INTERNAL DOSE CONVERSION FACTORS FOR 19 TARGET ORGANS AND 9 IRRADIATION TIMES AND EXTERNAL DOSE-RATE CONVERSION FACTORS FOR 21 TARGET ORGANS FOR 259 RADIONUCLIDES PRODUCED IN POTENTIAL FUSION REACTOR MATERIALS

Steve Fetter
(subcontractor)*

Published March 1988

*Center for Science and International Affairs
Harvard University
Cambridge, MA 02138

Prepared for EG&G Idaho, Inc.
Under Subcontract No. C87-101532
and the U.S. Department of Energy
Under Contract No. DE-AC07-76IDO1570

CONTENTS

PREFACE

Estimating radiological risks is an essential part of an assessment of fusion's potential to fill a niche in world energy supply, but many of the radionuclides that may be produced in fusion reactors have not been considered previously. In an effort to supply the basic data necessary to assess the radiological hazards of fusion, this report presents estimates of internal dose conversion factors (DCFs) and external dose-rate conversion factors (DRCFs) for 259 radionuclides, many of which may be important in fusion reactor materials. Five exposure modes are considered for each radionuclide: internal exposure from inhalation and ingestion, and external exposure to contaminated air, surface, and soil. For internal exposure, DCFs are computed for nineteen target organs and nine irradiation times; for external exposure, DRCFs are computed for twenty-one target organs. For many radionuclides, this report represents the only listing of DCFs and DRCFs for individual organs or for irradiation times of less than fifty years.

I would like to thank Steve Piet of EG&G Idaho for securing the financial assistance necessary to complete this project, and John Snyder of MIT for his help in entering metabolic and decay data and fitting exponentials to power functions.

1. INTERNAL DOSE CONVERSION FACTORS

The dose to an individual who has inhaled or ingested a certain amount of a given radionuclide is a fundamental parameter in many types of risk analyses. Computationally, this is done by dividing the body into several compartments and then modeling the transfer of the radionuclide between the compartments as a function of time. This report uses the model developed by the International Commission on Radiological Protection (ICRP) to estimate internal dose conversion factors (DCFs).[1] The following is a brief review of the ICRP model; those desiring more information should consult the original ICRP report.

1.1. DCFs for a One-time Intake of a Radionuclide

The DCF (rem/Ci) for a given organ *T* (the "target" organ) in time *t* after a one-time intake (inhalation or ingestion) of one curie of a radionuclide is given by

$$DCF_T(\tau) = 593 \sum_{s=1}^{S} \sum_{j=0}^{J} \left[U_{j,s}(\tau) SEE(T \leftarrow s)_j \right] \tag{1.1}$$

where the summation in *s* is over all source compartments and the summation in *j* is over all radioactive daughters involved;

593 = $(3.7 \cdot 10^{10}$ Bq/Ci) · $(1.602 \cdot 10^{-6}$ erg/MeV) ÷ (100 ergs/g·rad);

$U_{j,s}(\tau)$ is the number of transformations of radionuclide *j* in compartment *s* in time *t* per unit activity inhaled or ingested (transformations/Bq); and

$SEE(T \leftarrow s)_j$ is the specific effective energy, suitably modified by quality factor, absorbed in target organ *T* from each transformation of daughter *j* in compartment *s* (MeV/g·transformation)·(rem/rad).

1.2. Specific Effective Energy

The specific effective energy absorbed in organ *T* per transformation of radionuclide *j* in compartment *s* is given by

$$SEE(T \leftarrow s)_j = \frac{1}{M_T} \sum_i \left[Y_i \, E_i \, AF(T \leftarrow s)_i \, Q_i \right] \tag{1.2}$$

where the summation is over all radiations produced per transformation of radionuclide *j* in source compartment *s*;

Y_i is the yield of radiations of type *i* per transformation of radionuclide *j*;

E_i is the average energy of radiation *i* (MeV);

$AF(T \leftarrow s)_i$ is the fraction of energy absorbed in target organ *T* per emission of radiation *i* in *s*;

Q_i is the quality factor for radiation of type *i* (rem/rad):

Q = 1 for β particles and all photons;

Q = 10 for fission neutrons and for protons;

Q = 20 for α particles and heavy recoil particles; and

M_T is the mass of the target organ (g).

1.2.1. Absorbed fraction

Nonpenetrating radiations. For most organs it is assumed that the energies from all nonpenetrating radiations (i.e., α and β particles, recoil particles and fission fragments) are completely absorbed within the source organ. Exceptions are the mineral bone and sections of the gastrointestinal (GI) tract. The specific absorbed fraction for the mucosal layer of a section of the GI tract is equal to

$$\frac{AF(ml \leftarrow T)_{np}}{M_T^{m1}} = \frac{\delta}{2M_T^C} \tag{1.3}$$

where M_T^{ml} is the mass of the mucosal layer, M_T^C is the mass of the contents of that section of the GI tract, and δ is equal to one for β particles, zero for recoil atoms, and 0.01 for α particles and fission fragments. The values of the absorbed fraction for α and β radiation for mineral bone depend on whether the radionuclide is deposited on bone surfaces or throughout the volume of the bone, and, in the case of β emitters, whether the energy of the particle is greater than 0.2 MeV; the values given by the ICRP are summarized in Table 1.1. The values for fission fragments are taken to be the same as for α particles, and those for recoil atoms are set equal to zero.

