JAERI-Data/Code
99-047

JP0050128

DOSE COEFFICIENTS FOR INTAKES OF RADIONUCLIDES BY WORKERS: COEFFICIENTS FOR RADIONUCLIDES NOT LISTED IN ICRP PUBLICATION 68

December 1999

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編集兼発行　　日本原子力研究所

Dose Coefficients for Intakes of Radionuclides by Workers: Coefficients for Radionuclides not Listed in ICRP Publication 68

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(Received November 5, 1999)

Dose coefficients, the committed effective dose per unit intake, have been calculated for 149 radionuclides with half-lives $\geq$ 10 min that are not listed in ICRP Publication 68 (Publ. 68). Effective dose rates for inert gas have been calculated for 2 radionuclides.

The dose coefficients were calculated with the computer program LUDEP that calculates internal doses using the respiratory tract model of ICRP Publ. 66 and the biokinetic models of Publ. 30. Nuclear decay data used for the calculation were newly compiled from decay data sets of the Evaluated Nuclear Structure Data File (ENSDF). In the calculation of the effective dose rates, external irradiation from the surrounding cloud and irradiation of the lung from the gas within it were considered. The calculated results are presented in tables, which are the same forms as those in Publ. 68. The range of the differences in the dose coefficients due to the biokinetic models and nuclear decay data employed was also discussed by comparing the dose coefficients between LUDEP and Publ. 68. The dose coefficients and the effective dose rates will be used for dose calculation for radionuclides produced in high-energy proton accelerator and fusion reactor facilities.

Keywords: Radionuclide, Internal Exposure, Dose Coefficient, Inhalation, Ingestion, External Exposure, Effective Dose Rate, Submersion, Nuclear Decay Data.

作業者による放射性核種の摂取に対する線量係数:
ICRP Publication 68 に収録されていない核種の係数

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(1999 年 11 月 5 日受理)

半減期 10 分以上の核種の中で，ICRP Publication 68 (Publ. 68) に収録されていない 149 核種に対して，単位摂取量あたりの預託実効線量 (線量係数) を計算した。また，不活性ガス 2 核種に対して，実効線量率を計算した。

線量係数の計算は，ICRP Publ. 66 の呼吸気道モデル及び Publ. 30 の体内動態モデルに基づいた内部被ばく線量計算プログラム LUDEP を用いて行った。計算には，評価済み核構造データファイル (ENSDF) から新たに編集した崩壊データを用いた。実効線量率の計算では，放射性雲からの外部照射及び肺中のガスによる肺の照射を考慮した。計算した結果は，Publ. 68 の表形式にまとめられた。また，LUDEP と Publ. 68 の線量係数とを比較し，計算に用いた体内動態モデル及び崩壊データに基づく線量係数値の変動幅についても検討した。計算された線量係数及び実効線量率は，加速器施設，核融合炉施設において生成される核種に対する被ばく線量評価に利用することができる。

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1 Introduction

Dose coefficients $e(\tau)$,* the committed effective dose per unit acute intake via inhalation and ingestion, are used for evaluating radiation doses by intakes of radionuclides. The coefficients are also used for calculating the annual limit of intakes (ALI) and derived air concentrations (DAC), which are valuable operational guides for judging the significance of air monitoring data.

The International Commission on Radiological Protection (ICRP) has calculated the dose coefficients for about 800 radionuclides for workers[1] and members of the public.[2–6] In a series of calculations of the dose coefficients, ICRP has used the nuclear decay database of ICRP Publication 38 (Publ. 38).[7] The decay database of Publ. 38 was compiled from decay data sets in the Evaluated Nuclear Structure Data File (ENSDF)[8,9] using the computer program EDISTR,[10] which was designed to calculate energies and intensities of nuclear and atomic radiations associated with nuclear transformation. Publ. 38 covers mainly the decay data for radionuclides with half-lives $\geq$ 10 min and their daughters; the total number of radionuclides listed is 820.

The nuclear decay database of Publ. 38 is adequate for calculating the dose coefficients of radionuclides that are important in medical, environmental, and occupational exposures. It is found, however, that significant quantities of radionuclides whose dose coefficients are not given by ICRP are produced in high-energy proton accelerators[11,12] and fusion reactor facilities.[13] It is therefore necessary to enhance the database of the dose coefficients for such exotic radionuclides in order to ensure the radiation safety assessment in the development of high-power proton accelerator and thermal fusion reactors.

From that point of view, the authors compiled a nuclear decay database[14] for radionuclides that are not listed in Publ. 38. This report presents the dose coefficients for intakes of these radionuclides by workers using the compiled nuclear decay database. The calculated dose coefficients are presented in tables, which are the same forms as those in Publ. 68.

2 Method

2.1 Nuclear Decay Data

Figure 1 shows the flow of the calculations of dose coefficients and effective dose rates. The nuclear decay database used is those compiled in the preceding report.[14] The database contains the decay data for 204 radionuclides, consisting of 162 nuclides with half-lives $\geq$ 10 min, 28 daughters and 14 nuclides that may be important in fusion reactor facilities.

The database consists of the radiation data, β particle spectra, and bremsstrahlung spectra. The radiation data are the listings of the types, energies, and absolute intensities of radiations emitted by the nuclear transformation of radionuclides. Two types of formats for the radiation data, Publ. 38 and NUCDECAY formats, are included in the database. The difference between the Publ. 38 and NUCDECAY formats is that the former omits radiations below a specified cutoff value of energy while the latter does not. The details of the cutoff rule are described elsewhere.[7]

β particle spectra and external bremsstrahlung spectra are used for calculating the effective

*τ is the time period in years over which the dose is calculated. The integration time is 50 y for adults.

dose rates for inert gas, as described in subsection 2.3.

2.2 Calculation of Dose Coefficients for Inhalation and Ingestion of Particulates

Dose coefficients for inhalation and ingestion of particulates were calculated with the computer program LUDEP[15] (LUng Dose Evaluation Program), developed by the National Radiological Protection Board (NRPB). LUDEP calculates internal doses using the human respiratory tract model of Publ. 66,[16] the biokinetic models of Publ. 30,[17] and the tissue and radiation weighting factors recommended in Publ. 60.[18]

LUDEP has two built-in nuclear decay databases, the Publ. 38 and ORNL databases.[19] The number of radionuclides involved in the Publ. 38 database is more than that of the ORNL database. In addition, the former can treat the ingrowth of radioactive decay products in the body, while the latter does not.

