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Estimates of Health Risk from Exposure to Radioactive Pollutants

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DEPARTMENT OF ENERGY

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ORNL/TM-7745

Contract No. W-7405-eng-26

Health and Safety Research Division

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Manuscript Completed - August 1981

Date Published - November 1981

[1]U.S. Environmental Protection Agency, Office of Radiation Programs

Prepared for the
U.S. Environmental Protection Agency
Office of Radiation Programs
Under Interagency Agreement 40-1073-80

Prepared by the
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UNION CARBIDE CORPORATION
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A dosimetric and health effects analysis has been performed for the Office of Radiation Programs of the Environmental Protection Agency (EPA) to assess potential hazards from radioactive pollutants. Contemporary dosimetric methods were used to obtain estimates of dose rates to reference organs from internal exposures due to either inhalation of contaminated air or ingestion of contaminated food, or from external exposures due to either immersion in contaminated air or proximity to contaminated ground surfaces. These dose rates were then used to estimate the number of premature cancer deaths arising from such exposures and the corresponding number of years of life lost in a cohort of 100,000 persons, all simultaneously liveborn and all going through life with the same risks of dying from competing causes. The risk of dying from a competing cause for a given year was taken to be the probability of dying from all causes as given in a recent actuarial life table for the total U.S. population. This report provides a general description of the methods and includes a summary of metabolic parameters employed in the dosimetry. A summary of results, in terms of total premature deaths and years of life lost, is also provided for each of more than 150 radionuclides.

1. INTRODUCTION

This report provides a summary of results of research, performed at Oak Ridge National Laboratory for the Environmental Protection Agency, involving the synthesis of contemporary dosimetric and risk assessment methods and the application of these combined methodologies to obtain estimates of risk due to exposures to radioactive pollutants. The results described here represent the end product of only one of the steps involved in the methodology used by the Office of Radiation Programs of the EPA in calculating the dose and risk resulting from exposure to radionuclides discharged in air. These doses and risks were calculated for use in regulation of radioactive pollutants.

Three separate steps are involved in estimating the health impact of a specific source of radioactivity. Each step is associated with a computer code which performs the calculations. These computer codes are RADRISK [1], AIRDOS-EPA [2], and DARTAB [3].

This report explains the methodology and results associated with RADRISK, which calculates the radiation dose and risk resulting from a unit intake of a given radionuclide. This report also summarizes the results associated with estimating the risk resulting from external exposure to a unit concentration of a nuclide in air or on the ground surface. AIRDOS-EPA determines the actual magnitude (or number of units) of the intake, or external concentration, from a given source at the point of exposure. DARTAB scales the unit exposure results of RADRISK to match the magnitudes of the actual source exposures from AIRDOS-EPA. The resulting doses and estimated risks will then have the correct values for that source.

The RADRISK computer code was developed to estimate dose rates and subsequent health effects to a group of persons due to inhalation or ingestion of a radionuclide. The RADRISK code represents a synthesis and adaptation of two previous computer codes, INREM II [4] and CAIRD [5]. Dosimetry calculations are adapted from the INREM II computer code, which was developed at Oak Ridge National Laboratory and which includes information made available in Publication 30 of the International Commission on Radiological Protection (ICRP30) [6], and the resultant

dose estimates are then coupled with an adaptation of the CAIRD computer code developed by the EPA for estimation of potential health risks [7].

In applications of RADRISK, the group assumed to be at risk consists of a hypothetical cohort of 100,000 persons, born at the same time and all subject to the same competing risks of death throughout their lifetimes. The probability of dying at a particular age from a competing cause is calculated from the mortality rate for all causes for that age, as given in a recent actuarial life table for the total U.S. population [8]. Each member of the cohort is assumed to be subject to lifetime exposure, at a constant rate, to a unit concentration of each radionuclide. The exposure modes considered are inhalation of contaminated air, ingestion of contaminated material, immersion in contaminated air, and exposure from contaminated ground surfaces. The risks from the external exposure modes are not computed by RADRISK; rather, exposures are converted to dose rates through conversion factors calculated by the methods of Kocher [9], and these dose rates are entered directly into the CAIRD computer code.

RADRISK is an improvement over more conventional methods of risk estimation. Although the RADRISK code, in some instances, requires a more complete knowledge of chemical, physical, and biological data than is presently available, it affords a means for the consistent, detailed evaluation of large numbers of radionuclides. Major improvements in the analysis are the use of time-dependent doses in conjunction with age-dependent life table data which allow estimation of health effects, the years of life lost for each health effect, and the overall reduction in population life expectancy. These estimated quantities yield an improved basis for evaluating the impact of a specific industry or practice.

The general methodology developed in this study was described in some detail in an earlier document [1]. However, for the reader's convenience, a somewhat less technical description of the methodology is included here. In addition, a summary table of metabolic parameters used in calculations of dose rates from internal exposures is provided. A summary of results of the study is provided in tabular form. For each radionuclide considered and each of the four pathways (where applicable), results are summarized in terms of the number of premature deaths in the

cohort due to the radiation exposure, the number of years of life lost due to these fatalities, and a "risk equivalent factor" defined to be the number of premature deaths in the cohort resulting from the given exposure divided by the number of deaths in the cohort which would result from a continuous dose rate of 1 millirad per year of low-LET radiation to each organ of the whole body. By definition, the whole body is the collection of all the organs considered in the RADRISK code.

2. A DESCRIPTION OF THE METHODOLOGY

Background Information and Definitions

Radioactive decay may be thought of as a process whereby the nucleus of an atom gives up excess energy. The emission of this energy is referred to as radioactivity. The "activity" of a radioactive material is characterized by the number of atoms which give up energy, or disintegrate, in a given period of time. The unit of activity used in this report is the picocurie (pCi) which equals 2.22 disintegrations per minute. (The standard metric unit is the becquerel, which is one disintegration per second.) The excess energy is normally emitted as charged particles and photons moving at high velocity. While there are many types of emitted radiations, or particles, only three are commonly encountered in radioactive material found in the general environment. While these three were, historically, named after letters of the Greek alphabet--alpha, beta, and gamma--they are now known to be, respectively, the nucleus of the helium atom, the electron, and the photon.

The primary mechanism for radiation damage is the transfer of kinetic energy from the moving alpha and beta particles and photons to the living tissue. This transfer leads to rupture of cellular constituents resulting in electrically charged fragments (ionization). While the amount of energy transferred is small in absolute terms, it is sufficient to disrupt the molecular structure of living tissue and, depending on the amount and location of the energy release, lead to the risk of radiation damage.

Exposure and dose. The term "exposure" denotes physical contact with the radioactive material while the term "dose" refers to the amount of energy absorbed per gram of absorbing tissue. An exposure, for example, may be acute--take place over a short period of time--while the dose, for some internally deposited materials, may extend over a long period of time.

The dose is a measure of the amount of energy deposited by the alpha and beta particles or photons and their secondary radiations in the organ. The only units of dose used in this report are the rad--defined as 100 ergs (energy units) per gram (mass unit)--and the millirad (mrad)

which is one one-thousandth of a rad. (The corresponding metric unit for dose is the gray which is equivalent to 100 rad.) The rad represents on the average the amount of potentially disruptive energy delivered to each gram of tissue. Because it is necessary to know the yearly variation in dose for the calculations described in this report, the quantity used will be the average annual dose, or dose rate, in rads, or millirads, per year. All exposure modes are considered, where applicable, to obtain the total radiation dose from a variety of environmental pathways.

External and internal exposures. Radiation doses may be due to either external or internal exposures. External exposures are those caused by radioactive materials located outside the body. Examples are irradiation of the body by radioactive material lying on the ground or suspended in the air.

Internal exposures are caused by radioactive material which has entered the body--from inhaling or consuming radioactive material. Examples are inhaling contaminated air or consuming contaminated food or water. Having once entered the body, the contaminant may be transmitted to other internal organs and tissues.

The external exposures considered in this report are those due to irradiation of the body by gamma rays. Gamma rays, or photons, are the most penetrating of those radiations considered and external gammas may normally contribute to the radiation dose affecting all organs in the body. Beta particles (electrons), which are far less penetrating, would normally deliver their dose to, or slightly below, the unshielded surface of the skin and are not considered since their impact would be small, particularly on clothed individuals. Alpha particles (helium nuclei), which are of major importance internally, will not penetrate the unbroken skin and so are also excluded from the external dose calculations.

Different types of radiations differ in the rate at which their energy is transferred per unit of length traveled in tissue, a parameter which is termed the linear energy transfer (LET) of the radiation. Gamma rays and beta particles generally have a much lower LET than high LET particles. The latter are more damaging biologically, per rad, than

low LET radiations. In RADRISK, risk calculations were based on the assumption that the potential for cancer induction by 1 rad of high-LET (alpha) radiation is, depending on the organ irradiated, up to 20 times as great as the damage produced by 1 rad of low-LET (beta or gamma) radiation.

The external exposures considered in this document are those resulting either from immersion in contaminated air or from standing on a contaminated ground surface. The air immersion dose is based on the assumption that an individual is located in an infinite hemispherical cloud of uniformly contaminated air. The ground dose rate calculated is for an individual standing on an infinite, contaminated plane surface.

Risk. Risk may be defined as the chance of injury or damage. The possible types of damage considered in this report include genetic effects and fatal and nonfatal cancers. Risk is determined by calculating the radiation dose delivered to a susceptible organ, or tissue, as a result of exposure to radiation and relating the radiation dose rate delivered to the probability that a detriment to health occurs.

Genetic effects. Genetic effects are defined as serious deleterious mutations which are transmitted to subsequent generations by the person exposed. A mutation is an inheritable change in the genetic material within chromosomes. We assume that ionizing radiation causes the same kinds of mutations as those that occur from other causes. Generally speaking, mutations are of two types, dominant and recessive, but these categories are rough and somewhat arbitrary. The effects of dominant mutations usually appear in the first and subsequent generations. The effects of recessive mutations do not appear until a child receives a similarly changed gene for that trait from both parents. This may not occur for many generations or it may never occur. Although mutations may in time be eliminated from the population by chance or by natural selection, they can persist through many generations. The 1972 BEIR Committee of the National Academy of Sciences (NAS) [10] estimated that radiation-induced recessive mutations are spread over 10 to 20 generations. Dominant mutations are usually expressed (and often eliminated) in the first few generations.

The risk for genetic effects is assumed to depend on the accumulated gonadal dose during the first 30 years of life, rather than the annual dose rates during that period.

Fatal and nonfatal cancers. Cancers which are believed to be associated with radiation are listed in Table 1. The numerical radiation risk coefficients are based on estimates of excess deaths developed in the 1972 BEIR report [10]. This report calculates excess cancer deaths using both an absolute risk model and a relative risk model. With both models, calculations were made first assuming a 30-year plateau and then a lifetime plateau for expression of cancers in the case of solid tumors, and assuming a 25-year plateau for leukemia. The results obtained using these various models and assumptions were averaged to obtain an estimated risk of 200×10^{-6} excess cancer deaths per person-year-rad (pyr) at risk. The organ specific risk estimates in Table 1 were obtained by allotting the estimated risk of 200 excess cancer deaths per 10^6 pyr among selected organs on the basis of the authors' judgment on data in the published literature. Estimates for leukemia (bone marrow), bone surface, lung, breast, and thyroid are based on the extensive data on cancer presented in reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [11,12] and the BEIR reports [10,13]. Those for liver, pancreas, stomach, and lower large intestine were derived from the less extensive data on those cancers in the 1977 UNSCEAR report [12] and, to a limited extent, draft versions of the 1980 BEIR III report [13]. Although these estimates may be in error by a factor of 2 or more, we believe that they adequately reflect what is presently known about radiation risks to individual organs.

The lifetime risks from a dose of 1 rad to the liver, pancreas, stomach, and lower large intestine were calculated and subtracted from the risk calculated for a total body exposure of similar magnitude. The resultant residual risk was then split equally among the other organs listed in Table 1. The risk was equally divided because there is strong suggestion of increased cancer risk in these organs following radiation exposure and because there was not sufficient evidence to select one organ over another.

Table 1. Risk parameters for cancers considered

Cancer	Latency (years)	Plateau (years)	Risk factor for low-LET radiation (deaths/10^6 rad person years at risk)	Risk factor for high-LET radiation (deaths/10^6 rad person years at risk)	Number of premature deaths in cohort from chronic 1 mrad/yr exposure*
Leukemia	2	25	2.3	46	0.326
Bone	5	30	0.2	4	0.031
Lung	10	110	3.0	30	0.608
Breast	15	110	2.3	2.3	0.399
Liver	15	110	0.9	9	0.156
Stomach	15	110	0.5	5	0.087
Pancreas	15	110	0.7	7	0.121
Lower large intestine	15	110	0.4	4	0.069
Kidneys	15	110	0.2	2	0.035
Bladder	15	110	0.2	2	0.035
Upper large intestine	15	110	0.2	2	0.035
Small intestine	15	110	0.1	1	0.017
Ovaries	15	110	0.1	1	0.017
Testes	15	110	0.1	1	0.017
Spleen	15	110	0.1	1	0.017
Uterus	15	110	0.1	1	0.017
Thymus	15	110	0.1	1	0.017
Thyroid	2	45	0.4**	0.4**	0.085

*Low LET.

**0.04 for ^{131}I and longer-lived radioiodine.

The probability for each type of fatal cancer, per unit radiation dose, is also given in Table 1. Note that the probability is constant for a given cancer regardless of the magnitude of the dose received. There is an implicit assumption in the use of such numbers that the cancer probability is linear, i.e., that if 1,000 person rads yields 1 cancer, 10,000 person rads will yield 10 cancers, where person rad is the total dose to all exposed persons. This assumption is used throughout the calculations for fatal cancer risk and is commonly referred to as the "linear hypothesis."

The risk of nonfatal radiogenic cancers is not calculated because little information was available at the time these programs were developed. Almost all of the available epidemiological studies are based on mortality. In the absence of specific data on nonfatal radiogenic cancers, the total risk of radiogenic cancer must be estimated from state and national health statistics on cancer incidence and mortality in the general population. One way to do this is to compare the ratio of the incidence of fatal cancers to the incidence of all clinically observed cancers. Such estimates are not too satisfactory because cancer incidence statistics are incomplete and not directly related to cancer mortality statistics. In addition there is the possibility of differences in the relative frequency of cancer types between radiogenic cancers and those caused by other factors. We estimate that the total number of discovered radiogenic cancers, excluding skin cancer, is one and one half to two times the number of fatal cancers estimated.

General Procedure

There are two main steps involved in estimating the risk due to exposure to unit concentration of a radioactive material:

1. The dose rate to a susceptible organ or tissue must be calculated.

2. The dose rate must be related to the risk that a health effect occurs.

Any effort at calculating dose and risk must, of necessity, involve the use of models. In its simplest form, a model is a mathematical

representation of a physical or biological system. If, for example, the amount of radioactive material in an organ is measured at several times, a graph of the activity in the organ, such as that in Figure 1, is obtained. In the simplest case, analysis of these data may indicate that the fraction of the initial activity, R, retained in the organ at any time, t, is given by an equation of the form

$$R = e^{-\lambda t}$$

where λ is the elimination rate constant. (More generally, it may require the sum of two or more exponential functions to properly approximate the decrease of radioactivity in the organ. This may be interpreted physically as indicating the existence of two or more "compartments" in the organ from which the nuclide leaves at different rates.)

The elimination rate constant, λ, includes two terms, which may be measured experimentally, one inversely proportional to the biological clearance half-life and the other inversely proportional to the radioactive half-life. The effective half-life, $t_{1/2}$, for these processes is the time required for one-half of the material originally present to be removed. The elimination rate constant is calculated as $\lambda = \ln 2/t_{1/2}$.

If radionuclides are generally found to follow this behavior, then this equation may be used as a general model for the activity in an organ following deposition of any initial activity. The models used in this report are documented in detail in the cited references. A brief description of each model is given below as an aid to understanding the input data and results presented in the balance of this report.