Penetrating radiations. The specific absorbed fractions of photon energy are taken from the detailed Monte-Carlo calculations of Cristy and Eckerman for an adult male;[2] these values (in units of kg^{-1}) are reproduced in Appendix I. Although the calculations done here are for a standard 70 kg adult male, the results of Cristy and Eckerman could also be used to produce DCFs for newborns and children of one, five, ten, or fifteen years of age or for an adult female.

1.2.2. Decay schemes

Radionuclide decay data were taken from *The Table of Isotopes*,[3] *The Table of Radioactive Isotopes*,[4] and the National Nuclear Data Center.[5] In a few cases decay chains with small branching ratios have been omitted, but all the radionuclides thought to be most important in fusion reactor materials are described by the most complete and up-to-date data available. A listing of the decay data used is given in Appendix J.

Table 1.1. Absorbed fractions for α and β emitters in bone.

		Bone Dosimetry Class				
		Volume		Surface		
Source Organ	Target Organ	α	β	α	β E ≥ 0.2	β E < 0.2
Trabecular Bone	Bone Surface	0.025	0.025	0.25	0.025	0.25
	Red Marrow	0.05	0.35	0.5	0.5	0.5
Cortical Bone	Bone Surface	0.01	0.015	0.25	0.015	0.25
	Red Marrow	0.0	0.0	0.0	0.0	0.0

1.2.3. Masses of organs in the body

The masses of the nineteen source and target organs considered in this report are listed in Table 1.2. Except for ovaries they apply to the standard 70kg male.

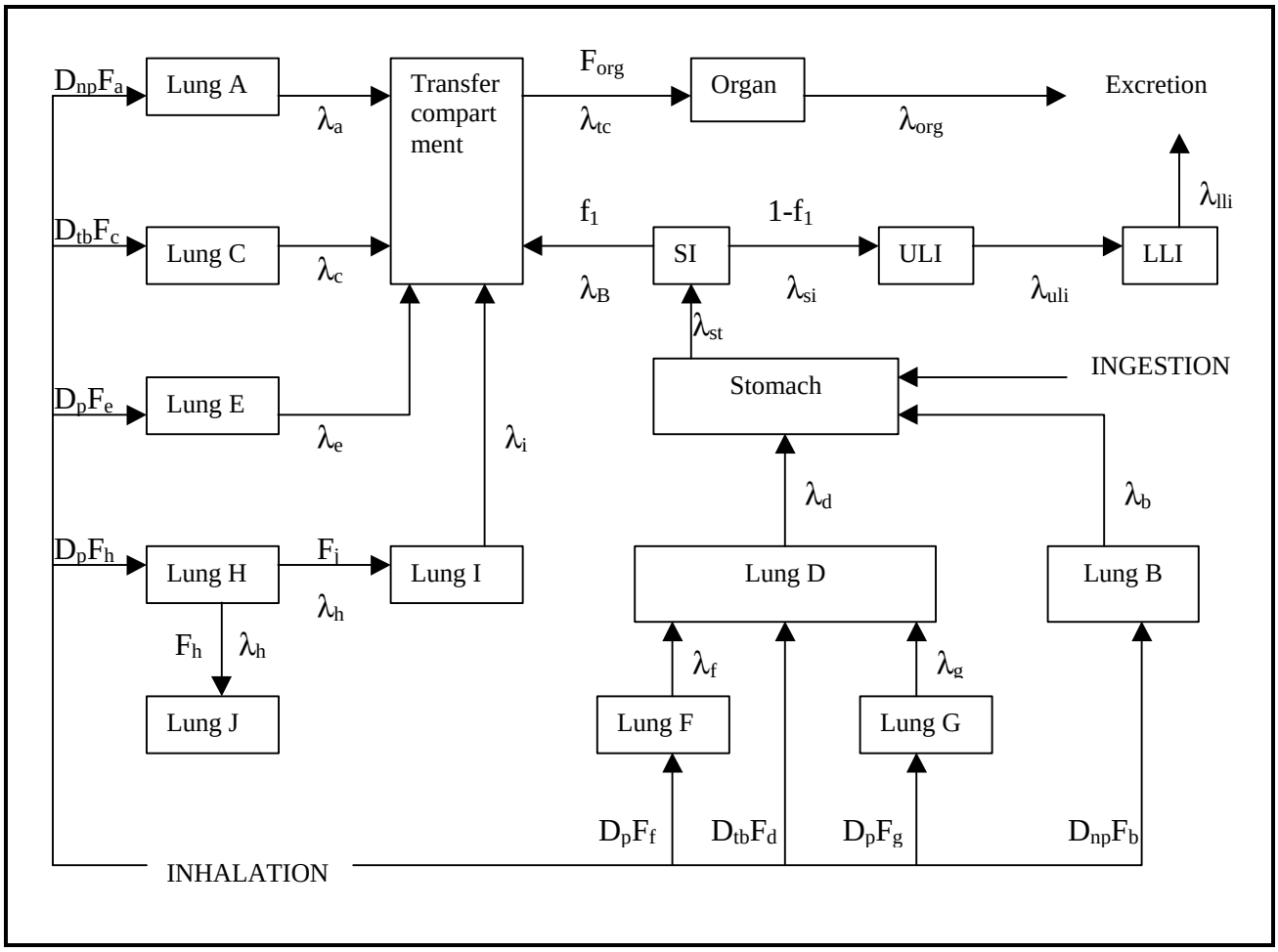
Table 1.2. Masses of organs and tissues used in this report.

