United States
Environmental Protection
Agency

Air and Radiation
(6601J)

EPA 402-R-99-001
September1999

EPA

Cancer Risk Coefficients for Environmental Exposure to Radionuclides

Federal Guidance Report No. 13

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This report was prepared for the
Office of Radiation and Indoor Air
U.S. Environmental Protection Agency
Washington, DC 20460
by
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

EPA 402-R-99-001

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Cancer Risk Coefficients for Environmental Exposure to Radionuclides

Radionuclide-Specific Lifetime Radiogenic Cancer Risk Coefficients for the U.S. Population, Based on Age-Dependent Intake, Dosimetry, and Risk Models

Keith F. Eckerman
Richard W. Leggett
Christopher B. Nelson
Jerome S. Puskin
Allan C. B. Richardson

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831

Office of Radiation and Indoor Air
United States Environmental Protection Agency
Washington, DC 20460

September 1999

PREFACE

The Federal Radiation Council (FRC) was formed in 1959, through Executive Order 10831. A decade later its functions were transferred to the Administrator of the newly formed Environmental Protection Agency (EPA) as part of Reorganization Plan No. 3 of 1970. Under these authorities it is the responsibility of the Administrator to "advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards and in the establishment and execution of programs of cooperation with States." The purpose of this guidance to Federal Agencies is to ensure that the regulation of exposure to ionizing radiation is adequately protective, reflects the best available scientific information, and is carried out in a consistent manner.

Since the mid-1980s, EPA has issued a series of Federal guidance documents for the purpose of providing the Federal and State agencies technical information to assist their implementation of radiation protection programs. The first report in this series, Federal Guidance Report No. 10 (EPA, 1984a), presented derived concentrations of radioactivity in air and water corresponding to the limiting annual doses recommended for workers in 1960. That report was superseded in 1988 by Federal Guidance Report No. 11 (EPA, 1988), which provided updated dose coefficients for internal exposure of members of the general public and limiting values of radionuclide intake and air concentrations for implementation of the 1987 Radiation Protection Guidance for Occupational Exposure (EPA, 1987). Federal Guidance Report No. 12 (EPA, 1993) tabulated dose coefficients for external exposure to radionuclides in air, water, and soil.

This report, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides, Federal Guidance Report No. 13*, provides numerical factors for use in estimating the risk of cancer from low-level exposure to radionuclides. A risk coefficient for a radionuclide that exposes persons through a given environmental medium is an estimate of the probability of radiogenic cancer mortality or morbidity per unit activity inhaled or ingested, for internal exposure, or per unit time-integrated activity concentration in air or soil, for external exposure. A risk coefficient may be interpreted either as the average risk per unit exposure for persons exposed throughout life to a constant activity concentration of a radionuclide in an environmental medium, or as the average risk per unit exposure for persons exposed for a brief period to the radionuclide in an environmental medium. The risk coefficients given in this document apply to populations that approximate the age, gender, and mortality experience characterized by the 1989-91 U.S. decennial life tables. These

coefficients are tabulated using the SI unit of activity (becquerel), as are the dose coefficients in Federal Guidance Report No. 11 and Report No. 12.

An interim version of this report was published for public comment in January 1998. That version described the methodology used for derivation of a risk coefficient and provided risk coefficients for exposure to any of approximately 100 important radionuclides through various environmental media. This final version includes the background information given in the interim version, extends the tabulation of risk coefficients to more than 800 radionuclides, and provides additional discussion of the sources and extent of uncertainty in estimates of cancer risk from exposure to radionuclides.

The tabulated risk coefficients are based on state-of-the-art methods and models that take into account age and gender dependence of intake, metabolism, dosimetry, radiogenic risk, and competing causes of death in estimating the risks to health from internal or external exposure to radionuclides. Although many of the biokinetic and dosimetric models used here are updates of models used in Federal Guidance Report No. 11, the present report does not replace either that document or Federal Guidance Report No. 12 or affect their use for radiation protection purposes. The dose coefficients given in Federal Guidance Report No. 11 and Report No. 12 continue to be recommended for determining conformance with the radiation protection guidance to Federal agencies issued by the President and will be updated in the future as warranted. The risk coefficients tabulated in the present report have a different purpose — they are intended for use in assessing risks from radionuclide exposure, in a variety of applications ranging from analyses of specific sites to the general analyses that support rule making. Although the application of these risk coefficients for purposes such as cost/benefit analysis, environmental impact statements (EISs), and environmental assessments (EAs) — especially by Federal agencies — is encouraged to promote consistency in risk assessment, such use is discretionary.