Dose Calculations. The example just described for modeling the activity of a radionuclide in an organ pertains to estimating doses from internal exposure. Alternatively the external immersion and surface doses are calculated as follows [9]. First, the number of photons reaching the body is determined. The model used here is a set of equations which govern the travel of photons (gamma radiation) in air. The simplifying assumptions used in these calculations are that the medium (air) is an infinite half-space and is the only material present. This makes the calculation relatively straightforward. In the second

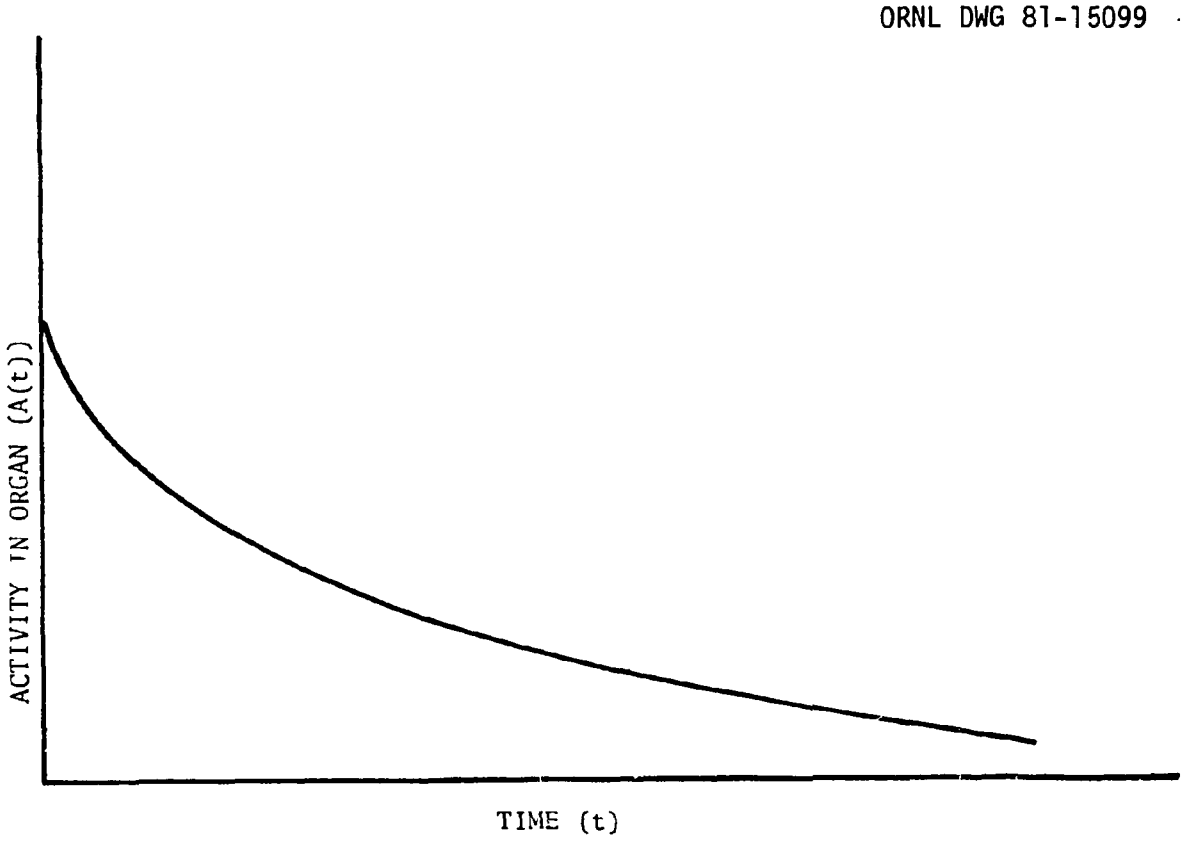

Fig. 1. Typical pattern of decline of activity of a radionuclide in an organ, assuming an initial activity in the organ and no additional uptake of radionuclide by the organ. Each axis is assumed to be on a linear scale. The time might be in days or seconds, and the activity might be in becquerels or picocuries, for example.

portion of the calculation, the photons reaching the body are followed through the body using a "Monte Carlo" method. The Monte Carlo method is a procedure in which the known properties of the radiation and tissues are used to trace (simulate) the paths of a large number of photons in the body [14]. The amount of energy released at each interaction of the radiation with body tissues is recorded and, thus, the dose to each organ or tissue is estimated on consideration of a large number of photon paths.

All radiations--gamma, beta, and alpha--are considered in assessing the doses resulting from internal exposure, that is, exposure resulting from the inhalation or ingestion of contaminated material. Since the material inhaled or ingested may not leave the body for a considerable period of time (up to decades), dose rates are calculated over a corresponding time interval.

The calculation of internal doses requires the use of several models. The most important are the ICRP lung model [15], depicted in Figure 2, and the gastrointestinal (GI) tract model [16,17] shown in Figure 3. The lung model is comprised of three regions, the nasopharyngial (N-P), the tracheobronchial (T-B), and the pulmonary (P) regions. A certain portion of the radioactive material inhaled is deposited in each of the three lung regions (N-P, T-B, and P) indicated in Figure 2. The material is then cleared (removed) from the lung to the blood and gastrointestinal tract as indicated by the arrows according to the specified clearance parameters for the solubility class of the inhaled material.

Deposition and clearance of inhaled materials in the lung are controlled by the particle size and solubility class of the material. The particle size distribution of the airborne material is specified by giving its Activity Median Aerodynamic Diameter (AMAD) in microns-one micron equals 10^{-6} meters. Where no AMAD is known, a value of 1.0 micron is assumed. Solubility classes are stated in terms of the time required for the material to leave the lung, that is, Class D (days), Class W (weeks), and Class Y (years).

The gastrointestinal tract model consists of four compartments, the stomach (S), small intestine (SI), upper large intestine (ULI), and

COMPARTMENT		CLASS D T	CLASS D F	CLASS W T	CLASS W F	CLASS Y T	CLASS Y F
N-P	a	0.01	0.5	0.01	0.1	0.01	0.01
(D_3 = 0.30)	b	0.01	0.5	0.4	0.9	0.4	0.99
T-B	c	0.01	0.95	0.01	0.5	0.01	0.01
(D_4 = 0.08)	d	0.2	0.05	0.2	0.5	0.2	0.99
	e	0.5	0.8	50	0.15	500	0.05
P	f	n.a.	n.a.	1.0	0.4	1.0	0.4
(D_5 = 0.25)	g	n.a.	n.a.	50	0.4	500	0.4
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1.0	50	1.0	1000	0.9

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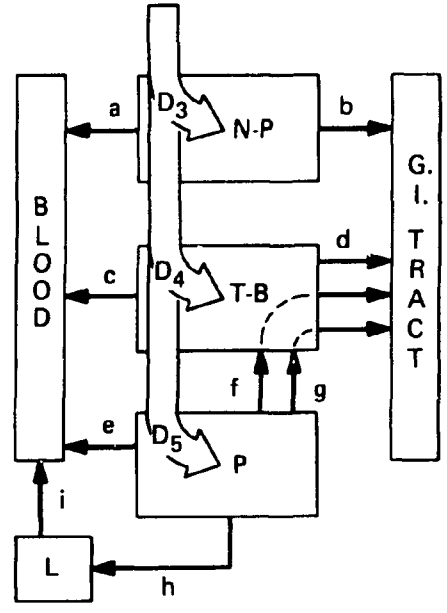

Fig. 2. The ICRP Task Group Lung Model for particulates. The columns labeled D, W, and Y correspond, respectively, to rapid, intermediate, and slow clearance of the inspired material. The symbols T and F denote the biological half-time (days) and coefficient, respectively, of a term in the appropriate retention function. The values shown for D_3, D_4, and D_5 correspond to activity median aerodynamic diameter AMAD = 1 μm and represent the fraction of the inspired material depositing in the lung regions.

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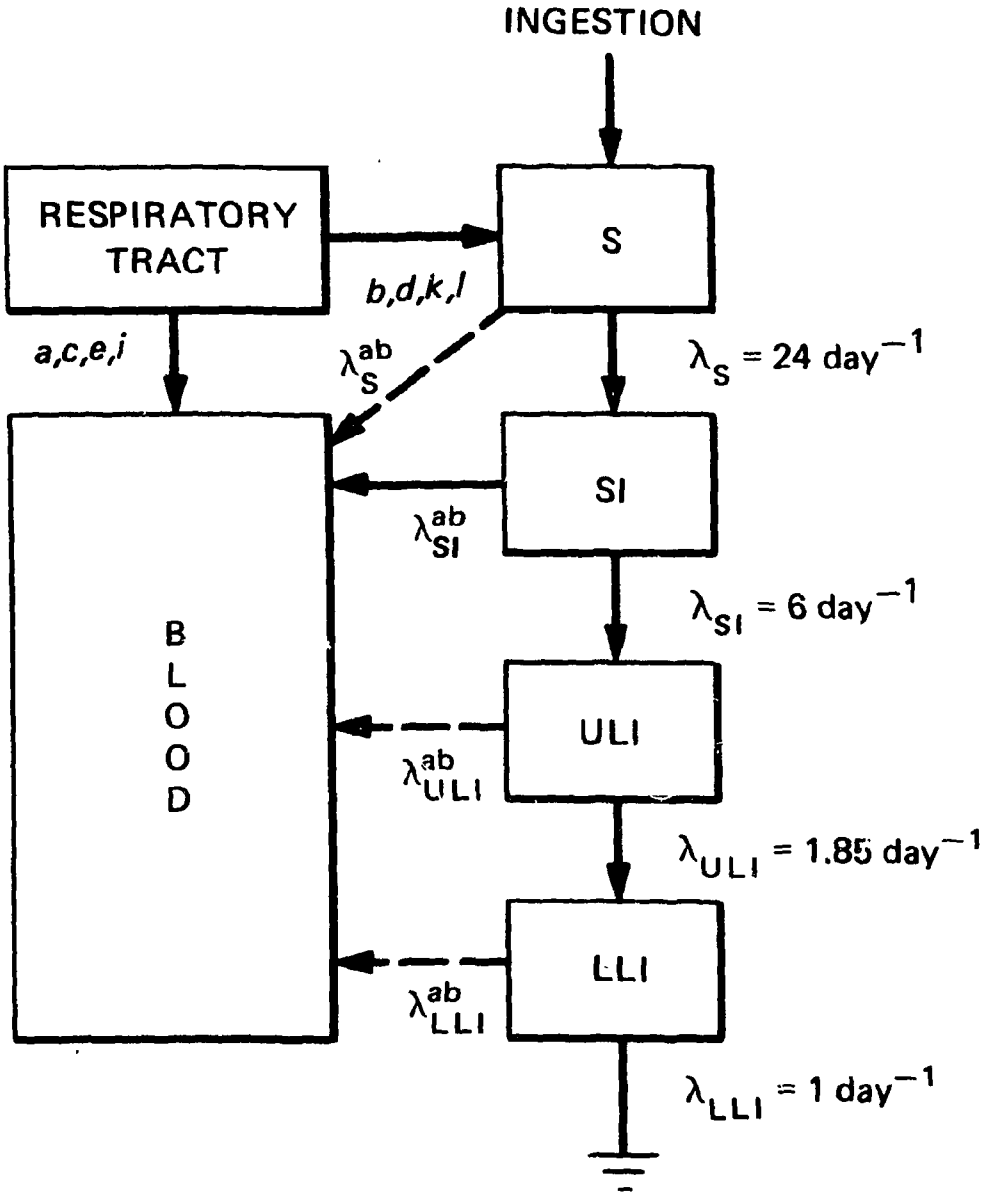

Fig. 3. Schematic representation of radioactivity movement among respiratory tract, GI tract, and blood.

lower large intestine (LLI). However, it is only from the small intestine (SI) that absorption into the blood is assumed to occur. The fraction of material which is transferred into blood is denoted by the symbol f_1.

Radionuclides may be absorbed by the blood from either the lungs or the GI tract. After absorption by the blood, the radionuclide is distributed among systemic organs according to fractional uptake coefficients, denoted by the symbol f_2. Since the radioactive material may be transported through the body, dose rates are calculated for each organ or tissue affected by using a model of the organ which mathematically simulates the biological processes involved. The general form of the model for each organ is relatively simple. It assumes that the radioactive material which enters the organ is removed by both radioactive decay and biological removal processes.

As indicated earlier, both radioactive decay in an organ and biological clearance from an organ are assumed to be exponential. That is, if A_o is the amount of material initially deposited in the organ, the amount left at any time, t, can be approximated by a function of the form

$$A = A_o \ (C_1 e^{\lambda_1 t} + C_2 e^{-\lambda_2 t} + \ldots)$$

Each coefficient C_i corresponds, in theory, to the fraction of the nuclide "assigned" to a compartment (denoted by subscript i) within the organ. The constant λ_i corresponds (again, in theory) to the removal rate (biological removal plus radioactive decay) from the i-th compartment. It is assumed that an organ has at most five compartments, so that A is the sum of at most five exponential terms. Where non-exponential clearance terms have been suggested by ICRP30, these have been fitted to the exponential series described.

Effects of decay products. In calculating doses from internal and external exposures, the occurrence of radioactive decay products (or daughters) must be considered for some radionuclides. When an atom undergoes radioactive decay, the new atom created in the process may also be radioactive and may contribute to the radiation dose. While

these daughter products may be treated as independent radionuclides in external exposures, the decay products of each parent must be followed through the body in internal exposures. The decay product contributions to the dose rate are included in the RADRISK code, based on their own metabolic properties and the organ in which they occur.

Dose Rate Estimates. For both external and internal exposures, dose rates to each of the organs listed in Table 1 are calculated for each radioisotope. These organ dose rates serve as input to the life table calculations described in the Life Table section, and the risk results are computed for each organ.

Since internal dose rates per unit intake rate vary with duration of the intake, these dose rates are calculated at ages 1, 3, 6, 12, 20, 30, 42, 50, 56, 70, and 87 years. The dose rates, of course, are constant for external sources of exposure.

Risk Calculation. The second part of the risk calculation involves multiplying the dose by the chance, or probability, of a health effect per unit dose. For example, assume that a dose of 10 rad is received by the kidney and that an individual's chance of cancer occurring is 0.02 per 1,000,000 rads. Note that, since the chance per rad for cancer induction is small, it is given in terms of a probability per million rad. This is usually written in exponential form as 0.02×10^{-6}. The risk is then obtained by multiplying the dose and probability per unit dose:

$$\text{risk} = 10 \text{ rad} \times \frac{0.02}{10^6 \text{ rad}} = 0.2 \times 10^{-6} \ .$$

This simple calculation is complicated by the fact that, in practice, cancers are not expected to appear immediately upon exposure. That is, after the dose is received, there is a latent (or induction) period of some years before the cancers are clinically observed. The length of this latency period depends on the type of cancer. The probability of occurrence of the cancer during a given year after the latency period is then presumed to be constant for a specified period. The length of this period, usually called the plateau period, varies with cancer type.

Since the exposures considered here are assumed to extend over the lifetime of an average member of the population, it is obvious that it is necessary to know when the dose was delivered as well as how large it was. To illustrate, suppose that a constant dose rate of 10 rad per year to the kidney is received in the year 1980. Assume that the latency period is 15 years and the probability for cancer of the kidney is 0.2×10^{-6} per rad per year for the balance of life. (See Figure 4.)

The risk of cancer expected from the 1980 dose would then be:

$$10 \frac{\text{rad}}{\text{yr}} \times 1 \text{ yr} \times 0.2 \times 10^{-6} \text{ rad}^{-1} \text{ yr}^{-1} = \frac{2 \times 10^{-6}}{\text{yr}} .$$

This risk would not be expected to be observed until 1995-1996 after which the risk would be expected to continue over the lifetime of the exposed population. A single exposure of this type, which takes place in a short period of time, is called an acute exposure. Many exposures from environmental sources can occur over extended periods of time. That is, a radioactive material released to the environment may persist for many years and result in varying radiation doses which are delivered over a period of years. Such continuous exposures may be treated in a manner similar to that indicated in Figure 5. Suppose, for example, that the 1980 dose of Figure 4 is followed by another exposure in 1981. This later dose must then be followed through in the same manner as the first but with latency and plateau periods advanced by one year. That is, the risk of expected cancers in 1995-1996 would remain at 2×10^{-6} but the 1996-1997 expectation would be about twice that value since the latency period for the 1981 dose would have elapsed at that time. Subsequent exposures are treated similarly. Since the dose from an exposure may be delivered to the organ at a variable rate over an extended period of time, it may be a complicated procedure to follow the dose from even an acute internal exposure. It is obvious that following lifetime exposures for many types of cancers, in many organs, presents a large bookkeeping problem. For this reason, both the dose rate and health effects calculations are performed by the computer code RADRISK. A more extensive discussion of those aspects of the calculation necessary to interpret the results is given in the following sections.