Source Organ	Mass (g)	Target Organ	Mass (g)
Adrenals	14	Adrenals	14
Brain	1,500	Brain	1,500
LLI contents	135	LLI wall	160
SI contents	400	SI wall	640
ST contents	250	ST wall	150
ULI contents	220	ULI wall	210
Kidneys	310	Kidneys	310
Liver	1,800	Liver	1,800
Lungs	1,000	Lungs	1,000
Muscles	28,000	Muscles	28,000
Ovaries	11	Ovaries	11
Pancreas	100	Pancreas	100
Trabecular bone	4,000	Red marrow	1,500
Cortical Bone	1,000	Bone surface	120
Spleen	180	Spleen	180
Testes	35	Testes	35
Thyroid	20	Thyroid	20
Bladder contents	200	Bladder contents	45
Whole body	70,000	Whole body	70,000

1.3. Number of Transformations in a Source Organ

The number of transformations of radionuclide *j* in source organ *s* during a period of time *t*, which is denoted by $U_{j,s}(\tau)$, is the integral of the activity of the radionuclide within that organ over the stated period of time. The function describing the uptake and retention of a radionuclide in body tissues following its ingestion and inhalation may be very complex. In the ICRP model, computations are facilitated by assuming that the body is composed of a number of separate compartments. Any organ or tissue may comprise one or a number of compartments. Loss of a radionuclide from any compartment is taken to be governed by first-order kinetics. Therefore, the retention of a radionuclide in any organ or tissue can be described by a sum of exponential terms. Although the ICRP makes an exception for alkaline earths, for which it uses a power function to describe retention and elimination,[6] I have approximated these functions by a sum of exponentials.

Figure 1.1. A diagram of the ICRP body model.



The ICRP body model, which is illustrated schematically in Figure 1.1, consists of ten lung compartments, four gastrointestinal (GI) tract compartments, a transfer compartment (i.e., body

fluids), and additional compartments that correspond to a particular organ, group of organs, or part of an organ. (Although Figure 1.1 shows only one additional compartment—the compartment marked "organ"—the metabolic model for a particular element may contain up to fifteen additional compartments.) Inhaled material enters one of eight lung compartments, while ingested material goes directly to the stomach. There is no feedback in the model; material inhaled or ingested progresses from compartment to compartment in a linear fashion until it is excreted. The ICRP metabolic model can be described by a system of first-order differential equations. According to the principle of superposition, this system of equations can be broken down into a series of independent linear chains. For each additional organ compartment there are fifteen linear chains—thirteen for inhalation and two for ingestion. Referring to Figure 1.1, these chains are as follows:

Inhalation

1. Lung A → TC → Organ → Excretion
2. Lung C → TC → Organ → Excretion
3. Lung E → TC → Organ → Excretion
4. Lung H → Lung I → TC → Organ → Excretion
5. Lung H → Lung J
6. Lung B → ST → SI → TC → Organ → Excretion
7. Lung D → ST → SI → TC → Organ → Excretion
8. Lung F → Lung D → ST → SI → TC → Organ →
9. Lung G → Lung D → ST → SI → TC → Organ →

10. Lung B → ST → SI → ULI → LLI → Excretion

11. Lung D → ST → SI → ULI → LLI → Excretion

12. Lung F → Lung D → ST → SI → ULI → LLI →

13. Lung G → Lung D → ST → SI → ULI → LLI →

Ingestion

1. ST → SI → TC → Organ → Excretion

2. ST → SI → ULI → LLI → Excretion

where TC is the transfer compartment, ST is the stomach, SI is the small intestine, ULI is the upper large intestine, and LLI is the lower large intestine.

