ornl

OAK
RIDGE
NATIONAL
LABORATORY

UNION
CARBIDE

NUREG/CR-0717
ORNL/NUREG-59

A Dynamic Model of the Global Iodine Cycle for the Estimation of Dose to the World Population from Releases of Iodine-129 to the Environment

D. C. Kocher

POOR ORIGINAL

Prepared for the U.S. Nuclear Regulatory Commission
Division of Safeguards, Fuel Cycle,
and Environmental Research
Under Interagency Agreement DOE 40-550-75

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

1534 005

HEALTH AND SAFETY RESEARCH DIVISION

7912120 033

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161

1534 006

NUREG/CR-0717
ORNL/NUREG-59
Dist. Category RH

Contract No. W-7405-eng-26

Health and Safety Research Division

A DYNAMIC MODEL OF THE GLOBAL IODINE CYCLE FOR THE ESTIMATION OF DOSE TO THE WORLD POPULATION FROM RELEASES OF IODINE-129 TO THE ENVIRONMENT

D. C. Kocher

Manuscript Completed September 1979

Date Published November 1979

Prepared for the U.S. Nuclear Regulatory Commission
Division of Safeguards, Fuel Cycle, and Environmental Research
Under Interagency Agreement DOE 40-550-75
NRC FIN No. B0188

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

1534 007

CONTENTS

1534 008

CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF TABLES

A DYNAMIC MODEL OF THE GLOBAL IODINE CYCLE FOR THE ESTIMATION OF DOSE TO THE WORLD POPULATION FROM RELEASES OF IODINE-129 TO THE ENVIRONMENT

D. C. Kocher

ABSTRACT

A dynamic linear compartment model of the global iodine cycle has been developed for the purpose of estimating long-term doses and dose commitments to the world population from releases of ^{129}I to the environment. The environmental compartments assumed in the model comprise the atmosphere, hydrosphere, lithosphere, and terrestrial biosphere. The global transport of iodine is described by means of time-invariant fractional transfer rates between the environmental compartments. The fractional transfer rates for ^{129}I are determined primarily from available data on compartment inventories and fluxes for naturally occurring stable iodine and from data on the global hydrologic cycle. The dose to the world population is estimated from the calculated compartment inventories of ^{129}I, the known compartment inventories of stable iodine, a pathway analysis of the intake of iodine by a reference individual, dose conversion factors for inhalation and ingestion, and an estimate of the world population. For an assumed constant population of 12.21 billion beyond the year 2075, the estimated population dose commitment is 2×10^5 man-rem/Ci. The sensitivity of the calculated doses to variations in some of the parameters in the model for the global iodine cycle is investigated. A computer code written to calculate global compartment inventories and dose rates and population doses is described and documented.

I. INTRODUCTION

In assessing potential radiation doses to man from releases of radioactivity to the environment, it is important to consider not only doses to the population in the vicinity of the release point but also, for some radionuclides, potential doses and dose commitments to the entire world population. The radionuclides that, because of their mobility in the environment and relatively long half-life, are expected to result in a global radiological impact until removal from the environment by radioactive decay include ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I.* Only ^{14}C and ^{129}I have sufficiently long half-lives to affect the population for many generations. Worldwide population dose commitments from releases of ^{14}C from the nuclear power industry and atmospheric weapons testing have received particular attention on the basis of current knowledge of the global transport of carbon dioxide.[1]

The purpose of the work presented here is the development of a model to describe the global transport and cycling of iodine for the purpose of estimating potential worldwide radiological impacts from releases of ^{129}I to the environment. Since ^{129}I has a half-life of 15.7 million years,[2] any release results in a potential exposure to man essentially in perpetuity.

The primary releases of ^{129}I from the nuclear power industry are expected to occur during fuel reprocessing. Production rates from a reprocessing plant with a capacity of 1500 metric tons of fuel per year are estimated to be 50 Ci/year, but release rates at least a factor of 100 less should be realized with current technology.[3-5] Other significant sources of ^{129}I in the environment include atmospheric weapons testing and natural production from spontaneous fission of ^{238}U and from cosmic ray interactions with atmospheric xenon and other elements. The estimated release from weapons testing up to the year 1973 is 12 Ci.[4] The steady-state activity circulating in the environment from natural production is estimated to be 33 Ci.[6,7]

Worldwide population dose assessments for ^{129}I present a difficulty not encountered in assessments for ^{14}C, resulting from the likelihood that ^{129}I is transported into global circulation relatively slowly following a release. For ^{14}C, the direct application of a global-scale model to a release even from a point source is a valid procedure because the mean residence time in the atmosphere, which is approximately 6 years,[8] is sufficiently long to allow mixing throughout the global

---

*Many radionuclides in the actinide series will also persist in the environment for very long times following a release, but it is usually assumed for radiological assessment purposes that these nuclides are relatively immobile and, thus, have their primary impact only in the vicinity of the point of release.

atmosphere before most of the release is transferred for the first time to other parts of the environment. For ^{129}I, on the other hand, a release to the atmosphere is likely to be deposited on land or the oceans relatively rapidly before mixing throughout the global atmosphere is achieved; in addition, releases directly to a small area of the land surface or to surface waters can occur. The resulting localized distribution of ^{129}I on the earth's surface shortly after a release may not enter into circulation throughout the global environment for many years. Therefore, for some types of releases, it is probable that a realistic long-term worldwide population dose assessment for ^{129}I should consider a progression from local to regional to global-scale models, wherein the time scales over which the different models are applicable are determined by the mobility of iodine in the environment.

In this work, we have not explicitly considered the local and regional scale dose assessment and transport models that might be applied following a localized release of ^{129}I. Rather, we have concentrated on development of a model for the global transport and cycling of iodine, and we have assumed for illustrative purposes that the global model can be applied immediately following a release of ^{129}I for the purpose of estimating worldwide population doses and dose commitments; i.e., we have assumed that the released ^{129}I is uniformly dispersed on a global scale throughout some part of the environment. A reasonable elucidation of the global iodine cycle should help determine the need for the intermediary local and regional scale models for certain types of releases and the time periods following a release over which they are appropriate. Regardless of whether or not the local and regional scale models are needed, we note that dose assessments for the so-called "first-pass" exposures immediately following a release are still needed prior to application of the models for estimating long-term doses.

In this report, the global iodine cycle is described by means of a linear compartment model. In this model, the global environment is divided into different compartments comprising the atmosphere, hydrosphere, lithosphere, and terrestrial biosphere. The parameters of the model descr the transport of ^{129}I between the different global compartmen wing a release are determined as much as possible by an analysis of data on compartment inventories and fluxes between compartments for naturally occurring stable iodine. The model then gives the inventories of ^{129}I as a function of time in the different compartments for a specified release to the environment. Given the estimated inventories of ^{129}I and stable iodine in the different compartments, worldwide population doses and dose commitments are calculated from a model for the intake of iodine by a reference individual, factors to convert intake by an individual to dose, and an estimate of the world population at future times.

This report also contains a description and documentation of the computer code written to implement the linear compartment model of the global iodine cycle and to calculate individual and population doses and dose commitments from releases of ^{129}I to the environment. Results of calculations for a hypothetical release of 1 Ci to various environmental compartments are presented and compared, and the sensitivity of the doses to variations in some of the parameters for the global iodine cycle is investigated.

2. DEFINITION OF A LINEAR COMPARTMENT MODEL

The linear compartment model used in this work to describe the global iodine cycle is illustrated by means of the general two-compartment model shown in Fig. 1. The quantity Y_i, i = 1 or 2, denotes the inventory or quantity of material (assumed to be nonradioactive) in the ith compartment at time t, and I_i^Y is the flux (quantity per unit time) into the ith compartment at time t from a particular source, either natural or anthropogenic, outside the environmental system. The arrows connecting the compartments represent the possible pathways for transport of material between the two. The quantity $k_{i,j}$ is defined as the fractional transfer rate, or the probability per unit time, for transport of material from the ith to the jth compartment. The reciprocal of the fractional transfer rate is defined as the mean residence time for transfer from the ith to the jth compartment.

In this model, we assume that the environmental compartments are well mixed at any time — i.e., any flux of material to a compartment is uniformly and instantaneously distributed throughout the compartment — so that any material in a given compartment has an equal probability of transport to another compartment. If we define $F_{i,j}^Y$ as the flux of stable material from the ith to the jth compartment at time t, the fluxes, fractional transfer rates, and compartment inventories at any time are related by

$$F_{i,j}^Y = k_{i,j} Y_i \quad . \tag{1}$$

The compartment model is thus linear because the fluxes are proportional to the inventories in the compartments. In general, the fractional transfer rates $k_{i,j}$ may be time dependent; however, we assume that they are constants, in which case the model is also time invariant.

The equations describing the linear compartment model are obtained from the requirement that the time rate of change of the inventory in a given compartment is equal to the input flux minus the rate of removal. Therefore, from Fig. 1 and Eq. 1, the inventory of a stable material in

ORNL–DWG 79-13045

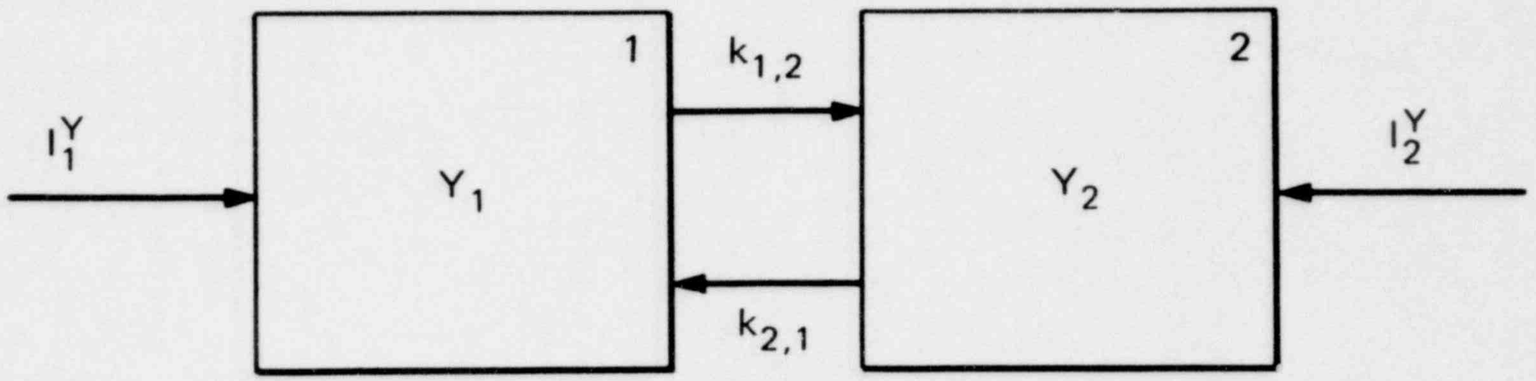

Fig. 1. Diagram of a general, linear two-compartment model for an environmental system. The quantity Y_i is the inventory in the ith compartment, I_i^Y is the flux into the ith compartment from sources outside the system, and $k_{i,j}$ is the fractional transfer rate for transport from the ith to the jth compartment.

the *i*th compartment as a function of time obeys the first-order ordinary differential equation

$$\mathrm{d}Y_i(t)/\mathrm{d}t = I_i^Y(t) + \sum_{j\neq i} k_{j,i} Y_j(t) - \Big(\sum_{j\neq i} k_{i,j}\Big) Y_i(t) \quad . \qquad (2)$$

For a radioactive material, which we denote by X, the model equation is

$$\mathrm{d}X_i(t)/\mathrm{d}t = I_i^X(t) + \sum_{j\neq i} k_{j,i} X_j(t) - \Big(\sum_{j\neq i} k_{i,j} + \lambda\Big) X_i(t) \quad , \qquad (3)$$

where λ is the radioactive decay constant. Writing Eq. 2 or 3 for each compartment for a stable or radioactive material then gives a system of equations that can be integrated to obtain the compartment inventories as a function of time, provided the fractional transfer rates are known.

The definitions of the parameters used in the linear compartment model are summarized in Table 1.

Table 1. Definition of parameters in a linear compartment model[a]

Parameter	Units	Definition
Y_i	Mass	Quantity of stable material in ith compartment
X_i	Mass	Quantity of radioactive material in ith compartment
I_i^Y	Mass/time	Flux of stable material into ith compartment from source outside compartmental system
I_i^X	Mass/time	Flux of radioactive material into ith compartment from source outside compartmental system
$F_{i,j}^Y$	Mass/time	Flux of stable material from ith to jth compartment
$F_{i,j}^X$	Mass/time	Flux of radioactive material from ith to jth compartment
$k_{i,j}$	Time^{-1}	Fractional transfer rate for stable or radioactive material from ith to jth compartment
$\tau_{i,j}$	Time	Mean residence time for transfer of stable or radioactive material from ith to jth compartment (= $1/k_{i,j}$)

[a] Parameters are discussed in Sect. 2.

3. PREVIOUS DESCRIPTIONS OF THE GLOBAL IODINE CYCLE AND ^{129}I POPULATION DOSE ESTIMATES

The abundance and transport of iodine in the environment has been of interest for many years[9-12] due to the critical importance of iodine as a trace constituent in the human diet. A schematic model of the global inventories and fluxes for naturally occurring stable iodine proposed by Miyake and Tsunogai[13] is shown in Fig. 2. Although we do not use this model explicitly in the present work, aspects of the model are important for the global model developed in Sect. 4 of this report. The model in Fig. 2 implies that the hydrosphere is the primary source of the iodine circulating in the global environment, even though the inventory in the lithosphere is much greater. This conclusion also follows from the observation that the concentration of iodine in soil is about an order of magnitude larger than the concentration in rock from which soil is derived.[11] The model suggests that the flux of iodine into the atmosphere via volcanic activity, combustion of fossil fuels, and transpiration from the terrestrial biosphere is negligible compared with evaporation from the ocean. The evaporation rate from the hydrosphere to the atmosphere assumed in the model is based on results of laboratory measurements[13] which showed that iodine escapes from the ocean surface by photochemical oxidation of iodide ions when exposed to solar ultraviolet light. This is an important result, because it rules out physical removal of iodine by evaporating water as the primary mechanism for transfer from the hydrosphere to the atmosphere. From data on the evaporation rate of seawater[14] and the concentration of iodine in the ocean,[12] one can show that the assumption of physical removal of iodine by evaporating water would result in a flux into the atmosphere more than a factor of 30 larger than the value given in Fig. 2. Finally, the inventory of iodine in the atmosphere assumed in Fig. 2 implies an atmospheric mean residence time of 2 years, a value considerably longer than expected for aerosols or reactive gases.[15] If this value were correct, it would be reasonable to assume that a release of ^{129}I to the atmosphere becomes mixed throughout the global atmosphere before deposition onto the land and oceans occurs. We note, however, ORNL–DWG 79-13047

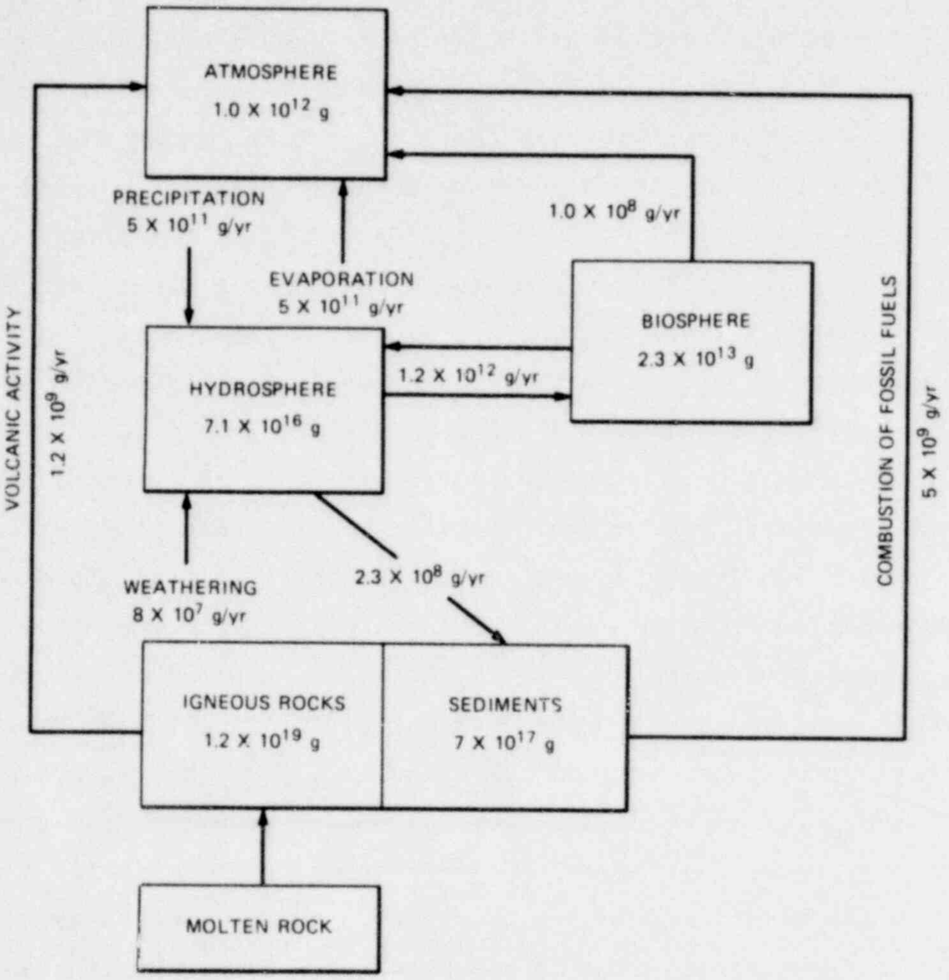

Fig. 2. Global inventories and fluxes for naturally occurring stable iodine proposed by Miyake and Tsunogai. Source: Y. Miyake and S. Tsunogai, "Evaporation of Iodine from the Ocean," *J. Geophys. Res.* 68, 3989 (1963).

1534 021

that the measured iodine concentration in the atmosphere on which the inventory in Fig. 2 is based[13] is more than an order of magnitude larger than values obtained from other extensive measurements.[12,16] The mean residence time for iodine in the atmosphere is discussed further in Sect. 4.5.1.

The specific activity method[17] has often been used to estimate potential radiation doses to man during chronic releases of ^{129}I to the atmosphere.[18-21] These dose estimates are based on the assumption that the specific activity (i.e., the activity of ^{129}I per gram of iodine) in the human thyroid at any time is the same as the value in the atmosphere. This method has the advantage that a detailed consideration of the transport of ^{129}I between the dispersing medium and man is avoided. However, the method does not account for the dynamic behavior in the environment of ^{129}I released to the atmosphere; thus, it does not account for possible time delays between a release to the atmosphere and deposition in the human thyroid, and it is not appropriate for estimating doses during the time period after the end of the release but prior to the time the released ^{129}I reaches equilibrium with the stable iodine circulating in the environment.* The model developed in Sect. 4 of this report indicates that thousands of years may elapse before a release of ^{129}I reaches equilibrium in that part of the environment to which man is exposed.

Two calculations of ^{129}I dose to the world population using a linear compartment model to simulate the global transport of iodine have recently been reported.[22,23] Kelly *et al.*[22] estimate doses by assuming that all of the released ^{129}I is dispersed immediately into the surface waters of the ocean. Global circulation is confined to ocean compartments, and fractional transfer rates are estimated from a model for the global tritium cycle. Population doses are calculated by the specific activity method. These calculations have the disadvantage that the global transport of ^{129}I is not based on known properties of the global transport of stable iodine and, as we have mentioned above, the specific activity method is not appropriate during the time period of perhaps

---

*At equilibrium, the specific activity resulting from a given release is the same throughout the global environment.

thousands of years before the ^{129}I released to the ocean reaches equilibrium with the stable iodine circulating in man's exposure environment. Bergman *et al.*[23] employ a model with atmosphere, land, ocean mixed layer, and deep ocean compartments. The model appears to be based largely on the global iodine cycle of Miyake and Tsunogai (Fig. 2),[13] but the fractional transfer rates assumed for the calculations are not given. Dose estimates of Bergman *et al.* are compared with those obtained in the present work in Sect. 7.1.

4. PROPOSED MODEL FOR THE GLOBAL IODINE CYCLE

In this section, a linear compartment model for the global iodine cycle is developed. In Sect. 4.1, the environmental compartments and transport pathways assumed in the model are defined. In Sect. 4.2, data on concentrations of iodine in the environment are examined which are used to calculate compartment inventories and fluxes between compartments for naturally occurring stable iodine. These results along with other data and assumptions are used to estimate the fractional transfer rates for the global iodine cycle in Sect. 4.3. The model equations for calculating ^{129}I inventories in the environmental compartments as a function of time after a release are summarized in Sect. 4.4. The implications of the global model are discussed in Sect. 4.5, particularly the extent to which the fractional transfer rates indicate a need for local and regional scale models for time periods immediately following a release.

4.1 Environmental Compartments and Transport Pathways for the Global Iodine Cycle

A diagram of the environmental compartments and transfer pathways for the proposed model of the global iodine cycle is shown in Fig. 3. The environmental compartments assumed in the model comprise the atmosphere, hydrosphere, lithosphere, and terrestrial biosphere. Each compartment is identified by a numerical label given in the corresponding box in the diagram. The quantities $k_{i,j}$ denote the fractional transfer rates as previously defined in Table 1.

Because the iodine concentration in the atmosphere over the ocean is significantly greater than over land,[16] the atmosphere is divided into separate compartments over the ocean and land. We assume that the two atmosphere compartments mutually exchange iodine. At steady state* the flux of iodine from the ocean atmosphere to the land atmosphere must be greater than the flux in the opposite direction, since the ocean is the primary source of iodine on land. The ocean and land atmospheres

---

*At steady state, the inventories of stable iodine in all environmental compartments are constant with time.

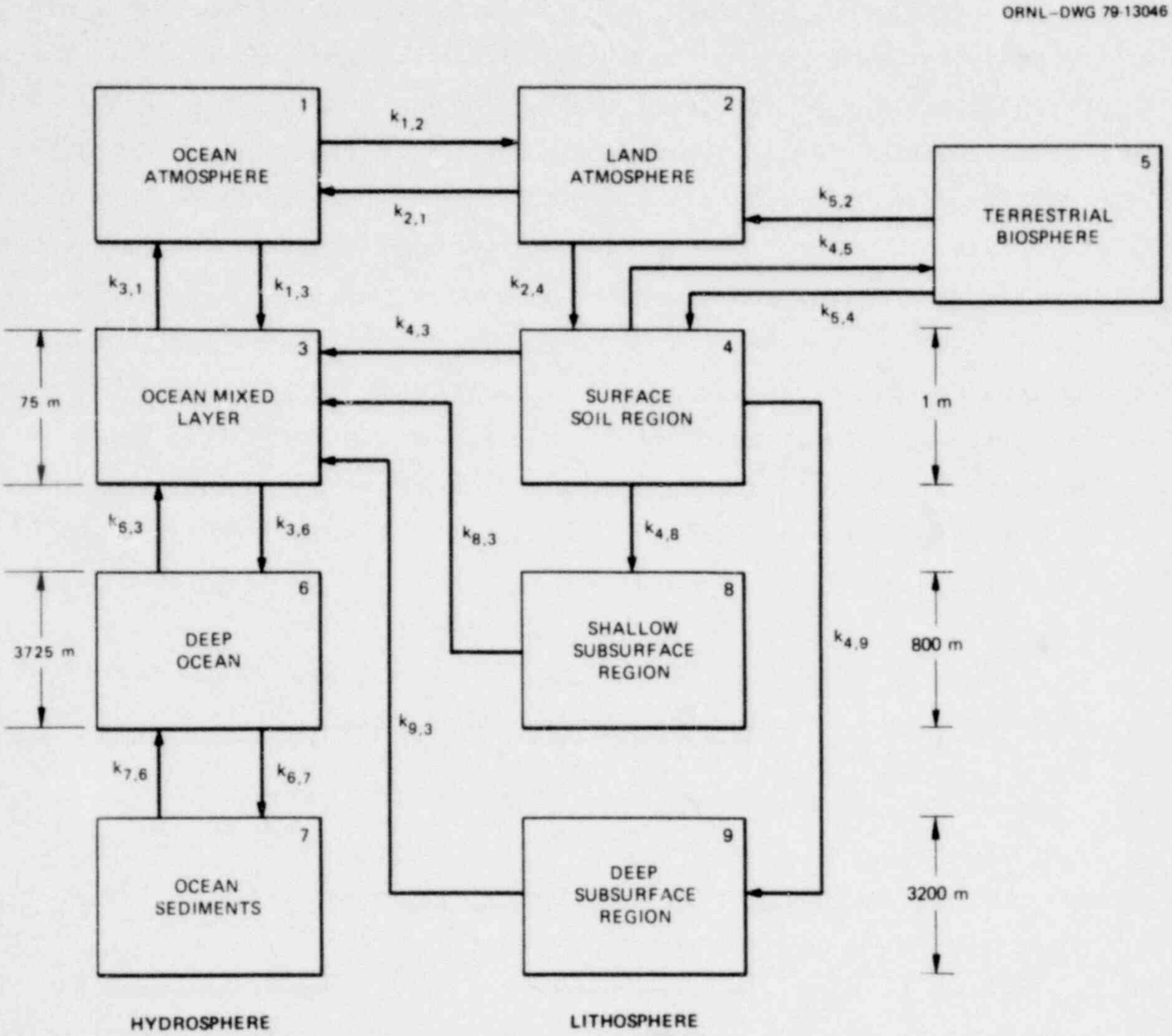

Fig. 3. Environmental compartments and transfer pathways for proposed model of the global iodine cycle (see Sect. 4.1). The quantity $k_{i,j}$ denotes the fractional transfer rate for transport from the ith to the jth compartment. The assumed depths of the ocean and land compartments are indicated.

deposit iodine onto the ocean mixed layer and surface soil region, respectively.