The tabulated risk coefficients are intended mainly for prospective assessments of potential cancer risks from long-term exposure to radionuclides in environmental media. While it is recognized that the tabulations are also likely to be used in retrospective analyses of radiation exposures of populations, it is emphasized that such analyses should be limited to estimation of total or average risks in large populations. The risk coefficients are not intended for application to specific individuals, ages, or genders and should not be used for that purpose. Also, the coefficients are based on radiation risk models developed for application either to low acute doses or low dose rates and should not be applied to accident cases involving high doses and dose rates, either in prospective or retrospective analyses.

Some risk assessment procedures are established as a matter of policy, and additional guidance may be needed before using these risk coefficients in such policy matters. For example, EPA recommends that radiation risk assessments for sites on the National Priorities List under the Comprehensive Environmental Response, Compensation, and Liability Act be performed using the Health Effects Assessment Summary Tables (HEAST), which are periodically updated to reflect new information, such as that contained in this report.

In using Federal Guidance Report No. 13, the cancer risk associated with a radionuclide intake or external exposure is calculated as the product of the appropriate cancer risk coefficient and the corresponding radionuclide intake or exposure. This calculation presumes that risk is directly proportional to intake or exposure, i.e., it follows a linear, no-threshold (LNT) model. Current scientific evidence does not rule out the possibility that the calculated risk at environmental exposure levels may be overestimates or underestimates. However, several recent expert panels (UNSCEAR, 1993, 1994; NRPB, 1993; NCRP, 1997) have concluded that the LNT model is sufficiently consistent with current information on carcinogenic effects of radiation that its use is scientifically justifiable for purposes of estimating risks from low doses of radiation. As a practical matter, the LNT approach is universally used for assessing the risk from environmental exposure to radionuclides as well as other carcinogens. Within the LNT context, sources of uncertainty in the radionuclide cancer risk coefficients are discussed in the report, and judgments of uncertainty in the risk coefficients are given in Chapter 2 for a number of radionuclides. As new scientific evidence becomes available, we shall consider its effect on the information presented in this report and shall update the report as needed.

The risk coefficients were calculated using the DCAL (Dose and Risk Calculation) software, developed at Oak Ridge National Laboratory for the EPA. DCAL is a comprehensive system for calculating dose and risk coefficients using age-dependent models. A manual describing the DCAL software and the quality assurance procedures for this software will be published separately.

This report would not have been possible without the contributions of the many investigators who produced the building blocks that provided the basis for the results presented here. These include: Jerome S. Puskin and Christopher B. Nelson, who assembled the models for age-dependent, organ-specific cancer risks; Richard W. Leggett and Keith F. Eckerman, who developed many of the age-specific biokinetic and dosimetric models published by the International Commission on Radiological Protection and who provided the basis for calculation of doses from internal and external exposure; and Robert Armstrong, who supplied pre-publication values for the 1989-91 U.S. decennial life tables. The major effort required to prepare the report itself was carried out by Keith F. Eckerman, Richard W. Leggett, Christopher B. Nelson, Jerome S. Puskin, and Allan C.B.

Richardson. Preparation of the report was funded by the U.S. Environmental Protection Agency, the U.S. Department of Energy (DOE), and the U.S. Nuclear Regulatory Commission (NRC).

Technical reviews for the draft interim version of the report were contributed by William J. Bair, Bernd Kahn, Charles E. Land, John R. Mauro, and Alan Phipps. Review comments on the interim version (EPA, 1998) were provided by Federal agencies (including NRC and DOE), State agencies, and members of the public. The EPA Science Advisory Board (SAB) formally reviewed and commented on the interim report. This final version of Federal Guidance Report No. 13 reflects consideration of all these comments.