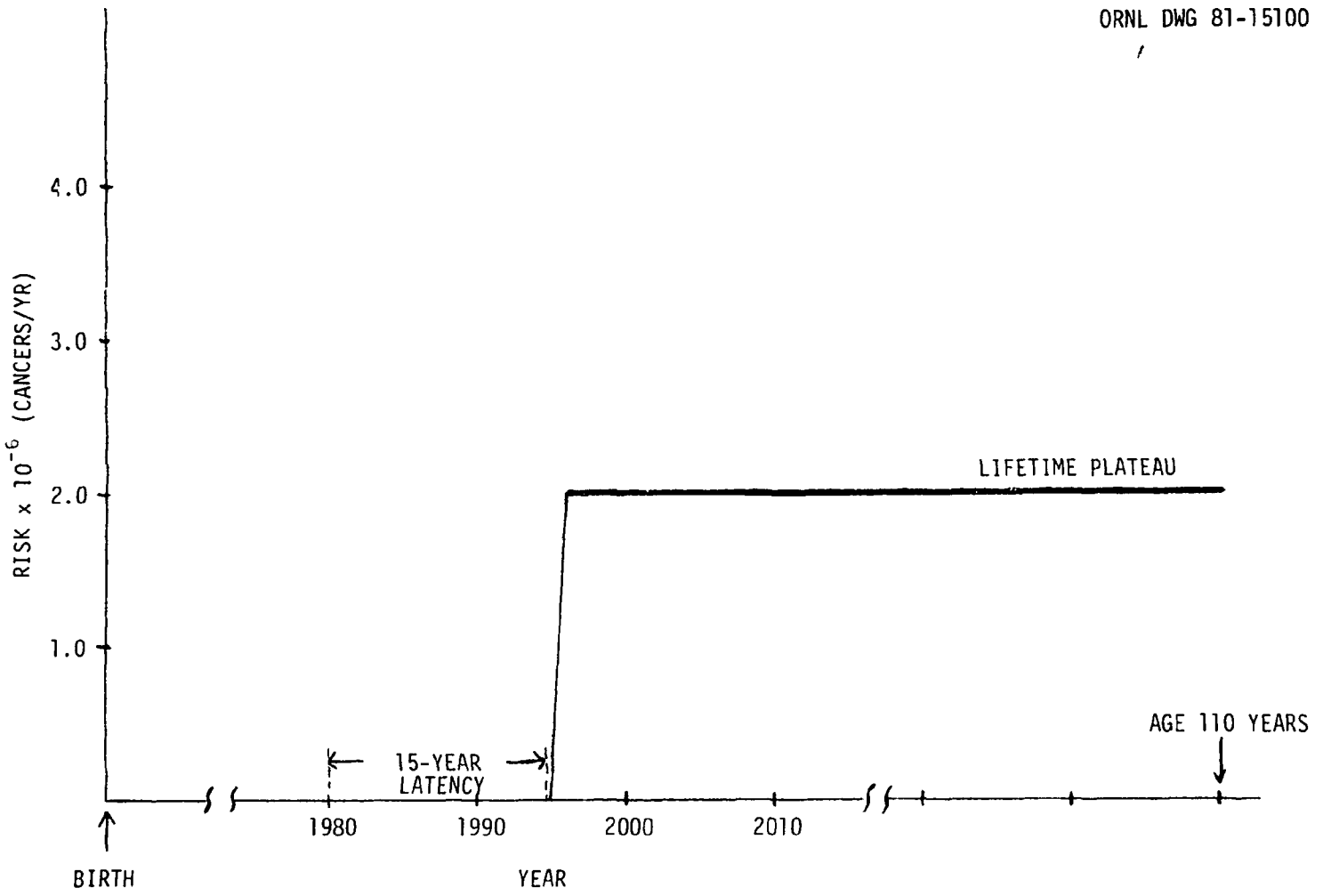

Fig. 4. Annual risk of kidney cancer mortality due to 10 rad/yr continuous dose rate in the year 1980.

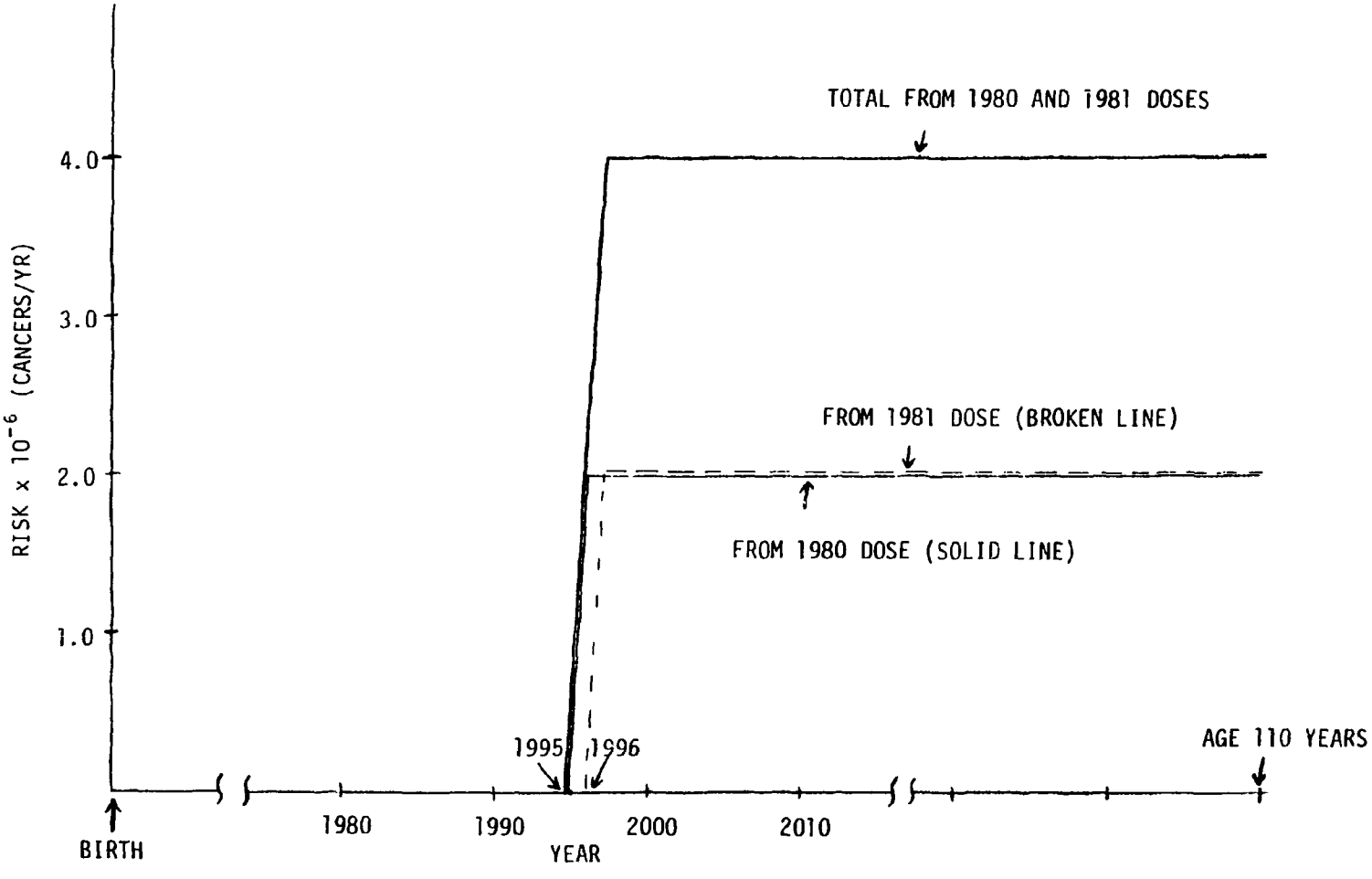

Fig. 5. Risk of kidney cancer mortality due to 10 rad/yr continuous dose rate in 1980 and 10 rad/yr continuous dose rate in 1981.

Life Table. The description of fatal cancer risk, latency period, and plateau period given above demonstrates the basic steps followed in calculating risk. From the latency periods shown in Table 1, it is obvious that a considerable period of time may elapse between delivery of a radiation dose and the cancer-induced death.

Since an individual, or population, is subject to many risks over a lifetime other than radiation, it is not correct to directly equate the radiation dose with a corresponding fatality without considering death from other causes, i.e., competing risks. Competing risks are defined as those risks, unrelated to the radiation exposure being considered, which operate on the population at risk. For example, in a given population which has been exposed to radiation some individuals will die, either accidentally or from natural causes, before the cancers resulting from irradiation are expressed. The number of fatal cancers estimated to occur must, therefore, be modified by taking into account these other risks. To do this, the concept of the "life table" will be introduced.

As used in this document, a life table is a description of the mortality history of a given population. This treatment starts with a cohort, defined as 100,000 newborn infants, and, using standard mortality rates, reduces this number for each year of life until the cohort is terminated at 110 years of age. The mortality rate takes into account all causes of death, other than those due to the additional radiation exposures considered here, for each age group and reduces the population at risk due to radiation accordingly.

For example, if there is an average of 95,000 persons left in the cohort at age 35 and the mortality rate is 0.002, then 95,000 x 0.002 = 190 in that age group will die and 95,000 - 190 = 94,810 will enter age group 36 of the cohort. It is evident that, given the initial cohort size and the age dependent mortality rates, it is possible to construct a complete life table showing the number of persons surviving in each year. Since the radiation dose rates are also entered on an annual basis, it is also possible to calculate the radiation risk in conjunction with the standard mortality rates. When this combined computation is performed, the results are automatically corrected for competing risks. That is, an individual irradiated in a given year, who might die from

other causes prior to the expiration of the latency period, would not be counted as a radiation fatality. The main impact of this correction is, of course, confined to the very old.

In similar fashion, other quantities related to age at death may be calculated. In this treatment, the quantities used are the number of premature deaths in the cohort, the average years of life lost per premature death, and the decrease in population life expectancy as a whole.

Risk Assessment. The general procedure followed in estimating the risk to an individual or population exposed to radiation has been outlined in preceding sections of this document. In this section additional details of the dose rate and risk calculation needed to interpret the results are presented.

The underlying assumptions made in the risk analysis described here are intended to reflect the conditions normally associated with environmental exposures. These exposures will usually be at low radiation levels, through a variety of pathways, and for an extended period of time. To match these conditions, both the dose rate and life table calculations use a lifetime exposure, sum over all pathways, and, consequently, yield results in terms of the lifetime, total risk to an average member of the cohort. In practice, this means that, although only adult physical characteristics are used in estimating dose rates, the dose/risk calculation follows an average individual who is born, lives, and dies in an environment exposed to a unit intake (or unit concentration) of the radionuclide in question. While the life table used (and the dose and risk calculation) covers the period from birth to 110 years, the average life span for a member of the cohort is 70.7 years.

It should be emphasized that all the RADRISK calculations are for unit intakes or concentrations, as indicated in the output. In order to relate the RADRISK results to the risk from a particular source, the actual intake, or concentration, from that source must be known. The procedures used in obtaining these actual intakes and concentrations are covered elsewhere [2].

The major objective of these calculations is to assess the risk due to exposure to radioactive material. Two types of risk, fatal cancers

and genetic effects, are considered. Since the technique used for each varies considerably, each will be discussed separately.

Fatal Cancers. The procedure used in applying the dose rates and cancer risks described previously to estimate the number of fatal cancers expected to occur in a population (cohort) is outlined in the Life Table section.

The overall scheme used in developing a detailed dose/risk methodology has been to categorize only those organs at risk. Since there is little value in calculating the dose rate to organs which are not susceptible to radiation induced fatal cancer, only those organs having a measurable risk are included in this study.

Numerical estimates of the potential risk of radiation-induced cancer were made by the National Academy of Sciences Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR) 1972 [10]. The Environmental Protection Agency used the average geometric mean of the estimates from the two models developed (absolute risk and relative risk) in its risk assessments. The calculated value, 180 excess fatal cancers per 10^6 person rad, was rounded to 200 excess fatal cancers per 10^6 person rad of uniform total body exposure.

For purposes of risk calculation for inhaled or ingested radioisotopes, risk estimates for individual organs are required since the exposure of individual organs is not uniform. The sum of the risk estimates for individual organs should add up to the 200 excess fatal cancers per 10^6 person rad exposure if the exposure were uniform. This fact is used in defining the Risk Equivalent Factor to be discussed below. The Interagency Task Force on the Health Effects of Ionizing Radiation classified radiation related cancers on the basis of evidence that they could be radiation induced. In epidemiological studies the excess leukemias, and thyroid, lung, and bone cancers ("excess" means the observed number minus the expected number in the absence of the radiation exposure) are strongly associated with radiation exposure. Excess liver and gastrointestinal cancers also have a meaningful association with radiation exposure. The association of several other cancers with radiation exposure is only suggestive. These organs have

been assigned relatively low risks per unit dose for purposes of these calculations.

Genetic Effects. The estimate of the potential frequency of genetic effects is obtained by a relatively straightforward modification of the recommendations of the National Academy of Sciences' Committee on the Biological Effects of Ionizing Radiation (BEIR) [10]. The BEIR committee estimated that the genetic risk of a 5 rad (low LET) exposure in a 30-year generation of parents would be from 300 to 7500 serious genetic effects per million live births. The geometric mean of this range is 1500 effects/10^6 live births for 5 rad delivered in a 30-year generation, or 300 effects/10^6 live births per rad delivered in a 30-year generation. In the calculations performed here, it was assumed that the annual birth rate in the population is 2% of the population size. Since the BEIR estimate was based on a birth rate of 3.33% per year, it was necessary to multiply the BEIR risk factor of 300 effects/10^6 live births per year by 2/3.33 to account for the fewer births (and hence fewer potential genetic effects) per exposed parent. The resulting factor of 180 effects/10^6 live births per rad was rounded to 200 effects/10^6 live births per rad.

The final modification to obtain a population risk estimate was made as follows. Assume each couple produces two children. Then 500,000 parents of each sex would replace their generation. The risk estimate would be 200 genetic effects per 10^6 person rad (10^6 parents each receiving one rad by age 30 and producing 10^6 liveborn). Note that this dose is merely the time integral of the dose rates calculated by the RADRISK code. The age 30 is not meant to imply that childbearing ends at that age but is a weighted value averaged over male and female reproductive ages.

The gonadal doses used as a basis for the genetic risk estimates are obtained by summing the RADRISK annual dose rates over a 30-year period. Separate low and high LET doses for the ovaries and testes, along with gonadal averages, are given as shown in Fig. 6 under the heading "30-year Genetic Dose Commitments (mrad)." Actual multiplication of genetic risk by the gonadal doses is accomplished in the population-dependent calculation described elsewhere [3]. Following

Ref. [27], the genetic risk estimate given above must be increased for high LET radiation.

Summary Table. A summary table for a sample calculation is shown in Figure 6. Note that the results are expressed in several ways. The heading shows the cohort (population) size (100,000), the radionuclide (Ra-226), the exposure type (inhalation) and the particle size (AMAD = 1.0 μ), clearance class (W) and GI absorption fraction (f_1 = 0.2). The main printout array shows, for each organ and radiation LET type, the input data (latency and plateau periods and risk coefficient) and the output data as described in the Life Table section. The most important results are the number of premature deaths and the average years of life lost. Note that the former quantity is for the cohort and would have to be divided by 100,000 to obtain the average probability of fatal cancer for an individual. The average years of life lost, however, is the average over all premature deaths. The total years of life lost column is, therefore, formed by multiplying the first two columns and the decrease in life expectancy for the cohort is found by dividing this product by 100,000.

The remaining output data are of less direct interest. Since the average life expectancy for the cohort is about 70 years, the dose rate at this age is given for reference purposes in the (mrad/yr) column. The dose equivalent rate, DER, which is another measure of radiation dose, is defined as the rad dose rate multiplied by a quality factor (Q) to account for the biological effectiveness of particular types of radiation. Following ICRP Publication 26 [18], the Q for high LET radiation is taken to be 20 and, for low LET, Q is 1. The dose equivalent rate in millirem (mrem) per year units is then

$$\text{DER}\left(\frac{\text{mrem}}{\text{yr}}\right) = 20\ \text{DR}_{\text{high LET}}\left(\frac{\text{mrad}}{\text{yr}}\right) + 1\ \text{DR}_{\text{low LET}}\left(\frac{\text{mrad}}{\text{yr}}\right)$$

The Risk Equivalent Factor (REF) is defined as the ratio of the number of premature deaths from a given radionuclide exposure to the number of deaths from a base calculation which assumes a constant 1 mrad/yr dose rate to each organ. This ratio is used in some auxiliary calculations.

