waste Unsuitable for Dumping at Sea
IAEA-TECDOC-211, IAEA, Vienna, 1978c

Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. The Definition Required by Annex I, Paragraph 6, to the Convention, and the Recommendations Required by Annex II, Section D
INFCIRC/205/Add 1/Rev 1, IAEA, Vienna, 1978d

Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems
Technical Report Series No. 190, IAEA, Vienna, 1979a

Application of the Dose Limitation System for Radiation Protection, Practical Implications
Proceedings Series, IAEA, Vienna, 1979b

An Oceanographic Model for the Dispersion of Wastes Disposed of in the Deepsea IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Pollution-GESAMP
Reports and Studies No. 19, IAEA, Vienna, 1983

The Oceanographic and Radiological Basis for the Definition of High-Level Wastes Unsuitable for Dumping at Sea
Safety Series No. 66, IAEA, Vienna, 1984

The Definition Required by Annex I, Paragraph 6 to the Convention, and the Recommendations Required by Annex II, Section D Final Draft
INFCIRC/205/Add 1/Rev 2, IAEA, Vienna, 1985

International Commission on Radiological Protection (ICRP)

Recommendations of the International Commission on Radiological Protection
ICRP Publication 2, Pergamon Press, Oxford, 1959

Recommendations of the International Commission on Radiological Protection
ICRP Publication 9, Pergamon Press, Oxford, 1965

Evaluation of Radiation Doses to Body Tissues from Internal Contamination due to Occupational Exposure
ICRP Publication 10, Pergamon Press, Oxford, 1968

The Metabolism of Compounds of Plutonium and Other Actinides
ICRP Publication 19, Pergamon Press, Oxford, 1972

Implications of Commission Recommendations that Doses be Kept as Low as Readily Achievable
ICRP Publication 22, Pergamon Press, Oxford, 1973

Recommendations of the International Commission on Radiological Protection
ICRP Publication 26, Pergamon Press, Oxford, 1977

Limits for Intakes of Radionuclides by Workers
ICRP Publication 30, Part I, Pergamon Press, NY, 1979a

Limits for Intakes of Radionuclides by Workers
ICRP Publication 30, Supplement to Part I, Pergamon Press, New York, 1979b

Limits for Intakes of Radionuclides by Workers
ICRP Publication 30, Part 2, Pergamon Press, NY, 1980a

Radionuclide Release into the Environment: Assessment of Doses to Man
ICRP Publication 29, Pergamon Press, New York, 1980b

Limits for Intakes of Radionuclides by Workers
ICRP Publication 30, Supplement to Part 2, Pergamon Press, New York, 1981a

Limits for Intakes of Radionuclides by Workers
ICRP Publication 30, Part 3 - including addendum to Parts 1 and 2, Pergamon Press, New York, 1981b

Limits for Intakes of Radionuclides by Workers
ICRP Publication 30, Supplement A to Part 3, Pergamon Press, New York, 1982a

Limits for Intakes of Radionuclides by Workers
ICRP Publication 30, Supplement B to Part 3 - including addendum to the supplements of Parts 1 and 2, Pergamon Press, New York, 1982b

Mitchell, N.T. and Shepherd, J.G.
"The UK Disposal of Solid Radioactive Waste into the Atlantic Ocean and its Environmental Impact" in Environmental Impact of Nuclear Power
British Nuclear Society, London, 1981

National Academy of Sciences/National Research Council (NAS/NRC)
Disposal of Low-Level Radioactive Waste into Pacific Coastal Waters
Publication 985, NAS/NRC, Washington, DC, 1962

National Council on Radiological Protection and Measurements (NCRP)
Review of the Current State of Radiation Protection Philosophy
Report No. 43, NCRP, Washington, DC, 1975

Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA)

Review of the Continued Suitability of the Dumping Site for Radioactive Waste in the North-East Atlantic
OECD/NEA, Paris, 1980