This system of linear chains exists not only for the parent radionuclide, but for each radioactive daughter as well. Moreover, each daughter is produced within each compartment. This problem is greatly simplified by assuming, as does the ICRP (except for parents decaying to inert gases or iodine), that radioactive daughters behave biologically like the parent radionuclide. Under these conditions, the system of linear chains has an exact solution. The activity of radioactive daughter *j* in compartment *s* at time *t* is given by:

$$Q_{j,s}(t) = Q_{o,1}(0)\prod_{i=1}^{s-1}\lambda_i^b \prod_{i=1}^{j}\lambda_i^r \sum_{i=1}^{s}\sum_{k=0}^{j}\left[\frac{e^{-\left(\lambda_i^b+\lambda_k^r\right)t}}{\prod_{\substack{p=1\\p\neq i}}^{s}\left(\lambda_p^b-\lambda_i^b\right)\prod_{\substack{p=0\\p\neq k}}^{j}\left(\lambda_p^r-\lambda_k^r\right)}\right] \qquad (1.4)$$

where the summation in s is over all source compartments and the summation in *j* is over all radioactive daughters involved;

$Q_{0,1}(0)$ is the activity of the parent radionuclide in the first compartment of the chain at t=0;

l_i^b is the biological decay constant of compartment *i*; and

l_i^r is the radioactive decay constant of radionuclide *i*.

Integrating Equation 1.4 between $t = 0$ and $t = \tau$, we obtain the number of transformations of daughter *j* in compartment *s* in time τ:

$$U_{j,s}(\tau) = Q_{0,1}(0) \prod_{i=1}^{s-1} \lambda_i^b \prod_{i=1}^{j} \lambda_i^r \sum_{i=1}^{s} \sum_{k=0}^{j} \left[\frac{1 - e^{-\left(\lambda_i^b + \lambda_k^r\right)\tau}}{\left(\lambda_i^b + \lambda_k^r\right) \prod_{\substack{p=1 \\ p \neq i}}^{s} \left(\lambda_p^b - \lambda_i^b\right) \prod_{\substack{p=0 \\ p \neq k}}^{j} \left(\lambda_p^r - \lambda_k^r\right)} \right] \tag{1.5}$$

If $\left[\left(\lambda_i^b + \lambda_k^r\right)^{-1} << \tau\right]$ for all *i* and *k*, this simplifies to:

$$U_{j,s} \approx \frac{U_{j-1,s}\, \lambda_j^r + U_{j,s-1}\, \lambda_{s-1}^b}{\lambda_j^r + \lambda_s^b} \tag{1.6}$$

where $U_{j,0} = 0$, $U_{-1,s} = 0$, and $U_{0,1} = Q_{0,1}(0) \cdot (\, l_1^b + l_0^r)^{-1}$. This is the familiar result for long integration times, and is the basis for the approximate expressions given by the ICRP in Appendix A of Reference 1.

1.3.1. *The ICRP lung model*

The model developed by the ICRP to describe the distribution, retention, and elimination of radionuclides from the lung is given in Table 1.3. The values given for D_{np}, D_{tb}, and D_p are the regional depositions for an aerosol with an activity median aerodynamic diameter (AMAD) of 1μm. DCFs for other AMADs can be calculated easily. The ICRP neglects the dose received by the nasopharyngeal (N-P) region because it is small for long integration times. Because this report considers much shorter integration times than does the ICRP, the dose to the N-P region is included here.

1.3.2. *The ICRP GI-tract model*

The ICRP GI-tract model consists of the four compartments shown in Figure 1.1: the stomach, the small intestine, the upper large intestine, and the lower large intestine. The mean residence times in these compartments are taken to be one hour (ST), four hours (SI), thirteen hours (ULI), and twenty-four hours (LLI). The rate of transfer of activity from the small intestine to the transfer compartment is estimated with the following equation:

$$\lambda_B = \frac{f_1 \lambda_{SI}}{1 - f_1} \tag{1.7}$$

where f_1 is the fraction of the element reaching the transfer compartment following ingestion and

l_{SI}, the biological decay constant in the SI, is the reciprocal of the mean residence time in the SI.

Table 1.3. The ICRP lung model.

Region	Compartment	Lung Clearance Class					
		Days		Weeks		Years	
		$T_{½}$ (days)	F	$T_{½}$ (days)	F	$T_{½}$ (days)	F
N-P (D_{np}=0.30)	A	0.01	0.5	0.01	0.1	0.01	0.01
	B	0.01	0.5	0.4	0.9	0.4	0.99
T-B (D_{tb}=0.08)	C	0.01	0.95	0.01	0.5	0.01	0.01
	D	0.2	0.05	0.2	0.5	0.2	0.99
P (D_p=0.25)	E	0.5	0.8	50	0.15	500	0.05
	F	—	—	1.	0.4	1.	0.4
	G	—	—	50	0.4	500	0.4
	H	0.5	0.2	50	0.05	500	0.15
L	I	0.5	1.	50	1.	1000	0.9
	J	—	—	—	—	∞	0.1