For calculating dose coefficients, the radiation data of the Publ. 38 format were employed to maintain consistency with the built-in database of LUDEP. A preprocessor program was developed to prepare input files of radiation data for LUDEP from the radiation data of the Publ. 38 format (Figure 1). If a radionuclide forms radioactive decay products, the decay chain data file was also prepared to specify the relation of nuclides in the decay chain and their branching fractions. If the decay products are included in Publ. 38, the decay data of the Publ. 38 database of LUDEP were used for the nuclides.

The biokinetic models used in LUDEP are those of Publ. 30, but the f_1 values, the fractional uptake of elements from the gastrointestinal tract, given in Publ. 68 were employed. If a radionuclide forms radioactive decay products, the contribution to the dose from their build-up in the body was evaluated by assuming that the decay products behave metabolically like the parent radionuclide.

Dose coefficients for radon isotopes and spontaneously fissioning nuclides were not calculated, because LUDEP does not deal with radon and the radiations concomitant with spontaneous fission.

2.3 Calculation of Effective Dose Rates for Inert Gas

Effective dose rates of ^{42}Ar and ^{44}Ar, were calculated by considering external irradiation from submersion in the cloud and irradiation of the lung from the gas within it. Irradiation from the deposited activity in the lung was not considered, since Ar belongs to SR-0 class and therefore doses from absorbed gas are considered to be negligible.[1]

Effective dose rates from submersion in the cloud were calculated by the method described in Publ. 30[17] and Federal Guidance Report (FGR) No. 12.[20] In a semi-infinite source region with a uniform concentration $C(t)$ (Bq m^{-3}) of a radionuclide at time t, the effective dose rate, e (Sv d^{-1}/Bq m^{-3}), is given by

$$e = \sum_T w_T \, h_T \int C(t) \, dt \, , \qquad (1)$$

where w_T is the tissue weighting factor recommended in Publ. 60,[18] and h_T is the equivalent dose rate in tissue T (Sv d^{-1}/Bq m^{-3}).

The equivalent dose rate in tissue T for exposure mode S, h_T^S, can be expressed as

$$h_T^S = \sum_{j=e^\pm,\gamma} \left[\sum_j y_i(E_i)\, h_{T,j}^S(E_i) + \int_0^\infty y_j(E)\, h_{T,j}^S(E) dE \right], \quad (2)$$

where $y_j(E_i)$ is the yield of discrete radiations of type j and energy E_i, and $y_j(E)$ denotes the yield of continuous radiations per nuclear transformation with energy between E and $E + dE$. The notation $e^\pm$ in the j denotes all electrons including $\beta^\pm$ particles, internal conversion electrons and Auger electrons, and the γ denotes all photons including γ rays, X rays and bremsstrahlung.

The values of e based on h_T^S for an isotropic exposure mode were calculated for twelve monoenergetic photon sources ranging 0.01 to 5 MeV and presented in Table II.4 of FGR No. 12, as shown in Figure 2. The values of h_T for skin ($h_{\rm skin}$), which should be considered in β particle and electron exposures, were also calculated for monoenergetic electron sources and presented in Figure II.25 of FGR No. 12, as shown in Figure 3. By using the data of Figure 2, the e due to γ rays and X rays from a radionuclide and external bremsstrahlung was calculated from their energies and intensities. In addition, the $h_{\rm skin}$ by β particles, internal conversion electrons and Auger electrons was calculated from the data of Figure 3 and added using the w_T for skin, 0.01, to the e.

Equivalent dose rates to the lung from the gas within it were calculated by assuming that the activity in the volume of gas within the airway is replaced by the same activity, uniformly deposited on the surface.[21)] The calculation was carried out using LUDEP according to the procedures described in Appendix B of the reference 21.

3 Results and Discussion

Tables 1 and 2 present the dose coefficients for inhalation and ingestion of particulates and the effective dose rates for inert gas, respectively. The tables are the same forms as those in Publ. 68.

In the following part of this section, we discuss the effects on the dose coefficients of the biokinetic models and nuclear decay data employed. The consideration is important to see the validity of the dose coefficients presented in this report.

The biokinetic models of Publ. 30 were used in the present calculation, while the revised models were applied to selected elements in Publ. 68. To clarify the range of the differences in the dose coefficients due to the update of the biokinetic models, comparisons were made for the dose coefficients between LUDEP and Publ. 68 for 17 elements listed in Table 3. These elements are those included in Table 1 and that the new biokinetic models are adopted in Publ. 68. For all isotopes of the 17 elements listed in Publ. 68, the dose coefficients were calculated using LUDEP both for inhalation of 1 μm and 5 μm AMAD aerosols with absorption types F, M and S and for ingestion and compared with those of Publ. 68. An index D (%) was used to examine the differences of the dose coefficients:

$$D = \frac{e(50)_{\rm LUDEP} - e(50)_{\rm Publ.\ 68}}{e(50)_{\rm Publ.\ 68}} \times 100\ , \quad (3)$$

where $e(50)_{\rm LUDEP}$ and $e(50)_{\rm Publ.\ 68}$ are the dose coefficients calculated by LUDEP and that given in Publ. 68, respectively. Figure 4 shows the distribution of D; the total number of cases compared was 836 for 172 radionuclides. It is shown that the $e(50)_{\mathrm{LUDEP}}$ values are generally in good agreement with $e(50)_{\mathrm{Publ.\ 68}}$, and the values of D are within ±25% for 686 cases. There are 25 cases in which the values of D exceed 100%. These were found in ^{133}I, ^{135}I, ^{226}Ra, ^{229}Th, ^{232}Th, ^{232}Np, ^{236m}Np, ^{236}Np, ^{237}Np and ^{238}Np. The greatest discrepancy was found in the case of ingestion of ^{232}Th with $f_1 = 5 \times 10^{-4}$; $e(50)_{\mathrm{LUDEP}}$ and $e(50)_{\mathrm{Publ.\ 68}}$ are 9.2×10^{-7} and 2.2×10^{-7} (Sv Bq^{-1}), respectively.

The results of the above analysis suggest that the use of the Publ. 30's biokinetic models causes no significant difference in the dose coefficients compared with those calculated using the revised biokinetic models. The dose coefficients might slightly differ in the several radionuclides of the elements, such as I, Ra, Th and Np, as a result of change in the biokinetic models, but the discrepancies are within a factor of 4.2.