We gratefully acknowledge the work of the authors, the agencies that contributed funding for this work, and the helpful comments of the technical reviewers, the Science Advisory Board, and the public. We would appreciate notice of any errors or suggestions for improvements so that they may be taken into account in future editions. You may address comments to Michael A. Boyd, Radiation Protection Division (6608J), U.S. Environmental Protection Agency, Washington, DC 20460.

Stephen D. Page, Director
Office of Radiation and Indoor Air

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CHAPTER 1. INTRODUCTION

Since the mid-1980s, a series of Federal guidance documents has been issued by the Environmental Protection Agency (EPA) for the purpose of providing Federal and State agencies with technical information to assist their implementation of radiation protection programs. Previous reports have dealt with numerical factors, called "dose factors" or "dose coefficients", for estimating radiation dose due to exposure to radionuclides. The present report is intended as the first of a series of documents that will provide numerical factors, called "risk coefficients", for estimating risks to health from exposure to radionuclides. These reports will apply state-of-the-art methods and models that take into account age and gender dependence of intake, metabolism, dosimetry, radiogenic risk, and competing causes of death in estimating the risks to health from internal or external exposure to radionuclides. The present report provides tabulations of cancer risk coefficients for internal or external exposure to any of more than 800 radionuclides through various environmental media. Subsequent reports may expand the exposure pathways and health endpoints considered.

The risk coefficients developed in this report apply to an average member of the public, in the sense that estimates of risk are averaged over the age and gender distributions of a hypothetical closed "stationary" population whose survival functions and cancer mortality rates are based on recent data for the U.S. Specifically, the total mortality rates in this population are defined by the 1989-91 U.S. decennial life table (NCHS, 1997), and cancer mortality rates are defined by U.S. cancer mortality data for the same period (NCHS, 1992, 1993a, 1993b). This hypothetical population is referred to as "stationary" because the gender-specific birth rates and survival functions are assumed to remain invariant over time.

For a given radionuclide and exposure mode, both a "mortality risk coefficient" and a "morbidity risk coefficient" are provided. A mortality risk coefficient is an estimate of the risk to an average member of the U.S. population, *per unit activity inhaled or ingested for internal exposures or per unit time-integrated activity concentration in air or soil for external exposures*, of dying from cancer as a result of intake of the radionuclide or external exposure to its emitted radiations. A morbidity risk coefficient is a comparable estimate of the average total risk of experiencing a radiogenic cancer, whether or not the cancer is fatal. The term "risk coefficient" with no modifier should be interpreted throughout this report as "mortality or morbidity risk coefficient".

It is a common practice to estimate the cancer risk from intake of a radionuclide or external exposure to its emitted radiations as the simple product of a "probability coefficient" and an estimated "effective dose" to a typical adult (see the Glossary for definitions). For example, a

"nominal cancer fatality probability coefficient" of 0.05 Sv^{-1} is given in ICRP Publication 60 (1991) for all cancer types combined. This value is referred to as nominal because of the uncertainties inherent in radiation risk estimates and because it is based on an idealized population receiving a uniform dose over the whole body. It is pointed out by the ICRP (1991) that such a probability coefficient may be a less accurate estimator in situations where the distribution of dose is nonuniform. There are also other situations in which the product of a probability coefficient and the effective dose may not accurately represent the risk implied by current biokinetic, dosimetric, and radiation risk models. For example, such a product may understate the implied risk for intakes of radionuclides for which there is an apparently multiplicative effect during childhood of elevated organ doses and elevated risk per unit dose. Such a product may overstate the risk implied by current models in the case of intake of a long-lived, tenaciously retained radionuclide because much of the dose may be received during late adulthood when there is a relatively high likelihood of dying from a competing cause before a radiogenic cancer can be expressed. Finally, the weighting factors commonly used to calculate effective dose do not reflect the most up-to-date knowledge of the distribution of risk among the organs and tissues of the body.