TOTAL COHORT (1.0E+5 PERSONS) CANCER FATALITIES FROM LIFETIME RA-226 INHALATION
AMAD = 1.00 , RESP CLEARANCE CLASS =W , F1 = 0.200E 00

FOR 1.00E 00 PCI/YR INTAKE

SUMMARY TABLE

CANCER	ADULT LATENCY PERIOD (YEARS)	ADULT PLATEAU PERIOD (YEARS)	RISK	LET	ADULT DEATH RATE (DTHS/ 1E6/MRAD/YR)	70-YEAR DOSE RATE (MRAD/YR)	NUMBER OF PREMATURE DEATHS IN COHORT	AVERAGE YEARS OF LIFE LOST (YEARS)	TOTAL YEARS OF LIFE LOST (YEARS)	DECREASE IN LIFE EXPECTANCY (YEARS)	70-YEAR DOSE EQUIV- ALENT RATE (MREM/YR)	RISK EQUIVALENT FACTOR
R MARROW	2	25	AES	LOW	2.30D-03	2.84E-05	6.43D-06	2.64D C1	1.70D-C4	1.70D-09	2.67E-03	2.02E-03
				HIGH	4.60D-02	1.32E-04	6.51D-04	2.76D C1	1.79D-C2	1.79D-07		
ENDOST	5	30	AES	LOW	2.00D-04	5.69E-05	1.18D-06	2.45D C1	2.88D-C5	2.88D-10	2.54E-02	8.56E-03
				HIGH	2.00D-03	1.27E-03	2.63D-04	2.45D C1	6.43D-C3	6.43D-08		
PULMNARY	10	110	AES	LOW	3.00D-03	6.33E-06	3.32D-06	2.23D C1	7.41D-C5	7.41D-10	9.55E-02	4.78E-02
				HIGH	3.00D-02	4.77E-03	2.90D-02	2.30D C1	6.68D-C1	6.68D-06		
BREAST	15	110	AES	LOW	2.30D-03	2.50E-06	5.95D-07	1.89D C1	1.13D-C5	1.13D-10	6.37E-04	3.05E-05
				HIGH	2.30D-03	3.17E-05	1.16D-05	2.08D C1	2.41D-C4	2.41D-09		
LIVER	15	110	AES	LOW	9.00D-04	1.70E-06	1.60D-07	1.90D C1	3.05D-C6	3.05D-11	5.97E-04	2.74E-04
				HIGH	9.00D-03	2.98E-05	4.25D-05	2.08D C1	8.85D-C4	8.85D-09		
ST WALL	15	110	ABS	LOW	5.00D-04	1.49E-06	8.39D-08	1.94D C1	1.63D-C6	1.63D-11	3.91E-06	2.17E-06
				HIGH	5.00D-03	1.21E-07	1.04D-07	2.14D C1	2.24D-C6	2.24D-11		
PANCREAS	15	110	ABS	LOW	7.00D-04	2.41E-06	1.75D-07	1.90D C1	3.32D-C6	3.32D-11	6.37E-04	2.93E-04
				HIGH	7.00D-03	3.17E-05	3.53D-05	2.08D C1	7.34D-C4	7.34D-09		
LLI WALL	15	110	AES	LOW	4.00D-04	2.38E-05	1.59D-06	2.13D C1	3.38D-C5	3.38D-10	1.81E-04	1.01E-04
				HIGH	4.00D-03	7.84E-06	5.43D-06	2.15D C1	1.16D-C4	1.16D-09		
KIDNEYS	15	110	ABS	LOW	2.00D-04	2.21E-06	4.57D-08	1.88D C1	8.61D-C7	8.61D-12	5.98E-04	2.74E-04
				HIGH	2.00D-03	2.98E-05	9.46D-06	2.08D C1	1.97D-C4	1.97D-09		
BL WALL	15	110	ABS	LOW	2.00D-04	1.56E-06	3.46D-08	1.93D C1	6.67D-07	6.67D-12	3.19E-04	1.46E-04
				HIGH	2.00D-03	1.59E-05	5.04D-06	2.08D C1	1.05D-C4	1.05D-09		
ULI WALL	15	110	AES	LOW	2.00D-04	5.57E-06	1.69D-07	2.09D C1	3.54D-C6	3.54D-11	4.44E-05	2.42E-05
				HIGH	2.00D-03	1.94E-06	6.72D-07	2.15D C1	1.44D-C5	1.44D-10		
SI WALL	15	110	AES	LOW	1.00D-04	2.42E-06	2.93D-08	1.98D C1	5.81D-C7	5.81D-12	7.59E-06	4.26E-06
				HIGH	1.00D-03	2.59E-07	4.48D-08	2.14D C1	9.59D-C7	9.59D-12		
OVARIES	15	110	ABS	LOW	1.00D-04	2.68E-06	3.16D-08	1.97D C1	6.23D-C7	6.23D-12	6.38E-04	2.91E-04
				HIGH	1.00D-03	3.17E-05	5.04D-06	2.08D C1	1.05D-C4	1.05D-09		
TESTES	15	110	ABS	LOW	1.00D-04	1.80E-06	1.86D-08	1.89D C1	3.51D-C7	3.51D-12	6.37E-04	2.91E-04
				HIGH	1.00D-03	3.17E-05	5.04D-06	2.08D C1	1.05D-C4	1.05D-09		
SPLEEN	15	110	AES	LOW	1.00D-04	1.75E-06	1.83D-08	1.89D C1	3.47D-C7	3.47D-12	5.97E-04	2.73E-04
				HIGH	1.00D-03	2.98E-05	4.73D-06	2.08D C1	9.83D-C5	9.83D-10		
UTERUS	15	110	AES	LOW	1.00D-04	1.73E-06	1.94D-08	1.93D C1	3.74D-C7	3.74D-12	6.37E-04	2.91E-04
				HIGH	1.00D-03	3.17E-05	5.04D-06	2.08D C1	1.05D-C4	1.05D-09		
THYMUS	15	110	AES	LOW	1.00D-04	1.58E-06	1.67D-08	1.90D C1	3.19D-C7	3.19D-12	6.36E-04	2.91E-04
				HIGH	1.00D-03	3.17E-05	5.04D-06	2.08D C1	1.05D-C4	1.05D-09		
THYROID	2	45	AES	LOW	4.00D-04	1.69E-06	9.60D-08	2.40D C1	2.31D-C6	2.31D-11	6.37E-04	3.10E-05
				HIGH	4.00D-04	3.17E-05	2.53D-06	2.72D C1	6.89D-C5	6.89D-10		
TOTAL (SOMATIC)							3.01E-02	2.31E C1	6.96E-C1	6.96E-06		1.44E-02

30-YEAR GENETIC DOSE COMMITMENTS (MRAD):

LET	TESTES	OVARIES	AVERAGE
LOW	2.82E-05	5.00E-05	3.91E-05
HIGH	8.57E-04	8.57E-04	8.57E-04

Fig. 6. Summary table for a sample calculation made by RADRISK.

3. METABOLIC DATA USED FOR RADRISK CALCULATIONS

As described earlier, inhaled or ingested radionuclides are assumed to be absorbed into the blood from the respiratory and gastrointestinal systems. Activity may then be distributed to systemic organs according to specified uptake coefficients. The fractional uptake coefficients used in calculations in this study are summarized in Table 2. Activity not explicitly designated for uptake to specific source organs may be excreted from the body (this fraction is labeled "Excretion" in Table 2) or may be uniformly distributed throughout the remainder of the body (this fraction is labeled "Other" in Table 2).

Activity deposited in an organ is assumed to be retained according to linear combinations of decaying exponential functions of the form

$$R_{ij}(t) = \sum_k c_{ijk} \exp\left[-\left(\frac{\ln 2}{t_i^r} + \frac{\ln 2}{t_{ijk}^b}\right)t\right],$$

where

t_i^r = radioactive half-life (days) for nuclide i,

t_{ijk}^b = biological half-time (days) for nuclide i in "compartment" k of organ j,

c_{ijk} = a dimensionless fractional coefficient for the k-th exponential term,

$R_{ij}(t)$ = the fraction of an initially deposited quantity of radionuclide i in organ j remaining after t days.

Values of c_{ijk} and t_{ijk}^b used in calculations in this study are shown in Table 2. For each element considered, Table 2 lists one or more principal reference indicating the origin of the information. Specific elements which may require additional explanation are discussed in the following paragraphs.

Hydrogen

An intake of tritium (^3H), as $^3H^1HO$ or ^3H_2O, by ingestion or inhalation, is assumed to be completely absorbed and to mix rapidly with the total water content of the body as described by Killough et al. [19].

Table 2. Metabolic parameters assumed for RADRISK calculations

Element	f_1	Respiratory Clearance Class	Fractional uptake Source Organ	f_s	Organ Retention Parameters c_1	t_1	c_2	t_2	c_3	t_3	c_4	t_4	c_5	t_5	References
Hydrogen[a]	0.95	Gas													Killough et al., 1978
Beryllium	0.002	W, D	Bone	0.32	1.0	450									ICRP, 1959
			Liver	0.10	1.0	270									
			Kidneys	0.03	1.0	120									
			Spleen	0.002	1.0	540									
			Other	0.548	1.0	180									
Carbon[a]	0.95	Gas	Bone	0.008											(used for ^{11}C and ^{15}C only; specific activity model of Killough et al., 1978, used for ^{14}C)
			Other	0.992											
Nitrogen	0.95	Gas	Other	1.0	1.0	90									ICRP, 1959
Oxygen	0.95	Gas	Other	1.0	1.0	14									ICRP, 1959
Sodium	0.95	D	Bone	0.3											Adams et al., 1978
			Other	0.7											
Phosphorus	0.8	D, W	Bone	0.3	1.0										ICRP, 1979
			Other	0.55	0.27	2	0.73	19							
			Excretion[b]	0.15											
Sulfur	0.95	D, W	Other	0.2	0.75	20	0.25	2000							Adams et al., 1978
			Excretion	0.8											
Argon[c]	0.0	Gas	Other	1.0	0.885	5.3E-03	0.092	6.2E-04	0.021	5.7E-03	1.5E-03	0.029	8.0E-04	0.19	Bernard and Snyder, 1975
Potassium	0.95	D	Other	1.0	1.0	30									Adams et al., 1978
Scandium	0.0001	W, Y	Bone	0.2	1.0	33									ICRP, 1959
			Liver	0.15	1.0	36									
			Kidneys	0.02	1.0	75									
			Other	0.63	1.0	30									
Chromium	0.1	D, W, Y	Bone	0.05	1.0	1000									Adams et al., 1978
			Other	0.65	0.62	6	0.38	80							
			Excretion	0.3											
Manganese	0.1	D, W	Bone	0.35	1.0	40									ICRP, 1979
			Liver	0.25	0.4	4	0.6	40							
			Other	0.40	0.5	4	0.5	40							
Iron	0.1	D, W	Liver	0.08											Adams et al., 1978
			Spleen	0.013	1.0	2000									
			Other	0.907											

Table 2. (continued)

Element	f_1	Respiratory Clearance Class	Fractional uptake Source Organ	f_2	Organ Retention Parameters c_1	t_1	c_2	t_2	c_3	t_3	c_4	t_4	c_5	t_5	References
Cobalt	0.05	W, Y	Kidneys	0.05											ICRP, 1979
			Other	0.45	0.6	6	0.2	60	0.2	800					
			Excretion	0.5											
Nickel	0.05	D, W	Kidneys	0.97	1.0	1									Adams et al., 1978
			Others	0.03	1.0	10,000									
Zinc	0.5	D, W, Y	Bone	0.2	1.0	400									Adams et al., 1978
			Other	0.8	0.3	20	0.7	400							
Gallium	0.001	D, W	Bone	0.3	1.0	40									Adams et al., 1978
			Liver	0.25	1.0	2									
			Spleen	*0.01*	*1.0*	*40*									
			Other	0.44	0.5	5	0.5	40							
Arsenic	0.03	W	Liver	0.03	1.0	550									ICRP, 1959
			Kidneys	0.01	1.0	550									
			Other	0.96	1.0	280									
Selenium	0.95, 0.05	D, W	Bone	0.1											Adams et al., 1978
			Liver	0.2											
			Kidneys	0.1	0.4	1	0.3	10	0.3	70					
			Other	0.6											
Krypton[c]	0.0	Gas	Other	0.0	0.89	9.8E-05	0.09	1.0E-03	0.02	9.5E-03	2.9E-01	0.049	1.5E-03	3.121	Bernard and Snyder, 1975
Rubidium	0.95	D	Bone	0.25											Adams et al., 1978
			Other	0.75	1.0	40									
Strontium	0.3, 0.01	D, Y	Bone	0.27	0.393	5	0.0496	170	0.186	1100	0.168	2500	0.203	8800	Adams et al., 1978; ICRP, 1979
			Other	0.73	0.8	1.8	0.15	30	0.041	200	0.003	1600			
Yttrium	0.0001	W, Y	Bone	0.5											Adams et al., 1978
			Liver	0.15											
			Other	0.1	1.0	*									
			Excretion	0.25											
Zirconium	0.002	D, W, Y	Bone	0.5	1.0	8000									ICRP, 1979
			Other	*0.5*	*1.0*	*7*									
Niobium	0.01	W, Y	Bone	0.71											ICRP 1979
			Kidneys	0.018											
			Spleen	0.01	0.5	6	0.5	200							
			Testes	0.002											
			Other	0.26											

Table 2. (Continued)

Element	f_1	Respiratory Clearance Class	Fractional uptake Source organ	f_2	Organ Retention Parameters										References
					c_1	t_1	c_2	t_2	c_3	t_3	c_4	t_4	c_5	t_5	
Molybdenum	0.8, 0.05	D, Y	Bone	0.15	0.1	1	0.9	50							ICRP, 1979
			Liver	0.3											
			Kidneys	0.05											
			Other	0.5											
Technetium	0.8	D, W	Liver	0.08	0.76	1.6	0.2	3.1	0.04	22					Adams et al., 1978
			Kidneys	0.01											
			Thyroid	0.02											
			Other	0.89											
Ruthenium	0.05	D, W, Y	Other	0.85	0.41	8	0.35	35	0.24	1000					Adams et al., 1978
			Excretion	0.15											
Rhodium	0.05	D, W, Y	Other	0.85	0.41	8	0.35	35	0.24	1000					Adams et al., 1978
			Excretion	0.15											
Silver	0.05	D, W, Y	Liver	0.8	0.1	3.5	0.9	50							Adams et al., 1978
			Other	0.2											
Indium	0.02	D, W	Bone	0.3	1.0	-									Adams et al., 1978
			Liver	0.2											
			Kidneys	0.07											
			Spleen	0.01											
			Other	0.42											
Tin	0.05	D, W	Bone	0.5	1.0	50									Adams et al., 1978
			Other	0.5											
Antimony	0.2	D, W	Liver	0.14	1.0	20									Adams et al., 1978
			Other	0.56											
			Excretion	0.3											
Tellurium	0.2	D, W	Bone	0.25	1.0	5000									ICRP, 1979
			Other	0.25	1.0	20									
			Excretion	0.5											
Iodine	0.95	D	Thyroid	0.3	0.05	11.3	0.95	117							USNRC, 1975
			Other	0.7	0.996	0.243	-0.0725	11.3	0.0765	117					
Xenon[c]	0.0	Gas	Other	0.0	0.87	1.78E-04	0.088	0.0021	0.037	0.019	0.0051	0.097	0.0028	0.642	Bernard and Snyder, 1975
Cesium	0.95	D	Other	1.0	0.1	2	0.9	110							ICRP, 1979

Table 2. (Continued)

Element	f_1	Respiratory Clearance Class	Fractional uptake Source Organ	f_1'	Organ Retention Parameters										References
					a_0	t_1	a_1	t_2	a_2	t_3	a_3	t_4	a_4	t_5	
Barium	0.1	D	Bone	0.6	0.43	0.02	0.1	3.5	0.08	190	0.0185	1400	0.0235	5500	Adams et al., 1978
			Other	0.3	0.73	0.8	0.13	18	0.1	130	0.017	1000			
			Excretion	0.1											
Lanthanum Cerium Praseodymium	0.0003	W, Y	Bone	0.2	1.0	3500									ICRP, 1979
			Liver	0.6											
			Spleen	0.05											
			Other	0.15											
Neodymium Promethium Samarium Europium Gadolinium Terbium	0.0001	W, Y	Bone	0.45	1.0	3500									Adams et al., 1978
			Liver	0.45											
			Other	0.0											
			Excretion	0.1											
Hafnium	0.0001	W, Y	Bone	0.15	1.0	600									ICRP, 1979
			Liver	0.45	1.0	625									
			Kidneys	0.02	1.0	563									
			Spleen	0.13	1.0	350									
			Other	0.25	1.0	563									
Wolfram	0.1	W, Y	Bone	0.07	1.0	9									ICRP, 1979
			Liver	0.06	1.0	-									
			Other	0.87	1.0	1									
Iridium	0.01	D, W, Y	Liver	0.2	0.2	8	0.8	200							Furchner et al., 1971
			Kidneys	0.04											
			Spleen	0.02											
			Other	0.54											
			Excretion	0.2											
Mercury	0.02	D, W	Kidneys	0.08	0.95	40	0.05	10,000							Adams et al., 1978
			Other	0.92											
Thallium	0.95	W	Kidneys	0.05	1.0	7									Adams et al., 1978
			Other	0.95											
Lead	0.2	D, W	Bone	0.55	0.6	12	0.15	180	0.25	12,000					Adams et al., 1978
			Liver	0.25											
			Kidneys	0.02	0.8	12	0.18	180	0.02	12,000					
			Other	0.18											
Bismuth	0.05	D, W	Kidneys	0.4	0.6	0.6	0.4	5							Adams et al., 1978
			Other	0.6											

Table 2. (Continued)

Element	f_1	Respiratory Clearance Class	Fractional uptake Source Organ	Fractional uptake	Organ retention parameters	Reference
Polonium	0.1	D, W	Liver	0.1	[illegible]	[illegible]
			Kidneys	[illegible]		
			Spleen	0.1		
			Other	[illegible]		
Radon	0.0	[illegible]	Bone	[illegible]	[illegible]	[illegible]
			Other	[illegible]	[illegible]	
Radium	0.2	W	Bone	[illegible]	[illegible]	[illegible]
			Other	[illegible]	[illegible]	
Actinium	0.001	W, Y	Bone	0.2	[illegible]	[illegible]
			Liver	0.6		
			Spleen	0.05		
			Other	0.15		
Thorium	0.0002	W, Y	Bone	[illegible]	[illegible]	[illegible]
			Liver	[illegible]	[illegible]	
			Other	[illegible]		
			Excretion	[illegible]		
Uranium	0.2	D, W	Bone	[illegible]	[illegible]	[illegible]
	0.002	Y	Kidneys	[illegible]	[illegible]	
			Other	[illegible]		
			Excretion	[illegible]		
Protactinium, Neptunium, Plutonium, Americium, Curium	0.001[c]	W, Y	Bone	[illegible]	[illegible]	[illegible]
			Liver	[illegible]	[illegible]	
			Testes	[illegible]	[illegible]	
			Ovaries	0.00011	[illegible]	
			Other	[illegible]	[illegible]	
			Excretion	[illegible]		

[a]Steady-state specific activity models are employed for [illegible]. These models are described in Killough et [illegible] and are briefly summarized in this report.