The radiation data of the Publ. 38 format were used to calculate the dose coefficients in the present calculation. The Publ. 38 format omits radiations below a specified cutoff value of energy to limit the number of radiations listed at maximum 175. In most radionuclides studied in this report, the energy of radiations omitted are less than 10%, and therefore, significant radiations are included in the calculation of the dose coefficients. However, the cutoff percentages exceed 10% in the following nuclides: ^{208}At (cutoff percentage 11.1%), ^{163}Tm (13.2%), ^{204}Bi (13.4%), ^{152}Tb (15.9%), ^{133m}Ce (16.0%), ^{192}Au (17.3%), ^{183}Ir (20.6%), ^{167}Lu (33.1%), and ^{153}Dy (34.7%). The dose coefficients for these radionuclides would be underestimated corresponding to the cutoff percentages.

4 Summary

Dose coefficients for intakes of radionuclides have been calculated for 149 radionuclides with half-lives $\geq$ 10 min that are not listed in ICRP Publication 68 (Publ. 68). Effective dose rates for inert gas have been calculated for 2 radionuclides. The calculated results are presented as tables of the same forms as those in Publ. 68. The dose coefficients and the effective dose rates will be used for dose calculation for the radionuclides produced in high-energy proton accelerator and fusion reactor facilities.

Acknowledgements

The authors are grateful to Dr. N. Jarvis of NRPB for useful suggestion on the lung dose calculation, and to Dr. H. Noguchi of JAERI for valuable comments to the manuscript.