In contrast to risk estimates based on the product of a probability coefficient and effective dose (for intake by the adult), the risk coefficients tabulated in this document take into account the age dependence of the biological behavior and internal dosimetry of ingested or inhaled radionuclides. Also, compared with risk estimates based on effective dose, the risk coefficients in this document characterize more precisely the implications of age and gender dependence in radiogenic risk models, U.S. cancer mortality rates, and competing risks from non-radiogenic causes of death in the U.S. Finally, these risk coefficients take into account the age and gender dependence in the usage of contaminated environmental media, which is generally not considered in risk estimates based on the simple product of a nominal probability coefficient and an estimated effective dose.

Radionuclides and exposure scenarios addressed

Risk coefficients are provided for the following modes of exposure to a given radionuclide: inhalation of air, ingestion of food, ingestion of tap water, external exposure from submersion in air, external exposure from the ground surface, and external exposure from soil contaminated to an infinite depth.

With a few exceptions described in Chapter 6, the radionuclides addressed in the external exposure scenarios are the same as those considered in Federal Guidance Report No. 12 (EPA,

Table 2.2a, continued

Nuclide	$T_{1/2}$	Chain P	Chain D	f_1	Tap Water Intakes Mortality (Bq^{-1})	Tap Water Intakes Morbidity (Bq^{-1})	Dietary Intakes Mortality (Bq^{-1})	Dietary Intakes Morbidity (Bq^{-1})
Francium								
Fr-222	14.4 m	Y	Y	1.0	2.85E-11	4.00E-11	3.88E-11	5.47E-11
Fr-223	21.8 m	Y	Y	1.0	1.32E-10	1.97E-10	1.80E-10	2.71E-10
Radium								
Ra-223	11.434 d	Y	Y	0.2	4.00E-09	6.44E-09	5.63E-09	9.15E-09
Ra-224	3.66 d	Y	Y	0.2	2.74E-09	4.50E-09	3.88E-09	6.42E-09
Ra-225	14.8 d	Y	Y	0.2	2.20E-09	3.09E-09	2.93E-09	4.15E-09
Ra-226[a]	1600 y	Y	Y	0.2	7.17E-09	1.04E-08	9.56E-09	1.39E-08
Ra-227	42.2 m	Y	-	0.2	2.15E-12	2.85E-12	2.96E-12	3.95E-12
Ra-228	5.75 y	Y	Y	0.2	2.00E-08	2.81E-08	2.74E-08	3.86E-08
Actinium								
Ac-224	2.9 h	Y	Y	0.0005	9.02E-11	1.51E-10	1.28E-10	2.17E-10
Ac-225	10.0 d	Y	Y	0.0005	2.94E-09	5.10E-09	4.20E-09	7.33E-09
Ac-226	29 h	Y	Y	0.0005	1.03E-09	1.87E-09	1.52E-09	2.74E-09
Ac-227	21.773 y	Y	Y	0.0005	4.43E-09	5.43E-09	5.34E-09	6.63E-09
Ac-228	6.13 h	Y	Y	0.0005	3.10E-11	5.38E-11	4.49E-11	7.82E-11
Thorium								
Th-226	30.9 m	Y	Y	0.0005	1.45E-11	1.80E-11	2.02E-11	2.52E-11
Th-227	18.718 d	Y	Y	0.0005	7.21E-10	1.28E-09	1.05E-09	1.87E-09
Th-228	1.9131 y	Y	Y	0.0005	1.82E-09	2.90E-09	2.46E-09	3.99E-09
Th-229	7340 y	Y	Y	0.0005	4.39E-09	6.05E-09	5.65E-09	7.85E-09
Th-230	7.7E4 y	Y	Y	0.0005	1.67E-09	2.46E-09	2.16E-09	3.22E-09
Th-231	25.52 h	Y	Y	0.0005	3.31E-11	5.96E-11	4.86E-11	8.75E-11
Th-232[a]	1.41E10 y	Y	Y	0.0005	1.87E-09	2.73E-09	2.45E-09	3.60E-09
Th-234	24.10 d	Y	Y	0.0005	3.46E-10	6.25E-10	5.07E-10	9.18E-10
Protactinium								
Pa-227	38.3 m	Y	-	0.0005	2.00E-11	2.62E-11	2.81E-11	3.70E-11
Pa-228	22 h	Y	-	0.0005	5.53E-11	9.72E-11	7.96E-11	1.40E-10
Pa-230	17.4 d	Y	-	0.0005	5.79E-11	1.02E-10	8.29E-11	1.46E-10
Pa-231	3.276E4 y	Y	Y	0.0005	3.30E-09	4.67E-09	4.29E-09	6.11E-09
Pa-232	1.31 d	Y	-	0.0005	5.32E-11	9.41E-11	7.68E-11	1.36E-10
Pa-233	27.0 d	Y	Y	0.0005	8.34E-11	1.50E-10	1.22E-10	2.20E-10
Pa-234	6.70 h	Y	Y	0.0005	4.00E-11	6.93E-11	5.77E-11	1.00E-10
Uranium								
U-230	20.8 d	Y	Y	0.02	3.24E-09	5.65E-09	4.59E-09	8.05E-09
U-231	4.2 d	Y	Y	0.02	2.63E-11	4.73E-11	3.84E-11	6.91E-11
U-232	72 y	Y	Y	0.02	5.52E-09	7.88E-09	7.22E-09	1.04E-08
U-233	1.585E5 y	Y	Y	0.02	1.26E-09	1.94E-09	1.69E-09	2.62E-09
U-234[a]	2.445E5 y	Y	Y	0.02	1.24E-09	1.91E-09	1.66E-09	2.58E-09
U-235	703.8E6 y	Y	Y	0.02	1.21E-09	1.88E-09	1.62E-09	2.55E-09
U-236	2.3415E7 y	Y	Y	0.02	1.17E-09	1.81E-09	1.57E-09	2.44E-09
U-237	6.75 d	Y	Y	0.02	7.31E-11	1.32E-10	1.07E-10	1.93E-10