[b]Excretion is considered only for nuclides directly inhaled or ingested, and assumes a clearance half-time of [illegible] when a radionuclide with an excretion fraction [illegible] daughter, this fraction of the activity is assigned to "Other".

[c]For noble gases no translocation of activity to organs other than the lungs is assumed. [illegible] retention models shown are [illegible] produced in situ by decay of a radioactive parent.

[d]A value of f_1 = 0.0001 was used for oxides (class Y) of [illegible].

We assume conditions of chronic exposure, a 1 pCi daily intake of ^{3}H, and a 350 g daily intake of ^{1}H; the assumption is also made that the $^{3}H/^{1}H$ ratio in the organ is equivalent to that in the daily intake. If we denote the fractional weight of hydrogen in the organ as F_H then the activity concentration in the organ (pCi per gram) is $F_H/350$.

For inhalation we assume complete absorption of each inspired microcurie as well as absorption of an additional 0.5 μCi through the skin, so that the activity concentration is estimated as

$$1.5 \times F_H/350 \text{ per } \mu Ci \text{ inspired.}$$

Estimates of ^{3}H dose rates to various organs of the body per unit exposure are presented in Table 3.

Carbon

In this analysis an important distinction is made between radiocarbon as ^{14}C, and that occurring as ^{11}C, ^{15}C, or other short-lived isotopes. For ^{14}C, which is assumed to reach man through inhalation of $^{14}CO_2$ or ingestion of biologically bound ^{14}C, a steady-state specific activity model of Killough [21] is employed. For other isotopes, the explicit dynamic retention equations shown in Table 2 are used.

Estimates of dose rates to each organ considered in this study from ^{14}C inhalation and ingestion are shown in Table 4. It should be noted that ^{14}C entering the body by inhalation is assumed to be diluted by a factor of approximately 100 by nonradioactive carbon from the GI tract, as if the individual consumed only uncontaminated food. This approach permits independent consideration of the inhalation and ingestion pathways. In a uniformly contaminated environment, more than 99 percent of the ^{14}C dose would result from the ingestion pathway.

For carbon isotopes which are short lived, the specific activity model is inappropriate. For these isotopes, an exponential retention model was employed, assuming a mean biological half-life of 200 days in bone and 35 days in other tissues of the body. Fractional uptake is assumed to be 0.008 in bone with the remainder distributed throughout other tissues.

Table 3. Dose rates to various organs (mrad/yr) resulting from 1.0 pCi/yr intake of ^{3}H as water

Organ	Inhalation/ skin-absorption	Ingestion
Red marrow	1.24×10^{-7}	8.26×10^{-8}
Endosteal	9.85×10^{-8}	6.56×10^{-8}
Pulmonary	1.25×10^{-7}	8.36×10^{-8}
Breast	1.25×10^{-7}	8.30×10^{-8}
Liver	1.24×10^{-7}	8.28×10^{-8}
Stomach	1.25×10^{-7}	1.08×10^{-7}
Pancreas	1.21×10^{-7}	8.06×10^{-8}
Lower large intestine	1.33×10^{-7}	1.43×10^{-7}
Kidneys	1.29×10^{-7}	8.56×10^{-8}
Bladder	1.23×10^{-7}	8.18×10^{-8}
Upper large intestine	1.37×10^{-7}	1.09×10^{-7}
Small intestine	1.30×10^{-7}	8.97×10^{-8}
Ovaries	1.24×10^{-7}	8.29×10^{-8}
Testes	1.25×10^{-7}	8.30×10^{-8}
Spleen	1.24×10^{-7}	8.28×10^{-8}
Uterus	1.25×10^{-7}	8.34×10^{-8}
Thymus	1.12×10^{-7}	7.45×10^{-8}
Thyroid	1.24×10^{-7}	8.28×10^{-8}

Table 4. Dose rates to various organs (mrad/yr) resulting from 1.0 pCi/yr intake of ^{14}C

Organ	Inhalation	Ingestion
Red marrow	2.42×10^{-8}	3.38×10^{-6}
Endosteal	2.22×10^{-8}	3.06×10^{-6}
Pulmonary	6.18×10^{-9}	8.94×10^{-7}
Breast	1.41×10^{-8}	1.92×10^{-6}
Liver	8.88×10^{-9}	1.23×10^{-6}
Stomach	7.35×10^{-9}	1.21×10^{-6}
Pancreas	7.84×10^{-9}	1.09×10^{-6}
Lower large intestine	7.22×10^{-9}	1.46×10^{-6}
Kidneys	7.92×10^{-9}	1.06×10^{-6}
Bladder	6.75×10^{-9}	9.00×10^{-7}
Upper large intestine	6.90×10^{-9}	1.11×10^{-6}
Small intestine	7.06×10^{-9}	1.01×10^{-6}
Ovaries	5.29×10^{-9}	7.36×10^{-7}
Testes	5.42×10^{-9}	7.23×10^{-7}
Spleen	6.77×10^{-9}	9.45×10^{-7}
Uterus	6.97×10^{-9}	9.51×10^{-7}
Thymus	7.11×10^{-9}	9.78×10^{-7}
Thyroid	6.48×10^{-9}	8.89×10^{-7}

Noble Gases

Lung retention of inhaled noble gas isotopes was determined by substituting special parameters into the ICRP Task Group Lung Model using an approach previously described by Dunning et al. [1] for radon gas. Translocation of gas to systemic organs from the respiratory system is not included in these calculations. Inhaled gas is assumed to reside in the lungs until it is eliminated by radiological decay or is lost from the body. Migration of activity to systemic organs and the GI tract is considered only for nongaseous radioactive daughters produced in the lungs. Thus, estimates of dose and risk to organs other than the lungs from inhaled noble gases may be underestimated. The organ dose from inhalation is generally not as significant as that from the immersion (external) exposure.

The retention equations indicated in Table 2 are utilized in these calculations only when a gas is produced *in situ* in systemic organs from the radiological decay of a progenitor species. In this case, retention equations are adopted from Bernard and Snyder [23].

Transuranics

For transuranic isotopes (Pa, Np, Pu, Am, and Cm), metabolic models and parameters from the EPA transuranic guidance document [27] were used. As recommended in that report, a GI tract to blood absorption fraction of $f_1 = 10^{-4}$ was used for oxides of low specific activity plutonium isotopes (^{239}Pu, ^{240}Pu, and ^{242}Pu), while a value of $f_1 = 10^{-3}$ was used for all other transuranic isotopes. Protactinium and neptunium were not explicitly treated in that study, but they are assumed to behave similarly to americium, curium, and soluble forms of plutonium.

Uranium

For soluble forms of uranium, selection of the GI tract to blood absorption fraction, f_1, deviated from recent ICRP recommendations [6] upon which all other parameters for our uranium calculations are based. On the basis of evidence of high levels of absorption for cases of low-level environmental exposures (see [28], [29]), a value of $f_1 = 0.2$ was selected for use in this study for soluble forms of uranium.

4. RESULTS OF RISK CALCULATIONS

The risks of developing fatal cancers in various organs of the body as a result of radionuclide exposures were computed as described in the preceding sections. Estimates of risk were based on the risk factors given in Table 1. As one might expect from examination of the risk factors in Table 1, risks from leukemia, pulmonary cancers, breast cancers, and endosteal cancers were usually found to be dominant.

For each radionuclide and exposure pathway considered, it was assumed that a cohort of 100,000 persons was exposed to a constant radionuclide concentration for the lifetime of the cohort. Dose rates for a reference adult were assumed to be appropriate for all members of the cohort at all times. Furthermore, no fetal exposures were considered. More refined calculations incorporating age-dependent dosimetry will be produced later in the study.

As a point of reference, a base case assuming a chronic lifetime exposure of 1 mrad/year of low-LET radiation to each organ of each member of the cohort was considered. Estimates of the radiation-induced mortalities in the cohort from this case are indicated in the last column of Table 1 and are summarized in Table 5. These results are used in the following tables to compute, in each case, the "risk equivalent factor," or "REF," defined earlier.

Estimates of potential risk resulting from chronic exposures to each of approximately 150 radionuclides have been computed for each of four exposure pathways (where applicable): inhalation, ingestion, immersion in contaminated air, and irradiation from a contaminated ground surface. Summary results are tabulated in Tables 6 through 9, with a separate table provided for each exposure pathway.

Estimates of radiation-induced mortalities from pulmonary cancer due to chronic exposure of the cohort to 10^{-4} working level of radon daughters have also been computed. It is assumed that residential exposure to 1 WL for a year results in a cumulative exposure of 27 WLM. Results of this analysis are presented in Table 10. In this case, a relative risk model was used; it was assumed that there would be a 3 percent increase in pulmonary cancer per working level month [30]. (A

Table 5. Estimates of radiation-induced mortality in cohort of 100,000 from continuous whole body exposure (1 mrad/yr)

Dose rate (mrad/yr)	Premature deaths	Years of life lost (years)
1.0	2.09	49.9

Table 6. Health effects from radionuclide inhalation (1.0 pCi/year chronic cohort exposure).

Nuclide	Inhalation class	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
H-3	GAS	9.50E-01	2.60E-07	6.17E-06	1.25E-07
BE-7	W	2.00E-03	1.15E-06	2.67E-05	5.50E-07
BE-7	D	2.00E-03	9.81E-07	2.36E-05	4.70E-07
C-11	GAS	9.50E-01	2.76E-08	6.25E-07	1.32E-08
C-14	GAS	9.50E-01	2.34E-08	5.65E-07	1.12E-08
C-15	GAS	9.50E-01	4.75E-09	1.09E-07	2.27E-09
N-13	GAS	9.50E-01	1.68E-08	3.73E-07	8.03E-09
O-15	GAS	9.50E-01	7.91E-09	1.80E-07	3.79E-09
NA-22	D	9.50E-01	2.33E-05	5.67E-04	1.12E-05
P-32	D	8.00E-01	1.52E-05	3.81E-04	7.26E-06
P-32	W	8.00E-01	1.04E-04	2.41E-03	4.95E-05
S-35	D	9.50E-01	1.06E-06	2.52E-05	5.10E-07
S-35	W	9.50E-01	2.00E-05	4.62E-04	9.59E-06
AR-41	GAS	0.00E+00	3.20E-09	7.17E-08	1.53E-09
K-40	D	9.50E-01	2.73E-05	6.65E-04	1.31E-05
SC-46	Y	1.00E-04	1.94E-04	4.46E-03	9.29E-05
SC-46	W	1.00E-04	9.30E-05	2.14E-03	4.45E-05
CR-51	Y	1.00E-01	2.13E-06	4.90E-05	1.02E-06
CR-51	W	1.00E-01	1.52E-06	3.51E-05	7.28E-07
CR-51	D	1.00E-01	2.45E-07	5.79E-06	1.17E-07
MN-54	W	1.00E-01	3.16E-05	7.31E-04	1.51E-05
MN-54	D	1.00E-01	1.11E-05	2.66E-04	5.33E-06
MN-56	W	1.00E-01	1.95E-06	4.49E-05	9.33E-07
MN-56	D	1.00E-01	1.86E-06	4.29E-05	8.92E-07
FE-55	W	1.00E-01	4.77E-06	1.11E-04	2.28E-06
FE-55	D	1.00E-01	4.24E-06	1.00E-04	2.03E-06
FE-59	W	1.00E-01	6.19E-05	1.43E-03	2.96E-05
FE-59	D	1.00E-01	2.97E-05	7.09E-04	1.42E-05
CO-57	Y	5.00E-02	6.68E-05	1.54E-03	3.20E-05
CO-57	W	5.00E-02	1.68E-05	3.88E-04	8.03E-06
CO-58	Y	5.00E-02	6.82E-05	1.58E-03	3.26E-05
CO-58	W	5.00E-02	3.47E-05	8.03E-04	1.66E-05
CO-60	Y	5.00E-02	1.35E-03	3.04E-02	6.47E-04
CO-60	W	5.00E-02	1.62E-04	3.76E-03	7.77E-05
NI-59	W	5.00E-02	4.41E-06	1.01E-04	2.11E-06
NI-59	D	5.00E-02	1.00E-06	2.07E-05	4.79E-07
NI-63	W	5.00E-02	1.18E-05	2.70E-04	5.64E-06
NI-63	D	5.00E-02	2.40E-06	5.03E-05	1.15E-06
ZN-65	Y	5.00E-01	1.98E-05	4.78E-04	9.47E-06
ZN-65	W	5.00E-01	1.82E-05	4.42E-04	8.70E-06
ZN-65	D	5.00E-01	2.49E-05	6.07E-04	1.19E-05
GA-67	W	1.00E-03	2.26E-06	5.18E-05	1.08E-06
GA-67	D	1.00E-03	8.46E-07	1.96E-05	4.05E-07
AS-76	W	3.00E-02	2.07E-05	4.76E-04	9.92E-06
KR-83M	GAS	0.00E+00	2.43E-10	3.73E-09	1.16E-10
KR-85M	GAS	0.00E+00	1.61E-09	3.30E-08	7.69E-10
KR-85	GAS	0.00E+00	1.52E-09	3.10E-08	7.27E-10
KR-87	GAS	0.00E+00	8.28E-09	1.89E-07	3.96E-09
KR-88	GAS	0.00E+00	1.52E-08	3.47E-07	7.28E-09
KR-89	GAS	0.00E+00	1.48E-08	3.39E-07	7.07E-09
RB-88	D	9.50E-01	5.31E-07	1.22E-05	2.54E-07
RB-89	D	9.50E-01	2.51E-07	5.76E-06	1.20E-07
SR-89	D	3.00E-01	1.58E-05	4.04E-04	7.55E-06
SR-89	Y	1.00E-02	3.32E-04	7.63E-03	1.59E-04
SR-90	D	3.00E-01	3.77E-04	1.02E-02	1.80E-04
SR-90	Y	1.00E-02	8.05E-03	1.74E-01	3.85E-03

Table 6. (Cont'd).