Agency Research and Environmental Surveillance Program Related to Sea Disposal of Radioactive Waste
OECD/NEA, Paris, 1981

Shepherd, J.G.
"A Simple Model for the Dispersion of Radioactive Wastes Dumped on the Deep Seabed" in Fish. Res. Tech. Report No. 29
Ministry of Agriculture, Food and Fisheries, UK, 1976

Thompson, R.C.
"A Consideration of the Wider Impact of Present Trends in Radiation Protection Systems" in Proceedings of a Topical Seminar on the Practical Limitations of the ICRP Recommendations (1977) and the Revised IAEA Basic Standards for Radiation Protection, pp. 629-637
IAEA, Vienna, March 5-9, 1979

US Code of Federal Regulations (CFR)

Title 10, Part 20 "Standards for Protection Against Radiation"

Title 40, Part 190 "Environmental Radiation Standards for Nuclear Power Operation"

Title 40, Part 191 "Environmental Standards for the Management and Disposal of Spent Nuclea Fuel, High-Level and Transuranic Radioactive Wastes"

US Environmental Protection Agency (EPA)
Environmental Radiation Dose Commitment: An Application to the Nuclear Power Industry
Report No. 520/4-73-002, EPA, Washington, DC, 1974

US Federal Radiation Council (FRC)

Background Material for the Development of Radiation Protection Standards
Staff Report No. 1, Washington, DC, 1960

Background Material for the Development of Radiation Protection Standards
Staff Report No. 2, Washington, DC, 1961

Webb, G.A.M.
"The Interaction Between Radiological Assessments and Research Requirements Related to Waste Disposal in the Deepsea" in Proceedings of the Third NEA Seminar on Marine Radioecology
NEA, Paris, 1980

Whicker, F.W. and Schultz, V.
Radioecology: Nuclear Energy and the Environment, Volume II
CRC Press, Inc., Boca Raton, FL, 1982

World Health Organization (WHO)
Health Implications of Nuclear Power Production
WHO Regional Publications, European Series No. 3, Copenhagen, 1978

9 GLOSSARY

This list provides some understanding of a selection of specialized terms used in this report.

Absorbed dose The amount of energy in the form of ionizing radiation absorbed in a unit mass of matter. The unit is the gray (Gy) = 1 joule/kg = 100 rad.

Activity A measure of the rate at which a material is emitting nuclear radiations; radioactivity usually given in terms of the number of nuclear disintegrations occurring in a given quantity of water over a period of time. The unit is the becquerel (Bq) = 1 disintegration per second = 27 picocuries.

Acute Pertains to short duration, intense effects. An acute dose would be that delivered over a short time period.

Adsorption The process of attachment onto particle surfaces.

Alpha radiation An emission of particles (helium nuclei) from a material undergoing nuclear transformation (decay); the particles have a mass number of 4 and a charge of +2.

Annual limit of intake (ALI) The limiting intake, in Bq, that a radiation worker might ingest without exceeding the effective dose limit of 50 mSv/yr (5 rem/yr).

Average individual An individual of the general public whose habits are average for the general population.

Becquerel (Bq) The international system (SI) unit of acitivity (1 Bq = 1 disintegration/second = 27 picocuries).

Benthic Pertains to biota living on or in the sea-bed.

Beta radiation Charged particles (electrons and positrons) emitted from the nucleus of atoms undergoing nuclear transformation (decay).

Biogenic Pertains to material originating from biological processes.

Biota Plant and animal life; the living things of a region.

Bioturbation Mixing of surface sediments by animal activity.

Chronic Pertains to long duration effects. A chronic dose would be that which is delivered over a long time period.

Collective dose equivalent The summation of the radiation dose (rem or Sv units) received by all individuals in a population group. It is principally applied to whole-body dose (units of man-rem, person-rem, or man-Sv. (Often referred to as "collective dose" or "population dose."

Committed dose equivalent The dose equivalent that will be accumulated over a 50 year period, representing a working lifetime, following intake of radioactive material.