Table 2.2a, continued

Nuclide	$T_{1/2}$	Chain P	Chain D	f_1	Tap Water Intakes Mortality (Bq^{-1})	Tap Water Intakes Morbidity (Bq^{-1})	Dietary Intakes Mortality (Bq^{-1})	Dietary Intakes Morbidity (Bq^{-1})
Uranium, continued								
U-238	4.468E9 y	Y	Y	0.02	1.13E-09	1.73E-09	1.51E-09	2.34E-09
U-239	23.54 m	Y	-	0.02	1.40E-12	2.00E-12	1.98E-12	2.86E-12
U-240	14.1 h	Y	Y	0.02	1.06E-10	1.90E-10	1.55E-10	2.79E-10
Neptunium								
Np-232	14.7 m	Y	-	0.0005	4.21E-13	5.33E-13	5.73E-13	7.29E-13
Np-233	36.2 m	Y	Y	0.0005	1.01E-13	1.36E-13	1.39E-13	1.89E-13
Np-234	4.4 d	Y	Y	0.0005	5.27E-11	9.19E-11	7.49E-11	1.31E-10
Np-235	396.1 d	Y	Y	0.0005	5.18E-12	9.34E-12	7.59E-12	1.37E-11
Np-236a	115E3 y	Y	-	0.0005	1.78E-10	2.83E-10	2.42E-10	3.90E-10
Np-236b	22.5 h	Y	Y	0.0005	1.68E-11	3.01E-11	2.46E-11	4.41E-11
Np-237	2.14E6 y	Y	Y	0.0005	1.10E-09	1.67E-09	1.44E-09	2.24E-09
Np-238	2.117 d	Y	Y	0.0005	8.14E-11	1.46E-10	1.19E-10	2.13E-10
Np-239	2.355 d	Y	Y	0.0005	7.70E-11	1.39E-10	1.13E-10	2.03E-10
Np-240	65 m	Y	-	0.0005	4.18E-12	6.04E-12	5.86E-12	8.55E-12
Plutonium								
Pu-234	8.8 h	Y	Y	0.0005	1.31E-11	2.32E-11	1.90E-11	3.37E-11
Pu-235	25.3 m	Y	-	0.0005	9.16E-14	1.18E-13	1.26E-13	1.63E-13
Pu-236	2.851 y	Y	Y	0.0005	1.44E-09	2.02E-09	1.87E-09	2.68E-09
Pu-237	45.3 d	Y	Y	0.0005	8.73E-12	1.56E-11	1.27E-11	2.27E-11
Pu-238[a]	87.74 y	Y	Y	0.0005	2.75E-09	3.55E-09	3.50E-09	4.58E-09
Pu-239[a]	24065 y	Y	Y	0.0005	2.85E-09	3.64E-09	3.63E-09	4.70E-09
Pu-240	6537 y	Y	Y	0.0005	2.85E-09	3.65E-09	3.63E-09	4.71E-09
Pu-241	14.4 y	Y	Y	0.0005	3.94E-11	4.77E-11	5.07E-11	6.17E-11
Pu-242	3.763E5 y	Y	Y	0.0005	2.71E-09	3.46E-09	3.45E-09	4.47E-09
Pu-243	4.956 h	Y	Y	0.0005	7.33E-12	1.28E-11	1.07E-11	1.87E-11
Pu-245	10.5 h	Y	-	0.0005	6.75E-11	1.21E-10	9.87E-11	1.77E-10
Pu-246	10.85 d	Y	Y	0.0005	2.60E-10	4.68E-10	3.80E-10	6.84E-10
Americium								
Am-237	73.0 m	Y	-	0.0005	9.26E-13	1.37E-12	1.30E-12	1.94E-12
Am-238	98 m	Y	Y	0.0005	1.70E-12	2.60E-12	2.36E-12	3.64E-12
Am-239	11.9 h	Y	-	0.0005	2.10E-11	3.73E-11	3.06E-11	5.44E-11