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Table 1. Effective dose coefficients for inhalation and ingestion of particulates.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Sulphur							
S-38	170.3 m	F	0.800	1.1E−10	1.9E−10	0.800	3.6E−10
(inorganic)		M	0.800	2.3E−10	3.3E−10	0.100	6.0E−10
Chlorine							
Cl-34m	32.00 m	F	1.000	2.8E−11	4.9E−11	1.000	1.0E−10
		M	1.000	4.5E−11	7.2E−11		
Vanadium							
V-50	1.5E+17 y	F	0.010	5.5E−08	6.5E−08	0.010	3.0E−09
		M	0.010	2.4E−08	1.7E−08		
Selenium							
Se-72	8.40 d	F	0.800	1.4E−09	1.9E−09	0.800	3.8E−09
		M	0.800	3.3E−09	3.0E−09	0.050	2.5E−09
Rubidium							
Rb-78	17.66 m	F	1.000	2.0E−11	3.6E−11	1.000	6.9E−11
Rb-84m	20.26 m	F	1.000	4.9E−12	8.7E−12	1.000	6.9E−12
Yttrium							
Y-84	40 m	M	1.0E−04	5.9E−11	9.9E−11	1.0E−04	1.2E−10
		S	1.0E−04	6.1E−11	1.0E−10		
Y-85m	4.86 h	M	1.0E−04	1.6E−10	2.5E−10	1.0E−04	3.6E−10
		S	1.0E−04	1.7E−10	2.6E−10		
Y-85	2.68 h	M	1.0E−04	9.2E−11	1.4E−10	1.0E−04	1.8E−10
		S	1.0E−04	9.6E−11	1.5E−10		
Y-87m	13.37 h	M	1.0E−04	1.3E−10	1.9E−10	1.0E−04	2.2E−10
		S	1.0E−04	1.4E−10	1.9E−10		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Zirconium							
Zr-87	1.68 h	F	0.002	4.6E−11	8.0E−11	0.002	1.9E−10
		M	0.002	8.8E−11	1.3E−10		
		S	0.002	9.2E−11	1.4E−10		
Niobium							
Nb-91m	60.86 d	M	0.010	3.2E−09	2.8E−09	0.010	4.1E−10
		S	0.010	3.9E−09	3.4E−09		
Nb-91	6.8E+2 y	M	0.010	2.5E−10	1.8E−10	0.010	4.2E−11
		S	0.010	1.7E−09	1.1E−09		
Nb-92m	10.15 d	M	0.010	4.1E−10	5.2E−10	0.010	5.0E−10
		S	0.010	4.4E−10	5.3E−10		
Nb-92	3.47E+7 y	M	0.010	4.2E−09	3.0E−09	0.010	9.7E−10
		S	0.010	2.5E−08	1.5E−08		
Molybdenum							
Mo-91	15.49 m	F	0.800	1.4E−11	2.3E−11	0.800	6.0E−11
		S	0.050	2.1E−11	3.4E−11	0.050	6.0E−11
Mo-102	11.3 m	F	0.800	1.7E−11	2.7E−11	0.800	6.9E−11
		S	0.050	2.6E−11	4.2E−11	0.050	6.9E−11
Ruthenium							
Ru-95	1.643 h	F	0.050	2.6E−11	4.9E−11	0.050	6.0E−11
		M	0.050	3.6E−11	6.2E−11		
		S	0.050	3.7E−11	6.4E−11		
Rhodium							
Rh-97m	46.2 m	F	0.050	1.9E−11	3.5E−11	0.050	4.7E−11
		M	0.050	2.7E−11	4.6E−11		
		S	0.050	2.8E−11	4.8E−11		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Rh-97	30.7 m	F	0.050	1.5E−11	2.7E−11	0.050	4.7E−11
		M	0.050	2.3E−11	3.9E−11		
		S	0.050	2.4E−11	4.0E−11		
Palladium							
Pd-98	17.7 m	F	0.005	1.6E−11	2.9E−11	0.005	6.2E−11
		M	0.005	2.7E−11	4.4E−11		
		S	0.005	2.9E−11	4.6E−11		
Pd-99	21.4 m	F	0.005	1.3E−11	2.2E−11	0.005	3.5E−11
		M	0.005	1.9E−11	3.2E−11		
		S	0.005	2.0E−11	3.3E−11		
Pd-111	23.4 m	F	0.005	1.3E−11	2.1E−11	0.005	4.9E−11
		M	0.005	2.5E−11	3.7E−11		
		S	0.005	2.7E−11	3.9E−11		
Pd-112	21.03 h	F	0.005	4.4E−10	6.4E−10	0.005	2.6E−09
		M	0.005	1.0E−09	1.4E−09		
		S	0.005	1.1E−09	1.5E−09		
Silver							
Ag-101	11.1 m	F	0.050	9.8E−12	1.7E−11	0.050	3.2E−11
		M	0.050	1.4E−11	2.3E−11		
		S	0.050	1.4E−11	2.3E−11		
Ag-113	5.37 h	F	0.050	7.1E−11	1.2E−10	0.050	3.9E−10
		M	0.050	1.7E−10	2.4E−10		
		S	0.050	1.6E−10	2.5E−10		
Cadmium							
Cd-105	55.5 m	F	0.050	1.5E−11	2.8E−11	0.050	4.1E−11
		M	0.050	2.3E−11	3.8E−11		
		S	0.050	2.3E−11	3.9E−11		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Cd-111m	48.54 m	F	0.050	1.1E−11	1.9E−11	0.050	1.4E−11
		M	0.050	2.2E−11	3.6E−11		
		S	0.050	2.4E−11	3.7E−11		
Cd-118	50.3 m	F	0.050	3.8E−11	6.3E−11	0.050	1.8E−10
		M	0.050	7.9E−11	1.2E−10		
		S	0.050	8.3E−11	1.2E−10		
Indium							
In-107	32.4 m	F	0.020	1.4E−11	2.5E−11	0.020	3.9E−11
		M	0.020	2.4E−11	3.8E−11		
In-108m	39.6 m	F	0.020	2.5E−11	4.5E−11	0.020	8.2E−11
		M	0.020	3.8E−11	6.3E−11		
In-108	58.0 m	F	0.020	3.8E−11	7.2E−11	0.020	7.9E−11
		M	0.020	5.0E−11	8.9E−11		
In-112m	20.56 m	F	0.020	1.1E−11	2.0E−11	0.020	1.7E−11
		M	0.020	2.2E−11	3.6E−11		
Tin							
Sn-108	10.30 m	F	0.020	7.6E−12	1.4E−11	0.020	2.2E−11
		M	0.020	1.2E−11	1.9E−11		
Sn-109	18.0 m	F	0.020	9.0E−12	1.7E−11	0.020	1.9E−11
		M	0.020	1.2E−11	2.1E−11		
Sn-113m	21.4 m	F	0.020	2.0E−12	3.0E−12	0.020	3.3E−12
		M	0.020	4.1E−12	5.4E−12		
Tellurium							
Te-117	62 m	F	0.300	2.1E−11	3.9E−11	0.300	5.2E−11
		M	0.300	3.2E−11	5.3E−11		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Te-118	6.00 d	F	0.300	6.9E−10	1.1E−09	0.300	2.8E−09
		M	0.300	2.1E−09	2.3E−09		
Te-119m	4.70 d	F	0.300	3.0E−10	5.2E−10	0.300	6.7E−10
		M	0.300	5.0E−10	6.8E−10		
Te-119	16.03 h	F	0.300	7.4E−11	1.4E−10	0.300	1.7E−10
		M	0.300	1.0E−10	1.7E−10		
Iodine							
I-118	13.7 m	F	1.000	8.1E−11	1.2E−10	1.000	2.0E−10
I-119	19.1 m	F	1.000	1.8E−11	2.9E−11	1.000	4.4E−11
Barium							
Ba-124	11.9 m	F	0.100	1.5E−11	2.5E−11	0.100	6.8E−11
Ba-127	12.7 m	F	0.100	7.4E−12	1.3E−11	0.100	2.5E−11
Ba-129m	2.16 h	F	0.100	3.3E−11	6.1E−11	0.100	7.0E−11
Ba-129	2.23 h	F	0.100	1.6E−11	2.9E−11	0.100	4.8E−11
Lanthanum							
La-129	11.6 m	F	5.0E−04	8.1E−12	1.4E−11	5.0E−04	2.6E−11
		M	5.0E−04	1.2E−11	2.0E−11		
La-132m	24.3 m	F	5.0E−04	1.2E−11	2.2E−11	5.0E−04	3.5E−11
		M	5.0E−04	2.0E−11	3.2E−11		
La-133	3.912 h	F	5.0E−04	1.5E−11	2.6E−11	5.0E−04	4.4E−11
		M	5.0E−04	2.3E−11	3.6E−11		
Cerium							
Ce-130	22.9 m	M	5.0E−04	3.4E−11	5.6E−11	5.0E−04	6.9E−11
		S	5.0E−04	3.6E−11	5.8E−11		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Ce-131	10.2 m	M	5.0E−04	1.4E−11	2.2E−11	5.0E−04	2.7E−11
		S	5.0E−04	1.4E−11	2.3E−11		
Ce-132	3.51 h	M	5.0E−04	1.3E−10	2.1E−10	5.0E−04	3.1E−10
		S	5.0E−04	1.4E−10	2.2E−10		
Ce-133m	4.9 h	M	5.0E−04	1.1E−10	1.8E−10	5.0E−04	1.9E−10
		S	5.0E−04	1.1E−10	1.9E−10		
Ce-133	97 m	M	5.0E−04	5.0E−11	7.4E−11	5.0E−04	8.6E−11
		S	5.0E−04	5.2E−11	7.7E−11		
Ce-146	13.52 m	M	5.0E−04	2.6E−11	4.1E−11	5.0E−04	4.5E−11
		S	5.0E−04	2.7E−11	4.3E−11		
Praseodymium							
Pr-134	11 m	M	5.0E−04	2.0E−11	3.2E−11	5.0E−04	4.6E−11
		S	5.0E−04	2.0E−11	3.3E−11		
Pr-134	17 m	M	5.0E−04	3.0E−11	4.7E−11	5.0E−04	8.0E−11
		S	5.0E−04	3.1E−11	4.9E−11		
Pr-135	24 m	M	5.0E−04	2.8E−11	4.4E−11	5.0E−04	5.7E−11
		S	5.0E−04	2.9E−11	4.6E−11		
Pr-146	24.15 m	M	5.0E−04	2.9E−11	4.6E−11	5.0E−04	7.6E−11
		S	5.0E−04	3.1E−11	4.8E−11		
Neodymium							
Nd-135	12.4 m	M	5.0E−04	3.0E−11	4.7E−11	5.0E−04	6.4E−11
		S	5.0E−04	3.1E−11	4.9E−11		
Nd-137	38.5 m	M	5.0E−04	2.9E−11	4.7E−11	5.0E−04	5.7E−11
		S	5.0E−04	3.0E−11	4.9E−11		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Nd-140	3.37 d	M	5.0E−04	1.0E−09	1.2E−09	5.0E−04	2.0E−09
		S	5.0E−04	1.1E−09	1.3E−09		
Nd-144	2.29E+15 y	M	5.0E−04	7.5E−06	5.1E−06	5.0E−04	4.2E−08
		S	5.0E−04	3.1E−06	1.6E−06		
Nd-152	11.4 m	M	5.0E−04	2.3E−11	3.8E−11	5.0E−04	4.8E−11
		S	5.0E−04	2.4E−11	3.9E−11		
Samarium							
Sm-140	14.82 m	M	5.0E−04	3.3E−11	5.0E−11	5.0E−04	9.7E−11
Sm-148	7E+15 y	M	5.0E−04	7.8E−06	5.3E−06	5.0E−04	4.3E−08
Europium							
Eu-152m	96 m	M	5.0E−04	8.6E−12	1.1E−11	5.0E−04	1.3E−11
Eu-154m	46.3 m	M	5.0E−04	4.3E−12	6.0E−12	5.0E−04	8.7E−12
Eu-159	18.1 m	M	5.0E−04	2.3E−11	3.5E−11	5.0E−04	4.8E−11
Gadolinium							
Gd-150	1.79E+6 y	F	5.0E−04	2.5E−05	2.9E−05	5.0E−04	5.3E−08
		M	5.0E−04	1.0E−05	6.7E−06		
Terbium							
Tb-148	60 m	M	5.0E−04	6.8E−11	9.8E−11	5.0E−04	1.2E−10
Tb-152	17.5 h	M	5.0E−04	2.8E−10	4.3E−10	5.0E−04	6.4E−10
Tb-163	19.5 m	M	5.0E−04	1.7E−11	2.8E−11	5.0E−04	2.1E−11
Dysprosium							
Dy-151	17.9 m	M	5.0E−04	1.1E−10	9.1E−11	5.0E−04	1.8E−11
Dy-152	2.38 h	M	5.0E−04	5.6E−11	7.9E−11	5.0E−04	1.0E−10