Complexation The formation of a complex compound that is a type of compound in which a part of the molecular binding is of the coordinate type.

Concentration Factor Ratio of concentration of an element or radionuclide in an aquatic plant or animal to that of the surrounding water at equilibrium.

Critical group For a given source or group of sources, the group of members of the public whose exposure is reasonably homogenous and is typical of individuals receiving the highest dose.

Critical pathway(s) The pathway(s) through which the critical group receives their radiation dose. Those paths by which an individual or population receives the highest dose.

Curie (Ci) Unit of activity defined as the amount of a radioactive material that has an activity of 3.7×10^{10} disintegrations/second. Replaced by the new SI standard unit "becquerel" = 1 disintegration/second = 27 picocuries.

Decay chain The sequence of radioactive disintegrations in succession from one nuclide to another until a stable daughter is reached.

Detriment The mathematical expectation of harm which is determined by taking into account the severity of an effect and the probability of its occurrence.

Dose commitment The integrated dose that results from external exposure to, or an intake of, radioactive material when dose is evaluated from the beginning of exposure, or intake, to a later time (usually 50 years). Also used for the long-term integrated dose to which people are considered committed because radioactive material has been released to the environment.

Dose equivalent The product of absorbed dose, quality factors, dose distribution factor, and other necessary modifying factors. The unit is the sievert (Sv) = 100 rem.

Dose factor A number which relates a dose to an intake of a radionuclide over a time period, usually a year (e.g. rem/Ci).

Disposal The planned release or placement of waste in a manner that precludes recovery; dumping (as used by the IAEA and related international organizations).

Effective dose equivalent The sum of the product of mean dose equivalents for an organ (tissue) and their respective weighting factors as defined in ICRP-26.

Exposure The condition of being made subject to the action of radiation or agents (i.e. chemical exposure).

Extreme near-field That part of the benthic boundary layer in the vicinity of a release. It is essentially the region where the model for predicting near-field concentration breaks down due to the differences between the mixing rates in the benthic boundary layer and in the over-lying water. In practice, this region could be on the order of 100m thick and, perhaps, 30km in radius.

Far-field The remaining ocean, outside the near-field (IAEA, 1984).

Food chain A number of organisms forming a feeding series through which energy is passed.

Gamma radiation Electromagnetic energy emitted in the process of a nuclear transition.

General population Group or population not employed in occupations dealing with radioactive materials.

Generic Pertains to the general characteristics of a number of sites.

Gray (Gy) The international system (SI) unit for absorbed dose (1 Gy = 1 J/kg = 100 rad).

Half-life The time required for the activity of a radionuclide to decay to half its value; used as a measure of persistance of radioactive materials.

High-Level radioactive waste (HLW) In general, that nuclear waste that is made up of fission products and actinides resulting from reprocessing spent fuel from nuclear reactors. For purposes of ocean disposal, the definition of the London Dumping Convention (see page 19) applies.

Hydrospheric dispersion factor The ratio of the concentration of a material in water at a location to the release rate of the material into the water at the point of origin. This factor is usually derived from oceanographic models. Analagous to the atmospeheric dispersion factor (x/g) for estimating concentrations of a material in air downwind from its release point.

Individual member of the public Individual member of the general population; not a worker in a radiation industry.

Justification A concept of the ICRP in which no practice shall be adopted unless its introduction produces a positive net benefit. It is concerned with the original practice that generated waste (i.e. nuclear power, weapons, medical isotopes, etc.), but not the disposal of that waste.

Life-saving dose Dose from radioactive material judged to be acceptable to an individual involved in saving the lives of others.

Maximum individual (maximally exposed individual) An individual of the general public whose locations and habits tend to maximize his/her radiation dose, resulting in a dose higher than that received by other individuals in the general population (see critical group).