1.3.3. *Metabolic data*

The lung clearance class, bone dosimetry class, and the fraction transferred from the GI tract to the transfer compartment for each element were taken from Reference 1. In each case, the data correspond to the oxide form of each element since oxides are the most likely compound to form in a scenario that leads to public exposure to radionuclides embedded in fusion reactor materials. It should be noted that for many elements, compounds other than oxides have different lung clearance classes from those used here. Reference 1 also gives a detailed metabolic model for each element that specifies the number of compartments in addition to the fifteen compartments in the standard model (ten lung, four GI, and one transfer compartment), the fraction transferred from the transfer compartment to each of these additional organ compartments, and the biological half-life of the element in each of these compartments. The ICRP makes exceptions for highly soluble gases such as H_2O and CO_2, which are assumed to be instantaneously distributed uniformly throughout the body without passing through the lung or GI tract. The data used are listed in Appendix H.

There are several minor differences between the ICRP metabolic model and the model used here. As noted above, the data given by the ICRP for alkaline earths have been fitted to exponential functions to facilitate computation (the accuracy of the fit is much better than the intrinsic accuracy of the ICRP model in every case). The ICRP assumes that inert elements produced by radioactive decay escape from the body with a half-life of two hours, while the present model assumes that daughter radionuclides behave biologically like the parent in every case. This will lead to a small overestimate in the DCFs for Te-131, Te-131m, I-133, and I-135, all of which decay to radioactive isotopes of xenon. In addition, the ICRP assumes that iodine produced by radioactive decay in the body behaves biologically like iodine instead of like the parent

radionuclide. This will lead to small differences in the DCFs computed for Te-129, Te-129m, Te-131, Te-131m, and Te-132. It should be noted that isotopes of tellurium and iodine are not important contributors to the radiological hazards of any likely fusion reactor material (indeed, DCFs were calculated for these radionuclides mostly to facilitate comparisons with fission). The internal dose from inert gases has been ignored in every case, since, in all these cases considered here, it is much smaller than the external dose from these radionuclides.

1.4. The IDCF Computer Code

The IDCF (Internal Dose Conversion Factor) computer code was written to translate the ICRP body model and metabolic data into estimates of internal DCFs for all organs and integration times. As noted above, calculations were done for an adult male exposed to oxide aerosols with an AMAD of 1μm, but the code can easily be modified to calculate DCFs for children of various ages, exposure to compounds other than oxides, or aerosols with any AMAD greater than 0.1μm. A complete listing of the IDCF code is given in Appendix F. The code is written in VAX FORTRAN, and, since it makes liberal use of VAX extensions to standard FORTRAN-77, substantial work would be required to modify the code for use on other machines. The code will be made available upon request.

1.4.1. *DCF estimates*.

The estimates produced by the IDCF code for nineteen target organs, nine irradiation times, and 259 radionuclides are given in Appendices A and B. Appendix A gives DCFs for inhalation; Appendix B for ingestion. The code takes about thirty minutes to run on a VAX-11/780. Although the values in the appendices are given to three significant digits, it should be noted that the accuracy of the calculations is generally considered to be on the order of a factor of two.

The final four target organs listed in Appendices A and B require some explanation. The column labeled "other" is the average dose to all body tissues other than the first eighteen organs listed. The column labeled "whole body" is the dose to the entire body computed as if all transformations were uniformly distributed throughout the body. The column labeled "total body" is the mass-weighted average of the doses to each organ. The final column, labeled "EDE" for "effective dose equivalent," is the weighted average of the dose to certain organs, with the weights determined by the stochastic risk factors for the generation of fatal cancers associated with the respective organs as specified by the ICRP[1]. The weights assigned are as follows: gonads (the greater of the dose to the ovaries or testes), 0.25; breasts (muscle has been used here), 0.15; red marrow, 0.12; lung, 0.12; thyroid, 0.03; bone surfaces, 0.03; remainder, 0.30. The remainder refers to the five organs, other than the skin or those listed above, receiving the highest doses; each of these is assigned a weight of 0.06. This procedure allows a single number, the effective dose equivalent DCF, to represent the number of latent cancer fatalities from chronic exposure to a radionuclide.

The values of the EDE produced by the IDCF code were compared with similar calculations done at Oak Ridge by Killough, et al.[7] Of the 49 radionuclides common to both listings, over half agreed to within 10%, 80% agreed to within 30%, and 90% agreed to within a factor of two. These differences have two main sources: different assumptions about the biological behavior of

radioactive daughters, and differences in metabolic data. Unlike the IDCF model, the Oak Ridge model assumes that daughters always behave according to their own atomic number, which leads to differences in several cases. In addition, the metabolic data used in the Oak Ridge calculations varies considerably from that used here in several cases. With the exception of two radionuclides (Nb-97m and Sm-147), all differences in the EDE values can be adequately accounted for by differences in daughter behavior or metabolic data.