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Dy-153	6.4 h	M	5.0E−04	9.7E−11	1.3E−10	5.0E−04	1.4E−10
Dy-154	3.0E+6 y	M	5.0E−04	1.1E−05	7.3E−06	5.0E−04	5.7E−08
Holmium							
Ho-154	11.76 m	M	5.0E−04	1.6E−11	2.5E−11	5.0E−04	4.1E−11
Ho-156	56 m	M	5.0E−04	5.3E−11	8.4E−11	5.0E−04	9.8E−11
Ho-160	25.6 m	M	5.0E−04	1.4E−11	2.3E−11	5.0E−04	1.7E−11
Ho-163	4570 y	M	5.0E−04	2.4E−10	1.7E−10	5.0E−04	6.8E−12
Erbium							
Er-156	19.5 m	M	5.0E−04	1.8E−11	2.8E−11	5.0E−04	3.4E−11
Er-159	36 m	M	5.0E−04	1.6E−11	2.7E−11	5.0E−04	2.2E−11
Er-163	75.0 m	M	5.0E−04	1.4E−12	2.5E−12	5.0E−04	2.6E−12
Thulium							
Tm-163	1.810 h	M	5.0E−04	3.3E−11	5.4E−11	5.0E−04	4.8E−11
Tm-165	30.06 h	M	5.0E−04	2.1E−10	3.0E−10	5.0E−04	3.4E−10
Tm-168	93.1 d	M	5.0E−04	3.9E−09	3.1E−09	5.0E−04	1.0E−09
Ytterbium							
Yb-163	11.05 m	M	5.0E−04	7.5E−12	1.2E−11	5.0E−04	1.4E−11
		S	5.0E−04	7.8E−12	1.3E−11		
Yb-164	75.8 m	M	5.0E−04	4.1E−11	6.2E−11	5.0E−04	8.5E−11
		S	5.0E−04	4.3E−11	6.5E−11		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Lutetium							
Lu-165	10.74 m	M	5.0E−04	1.3E−11	2.0E−11	5.0E−04	2.1E−11
		S	5.0E−04	1.3E−11	2.0E−11		
Lu-167	51.5 m	M	5.0E−04	2.9E−11	4.3E−11	5.0E−04	3.8E−11
		S	5.0E−04	3.1E−11	4.5E−11		
Hafnium							
Hf-174	2.0E+15 y	F	0.002	3.1E−05	3.6E−05	0.002	2.6E−07
		M	0.002	1.2E−05	8.4E−06		
Tungsten							
W-190	30.0 m	F	0.300	3.1E−11	6.3E−11	0.300	8.3E−11
						0.010	8.3E−11
Rhenium							
Re-179	19.5 m	F	0.800	8.1E−12	1.4E−11	0.800	1.5E−11
		M	0.800	1.2E−11	1.9E−11		
Re-183	70.0 d	F	0.800	1.3E−10	2.0E−10	0.800	3.2E−10
		M	0.800	2.4E−09	1.9E−09		
Osmium							
Os-183m	9.9 h	F	0.010	7.7E−11	1.4E−10	0.010	2.0E−10
		M	0.010	1.4E−10	2.1E−10		
		S	0.010	1.5E−10	2.1E−10		
Os-183	13.0 h	F	0.010	7.5E−11	1.3E−10	0.010	2.2E−10
		M	0.010	1.7E−10	2.3E−10		
		S	0.010	1.8E−10	2.4E−10		
Os-186	2.0E+15 y	F	0.010	7.1E−07	8.4E−07	0.010	3.2E−08
		M	0.010	1.1E−06	6.3E−07		
		S	0.010	3.8E−06	2.4E−06		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Os-196	34.9 m	F	0.010	2.8E−11	4.8E−11	0.010	1.1E−10
		M	0.010	5.6E−11	8.6E−11		
		S	0.010	5.9E−11	9.1E−11		
Iridium							
Ir-183	58 m	F	0.010	1.8E−11	3.3E−11	0.010	4.6E−11
		M	0.010	3.2E−11	5.0E−11		
		S	0.010	3.4E−11	5.2E−11		
Ir-193m	10.53 d	F	0.010	9.1E−11	1.4E−10	0.010	2.9E−10
		M	0.010	1.0E−09	8.9E−10		
		S	0.010	1.2E−09	1.0E−09		
Ir-196m	1.40 h	F	0.010	5.2E−11	9.5E−11	0.010	1.2E−10
		M	0.010	9.4E−11	1.5E−10		
		S	0.010	9.8E−11	1.6E−10		
Platinum							
Pt-184	17.3 m	F	0.010	1.3E−11	2.3E−11	0.010	2.6E−11
Pt-187	2.35 h	F	0.010	3.1E−11	5.8E−11	0.010	8.4E−11
Pt-190	6.5E+11 y	F	0.010	1.1E−07	1.2E−07	0.010	6.9E−09
Pt-202	44 h	F	0.010	6.3E−10	1.1E−09	0.010	4.4E−09
Gold							
Au-186	10.7 m	F	0.100	1.4E−11	2.4E−11	0.100	4.4E−11
		M	0.100	2.0E−11	3.2E−11		
		S	0.100	2.0E−11	3.3E−11		
Au-190	42.8 m	F	0.100	1.7E−11	3.1E−11	0.100	4.4E−11
		M	0.100	2.4E−11	4.0E−11		
		S	0.100	2.4E−11	4.1E−11		