Maximum permissible concentration (MPC) The average concentration of a radionuclide in air (MPCa) or water (MPCw) to which a worker or member of the general population may be exposed continuously without exceeding an established standard of radiation dose limitation.

Maximum permissible rates of intake (MPRI) of a radionuclide The product of MPC and the annual consumption rate.

Model (mathematical) Representation of a physical, chemical, or biological system by mathematical expressions designed to aid in predicting the behavior of that system under specified conditions.

Near-field The region in the vicinity of the release in which the concentration is significantly greater than the ocean basin average. Its size is variable, but it is usually less than 10 per cent of the volume of the ocean basin, and may be very much less for very long-lived contaminants (IAEA, 1984).

Nonstochastic effects Those effects for which the severity of the effect varies with the dose.

Nuclide A specie of atom having a specific mass, atomic number and nuclear energy state.

Optimization A concept of the ICRP in which all exposures shall be kept as low as reasonably achievable (ALARA), economic and social factors being considered.

Other than high-level [radioactive waste] (OTHL) Nuclear waste that is not defined as high-level by the London Dumping Convention.

Quality factor (Q) The factor by which the absorbed dose (rad or Gy) is multiplied to obtain a quantity that expresses the effectiveness of the absorbed dose on a common scale for all ionizing radiation. In practice, Q is taken as unity for x-rays, gamma rays and beta particles (see Dose Equivalent).

Radiation (ionizing) Particles and electromagnetic energy emitted by nuclear transformations that are capable of producing ions when interacting with matter; gamma rays and alpha/beta particles are examples.

Radioactivity See Activity.

Radionuclide Any nuclide that is radioactive.

Radon daughters The members of the decay chain of radon-222, polonium-218, lead-214, bismuth-214, polonium-214, lead-210, bismuth-210, polonium-210 and lead-206 (stable).

Radwaste Waste that contains radioactive materials.

Release limit Number against which the concentration of radioactive material released to the environment from a facility or practice is controlled; usually derived from a dose limit for persons in the environment by considering the environmental behavior of the released material and habits of persons considered to be at risk.

Rem A unit of dose equivalent. The absorbed dose of ionizing radiation modified by the quality factor and, sometimes, other factors that result in the same biological effect as one rad of radiation; 1 rem = 1 rad for X or gamma radiation. It is the standard unit of dose equivalent in U.S. government regulations.

Residence time A time characteristic of the length of time spent by a substance in an oceanic system.

Scavenging The removal of chemical elements from the ocean by their incorporation into, or attachment onto, surfaces of particles; or by their ingestion by living organisms.

Sediment A solid material that is not in solution and is either distributed throughout the liquid (suspended) or has settled out of the liquid.

Sievert (Sv) The international system (SI) unit of dose equivalent (1 Sv = 100 rem). The standard unit for dose equivalent in European literature and regulations.

Site specific Pertains to the characteristics of one particular site.

Somatic effects Those effects of radiation that are expressed during the lifetime of an individual, but are not passed on to future generations.

Specific activity As used in this report, the ratio of concentration of an isotope in a media to the concentration of its stable analog in that same media. It is also the activity of an isotope per unit mass of compound, element or radionuclide. As used in the IAEA definition of HLW, it is the ratio of the activity of a material disposed into the sea to that of its mass in Bq/kg.

Stochastic effects Those effects for which the probability of occurrence, rather than severity, are regarded as a function of dose.

Terabecquerels (TBq) Equal to 10^{12} Bq.

Tonne (t) A metric ton (1 t = 1 megagram = 1000 kilograms).

Transuranic Pertains to elements having atomic numbers greater than that of uranium (# 92); all are radioactive and members of the actinide group.

Tritium Isotope of hydrogen with atomic mass number 3.

Weighted whole-body dose Effective dose equivalent to the body as a whole.

Weighting factor (W_T) A weighting factor representing the proportion of the stochastic risk resulting from tissue (T) to the total risk, when the whole-body is irradiated uniformly (ICRP-26).