Am-240	50.8 h	Y	-	0.0005	4.00E-11	6.99E-11	5.71E-11	1.00E-10
Am-241	432.2 y	Y	Y	0.0005	2.01E-09	2.81E-09	2.56E-09	3.63E-09
Am-242	16.02 h	Y	Y	0.0005	2.71E-11	4.83E-11	3.96E-11	7.08E-11
Am-242m	152 y	Y	-	0.0005	1.47E-09	1.91E-09	1.80E-09	2.37E-09
Am-243	7380 y	Y	Y	0.0005	2.00E-09	2.79E-09	2.54E-09	3.61E-09
Am-244	10.1 h	Y	-	0.0005	3.86E-11	6.80E-11	5.60E-11	9.89E-11
Am-244m	26 m	Y	-	0.0005	1.14E-12	1.38E-12	1.58E-12	1.92E-12
Am-245	2.05 h	Y	Y	0.0005	3.73E-12	6.01E-12	5.37E-12	8.71E-12
Am-246	39 m	Y	-	0.0005	2.54E-12	3.33E-12	3.53E-12	4.67E-12
Am-246m	25.0 m	Y	Y	0.0005	1.43E-12	1.78E-12	1.97E-12	2.46E-12

Table 7.1. Revised mortality risk model coefficients[a,b] for cancers other than leukemia, based on the EPA radiation risk methodology (EPA, 1994).

Cancer type	Risk model type[c]	Age group (x_e)				
		0-9 y	10-19 y	20-29 y	30-39 y	40+ y
Male:						
Esophagus	R	0.2877	0.2877	0.2877	0.2877	0.2877
Stomach	R	1.223	1.972	2.044	0.3024	0.2745
Colon	R	2.290	2.290	0.2787	0.4395	0.08881
Liver	R	0.9877	0.9877	0.9877	0.9877	0.9877
Lung	R	0.4480	0.4480	0.0435	0.1315	0.1680
Bone	A	0.09387	0.09387	0.09387	0.09387	0.09387
Skin	A	0.06597	0.06597	0.06597	0.06597	0.06597
Breast	R	0.0	0.0	0.0	0.0	0.0
Ovary	R	0.0	0.0	0.0	0.0	0.0
Bladder	R	1.037	1.037	1.037	1.037	1.037
Kidney	R	0.2938	0.2938	0.2938	0.2938	0.2938
Thyroid	A	0.1667	0.1667	0.08333	0.08333	0.08333
Residual	R	0.5349	0.5349	0.6093	0.2114	0.04071
Female:						
Esophagus	R	1.805	1.805	1.805	1.805	1.805
Stomach	R	3.581	4.585	4.552	0.6309	0.5424
Colon	R	3.265	3.265	0.6183	0.8921	0.1921
Liver	R	0.9877	0.9877	0.9877	0.9877	0.9877
Lung	R	1.359	1.359	0.1620	0.4396	0.6047
Bone	A	0.09387	0.09387	0.09387	0.09387	0.09387
Skin	A	0.06597	0.06597	0.06597	0.06597	0.06597
Breast	R	0.7000	0.7000	0.3000	0.3000	0.1000
Ovary	R	0.7185	0.7185	0.7185	0.7185	0.7185
Bladder	R	1.049	1.049	1.049	1.049	1.049
Kidney	R	0.2938	0.2938	0.2938	0.2938	0.2938
Thyroid	A	0.3333	0.3333	0.1667	0.1667	0.1667
Residual	R	1.122	1.122	0.8854	0.3592	0.1175