2. EXTERNAL DOSE-RATE CONVERSION FACTORS

This chapter describes the models and the computer code used to calculate dose-rate conversion factors (DRCFs) for external exposure to contaminated air, ground surface, and soil. The model used here is mainly that developed by Kocher;[8] readers seeking more information should consult the original work.

Radiations considered. The calculation of external DRCFs in this report takes into account photon radiations only. Alpha particles, recoil particles, and fission fragments are easily absorbed in clothing or the inert layer of the skin (the epidermis) where they produce no damage. The case of electrons is more complicated. The highest-energy electron emitted by a radionuclide considered in this report is the 10.4 MeV β particle emitted by N-16, which has a maximum range in tissue of about 5 cm. This clearly is sufficient to deliver a substantial dose to internal organs. But virtually all electron emissions from all other radionuclides have mean energies of less than 1 MeV, which corresponds to a range of less than 0.4 cm in tissue.[9] About half of the electron's energy is deposited in the first 18% of the mean range, and nearly all of the energy is absorbed in the first 30% of the mean electron range.[10] Therefore, the electron energy will be deposited primarily (and in most cases, totally) in the dermis (the layer of skin below the epidermis), which is about 0.14 cm thick. Since the ICRP neglects the dose to the dermis[1], and since the dose to the skin does not contribute to the EDE, the contribution of electrons to the external dose rate is neglected here. Indeed, the contribution of electron radiations to the whole-body dose rate has been found to be small compared to the external dose rate from photons in all release scenarios considered by a major study of fusion-reactor accidents.[10]

2.1. Immersion in Contaminated Air

If a radionuclide is distributed uniformly throughout an infinite volume of air, conservation of energy requires that the amount of energy emitted in a given volume of air equal the amount absorbed in that volume. The absorbed dose rate in air for a monoenergetic photon emitter at a concentration of 1 Ci/m^3 is therefore equal to

$$R = 593\frac{E}{\rho_a} \tag{2.1}$$

where

593 = $(3.7\cdot10^{10}$ Bq/Ci) · $(1.602\cdot10^{-6}$ erg/MeV) ÷(100 ergs/g·rad);

E = photon energy (MeV/transformation); and

ρ_a = density of air (1189 g/m^3).

In order to convert Equation 2.1 into the dose rate received by a particular organ, modifications for the following effects must be made: (1) the difference between energy absorption in tissue and in air, (2) the difference between an infinite cloud and the semi-infinite hemisphere that would actually surround an individual, (3) the self-shielding of body tissues, and (4) the fraction

of the incident energy that contributes to the dose rate in a particular organ. These modifications are discussed below.

1. For a monoenergetic photon source, the ratio of the energy absorbed in tissue to that absorbed in air is equal to the ratio of the mass energy-absorption coefficients in the two media at that energy:

$$\varepsilon = \frac{(\mu_{en}/\rho)_t}{\mu_{en}/\rho)_a} \tag{2.2}$$

When monoenergetic photons Compton-scatter off air molecules (the dominant effect at energies of interest here) a continuum of photon energies results. Dillman has accounted for this effect in his calculations of the ratio of the absorbed dose in tissue to that in air for a monoenergetic photon emitter uniformly distributed in air.[11] Dillman's results are lower than those given by Equation 2.2 by 10% at 0.01 MeV, with the difference becoming smaller at higher energies. The correction is therefore rather small, and Equation 2.2 can be used with little error.

2. Since a receptor at the ground surface would absorb only half of the infinite cloud dose, the simplest way of accounting for the presence of the ground is to multiply the infinite cloud dose by one-half. But since photons scatter differently off air and ground, this assumption is not strictly valid. These air-ground interface effects have been reviewed by Dillman.[11] He concludes, after integrating numerically over the semi-infinite cloud, that within the accuracy of the data the correction factor is simply one-half.

3. At energies of about 1 MeV, the mean-free-path of photons in tissue is so large that body tissues provide little self-shielding, and each volume of tissue can be assumed to be irradiated from all directions. At very low photon energies, absorption by body tissues reduces the dose by a factor of two. But the mean-free-path in air is then also small, and since most body tissues are located somewhat above the ground surface, the presence of the ground no longer matters—the volume of tissue "sees" an infinite cloud at very low photon energies. For these reasons, we can combine the air-ground interface and self-shielding effects with an overall correction factor of one-half.