Nuclide	Inhalation class	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
SR-91	D	3.00E-01	4.29E-06	9.98E-05	2.05E-06
SR-91	Y	1.00E-02	7.92E-06	1.82E-04	3.79E-06
Y-90	Y	1.00E-04	3.87E-05	8.83E-04	1.85E-05
Y-90	W	1.00E-04	3.72E-05	8.52E-04	1.78E-05
Y-91M	Y	1.00E-04	2.70E-07	6.21E-06	1.29E-07
Y-91M	W	1.00E-04	1.71E-07	3.92E-06	8.18E-08
Y-91	Y	1.00E-04	3.91E-04	8.99E-03	1.87E-04
Y-91	W	1.00E-04	2.15E-04	4.98E-03	1.03E-04
ZR-93	Y	2.00E-03	2.19E-04	4.61E-03	1.05E-04
ZR-93	W	2.00E-03	1.41E-05	3.27E-04	6.76E-06
ZR-93	D	2.00E-03	5.26E-06	1.27E-04	2.52E-06
ZR-95	Y	2.00E-03	1.81E-04	4.17E-03	8.64E-05
ZR-95	W	2.00E-03	8.30E-05	1.92E-03	3.97E-05
ZR-95	D	2.00E-03	1.59E-05	4.22E-04	7.62E-06
NB-93M	Y	1.00E-02	2.20E-04	4.86E-03	1.05E-04
NB-93M	W	1.00E-02	1.93E-05	4.44E-04	9.22E-06
NB-94	Y	1.00E-02	2.19E-03	4.68E-02	1.05E-03
NB-94	W	1.00E-02	1.70E-04	3.95E-03	8.15E-05
NB-95	Y	1.00E-02	7.09E-05	1.62E-03	3.39E-05
NB-95	W	1.00E-02	4.68E-05	1.08E-03	2.24E-05
MO-99	Y	5.00E-02	1.79E-05	4.09E-04	8.56E-06
MO-99	D	8.00E-01	6.57E-06	1.51E-04	3.14E-06
TC-97	W	8.00E-01	7.76E-06	1.79E-04	3.71E-06
TC-97	D	8.00E-01	3.23E-07	8.09E-06	1.55E-07
TC-99M	W	8.00E-01	1.26E-07	2.89E-06	6.03E-08
TC-99M	D	8.00E-01	1.13E-07	2.63E-06	5.39E-08
TC-99	W	8.00E-01	5.58E-05	1.29E-03	2.67E-05
TC-99	D	8.00E-01	2.28E-06	5.74E-05	1.09E-06
RU-97	Y	5.00E-02	1.51E-06	3.48E-05	7.23E-07
RU-97	W	5.00E-02	1.47E-06	3.39E-05	7.02E-07
RU-97	D	5.00E-02	6.40E-07	1.50E-05	3.06E-07
RU-103	Y	5.00E-02	6.34E-05	1.46E-03	3.03E-05
RU-103	W	5.00E-02	4.07E-05	9.38E-04	1.95E-05
RU-103	D	5.00E-02	6.92E-06	1.65E-04	3.31E-06
RU-106	Y	5.00E-02	4.01E-03	9.13E-02	1.92E-03
RU-106	W	5.00E-02	8.50E-04	1.96E-02	4.07E-04
RU-106	D	5.00E-02	1.29E-04	3.12E-03	6.17E-05
RH-103M	Y	5.00E-02	2.91E-08	6.62E-07	1.39E-08
RH-103M	W	5.00E-02	2.91E-08	6.65E-07	1.39E-08
RH-103M	D	5.00E-02	2.93E-08	6.64E-07	1.40E-08
RH-106	Y	5.00E-02	9.69E-09	2.24E-07	4.63E-09
RH-106	W	5.00E-02	9.69E-09	2.24E-07	4.64E-09
RH-106	D	5.00E-02	9.72E-09	2.24E-07	4.65E-09
AG-110M	Y	5.00E-02	3.01E-03	6.90E-02	1.44E-03
AG-110M	W	5.00E-02	8.12E-04	1.86E-02	3.89E-04
AG-110M	D	5.00E-02	2.28E-04	5.03E-03	1.09E-04
AG-110	Y	5.00E-02	6.61E-09	1.51E-07	3.16E-09
AG-110	W	5.00E-02	6.62E-09	1.51E-07	3.17E-09
AG-110	D	5.00E-02	6.64E-09	1.52E-07	3.18E-09
IN-113M	W	2.00E-02	2.06E-07	4.70E-06	9.84E-08
IN-113M	D	2.00E-02	2.04E-07	4.65E-06	9.76E-08
SN-113	W	5.00E-02	7.25E-05	1.68E-03	3.47E-05
SN-113	D	5.00E-02	1.10E-05	2.81E-04	5.26E-06
SN-126	W	5.00E-02	5.95E-04	1.38E-02	2.85E-04
SN-126	D	5.00E-02	8.59E-05	2.20E-03	4.11E-05
SB-124	W	2.00E-01	1.74E-04	4.01E-03	8.34E-05

Table 6. (Cont'd).

Nuclide	Inhalation class	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
SB-124	D	2.00E-01	2.21E-05	5.16E-04	1.06E-05
SB-125	W	2.00E-01	8.54E-05	1.97E-03	4.09E-05
SB-125	D	2.00E-01	7.26E-06	1.70E-04	3.47E-06
SB-126M	W	2.00E-01	1.92E-07	4.41E-06	9.20E-08
SB-126M	D	2.00E-01	1.94E-07	4.44E-06	9.27E-08
SB-126	W	2.00E-01	6.19E-05	1.42E-03	2.96E-05
SB-126	D	2.00E-01	1.60E-05	3.73E-04	7.68E-06
TE-125M	W	2.00E-01	4.11E-05	9.48E-04	1.97E-05
TE-125M	D	2.00E-01	3.45E-06	8.89E-05	1.65E-06
TE-132	W	2.00E-01	4.82E-05	1.19E-03	2.31E-05
TE-132	D	2.00E-01	1.63E-05	4.16E-04	7.80E-06
I-122	D	9.50E-01	6.88E-08	1.65E-06	3.29E-08
I-123	D	9.50E-01	1.24E-06	3.36E-05	5.93E-07
I-125	D	9.50E-01	6.93E-06	1.93E-04	3.31E-06
I-129	D	9.50E-01	4.32E-05	1.21E-03	2.06E-05
I-131	D	9.50E-01	1.22E-05	3.30E-04	5.84E-06
I-132	D	9.50E-01	3.04E-06	8.00E-05	1.45E-06
I-133	D	9.50E-01	2.30E-05	6.32E-04	1.10E-05
I-134	D	9.50E-01	1.21E-06	3.13E-05	5.81E-07
I-135	D	9.50E-01	6.86E-06	1.84E-04	3.28E-06
XE-122	GAS	0.00E+00	6.85E-09	1.55E-07	3.28E-09
XE-123	GAS	0.00E+00	1.65E-09	3.32E-08	7.88E-10
XE-125	GAS	0.00E+00	4.68E-10	7.54E-09	2.24E-10
XE-127	GAS	0.00E+00	3.15E-10	4.99E-09	1.51E-10
XE-131M	GAS	0.00E+00	8.91E-10	1.84E-08	4.27E-10
XE-133M	GAS	0.00E+00	1.19E-09	2.43E-08	5.71E-10
XE-133	GAS	0.00E+00	8.59E-10	1.78E-08	4.11E-10
XE-135M	GAS	0.00E+00	7.33E-10	1.42E-08	3.51E-10
XE-135	GAS	0.00E+00	2.02E-09	4.55E-08	9.67E-10
XE-137	GAS	0.00E+00	1.05E-08	2.43E-07	5.03E-09
XE-138	GAS	0.00E+00	1.19E-08	2.72E-07	5.67E-09
CS-134	D	9.50E-01	9.23E-05	2.22E-03	4.42E-05
CS-135	D	9.50E-01	8.59E-06	2.11E-04	4.11E-06
CS-136	D	9.50E-01	1.65E-05	3.94E-04	7.88E-06
CS-137	D	9.50E-01	6.35E-05	1.54E-03	3.04E-05
CS-138	D	9.50E-01	6.11E-07	1.40E-05	2.92E-07
BA-133M	D	1.00E-01	2.32E-06	5.33E-05	1.11E-06
BA-133	D	1.00E-01	1.18E-05	2.95E-04	5.64E-06
BA-137M	D	1.00E-01	3.67E-09	7.75E-08	1.76E-09
BA-139	D	1.00E-01	9.84E-07	2.26E-05	4.71E-07
BA-140	D	1.00E-01	1.03E-05	2.42E-04	4.93E-06
LA-140	Y	3.00E-04	1.92E-05	4.41E-04	9.21E-06
LA-140	W	3.00E-04	1.92E-05	4.39E-04	9.18E-06
CE-141	Y	3.00E-04	6.68E-05	1.54E-03	3.20E-05
CE-141	W	3.00E-04	4.73E-05	1.08E-03	2.26E-05
CE-144	Y	3.00E-04	3.06E-03	6.98E-02	1.46E-03
CE-144	W	3.00E-04	8.99E-04	2.05E-02	4.30E-04
PR-144M	Y	3.00E-04	1.23E-07	2.84E-06	5.90E-08
PR-144M	W	3.00E-04	1.25E-07	2.86E-06	5.96E-08
PR-144	Y	3.00E-04	2.85E-07	6.55E-06	1.36E-07
PR-144	W	3.00E-04	2.87E-07	6.59E-06	1.37E-07
SM-151	Y	1.00E-04	1.84E-04	3.94E-03	8.78E-05
SM-151	W	1.00E-04	2.84E-05	5.95E-04	1.36E-05
SM-153	Y	1.00E-04	8.72E-06	2.00E-04	4.17E-06
SM-153	W	1.00E-04	8.51E-06	1.95E-04	4.07E-06
EU-152	Y	1.00E-04	1.53E-03	3.35E-02	7.30E-04

Table 6. (Cont'd).

Nuclide	Inhalation class	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
EU-152	W	1.00E-04	4.60E-04	1.01E-02	2.20E-04
EU-154	Y	1.00E-04	2.51E-03	5.56E-02	1.20E-03
EU-154	W	1.00E-04	6.11E-04	1.35E-02	2.92E-04
EU-155	Y	1.00E-04	2.14E-03	4.78E-02	1.02E-03
EU-155	W	1.00E-04	5.13E-04	1.15E-02	2.46E-04
EU-156	Y	1.00E-04	9.19E-05	2.12E-03	4.40E-05
EU-156	W	1.00E-04	7.80E-05	1.79E-03	3.73E-05
GD-152	Y	1.00E-04	1.29E-01	2.89E+00	6.19E-02
GD-152	W	1.00E-04	3.15E-02	6.54E-01	1.51E-02
TB-160	Y	1.00E-04	2.44E-04	5.63E-03	1.17E-04
TB-160	W	1.00E-04	1.33E-04	3.06E-03	6.38E-05
HF-181	Y	1.00E-04	1.21E-04	2.80E-03	5.81E-05
HF-181	W	1.00E-04	7.91E-05	1.82E-03	3.78E-05
W-187	Y	1.00E-01	5.70E-06	1.31E-04	2.73E-06
W-187	W	1.00E-01	5.57E-06	1.27E-04	2.67E-06
IR-192	Y	1.00E-02	2.12E-04	4.87E-03	1.01E-04
IR-192	W	1.00E-02	1.07E-04	2.47E-03	5.14E-05
IR-192	D	1.00E-02	3.32E-05	7.66E-04	1.59E-05
HG-203	W	2.00E-02	3.89E-05	8.96E-04	1.86E-05
HG-203	D	2.00E-02	7.28E-06	1.73E-04	3.48E-06
TL-207	W	9.50E-01	3.21E-08	7.37E-07	1.54E-08
TL-208	W	9.50E-01	3.26E-08	7.33E-07	1.56E-08
PB-210	W	2.00E-01	3.82E-03	8.80E-02	1.83E-03
PB-210	D	2.00E-01	8.59E-04	2.01E-02	4.11E-04
PB-211	W	2.00E-01	2.90E-05	6.69E-04	1.39E-05
PB-211	D	2.00E-01	2.94E-05	6.90E-04	1.41E-05
PB-212	W	2.00E-01	6.30E-04	1.46E-02	3.01E-04
PB-212	D	2.00E-01	4.41E-04	1.07E-02	2.11E-04
PB-214	W	2.00E-01	2.94E-05	6.80E-04	1.40E-05
PB-214	D	2.00E-01	2.95E-05	6.90E-04	1.41E-05
BI-210	W	5.00E-02	5.75E-04	1.33E-02	2.75E-04
BI-210	D	5.00E-02	5.47E-05	1.29E-03	2.62E-05
BI-211	W	5.00E-02	1.96E-06	4.49E-05	9.37E-07
BI-211	D	5.00E-02	1.96E-06	4.51E-05	9.38E-07
BI-212	W	5.00E-02	6.59E-05	1.51E-03	3.15E-05
BI-212	D	5.00E-02	6.42E-05	1.48E-03	3.07E-05
BI-214	W	5.00E-02	2.15E-05	4.96E-04	1.03E-05
BI-214	D	5.00E-02	2.16E-05	4.98E-04	1.04E-05
PO-210	W	1.00E-01	2.49E-02	5.73E-01	1.19E-02
PO-210	D	1.00E-01	3.90E-03	9.35E-02	1.87E-03
PO-212	W	1.00E-01	6.20E-15	1.40E-13	2.97E-15
PO-212	D	1.00E-01	6.20E-15	1.40E-13	2.97E-15
PO-214	W	1.00E-01	2.91E-12	6.69E-11	1.39E-12
PO-214	D	1.00E-01	2.91E-12	6.70E-11	1.39E-12
PO-215	W	1.00E-01	5.81E-11	1.34E-09	2.78E-11
PO-215	D	1.00E-01	5.86E-11	1.36E-09	2.81E-11
PO-216	W	1.00E-01	4.83E-09	1.11E-07	2.31E-09
PO-216	D	1.00E-01	4.09E-09	9.36E-08	1.95E-09
PO-218	W	1.00E-01	5.90E-06	1.37E-04	2.82E-06
PO-218	D	1.00E-01	5.90E-06	1.36E-04	2.82E-06
RN-219	GAS	0.00E+00	4.60E-07	1.07E-05	2.20E-07
RN-220	GAS	0.00E+00	1.09E-06	2.50E-05	5.20E-07
RN-222	GAS	0.00E+00	3.19E-07	7.33E-06	1.52E-07
RA-223	W	2.00E-01	2.31E-02	5.34E-01	1.10E-02
RA-224	W	2.00E-01	3.90E-03	9.09E-02	1.87E-03
RA-226	W	2.00E-01	3.01E-02	6.96E-01	1.44E-02

Table 6. (Cont'd).

Nuclide	Inhalation class	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
RA-228	W	2.00E-01	3.24E-03	7.70E-02	1.55E-03
AC-227	Y	1.00E-03	6.83E-01	1.53E+01	3.27E-01
AC-227	W	1.00E-03	3.99E-01	9.20E+00	1.91E-01
AC-228	Y	1.00E-03	1.30E-04	2.97E-03	6.21E-05
AC-228	W	1.00E-03	4.67E-05	1.21E-03	2.25E-05
TH-227	Y	2.00E-04	3.98E-02	9.15E-01	1.90E-02
TH-227	W	2.00E-04	2.84E-02	6.65E-01	1.36E-02
TH-228	Y	2.00E-04	3.79E-01	8.67E+00	1.81E-01
TH-228	W	2.00E-04	1.22E-01	3.22E+00	5.85E-02
TH-230	Y	2.00E-04	3.57E-01	8.05E+00	1.71E-01
TH-230	W	2.00E-04	2.76E-01	6.66E+00	1.32E-01
TH-231	Y	2.00E-04	3.32E-04	7.58E-03	1.59E-06
TH-231	W	2.00E-04	3.26E-04	7.45E-03	1.56E-06
TH-232	Y	2.00E-04	3.38E-01	7.60E+00	1.62E-01
TH-232	W	2.00E-04	2.58E-01	6.21E+00	1.24E-01
TH-234	Y	2.00E-04	2.56E-04	5.88E-03	1.22E-04
TH-234	W	2.00E-04	1.89E-04	4.38E-03	9.06E-05
PA-231	Y	1.00E-03	5.20E-01	1.09E+01	2.49E-01
PA-231	W	1.00E-03	5.98E-01	1.19E+01	2.86E-01
PA-233	Y	1.00E-03	6.58E-05	1.52E-03	3.15E-05
PA-233	W	1.00E-03	4.87E-05	1.12E-03	2.33E-05
PA-234M	Y	1.00E-03	1.31E-08	3.01E-07	6.27E-09
PA-234M	W	1.00E-03	1.31E-08	3.02E-07	6.28E-09
PA-234	Y	1.00E-03	3.26E-06	7.48E-05	1.56E-06
PA-234	W	1.00E-03	3.26E-06	7.48E-05	1.56E-06
U-233	Y	2.00E-03	2.74E-01	6.16E+00	1.31E-01
U-233	D	2.00E-01	1.78E-03	4.33E-02	8.54E-04
U-233	W	2.00E-01	2.99E-02	6.88E-01	1.43E-02
U-234	Y	2.00E-03	2.70E-01	6.09E+00	1.29E-01
U-234	W	2.00E-01	2.95E-02	6.79E-01	1.41E-02
U-234	D	2.00E-01	1.76E-03	4.25E-02	8.40E-04
U-235	Y	2.00E-03	2.45E-01	5.51E+00	1.17E-01
U-235	W	2.00E-01	2.66E-02	6.12E-01	1.27E-02
U-235	D	2.00E-01	1.49E-03	3.58E-02	7.11E-04
U-236	Y	2.00E-03	2.55E-01	5.74E+00	1.22E-01
U-236	W	2.00E-01	2.78E-02	6.40E-01	1.33E-02
U-236	D	2.00E-01	1.59E-03	3.84E-02	7.60E-04
U-238	Y	2.00E-03	2.71E-01	6.07E+00	1.30E-01
U-238	W	2.00E-01	2.61E-02	6.03E-01	1.25E-02
U-238	D	2.00E-01	1.50E-03	3.62E-02	7.17E-04
NP-237	Y	1.00E-03	4.10E-01	8.89E+00	1.96E-01
NP-237	W	1.00E-03	3.67E-01	7.78E+00	1.76E-01
NP-239	Y	1.00E-03	9.45E-06	2.17E-04	4.52E-06
NP-239	W	1.00E-03	9.21E-06	2.11E-04	4.41E-06
PU-238	Y	1.00E-03	4.14E-01	9.11E+00	1.98E-01
PU-238	W	1.00E-03	3.38E-01	7.37E+00	1.62E-01
PU-239	Y	1.00E-04	4.14E-01	9.00E+00	1.98E-01
PU-239	W	1.00E-03	3.72E-01	7.88E+00	1.78E-01
PU-240	Y	1.00E-04	4.14E-01	9.00E+00	1.98E-01
PU-240	W	1.00E-03	3.71E-01	7.88E+00	1.78E-01
PU-241	Y	1.00E-03	2.90E-03	5.42E-02	1.39E-03
PU-241	W	1.00E-03	5.79E-03	1.07E-01	2.77E-03
PU-242	Y	1.00E-04	3.96E-01	8.62E+00	1.90E-01
PU-242	W	1.00E-03	3.59E-01	7.62E+00	1.72E-01
AM-241	Y	1.00E-03	4.33E-01	9.45E+00	2.07E-01
AM-241	W	1.00E-03	3.75E-01	7.99E+00	1.79E-01

Table 6. (Cont'd).