Iodine is assumed to enter the atmosphere by evaporation from the ocean mixed layer and by gaseous releases from the terrestrial biosphere. We have assumed that evaporation from the surface soil region to the atmosphere is negligible; this assumption is justified in Sect. 4.3.4.

The ocean is divided into a surface mixed layer with an assumed depth of 75 m and a deep ocean of depth 3725 m. Iodine is exchanged between these two compartments, and iodine in the deep ocean also exchanges with ocean sediments.

Iodine in the surface soil region, assumed to be 1 m in depth, is removed either by (1) incorporation into the terrestrial biosphere and subsequent release to the atmosphere, (2) runoff into surface waters and thence into the ocean mixed layer, or (3) infiltration into the lithosphere below the surface. The subsurface lithosphere is divided into a shallow subsurface region of depth assumed to be 800 m and a deep subsurface region between 800 and 4000 m. This subdivision, which is somewhat arbitrary, is based on the availability of separate data on groundwater inventories and circulation rates for the shallow and deep subsurface regions,[14,24] and on the assumption that iodine which has infiltrated below the surface soil region is transported from the two subsurface regions into the ocean mixed layer by groundwater flow.

Although a terrestrial biosphere compartment is included in the model, it will affect the iodine inventories in other compartments only if the input flux from the surface soil region is significant and if most of the compartment inventory is transferred to the atmosphere. Otherwise, the terrestrial biosphere acts only as a shunt for a brief time period for a small fraction of the iodine in the surface soil region, in which case the compartment could be neglected in the model.

4.2 Data for Determining Global Inventories and Fluxes for Naturally Occurring Stable Iodine

We assume in this work that the fractional transfer rates between environmental compartments for the transport of ^{129}I are the same as the values for the global circulation of naturally occurring stable iodine. In this section, data on concentrations of stable iodine in the environment and other data relevant to the determination of fractional transfer rates for the global iodine cycle are presented.

A summary of selected data on concentrations and transport of iodine throughout the global environment is presented in Table 2. With each set of data, an adopted value used in Sect. 4.3 to estimate fractional transfer rates for the global iodine cycle is indicated. Table 3 gives adopted values of other parameters used in the calculations in Sect. 4.3. Many of these parameters pertain to the global hydrologic cycle, since the transport of iodine in some parts of the proposed global cycle in Fig. 3 results directly from the global circulation of water.

Although iodine is ubiquitous in the environment, the data in Table 2 show that it normally occurs only in concentrations between a few parts per billion (ppb) and a few parts per million (ppm). Thus, it is not surprising that the concentration within a given environmental compartment can vary widely with geographical location. This is particularly the case for measurements associated with the land portion of the earth's surface, i.e., concentrations in the land atmosphere, rainfall on land, river water, and soil. Normally, these concentrations are considerably greater near the ocean than far inland, which is the expected result when the ocean is the primary source of globally circulating iodine and atmospheric iodine is deposited relatively rapidly on the earth's surface. However, the absence of recent glaciation or the presence of deep mineral springs rich in iodine can produce anomalously large concentrations in soil and river water far from the ocean.[11] Man's industrial activities can also have significant effects on local and regional concentrations of iodine, particularly in the

1534 027

Table 2. Selected measurements on iodine in the environment

Location	Concentration	References[a]
Atmosphere	0.2–1200 ng/m^3	1–9
Land	2–14 ng/m^3 [A]5 ng/m^3	2
Ocean	17–52 ng/m^3 [A]30 ng/m^3	2
Rainwater	0.4–15 µg/liter[b]	4, 10–14
On land	[A]1 µg/liter	
On oceans	1–15 µg/liter [A]6 µg/liter	4
River water	0.1–18 µg/liter [A]3 µg/liter	1, 10, 11, 15, 16
Seawater	40–65 µg/liter	15, 17
Ocean mixed layer	[A]50 µg/liter	
Deep ocean	[A]60 µg/liter	
Ocean sediments[c]	40–250 ppm [A]100 ppm	15
Soil	0.6–18 ppm [A]5 ppm	11, 15
Rock	[A]0.5 ppm	18
Terrestrial biosphere	[A]0.1 ppm	19
Fraction of iodine in terrestrial biosphere released to atmosphere	[A]0.1	20, 21

[A] Adopted value.

[a] References appear on the following two pages.

[b] 1 µg/liter in water is equivalent to 1 ppb.

[c] Recent ocean sediments; range of values does not include sedimentary rock in the lithosphere.

References for Table 2

---

1. T. von Fellenberg, "Das Vorkommen, der Kreislauf und der Stoffwechsel des Jods," *Ergeb. Physiol.* 25, 175 (1926).

2. F. B. Brauer, H. G. Rieck, Jr., and R. L. Hooper, "Particulate and Gaseous Atmospheric Iodine Concentrations," p. 351 in *Physical Behaviour of Radioactive Contaminants in the Atmosphere*, International Atomic Energy Agency, Vienna, 1974.

3. R. A. Duce, J. T. Wasson, J. W. Winchester, and F. Burns, "Atmospheric Iodine, Bromine, and Chlorine," *J. Geophys. Res.* 68, 3943 (1963).

4. R. A. Duce, J. W. Winchester, and T. W. Van Nahl, "Iodine, Bromine, and Chlorine in the Hawaiian Marine Atmosphere," *J. Geophys. Res.* 70, 1775 (1965).

5. R. Heindryckx and R. Dams, "Continental, Marine, and Anthropogenic Contributions to the Inorganic Composition of the Aerosol of an Industrial Zone," *J. Radioanal. Chem.* 19, 339 (1974).

6. R. B. Platt, J. M. Palms, H. L. Ragsdale, D. J. Shure, P. G. Mayer, and J. A. Mohrbacher, "Empirical Benefits Derived from an Ecosystem Approach to Environmental Monitoring of a Nuclear Fuel Reprocessing Plant," p. 673 in *Environmental Behaviour of Radionuclides Released in the Nuclear Industry*, International Atomic Energy Agency, Vienna, 1973.

7. R. C. McFarland, D. M. Walker, and M. E. McLain, Jr., "Determination of Atmospheric Concentrations of Stable Iodine," *IEEE Trans. Nucl. Sci.* 21, 503 (1974).

8. H. Vogg and R. Haertel, "Experience in the Analysis of Atmospheric Aerosols of the Karlsruhe Nuclear Research Center," *J. Radioanal. Chem.* 37, 857 (1977).

9. L. Salmon, D. H. F. Atkins, E. M. R. Fischer, and D. V. Law, "Retrospective Analysis of Air Samples in the U.K. 1957-1974," *J. Radioanal. Chem.* 37, 867 (1977).

10. J. F. McLendon, *Iodine and the Incidence of Goiter*, University of Minnesota-Oxford Press, 1939.

11. V. M. Goldschmidt, *Geochemistry*, Oxford University Press, London, 1954.

12. R. A. Duce, J. W. Winchester, and T. W. Van Nahl, "Iodine, Bromine, and Chlorine in Winter Aerosols and Snow from Barrow, Alaska," *Tellus* 18, 238 (1966).

13. K. Sugawara, "Migration of the Elements Through Phases of the Hydrosphere and Atmosphere," in *Chemistry of the Earth's Crust*, vol. 2, ed. by A. P. Vinogradov, Acad. Sci. U.S.S.R.; Israel Program for Scientific Translations, Jerusalem, 1967.

References for Table 2

---

14. J. B. Luten, "The Determination of Some Trace Elements in Rainwater by Neutron Activation Analysis," *J. Radioanal. Chem.* 37, 897 (1977).

15. B. Brehler and R. Fuge, "Iodine," vol. II/3, Chap. 53 in *Handbook of Geochemistry*, ed. by K. H. Wedepohl, Springer-Verlag, Berlin, 1974.

16. E. J. Underwood, *Trace Elements in Human and Animal Nutrition*, 3d ed., Academic Press, New York, 1971.

17. R. A. Barkley and T. G. Thompson, "The Total Iodine and Iodate-Iodine Content of Sea Water," *Deep-Sea Res.* 7, 24 (1960).

18. B. Mason, *Principles of Geochemistry*, 3d ed., John Wiley & Sons, New York, 1966.

19. A. P. Vinogradov, *The Elementary Chemical Composition of Marine Organisms*, Sears Foundation for Marine Research, Yale University, New Haven, Conn., 1953.

20. A. Saas and A. Grauby, *Degagement Gazeux d'Iode Radioactif a Partir de Vegetaux en Decomposition. I. Degezage Apres Absorption Foliare et Absorption Racinaire*, CEA-N-1846, Centre d'Etudes Nucleaires de Cadarache, 1975.

21. A. Saas and A. Grauby, *Degagement Gazeux d'Iode Radioactif a Partir de Vegetaux en Decomposition. II. Formes Chimiques de l'Iode Provenant des Vegetaux en Decomposition*, CEA-N-1881, Centre d'Etudes Nucleaires de Cadarche, 1976.

Table 3. Miscellaneous data relevant to the global iodine cycle

Parameter	Value	Reference
River water flow	3.23×10^{19} g/year	1
Precipitation rate		2
On land	1×10^{20} g/year	
On oceans	3.2×10^{20} g/year	
Fraction of river flow		2
From surface runoff	0.83	
From shallow groundwater flow	0.17	
From deep groundwater flow	0.0033	
Earth's surface area		3
Land	1.49×10^{14} m^2	
Oceans	3.61×10^{14} m^2	
Ocean sedimentation rate	2×10^{-4} cm/year	4
Terrestrial biomass	1×10^{18} g	5
Net primary production rate	5.2×10^{16} g/year	5

References:

1. D. A. Livingstone, "Chemical Composition of Rivers and Lakes," in *Data of Geochemistry*, 6th ed., Geological Survey Professional Paper 440-G, U.S. Department of the Interior, 1963.

2. *The Water Encyclopedia*, ed. by D. K. Todd, Water Information Center, Port Washington, N.Y., 1970.

3. A. Heydemann, "Tables," vol. I, Chap. 12 in *Handbook of Geochemistry*, ed. by K. H. Wedepohl, Springer-Verlag, Berlin, 1974.

4. H. U. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans*, Prentice-Hall, New York, 1942.

5. J. S. Olson, "Productivity of Forest Ecosystems," p. 33 in *Productivity of World Ecosystems*, ed. by D. E. Reichle, J. F. Franklin, and D. W. Goodell, National Academy of Sciences, Washington, D.C., 1975.

atmosphere.[12,25,26] These observations lead to the conclusion that there is likely to be considerable uncertainty in estimating worldwide average values for iodine concentrations in some of the environmental compartments from measurements taken at a limited number of locations.

Except for the iodine concentrations in the land atmosphere and in rainfall on land, the adopted values given in Table 2 are our estimated average values based on the data available in the literature. The concentration in the ocean atmosphere is based on data collected on oceanographic cruises.[16] The value for rainfall on the ocean is based on measurements near sea level in Hawaii.[27] The adopted concentration in river water is within the range of values suggested by Goldschmidt.[11] The adopted concentration in soil is based on data cited by Brehler and Fuge,[12] which is mostly from the Soviet Union, and is a factor of 2.5 larger than an estimate based on soil samples in western Europe.[11]

Because reliable values of average iodine concentrations in the land atmosphere and in rainfall on land are particularly difficult to determine from the wide range of measured values, we have obtained the adopted values indirectly by requiring a balance between the flux of iodine from the land atmosphere onto the land surface via deposition and the flux from the lithosphere into the ocean via river flow since, presumably, the inventory of circulating iodine in the lithosphere is at steady state.[*] As noted previously by Bolin,[28] the measured concentrations of iodine in rainfall on land and in river water combined with the known precipitation rate on land and river flow into the ocean are consistent with the conclusion that the *net* transfer of iodine from the atmosphere to land occurs primarily by the process of wet deposition and that no significant net dry deposition occurs. According to Bolin,[28] dry deposition of iodine is a process occurring near the ground surface in which iodine is deposited on vegetation and the soil but is then returned to the atmosphere within a few tens of days by mechanisms similar to ordinary condensation and evaporation. Therefore, the net

---

[*] Comparison of iodine concentrations in soils in glaciated and nonglaciated regions[11] suggests that the iodine content in soils may, on the average, be slowly increasing with time rather than at steady state. Thus, the flux of iodine onto land may be somewhat greater than the flux in river flow.

flux from the atmosphere to land by dry deposition is very much less than the gross transfer in either direction.

For our analysis, therefore, we assume that the rate of removal of iodine from land into the ocean by river flow is balanced by the flux of iodine from the atmosphere to land in precipitation. With this assumption, we then obtain the adopted value for the concentration of iodine in rainfall on land, a result that is within the range of measured values at locations away from the ocean.[9-11] The adopted concentration in the land atmosphere is obtained by assuming that the ratio of the concentration in the atmosphere to the concentration in rainwater is the same over land and ocean. The value so obtained is in excellent agreement with the average of values measured at several locations by Brauer *et al.*[16] and with other recent data[25,29-31] which do not appear to be unduly influenced by proximity to the ocean or by industrial activity.

4.3 Fractional Transfer Rates for the Global Iodine Cycle

The fractional transfer rates between the various environmental compartments for the global iodine cycle depicted in Fig. 3 are based as much as possible on the available data on stable iodine in the environment given in Table 2 and discussed in Sect. 4.2. For the most part, the fractional transfer rates are estimated by using Eq. 1, i.e., dividing a flux by a compartment inventory at steady state.

4.3.1 Transfers from ocean atmosphere to ocean mixed layer and from land atmosphere to surface soil region

Estimation of the inventory of iodine in the atmosphere from measurements of concentrations at the earth's surface is an uncertain procedure because the mixing ratio (mass of iodine per unit mass of dry air) as a function of altitude is not known. The vertical distribution in the atmosphere would be quite different for iodine attached to particulates, attached to water vapor, or in gaseous form.[32] The measurements of Brauer *et al.*[16] have shown that the amount of iodine in gaseous form is approximately 2.5 times greater than the amount attached to aerosols for both the ocean and land atmospheres. Therefore, we make the simple assumption that the mixing ratio for iodine is independent of altitude, as it would be for an ideal gas. This assumption was also used by Miyake and Tsunogai[13] to obtain the atmospheric inventory in Fig. 2. Using ocean and land surface areas from Table 3 and a height of 7.7 km for a "homogeneous" atmosphere (i.e., the height for an atmosphere with constant density equal to the value at sea level), the iodine inventories in the ocean and land atmosphere compartments are then estimated to be

$$\begin{aligned} Y_1 &= (3 \times 10^{-8}\ \mathrm{g/m^3})(3.61 \times 10^{14}\ \mathrm{m^2})(7.7 \times 10^{3}\ \mathrm{m}) \\ &= 8.3 \times 10^{10}\ \mathrm{g}\ , \end{aligned} \tag{4}$$

$$\begin{aligned} Y_2 &= (5 \times 10^{-9}\ \mathrm{g/m^3})(1.49 \times 10^{14}\ \mathrm{m^2})(7.7 \times 10^{3}\ \mathrm{m}) \\ &= 5.7 \times 10^{9}\ \mathrm{g}\ . \end{aligned} \tag{5}$$

From the discussion in Sect. 4.2, we have assumed that the flux from the atmosphere to the ocean and land surfaces is given by the flux of iodine in precipitation. Therefore, from Eq. 1 and from data in Tables 2 and 3, the fractional transfer rates are

$$\begin{aligned} k_{1,3} = F^{Y}_{1,3}/Y_1 &= (3.2 \times 10^{20}\ \mathrm{g/year})(6 \times 10^{-9})/(8.3 \times 10^{10}\ \mathrm{g}) \\ &= 23\ \mathrm{year}^{-1}\ , \end{aligned} \tag{6}$$

$$\begin{aligned} k_{2,4} = F^{Y}_{2,4}/Y_2 &= (1 \times 10^{20}\ \mathrm{g/year})(1 \times 10^{-9})/(5.7 \times 10^{9}\ \mathrm{g}) \\ &= 17\ \mathrm{year}^{-1}\ . \end{aligned} \tag{7}$$

4.3.2 Transfers to and from the terrestrial biosphere

For the surface soil region, we assume an average soil density of 1.4 g/cm^3. The iodine inventory in the surface soil region of depth 1 m is then given by

$$\begin{aligned} Y_4 &= (1.4\ \mathrm{g/cm^3})(5 \times 10^{-6})(1.49 \times 10^{14}\ \mathrm{m^2})(1\ \mathrm{m})(10^{6}\ \mathrm{cm^3/m^3}) \\ &= 1.0 \times 10^{15}\ \mathrm{g}\ . \end{aligned} \tag{8}$$

The iodine inventory in the terrestrial biosphere is

$$Y_5 = (1 \times 10^{18}\ \text{g})(1 \times 10^{-7}) \approx 1 \times 10^{11}\ \text{g} \quad . \tag{9}$$

Therefore, using the net primary production rate for the terrestrial biosphere and the iodine concentration therein, the fractional transfer rate from the surface soil region to the terrestrial biosphere is

$$\begin{aligned} k_{4,5} &= F^Y_{4,5}/Y_4 \\ &= (5.2 \times 10^{16}\ \text{g/year})(1 \times 10^{-7})/(1.0 \times 10^{15}\ \text{g}) \\ &= 5.0 \times 10^{-6}\ \text{year}^{-1} \quad . \end{aligned} \tag{10}$$

Since 10% of the iodine in the terrestrial biosphere is assumed to be released to the atmosphere and the remaining 90% returned to the surface soil region, the fractional transfer rates from the terrestrial biosphere are

$$\begin{aligned} k_{5,2} &= F^Y_{5,2}/Y_5 \\ &= (5.2 \times 10^{16}\ \text{g/year})(1 \times 10^{-7})(0.1)/(1 \times 10^{11}\ \text{g}) \\ &= 5.2 \times 10^{-3}\ \text{year}^{-1} \quad , \end{aligned} \tag{11}$$

$$k_{5,4} = 9k_{5,2} = 4.7 \times 10^{-2}\ \text{year}^{-1} \quad . \tag{12}$$

4.3.3 Transfer from ocean mixed layer to ocean atmosphere

For a density of seawater of 1 g/cm^3, the iodine inventory in the ocean mixed layer of depth 75 m is

$$\begin{aligned} Y_3 &= (5 \times 10^{-8}\ \text{g/cm}^3)(3.61 \times 10^{14}\ \text{m}^2)(75\ \text{m})(10^6\ \text{cm}^3/\text{m}^3) \\ &= 1.4 \times 10^{15}\ \text{g}. \end{aligned} \tag{13}$$

At steady state, the flux of iodine into the atmosphere is equal to the flux from the atmosphere to the earth's surface. Therefore, from Fig. 3, the evaporation rate from the ocean mixed layer to the ocean atmosphere is

$$F^Y_{3,1} = F^Y_{1,3} + F^Y_{2,4} - F^Y_{5,2} \ .$$

The fluxes on the right-hand side of this equation are given in the numerators in Eqs. 6, 7, and 11. Thus,

$$\begin{aligned} F^Y_{3,1} &= (1.9 \times 10^{12}\ \text{g/year}) + (1.0 \times 10^{11}\ \text{g/year}) \\ &\quad - (5.2 \times 10^{8}\ \text{g/year}) \\ &= 2.0 \times 10^{12}\ \text{g/year} \ . \end{aligned} \qquad (14)$$

We note that the contribution from the terrestrial biosphere is negligible. The fractional transfer rate is then

$$\begin{aligned} k_{3,1} &= F^Y_{3,1}/Y_3 \\ &= (2.0 \times 10^{12}\ \text{g/year})/(1.4 \quad 10^{15}\ \text{g}) \\ &= 1.5 \times 10^{-3}\ \text{year}^{-1} \ . \end{aligned} \qquad (15)$$

4.3.4 Evaporation rate from land surface to atmosphere

We can now verify the assumption made in the global model in Fig. 3 that the evaporation of iodine from the land surface to the atmosphere is negligible. The total amount of water in lakes and rivers[14] is approximately 2.3×10^5 km^3. With an assumed average concentration of 3 μg/liter, the iodine inventory is approximately 7×10^{11} g. If the fractional transfer rate from surface waters on land to the atmosphere is assumed to be the same as the value for transfer from the ocean mixed layer to the atmosphere given in Eq. 15, then the flux of iodine from the land surface is approximately 1×10^9 g/year, a value that is only 1% of the flux from the atmosphere to the land surface.