4. Poston and Snyder have computed the dose rate to 20 organs and the whole body from a semi-infinite cloud of a monoenergetic photon emitter by integrating over an anthropomorphic phantom.[12] The organs include all those in Table 1.2 except the adrenals and the brain. In addition, Poston and Snyder give results for three organs not included in Table 1: yellow marrow, skin, thymus, and uterus. The results are presented in terms of the absorbed dose rate for a concentration of 1 Ci/m^3 for twelve photon energies. We can define the ratio of the absorbed dose rate in the organ to that at the body surface in the following way:

$$G_T = \frac{2R_T}{\varepsilon R} \tag{2.3}$$

where

G_T = the ratio of the dose rate received by target organ T to that at the body surface; and

R_T = dose rate calculated by Poston and Snyder for organ *T*.

The final expression for the photon DRCF for cloudshine is

$$DRCF_T = \frac{296}{\rho_a} \sum_i [Y_i E_i \varepsilon_i G_{T,i}]$$

where the summation is over all photons emitted by the radionuclide, and Y_i equals the probability of photon emission *i* per transformation of the radionuclide.

The results obtained in this way are identical to those of Poston and Snyder, except that the calculation is broken down into several parts. This was done because the organ dose-rate factors given by Equation 2.3 can be used in computing the dose rate from ground-deposited radionuclides, as discussed below.

2.2. Exposure to a Contaminated Surface

The absorbed photon dose rate in air a distance *b* (taken to be one meter) above an infinite plane uniformly contaminated with a monoenergetic photon emitter at a concentration of 1 Ci/m^2 is given by

$$R = 296 E \int_b^\infty (\mu_{en}/\rho)_a B \frac{e^{-\mu r}}{r} dr \qquad (2.5)$$

where

B = energy-absorption buildup factor in air;

= $1 + C\mu r\, e^{D\mu r}$, where C and D are functions of the photon energy; and

μ = linear attenuation coefficient in air.

As before, to convert the dose rate in air to the dose rate received by a particular organ we must account for the difference in energy absorption between air and tissue and for the fraction of the incident energy that is absorbed by the organ. The former is accomplished simply by multiplying Equation 2.5 by Equation 2.2, but the later consideration is more problematic because there are no accurate calculations in the literature of the dose rate received by various organs for external exposure to a contaminated surface. Because of this lack of data, Kocher used the same organ dose-rate factors as those derived from the calculations of Poston and Snyder for cloudshine.[8] This is obviously a rough approximation, since the angular distribution of photons incident on the body surface is very different in these two cases. The work of Jacob, et al.[14] indicates that this procedure will result in relatively small errors (i.e., less than 25%) in the EDE for photon energies greater than 0.05 MeV, although the error for particular organs may be much greater. Because better data are not available, I have followed Kocher's procedure of multiplying Equation 2.5 by Equation 2.3.

The final expression for the photon DRCF for exposure to a contaminated surface is

$$DRCF_T = 296 \sum_i \left[Y_i \, E_i \, (\mu_{en} / \rho)_{t,i} \, G_{T,i} \left[\Phi(\mu, b) - \frac{C}{D-1} e^{(D-1)\mu b} \right] \right] \tag{2.6}$$

where

$$\Phi(\mu, b) = \int_b^\infty \frac{e^{-\mu r}}{r} dr$$

2.3. Exposure to Contaminated Soil

Now consider exposure to a contaminated volume of soil. Estimating the photon dose rate some distance above the soil requires accounting for the buildup and attenuation of scattered photons in the soil as well as in the air. Such calculations have already been done by Beck and de Planque,[13] who used Monte-Carlo techniques to compute the photon dose rate in air at various distances above a semi-infinite volume of soil uniformly contaminated with a monoenergetic photon emitter at 1 Ci/m^3. Their results for a distance of one meter are shown in Table 2.1. The density of the air and soil are assumed to be 1204 g/m^3 and 1.6 g/cm^3, respectively, and the composition of the soil is as follows: 1.12% H, 1.23% C, 55.81% O, 7.14% Al, 31.55% Si, and 3.15% Fe.

Table 2.1. Dose rate in air one meter above contaminated soil. [13]

Photon Energy (MeV)	Dose Rate $\left[\frac{rem/s}{Ci/m^3}\right]$	Photon Energy (MeV)	Dose Rate $\left[\frac{rem/s}{Ci/m^3}\right]$
0.25	$3.55 \cdot 10^{-5}$	1.46	$2.54 \cdot 10^{-4}$
0.364	$5.74 \cdot 10^{-5}$	1.76	$3.07 \cdot 10^{-4}$
0.50	$8.12 \cdot 10^{-5}$	2.0	$3.50 \cdot 10^{-4}$
0.662	$1.10 \cdot 10^{-4}$	2.25	$3.91 \cdot 10^{-4}$
0.75	$1.27 \cdot 10^{-4}$	2.50	$4.34 \cdot 10^{-4}$
1.0	$1.71 \cdot 10^{-4}$	2.62	$4.56 \cdot 10^{-4}$
1.25	$2.16 \cdot 10^{-4}$	2.75	$4.78 \cdot 10^{-4}$

To convert the dose rate in air to a dose rate in a particular organ, we follow the same procedure as for exposure to a contaminated surface. The final expression for the photon DRCF for exposure to contaminated soil is

$$DRCF_T = \sum_i Y_i R_{B,i} \varepsilon_i G_{T,i} \quad (2.7)$$

where the summation in i is over all photon emissions, Y_i is the probability of photon emission i per transformation of the radionuclide, $R_{B,i}$ is the photon dose rate in air for photon emission i as given by Beck and de Planque, and where e_i and $G_{T,i}$ are given by Equations 2.2 and 2.3.