[a]The tabulated risk model coefficients are the precise values derived from the epidemiological data and used in the calculations. The use of four significant digits should not be interpreted as indicating a low level of uncertainty in the risk model coefficients.

[b]Age-specific risk model coefficients were used to derive composite risk coefficients representing averages over all ages. Application of these risk model coefficients to a specific age group is not recommended due to the high sampling variability in the underlying epidemiological data for some age groups.

[c]A indicates that an absolute risk model is used (coefficient units, 10^{-4} Gy^{-1} y^{-1}), and R indicates that a relative risk model is used (Gy^{-1}). $\alpha(x_e)$ is given for absolute risk model (Eq. 7.1) and $\beta(x_e)$ for a relative risk model (Eq. 7.2).

Table 7.2. **Revised mortality risk model coefficients (Gy^{-1}) for leukemia, based on the EPA radiation risk methodology (EPA, 1994).[a]**

	Age group (x_e)				
Gender	0-9 y	10-19 y	20-29 y	30-39 y	40+ y
Male	982.3	311.3	416.6	264.4	143.6
Female:	1176	284.9	370.0	178.8	157.1

[a]A relative risk model is used (coefficient units, Gy^{-1}). Risk model coefficients for leukemia are not directly comparable to those for other types of cancer (Table 7.1) due to differences in the scales of the time-since-exposure response functions for leukemia and other cancers (see the discussion following Eq. 7.2).

by Land and Sinclair for transporting risk from one population to another. Both methods assume a constant excess relative risk coefficient beginning 10 y after an exposure and continuing throughout the rest of life for each cancer site, excluding leukemia. One method (multiplicative) assumes that the relative risk estimator is the same across populations. The other (NIH, for National Institutes of Health) assumes that the relative risk model coefficients for the target population should yield the same risks as those calculated with the additive risk model coefficients from the original population over the period of epidemiological follow-up, excluding the minimal latency period. These excess relative risk model coefficients are then used to project the risk over the remaining years of life. The data considered in deriving risk model coefficients consisted of cancers observed 10-40 y after exposure for solid tumors and 5-40 y after exposure for leukemia.

As described below, some modifications in the method of calculation of the NIH model coefficients have been made to remove inconsistencies in the derived coefficients. Some but not all of these changes were made in the EPA report on radiation risk models (EPA, 1994); therefore, some of the risk coefficients in Tables 7.1 and 7.2 differ from values given in that report.

An examination of the coefficients for the additive and multiplicative models of Land and Sinclair (1991) reveals that in several instances data for exposures of two or more age groups were combined to calculate a single risk coefficient. In such cases, a single NIH model coefficient has been calculated for use in the present report by combining the risks calculated for the corresponding groups. This was done in the EPA report (EPA, 1994) for model coefficients for lung and colon cancer for two exposure age groups (0-9 y and 10-19 y), and the same principle has been extended in the present report to the coefficients for esophagus, ovary, and bladder cancer. For these three sites, the age-group-specific additive coefficients of Land and Sinclair were based on a single-coefficient multiplicative risk model. For the present report, an NIH model excess relative

Table 7.3. **Age-averaged site-specific cancer mortality risk estimates (cancer deaths per person-Gy) from low-dose, low-LET uniform irradiation of the body.**