4.3.5 Transfers between ocean and land atmospheres

Since the flux from the terrestrial biosphere to the atmosphere is negligible compared with the other fluxes to and from the atmosphere (see Eq. 14), the net flux from the ocean atmosphere to the land atmosphere must equal the flux from the land atmosphere to the surface soil region. Therefore,

$$F^{Y}_{1,2} - F^{Y}_{2,1} = k_{1,2}Y_1 - k_{2,1}Y_2 = 1.0 \times 10^{11} \text{ g/year}, \tag{16}$$

where the net flux is given by the numerator in Eq. 7. In order to relate the two fractional transfer rates, we assume that the mean residence time (i.e., the reciprocal of the fractional transfer rate) in the land atmosphere for transfer to the ocean atmosphere is proportional to the land surface area, and similarly for the ocean atmosphere. Therefore,

$$k_{2,1}/k_{1,2} = (3.61 \times 10^{14} \text{ m}^2)/(1.49 \times 10^{14} \text{ m}^2) = 2.4 \quad .$$

The fractional transfer rates are then obtained from Eq. 16 as

$$\begin{aligned} k_{1,2} &= (1.0 \times 10^{11} \text{ g/year})/[(8.3 \times 10^{10} \text{ g}) - (2.4)(5.7 \times 10^{9} \text{ g})] \\ &= 1.4 \text{ year}^{-1}, \end{aligned} \tag{17}$$

$$k_{2,1} = 2,4k_{1,2} = 3.5 \text{ year}^{-1} \quad . \tag{18}$$

4.3.6 Transfers between ocean mixed layer and deep ocean

There are no data on the fluxes of iodine between the ocean mixed layer and deep ocean. We assume, therefore, that data on carbon can be used. According to Oeschger *et al.*,[33] the mean residence time for carbon in the deep ocean is 1127 years, so that the fractional transfer rate from deep ocean to ocean mixed layer is

$$k_{6,3} = 1/(1127 \text{ years}) = 8.9 \times 10^{-4} \text{ year}^{-1} \quad . \tag{19}$$

The fractional transfer rate from ocean mixed layer to deep ocean is obtained by requiring the iodine inventory in the mixed layer to be at steady state. From Fig. 3, this condition gives

$$F^{Y}_{3,6} = F^{Y}_{6,3} \quad ,$$

so that

$$k_{3,6} = k_{6,3}Y_6/Y_3 \quad .$$

The iodine inventory in the deep ocean of depth 3725 m is

$$Y_6 = (6 \times 10^{-8}\ \mathrm{g/cm^3})(3.61 \times 10^{14}\ \mathrm{m^2})(3.725 \times 10^{3}\ \mathrm{m})(10^{6}\ \mathrm{cm^3/m^3})$$

$$= 8.1 \times 10^{16}\ \mathrm{g} \quad . \qquad (20)$$

Therefore, using Eqs. 13 and 19, we obtain

$$k_{3,6} = (8.9 \times 10^{-4}\ \mathrm{year^{-1}})(8.1 \times 10^{16}\ \mathrm{g})/(1.4 \times 10^{15}\ \mathrm{g})$$

$$= 5.3 \times 10^{-2}\ \mathrm{year^{-1}} \quad . \qquad (21)$$

4.3.7 Transfers between deep ocean and ocean sediments

Assuming an ocean sediment density of 2.5 g/cm^3 (dry weight), and a sediment deposition rate and iodine concentration in sediments given in Tables 2 and 3, the flux of iodine in sedimentation is

$$F^{Y}_{6,7} = (2 \times 10^{4}\ \mathrm{cm/year})(2.5\ \mathrm{g/cm^3})(1 \times 10^{-4})(3.61 \times 10^{14}\ \mathrm{m^2})$$

$$\times\ (10^{4}\ \mathrm{cm^2/m^2})$$

$$= 1.8 \times 10^{11}\ \mathrm{g/year} \quad .$$

The fractional transfer rate from deep ocean to ocean sediments is then

$$k_{6,7} = F^{Y}_{6,7}/Y_6 = (1.8 \times 10^{11}\ \mathrm{g/year})/(8.1 \times 10^{16}\ \mathrm{g})$$

$$= 2.2 \times 10^{-6}\ \mathrm{year^{-1}} \quad . \qquad (22)$$

In the global model in Fig. 3, we have assumed that iodine in sedimentary rock on land is not accessible to global circulation. Therefore, the ocean sediments compartment contains only that iodine which has been deposited relatively recently on the ocean floor. We assume that iodine is returned from ocean sediments to deep ocean. This flux is not known, but we can estimate the fractional transfer rate from the measurement of Shishkina and Pavlova[34] that the iodine concentration is roughly a factor of 2 less at a depth of 7 m than at the top of the sediment layer. Assuming that the iodine concentration decreases exponentially with time after deposition and using the sedimentation rate in Table 3, the fractional transfer rate from ocean sediments to deep ocean is then obtained from the equation

$$1/2 = \exp[-k_{7,6}(7 \times 10^{2}\ \text{cm})/(2 \times 10^{-4}\ \text{cm/year})]$$

$$k_{7,6} = 2.0 \times 10^{-7}\ \text{year}^{-1} \quad . \tag{23}$$

4.3.8 Transfers from surface soil region to ocean mixed layer, shallow subsurface region, and deep subsurface region

From Table 3, we assume that 83% of river flow is runoff from the surface soil region, 17% results from circulation of groundwater from the shallow subsurface region, and 0.33% is groundwater flow from the deep subsurface region. Measured iodine concentrations in subsurface and spring waters[11,12] show wide variations from less than 1 ppb to several ppm, so that it is very difficult to estimate a reliable worldwide average value for the iodine concentration in groundwater. Therefore, we make the simplest assumption that the iodine concentration is the same in all three sources of river flow and is given by the value in Table 2.

If we define F_w^Y as the flux of iodine in river flow, then, from Tables 2 and 3,

$$F_w^Y = (3.23 \times 10^{19}\ \text{g/year})(3 \times 10^{-9}) = 9.7 \times 10^{10}\ \text{g/year} \quad ,$$

and the fractional transfer rates from the surface soil region to the ocean mixed layer, shallow subsurface region, and deep subsurface region are given by

$$\begin{aligned} k_{4,3} &= (0.83)F_w^Y/Y_4 \\ &= (0.83)(9.7 \times 10^{10}\ \text{g/year})/(1.0 \times 10^{15}\ \text{g}) \end{aligned}$$

$$= 7.7 \times 10^{-5}\ \text{year}^{-1} \quad , \tag{24}$$

$$k_{4,8} = (0.17)F_w^Y/Y_4 = 1.6 \times 10^{-5}\ \text{year}^{-1} \quad , \tag{25}$$

$$k_{4,9} = (3.3 \times 10^{-3})F_w^Y/Y_4 = 3.1 \times 10^{-7}\ \text{year}^{-1} \quad . \tag{26}$$

4.3.9 Transfers from shallow and deep subsurface regions to ocean mixed layer

The iodine in the lithosphere below the surface soil region may be divided into accessible and inaccessible pools with regard to movement into groundwater and thence into the ocean mixed layer. The accessible pool consists of iodine that has infiltrated into the region below the surface via downward percolation of rainwater plus iodine that has been leached from rock by the percolating water. The inaccessible pool consists of iodine bound in rock which is essentially impermeable to water.

At steady state, the fluxes of iodine from the shallow and deep subsurface regions into the ocean mixed layer resulting from the downward percolation of water from the surface soil region are obtained from the numerators in Eqs. 25 and 26 as 1.6×10^{10} g/year and 3.1×10^{8} g/year, respectively, for a total flux of 1.6×10^{10} g/year. The iodine content in groundwater flow from weathering of rock is estimated from the weathering rate of rock,[35] 2×10^{15} g/year, and the iodine concentration in the earth's crust, 0.5 ppm from Table 2, as 1×10^{9} g/year. Thus, the iodine flux into the ocean mixed layer from leaching of iodine in rock is estimated to be an order of magnitude less than the iodine flux from infiltration from the surface soil region. Therefore, we assume for the purposes of this model that all iodine in rock is inaccessible to removal by groundwater flow, and we define the shallow and deep subsurface regions of the lithosphere in Fig. 3 as consisting entirely of iodine that has infiltrated from the surface soil region. The fractional transfer rates from the shallow and deep subsurface regions can then be estimated from the mean time required for infiltration of iodine from the surface soil region to the groundwater in each subsurface region plus the mean time required for the flow of iodine in groundwater into the ocean mixed layer.

If we assume saturated flow for the percolating water below the surface soil region, the average downward flow velocity of iodine can be estimated from the equation[36]

$$V_I = V_w/[1 + (\rho K_d/\theta)] \quad , \tag{27}$$

where V_I and V_w are the velocity of iodine and water, respectively, in m/year, ρ is the density of the porous medium in g/cm^3, θ is the porosity of the medium, and K_d is the distribution coefficient in ml/g. The quantity K_d is the ratio of iodine concentration in the solid phase to the concentration in solution, and the denominator in Eq. 27 is called the retardation factor.

Some of the parameters in Eq. 27 are not well known for percolation through the rock deep in the earth's crust. For this analysis, we assume an average downward water flow velocity of 0.5 m/year, a rock density of 2.5 g/cm^3, and an average porosity of 10%. From measurements of Wildung *et al.*,[37] we assume an average distribution coefficient for iodine of 10 ml/g. Therefore, the retardation factor is estimated to be

$$\text{R.F.} = 1 + (2.5\ \text{g/cm}^3)(10\ \text{cm}^3/\text{g})/(0.1) = 250 \quad , \tag{28}$$

and the downward flow velocity for iodine is

$$V_I = (0.5\ \text{m/year})/(250) = 2 \times 10^{-3}\ \text{m/year} \quad . \tag{29}$$

The average time required for the infiltrating iodine to reach groundwater is the average distance to groundwater divided by the average flow velocity. We make the simplest assumption that groundwater is uniformly distributed with depth in the shallow and deep subsurface regions, so that the average depth of groundwater is 400 m and [illegible]0 m, respectively. Therefore, the mean transit times for iodine to reach groundwater, τ_1, in the shallow (s) and deep (d) regions are

$$\tau_1^s = (4 \times 10^2\ \text{m})/(2 \times 10^{-3}\ \text{m/year}) = 2 \times 10^5\ \text{year} \quad , \tag{30}$$

$$\tau_1^d = (2.4 \times 10^3\ \text{m})/(2 \times 10^{-3}\ \text{m/year}) = 1.2 \times 10^6\ \text{year} \quad . \tag{31}$$

The mean residence times for groundwater in the shallow and deep subsurface regions[14] are 200 years and 10,000 years, respectively. Therefore, using the retardation factor for iodine from Eq. 28, the average times for iodine in groundwater to reach the ocean mixed layer, τ_2, for the two compartments are

$$\tau_2^s = (2 \times 10^2 \text{ year})(250) = 5 \times 10^4 \text{ year} \quad , \tag{32}$$

$$\tau_2^d = (1 \times 10^4 \text{ year})(250) = 2.5 \times 10^6 \text{ year} \quad . \tag{33}$$

The estimated fractional transfer rates for iodine from the shallow and deep subsurface regions to the ocean mixed layer are then given by

$$\begin{aligned} k_{8,3} &= 1/(\tau_1^s + \tau_2^s) = 1/(2 \times 10^5 \text{ year} + 5 \times 10^4 \text{ year}) \\ &= 4.0 \times 10^{-6} \text{ year}^{-1} \quad , \end{aligned} \tag{34}$$

$$\begin{aligned} k_{9,3} &= 1/(\tau_1^d + \tau_2^d) = 1/(1.2 \times 10^6 \text{ year} + 2.5 \times 10^6 \text{ year}) \\ &= 2.7 \times 10^{-7} \text{ year}^{-1} \quad . \end{aligned} \tag{35}$$

4.4 Model Equations for Global Circulation of ^{129}I Released to the Environment

From the proposed model of the global iodine cycle shown in Fig. 3 and from the general form of the model equations given in Eq. 3, the system of equations for obtaining the inventory of ^{129}I as a function of time in each of the environmental compartments is as follows:

Ocean atmosphere

$$\begin{aligned} \mathrm{d}X_1(t)/\mathrm{d}t &= I_1^X(t) + k_{2,1}X_2(t) + k_{3,1}X_3(t) \\ &\quad - (k_{1,2} + k_{1,3} + \lambda)X_1(t) \quad , \end{aligned} \tag{36}$$

Land atmosphere

$$dX_2(t)/dt = I_2^X(t) + k_{1,2}X_1(t) + k_{5,2}X_5(t) - (k_{2,1} + k_{2,4} + \lambda)X_2(t) \quad , \tag{37}$$

Ocean mixed layer

$$dX_3(t)/dt = I_3^X(t) + k_{1,3}X_1(t) + k_{4,3}X_4(t) + k_{6,3}X_6(t) + k_{8,3}X_8(t) + k_{9,3}X_9(t) - (k_{3,1} + k_{3,6} + \lambda)X_3(t) \quad , \tag{38}$$

Surface soil region

$$dX_4(t)/dt = I_4^X(t) + k_{2,4}X_2(t) + k_{5,4}X_5(t) - (k_{4,3} + k_{4,5} + k_{4,8} + k_{4,9} + \lambda)X_4(t) \quad , \tag{39}$$

Terrestrial biosphere

$$dX_5(t)/dt = I_5^X(t) + k_{4,5}X_4(t) - (k_{5,2} + k_{5,4} + \lambda)X_5(t) \tag{40}$$

Deep ocean

$$dX_6(t)/dt = I_6^X(t) + k_{3,6}X_3(t) - (k_{6,3} + k_{6,7} + \lambda)X_6(t) \quad , \tag{41}$$

Ocean sediments

$$dX_7(t)/dt = I_7^X(t) + k_{6,7}X_6(t) - (k_{7,6} + \lambda)X_7(t) \quad , \tag{42}$$

Shallow subsurface region of lithosphere

$$dX_8(t)/dt = I_8^X(t) + k_{4,8}X_4(t) - (k_{8,3} + \lambda)X_8(t) \quad . \tag{43}$$

Deep subsurface region of lithosphere

$$dX_9(t)/dt = I_9^X(t) + k_{4,9}X_4(t) - (k_{9,3} + \lambda)X_9(t) \quad . \tag{44}$$

The symbols in these equations are defined in Sect. 2 and Table 1. In our calculations, iodine inventories are given in grams and fluxes in g/year. We allow an arbitrary time-dependent input function for each compartment. It is important to bear in mind that the model calculates only the compartment inventories resulting from the specified input function and does not include contributions from any other sources. For anthropogenic sources, the only non-zero input functions will normally be those for the atmosphere, ocean mixed layer, or surface soil region. For an application such as natural production of ^{129}I, input functions for most of the other compartments should also be included.

Implicit in the model equations is the assumption that the inventories of naturally occurring stable iodine in each of the environmental compartments are at steady state. Although volcanic releases and industrial activities such as burning of fossil fuels are undoubtedly increasing the inventory of iodine circulating in the environment, there are insufficient data upon which to estimate future trends. Consequently, we assume as in Fig. 2 that such increases will be relatively insignificant.[13] We have also ignored increases in the global inventory resulting from leaching of iodine in rock (see Sect. 4.3.9) and the possibility that the iodine inventory in the surface soil region is not at steady state.[11]

The fractional transfer rates for the global iodine cycle derived in Sect. 4.3 and the mean residence times for iodine in the environmental compartments are summarized in Table 4. The compartment inventories and fluxes at steady state for naturally occurring stable iodine are summarized in Table 5 and are shown in Fig. 4. The inventories in the ocean sediments and in the shallow and deep subsurface regions of the lithosphere are estimated using Eq. 1 for both the input and output fluxes.

4.5 Implications of the Global Model

In this section, we discuss some of the properties of the global iodine cycle on the basis of the results given in Tables 4 and 5.

Table 4. Mean residence times and fractional transfer rates for global iodine cycle

Compartment	Mean residence time (year)	Fractional transfer rate to[a]	Value (year^{-1})
Ocean atmosphere	4.1×10^{-2}	Land atmosphere	1.4
		Ocean mixed layer	2.3×10^{1}
Land atmosphere	4.9×10^{-2}	Ocean atmosphere	3.5
		Surface soil region	1.7×10^{1}
Ocean mixed layer	1.8×10^{1}	Ocean atmosphere	1.5×10^{-3}
		Deep ocean	5.3×10^{-2}
Surface soil region	1.0×10^{4}	Ocean mixed layer	7.7×10^{-5}
		Terrestrial biosphere	5.0×10^{-6}
		Shallow subsurface region	1.6×10^{-5}
		Deep subsurface region	3.1×10^{-7}
Terrestrial biosphere	1.9×10^{1}	Land atmosphere	5.2×10^{-3}
		Surface soil region	4.7×10^{-2}
Deep ocean	1.1×10^{3}	Ocean mixed layer	8.9×10^{-4}
		Ocean sediments	2.2×10^{-6}
Ocean sediments	5.0×10^{6}	Deep ocean	2.0×10^{-7}
Shallow subsurface region	2.5×10^{5}	Ocean mixed layer	4.0×10^{-6}
Deep subsurface region	3.7×10^{6}	Ocean mixed layer	2.7×10^{-7}

[a] Values are derived in Sect. 4.3 for the global iodine cycle shown in Fig. 3.

ORNL-DWG 79-12607

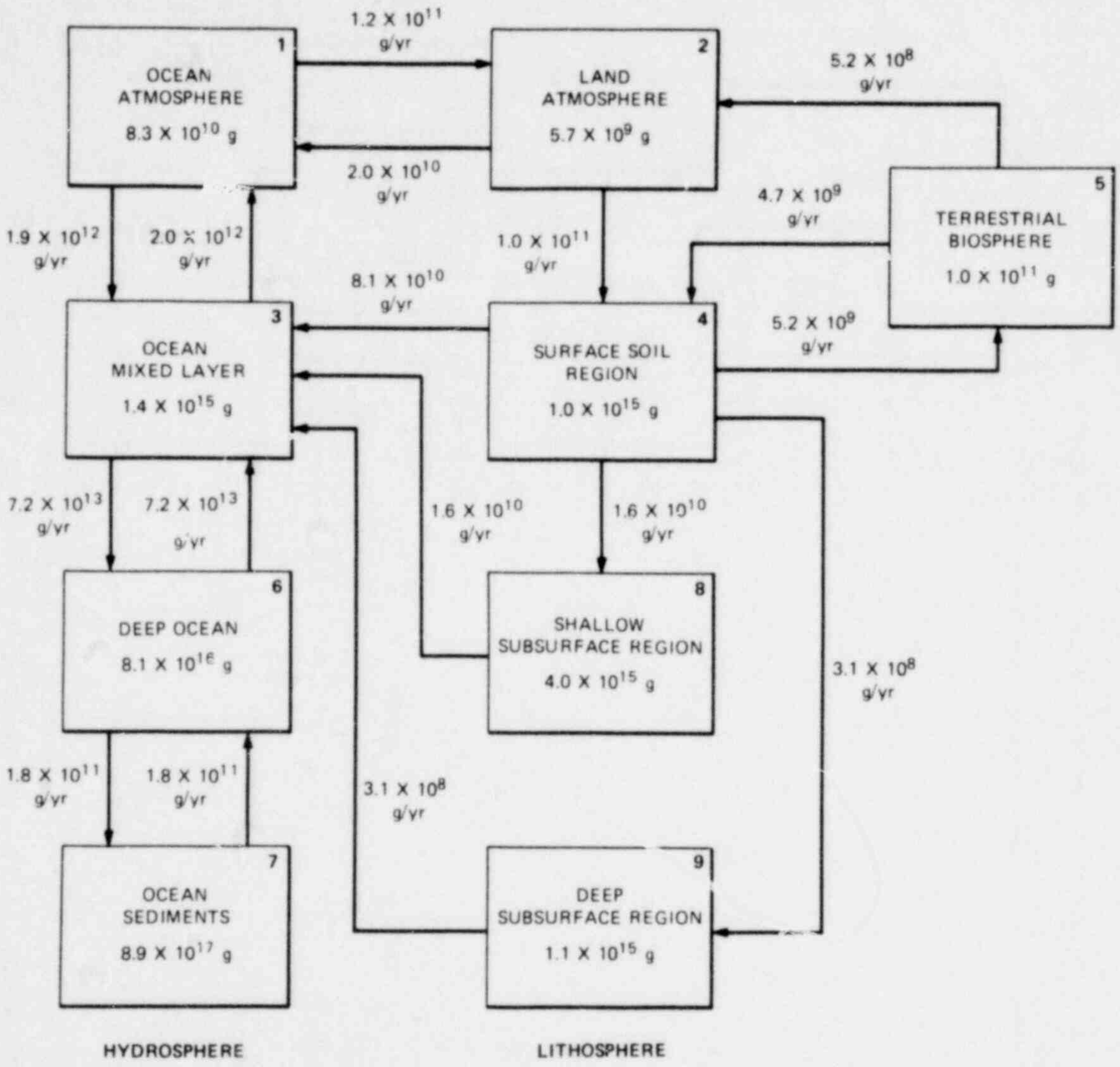

Fig. 4. Global inventories and fluxes for naturally occurring stable iodine proposed in this work (see Sect. 4).

Table 5. Compartment inventories and fluxes for global iodine cycle[a]

Compartment	Inventory (g)	Flux to	Value (g/year)
Ocean atmosphere	8.3×10^{10}	Land atmosphere	1.2×10^{11}
		Ocean mixed layer	1.9×10^{12}
Land atmosphere	5.7×10^{9}	Ocean atmosphere	2.0×10^{10}
		Surface soil region	1.0×10^{11}
Ocean mixed layer	1.4×10^{15}	Ocean atmosphere	2.0×10^{12}
		Deep ocean	7.2×10^{13}
Surface soil region	1.0×10^{15}	Ocean mixed layer	8.1×10^{10}
		Terrestrial biosphere	5.2×10^{9}
		Shallow subsurface region	1.6×10^{10}
		Deep subsurface region	3.1×10^{8}
Terrestrial biosphere	1.0×10^{11}	Land atmosphere	5.2×10^{8}
		Surface soil region	4.7×10^{9}
Deep ocean	8.1×10^{16}	Ocean mixed layer	7.2×10^{13}
		Ocean sediments	1.8×10^{11}
Ocean sediments	8.9×10^{17}	Deep ocean	1.8×10^{11}
Shallow subsurface region	4.0×10^{15}	Ocean mixed layer	1.6×10^{10}
Deep subsurface region	1.1×10^{15}	Ocean mixed layer	3.1×10^{8}

---

[a] Values are for naturally occurring stable iodine at steady state.

Particular attention is given to the need for local and regional scale models to describe the transport of ^{129}I following a release.

4.5.1 Mean residence time for iodine in the atmosphere

From Table 4, the mean residence time for iodine in the atmosphere is approximately 15 days. This value is much less than the mean residence time of 2 years proposed by Miyake and Tsunogai[13] in Fig. 2. The latter value is based on an average iodine concentration in the atmosphere of 160 ng/m^3 measured in Tokyo, Japan, which is much larger than the values we have adopted in Table 2 from the measurements of Brauer *et al.*[16] It seems unlikely that the average concentration over the earth's surface could be greater than values measured in the ocean atmosphere. We note that the value of Miyake and Tsunogai may be an unreliable indicator of worldwide average conditions, since it is based on measurements in a location of high industrial activity.

For an atmospheric mean residence time of 15 days and assuming an average wind speed of 3 m/sec at the earth's surface, we estimate that a release of iodine to the atmosphere from a point source would travel a distance of 4000 km before half of the release is deposited on the earth's surface, a distance that is only one-tenth of the circumference of the earth. Therefore, the model indicates that mixing of iodine throughout the global atmosphere for a release to the atmosphere from a point source is not likely to occur prior to deposition, so that the resulting distribution on the earth's surface will be highly nonuniform. The need for regional-scale dose assessments for such cases is thus indicated.

4.5.2 Mean residence time for iodine in the surface soil region

A surprising consequence of the global transport model proposed in this report is the mean residence time for iodine in the surface soil region, which, from Table 4, is approximately 10,000 years. This value is more than two orders of magnitude larger than expected on the basis of a mean residence time for water of 0.2 years[14] and the range of measured distribution coefficients for iodine in soils.[37] In order for the value obtained from the present analysis to be too large by a factor of 100, the values of the iodine concentration in river water (and also the balancing flux from the atmosphere to the land surface) and the iodine concentration in soil would each have to be a factor of 10 too large, which does not seem reasonable from the available data. It appears that naturally occurring iodine is relatively easily fixed in soil and is transported relatively slowly to other parts of the environment.

An important consequence of the mean residence time in the surface soil region is that a localized release of ^{129}I to the land surface will not enter into global circulation for 10,000 years or more on the average, so that local or regional scale models would be needed during this considerable time span. The 10,000-year mean residence time in soil is also indicative of the time required for a release of ^{129}I to reach a state of near equilibrium with the natural iodine circulating in the environmental compartments to which man is exposed.

4.5.3 Mixing of iodine in the oceans

The model assumes that a release of ^{129}I into surface waters is instantaneously and uniformly mixed throughout the ocean mixed layer. This is certainly not the case for a release from a point source. A proper treatment of global transport for such a release would have to account for mixing times throughout the oceans. Available data indicate that 1000 years or more may be required for such mixing to occur.[38]

4.5.4 Importance of the terrestrial biosphere

In the model summarized in Tables 4 and 5, the inventory of stable iodine in the terrestrial biosphere and the flux from the terrestrial biosphere to the atmosphere are sufficiently small that the inclusion of the terrestrial biosphere compartment has negligible consequences on the iodine inventories in any other compartment. Therefore, this compartment could just as well be excluded from the model. We have nonetheless chosen to include the terrestrial biosphere because of the possibility suggested by some measurements[39] that the assumed iodine concentration of 0.1 ppm in Table 2 is more than an order of magnitude too low and

1534 049

the possibility that the fraction of iodine released to the atmosphere is greater than the assumed value of 10%.

4.5.5 Role of ocean sediments and subsurface regions of the lithosphere in the global iodine cycle

The mean residence times given in Table 4 for iodine circulating in ocean sediments and in the subsurface regions of the lithosphere are between 2.5×10^5 and 5×10^6 years. The values for ocean sediments and the deep subsurface region are within an order of magnitude of the mean lifetime for decay of ^{129}I. These compartments then act as sinks in the global iodine cycle because they retain iodine for long periods of time in compartments not normally accessible to man. By far the most important sink is ocean sediments, since relatively little of the iodine is circulating through the deep subsurface region of the lithosphere. If the mean residence time in ocean sediments were an order of magnitude larger than the value estimated in Table 4, most of the ^{129}I entering the compartment would decay before returning to the deep ocean.

5. INTAKE OF ^{129}I BY A REFERENCE INDIVIDUAL AND POPULATION DOSE

In order to calculate individual dose rates and cumulative individual and population doses as a function of time following a release of ^{129}I, the inventories of ^{129}I in the environmental compartments calculated from Eqs. 36-44 are combined with a model for the intake of iodine by a reference individual and an estimate of the world population at future times. In this section, the methods used to estimate average iodine intake, average dose rates from a release of ^{129}I, and population dose are described.