Nuclide	Inhalation class	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
AM-243	Y	1.00E-03	4.26E-01	9.27E+00	2.04E-01
AM-243	W	1.00E-03	3.78E-01	7.99E+00	1.81E-01
CM-243	Y	1.00E-03	3.99E-01	8.91E+00	1.91E-01
CM-243	W	1.00E-03	2.79E-01	6.35E+00	1.34E-01
CM-244	Y	1.00E-03	3.71E-01	8.35E+00	1.78E-01
CM-244	W	1.00E-03	2.37E-01	5.53E+00	1.13E-01

Table 7. Health effects from radionuclide ingestion (1.0 pCi/year chronic cohort exposure).

Nuclide	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
H-3	9.50E-01	1.80E-07	4.25E-06	8.62E-08
BE-7	2.00E-03	9.44E-08	2.15E-06	4.52E-08
C-11	9.50E-01	7.89E-08	1.69E-06	3.77E-08
C-14	9.50E-01	3.31E-06	8.43E-05	1.58E-06
C-15	9.50E-01	1.20E-09	2.58E-08	5.76E-10
N-13	9.50E-01	5.17E-08	1.10E-06	2.48E-08
O-15	9.50E-01	1.61E-08	3.41E-07	7.72E-09
NA-22	9.50E-01	3.00E-05	7.36E-04	1.44E-05
P-32	8.00E-01	1.16E-05	3.06E-04	5.54E-06
S-35	9.50E-01	7.85E-07	1.92E-05	3.76E-07
K-40	9.50E-01	3.33E-05	8.21E-04	1.59E-05
SC-46	1.00E-04	5.16E-06	1.16E-04	2.47E-06
CR-51	1.00E-01	1.35E-07	3.06E-06	6.48E-08
MN-54	1.00E-01	3.46E-06	8.14E-05	1.66E-06
MN-56	1.00E-01	8.09E-07	1.77E-05	3.87E-07
FE-55	1.00E-01	8.99E-07	2.11E-05	4.30E-07
FE-59	1.00E-01	8.89E-06	2.07E-04	4.25E-06
CO-57	5.00E-02	7.79E-07	1.80E-05	3.73E-07
CO-58	5.00E-02	2.67E-06	6.10E-05	1.28E-06
CO-60	5.00E-02	1.24E-05	2.84E-04	5.92E-06
NI-59	5.00E-02	1.64E-07	3.39E-06	7.83E-08
NI-63	5.00E-02	4.80E-07	1.01E-05	2.30E-07
ZN-65	5.00E-01	2.27E-05	5.52E-04	1.08E-05
GA-67	1.00E-03	6.36E-07	1.41E-05	3.04E-07
AS-76	3.00E-02	7.99E-06	1.72E-04	3.82E-06
RB-88	9.50E-01	2.61E-07	5.61E-06	1.25E-07
RB-89	9.50E-01	1.49E-07	3.22E-06	7.14E-08
SR-89	3.00E-01	1.10E-05	2.67E-04	5.26E-06
SR-89	1.00E-02	9.17E-06	1.98E-04	4.39E-06
SR-90	3.00E-01	2.17E-04	5.82E-03	1.04E-04
SR-90	1.00E-02	1.46E-05	3.53E-04	6.97E-06
SR-91	3.00E-01	2.30E-06	5.09E-05	1.10E-06
SR-91	1.00E-02	2.57E-06	5.58E-05	1.23E-06
Y-90	1.00E-04	1.02E-05	2.20E-04	4.89E-06
Y-91M	1.00E-04	4.47E-08	9.60E-07	2.14E-08
Y-91	1.00E-04	9.39E-06	2.01E-04	4.49E-06
ZR-93	2.00E-03	3.31E-07	7.17E-06	1.59E-07
ZR-95	2.00E-03	3.23E-06	7.18E-05	1.54E-06
NB-93M	1.00E-02	4.86E-07	1.05E-05	2.33E-07
NB-94	1.00E-02	6.51E-06	1.50E-04	3.12E-06
NB-95	1.00E-02	2.75E-06	5.96E-05	1.32E-06
MO-99	5.00E-02	4.81E-06	1.04E-04	2.30E-06
MO-99	8.00E-01	4.47E-06	1.02E-04	2.14E-06
TC-97	8.00E-01	2.70E-07	7.06E-06	1.29E-07
TC-99M	8.00E-01	7.29E-08	1.73E-06	3.49E-08
TC-99	8.00E-01	1.92E-06	5.05E-05	9.20E-07
RU-97	5.00E-02	5.31E-07	1.21E-05	2.54E-07
RU-103	5.00E-02	2.96E-06	6.61E-05	1.42E-06
RU-106	5.00E-02	3.29E-05	7.41E-04	1.57E-05
RH-103M	5.00E-02	1.06E-08	2.23E-07	5.08E-09
RH-106	5.00E-02	6.35E-09	1.32E-07	3.04E-09
AG-110M	5.00E-02	4.46E-05	9.77E-04	2.14E-05
AG-110	5.00E-02	4.29E-09	8.85E-08	2.05E-09
IN-113M	2.00E-02	8.88E-08	1.91E-06	4.25E-08
SN-113	5.00E-02	3.46E-06	7.95E-05	1.65E-06
SN-126	5.00E-02	2.18E-05	5.06E-04	1.04E-05

Table 7. (Cont'd).

Nuclide	r_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
SB-124	2.00E-01	1.33E-05	3.02E-04	6.37E-06
SB-125	2.00E-01	4.08E-06	9.33E-05	1.95E-06
SB-126M	2.00E-01	1.18E-07	2.53E-06	5.63E-08
SB-126	2.00E-01	1.11E-05	2.53E-04	5.33E-06
TE-125M	2.00E-01	2.23E-06	5.30E-05	1.07E-06
TE-132	2.00E-01	4.05E-05	1.12E-03	1.94E-05
I-122	9.50E-01	4.31E-08	9.57E-07	2.06E-08
I-123	9.50E-01	1.87E-06	5.25E-05	8.97E-07
I-125	9.50E-01	9.98E-06	2.79E-04	4.78E-06
I-129	9.50E-01	6.39E-05	1.79E-03	3.06E-05
I-131	9.50E-01	1.54E-05	4.31E-04	7.38E-06
I-132	9.50E-01	4.32E-06	1.19E-04	2.07E-06
I-133	9.50E-01	3.53E-05	9.93E-04	1.69E-05
I-134	9.50E-01	1.47E-06	3.97E-05	7.02E-07
I-135	9.50E-01	1.05E-05	2.94E-04	5.04E-06
CS-134	9.50E-01	1.35E-04	3.25E-03	6.45E-05
CS-135	9.50E-01	1.20E-05	2.95E-04	5.73E-06
CS-136	9.50E-01	2.13E-05	5.11E-04	1.02E-05
CS-137	9.50E-01	9.11E-05	2.21E-03	4.36E-05
CS-138	9.50E-01	3.02E-07	6.59E-06	1.45E-07
BA-133M	1.00E-01	1.90E-06	4.12E-05	9.09E-07
BA-133	1.00E-01	3.68E-06	8.87E-05	1.76E-06
BA-137M	1.00E-01	3.82E-09	7.37E-08	1.83E-09
BA-139	1.00E-01	3.41E-07	7.32E-06	1.63E-07
BA-140	1.00E-01	9.29E-06	2.04E-04	4.45E-06
LA-140	3.00E-04	7.40E-06	1.63E-04	3.54E-06
CE-141	3.00E-04	2.80E-06	6.05E-05	1.34E-06
CE-144	3.00E-04	2.10E-05	4.52E-04	1.00E-05
PR-144M	3.00E-04	5.47E-08	1.17E-06	2.62E-08
PR-144	3.00E-04	1.41E-07	3.00E-06	6.75E-08
SM-151	1.00E-04	3.27E-07	7.00E-06	1.56E-07
SM-153	1.00E-04	2.75E-06	5.93E-05	1.31E-06
EU-152	1.00E-04	4.32E-06	9.62E-05	2.07E-06
EU-154	1.00E-04	6.96E-06	1.53E-04	3.33E-06
EU-155	1.00E-04	6.88E-06	1.52E-04	3.29E-06
EU-156	1.00E-04	8.22E-06	1.79E-04	3.93E-06
GD-152	1.00E-04	1.86E-05	3.66E-04	8.90E-06
TB-160	1.00E-04	5.87E-06	1.29E-04	2.81E-06
HF-181	1.00E-04	4.20E-06	9.19E-05	2.01E-06
W-187	1.00E-01	2.26E-06	4.94E-05	1.08E-06
IR-192	1.00E-02	5.47E-06	1.21E-04	2.62E-06
HG-203	2.00E-02	2.30E-06	5.08E-05	1.10E-06
TL-207	9.50E-01	1.91E-08	4.09E-07	9.16E-09
TL-208	9.50E-01	2.87E-08	6.02E-07	1.37E-08
PB-210	2.00E-01	3.35E-04	7.84E-03	1.60E-04
PB-211	2.00E-01	4.78E-07	1.17E-05	2.29E-07
PB-212	2.00E-01	4.76E-05	1.33E-03	2.28E-05
PB-214	2.00E-01	4.58E-07	1.10E-05	2.19E-07
BI-210	5.00E-02	9.87E-06	2.23E-04	4.72E-06
BI-211	5.00E-02	2.04E-08	4.34E-07	9.77E-09
BI-212	5.00E-02	6.39E-07	1.40E-05	3.06E-07
BI-214	5.00E-02	2.36E-07	5.09E-06	1.13E-07
PO-210	1.00E-01	6.88E-04	1.66E-02	3.29E-04
PO-212	1.00E-01	3.97E-17	8.53E-16	1.90E-17
PO-214	1.00E-01	1.95E-14	4.20E-13	9.35E-15
PO-215	1.00E-01	6.54E-13	1.54E-11	3.13E-13

Table 7. (Cont'd).

Nuclide	f_1	Total deaths in cohort	Total years of life lost	Risk equivalent factor
PO-216	1.00E-01	2.02E-10	5.28E-09	9.68E-11
PO-218	1.00E-01	6.84E-08	1.59E-06	3.27E-08
RA-223	2.00E-01	6.05E-04	1.78E-02	2.90E-04
RA-224	2.00E-01	2.37E-04	5.90E-03	1.13E-04
RA-226	2.00E-01	9.56E-04	2.47E-02	4.57E-04
RA-228	2.00E-01	4.47E-04	1.21E-02	2.14E-04
AC-227	1.00E-03	2.95E-03	6.80E-02	1.41E-03
AC-228	1.00E-03	1.22E-06	2.74E-05	5.85E-07
TH-227	2.00E-04	2.48E-05	5.22E-04	1.18E-05
TH-228	2.00E-04	1.35E-04	3.84E-03	6.47E-05
TH-230	2.00E-04	4.19E-04	1.01E-02	2.00E-04
TH-231	2.00E-04	1.21E-06	2.61E-05	5.81E-07
TH-232	2.00E-04	3.95E-04	9.52E-03	1.89E-04
TH-234	2.00E-04	1.35E-05	2.99E-04	6.46E-06
PA-231	1.00E-03	4.70E-03	9.29E-02	2.25E-03
PA-233	1.00E-03	3.30E-06	7.16E-05	1.58E-06
PA-234M	1.00E-03	8.39E-09	1.79E-07	4.01E-09
PA-234	1.00E-03	1.68E-06	3.72E-05	8.04E-07
U-233	2.00E-03	1.28E-05	2.92E-04	6.13E-06
U-233	2.00E-01	5.15E-04	1.27E-02	2.47E-04
U-234	2.00E-03	1.27E-05	2.89E-04	6.09E-06
U-234	2.00E-01	5.06E-04	1.25E-02	2.42E-04
U-235	2.00E-03	1.32E-05	2.97E-04	6.32E-06
U-235	2.00E-01	4.20E-04	1.03E-02	2.01E-04
U-236	2.00E-03	1.17E-05	2.66E-04	5.62E-06
U-236	2.00E-01	4.51E-04	1.11E-02	2.16E-04
U-238	2.00E-03	1.16E-05	2.62E-04	5.56E-06
U-238	2.00E-01	4.28E-04	1.05E-02	2.05E-04
NP-237	1.00E-03	2.79E-03	5.88E-02	1.33E-03
NP-239	1.00E-03	2.78E-06	6.01E-05	1.33E-06
PU-238	1.00E-03	2.53E-03	5.49E-02	1.21E-03
PU-239	1.00E-04	2.90E-04	6.11E-03	1.39E-04
PU-239	1.00E-03	2.82E-03	5.95E-02	1.35E-03
PU-240	1.00E-04	2.90E-04	6.11E-03	1.39E-04
PU-240	1.00E-03	2.82E-03	5.95E-02	1.35E-03
PU-241	1.00E-03	4.77E-05	8.82E-04	2.28E-05
PU-242	1.00E-03	2.73E-03	5.76E-02	1.31E-03
PU-242	1.00E-04	2.80E-04	5.92E-03	1.34E-04
AM-241	1.00E-03	2.84E-03	6.01E-02	1.36E-03
AM-243	1.00E-03	2.87E-03	6.03E-02	1.37E-03
CM-243	1.00E-03	2.03E-03	4.61E-02	9.73E-04
CM-244	1.00E-03	1.69E-03	3.95E-02	8.07E-04

Table C. Health effects from radionuclide air immersion (1.0 rad cc chronic cohort exposure).

Nuclide	Total deaths in cohort	Total years of life lost	Risk equivalent factor
BE-7	5.35E+02	1.30E+04	2.56E+02
C-11	1.10E+04	2.66E+05	5.25E+03
C-15	5.30E+04	1.26E+06	2.54E+04
N-13	1.10E+04	2.67E+05	5.25E+03
O-15	1.10E+04	2.67E+05	5.26E+03
NA-22	2.44E+04	5.88E+05	1.17E+04
AR-41	1.47E+04	3.53E+05	7.03E+03
K-40	1.85E+03	4.43E+04	8.84E+02
SC-46	2.17E+04	5.20E+05	1.04E+04
CR-51	3.43E+02	8.41E+03	1.64E+02
MN-54	8.80E+03	2.12E+05	4.21E+03
MN-56	1.90E+04	4.55E+05	9.09E+03
FE-55	2.10E-02	4.92E-01	1.01E-02
FE-59	1.33E+04	3.18E+05	6.34E+03
CO-57	1.34E+03	3.37E+04	6.43E+02
CO-58	1.03E+04	2.48E+05	4.93E+03
CO-60	2.84E+04	6.81E+05	1.36E+04
NI-59	3.51E-02	8.22E-01	1.68E-02
ZN-65	6.35E+03	1.53E+05	3.04E+03
GA-67	1.58E+03	3.92E+04	7.56E+02
AS-76	4.69E+03	1.13E+05	2.24E+03
KR-83M	2.11E-01	5.16E+00	1.01E-01
KR-85M	1.74E+03	4.34E+04	8.35E+02
KR-85	2.40E+01	5.83E+02	1.15E+01
KR-87	9.25E+03	2.22E+05	4.43E+03
KR-88	2.34E+04	5.60E+05	1.12E+04
KR-89	2.20E+04	5.27E+05	1.05E+04
RB-88	7.68E+03	1.84E+05	3.68E+03
RB-89	2.40E+04	5.75E+05	1.15E+04
SR-89	1.44E+00	3.46E+01	6.89E-01
SR-91	7.45E+03	1.79E+05	3.57E+03
Y-90	3.74E-04	9.26E-03	1.79E-04
Y-91M	5.68E+03	1.38E+05	2.72E+03
Y-91	4.06E+01	9.73E+02	1.94E+01
ZR-95	7.79E+03	1.88E+05	3.73E+03
NB-93M	5.13E-01	1.28E+01	2.45E-01
NB-94	1.55E+04	3.71E+05	7.42E+03
NB-95	8.08E+03	1.95E+05	3.87E+03
MO-99	1.70E+03	4.11E+04	8.12E+02
TC-97	4.08E+00	1.02E+02	1.95E+00
TC-99M	1.39E+03	3.49E+04	6.67E+02
RU-97	2.52E+03	6.21E+04	1.20E+03
RU-103	5.04E+03	1.22E+05	2.41E+03
RH-103M	1.18E+00	2.97E+01	5.62E-01
RH-106	2.20E+03	5.34E+04	1.06E+03
AG-110M	2.99E+04	7.19E+05	1.43E+04
AG-110	3.24E+02	7.82E+03	1.55E+02
IN-113M	2.76E+03	6.73E+04	1.32E+03
SN-113	7.75E+01	1.93E+03	3.71E+01
SN-126	4.90E+02	1.24E+04	2.34E+02
SB-124	2.10E+04	5.05E+05	1.00E+04
SB-125	4.49E+03	1.09E+05	2.15E+03
SB-126M	1.65E+04	3.98E+05	7.87E+03
SB-126	3.01E+04	7.27E+05	1.44E+04
TE-125M	8.01E+01	2.04E+03	3.83E+01
TE-132	2.37E+03	5.87E+04	1.14E+03

Table 8. (Cont'd).