2.4. The EDRCF Computer Code

The EDRCF computer code was written to compute the dose conversion factors for external exposure to contaminated air, surface, and soil. A complete listing of the code is given in Appendix G. Like the IDCF code, EDRCF was written in VAX FORTRAN.

2.4.1. *DRCF estimates*

The results of the EDRCF code for 259 radionuclides and twenty-one target organs are given in Appendix C for contaminated air, Appendix D for a contaminated surface, and Appendix E for contaminated soil. These results took about two minutes to produce on a VAX-11/780. Since there is a large overlap between the results of Kocher and those given here, evaluating the accuracy of the EDRCF code is easy. The values of the photon DRCFs for all radionuclides common to both listings are in excellent agreement (usually ± 5%). Since the EDRCF code uses the same equations as Kocher's computer code, this agreement is more a reflection of the accuracy of an agreement on radionuclide decay data than anything else.

REFERENCES

[1] International Commission on Radiological Protection, "Limits for Intakes of Radionuclides by Workers," ICRP Publication 30, Parts 1-4 (Oxford: Pergamon Press, 1978).

[2] M. Cristy and K. F. Eckerman, "Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources," ORNL/TM-8381/V1-V6 (Oak Ridge, TN: Oak Ridge National Laboratory, April 1987).

[3] C. Michael Lederer and Virginia S. Shirley, eds., Table of Isotopes, 7th Edition (New York: John Wiley & Sons, Inc., 1978).

[4] Edgardo Browne and Richard B. Firestone, Table of Radioactive Isotopes (New York: John Wiley & Sons, Inc., 1986)

[5] C.L. Dunford, T.W. Burrows, and J.K. Tuli, National Nuclear Data Center On-Line Services Documentation, BNL-NCS-39756 (Upton, NY: Brookhaven National Laboratory, March 31, 1987).

[6] International Commission on Radiological Protection, "Alkaline Earth Metabolism in Adult Man," ICRP Publication 20 (Oxford: Pergamon Press, 1972).

[7] G.G. Killough, D.E. Dunning, Jr., S.R. Bernard, and J.C. Pleasant, "Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel-Cycle Facilities. Vol. I," ORNL/NUREG/TM-190 (Oak Ridge, TN: Oak Ridge National Laboratory, June 1978), and D.E. Dunning, Jr., G.G. Killough, S.R. Bernard, J.C. Pleasant, and P.J. Walsh, "Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel-Cycle Facilities. Vol. III," ORNL/NUREG/TM-190/V3 (Oak Ridge, TN: Oak Ridge National Laboratory, June 1981

[8] D.C. Kocher, "Dose-Rate Conversion Factors for External Exposure to Photon and Electron Radiation from Radionuclides Occurring in Routine Releases from Nuclear Fuel-Cycle Facilities," ORNL/NUREG/TM-283 (Oak Ridge, TN: Oak Ridge National Laboratory, 1979).

[9] Bureau of Radiological Health, Radiological Health Handbook (Washington, DC: U.S. Department of Health, Education, and Welfare, 1970).

[10] Steve Fetter, "The Radiological Hazards of Fusion Reactors: Models and Comparisons," Ph.D. dissertation, University of California, Berkeley, 1985

[11] L.T. Dillman, "Absorbed Gamma Dose Rate for Immersion in a Semi-Infinite Radioactive Cloud," Health Physics, Vol. 27 (1974), p. 571

[12] J.W. Poston and W.S. Snyder, "A Model for Exposure to a Semi-Infinite Cloud of a Photon Emitter," Health Physics, Vol. 26 (1974), p. 287

[14] P. Jacob, H.G. Paretzke, H. Rosenbaum, and M. Zankl, "Effective Dose Equivalents for Photon Exposures from Plane Sources on the Ground," Radiation Protection Dosimetry, Vol. 14, No. 4 (1986), pp. 299-310

[13] H. Beck and G. de Planque, "The Radiation Field in Air Due to Distributed Gamma-Ray Sources in the Ground," HASL-195 (Washington, DC: U.S. Atomic Energy Commission, May 1968).

[14] P. Jacob, H.G. Paretzke, H. Rosenbaum, and M. Zankl, "Effective Dose Equivalents for Photon Exposures from Plane Sources on the Ground," Radiation Protection Dosimetry, Vol. 14, No. 4 (1986), pp. 299-310