The model of the global iodine cycle developed in Sect. 4 suggests that a period of more than 10,000 years is required for a release of ^{129}I to reach equilibrium with the natural iodine circulating in the parts of the environment to which man is normally exposed. Prior to equilibrium, a specific activity calculation based on ^{129}I and stable iodine inventories in a chosen environmental compartment is not appropriate. We must consider instead the intake of iodine from all of the compartments accessible to man; i.e., a pathway analysis is required. In Sect. 5.1, estimates of the intake of stable iodine by a reference individual from the different environmental compartments are given. In Sect. 5.2, the dose rates for intake of ^{129}I from the compartments are derived. The methods used to estimate world population and the population doses and dose commitments are given in Sect. 5.3.

5.1 Intake of Stable Iodine from Environmental Compartments by a Reference Individual

It is very difficult to estimate reliably worldwide average values for the intake of stable iodine from the different environmental compartments because of wide variations in typical diet, iodine content in foods, and extent of artificial iodine supplements in the diet. Our approach has been to estimate an average diet from available data for different geographical regions and to calculate iodine intake for this diet from a pathways model given in the literature.

In this analysis, we assume that the environmental compartments from which man receives intake of iodine include the atmosphere, land surface waters, ocean mixed layer, and the surface soil region. We have ignored iodine supplements in the human diet and in livestock feeding. Since many of these supplements are taken from minerals in the earth's crust which are presumably not accessible to ^{129}I in global circulation, their omission from the average diet probably results in an overestimate of the dose from ^{129}I. The effect of iodine supplements on intake by man can be quite striking. As an example, the natural iodine concentration in milk is normally less than 100 μg/liter,[10] whereas milk from cows receiving iodine supplements can have concentrations an order of magnitude larger.[40] We note also that because of the extensive use of iodine supplements in the human diet, livestock feed, and fertilizer in this country, surveys of iodine content in food in the United States[41] may not provide accurate worldwide average values.

5.1.1 Assumed average diet for a reference individual

Based on current levels of world population in Asia (59%), Africa (10%), Latin America (5%), Europe (16%), North America (9%), and Oceania (1%),[42] and on average food consumption rates estimated for people in different regions of the world in Table 122 of *Reference Man*,[43] we obtain the estimates of average intake of foods by a reference individual given in Table 6. The division of the intake between leafy vegetables and other vegetables, fruits, and nuts is based on dietary data for the United States used by Book *et al.*[44] The assumed intake of fluids exclusive of milk is based on data given in *Reference Man*.[43]

5.1.2 Intake of stable iodine from the atmosphere

We assume that intake of iodine from the land atmosphere results from inhalation and from incorporation into milk, meat, and other foods following foliar deposition.

For inhalation, we assume an air intake rate of 2.2 × 10^4 liters/day.[43] Therefore, since we assume an iodine concentration in the land atmosphere from Table 2 of 5 ng/m^3,

Table 6. Assumed intake of foods by a reference individual[a]

Type of food	Intake (kg/day)
Milk	0.26
Meat	0.070
Leafy vegetables	0.080
Other vegetables, fruits, and nuts	0.25
Cereals	0.38
Fish	0.023
Other foods	0.28
Fluids excluding milk	1.4

[a] Values are estimated as described in Sect. 5.1.1.

$$\begin{aligned}\text{Iodine inhalation rate} &= (2.2 \times 10^{4}\ \text{liters/day})(5 \times 10^{-9}\ \text{g/m}^{3}) \\ &\quad \times (10^{3}\ \text{m}^{3}/\text{liter})(365\ \text{days/year}) \\ &= 4.0 \times 10^{-5}\ \text{g/year}\ . \qquad (45)\end{aligned}$$

For foliar deposition, Soldat[45] and Book *et al.*[44] recommend the following values of iodine concentrations in food relative to the concentration in the atmosphere in units of m^3/kg: milk, 1.25×10^3; meat, 1.6×10^3; leafy vegetables, 2.9×10^3: other vegetables and fruits, 2.9×10^2; and cereals, 5.4×10^2. Hoffman[46] has recommended that these values should be increased by a factor of 4 to account for an inappropriate application of the interception fraction for the deposited iodine. On the other hand, Chamberlain and Chadwick[47] report that the deposition velocity for natural iodine is a factor of 4 less than the value of 1 cm/sec assumed by Soldat.[45] Therefore, we assume that the concentration factors given above are reasonable values to use for the intake of natural iodine. Combining these values with the dietary intake for each type of food given in Table 6 and using 5 ng/m^3 as the iodine concentration in the atmosphere, we obtain the following result:

Iodine intake rate from foliar deposition =

$$1.7 \times 10^{-3}\ \text{g/year} \quad . \tag{46}$$

Intake via foliar deposition is thus much more important than intake via inhalation.

5.1.3 Intake of stable iodine from land surface waters

For intake of iodine from land surface waters, we consider direct ingestion of fluids by man, ingestion of freshwater fish, and ingestion of water by dairy and beef cattle leading to iodine in milk and meat.

From Table 6, we assume a fluid intake rate exclusive of milk of 1.4 liters/day. Assuming that the average iodine concentration in fluids is the same as the concentration in river water (3 μg/liter from Table 2), we obtain

Iodine intake rate from direct ingestion of fluids =

$$(1.4\ \text{liters/day})(3 \times 10^{-6}\ \text{g/liter})(365\ \text{days/year})$$

$$= 1.5 \times 10^{-3}\ \text{g/year} \quad . \tag{47}$$

For ingestion of freshwater fish, we assume an intake of half of the average intake of fish given in Table 6 and an iodine concentration factor for freshwater fish of 200 liters/kg.[48] Therefore,

Iodine intake rate from freshwater fish =

$$1/2(2.3 \times 10^{-2}\ \text{kg/day})(2 \times 10^{2}\ \text{liters/kg})(3\ \mu\text{g/liter})$$

$$\times\ (365\ \text{days/year}) = 2.5 \times 10^{-3}\ \text{g/year} \quad . \tag{48}$$

For transfer of iodine to milk and meat following ingestion of water by dairy and beef cattle, we assume a water intake rate of 40 liters/day and 60 liters/day for beef and dairy cattle,[49] respectively, and transfer coefficients of 7×10^{-3} day/kg for iodine in meat[49] and 1×10^{-2} day/liter for iodine in milk.[50] The assumed intake of milk and meat by man is given in Table 6. Therefore,

Iodine intake rate from surface waters via milk =

$$(60\ \text{liters/day})(3\ \mu\text{g/liter})(1 \times 10^{-2}\ \text{day/liter})$$

$$\times\ (0.26\ \text{liters/day})(365\ \text{days/year}) = 1.7 \times 10^{-4}\ \text{g/year} \quad , \tag{49}$$

Iodine intake rate from surface waters via meat =

$$(40\ \text{liters/day})(3\ \mu\text{g/liter})(7 \times 10^{-3}\ \text{day/kg})(0.07\ \text{kg/day})$$

$$\times\ (365\ \text{days/year}) = 2.2 \times 10^{-5}\ \text{g/year} \quad . \qquad (50)$$

The intake by man from ingestion of water by livestock is seen to be relatively small.

Combining Eqs. 47-50, the total iodine intake rate by this pathway is

Iodine intake rate from land surface waters =

$$4.2 \times 10^{-3}\ \text{g/year} \quad . \qquad (51)$$

5.1.4 Intake of stable iodine from ocean mixed layer

We assume an intake of half of the average intake of fish given in Table 6 and an average concentration factor for iodine in saltwater fish and shellfish of 30 liters/kg.[48] From Table 2, the average iodine concentration in the ocean mixed layer is 50 μg/liter. Therefore,

Iodine intake rate from ocean mixed layer =

$$1/2(2.3 \times 10^{-2}\ \text{kg/day})(3 \times 10^{1}\ \text{liters/kg})(50\ \mu\text{g/liter})$$

$$\times\ (365\ \text{days/year}) = 6.2 \times 10^{-3}\ \text{g/year} \quad . \qquad (52)$$

5.1.5 Intake of stable iodine from surface soil region

Intake of iodine in soil by man results from direct consumption of iodine in plants following root uptake and from ingestion of milk and meat following consumption of forage by dairy and beef cattle. From Table 2, we assume an average iodine concentration in plants of 0.1 ppm. This value is consistent with a concentration factor of 0.02 adopted by Soldat[45] and the Nuclear Regulatory Commission[51] and with the assumed iodine concentration in soil of 5 ppm given in Table 2.

For transfer of iodine to milk and meat following ingestion of forage by livestock, we assume a forage consumption rate of 55 kg/day.[45] Therefore, using the intake rates by man in Table 6 and the transfer coefficients for livestock given in Sect. 5.1.3, we obtain

Iodine intake rate from soil via milk =

$$(55 \text{ kg/day})(1 \times 10^{-4} \text{ g/kg})(1 \times 10^{-2} \text{ day/kg})$$

$$\times (0.26 \text{ kg/liter})(365 \text{ days/year}) = 5.1 \times 10^{-3} \text{ g/year}, \quad (53)$$

Iodine intake rate from soil via meat =

$$(55 \text{ kg/day})(1 \times 10^{-4} \text{ g/kg})(7 \times 10^{-3} \text{ day/kg})$$

$$\times (0.07 \text{ kg/day})(365 \text{ days/year}) = 9.9 \times 10^{-4} \text{ g/year}. \quad (54)$$

From Table 6, the total intake of foods exclusive of milk, meat, and fluids is 1 kg/day. If this intake contains 0.1 ppm iodine from root uptake, then

Iodine intake rate from soil via root uptake =

$$(1 \text{ kg/day})(1 \times 10^{-4} \text{ g/kg})(365 \text{ days/year})$$

$$= 3.7 \times 10^{-2} \text{ g/year} \quad . \quad (55)$$

This is by far the most significant intake for any of the pathways considered.

Combining Eqs. 53-55, we obtain

Iodine intake rate from surface soil region =

$$4.3 \times 10^{-2} \text{ g/year} \quad . \quad (56)$$

5.1.6 Total intake of stable iodine

The total intake rates of stable iodine from the atmosphere, land surface waters, ocean mixed layer, and surface soil region for a reference individual estimated in Eqs. 45, 46, 51, 52, and 56 are summarized in Table 7. In this analysis, we find that approximately 80% of an average individual's intake of stable iodine from the globally circulating inventory comes from the soil, with about 10% or less coming from each of the other compartments. It is clear, therefore, that specific activity calculations based on iodine concentrations in either the atmosphere or the ocean mixed layer are not appropriate for assessing doses for ^{129}I prior to the time the released ^{129}I reaches equilibrium with the natural iodine in man's exposure environment.

The total iodine intake from the globally circulating inventory given in Table 7 is equivalent to 150 μg/day. This value is in reasonable agreement with the estimate of 200 μg/day given in *Reference Man*.[43] This latter value was derived by calculating the constant intake required to maintain an average iodine content in the thyroid of 12 mg,[43] assuming a biological half-time of 138 days and a fraction of the iodine in blood reaching the thyroid of 0.3 (ref. 52). From this comparison, we conclude that the rudimentary pathway analysis of iodine intake by a reference individual presented here gives quite reasonable results.

5.2 Individual Dose Rates from Intake of ^{129}I from Environmental Compartments

Calculation of the dose rates from intake of ^{129}I by a reference individual from the different environmental compartments requires the specific activity of ^{129}I and the dose conversion factors for inhalation and ingestion. The half-life for ^{129}I of 1.57×10^{7} years corresponds to a specific activity of

$$\mathrm{SpA}(^{129}\mathrm{I}) = 177\ \mu\mathrm{Ci/g}\ . \tag{57}$$

The adopted dose conversion factors for inhalation and ingestion are[53]

Table 7. Estimated intake of iodine by a reference individual[a]

Source in environment	Intake rate (g/year)
Atmosphere	
Inhalation	4.0×10^{-5}
Foliar Deposition	1.7×10^{-3}
Land surface waters	4.2×10^{-3}
Ocean mixed layer	6.2×10^{-3}
Surface soil region	4.3×10^{-2}
Total	5.5×10^{-2}

[a] Values are calculated in Sect. 5.1.

$$\mathrm{DCF(inh)} = 4.97\ \mathrm{rems}/\mu\mathrm{Ci} \tag{58}$$

and

$$\mathrm{DCF(ing)} = 7.78\ \mathrm{rems}/\mu\mathrm{Ci}\ , \tag{59}$$

respectively. These values are the maximum 50-year dose commitments to the thyroid for an acute intake of 1 μCi. Since the biological half-time for iodine in the thyroid is approximately 120 days,[53] the dose conversion factors give, to a very good approximation, the dose rate to the thyroid in rems/year for a chronic intake at a rate of 1 μCi/year.

Given the specific activity and dose conversion factors for ^{129}I and the pathway analysis for intake of stable iodine by a reference individual in Sect. 5.1, the dose rates for intake of ^{129}I from the different environmental compartments are easily estimated.

5.2.1 Dose rate from intake from atmosphere

From Tables 5 and 7, a stable iodine inventory in the land atmosphere of 5.7×10^{9} g results in an intake of 4.0×10^{-5} g/year. Therefore, the dose rate for an average individual from inhalation of ^{129}I from the land atmosphere with inventory $X_2(t)$ is

$$\begin{aligned}\text{Dose rate from inhalation} &= [(4.0 \times 10^{-5}\ \mathrm{g/year})/(5.7 \times 10^{9}\ \mathrm{g})] \\ &\quad \times (177\ \mu\mathrm{Ci/g})(4.97\ \mathrm{rems}/\mu\mathrm{Ci})X_2(t) \\ &= (6.1 \times 10^{-12}\ \mathrm{rem/g{\cdot}year})X_2(t)\ . \end{aligned} \tag{60}$$

For foliar deposition, a similar calculation gives

$$\begin{aligned}&\text{Dose rate from foliar deposition} = \\ &\quad [(1.7 \times 10^{-3}\ \mathrm{g/year})/(5.7 \times 10^{9}\ \mathrm{g})](177\ \mu\mathrm{Ci/g}) \\ &\quad \times (7.78\ \mathrm{rems}/\mu\mathrm{Ci})X_2(t) \\ &= (4.1 \times 10^{-10}\ \mathrm{rem/g{\cdot}year})X_2(t)\quad . \end{aligned} \tag{61}$$

5.2.2 Dose rate from land surface waters

From Sect. 4.3.8, the flux of iodine in river water is 9.7×10^{10} g/year. This flux consists of runoff from the surface soil region and groundwater flow from the shallow and deep subsurface regions of the lithosphere. Therefore, from Fig. 3, the flux of ^{129}I in river water F_w^X, can be written as

$$F_w^X(t) = k_{4,3}X_4(t) + k_{8,3}X_8(t) + k_{9,3}X_9(t) \quad . \qquad (62)$$

Since the intake rate of stable iodine from land surface waters is 4.2×10^{-3} g/year, we obtain

$$\begin{aligned} &\text{Dose rate from land surface waters} = \\ &\quad [(4.2 \times 10^{-3}\ \text{g/year})/(9.7 \times 10^{10}\ \text{g/year})](177\ \mu\text{Ci/g}) \\ &\quad \times (7.78\ \text{rems}/\mu\text{Ci})F_w^X(t) \\ &= (5.8 \times 10^{-11}\ \text{rem/g})F_w^X(t) \quad . \qquad (63) \end{aligned}$$

5.2.3 Dose rate from intake from ocean mixed layer

From the stable iodine inventory in the ocean mixed layer in Table 5 and the intake rate in Table 7, we obtain

$$\begin{aligned} &\text{Dose rate from ocean mixed layer} = \\ &\quad [(6.2 \times 10^{-3}\ \text{g/year})/(1.4 \times 10^{15}\ \text{g})](177\ \mu\text{Ci/g}) \\ &\quad \times (7.78\ \text{rems}/\mu\text{Ci})X_3(t) \\ &= (6.4 \times 10^{-15}\ \text{rem/g}\cdot\text{year})X_3(t) \quad , \qquad (64) \end{aligned}$$

where $X_3(t)$ is the ^{129}I inventory in the ocean mixed layer.

5.2.4 Dose rate from intake from surface soil region

From the stable iodine inventory in the surface soil region in Table 5 and the intake rate in Table 7, we obtain

$$\begin{aligned} &\text{Dose rate from surface soil region} = \\ &\quad [(4.3 \times 10^{-2}\ \text{g/year})/(1.0 \times 10^{15}\ \text{g})](177\ \mu\text{Ci/g}) \\ &\quad \times (7.78\ \text{rems}/\mu\text{Ci})X_4(t) \\ &= (5.6 \times 10^{-14}\ \text{rem/g}\cdot\text{year})X_4(t) \quad , \qquad (65) \end{aligned}$$

where $X_4(t)$ is the ^{129}I inventory in the surface soil region.

5.2.5 Summary of dose rates from intake of ^{129}I

The coefficients derived in Eqs. 60, 61, and 63-65 for obtaining the dose rate to a reference individual from intake of ^{129}I from the atmosphere, land surface waters, ocean mixed layer, and surface soil region are summarized in Table 8. The total individual dose rate at any time is obtained by multiplying each coefficient by the ^{129}I inventory or flux in the particular exposure environment at that time and adding the resulting dose rates. From Eq. 62, the ^{129}I flux in river water arises from the inventory in all three compartments of the lithosphere.

Table 8. Coefficients for dose rates from intake of ^{129}I by a reference individual[a]

Intake pathway	Exposure environment	Coefficient
Inhalation	Land atmosphere	6.1×10^{-12} rem/g·year
Ingestion following foliar deposition	Land atmosphere	4.1×10^{-10} rem/g·year
Ingestion from water	Land surface waters	5.8×10^{-11} rem/g
Ingestion of sea food	Ocean mixed layer	6.4×10^{-15} rem/g·year
Ingestion following root uptake	Surface soil region	5.6×10^{-14} rem/g·year

[a] The coefficients are derived in Sect. 5.2.

5.3 Estimate of World Population and Population Dose

If $dD(t)/dt$ is defined as the individual dose rate at time t, the population dose delivered between times t_0 and t_1 is given by

$$D(t_0, t_1) = \int_{t_0}^{t_1} N(t)\ [dD(t)/dt]\ dt \ \ \text{man-rem} \ , \tag{66}$$

where $N(t)$ is the world population at time t. We adopt a United Nations projection[54] which assumes a population of 3.988 billion in 1975 increasing to 12.21 billion in 2075. Beyond 2075, we assume a constant population of 12.21 billion. We note that since ^{129}I has a half-life of

15.7 million years,[2] the calculation of population dose commitments requires, in principle, integration of Eq. 66 for more than 100 million years. It is obvious that any projection of world population over that time period is purely speculative.

In the calculations presented in Sect. 7 of this report, the population dose commitment from a given release is obtained by integrating Eq. 66 to infinite time. The computer code described in Sect. 6 can only integrate the model equations over a finite time interval. In the calculations performed here, the equations are integrated to a time t_1 at which a state of near equilibrium of the released ^{129}I in the environmental compartments is achieved. The time t_1 is taken to be

$$t_1 = 2/\min(k_{i,j}) \quad , \tag{67}$$

where $\min(k_{i,j})$ is the smallest fractional transfer rate in the global model. The population dose from time t_1 to infinity is then given by

$$D(t_1, +\infty) = N(t_1)[\mathrm{d}D(t_1)/\mathrm{d}t]/\lambda \tag{68}$$

where $N(t_1)$ is the population at time t_1 (12.21 billion), $\mathrm{d}D(t_1)/\mathrm{d}t$ is the individual dose rate at time t_1, and $\lambda = 4.41 \times 10^{-8}\ \mathrm{year}^{-1}$ is the radiological decay constant for ^{129}I. The population dose commitment is then the sum of the doses calculated in Eqs. 66 and 68.

6. THE COMPUTER CODE

The computer code IODES (Iodine, *Gr.*) has been written to perform calculations for the global iodine model proposed in this report. The code calculates inventories of ^{129}I in the nine environmental compartments for a given release by integrating Eqs. 36-44, calculates individual dose rates and cumulative individual doses from intake of ^{129}I from Eqs. 60, 61, and 63-65, and calculates cumulative population doses from Eqs. 66 and 68. The code is written in FORTRAN IV for the IBM 360-75/91 computers. All floating-point arithmetic is performed in double precision. The total computing time for a typical set of calculations presented in Sec. 7 is approximately 7 sec.

The code uses the numerical analysis software package GEAR,[55] which is available on-line at the Oak Ridge National Laboratory Computing Center, to integrate the system of differential equations for the model. The GEAR package contains options specifically designed for the solution of stiff systems of equations,[56] in which the coefficients differ by several orders of magnitude as they do in this work (see Table 4).

With the exception of the on-line GEAR package, a listing of the computer code IODES is given in the Appendix.

In the MAIN PROGRAM, the fractional transfer rates for the global iodine cycle and the coefficients for obtaining individual dose rates from intake of ^{129}I via the different pathways are calculated, the input variables for the GEAR package are initialized, and the results of the calculations are written. Rather than have the user input fractional transfer rates and intake coefficients directly, the code calculates these quantities from values of basic parameters (e.g., physical dimensions of environmental compartments, average iodine concentrations, average dietary intake of foods, etc.) contained in data statements. This procedure allows the user complete flexibility in modifying the particular assumptions and models used to calculate the fractional transfer rates and intake coefficients.

SUBROUTINE BALCHK compares the input and output fluxes for the global iodine cycle at steady state for the ocean and land atmosphere, the ocean mixed layer and deep ocean, the surface soil region, and the terrestrial biosphere calculated from the assumed compartment inventories and the derived fractional transfer rates. When changing input parameters for a calculation, the output from this subroutine provides a check that the global iodine cycle remains at steady state.

SUBROUTINE DIFFUN, which is called by SUBROUTINE GEAR, evaluates the system of differential equations for the model at a particular time. We note that the individual dose rates and individual and population doses are evaluated along with the derivatives of the compartment inventories, since they are functions only of the compartment inventories at the particular time.

SUBROUTINE PEDERV, which is called by SUBROUTINE GEAR, calculates the Jacobian matrix for the system of differential equations for the model.

SUBROUTINE INPUT, which is called by SUBROUTINE DIFFUN, calculates the input flux of ^{129}I for the environmental compartments for a particular release. The version in the Appendix assumes an input into the land atmosphere at a constant rate of 1 Ci/year for 1 year, with no input to any other compartment. This subroutine must be rewritten by the user for each different input function desired.

POPULA calculates the world population at any time after the beginning of a release by linear interpolation of the estimated population described in Sect. 5.3. The population is assumed to be constant at 12.21 billion beyond the year 2075.

DYEAR calculates the times following the beginning of a release at which output of compartment inventories, individual dose rates and cumulative dose, and population dose is desired. The user can modify this function to obtain different time increments.

7. SAMPLE CALCULATIONS

In this section, results of sample calculations of inventories in the environmental compartments, individual dose rates and cumulative doses, and population doses and dose commitments from hypothetical releases of ^{129}I to the environment are presented. In all calculations, the input function describes a pulse release of ^{129}I beginning in the year 1980 at a rate of 1 Ci/year for a duration of one year into a single environmental compartment. We assume that the release occurs uniformly throughout the specified compartment so that the global transport model may be applied directly to the release.

7.1 Calculations for Reference Model

We first consider calculations for the so-called reference model, for which the fractional transfer rates for the global iodine cycle and the coefficients for individual dose rates from intake of ^{129}I are given in Tables 4 and 8, respectively. Calculations were performed with the reference model for a 1-Ci release to either the land atmosphere, the ocean atmosphere, the ocean mixed layer, or the surface soil region.