Site	Males	Females	Combined genders
Esophagus	7.30×10^{-4}	1.59×10^{-3}	1.17×10^{-3}
Stomach	3.25×10^{-3}	4.86×10^{-3}	4.07×10^{-3}
Colon	8.38×10^{-3}	1.24×10^{-2}	1.04×10^{-2}
Liver	1.84×10^{-3}	1.17×10^{-3}	1.50×10^{-3}
Lung	7.71×10^{-3}	1.19×10^{-2}	9.88×10^{-3}
Bone	9.40×10^{-5}	9.60×10^{-5}	9.50×10^{-5}
Skin	9.51×10^{-5}	1.05×10^{-4}	1.00×10^{-4}
Breast	—	9.90×10^{-3}	5.06×10^{-3}
Ovary	—	2.92×10^{-3}	1.49×10^{-3}
Bladder	3.28×10^{-3}	1.52×10^{-3}	2.38×10^{-3}
Kidney	6.43×10^{-4}	3.92×10^{-4}	5.15×10^{-4}
Thyroid	2.05×10^{-4}	4.38×10^{-4}	3.24×10^{-4}
Leukemia	6.48×10^{-3}	4.71×10^{-3}	5.57×10^{-3}
Residual[a]	1.35×10^{-2}	1.63×10^{-2}	1.49×10^{-2}
Total	4.62×10^{-2}	6.83×10^{-2}	5.75×10^{-2}

[a]Residual is a composite of all radiogenic cancers that are not explicitly identified by site in the model.

Publication 60 (1991), except that the weights assigned to regions within the colon and lung are based on more recent recommendations in ICRP Publication 66 (1994a) and 67 (1993), respectively. The residual cancer category represents a composite of primary and secondary cancers that are not otherwise considered in the model. The three dose locations associated with these cancers (skeletal muscle, pancreas, and adrenals) were chosen to be generally representative of doses to soft tissues and are not considered to be the sites where all residual neoplasms originate.

Table 7.6. Age-averaged site-specific cancer morbidity risk estimates (cancer cases per person-Gy) from low-dose, low-LET uniform irradiation of the body.

Site	Male	Female	Combined genders
Esophagus	7.69×10^{-4}	1.68×10^{-3}	1.23×10^{-3}
Stomach	3.61×10^{-3}	5.40×10^{-3}	4.53×10^{-3}
Colon	1.52×10^{-2}	2.25×10^{-2}	1.89×10^{-2}
Liver	1.94×10^{-3}	1.23×10^{-3}	1.58×10^{-3}
Lung	8.12×10^{-3}	1.26×10^{-2}	1.04×10^{-2}
Bone	1.34×10^{-4}	1.37×10^{-4}	1.36×10^{-4}
Skin[a]	9.51×10^{-5}	1.05×10^{-4}	1.00×10^{-4}
Breast	—	1.98×10^{-2}	1.01×10^{-2}
Ovary	—	4.17×10^{-3}	2.13×10^{-3}
Bladder	6.55×10^{-3}	3.04×10^{-3}	4.76×10^{-3}
Kidney	9.88×10^{-4}	6.03×10^{-4}	7.91×10^{-4}
Thyroid	2.05×10^{-3}	4.38×10^{-3}	3.24×10^{-3}
Leukemia	6.54×10^{-3}	4.75×10^{-3}	5.63×10^{-3}
Residual[b]	1.91×10^{-2}	2.29×10^{-2}	2.11×10^{-2}
Total	6.51×10^{-2}	1.03×10^{-1}	8.46×10^{-2}

[a]Skin cancer morbidity risk coefficients include fatal cancer risks only. See text.

[b]Residual is a composite of all radiogenic cancers that are not explicitly identified by site in the model.

averaged values for the hypothetical stationary population described in Chapter 3. The method of computation is described in a later section.

Based on the methods of this report, skin is projected to contribute most of the nonfatal cancers induced by uniform whole body irradiation. At least 83% of all skin cancers are basal cell carcinomas and the remainder are squamous cell carcinomas. Approximately 99.99% of the former and 99% of the latter are non-fatal. The morbidity estimates for skin cancer given in the present report reflect only fatal cases.