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Au-191	3.18 h	F	0.100	2.9E−11	5.2E−11	0.100	6.8E−11
		M	0.100	5.7E−11	8.3E−11		
		S	0.100	6.0E−11	8.6E−11		
Au-192	4.94 h	F	0.100	6.1E−11	1.1E−10	0.100	1.5E−10
		M	0.100	8.2E−11	1.4E−10		
		S	0.100	8.4E−11	1.4E−10		
Au-196m	9.6 h	F	0.100	1.4E−10	2.4E−10	0.100	4.0E−10
		M	0.100	4.6E−10	5.8E−10		
		S	0.100	4.3E−10	6.2E−10		
Au-196	6.183 d	F	0.100	1.8E−10	2.9E−10	0.100	5.4E−10
		M	0.100	5.5E−10	6.8E−10		
		S	0.100	6.2E−10	7.4E−10		
Mercury							
Hg-191m	50.8 m	F	0.400	2.3E−11	4.2E−11	1.000	3.2E−11
(organic)						0.400	4.7E−11
Hg-191m	50.8 m	F	0.020	2.3E−11	4.3E−11	0.020	5.1E−11
(inorganic)		M	0.020	4.0E−11	6.4E−11		
Thallium							
Tl-196	1.84 h	F	1.000	3.0E−11	5.5E−11	1.000	5.1E−11
Lead							
Pb-194	12.0 m	F	0.200	6.1E−12	1.1E−11	0.200	9.5E−12
Pb-196	37 m	F	0.200	1.7E−11	3.2E−11	0.200	3.8E−11
Pb-197m	43 m	F	0.200	2.5E−11	4.5E−11	0.200	4.8E−11
Pb-204m	67.2 m	F	0.200	2.3E−11	4.2E−11	0.200	4.8E−11

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Bismuth							
Bi-204	11.22 h	F	0.050	1.9E−10	3.6E−10	0.050	5.3E−10
		M	0.050	2.9E−10	4.8E−10		
Bi-208	3.68E+5 y	F	0.050	4.1E−10	7.4E−10	0.050	1.1E−09
		M	0.050	4.1E−09	2.8E−09		
Polonium							
Po-204	3.53 h	F	0.100	1.3E−10	2.1E−10	0.100	2.8E−10
		M	0.100	3.9E−10	4.6E−10		
Po-206	8.8 d	F	0.100	7.2E−09	8.7E−09	0.100	4.2E−09
		M	0.100	5.1E−08	3.8E−08		
Po-208	2.898 y	F	0.100	6.6E−07	7.9E−07	0.100	2.7E−07
		M	0.100	3.3E−06	2.3E−06		
Po-209	102 y	F	0.100	6.6E−07	7.9E−07	0.100	2.6E−07
		M	0.100	3.2E−06	2.2E−06		
Astatine							
At-205	26.2 m	F	1.000	2.0E−10	2.7E−10	1.000	5.9E−11
		M	1.000	6.1E−10	6.1E−10		
At-208	1.63 h	F	1.000	6.3E−11	1.0E−10	1.000	8.5E−11
		M	1.000	3.4E−10	3.6E−10		
At-209	5.41 h	F	1.000	2.9E−10	4.2E−10	1.000	3.7E−10
		M	1.000	2.3E−09	2.0E−09		
At-210	8.1 h	F	1.000	3.8E−10	5.9E−10	1.000	8.4E−10
		M	1.000	7.1E−09	5.3E−09		
Francium							
Fr-212	20.0 m	F	1.000	2.0E−09	2.8E−09	1.000	7.1E−10

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Radium							
Ra-230	93 m	M	0.200	1.1E−10	1.6E−10	0.200	1.7E−10
Actinium							
Ac-229	62.7 m	F	5.0E−04	2.4E−11	3.0E−11	5.0E−04	3.8E−11
		M	5.0E−04	3.8E−11	5.2E−11		
		S	5.0E−04	3.5E−11	5.2E−11		
Thorium							
Th-233	22.3 m	M	5.0E−04	1.7E−11	2.7E−11	5.0E−04	2.1E−11
		S	2.0E−04	1.8E−11	2.8E−11	2.0E−04	2.1E−11
Th-236	37.5 m	M	5.0E−04	5.5E−11	8.5E−11	5.0E−04	8.3E−11
		S	2.0E−04	5.8E−11	8.9E−11	2.0E−04	8.3E−11
Protactinium							
Pa-229	1.50 d	M	5.0E−04	5.8E−09	4.8E−09	5.0E−04	7.8E−11
		S	5.0E−04	6.6E−09	5.4E−09		
Uranium							
U-235m	25 m	F	0.020	4.5E−16	8.0E−16	0.020	4.2E−15
		M	0.020	6.2E−16	1.2E−15	0.002	4.2E−15
		S	0.002	6.4E−16	1.2E−15		
Neptunium							
Np-231	48.8 m	M	5.0E−04	1.5E−09	1.9E−09	5.0E−04	1.9E−11
Np-241	13.9 m	M	5.0E−04	1.4E−11	2.1E−11	5.0E−04	1.5E−11
Americium							
Am-247	23.0 m	M	5.0E−04	2.7E−11	4.3E−11	5.0E−04	3.0E−11
Curium							
Cm-239	2.9 h	M	5.0E−04	6.2E−11	8.4E−11	5.0E−04	7.8E−11

Table 1. continued.

		Effective dose coefficient (Sv Bq^{-1})					
		Inhalation, $e_{inh}(50)$				Ingestion	
Nuclide	$t_{1/2}$	Type	f_1	1μm AMAD	5μm AMAD	f_1	$e_{ing}(50)$
Cm-251	16.8 m	M	5.0E−04	2.5E−11	3.7E−11	5.0E−04	2.8E−11
Berkelium							
Bk-248m	23.7 h	M	5.0E−04	2.4E−08	1.8E−08	5.0E−04	5.2E−10
Bk-251	55.6 m	M	5.0E−04	4.5E−11	6.2E−11	5.0E−04	3.7E−11
Californium							
Cf-247	3.11 h	M	5.0E−04	3.8E−11	4.7E−11	5.0E−04	2.0E−11
Cf-255	85 m	M	5.0E−04	5.3E−09	4.4E−09	5.0E−04	3.8E−11
Einsteinium							
Es-249	102.2 m	M	5.0E−04	2.4E−10	2.7E−10	5.0E−04	2.1E−11
Es-255	39.8 d	M	5.0E−04	3.6E−06	2.9E−06	5.0E−04	5.9E−09
Fermium							
Fm-251	5.30 h	M	5.0E−04	1.7E−09	1.9E−09	5.0E−04	7.0E−11

Table 2. Effective dose rates for inert gases.