The inventories of ^{129}I in the environmental compartments as a function of time for the first 10^5 years following a release of 1 Ci to the land atmosphere are shown in Fig. 5. The numerical label with each curve identifies the particular environmental compartment as defined in Fig. 3 (see Sect. 4.1). The curves in Fig. 5 demonstrate clearly the dynamic nature of the global transport of iodine following a release to a single compartment, i.e., the very different time dependences of the inventories in the separate compartments prior to equilibrium. Because the mean residence time in the atmosphere is very short, the inventories in the ocean mixed layer and surface soil region increase almost linearly with time during the release. The essentially constant inventory in the surface soil region for the first 1000 years after the release results from the long mean residence time of iodine in soil and the relatively small influx from the land atmosphere. The inventories in the atmosphere are essentially in equilibrium with the inventory in the ocean mixed

ORNL-DWG 79-12558

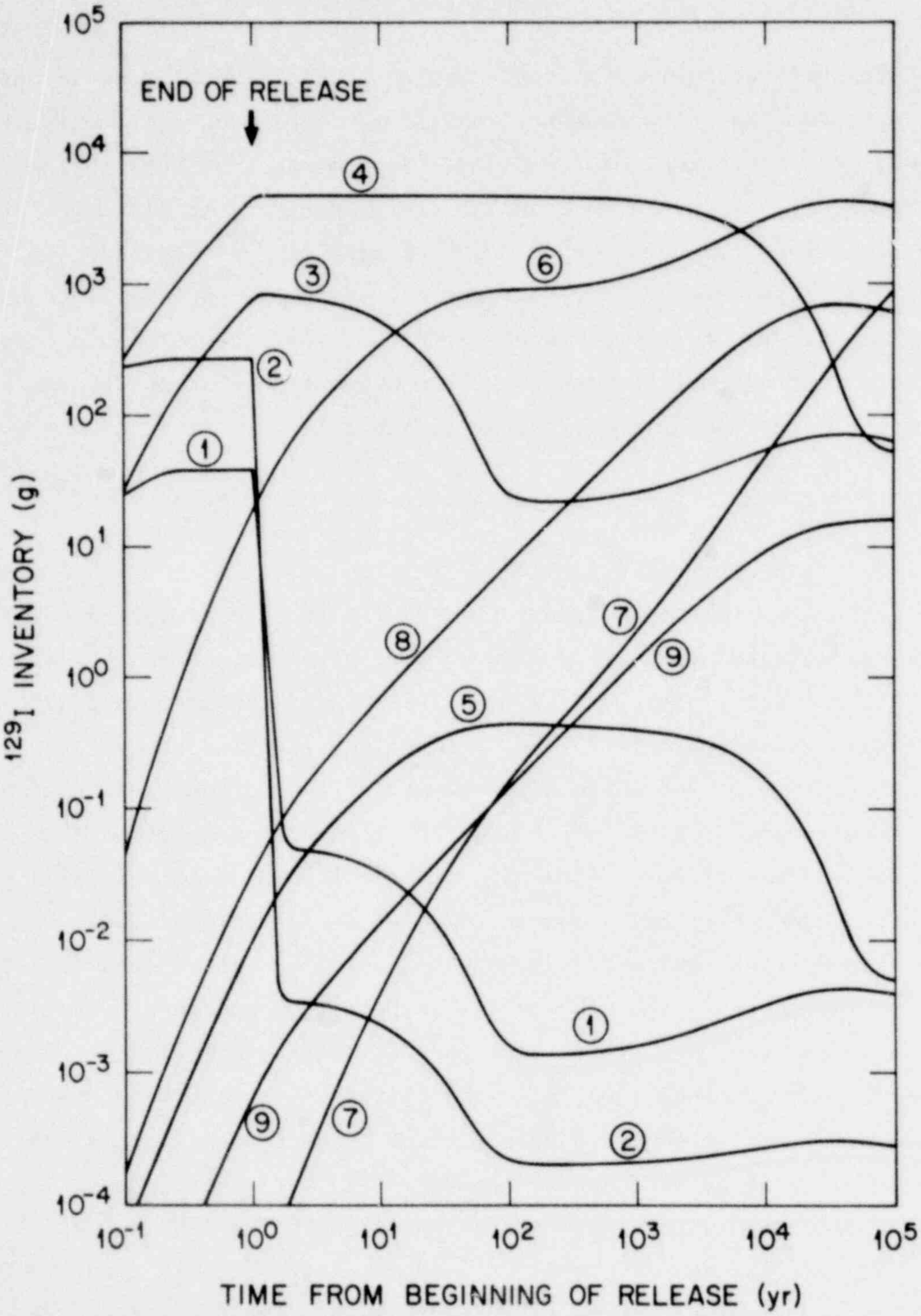

Fig. 5. Compartment inventories vs. time for a release of 1 Ci of ^{129}I to the land atmosphere over a period of 1 year for the reference model defined in Table 4. The label for each curve identifies the compartment as follows: 1 = ocean atmosphere, 2 = land atmosphere, 3 = ocean mixed layer, 4 = surface soil region, 5 = terrestrial biosphere, 6 = deep ocean, 7 = ocean sediments, 8 = shallow subsurface region of lithosphere, 9 = deep subsurface region of lithosphere.

layer after 10 years. The decreasing inventories in these compartments for the first 100 years following the release result from the net transport of ^{129}I into the deep ocean; these inventories then increase somewhat between 100 and 40,000 years as ^{129}I is returned from the deep ocean and is transported from the surface soil region into the ocean mixed layer. The relatively small inventory in the terrestrial biosphere reaches equilibrium with the surface soil region within 100 years. The inventory in the deep ocean increases rapidly during the first 100 years but increases more slowly thereafter as ^{129}I is transported into ocean sediments. The inventories in ocean sediments and the shallow and deep subsurface regions of the lithosphere are increasing with time during most of the first 10^5 years, demonstrating that these compartments are acting as sinks for the globally circulating iodine.

The calculations in Fig. 5 also demonstrate the relatively slow transport of iodine in the global environment, since the released ^{129}I has not reached equilibrium in the different environmental compartments within the first 10^5 years. In fact, equilibrium throughout the global cycle is not achieved until approximately 10^7 years following the release, at which time most of the released ^{129}I resides in ocean sediments and the inventories in each of the compartments are proportional to the steady-state inventories for stable iodine given in Table 5 and Fig. 4. We note from Fig. 5, however, that the inventories in the compartments from which man receives most of the intake of ^{129}I - the atmosphere, ocean mixed layer, and surface soil region - reach a state of near equilibrium after approximately 10^5 years.

The dose rates to a reference individual from intake of ^{129}I from different parts of the environment as a function of time for a 1-Ci release to the land atmosphere are shown in Fig. 6. The dose rates from intake from the atmosphere, ocean, and soil are proportional to the inventories of ^{129}I in the land atmosphere, ocean mixed layer, and surface soil region, respectively, shown in Fig. 5. The dose rate from intake from land surface waters is proportional to the inventory in the surface soil region for the first 10^4 years; by 10^5 years, intake from the shallow subsurface region of the lithosphere has become significant. For this particular type of release, the atmosphere is the critical

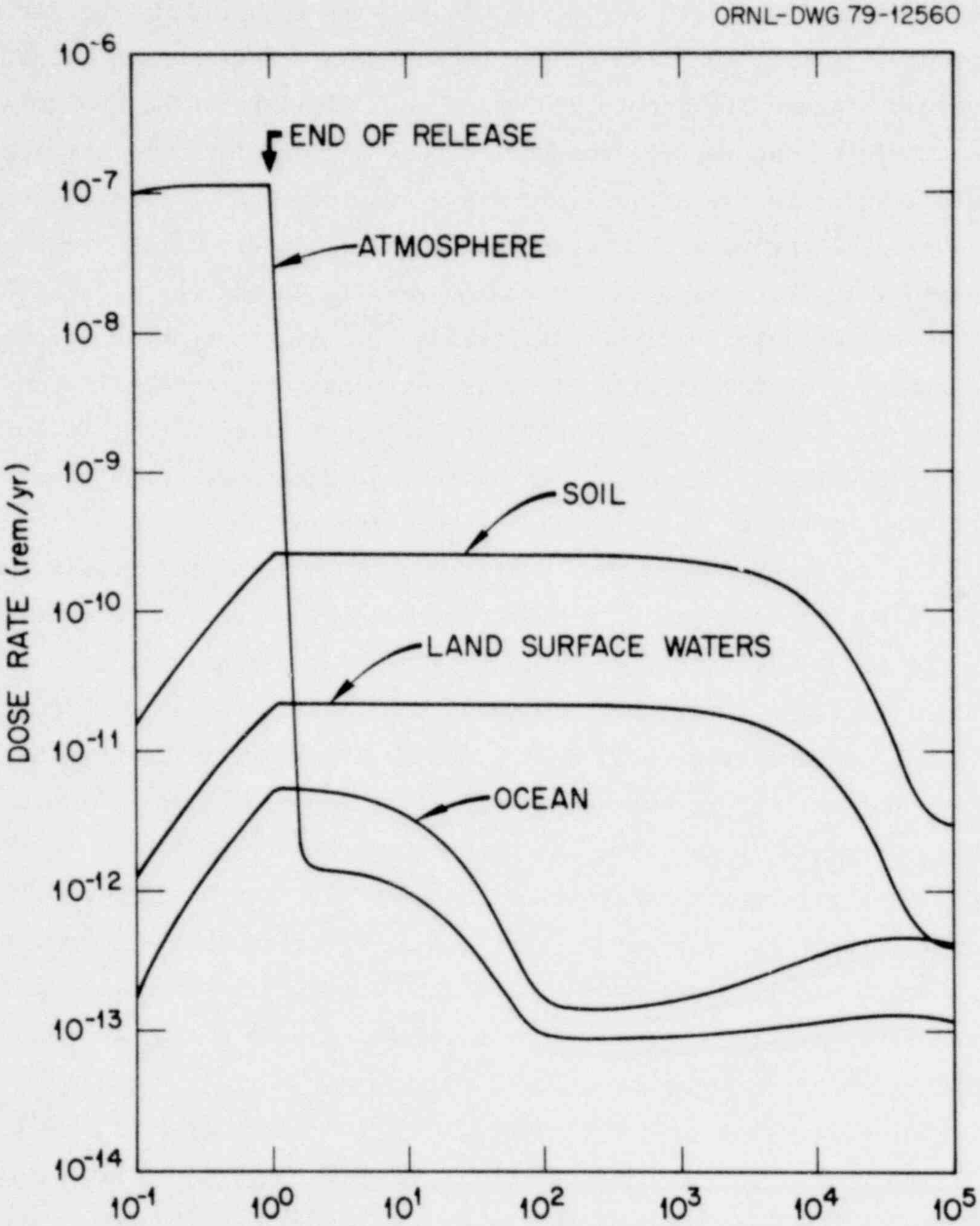

Fig. 6. Individual dose rates vs. time from intake from different parts of the environment for a release of 1 Ci of ^{129}I to the land atmosphere over a period of 1 year for the reference model defined in Tables 4 and 8.

1534 067

compartment for exposure during the release, whereas the surface soil region is the most important compartment thereafter.

Curves similar to those in Figs. 5 and 6 could be generated for a 1-Ci release to the ocean atmosphere, ocean mixed layer, and surface soil region, but we have not done so here. A comparison of the individual dose rates for the first 10^5 years for a 1-Ci release to each of the four environmental compartments is shown in Fig. 7. During the release period, the dose rate is the highest for a release to the land atmosphere, the value being 1×10^{-7} rem/year. Following the end of the release, the dose rates are the highest for a release to the ocean atmosphere or surface soil region but are considerably less for a release to the other two compartments. The dose rates for the four types of release are approximately the same after 10^5 years, since, as shown in Fig. 5, the ^{129}I inventories in the environmental compartments accessible to man are nearly in equilibrium by this time.

By integrating the dose rates for a 1-Ci release to the different environmental compartments shown in Fig. 7 to infinite time, we obtain the individual dose commitments given in Table 9. These dose commitments are equivalent to the individual dose rate in rems/year for a chronic release of ^{129}I to the environmental compartment at a rate of 1 Ci/year provided the global circulation of ^{129}I is at steady state. In spite of the large differences in individual dose rates for releases to the different compartments for the first 10^5 years (see Fig. 7), we note that the resulting dose commitments have nearly the same value. This results from the fact that most of the dose commitment is received after a state of near equilibrium in the global circulation is achieved.

The estimated population doses at selected times and population dose commitments for a 1-Ci release to each of the four environmental compartments are given in Table 10. The relative population doses for releases to the different compartments for the first 10^6 years reflect the differences in the individual dose rates shown in Fig. 7. The population dose commitments, however, are nearly the same for each of the releases because most of the dose is received after 10^5 years. It is noteworthy that the population doses after 10^6 years are between 20 and 40% of the infinite-time dose commitment, whereas only 4% of the

ORNL-DWG 79-12559

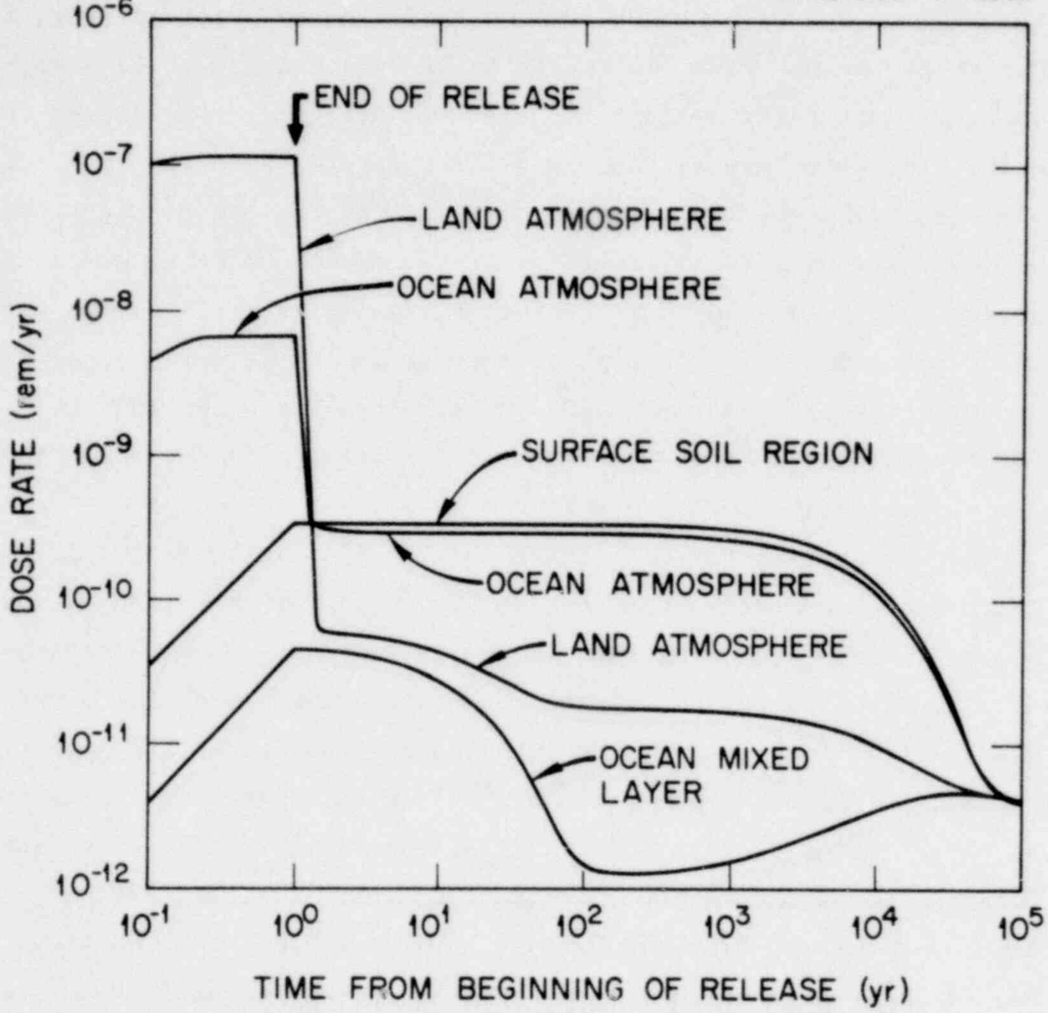

Fig. 7. Individual dose rate vs. time for a release of 1 Ci of ^{129}I to different environmental compartments over a period of 1 year for the reference model defined in Tables 4 and 8.

Table 9. Individual dose commitments for a release of 1 Ci of ^{129}I to the environment[a]

Release to	Individual dose commitment (rem)
Land atmosphere	1.5×10^{-5}
Ocean atmosphere	1.2×10^{-5}
Ocean mixed layer	1.2×10^{-5}
Surface soil region	1.6×10^{-5}

[a] Calculations are for the reference model defined in Tables 4 and 8.

released ^{129}I has decayed during this time period. This reflects the property of the reference model that most of the released ^{129}I is transported to the ocean sediments compartment within 10^6 years, where radioactive decay can occur without resulting in a potential exposure to man. If there were no environmental sinks in the model, then we would expect the population dose at any time after a state of near equilibrium is reached relative to the dose commitment to be approximately equal to the fraction of the released ^{129}I which has decayed during that time.

Bergman *et al.*[23] have also reported individual dose rates and dose commitments based on a linear compartment model of the global iodine cycle. They obtain an individual dose commitment of 1.3×10^{-4} rem/Ci, which is a factor of 10 larger than the values we obtained in Table 9. The larger value appears to result primarily from the absence of an environmental sink in the global transport model, so that the circulating ^{129}I has a considerably greater probability of intake by man. For a release to the atmosphere, Bergman *et al.* report that 0.5 and 0.6% of the dose commitment is received in the first 30 and 500 years, respectively, after the release. In our calculations, 0.8% of the individual dose commitment is received after 30 years and 1.7% is received after 500 years. The smaller fraction of the dose commitment estimated by Bergman *et al.* after 500 years appears to result from a much shorter mean

Table 10. Population doses and dose commitments from release of 1 Ci of ^{129}I

	Dose (man-rem) for release to			
Time (year)[a]	Land atmosphere	Ocean atmosphere	Ocean mixed layer	Surface soil region
10^1	5.3×10^2	3.3×10^1	1.7	1.6×10^1
10^2	7.9×10^2	5.2×10^1	6.4	3.1×10^2
10^3	3.8×10^3	2.4×10^2	2.2×10^1	3.9×10^3
10^4	2.3×10^4	1.7×10^3	3.2×10^2	2.7×10^4
10^5	4.3×10^4	7.4×10^3	5.2×10^3	4.9×10^4
10^6	6.5×10^4	2.9×10^4	2.7×10^4	7.1×10^4
Infinity	1.8×10^5	1.5×10^5	1.4×10^5	1.9×10^5

[a] Time from beginning of 1-year release.

residence time for iodine in the land compartment than the value of approximately 10^4 years we have assumed for the surface soil region. In Bergman's calculations, the dose rate reaches its equilibrium value within a few hundred years of the release, whereas from Fig. 7 nearly 10^5 years is required in our model. A proper comparison of the two sets of calculations cannot be made here, since Bergman *et al.* have given no details of their models for global transport and intake of ^{129}I.

7.2 Parameter Sensitivity Analysis

In this section, population doses and dose commitments are presented for a series of calculations in which one or more of the input parameters for the reference model of the global iodine cycle is varied in a systematic fashion, in order to determine the sensitivity of the results to these parameters. A parameter sensitivity analysis is potentially useful in demonstrating a need for further improvements in measurements of stable iodine in the environment or in the assumptions used in estimating some of the fractional transfer rates.

The results of the parameter sensitivity analysis are presented in Tables 11-14. Each table gives the population doses and dose commitments for a 1-Ci release to one of the four environmental compartments for which the results of an input were studied in Sect. 7.1. The doses and dose commitments in the first line of each table give the results for the reference model defined in Tables 4 and 8. The other calculations in Tables 11-14 are identified in the following paragraphs.

7.2.1 Variation of the mean residence time in ocean sediments

A major uncertainty in the reference model is the mean residence time for iodine in ocean sediments, which is the reciprocal of the fractional transfer rate from ocean sediments to deep ocean. The calculations labeled 1(a) and 1(b) assume a decrease and an increase, respectively, of the mean residence time in ocean sediments by a factor of 10. This parameter is seen to have a significant effect on the population dose beyond 10^6 years but no effect on the doses for the first 10^4 years. These results can be understood by reference to Fig. 5, which shows that the inventory in ocean sediments is insignificant for the first 10^4

Table 11. Comparison of population doses and dose commitments from reference model with values from variations in parameters of the global iodine cycle for a 1-Ci release to the land atmosphere

	Dose (man-rem) after time			
Calculation[a]	10^2 years	10^4 years	10^6 years	Infinity
Reference	7.9×10^2	2.3×10^4	6.5×10^4	1.8×10^5
1(a)	7.9×10^2	2.3×10^4	7.4×10^4	7.1×10^5
1(b)	7.9×10^2	2.3×10^4	6.3×10^4	8.0×10^4
2(a)	7.9×10^2	2.3×10^4	6.5×10^4	1.8×10^5
2(b)	7.8×10^2	2.3×10^4	6.5×10^4	1.8×10^5
3(a)	7.9×10^2	2.4×10^4	6.5×10^4	1.8×10^5
3(b)	7.8×10^2	2.3×10^4	6.5×10^4	1.8×10^5
4(a)	7.9×10^2	2.4×10^4	6.6×10^4	1.8×10^5
4(b)	7.9×10^2	2.3×10^4	6.1×10^4	1.7×10^5
5(a)	6.5×10^2	1.5×10^4	6.4×10^4	1.8×10^5
5(b)	1.1×10^3	3.3×10^4	6.5×10^4	1.8×10^5

[a] Doses for reference calculation are given in Table 10; other calculations are described in Sect. 7.2.

Table 12. Comparison of population doses and dose commitments from reference model with values from variations in parameters of the global iodine cycle for a 1-Ci release to the ocean atmosphere

Calculation[a]	Dose (man-rem) after time			
	10^2 years	10^4 years	10^6 years	Infinity
Reference	5.2×10^1	1.7×10^3	2.9×10^4	1.5×10^5
1(a)	5.2×10^1	1.7×10^3	3.9×10^4	6.8×10^5
1(b)	5.2×10^1	1.7×10^3	2.8×10^4	4.4×10^4
2(a)	5.3×10^1	1.7×10^3	2.9×10^4	1.5×10^5
2(b)	5.2×10^1	1.7×10^3	2.9×10^4	1.5×10^5
3(a)	5.8×10^1	1.7×10^3	2.9×10^4	1.5×10^5
3(b)	4.9×10^1	1.7×10^3	2.9×10^4	1.5×10^5
4(a)	5.2×10^1	1.7×10^3	2.9×10^4	1.5×10^5
4(b)	5.2×10^1	1.7×10^3	2.8×10^4	1.4×10^5
5(a)	4.4×10^1	1.1×10^3	2.9×10^4	1.5×10^5
5(b)	6.8×10^1	2.3×10^3	2.9×10^4	1.5×10^5

[a] Doses for reference calculation are given in Table 10; other calculations are described in Sect. 7.2.

1534 074

Table 13. Comparison of population doses and dose commitments from reference model with values from variations in parameters of the global iodine cycle for a 1-Ci release to the ocean mixed layer

	Dose (man-rem) after time			
Calculation[a]	10^2 years	10^4 years	10^6 years	Infinity
Reference	6.4	3.2×10^2	2.7×10^4	1.4×10^5
1(a)	6.4	3.2×10^2	3.6×10^4	6.8×10^5
1(b)	6.4	3.2×10^2	2.5×10^4	4.1×10^4
2(a)	6.5	3.2×10^2	2.7×10^4	1.4×10^5
2(b)	6.4	3.2×10^2	2.7×10^4	1.4×10^5
3(a)	1.3×10^1	3.6×10^2	2.7×10^4	1.4×10^5
3(b)	3.2	3.0×10^2	2.7×10^4	1.4×10^5
4(a)	6.4	3.2×10^2	2.7×10^4	1.5×10^5
4(b)	6.4	3.2×10^2	2.5×10^4	1.4×10^5
5(a)	6.3	2.3×10^2	2.6×10^4	1.4×10^5
5(b)	6.8	4.4×10^2	2.7×10^4	1.4×10^5

[a] Doses for reference calculation are given in Table 10; other calculations are described in Sect. 7.2.

Table 14. Comparison of population doses and dose commitments from reference model with values from variations in parameters of the global iodine cycle for a 1-Ci release to the surface soil region

Calculation[a]	Dose (man-rem) after time			
	10^2 years	10^4 years	10^6 years	Infinity
Reference	3.1×10^2	2.7×10^4	7.1×10^4	1.9×10^5
1(a)	3.1×10^2	2.7×10^4	8.0×10^4	7.2×10^5
1(b)	3.1×10^2	2.7×10^4	7.0×10^4	8.7×10^4
2(a)	3.1×10^2	2.7×10^4	7.1×10^4	1.9×10^5
2(b)	3.1×10^2	2.7×10^4	7.1×10^4	1.9×10^5
3(a)	3.1×10^2	2.7×10^4	7.1×10^4	1.9×10^5
3(b)	3.1×10^2	2.7×10^4	7.1×10^4	1.9×10^5
4(a)	3.1×10^2	2.7×10^4	7.2×10^4	1.9×10^5
4(b)	3.1×10^2	2.7×10^4	6.7×10^4	1.8×10^5
5(a)	1.6×10^2	1.7×10^4	7.1×10^4	1.9×10^5
5(b)	6.2×10^2	3.8×10^4	7.1×10^4	1.9×10^5

[a] Doses for reference calculation are given in Table 10; other calculations are described in Sect. 7.2.

years but that the ocean sediments compartment becomes the most important sink for the circulating ^{129}I beyond 10^5 years. If ^{129}I were deposited in the ocean sediments for longer times, the isolation from man would be greater and the dose commitment consequently lower. The opposite would be the case for shorter mean residence times.