Nuclide	Total deaths in cohort	Total years of life lost	Risk equivalent factor
I-122	1.05E+04	2.54E+05	5.00E+03
I-123	1.70E+03	4.23E+04	8.13E+02
I-125	8.52E+01	2.16E+03	4.24E+01
I-129	6.97E+01	1.77E+03	3.47E+01
I-131	3.97E+03	9.65E+04	1.98E+03
I-132	2.45E+04	5.91E+05	1.17E+04
I-133	6.56E+03	1.59E+05	3.14E+03
I-134	2.83E+04	6.82E+05	1.36E+04
I-135	1.79E+04	4.30E+05	8.58E+03
XE-122	6.36E+02	1.57E+04	3.04E+02
XE-123	6.78E+03	1.65E+05	3.24E+03
XE-125	2.68E+03	6.61E+04	1.28E+03
XE-127	2.86E+03	7.06E+04	1.37E+03
XE-131M	8.18E+01	2.06E+03	3.91E+01
XE-133M	3.12E+02	7.75E+03	1.49E+02
XE-133	3.50E+02	8.87E+03	1.67E+02
XE-135M	4.61E+03	1.12E+05	2.20E+03
XE-135	2.71E+03	6.68E+04	1.30E+03
XE-137	2.00E+03	4.86E+04	9.59E+02
XE-138	1.30E+04	3.12E+05	6.23E+03
CS-134	1.65E+04	3.99E+05	7.91E+03
CS-136	2.32E+04	5.60E+05	1.11E+04
CS-138	2.74E+04	6.57E+05	1.31E+04
BA-133M	6.02E+02	1.49E+04	2.88E+02
BA-133	3.94E+03	9.67E+04	1.88E+03
BA-137M	6.31E+03	1.53E+05	3.02E+03
BA-139	4.19E+02	1.04E+04	2.01E+02
BA-140	1.57E+03	3.82E+04	7.50E+02
LA-140	2.64E+04	6.34E+05	1.26E+04
CE-141	8.05E+02	2.01E+04	3.85E+02
CE-144	1.98E+02	4.98E+03	9.48E+01
PR-144M	4.70E+01	1.20E+03	2.25E+01
PR-144	3.66E+02	8.77E+03	1.75E+02
SM-151	5.27E-03	1.33E-01	2.52E-03
SM-153	5.31E+02	1.34E+04	2.54E+02
EU-152	1.25E+04	3.01E+05	5.98E+03
EU-154	1.34E+04	3.23E+05	6.41E+03
EU-155	5.89E+02	1.49E+04	2.82E+02
EU-156	1.53E+04	3.66E+05	7.30E+03
TB-160	1.21E+04	2.92E+05	5.80E+03
HF-181	5.84E+03	1.43E+05	2.79E+03
W-187	5.04E+03	1.22E+05	2.41E+03
IR-192	8.85E+03	2.16E+05	4.24E+03
HG-203	2.48E+03	6.12E+04	1.19E+03
TL-207	2.27E+01	5.47E+02	1.09E+01
TL-208	4.04E+04	9.67E+05	1.93E+04
PB-210	1.26E+01	3.23E+02	6.05E+00
PB-211	5.35E+02	1.30E+04	2.56E+02
PB-212	1.58E+03	3.91E+04	7.55E+02
PB-214	2.66E+03	6.52E+04	1.27E+03
BI-211	4.84E+02	1.19E+04	2.32E+02
BI-212	2.03E+03	4.88E+04	9.70E+02
BI-214	1.72E+04	4.12E+05	8.21E+03
PO-210	8.97E-02	2.16E+00	4.29E-02
PO-214	1.16E+00	2.79E+01	5.53E-01
RN-219	6.05E+02	1.48E+04	2.89E+02

Table c. (Cont'd).

Nuclide	Total deaths in cohort	Total years of life lost	Risk equivalent factor
RN-220	5.89E+00	1.43E+02	2.82E+00
RN-222	4.19E+00	1.02E+02	2.00E+00
PA-223	1.40E+03	3.49E+04	6.72E+02
PA-224	1.08E+02	2.67E+03	5.18E+01
PA-226	7.36E+01	1.83E+03	3.52E+01
RA-228	5.63E-08	1.30E-06	2.69E-08
AC-227	1.30E+00	3.27E+01	6.22E-01
AC-228	1.00E+04	2.41E+05	4.79E+03
TH-227	1.12E+03	2.77E+04	5.35E+02
TH-228	2.10E+01	5.26E+02	1.01E+01
TH-230	3.88E+00	9.75E+01	1.85E+00
TH-231	1.46E+02	3.68E+03	6.97E+01
TH-232	1.62E+00	4.09E+01	7.75E-01
TH-234	8.22E+01	2.08E+03	3.93E+01
PA-231	3.23E+02	7.97E+03	1.55E+02
PA-233	2.05E+03	5.05E+04	9.79E+02
PA-234M	1.20E+02	2.89E+03	5.74E+01
PA-234	2.13E+04	5.14E+05	1.02E+04
U-233	3.29E+00	8.27E+01	1.57E+00
U-234	1.15E+00	2.90E+01	5.52E-01
U-235	1.66E+03	4.12E+04	7.92E+02
U-236	4.19E-01	1.05E+01	2.00E-01
U-238	3.52E-01	8.86E+00	1.68E-01
NP-237	2.51E+02	6.34E+03	1.20E+02
NP-239	1.82E+03	4.54E+04	8.71E+02
PU-238	3.69E-01	9.23E+00	1.77E-01
PU-239	6.60E-01	1.66E+01	3.16E-01
PU-240	3.77E-01	9.44E+00	1.80E-01
PU-242	3.12E-01	7.80E+00	1.49E-01
AM-241	1.88E+02	4.78E+03	8.98E+01
AM-243	5.01E+02	1.27E+04	2.40E+02
CM-243	1.37E+03	3.41E+04	6.56E+02
CM-244	2.53E-01	6.25E+00	1.21E-01

Table 9. Health effects from radionuclide ground surface exposure (1.0 pCi/cm² chronic cohort exposure).

Nuclide	Total deaths in cohort	Total years of life lost	Risk equivalent factor
BE-7	1.11E-01	2.70E+00	5.32E-02
C-11	2.26E+00	5.48E+01	1.08E+00
C-15	6.14E+00	1.46E+02	2.94E+00
N-13	2.26E+00	5.48E+01	1.08E+00
O-15	2.26E+00	5.49E+01	1.08E+00
NA-22	4.58E+00	1.10E+02	2.19E+00
AR-41	2.56E+00	6.14E+01	1.22E+00
K-40	3.12E-01	7.49E+00	1.49E-01
SC-46	3.99E+00	9.59E+01	1.91E+00
CR-51	7.37E-02	1.81E+00	3.53E-02
MN-54	1.69E+00	4.08E+01	8.11E-01
MN-56	3.27E+00	7.84E+01	1.56E+00
FE-55	3.97E-05	9.29E-04	1.90E-05
FE-59	2.36E+00	5.67E+01	1.13E+00
CO-57	3.01E-01	7.54E+00	1.44E-01
CO-58	2.01E+00	4.85E+01	9.62E-01
CO-60	4.98E+00	1.19E+02	2.38E+00
NI-59	7.46E-05	1.75E-03	3.57E-05
ZN-65	1.15E+00	2.76E+01	5.50E-01
GA-67	3.49E-01	8.65E+00	1.67E-01
AS-76	9.05E-01	2.19E+01	4.33E-01
KR-83M	4.33E-04	1.05E-02	2.07E-04
KR-85M	3.84E-01	9.55E+00	1.84E-01
KR-85	4.94E-03	1.20E-01	2.36E-03
KR-87	1.54E+00	3.70E+01	7.37E-01
KR-88	3.66E+00	8.77E+01	1.75E+00
KR-89	3.61E+00	8.67E+01	1.73E+00
RB-88	1.24E+00	2.96E+01	5.91E-01
RB-89	4.02E+00	9.63E+01	1.92E+00
SR-89	2.72E-04	6.55E-03	1.30E-04
SR-91	1.40E+00	3.38E+01	6.72E-01
Y-90	6.44E-07	1.59E-05	3.08E-07
Y-91M	1.16E+00	2.80E+01	5.54E-01
Y-91	7.17E-03	1.72E-01	3.43E-03
ZR-95	1.53E+00	3.69E+01	7.32E-01
NB-93M	7.66E-04	1.91E-02	3.66E-04
NB-94	3.01E+00	7.21E+01	1.44E+00
NB-95	1.58E+00	3.80E+01	7.55E-01
MO-99	3.40E-01	8.24E+00	1.63E-01
TC-97	5.46E-03	1.36E-01	2.61E-03
TC-99M	3.10E-01	7.76E+00	1.49E-01
RU-97	5.52E-01	1.36E+01	2.64E-01
RU-103	1.04E+00	2.53E+01	4.98E-01
RH-103M	1.30E-03	3.27E-02	6.20E-04
RH-106	4.40E-01	1.07E+01	2.11E-01
AG-110M	5.63E+00	1.35E+02	2.69E+00
AG-110	6.45E-02	1.56E+00	3.08E-02
IN-113M	5.87E-01	1.43E+01	2.81E-01
SN-113	2.51E-02	6.29E-01	1.20E-02
SN-126	1.23E-01	3.11E+00	5.88E-02
SB-124	3.73E+00	8.96E+01	1.78E+00
SB-125	9.31E-01	2.26E+01	4.45E-01
SB-126M	3.31E+00	8.00E+01	1.58E+00
SB-126	5.99E+00	1.45E+02	2.87E+00
TE-125M	3.51E-02	8.96E-01	1.68E-02
TE-132	5.36E-01	1.33E+01	2.57E-01

Table 9. (Cont'd).

Nuclide	Total deaths in cohort	Total years of life lost	Risk equivalent factor
I-122	2.13E+00	5.17E+01	1.02E+00
I-123	3.85E-01	9.59E+00	1.84E-01
I-125	3.83E-02	9.72E-01	1.91E-02
I-129	3.68E-02	9.33E-01	1.83E-02
I-131	8.41E-01	2.04E+01	4.18E-01
I-132	4.71E+00	1.13E+02	2.25E+00
I-133	1.32E+00	3.19E+01	6.31E-01
I-134	5.30E+00	1.28E+02	2.54E+00
I-135	3.11E+00	7.46E+01	1.49E+00
XE-122	1.51E-01	3.74E+00	7.23E-02
XE-123	1.33E+00	3.24E+01	6.38E-01
XE-125	5.92E-01	1.46E+01	2.83E-01
XE-127	6.38E-01	1.58E+01	3.05E-01
XE-131M	3.34E-02	8.48E-01	1.60E-02
XE-133M	8.43E-02	2.10E+00	4.03E-02
XE-133	9.96E-02	2.53E+00	4.76E-02
XE-135M	9.49E-01	2.30E+01	4.54E-01
XE-135	5.86E-01	1.44E+01	2.81E-01
XE-137	3.97E-01	9.62E+00	1.90E-01
XE-138	2.20E+00	5.28E+01	1.05E+00
CS-134	3.26E+00	7.87E+01	1.56E+00
CS-136	4.41E+00	1.06E+02	2.11E+00
CS-138	4.63E+00	1.11E+02	2.22E+00
BA-133M	1.45E-01	3.60E+00	6.96E-02
BA-133	8.90E-01	2.19E+01	4.26E-01
BA-137M	1.26E+00	3.05E+01	6.03E-01
BA-139	9.01E-02	2.23E+00	4.31E-02
BA-140	3.30E-01	8.05E+00	1.58E-01
LA-140	4.55E+00	1.09E+02	2.18E+00
CE-141	1.83E-01	4.57E+00	8.75E-02
CE-144	4.71E-02	1.18E+00	2.25E-02
PR-144M	1.77E-02	4.53E-01	8.48E-03
PR-144	6.11E-02	1.46E+00	2.92E-02
SM-151	5.68E-06	1.44E-04	2.72E-06
SM-153	1.44E-01	3.64E+00	6.88E-02
EU-152	2.35E+00	5.68E+01	1.13E+00
EU-154	2.50E+00	6.02E+01	1.19E+00
EU-155	1.46E-01	3.70E+00	7.00E-02
EU-156	2.61E+00	6.26E+01	1.25E+00
TB-160	2.28E+00	5.51E+01	1.09E+00
HF-181	1.24E+00	3.02E+01	5.92E-01
W-187	1.03E+00	2.50E+01	4.93E-01
IR-192	1.87E+00	4.58E+01	8.96E-01
HG-203	5.40E-01	1.33E+01	2.58E-01
TL-207	4.32E-03	1.04E-01	2.07E-03
TL-208	6.22E+00	1.49E+02	2.98E+00
PB-210	4.30E-03	1.09E-01	2.06E-03
PB-211	1.07E-01	2.60E+00	5.13E-02
PB-212	3.51E-01	8.71E+00	1.68E-01
PB-214	5.72E-01	1.40E+01	2.74E-01
BI-211	1.04E-01	2.55E+00	4.98E-02
BI-212	3.74E-01	9.01E+00	1.79E-01
BI-214	2.98E+00	7.15E+01	1.43E+00
PO-210	1.74E-05	4.19E-04	8.32E-06
PO-214	3.63E-04	8.38E-03	1.74E-04
RN-219	1.30E-01	3.19E+00	6.22E-02

Table 9. (Cont'd).

Nuclide	Total deaths in cohort	Total years of life lost	Risk equivalent factor
RN-220	1.20E-03	2.92E-02	5.75E-04
RN-222	8.62E-04	2.09E-02	4.13E-04
RA-223	3.16E-01	7.85E+00	1.51E-01
RA-224	2.36E-02	5.83E-01	1.13E-02
RA-226	1.62E-02	4.04E-01	7.77E-03
RA-228	1.15E-10	2.53E-09	5.52E-11
AC-227	3.05E-04	7.65E-03	1.46E-04
AC-228	1.88E+00	4.53E+01	8.99E-01
TH-227	2.49E-01	6.17E+00	1.19E-01
TH-228	5.00E-03	1.25E-01	2.39E-03
TH-230	1.09E-03	2.72E-02	5.20E-04
TH-231	3.88E-02	9.78E-01	1.86E-02
TH-232	5.63E-04	1.41E-02	2.69E-04
TH-234	2.03E-02	5.15E-01	9.73E-03
PA-231	7.22E-02	1.78E+00	3.46E-02
PA-233	4.49E-01	1.11E+01	2.15E-01
PA-234M	2.27E-02	5.46E-01	1.08E-02
PA-234	4.09E+00	9.88E+01	1.96E+00
U-233	8.94E-04	2.23E-02	4.28E-04
U-234	5.42E-04	1.34E-02	2.59E-04
U-235	3.66E-01	9.11E+00	1.75E-01
U-236	3.55E-04	8.73E-03	1.70E-04
U-238	3.09E-04	7.59E-03	1.48E-04
NP-237	6.29E-02	1.58E+00	3.01E-02
NP-239	4.09E-01	1.02E+01	1.96E-01
PU-238	4.40E-04	1.08E-02	2.11E-04
PU-239	2.80E-04	6.92E-03	1.34E-04
PU-240	4.27E-04	1.05E-02	2.05E-04
PU-242	3.39E-04	8.31E-03	1.62E-04
AM-241	5.45E-02	1.39E+00	2.61E-02
AM-243	1.25E-01	3.18E+00	6.00E-02
CM-243	3.08E-01	7.65E+00	1.47E-01
CM-244	4.60E-04	1.13E-02	2.20E-04

Table 10. Cohort risk from chronic 10^{-4} working level exposure

Exposure rate	Radiation-induced deaths	Years of life lost	REF
0.0027 WLM/yr	17	240	22.5

working level month (WLM) is exposure to one working level for 170 hours. A working level is any combination of radon daughters in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha particle energy.) The calculation for radon daughters also differs from calculations for other nuclides in that age-dependent estimates of exposure (WLM/yr) were used as indicated in Table 11.

Table 11. Age-dependence of radon daughter annual exposure

Age (years)	Annual exposure[a,b]
0-2	35.1
2-5	43.2
5-11	49.5
11-15	43.2
15-19	37.8
19-23	32.4
23-110	27

[a]WLM/yr for continuous exposure to a concentration of 1 WL.

[b]Pediatric annual exposures scaled using age dependent respiration rates and organ masses [30, 31].

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