Nuclide	$t_{1/2}$	Effective dose rate per unit air concentration ($Sv\ d^{-1}/Bq\ m^{-3}$)
Argon		
Ar-42	32.9 y	1.5E−11
Ar-44	11.87 m	8.2E−09

Table 3. Elements selected for the comparison of the dose coefficients between Publ. 68 and LUDEP.

Element*1	Publication*2	Element	Publication
Se	69	Pb	67
Zr	67	Po	67
Nb	56	Ra	67
Mo	67	Th	69
Ag	67	U	69
Te	67	Np	67
I	56	Pu	67
Ba	67	Am	67
Ce	67		

*1 In addition to these 17 elements, new biokinetic models were adopted for tritiated water, ^{3}H as organically bound tritium, Fe, Zn, Sr and Sb in Publ. 68.

*2 The number of ICRP Publication in which the new biokinetic models were proposed.

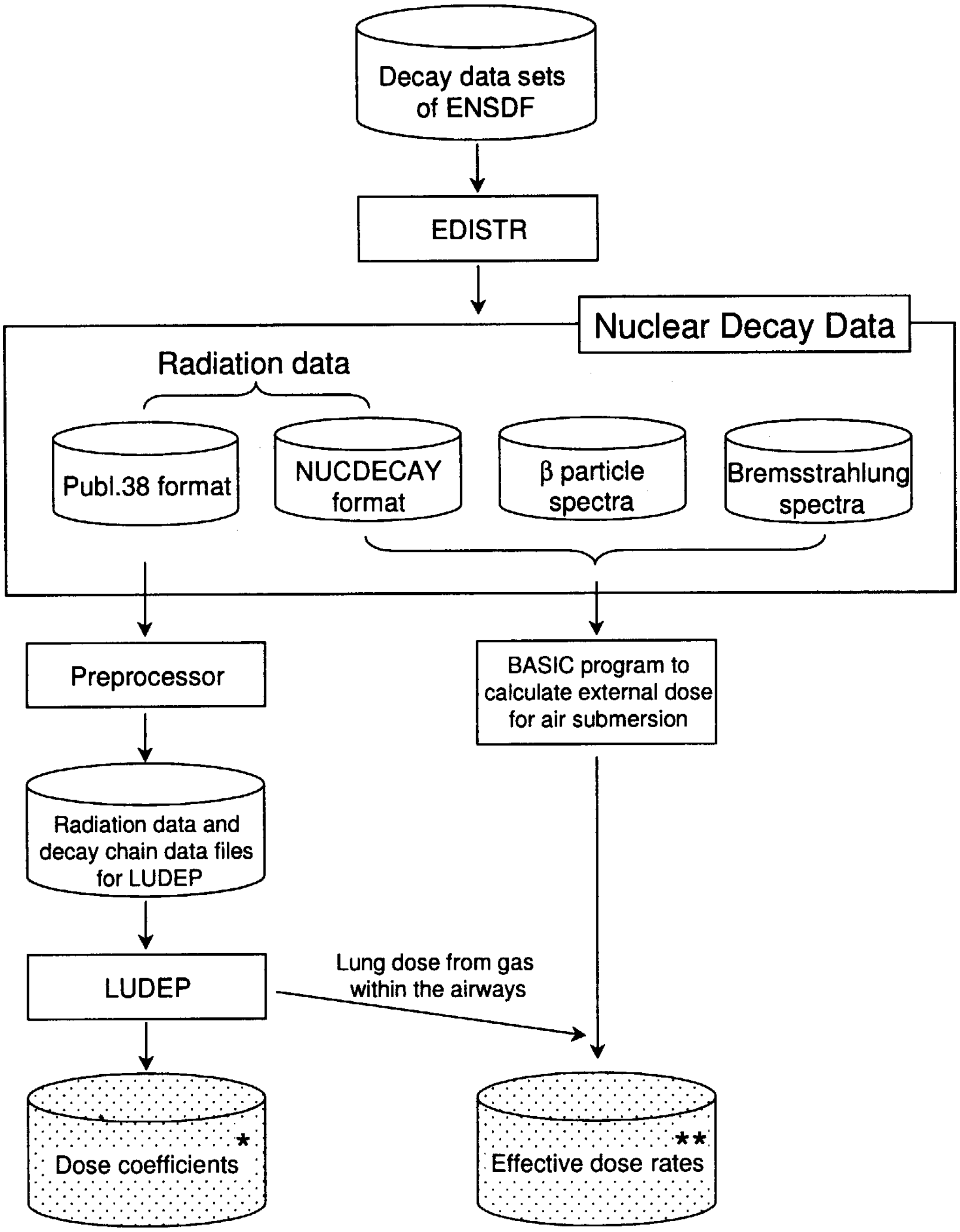

Figure 1. Flow of the calculation. The dose coefficients (*) and effective dose rates (**) are presented in Tables 1 and 2, respectively.

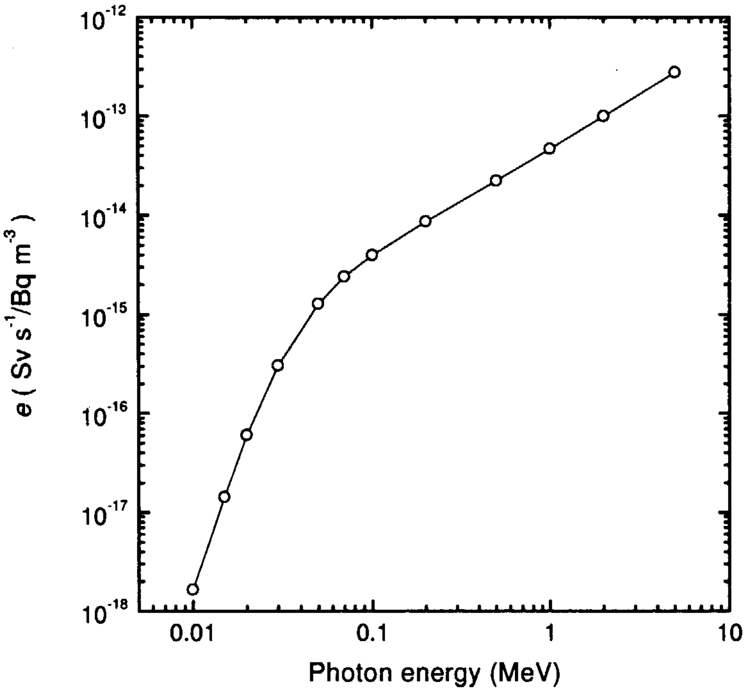

Figure 2. Effective dose rate as a function of photon energy (from reference 20).