7.2.2 Variation of the stable iodine inventory in the atmosphere

In the reference model, the inventory of stable iodine in the atmosphere was estimated from measured concentrations at ground and sea level by assuming that the vertical distribution for iodine is the same as that for air. The validity of this assumption is not known. The calculations labeled 2(a) and 2(b) assume an increase and decrease, respectively, of the inventory of stable iodine in both the ocean and land atmospheres by a factor of 10. These changes are equivalent to an increase and decrease, respectively, of the mean residence time in the atmosphere by the same factor. We find that these changes have an insignificant effect on the population dose beyond 100 years. In fact, varying the atmospheric mean residence time affects the population dose only during a release to the atmosphere and for the short time thereafter during which the released ^{129}I is initially deposited on the land or ocean. After the atmosphere is depleted, the results in Fig. 6 show that the dose from intake from the atmosphere is insignificant.

7.2.3 Variation of the mean residence time in deep ocean

The mean residence time for iodine in the deep ocean compartment assumed in the reference model was taken directly from an analysis of the global carbon cycle. The calculations labeled 3(a) and 3(b) assume an increase and decrease, respectively, of the mean residence time in the deep ocean by a factor of 2. In order to maintain a balance of the fluxes in the global iodine cycle at steady state, this change also results in a corresponding change in the mean residence time in the ocean mixed layer by the same factor. These parameter variations affect the population doses only for releases to the ocean atmosphere or ocean mixed layer and only for the first 100 to 10,000 years. The insensitivity of the doses to these parameter variations for a release to the land atmosphere or the surface soil region can be understood from the long mean residence time in soil compared with the values in the two ocean compartments.

7.2.4 Variation of the mean residence time in the shallow and deep subsurface regions of the lithosphere

Estimation of the fractional transfer rates from the shallow and deep subsurface regions of the lithosphere to the ocean mixed layer in the reference model involved many uncertain assumptions and approximations. The calculations labeled 4(a) and 4(b) assume a decrease and increase, respectively, of the mean residence times in the subsurface lithosphere compartments by a factor of 10. These changes have little effect on the population dose before 10^6 years and only slightly thereafter. Only if the mean residence times were increased by much more than a factor of 10 would the long-term population dose and dose commitment be significantly reduced because these compartments would then become effective sinks in the global iodine cycle. Decreasing these mean residence times by any amount has little effect on any of the doses. The insensitivity of the dose commitments to the mean residence times in the subsurface compartments of the lithosphere compared with the mean residence time in ocean sediments can be understood from the property of the reference model that relatively little of the iodine is circulating in the subsurface lithosphere.

7.2.5 Variation of the stable iodine inventory in the surface soil region

The calculations labeled 5(a) and 5(b) assume an increase and decrease, respectively, of the inventory of stable iodine in the surface soil region by a factor of 2. These changes are equivalent to an increase and decrease, respectively, of the mean residence time in the surface soil region by the same factor. This parameter is seen to have a significant effect on the population dose for the first 10^4 years but has a negligible effect on the doses for times after the released ^{129}I has reached a state of near equilibrium in man's exposure environment. It is not surprising that the inventory of stable iodine in soil is the most important parameter for determining doses prior to equilibrium because the soil is the critical exposure environment for man after the end of a release (see Fig. 6).

7.2.6 Observations from parameter sensitivity analysis

Although an exhaustive parameter sensitivity analysis has not been performed here, the calculations that have been described lead to some important general results. We have shown that the transport of iodine in the environmental compartments to which man is exposed (atmosphere, soil, etc.) affects the population dose only for the period following a release prior to the time the ^{129}I reaches equilibrium with the natural iodine circulating in man's exposure environment, but the dose thereafter is insensitive to the parameters for these compartments. This rsult also depends on the fact that the half-life of ^{129}I is long compared with the mean residence times of iodine in these compartments. Eventually, then, the released ^{129}I will deliver the same dose as long as it remains in circulation among the compartments to which man is exposed but regardless of how the ^{129}I is apportioned among these compartments at equilibrium. On the other hand, the transport of iodine into the regions of the global environment inaccessible to man (ocean sediments and subsurface regions of the lithosphere) is apparently sufficiently slow that the parameters for these compartments have no effect on the dose prior to the time a state of near equilibrium is reached in the compartments to which man is exposed. Thereafter, however, the inaccessible compartments can provide significant sinks for the circulating ^{129}I and thus affect the long-term doses and dose commitments.

8. SUMMARY AND CONCLUSIONS

In this report, a model for the global transport of iodine has been developed for the purpose of estimating worldwide population doses and dose commitments from releases of ^{129}I to the environment. Estimates of dose rates to a reference individual and population doses are obtained from (1) the inventories of ^{129}I in various parts of the environment calculated by the global transport model, (2) assumptions concerning the intake of iodine by a reference individual from the environment based on a pathway analysis, (3) conversion factors giving dose per unit intake, and (4) an estimate of the world population.

The global iodine cycle is described by means of a linear time-invariant, environmental compartment model. The environmental compartments assumed in the model comprise the atmosphere, hydrosphere, lithosphere, and terrestrial biosphere. Some of the parameters describing the transport of iodine between the environmental compartments were determined directly from measured concentrations and fluxes of naturally occurring stable iodine and data on the global hydrologic cycle. Additional assumptions were required in order to completely specify the model. These included (1) a crude estimate of the mean residence time for iodine in ocean sediments, (2) the assumption that the mean residence time for iodine in the deep ocean is the same as the value for carbon, (3) the assumption that the rate at which iodine is leached from rock by percolating water is negligible compared with the rate at which iodine infiltrates into the lithosphere from the surface soil region, and (4) assumptions concerning the percolation velocity of iodine in the lithosphere, the distribution with depth and mean residence times for groundwater in the lithosphere, and the concentration of iodine in groundwater.

An important consequence of the model for the global iodine cycle which we have developed is the prediction that the global circulation of iodine is a relatively slow process, so that a release of ^{129}I from a point source may require tens of thousands of years before it is dispersed in the environment on a global scale. The model predicts an atmospheric mean residence time of approximately 15 days, which is much shorter than the value of 2 years previously assumed.[13] If the shorter mean residence time is the more realistic, then a release to the atmosphere from a point source will be deposited on the land or ocean surface before mixing throughout the global atmosphere occurs. Thus, such a release to the atmosphere, as well as releases directly to a localized region of the land surface or surface waters, will result in a nonuniform distribution of ^{129}I over the earth's surface. Since the mean residence time of iodine in the surface soil region is predicted to be 10,000 years and mixing of iodine throughout the oceans may require 1000 years or more, it is clear that a long time may be required for an initially nonuniform distribution of ^{129}I on the earth's surface to enter into global circulation. Therefore, for some releases to the environment, a realistic long-term population dose assessment would seem to require a progression from local to regional to global scale models.

In this report, we have presented calculations of dose rates, population doses, and dose commitments for hypothetical releases of ^{129}I to the environment with the assumption that the model for the global iodine cycle can be applied directly to the release; i.e., the release is instantaneously and uniformly dispersed throughout a given environmental compartment. Releases of 1 Ci over a period of 1 year to the atmosphere, ocean mixed layer, and surface soil region were considered. The calculations showed that for the first 10^5 years following a release, the most important parameter for determining dose rates and cumulative doses is the 10^4-year mean residence time for iodine in the surface soil region. After 10^5 years, the released ^{129}I is nearly in equilibrium with the inventories of natural iodine in the environmental compartments to which man is exposed. The doses beyond 10^5 years and the infinite-time dose commitments are then determined primarily by the presence of sinks in the global cycle which are inaccessible to man. In our model, the ocean sediments compartment is the most effective in removing ^{129}I from man's exposure environment.

For a release of 1 Ci of ^{129}I, the resulting dose rate to an individual after the end of the release is very low, being 10^{-12}-10^{-9} rem/year depending on the compartment in which the release occurs. The total dose that would be accumulated by an individual over infinite time is only 10-20 µrems. Therefore, it is apparent that large quantities of globally dispersed ^{129}I would be required to produce a significant radiological impact on man.

On the basis of the linear, no-threshold hypothesis for converting dose to resultant health effects, the health risk to the world population is based on the population dose integrated to infinite time. Our calculations predict that for a constant population of 12.21 billion, the world-wide population dose commitment for ^{129}I is approximately 2×10^5 man-rems/Ci. We caution, however, that a result such as this has little credibility if it is to be used to set standards for release rates or to compare potential radiological impacts with those from other globally significant radionuclides, such as ^{14}C. Because of the 15.7 million-year half-life for ^{129}I, only a small percentage of the population dose commitment will be delivered during the first 10^5 years following a release, and it is unlikely that a model based on current environmental conditions and population levels could accurately predict population doses beyond that time. Therefore, careful consideration is needed not only of the time span over which doses should sensibly be calculated but also of the significance of large population doses obtained from the accumulation of very small individual doses over a large population.

It seems reasonable that the calculation of population dose and consequent estimation of health risks for ^{129}I for times as long as a few tens of thousands of years is a potentially meaningful exercise. It is during this time following a release that the ^{129}I circulates primarily in the environmental compartments to which man is exposed, so that the dose rate to an individual is larger than at later times when the ^{129}I has reached equilibrium with the globally circulating natural iodine. We suggest, therefore, that future efforts in describing the transport of iodine in the environment should concentrate on those aspects of the models that are important for relatively short time periods (up to 10^4-10^5 years) after a release, e.g., the development of local and regional scale long-term dose assessment models, rather than on aspects of importance for longer time periods. Calculations should also be performed using realistic input functions for anthropogenic and natural sources of ^{129}I.

9. ACKNOWLEDGMENTS

The author is grateful to K. F. Eckerman, F. O. Hoffman, G. Schwarz, and, most of all, G. G. Killough for many helpful discussions throughout the course of this work.

10. REFERENCES

1. G. G. Killough and J. E. Till, "Scenarios of ^{14}C Releases from the World Nuclear Power Industry from 1975 to 2020 and the Estimated Radiological Impact," *Nucl. Saf.* 19, 602 (1978).
2. J. F. Emery, S. A. Reynolds, E. I. Wyatt, and G. I. Gleason, "Half-Lives of Radionuclides - IV," *Nucl. Sci. Eng.* 48, 319 (1972).
3. B. C. Finney, R. E. Blanco, R. C. Dahlman, G. S. Hill, F. G. Kitts, R. E. Moore, and J. P. Witherspoon, *Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle--Reprocessing Light-Water Reactor Fuel*, ORNL/NUREG/TM-6, Oak Ridge National Laboratory, 1977.
4. G. Haury and W. Schikarski, "Radioactivity Inputs into the Environment; Comparison of Natural and Man-Made Inventories," p. 165 in *Global Chemical Cycles and Their Alterations by Man*, ed. by W. Stumm, Dahlem Conference, Berlin, 1977.
5. R. E. Cooper, *Population Dose Estimates Resulting from Radioactive Materials Discharging from a Nuclear Reprocessing Facility*, DPST-78-217, Savannah River Laboratory, 1978.
6. T. P. Kohman and R. R. Edwards, *Iodine-129 as a Geochemical and Ecological Tracer*, NYO-3624-1, U.S. Atomic Energy Commission, 1966.
7. R. R. Edwards and P. Rey, *Terrestrial Occurrence and Distribution of Iodine-129*, NYO-3624-3, U.S. Atomic Energy Commission, 1967.
8. G. G. Killough, "A Dynamic Model for Estimating Radiation Dose to the World Population from Releases of ^{14}C to the Atmosphere," *Health Phys.*, to be published.
9. T. von Fellenberg, "Das Vorkommen, der Kreislauf und der Stoffwechsel des Jods," *Ergeb. Physiol.* 25, 175 (1926).
10. J. F. McLendon, *Iodine and the Incidence of Goiter,* University of Minnesota-Oxford Press, 1939.
11. V. M. Goldschmidt, *Geochemistry*, Oxford University Press, London, 1954.
12. B. Brehler and R. Fuge, "Iodine," vol. II/3, Chap. 53 in *Handbook of Geochemistry*, ed. by K. H. Wedepohl, Springer-Verlag, Berlin, 1974.
13. Y. Miyake and S. Tsunogai, "Evaporation of Iodine from the Ocean," *J. Geophys. Res.* 68, 3989 (1963).

14. *The Water Encyclopedia*, ed. by D. K. Todd, Water Information Center, Port Washington, N.Y., 1970.
15. W. G. N. Slinn, L. Hasse, B. B. Hicks, A. W. Hogan, D. Lal, P. S. Liss, K. O. Munnich, G. A. Sehmel, and O. Vittori, "Some Aspects of the Transfer of Atmospheric Trace Constituents Past the Air-Sea Interface," *Atmos. Environ.* 12, 2055 (1978).
16. F. B. Brauer, H. G. Rieck, Jr., and R. L. Hooper, "Particulate and Gaseous Atmospheric Iodine Concentrations," p. 351 in *Physical Behaviour of Radioactive Contaminants in the Atmosphere*, International Atomic Energy Agency, Vienna, 1974.
17. S. V. Kaye and D. J. Nelson, "Analysis of Specific-Activity Concept as Related to Environmental Concentration of Radionuclides," *Nucl. Saf.* 9, 53 (1968).
18. P. M. Bryant, "Derivation of Working Limits for Continuous Release Rates of ^{129}I to the Atmosphere," *Health Phys.* 19, 611 (1970).
19. J. L. Russell and P. B. Hahn, "Public Health Aspects of Iodine-129 from the Nuclear Power Industry," *Radiol. Health Data Rep.* 12, 189 (1971).
20. J. Tadmor, "Consideration of Stable Iodine in the Environment in the Evaluation of Maximum Permissible Concentrations for Iodine-129," *Radiol. Health Data Rep.* 12, 611 (1971).
21. J. M. Palms, V. R. Veluri, and F. W. Boone, "The Environmental Impact of ^{129}I Released by a Nuclear Fuel-Reprocessing Plant," *Nucl. Saf.* 16, 593 (1975).
22. G. N. Kelly, J. A. Jones, P. M. Bryant, and F. Morley, *The Predicted Radiation Exposure of the Population of the European Community Resulting from Discharges of Krypton-85, Tritium, Carbon-14, and Iodine-129 from the Nuclear Power Industry to the Year 2000*, Commission of the European Communities, Luxembourg, 1975.
23. R. Bergman, U. Bergstrom, and S. Evans, *Environmental Transport and Long-Term Dose. A Preliminary Study of Iodine 129*, S-575, Aktiebolaget Atomenergi, 1977.
24. V. T. Chow, "Hydrology and Its Development," Sect. I in *Handbook of Applied Hydrology*, ed. by V. T. Chow, McGraw-Hill, New York, 1964.

25. R. Heindryckx and R. Dams, "Continental, Marine, and Anthropogenic Contributions to the Inorganic Composition of the Aerosol of an Industrial Zone," *J. Radioanal. Chem.* 19, 339 (1974).
26. H. Cauer, "Schwankungen der Jodmenge der Luft in Mitteleuropa, deren Ursachen und deren Bedeutung fuer den Jodgehalt unserer Nahrung (Auszug)," *Angew. Chem.* 52, 625 (1939).
27. R. A. Duce, J. W. Winchester, and T. W. Van Nahl, "Iodine, Bromine, and Chlorine in the Hawaiian Marine Atmosphere," *J. Geophys. Res.* 70, 1775 (1965).
28. B. Bolin, "Note on the Exchange of Iodine between the Atmosphere, Land, and Sea," *Int. J. Air. Pollut.* 2, 127 (1959).
29. R. B. Platt, J. M. Palms, H. L. Ragsdale, D. J. Shure, P. G. Mayer, and J. A. Mohrbacher, "Empirical Benefits Derived from an Ecosystem Approach to Environmental Monitoring of a Nuclear Fuel Reprocessing Plant," p. 673 in *Environmental Behaviour of Radionuclides Released in the Nuclear Industry*, International Atomic Energy Agency, Vienna, 1973.
30. R. C. McFarland, D. M. Walker, and M. E. McLain, Jr., "Determination of Atmospheric Concentrations of Stable Iodine," *IEEE Trans. Nucl. Sci.* 21, 503 (1974).
31. H. Vogg and R. Haertel, "Experience in the Analysis of Atmospheric Aerosols of the Karlsruhe Nuclear Research Center," *J. Radioanal. Chem.* 37, 857 (1977).
32. E. R. Reiter, *Atmospheric Transport Processes. Part 2; Chemical Tracers*, U.S. Atomic Energy Commission, 1971.
33. H. Oeschger, U. Siegenthaler, U. Schotterer, and A. Gugelmann, "A Box Diffusion Model to Study the Carbon Dioxide Exchange in Nature," *Tellus* 27, 168 (1975).
34. O. V. Shishkina and G. A. Pavlova, "Iodine Distribution in Marine and Oceanic Bottom Muds and in Their Pore Fluids," *Geochem. Int.* 2, 559 (1965).
35. E. D. Goldberg and G. O. S. Arrhenius, "Chemistry of Pelagic Sediments," *Geochim. Cosmochim. Acta* 13, 153 (1958).
36. C. C. Travis, *Mathematical Description of Adsorption and Transport of Reactive Solutes in Soil: A Review of Selected Literature*, ORNL-5403, Oak Ridge National Laboratory, 1978.

37. R. E. Wildung, R. C. Routson, R. J. Serne, and T. R. Garland, "Pertechnetate, Iodide, and Methyl Iodide Retention by Surface Soils," p. 37 in *Pacific Northwest Laboratory Annual Report for 1974 to the USAEC Division of Biomedical and Environmental Research, Part 2, Environmental Sciences*, BNWL-1950 PT 2, 1975.

38. W. S. Broecker, R. D. Gerard, M. Ewing, and B. C. Heezen, "Geochemistry and Physics of Ocean Circulation," p. 301 in *Oceanography*, ed. by M. Sears, Publication 67, American Association for the Advancement of Science, Washington, D.C., 1961.

39. H. T. Shacklette and M. E. Cuthbert, "Iodine Content of Plant Groups as Influenced by Variation in Rock and Soil Type," in *Relation of Geology and Trace Elements to Nutrition*, ed. by H. E. Cannon and D. F. Davidson, U.S. Geol. Soc. Spec. Paper 90, 1967, p. 31.

40. R. C. Ragaini, A. L. Langhorst, H. R. Ralston, and R. Heft, *Instrumental Trace Element Analysis of California Market Milk*, UCRL-51859, Lawrence Livermore Laboratory, 1975.

41. K. D. Fisher and C. J. Carr, *Iodine in Foods: Chemical Methodology and sources of Iodine in the Human Diet*, U.S. Food and Drug Administration, Washington, D.C., 1974.

42. *The International Atlas*, Rand McNally & Co., Chicago, 1977.

43. *Report of the Task Group on Reference Man*, International Commission on Radiological Protection Publication 23, Pergamon Press, Oxford, 1974.

44. S. A. Book, R. J. Garner, J. K. Soldat, and L. K. Bustad, "Thyroidal Burdens of ^{129}I from Various Dietary Sources," *Health Phys.* 32, 143 (1977).

45. J. K. Soldat, "Radiation Doses from Iodine-129 in the Environment," *Health Phys.* 30, 61 (1976).

46. F. O. Hoffman, "A Reassessment of the Deposition Velocity in the Prediction of the Environmental Transport of Radioiodine from Air to Milk," *Health Phys.* 32, 437 (1977).

47. A. C. Chamberlain and R. C. Chadwick, AERE-R 4870, United Kingdom Atomic Energy Agency, 1965.

48. Y. C. Ng, W. A. Phillips, Y. E. Ricker, R. K. Tandy, and S. E. Thompson, *Assessment of the Dose Commitment from Ingestion of Aquatic Foods Contaminated by Emissions from a Proposed Nuclear Fuel Reprocessing Plant*, UCID-17882, Lawrence Livermore Laboratory, 1978.

49. Y. C. Ng, W. A. Phillips, Y. E. Ricker, R. K. Tandy, and S. E. Thompson, *Methodology for Assessing Dose Commitment to Individuals and to the Population from Ingestion of Terrestrial Foods Contaminated by Emissions from a Nuclear Fuel Reprocessing Plant at the Savannah River Plant*, UCID-17743, Lawrence Livermore Laboratory, 1978.
50. Y. C. Ng, C. S. Colsher, D. J. Quinn, and S. E. Thompson, *Transfer Coefficients for the Prediction of the Dose to Man via the Forage-Cow-Milk Pathway from Radionuclides Released to the Biosphere*, UCRL-51939, Lawrence Livermore Laboratory, 1977.
51. *Regulatory Guide 1.109. Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I*, U.S. Nuclear Regulatory Commission, Washington, D.C., 1977.
52. *Report of Committee II on Permissible Dose for Internal Radiation*, International Commission on Radiological Protection Publication 2, Pergamon Press, Oxford, 1959.
53. G. G. Killough, D. E. Dunning, Jr., S. R. Bernard, and J. C. Pleasant, *Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities*, vol. 1, ORNL/NUREG/TM-190, Oak Ridge National Laboratory, 1978.
54. *Concise Report on the World Population Situation in 1970-1975 and Its Long Range Implications*, ST/ESA/SER.A/56, United Nations, 1974.
55. A. C. Hindmarsh, *GEAR: Ordinary Differential Equation System Solver*, Rev. 3, UCID-30001, Lawrence Livermore Laboratory, 1974.
56. G. E. Forsythe, M. A. Malcolm, and C. B. Moler, *Computer Methods for Mathematical Computations*, Prentice-Hall, Englewood Cliffs, N.J., 1977.

Appendix

LISTING OF THE CODE IODES

A listing of the computer code IODES is given on the following pages, with the exception of the on-line software package GEAR[1] which solves systems of ordinary differential equations. The other subroutines and function subprograms are listed in the same order as they are described in Sect. 6.

REFERENCE FOR APPENDIX

1. A. C. Hindmarsh, *GEAR: Ordinary Differential Equation System Solver*, Rev. 3, UCID-30001, Lawrence Livermore Laboratory, 1974.

```
C
C PROGRAM IODES (IODINE, GR.)
C
C A PROGRAM TO ESTIMATE DOSE RATES AND CUMULATIVE DOSES TO THE WORLD POPULATION
C   FROM ENVIRONMENTAL RELEASES OF I-129. A LINEAR, TIME-INVARIANT COMPARTMENT
C   MODEL IS USED TO CALCULATE INVENTORIES OF I-129 IN VARIOUS ENVIRONMENTAL
C   COMPARTMENTS AS A FUNCTION OF TIME AFTER THE BEGINNING OF A RELEASE. THE
C   AVERAGE INTAKE OF I-129 IS CALCULATED FROM THE COMPARTMENT INVENTORIES OF
C   I-129 AND THE ESTIMATED INTAKE OF STABLE IODINE FROM THE DIFFERENT
C   COMPARTMENTS BY A REFERENCE INDIVIDUAL.
C
C PROGRAM AUTHOR:  D. C. KOCHER
C                  HEALTH AND SAFETY RESEARCH DIVISION
C                  OAK RIDGE NATIONAL LABORATORY
C                  P. O. BOX X
C                  OAK RIDGE, TENNESSEE  37830
C
C DATE:  APRIL 1979
C
      IMPLICIT REAL*8 (A-H, O-Z)
      EXTERNAL DIFFUN, PEDERV
      DIMENSION X(15), XP(15)
      COMMON/ BLK1/ FK12, FK13, FK21, FK24, FK31, FK36, FK43, FK45,
     2 FK48, FK49, FK52, FK54, FK63, FK67, FK76, FK83, FK93, CLAM
      COMMON/ BLK2/ FK10IN, FK10FD, FK11, FK120, FK13S
      COMMON/ BLK3/ YSTART
      COMMON/ BLK5/ SPA129
C
C DEFINE PARAMETERS FOR CALCULATION OF FRACTIONAL TRANSFER RATES OF I-129
C   BETWEEN ENVIRONMENTAL COMPARTMENTS
C
C   AVERAGE ANNUAL RAINFALL ON LAND IN G/YR
C   AVERAGE FRACTIONAL CONTENT OF IODINE IN RAINFALL OVER LAND
C   AVERAGE ANNUAL RAINFALL ON OCEANS IN G/YR
C   AVERAGE FRACTIONAL CONTENT OF IODINE IN RAINFALL OVER OCEANS
C
      DATA RAINL, FIODRL, RAINO, FIODRO/ 1.0D20, 1.0D-9, 3.2D20, 6.0D-9/
C
C   AVERAGE ANNUAL RUNOFF OF RIVERS IN G/YR
C   AVERAGE FRACTIONAL CONTENT OF IODINE IN RIVER WATER
C
      DATA RIVRUN, FIODRV/ 3.23D19, 3.0D-9/
C
C   AVERAGE CONCENTRATION OF IODINE IN ATMOSPHERE OVER LAND IN G/(CU M)
C   AVERAGE CONCENTRATION OF IODINE IN ATMOSPHERE OVER OCEANS IN G/(CU M)
C
      DATA CIODAL, CIODAO/ 5.0D-9, 3.0D-8/
C
C   ATOMIC MASS OF I-129
C   HALF-LIFE OF I-129 IN YR
C   AVOGADRO'S NUMBER
C
      DATA EMI129, THALF, AVO/ 1.29D2, 1.57D7, 6.02D23/
C
C   AREA OF LAND SURFACE IN SQ M
C   AREA OF OCEAN SURFACE IN SQ M
```

```
C    HEIGHT OF HOMOGENEOUS ATMOSPHERE IN M
C    DENSITY OF WATER IN G/(CU CM)
C    DEPTH OF OCEAN MIXED LAYER IN M
C    DEPTH OF DEEP OCEAN IN M
C
       DATA AREAL, AREAO, ZATM, RHOW, ZML, ZDO/ 1.49D14, 3.61D14, 7.7D3,
      2 1.0D0, 7.5D1, 3.725D3/
C
C    AVERAGE FRACTIONAL CONTENT OF IODINE IN OCEAN MIXED LAYER
C    AVERAGE FRACTIONAL CONTENT OF IODINE IN DEEP OCEAN
C
       DATA FIODML, FIODDO/ 5.0D-8, 6.0D-8/
C
C    DEPOSITION RATE OF OCEAN SEDIMENTS IN CM/YR
C    AVERAGE DENSITY OF SEDIMENTS IN G/(CU CM)
C    AVERAGE FRACTIONAL CONTENT OF IODINE IN SEDIMENTS
C
       DATA SEDRAT, RHOSED, FIODSD/ 2.0D-4, 2.5D0, 1.0D-4/
C
C    FRACTION OF RIVER RUNOFF FROM SURFACE SOIL REGION
C    FRACTION OF RIVER RUNOFF FROM SHALLOW SUBSURFACE REGION
C    FRACTION OF RIVER RUNOFF FROM DEEP SUBSURFACE REGION
C
       DATA FRUNSL, FRUNSH, FRUNDP/ 8.3D-1, 1.7D-1, 3.3D-3/
C
C    AVERAGE DENSITY OF SOIL IN G/(CU CM)
C    ASSUMED DEPTH OF SURFACE SOIL REGION IN M
C    AVERAGE FRACTIONAL CONTENT OF IODINE IN SOIL
C
       DATA RHOSL, ZSOIL, FIODSL/ 1.4D0, 1.0D0, 5.0D-6/
C
C    TERRESTRIAL BIOMASS IN G
C    NET PRIMARY PRODUCTION OF TERRESTRIAL BIOMASS IN G/YR
C    AVERAGE FRACTIONAL CONTENT OF IODINE IN TERRESTRIAL BIOSPHERE
C    AVERAGE FRACTION OF IODINE IN TERRESTRIAL BIOSPHERE RELEASED TO ATMOSPHERE
C
       DATA BIOMAS, BIPROD, FIODTB, FIBTA/ 1.0D18, 5.2D16, 1.0D-7,
      2 1.0D-1/
C
C    ASSUMED AVERAGE DOWNWARD WATER FLOW VELOCITY THROUGH POROUS ROCK IN M/YR
C    ASSUMED AVERAGE DENSITY OF POROUS ROCK IN SHALLOW AND DEEP SUBSURFACE
C      REGIONS IN G/(CU CM)
C    ASSUMED AVERAGE POROSITY OF ROCK
C    ASSUMED AVERAGE IODINE SOIL-WATER DISTRIBUTION COEFFICIENT IN L/KG
C
       DATA VELWAT, RHORCK, POROS, FKD/ 5.0D-1, 2.5D0, 1.0D-1, 1.0D1/
C
C    ASSUMED AVERAGE DEPTH OF GROUNDWATER IN SHALLOW SUBSURFACE REGION IN M
C    MEAN RESIDENCE TIME OF GROUNDWATER IN SHALLOW SUBSURFACE REGION IN YR
C    ASSUMED AVERAGE DEPTH OF GROUNDWATER IN DEEP SUBSURFACE REGION IN M
C    MEAN RESIDENCE TIME OF GROUNDWATER IN DEEP SUBSURFACE REGION IN YR
C
       DATA ZSHGRW, TSHGRW, ZDPGRW, TDPGRW/ 4.0D2, 2.0D2, 2.4D3, 1.0D4/
C
C DEFINE ADDITIONAL PARAMETERS FOR CALCULATION OF DOSE FROM INTAKE OF I-129 BY A
C    REFERENCE INDIVIDUAL
C
C    AVERAGE INTAKE OF FOODSTUFFS IN KG/D--
```

```
C      MILK
C      OTHER FLUIDS
C      MEAT
C      LEAFY VEGETABLES
C      OTHER VEGETABLES, FRUITS, AND NUTS
C      CEREALS
C      FISH
C      OTHER FOODSTUFFS
C
       DATA QMILK, QFLUID, QMEAT, QLVEG, QOVEG, QCER, QFISH, QOTHER/
     2 2.6D-1, 1.4D0, 7.0D-2, 8.0D-2, 2.5D-1, 3.8D-1, 2.3D-2, 2.8D-1/
C
C     AVERAGE INTAKE OF AIR IN L/D
C
       DATA QAIR/ 2.2D4/
C
C     TRANSFER COEFFICIENTS FROM ATMOSPHERE TO FOODSTUFFS VIA FOLIAR DEPOSITION IN
C       (CU M)/KG--
C       MILK
C       MEAT
C       LEAFY VEGETABLES
C       OTHER VEGETABLES AND FRUITS
C       CEREALS
C
       DATA CAMILK, CAMEAT, CALVEG, CAOVEG, CACER/ 1.25D3, 1.6D3, 2.9D3,
     2 2.9D2, 5.4D2/
C
C     AVERAGE INTAKE OF WATER BY CATTLE IN KG/D--
C       DAIRY CATTLE
C       BEEF CATTLE
C
       DATA DCWAT, BCWAT/ 6.0D1, 4.0D1/
C
C     TRANSFER COEFFICIENTS FOR CATTLE FROM INGESTION--
C       MILK IN D/L
C       MEAT IN D/KG
C
       DATA CIMILK, CIMEAT/ 1.0D-2, 7.0D-3/
C
C     CONCENTRATION FACTORS FOR IODINE IN FISH IN L/KG--
C       FRESHWATER FISH
C       SALTWATER FISH
C
       DATA CFFRF, CFSAF/ 2.0D2, 3.0D1/
C
C     AVERAGE INTAKE OF FORAGE BY CATTLE IN KG/D
C
       DATA QFORG/ 5.5D1/
C
C     DOSE CONVERSION FACTORS FOR MAXIMUM 50-YEAR DOSE COMMITMENT TO THYROID FROM
C       INHALATION AND INGESTION OF I-129 IN REM/MICROCURIE
C
       DATA DCFINH, DCFING/ 4.97D0, 7.78D0/
C
C     NUMBER OF DAYS PER YEAR
C     NUMBER OF DISINTEGRATIONS PER SECOND PER CURIE
C     NUMBER OF SECONDS PER YEAR
C
```

```
      DATA DPY, DPSPCI, SPY/ 3.65D2, 3.7D10, 3.1536D7/
C
C CALCULATE FRACTIONAL TRANSFER RATES OF IODINE BETWEEN ENVIRONMENTAL
C   COMPARTMENTS. THE QUANTITY YI DENOTES THE MASS OF STABLE IODINE IN
C   COMPARTMENT I IN G. THE QUANTITY YIJ DENOTES THE FLUX OF STABLE
C   IODINE FROM COMPARTMENT I TO COMPARTMENT J IN G/YR. THE QUANTITY FKIJ
C   DENOTES THE FRACTIONAL TRANSFER RATE FROM COMPARTMENT I TO COMPARTMENT J IN
C   UNITS OF 1/YR. THE INDICES HAVE THE FOLLOWING MEANING--
C      1 - OCEAN ATMOSPHERE
C      2 - LAND ATMOSPHERE
C      3 - OCEAN MIXED LAYER
C      4 - SURFACE SOIL REGION
C      5 - TERRESTRIAL BIOSPHERE
C      6 - DEEP OCEAN
C      7 - OCEAN SEDIMENTS
C      8 - SHALLOW SUBSURFACE REGION OF LITHOSPHERE
C      9 - DEEP SUBSURFACE REGION OF LITHOSPHERE
C
C   OCEAN ATMOSPHERE TO MIXED LAYER; LAND ATMOSPHERE TO SURFACE SOIL REGION
C
C      FLUXES
C
      Y13=RAINO*FIODRO
      Y24=RAINL*FIODRL
C
C      IODINE CONTENT OF OCEAN AND LAND ATMOSPHERE IN HOMOGENEOUS APPROXIMATION
C
      Y1=CIODAO*AREAO*ZATM
      Y1=(1.0D1)*Y1
      Y2=CIODAL*AREAL*ZATM
      Y2=(1.0D1)*Y2
C
C      FRACTIONAL TRANSFER RATES
C
      FK13=Y13/Y1
      FK24=Y24/Y2
C
C   TERRESTRIAL BIOSPHERE TO ATMOSPHERE AND SURFACE SOIL REGION
C
C      IODINE CONTENT IN TERRESTRIAL BIOSPHERE
C
      Y5=BIOMAS*FIODTB
C
C      FLUXES
C
      Y52=BIPROD*FIODTB*FIBTA
      Y54=BIPROD*FIODTB*(1.0D0-FIBTA)
C
C      FRACTIONAL TRANSFER RATES
C
      FK52=BIPROD*FIBTA/BIOMAS
      FK54=BIPROD*(1.0D0-FIBTA)/BIOMAS
C
C   LAND ATMOSPHERE TO OCEAN ATMOSPHERE AND VICE VERSA
C
C      NET FLUX FROM OCEAN ATMOSPHERE TO LAND ATMOSPHERE
C
      Y12=Y24-Y52
```

```
C
C     ASSUMED RATIO OF FK21 TO FK12
C
      RATOA=AREAO/AREAL
C
C     FRACTIONAL TRANSFER RATES
C
      FK12=Y12/(Y1-RATOA*Y2)
      FK21=RATOA*FK12
C
C   MIXED LAYER TO OCEAN ATMOSPHERE
C
C     IODINE CONTENT IN MIXED LAYER
C
      Y3=RHOW*AREAO*ZML*FIODML*(1.0D6)
C
C     FRACTIONAL TRANSFER RATE
C
      FK31=(Y13+Y24)/Y3
C
C   DEEP OCEAN TO MIXED LAYER
C
C     ASSUMED MEAN RESIDENCE TIME FOR IODINE IN DEEP OCEAN IN YR
C
      TDPOC=1.127D3
C
C     FRACTIONAL TRANSFER RATE
C
      FK63=(1.0D0)/TDPOC
C
C   MIXED LAYER TO DEEP OCEAN
C
C     IODINE CONTENT OF DEEP OCEAN
C
      Y6=RHOW*AREAO*ZDO*FIODDO*(1.0D6)
C
C     FRACTIONAL TRANSFER RATE
C
      FK36=Y6*FK63/Y3
C
C   DEEP OCEAN TO OCEAN SEDIMENTS
C
C     FLUX
C
      Y67=SEDRAT*AREAO*RHOSED*FIODSD*(1.0D4)
C
C     FRACTIONAL TRANSFER RATE
C
      FK67=Y67/Y6
C
C   OCEAN SEDIMENTS TO DEEP OCEAN
C
C     CALCULATION IS BASED ON MEASUREMENT THAT IODINE CONTENT IN SEDIMENTS IS
C       REDUCED BY A FACTOR OF 2 AT A DEPTH OF 7 M
C
      FK76=-(DLOG(0.5D0))*SEDRAT/(7.0D2)
C
C   SURFACE SOIL REGION TO TERRESTRIAL BIOSPHERE, OCEAN MIXED LAYER, AND SHALLOW
```

```
C     SUBSURFACE AND DEEP SUBSURFACE REGIONS OF LITHOSPHERE
C
C     IODINE CONTENT OF SURFACE SOIL REGION
C
      Y4=RHOSL*AREAL*ZSOIL*FIODSL*(1.0D6)
C
C     FLUX FROM LITHOSPHERE TO OCEAN MIXED LAYER
C
      YLAND2=RIVRUN*FIODRV
C
C     FRACTIONAL TRANSFER RATES
C
      FK45=(Y52+Y54)/Y4
      FK43=YLAND2*FRUNSL/Y4
      FK48=YLAND2*FRUNSH/Y4
      FK49=YLAND2*FRUNDP/Y4
C
C   SHALLOW SUBSURFACE AND DEEP SUBSURFACE REGIONS OF LITHOSPHERE TO OCEAN MIXED
C     LAYER
C
C     THIS CALCULATION GIVES MEAN RESIDENCE TIMES BY ASSUMING THAT ONLY IODINE
C       WHICH IS TRANSPORTED BY THE DOWNWARD FLOW OF WATER FROM THE SURFACE SOIL
C       REGION IS ACCESSIBLE TO GROUNDWATER
C
C     RETARDATION FACTOR FOR IODINE
C
      RETARD=1.0D0+RHORCK*FKD/POROS
C
C     DOWNWARD FLOW VELOCITY OF IODINE IN M/YR
C
      VIOD=VELWAT/RETARD
C
C     AVERAGE TIME OF TRANSPORT TO GROUNDWATER IN SHALLOW AND DEEP SUBSURFACE
C       REGIONS IN YR
C
      TRANSH=ZSHGRW/VIOD
      TRANDP=ZDPGRW/VIOD
C
C     FRACTIONAL TRANSFER RATES
C
      FK83=(1.0D0)/(TRANSH+TSHGRW*RETARD)
      FK93=(1.0D0)/(TRANDP+TDPGRW*RETARD)
C
C CALCULATE RADIOACTIVE DECAY CONSTANT IN 1/YR
C
      CLAM=DLOG(2.0D0)/THALF
C
C CALCULATE COEFFICIENTS FOR OBTAINING DOSE RATES FROM INTAKE OF I-129 FROM
C   INVENTORIES IN ENVIRONMENTAL COMPARTMENTS. THE INDICES HAVE THE FOLLOWING
C   MEANING--
C     10 - INTAKE FROM ATMOSPHERE
C     11 - INTAKE FROM SURFACE WATERS OF LITHOSPHERE
C     12 - INTAKE FROM OCEAN MIXED LAYER
C     13 - INTAKE FROM SURFACE SOIL REGION
C
C   SPECIFIC ACTIVITY OF I-129 IN CI/G
C
      SPA129=AVO*CLAM/(EMI129*SPY*DPSPCI)
```

```
C
C    INTAKE FROM ATMOSPHERE
C
C      IODINE INTAKE FROM INHALATION AND FOLIAR DEPOSITION IN MICROGRAMS/YR
C
      QIOINH=QAIR*CIODAL*DPY*(1.0D3)
      QIOFOD=(QMILK*CAMILK+QMEAT*CAMEAT+QLVEG*CALVEG+QOVEG*CAOVEG+QCER*
     2 CACER)*CIODAL*DPY*(1.0D6)
C
C      INTAKE COEFFICIENTS FOR INHALATION AND FOLIAR DEPOSITION
C
      FK10IN=QIOINH*SPA129*DCFINH/Y2
      FK10FD=QIOFOD*SPA129*DCFING/Y2
C
C    INTAKE FROM SURFACE WATERS OF LITHOSPHERE
C
C      IODINE INTAKE FROM INGESTION OF FLUIDS BY MAN, INGESTION OF WATER BY DAIRY
C        CATTLE, INGESTION OF WATER BY BEEF CATTLE, AND INGESTION OF FRESHWATER
C        FISH IN MICROGRAMS/YR
C
      QIOFL=QFLUID*FIODRV*DPY*(1.0D9)
      QIODCW=DCWAT*FIODRV*CIMILK*QMILK*DPY*(1.0D9)
      QIOBCW=BCWAT*FIODRV*CIMEAT*QMEAT*DPY*(1.0D9)
      QIOFWF=QFISH*CFFRF*FIODRV*DPY*(1.0D9)/(2.0D0)
C
C      INTAKE COEFFICIENT
C
      FK11=(QIOFL+QIODCW+QIOBCW+QIOFWF)*SPA129*DCFING/YLAND2
C
C    INTAKE FROM OCEAN MIXED LAYER
C
C      IODINE INTAKE FROM INGESTION OF SALTWATER FISH IN MICROGRAMS/YR
C
      QIOSWF=QFISH*CFSAF*FIODML*DPY*(1.0D9)/(2.0D0)
C
C      INTAKE COEFFICIENT
C
      FK12O=QIOSWF*SPA129*DCFING/Y3
C
C    INTAKE FROM SURFACE SOIL REGION
C
C      IODINE INTAKE FROM ROOT UPTAKE IN FOODSTUFFS CONSUMED BY MAN, FORAGE
C        CONSUMED BY DAIRY CATTLE, AND FORAGE CONSUMED BY BEEF CATTLE IN
C        MICROGRAMS/YR
C
      QIOSL=(QLVEG+QOVEG+QCER+QOTHER)*FIODTB*DPY*(1.0D9)
      QIODCS=QFORG*FIODTB*CIMILK*QMILK*DPY*(1.0D9)
      QIOBCS=QFORG*FIODTB*CIMEAT*QMEAT*DPY*(1.0D9)
C
C      INTAKE COEFFICIENT
C
      FK13S=(QIOSL+QIODCS+QIOBCS)*SPA129*DCFING/Y4
C
C WRITE CALCULATED FRACTIONAL TRANSFER RATES FOR TRANSPORT OF IODINE BETWEEN
C    ENVIRONMENTAL COMPARTMENT
C
      WRITE (10,1)
    1 FORMAT (1H1)
```

```
      WRITE (10,2)
    2 FORMAT (1H0, 5X, 66HFRACTIONAL TRANSFER RATES FOR GLOBAL IODINE CY
     2CLE IN UNITS OF 1/YR)
      WRITE (10,3) FK12
    3 FORMAT (1H0, 10X, 36HOCEAN ATMOSPHERE TO LAND ATMOSPHERE=, 1PE9.2)
      WRITE (10,4) FK13
    4 FORMAT (1H0, 10X, 38HOCEAN ATMOSPHERE TO OCEAN MIXED LAYER=,
     2 1PE9.2)
      WRITE (10,5) FK21
    5 FORMAT (1H0, 10X, 36HLAND ATMOSPHERE TO OCEAN ATMOSPHERE=, 1PE9.2)
      WRITE (10,6) FK24
    6 FORMAT (1H0, 10X, 39HLAND ATMOSPHERE TO SURFACE SOIL REGION=,
     2 1PE9.2)
      WRITE (10,7) FK31
    7 FORMAT (1H0, 10X, 38HOCEAN MIXED LAYER TO OCEAN ATMOSPHERE=,
     2 1PE9.2)
      WRITE (10,8) FK36
    8 FORMAT (1H0, 10X, 32HOCEAN MIXED LAYER TO DEEP OCEAN=, 1PE9.2)
      WRITE (10,9) FK43
    9 FORMAT (1H0, 10X, 41HSURFACE SOIL REGION TO OCEAN MIXED LAYER=,
     2 1PE9.2)
      WRITE (10,10) FK45
   10 FORMAT (1H0, 10X, 45HSURFACE SOIL REGION TO TERRESTRIAL BIOSPHERE=
     2, 1PE9.2)
      WRITE (10,11) FK48
   11 FORMAT (1H0, 10X, 49HSURFACE SOIL REGION TO SHALLOW SUBSURFACE REG
     2ION=, 1PE9.2)
      WRITE (10,12) FK49
   12 FORMAT (1H0, 10X, 46HSURFACE SOIL REGION TO DEEP SUBSURFACE REGION
     2=, 1PE9.2)
      WRITE (10,13) FK52
   13 FORMAT (1H0, 10X, 41HTERRESTRIAL BIOSPHERE TO LAND ATMOSPHERE=,
     2 1PE9.2)
      WRITE (10,14) FK54
   14 FORMAT (1H0, 10X, 45HTERRESTRIAL BIOSPHERE TO SURFACE SOIL REGION=
     2, 1PE9.2)
      WRITE (10,56) FK63
   56 FORMAT (1H0, 10X, 32HDEEP OCEAN TO OCEAN MIXED LAYER=, 1PE9.2)
      WRITE (10,57) FK67
   57 FORMAT (1H0, 10X, 30HDEEP OCEAN TO OCEAN SEDIMENTS=, 1PE9.2)
      WRITE (10,58) FK76
   58 FORMAT (1H0, 10X, 30HOCEAN SEDIMENTS TO DEEP OCEAN=, 1PE9.2)
      WRITE (10,59) FK83
   59 FORMAT (1H0, 10X, 47HSHALLOW SUBSURFACE REGION TO OCEAN MIXED LAYE
     2R=, 1PE9.2)
      WRITE (10,60) FK93
   60 FORMAT (1H0, 10X, 44HDEEP SUBSURFACE REGION TO OCEAN MIXED LAYER=,
     2 1PE9.2)
      WRITE (10,15) CLAM
   15 FORMAT (1H0, 10X, 28HRADIOLOGICAL DECAY CONSTANT=, 1PE9.2)
C
C WRITE CALCULATED COEFFICIENTS FOR DOSE RATES FROM INTAKE OF I-129
C
      WRITE (11,1)
      WRITE (11,16)
   16 FORMAT (1H0, 5X, 63HCOEFFICIENTS FOR CALCULATION OF DOSE RATES FRO
     2M INTAKE OF I-129)
      WRITE (11,17) SPA129
```

```
   17 FORMAT (1H0, 10X, 27HSPECIFIC ACTIVITY OF I-129=, 1PE9.2, 1X,
     2 4HCI/G)
      WRITE (11,18)
   18 FORMAT (1H0, 10X, 72HDOSE CONVERSION FACTORS FOR MAXIMUM 50-YEAR D
     2OSE COMMITMENT TO THYROID--)
      WRITE (11,19) DCFINH
   19 FORMAT (1H0, 20X, 11HINHALATION=, 1PE9.2, 1X, 18HREM PER MICROCURI
     2E)
      WRITE (11,20) DCFING
   20 FORMAT (1H0, 21X, 10HINGESTION=, 1PE9.2, 1X, 18HREM PER MICROCURIE
     2)
      WRITE (11,21)