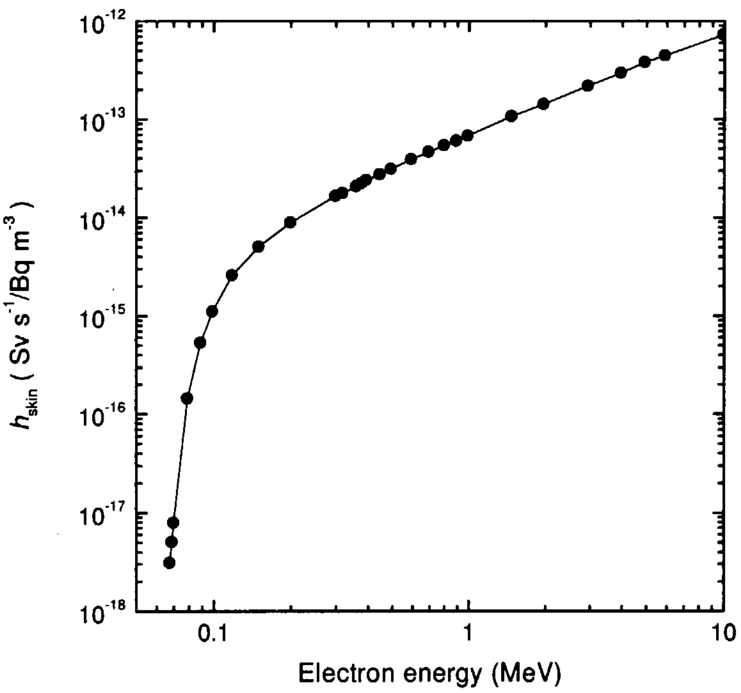

Figure 3. Skin dose rate as a function of electron energy (from reference 20).

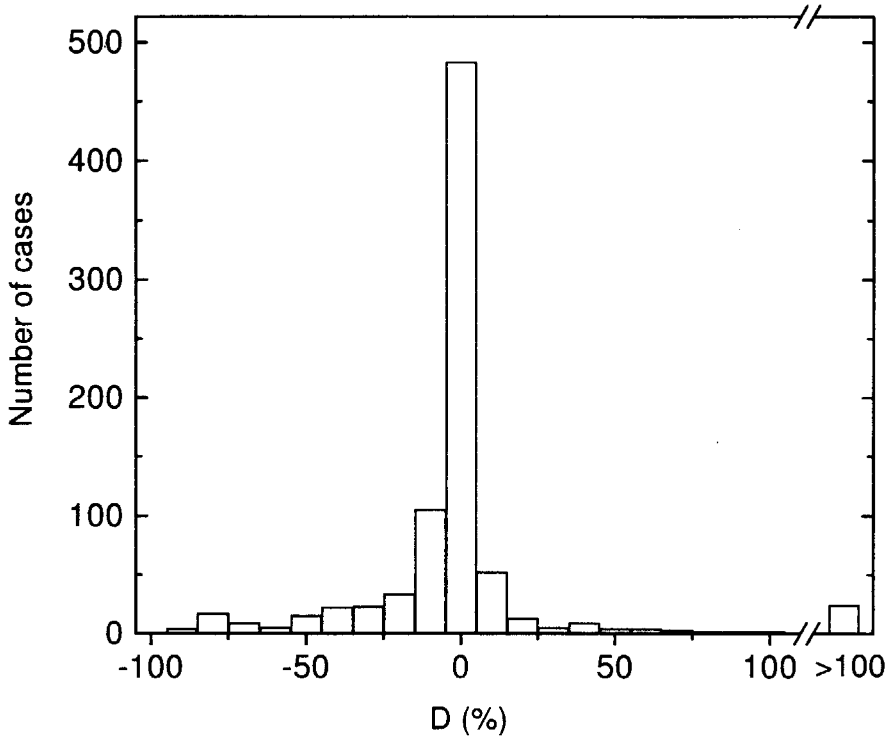

Figure 4. Difference in the dose coefficients between Publ. 68 and LUDEP.

国際単位系（SI）と換算表

表1　SI基本単位および補助単位

量	名　称	記　号
長　さ	メートル	m
質　量	キログラム	kg
時　間	秒	s
電　流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光　度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	$N\cdot m$
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	$A\cdot s$
電位，電圧，起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	$V\cdot s$
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	$cd\cdot sr$
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表2　SIと併用される単位

名　称	記　号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ eV=1.60218\times10^{-19}J$
$1\ u=1.66054\times10^{-27}kg$

表4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ Å=0.1nm=10^{-10}m$
$1\ b=100fm^2=10^{-28}m^2$
$1\ bar=0.1MPa=10^5Pa$
$1\ Gal=1cm/s^2=10^{-2}m/s^2$
$1\ Ci=3.7\times10^{10}Bq$
$1\ R=2.58\times10^{-4}C/kg$
$1\ rad=1cGy=10^{-2}Gy$
$1\ rem=1cSv=10^{-2}Sv$

表5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

（注）

1．表1－5は「国際単位系」第5版，国際度量衡局1985年刊行による。ただし，1 eVおよび1 uの値はCODATAの1986年推奨値によった。

2．表4には海里，ノット，アール，ヘクタールも含まれているが日常の単位なのでここでは省略した。

3．barは，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。

4．EC閣僚理事会指令ではbar，barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換　算　表

力	$N(=10^5dyn)$	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　$1\ Pa\cdot s(N\cdot s/m^2)=10\ P$(ポアズ)$(g/(cm\cdot s))$

動粘度　$1m^2/s=10^4St$(ストークス)(cm^2/s)

圧力	MPa(=10bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	$J(=10^7\ erg)$	$kgf\cdot m$	$kW\cdot h$	cal(計量法)	Btu	$ft\cdot lbf$	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal＝4.18605J（計量法）
＝4.184J（熱化学）
＝4.1855J（15℃）
＝4.1868J（国際蒸気表）

仕事率　1 PS(仏馬力)
＝75 $kgf\cdot m/s$
＝735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

DOSE COEFFICIENTS FOR INTAKES OF RADIONUCLIDES BY WORKERS: COEFFICIENTS FOR RADIONUCLIDES NOT LISTED IN ICRP PUBLICATION 68