   21 FORMAT (1H0, 10X, 41HCOEFFICIENTS FOR INTAKE FROM ATMOSPHERE--)
      WRITE (11,22) FK10IN
   22 FORMAT (1H0, 27X, 11HINHALATION=, 1PE9.2)
      WRITE (11,23) FK10FD
   23 FORMAT (1H0, 20X, 18HFOLIAR DEPOSITION=, 1PE9.2)
      WRITE (11,24) FK11
   24 FORMAT (1H0, 10X, 58HCOEFFICIENT FOR INTAKE FROM SURFACE WATERS OF
     2 LITHOSPHERE=, 1PE9.2)
      WRITE (11,25) FK12O
   25 FORMAT (1H0, 10X, 46HCOEFFICIENT FOR INTAKE FROM OCEAN MIXED LAYER
     2=, 1PE9.2)
      WRITE (11,26) FK13S
   26 FORMAT (1H0, 10X, 48HCOEFFICIENT FOR INTAKE FROM SURFACE SOIL REGI
     2ON=, 1PE9.2)
C
C CHECK BALANCE OF THE GLOBAL IODINE CYCLE AT STEADY STATE
C
      CALL BALCHK (Y1, Y2, Y3, Y4, Y5, Y6)
C
C DEFINE PARAMETERS FOR INPUT TO SUBROUTINE GEAR
C
C   NUMBER OF DIFFERENTIAL EQUATIONS
C   STARTING TIME FOR INTEGRATION
C   INTEGRATION STEP SIZE
C   TIME AT WHICH OUTPUT IS DESIRED
C   RELATIVE ERROR BOUND
C   METHOD FLAG
C   TYPE OF CALL
C
      N=15
      T0=0.0D0
      H0=1.0D-9
      TOUT=1.0D-1
      EPS=1.0D-8
      MF=21
      INDEX=1
C
C   INITIALIZE INVENTORIES OF I-129 IN THE ENVIRONMENTAL COMPARTMENTS, DOSE
C     RATES, AND POPULATION DOSE
C
      DO 27 I=1,N
      X(I)=0.0D0
   27 CONTINUE
C
C DEFINE YEAR CORRESPONDING TO STARTING TIME FOR INTEGRATION
C
```

```
      YSTART=1.98003
C
C ESTIMATE TIME AT WHICH RELEASED IODINE REACHES EQUILIBRIUM IN GLOBAL
C   CIRCULATION
C
      TF=(2.0D0)/DMIN1(FK12, FK13, FK21, FK24, FK31, FK36, FK43, FK45,
     2 FK48, FK49, FK52, FK54, FK63, FK67, FK76, FK83, FK93)
C
C WRITE DEFINITIONS OF OUTPUT VARIABLES
C
C   INVENTORIES OF I-129 IN ENVIRONMENTAL COMPARTMENTS
C
      WRITE (10,1)
      WRITE (10,28)
   28 FORMAT (1H0, 5X, 59HINVENTORIES OF I-129 IN ENVIRONMENTAL COMPARTM
     2ENTS IN GRAMS)
      WRITE (10,29)
   29 FORMAT (1H0, 10X, 23HX(1) - OCEAN ATMOSPHERE)
      WRITE (10,30)
   30 FORMAT (1H0, 10X, 22HX(2) - LAND ATMOSPHERE)
      WRITE (10,31)
   31 FORMAT (1H0, 10X, 24HX(3) - OCEAN MIXED LAYER)
      WRITE (10,32)
   32 FORMAT (1H0, 10X, 26HX(4) - SURFACE SOIL REGION)
      WRITE (10,33)
   33 FORMAT (1H0, 10X, 28HX(5) - TERRESTRIAL BIOSPHERE)
      WRITE (10,34)
   34 FORMAT (1H0, 10X, 17HX(6) - DEEP OCEAN)
      WRITE (10,35)
   35 FORMAT (1H0, 10X, 22HX(7) - OCEAN SEDIMENTS)
      WRITE (10,54)
   54 FORMAT (1H0, 10X, 47HX(8) - SHALLOW SUBSURFACE REGION OF LITHOSPHE
     2RE)
      WRITE (10,55)
   55 FORMAT (1H0, 10X, 44HX(9) - DEEP SUBSURFACE REGION OF LITHOSPHERE)
      ISTART=IFIX(SNGL(YSTART))
      WRITE (10,36) ISTART
   36 FORMAT (1H0, 20X, 35HYEAR FOR BEGINNING OF CALCULATION -, 1X, I4)
C
C   DOSE RATES AND POPULATION DOSE
C
      WRITE (11,1)
      WRITE (11,37)
   37 FORMAT (1H0, 5X, 103HDOSE RATES FROM INTAKE OF I-129 BY A REFERENC
     2E INDIVIDUAL IN REM/YR, CUMULATIVE INDIVIDUAL DOSE IN REM,)
      WRITE (11,52)
   52 FORMAT (1H , 15X, 41HAND CUMULATIVE POPULATION DOSE IN MAN-REM)
      WRITE (11,38)
   38 FORMAT (1H0, 10X, 54HD(1) - INDIVIDUAL DOSE RATE FOR INTAKE FROM A
     2TMOSPHERE)
      WRITE (11,39)
   39 FORMAT (1H0, 10X, 73HD(2) - INDIVIDUAL DOSE RATE FOR INTAKE FROM S
     2URFACE WATERS OF LITHOSPHERE)
      WRITE (11,40)
   40 FORMAT (1H0, 10X, 61HD(3) - INDIVIDUAL DOSE RATE FOR INTAKE FROM O
     2CEAN MIXED LAYER)
      WRITE (11,41)
   41 FORMAT (1H0, 10X, 63HD(4) - INDIVIDUAL DOSE RATE FOR INTAKE FROM S
```

```
    2URFACE SOIL REGION)
     WRITE (11,53)
  53 FORMAT (1HO, 10X, 33HD(5) - TOTAL INDIVIDUAL DOSE RATE)
     WRITE (11,49)
  49 FORMAT (1HO, 10X, 33HD(6) - CUMULATIVE INDIVIDUAL DOSE)
     WRITE (11,42)
  42 FORMAT (1HO, 10X, 33HD(7) - CUMULATIVE POPULATION DOSE)
C
C WRITE TABLE HEADINGS
C
     WRITE (10,1)
     WRITE (10,43)
  43 FORMAT (1HO, 3X, 5HT(YR), 9X, 4HX(1), 9X, 4HX(2), 9X, 4HX(3), 9X,
    2 4HX(4), 9X, 4HX(5), 9X, 4HX(6), 9X, 4HX(7), 9X, 4HX(8), 9X,
    3 4HX(9)/)
     WRITE (11,1)
     WRITE (11,44)
  44 FORMAT (1HO, 10X, 5HT(YR), 11X, 4HD(1), 11X, 4HD(2), 11X, 4HD(3),
    2 11X, 4HD(4), 11X, 4HD(5), 11X, 4HD(6), 11X, 4HD(7)/)
C
C CALCULATE COMPARTMENT INVENTORIES, DOSE RATES, INDIVIDUAL DOSE, AND POPULATION
C   DOSE UNTIL EQUILIBRIUM IS REACHED, AND WRITE RESULTS
C
  45 CALL GEAR (DIFFUN, PEDERV, N, TO, HO, X, TOUT, EPS, MF, INDEX)
     WRITE (10,46) TOUT, (X(I), I=1.9)
  46 FORMAT (1H , 1PE8.1, 9(1PE13.2))
     CALL DIFFUN (N, TOUT, X, XP)
     WRITE (11,61) TOUT, (XP(I), I=10,14), X(14), X(15)
  61 FORMAT (1H , 1PE15.1, 7(1PE15.2))
C
C   CALCULATE NEXT TIME AT WHICH OUTPUT IS DESIRED
C
     TOUMMY=TOUT
     TOUT=TOUMMY+DYEAR(TOUMMY)
     IF (TOUT .LE. TF) GO TO 45
C
C CALCULATE INDIVIDUAL AND POPULATION DOSES FROM EQUILIBRIUM UNTIL DECAY IS
C   COMPLETE, TOTAL DOSES, AND WRITE RESULTS
C
     DITI=XP(14)/CLAM
     WRITE (11,50) DITI
  50 FORMAT (1HO, 51X, 29HINDIVIDUAL DOSE TO INFINITY -, 1PE9.2)
     DPTI=XP(15)/CLAM
     WRITE (11,47) DPTI
  47 FORMAT (1HO, 51X, 29HPOPULATION DOSE TO INFINITY -, 1PE9.2)
     TOTIND=X(14)+DITI
     WRITE (11,51) TOTIND
  51 FORMAT (1HO, 57X, 23HTOTAL INDIVIDUAL DOSE -, 1PE9.2)
     TOTDOS=X(15)+DPTI
     WRITE (11,48) TOTDOS
  48 FORMAT (1HO, 57X, 23HTOTAL POPULATION DOSE -, 1PE9.2)
     STOP
     END
```

```
C
      SUBROUTINE BALCHK (Y1, Y2, Y3, Y4, Y5, Y6)
C
C CHECKS BALANCE OF INPUT AND OUTPUT FLUXES FOR GLOBAL IODINE CYCLE AT STEADY
C   STATE FROM ASSUMED COMPARTMENT INVENTORIES AND FRACTIONAL TRANSFER RATES
C
      IMPLICIT REAL*8 (A-H, O-Z)
      COMMON/ BLK1/ FK12, FK13, FK21, FK24, FK31, FK36, FK43, FK45,
     2 FK48, FK49, FK52, FK54, FK63, FK67, FK76, FK83, FK93, CLAM
C
C WRITE TABLE HEADINGS
C
      WRITE (10,1)
    1 FORMAT (1H1)
      WRITE (10,2)
    2 FORMAT (1H0, 5X, 77HCOMPARISON OF INPUT AND OUTPUT FLUXES FOR GLOB
     2AL IODINE CYCLE AT STEADY STATE)
      WRITE (10,3)
    3 FORMAT (1H0, 20X, 11HCOMPARTMENT, 10X, 17HINPUT FLUX (G/YR), 10X,
     2 18HOUTPUT FLUX (G/YR)/)
C
C BALANCE FOR OCEAN ATMOSPHERE
C
      FLIN=FK21*Y2+FK31*Y3
      FLOUT=(FK12+FK13)*Y1
      WRITE (10,4) FLIN, FLOUT
    4 FORMAT (1H , 15X, 16HOCEAN ATMOSPHERE, 12X, 1PE15.2, 13X, 1PE15.2)
C
C BALANCE FOR LAND ATMOSPHERE
C
      FLIN=FK12*Y1+FK52*Y5
      FLOUT=(FK21+FK24)*Y2
      WRITE (10,5) FLIN, FLOUT
    5 FORMAT (1H , 16X, 15HLAND ATMOSPHERE, 12X, 1PE15.2, 13X, 1PE15.2)
C
C BALANCE FOR OCEAN MIXED LAYER
C
      FLIN=FK13*Y1+FK24*Y2+FK63*Y6
      FLOUT=(FK31+FK36)*Y3
      WRITE (10,6) FLIN, FLOUT
    6 FORMAT (1H , 14X, 17HOCEAN MIXED LAYER, 12X, 1PE15.2, 13X,
     2 1PE15.2)
C
C BALANCE FOR SURFACE SOIL REGION
C
      FLIN=FK24*Y2+FK54*Y5
      FLOUT=(FK43+FK45+FK48+FK49)*Y4
      WRITE (10,7) FLIN, FLOUT
    7 FORMAT (1H , 12X, 19HSURFACE SOIL REGION, 12X, 1PE15.2, 13X,
     2 1PE15.2)
C
C BALANCE FOR TERRESTRIAL BIOSPHERE
C
      FLIN=FK45*Y4
      FLOUT=(FK52+FK54)*Y5
      WRITE (10,8) FLIN, FLOUT
```

```
    8 FORMAT (1H , 10X, 21HTERRESTRIAL BIOSPHERE, 12X, 1PE15.2, 13X,
     2 1PE15.2)
C
C BALANCE FOR DEEP OCEAN
C
      FLIN=FK36*Y3
      FLOUT=FK63*Y6
      WRITE (10,9) FLIN, FLOUT
    9 FORMAT (1H , 21X, 10HDEEP OCEAN, 12X, 1PE15.2, 13X, 1PE15.2)
      RETURN
      END
```

```
C
      SUBROUTINE DIFFUN (N, T, X, XP)
C
C CALCULATES TIME DERIVATIVES OF COMPARTMENT INVENTORIES, INDIVIDUAL DOSES, AND
C   POPULATION DOSE. THE DIFFERENTIAL EQUATIONS ALLOW ARBITRARY INPUT FUNCTIONS
C   OF I-129 TO EACH ENVIRONMENTAL COMPARTMENT.
C
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION X(15), XP(15), XIN(9)
      COMMON/ BLK1/ FK12, FK13, FK21, FK24, FK31, FK36, FK43, FK45,
     2 FK48, FK49, FK52, FK54, FK63, FK67, FK76, FK83, FK93, CLAM
      COMMON/ BLK2/ FK10IN, FK10FD, FK11, FK12O, FK13S
      COMMON/ BLK3/ YSTART
      COMMON/ BLK4/ PEOPLE
C
C CALCULATE INPUT FUNCTION TO ENVIRONMENTAL COMPARTMENTS
C
      CALL INPUT (T, XIN)
C
C DEFINE DIFFERENTIAL EQUATIONS FOR ENVIRONMENTAL COMPARTMENTS
C
C   OCEAN ATMOSPHERE
C
      XP(1)=XIN(1)+FK21*X(2)+FK31*X(3)-(FK12+FK13+CLAM)*X(1)
C
C   LAND ATMOSPHERE
C
      XP(2)=XIN(2)+FK12*X(1)+FK52*X(5)-(FK21+FK24+CLAM)*X(2)
C
C   OCEAN MIXED LAYER
C
      XP(3)=XIN(3)+FK13*X(1)+FK43*X(4)+FK63*X(6)+FK83*X(8)+FK93*X(9)-
     2 (FK31+FK36+CLAM)*X(3)
C
C   SURFACE SOIL REGION
C
      XP(4)=XIN(4)+FK24*X(2)+FK54*X(5)-(FK43+FK45+FK48+FK49+CLAM)*X(4)
C
C   TERRESTRIAL BIOSPHERE
C
      XP(5)=XIN(5)+FK45*X(4)-(FK52+FK54+CLAM)*X(5)
C
C   DEEP OCEAN
C
      XP(6)=XIN(6)+FK36*X(3)+FK76*X(7)-(FK63+FK67+CLAM)*X(6)
C
C   OCEAN SEDIMENTS
C
      XP(7)=XIN(7)+FK67*X(6)-(FK76+CLAM)*X(7)
C
C   SHALLOW SUBSURFACE REGION OF LITHOSPHERE
C
      XP(8)=XIN(8)+FK48*X(4)-(FK83+CLAM)*X(8)
C
C   DEEP SUBSURFACE REGION OF LITHOSPHERE
C
```

```
      XP(9)=XIN(9)+FK49*X(4)-(FK93+CLAM)*X(9)
C
C DEFINE DIFFERENTIAL EQUATIONS FOR INDIVIDUAL AND POPULATION DOSES
C
C   CALCULATE POPULATION
C
      TIME=YSTART+T
      PEOPLE=POPULA(TIME)
C
C   INDIVIDUAL DOSE RATE FOR INTAKE FROM ATMOSPHERE
C
      XP(10)=(FK10IN+FK10FD)*X(2)
C
C   INDIVIDUAL DOSE RATE FOR INTAKE FROM SURFACE WATERS OF LITHOSPHERE
C
      XP(11)=FK11*(FK43*X(4)+FK83*X(8)+FK93*X(9))
C
C   INDIVIDUAL DOSE RATE FOR INTAKE FROM OCEAN MIXED LAYER
C
      XP(12)=FK12O*X(3)
C
C   INDIVIDUAL DOSE RATE FOR INTAKE FROM SURFACE SOIL REGION
C
      XP(13)=FK13S*X(4)
C
C   TOTAL INDIVIDUAL DOSE RATE
C
      XP(14)=XP(10)+XP(11)+XP(12)+XP(13)
C
C   POPULATION DOSE RATE
C
      XP(15)=PEOPLE*XP(14)
      RETURN
      END
```

```
C
      SUBROUTINE PEDERV (N, T, X, PD, NO)
C
C CALCULATES JACOBIAN MATRIX FOR SYSTEM OF DIFFERENTIAL EQUATIONS
C
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION X(15), PD(15,15), XP(15)
      COMMON/ BLK1/ FK12, FK13, FK21, FK24, FK31, FK36, FK43, FK45,
     2 FK48, FK49, FK52, FK54, FK63, FK67, FK76, FK83, FK93, CLAM
      COMMON/ BLK2/ FK10IN, FK10FD, FK11, FK12O, FK13S
      COMMON/ BLK4/ PEOPLE
C
C INITIALIZE MATRIX TO ZERO
C
      DO 1 I=1,N
      DO 1 J=1,N
      PD(I,J)=0.0D0
    1 CONTINUE
C
C DEFINE NON-ZERO MATRIX ELEMENTS FOR EACH ENVIRONMENTAL COMPARTMENT
C
C   OCEAN ATMOSPHERE
C
      PD(1,1)=-(FK12+FK13+CLAM)
      PD(1,2)=FK21
      PD(1,3)=FK31
C
C   LAND ATMOSPHERE
C
      PD(2,1)=FK12
      PD(2,2)=-(FK21+FK24+CLAM)
      PD(2,5)=FK52
C
C   OCEAN MIXED LAYER
C
      PD(3,1)=FK13
      PD(3,3)=-(FK31+FK36+CLAM)
      PD(3,4)=FK43
      PD(3,6)=FK63
      PD(3,8)=FK83
      PD(3,9)=FK93
C
C   SURFACE SOIL REGION
C
      PD(4,2)=FK24
      PD(4,4)=-(FK43+FK45+FK48+FK49+CLAM)
      PD(4,5)=FK54
C
C   TERRESTRIAL BIOSPHERE
C
      PD(5,4)=FK45
      PD(5,5)=-(FK52+FK54+CLAM)
C
C   DEEP OCEAN
C
      PD(6,3)=FK36
```

```
      PD(6,6)=-(FK63+FK67+CLAM)
      PD(6,7)=FK76
C
C   OCEAN SEDIMENTS
C
      PD(7,6)=FK67
      PD(7,7)=-(FK76+CLAM)
C
C   SHALLOW SUBSURFACE REGION OF LITHOSPHERE
C
      PD(8,4)=FK48
      PD(8,8)=-(FK83+CLAM)
C
C   DEEP SUBSURFACE REGION OF LITHOSPHERE
C
      PD(9,4)=FK49
      PD(9,9)=-(FK93+CLAM)
C
C DEFINE NON-ZERO MATRIX ELEMENTS FOR INDIVIDUAL AND POPULATION DOSES
C
C    INDIVIDUAL DOSE RATE FOR INTAKE FROM ATMOSPHERE
C
      PD(10,2)=FK10IN+FK10FD
C
C    INDIVIDUAL DOSE RATE FOR INTAKE FROM SURFACE WATERS OF LITHOSPHERE
C
      PD(11,4)=FK11*FK43
      PD(11,8)=FK11*FK83
      PD(11,9)=FK11*FK93
C
C    INDIVIDUAL DOSE RATE FOR INTAKE FROM OCEAN MIXED LAYER
C
      PD(12,3)=FK12O
C
C    INDIVIDUAL DOSE RATE FOR INTAKE FROM SURFACE SOIL REGION
C
      PD(13,4)=FK13S
C
C    TOTAL INDIVIDUAL DOSE RATE
C
      PD(14,2)=PD(10,2)
      PD(14,3)=PD(12,3)
      PD(14,4)=PD(11,4)+PD(13,4)
      PD(14,8)=PD(11,8)
      PD(14,9)=PD(11,9)
C
C    POPULATION DOSE RATE
C
      PD(15,2)=PEOPLE*PD(14,2)
      PD(15,3)=PEOPLE*PD(14,3)
      PD(15,4)=PEOPLE*PD(14,4)
      PD(15,8)=PEOPLE*PD(14,8)
      PD(15,9)=PEOPLE*PD(14,9)
      RETURN
      END
```

```
C
      SUBROUTINE INPUT (T, XIN)
C
C CALCULATES INPUT FUNCTION IN G/YR FOR ENVIRONMENTAL COMPARTMENTS. SUBROUTINE
C   MUST BE REWRITTEN FOR EACH DIFFERENT INPUT FUNCTION DESIRED
C
C FOR THIS CALCULATION, AN INPUT OF 1 CI IS PLACED IN THE LAND ATMOSPHERE
C   BEGINNING AT TIME ZERO AT A RATE OF 1 CI/YR FOR 1 YEAR, WITH NO INPUT TO ANY
C   OTHER COMPARTMENTS
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION XIN(9)
      COMMON/ BLK5/ SPA129
C
C INITIALIZE INPUT FUNCTION TO ZERO
C
      DO 1 I=1,9
      XIN(I)=0.0D0
    1 CONTINUE
C
C CALCULATE INPUT TO ENVIRONMENTAL COMPARTMENTS
C
      IF (T .LE. 1.0D0) XIN(2)=(1.0D0)/SPA129
      RETURN
      END
```

```
C
      DOUBLE PRECISION FUNCTION POPULA(T)
C
C CALCULATES WORLD POPULATION BY LINEAR INTERPOLATION OF TABULAR DATA
C
      IMPLICIT REAL*8 (A-H, O-Z)
      DIMENSION PEOPLE(7), YEAR(7)
C
C YEARS FOR POPULATION DATA
C
      DATA YEAR/ 1925.D0, 1950.D0, 1975.D0, 2000.D0, 2025.D0, 2050.D0,
     2 2075.D0/
C
C WORLD POPULATION IN BILLIONS
C
      DATA PEOPLE/ 1.960D0, 2.505D0, 3.988D0, 6.406D0, 9.605D0,
     2 11.163D0, 12.210D0/
C
C CALCULATE POPULATION USING LINEAR INTERPOLATION
C
      IF (T .GE. YEAR(7)) GO TO 1
      IF (T .GE. YEAR(1) .AND. T .LT. YEAR(2)) INT=1
      IF (T .GE. YEAR(2) .AND. T .LT. YEAR(3)) INT=2
      IF (T .GE. YEAR(3) .AND. T .LT. YEAR(4)) INT=3
      IF (T .GE. YEAR(4) .AND. T .LT. YEAR(5)) INT=4
      IF (T .GE. YEAR(5) .AND. T .LT. YEAR(6)) INT=5
      IF (T .GE. YEAR(6) .AND. T .LT. YEAR(7)) INT=6
      INTP=INT+1
      POPULA=(1.009)*(PEOPLE(INT)+((T-YEAR(INT))/(YEAR(INTP)-YEAR(INT)))
     2 *(PEOPLE(INTP)-PEOPLE(INT)))
      GO TO 2
    1 POPULA=PEOPLE(7)*(1.009)
    2 RETURN
      END
```

```
C
      DOUBLE PRECISION FUNCTION DYEAR(T)
C
C CALCULATES TIME INCREMENT FOR NEXT STEP IN INTEGRATION
C
      IMPLICIT REAL*8 (A-H, O-Z)
      IF (T .LE. 9.0D-1) DYEAR=1.0D-1
      IF (T .GE. 1.0D0 .AND. T .LT. 1.0D1) DYEAR=1.0D0
      IF (T .GE. 1.0D1 .AND. T .LT. 1.0D2) DYEAR=1.0D1
      IF (T .GE. 1.0D2 .AND. T .LT. 1.0D3) DYEAR=1.0D2
      IF (T .GE. 1.0D3 .AND. T .LT. 1.0D4) DYEAR=1.0D3
      IF (T .GE. 1.0D4 .AND. T .LT. 1.0D5) DYEAR=1.0D4
      IF (T .GE. 1.0D5 .AND. T .LT. 1.0D6) DYEAR=1.0D5
      IF (T .GE. 1.0D6 .AND. T .LT. 1.0D7) DYEAR=1.0D6
      IF (T .GE. 1.0D7 .AND. T .LT. 1.0D8) DYEAR=1.0D7
      IF (T .GE. 1.0D8 .AND. T .LT. 1.0D9) DYEAR=1.0D8
      IF (T .GE. 1.0D9 .AND. T .LT. 1.0D10) DYEAR=1.0D9
      RETURN
      END
```

NUREG/CR-0717
ORNL/NUREG-59
Dist. Category RH

INTERNAL DISTRIBUTION

1. R. O. Chester
2. D. E. Dunning, Jr.
3. K. F. Eckerman
4. F. O. Hoffman
5. S. V. Kaye
6. G. G. Killough
7-41. D. C. Kocher
42. F. R. Mynatt
43. C. R. Richmond
44. P. S. Rohwer
45. G. Schwarz
46. J. P. Witherspoon
47. Laboratory Records
48. Laboratory Records, ORNL-RC
49. ORNL Patent Section
50. RSIC Library

EXTERNAL DISTRIBUTION

51. S. Acharya, Radiological Assessment Branch, Division of Site Safety and Environmental Analysis, Mail Stop P-712, Nuclear Regulatory Commission, Washington, D.C. 20555
52. Office of Assistant Manager, Energy Research and Development, DOE-ORO, Oak Ridge, Tennessee 37830
53-54. Technical Information Center, Oak Ridge, Tennessee 37830
55-204. Given distribution according to NRC Category RH

1534 111