Bull. Inst. Chem. Res., Kyoto Univ., Vol. 54, No. 1, 1976

Tabulated Value Used for Radiation Shielding against γ Rays from Radioisotopes

Takeshi Mukoyama*

Received December 18, 1975

Tables that are suitable for calculations of radiation shielding against point isotropic γ-ray sources have been generated by spline interpolation from the recent data. As γ-ray sources, the commom radioisotopes are considered and interpolation has been made for the major γ-ray energies of these nuclides.

Values of the energy absorption coefficients for air are obtained and the Rhm values of these nuclides are calculated. Table of the total attenuation coefficients is presented for six materials of interest. The dose buildup factors are approximated by the Berger's two-parameter formula. Tables of the coefficients of the Berger function are given for five shielding materials.

I. INTRODUCTION

Owing to wide use of radioisotopes in various fields, such as physics, chemistry, biology, and medicine, the need has often arisen to perform simple calculations of radiation shielding. In order to estimate dose distribution and to determine the shielding necessary to reduce the radiation to tolerable limits, one must use information given in the forms of numerical tables.

Since the tables are given for certain sets of discrete γ-ray energies, it is necessary to obtain intermediate values corresponding to the radiations emitted from the radioisotopes by interpolation from the tables. Therefore, it is convenient to generate the tables which are suitable for performing quick, easy, and reasonably accurate calculations for radioisotopes. In the present work, this has been done by spline interpolation using the computer. The results of the interpolation are given in four tables; energy absorption coefficients for air, total attenuation coefficients for six materials, and parameters to calculate buildup factors for five shielding materials.

The data contained herein should find its great use in calculations of dose distribution necessary for radiation shielding.

II. DOSE CALCULATIONS

The dose rate D (R/h) at a distance d (m) from a point isotropic source having an activity Q (Ci) is given by

$$D = 1.50 \times 10^4 Q/d^2 \sum_i \eta_i E_i \mu_{ei}, \tag{1}$$

where E_i is the γ-ray energy (MeV), η_i is the number of gammas emitted with

---

* 向山 毅: Laboratory of Nuclear Radiation, Institute for Chemical Research, Kyoto Univerity, Kyoto.

energy E_i per disintegration, and μ_{ei} is the linear energy absorption coefficient of air for γ-rays with the energy E_i (cm^{-1}).

The Rhm value D_0 of a γ-emitting nuclide is the dose rate (R/h) at 1 m from a point source of this nuclide having activity of 1 Ci and is obtained by setting $Q=d=1$ in Eq. (1):

$$D_0 \doteq 1.50\times 10^4 \sum_i \eta_i E_i \mu_{ei} \,. \qquad (2)$$

This quantity is closely related to the specific γ-ray constant Γ. If Γ is expressed in dimension ($\mathrm{R\cdot cm^2/h\cdot mCi}$), the value of Γ is equal to 10 times as large as D_0.

Using the Rhm value, Eq. (1) can be expressed as

$$D = D_0 Q/d^2 \,. \qquad (3)$$

When the shielding material of thickness x is placed between the source and the point considered, it is convenient to express the dose rate in terms of buildup factors:

$$D = 1.50\times 10^4\, Q/d^2 \sum_i \eta_i E_i \mu_{ei} B_i \exp\left(-\mu_i x\right) , \qquad (4)$$

where B_i and μ_i are the dose buildup factor and the total attenuation coefficient of the shielding material for the γ-ray energy E_i, respectively.

III. METHOD OF CALCULATION

In calculations presented here, sixteen radioisotopes which are commonly used are chosen. These nuclides are shown in Table I. All the nuclear parameters such as η_i and E_i are taken from the table prepared by Lederer *et al.*[1] The γ-ray energies corresponding to the major transitions in the nuclides of Table I are listed in Table II in order of increasing energies. In order to calculate the dose rate D for given values of Q, d, and x from Eq. (4), the values of μ_{ei}, μ_i, and B_i should be known.

These values were obtained by interpolation with respect to the γ-ray energies from the numerical tables. For this purpose, spline interpolation formula was used.[2] Spline function is defined by the piecewise polynomial arcs whose derivatives up to the order one less than the degree of polynomials are continuous everywhere. Cubic spline functions were used in the present work, and so the curve obtained is continuous through the second derivatives.

Much greater smooth curve can be obtained with this method than with other piecewise interpolation formulas, which give rise to discontinuities in the first derivative. Furthermore, this method can avoid the undulatory behavior of the interpolating function which often arises when a large number of data points are interpolated by a single high-degree polynomial.

All the numerical calculations in the present work have been performed on the FACOM 230–75 computer in the Data Processing Center of Kyoto University.

Table I. Roentgens per Hour Produced at 1 m by the Nuclear γ-Rays from 1 Ci (Rhm) of the Radionuclides Listed

Nuclide	Half-life	Rhm
^{22}Na	2.60 y	1.10*
^{24}Na	15.0 h	1.69
^{51}Cr	27.8 d	0.0151
^{54}Mn	303 d	0.434
^{57}Co	270 d	0.0890
^{60}Co	5.26 y	1.20
^{65}Zn	245 d	0.279*
^{82}Br	35.34 h	1.31
^{99}Mo	67 h	0.0721
^{99m}Tc	6.0 h	0.0574
^{111}In	2.81 d	0.190
^{123}I	13.3 h	0.0604
^{131}I	8.05 d	0.196
^{137}Cs	30.0 y	0.299
^{141}Ce	33 d	0.0313
^{198}Au	2.70 d	0.214

* Annihilation radiations are included.

Table II. Nuclear γ-Ray Energies Used for Calculations

Energy (MeV)	Nuclide	Enery (MeV)	Nuclide
0.12194	^{57}Co	0.6984	^{82}Br
0.1426	^{99m}Tc	0.740	^{99}Mo
0.14543	^{141}Ce	0.7769	^{82}Br
0.159	^{123}I	0.8276	^{82}Br
0.173	^{111}In	0.8353	^{54}Mn
0.247	^{111}In	1.0440	^{82}Br
0.28431	^{131}I	1.115	^{65}Zn
0.31980	^{51}Cr	1.17323	^{60}Co
0.36447	^{131}I	1.2746	^{22}Na
0.41180	^{198}Au	1.3171	^{82}Br
0.510976	Annihilation radiation	1.33245	^{60}Co
0.5541	^{82}Br	1.36853	^{24}Na
0.6187	^{82}Br	1.4753	^{82}Br
0.63700	^{131}I	2.7539	^{24}Na
0.6616	^{137}Cs		

IV. RESULTS

1. Rhm Value and Energy Absorption Coefficient

The dose rate is defined as the energy absorbed in unit volume per unit time. The incident energy of the photon is absorbed in the medium via electrons or positrons. It is converted into kinetic energy of these particles, and then they dissipate their energy in the medium as heat. In the low-energy region considered here, energy deposition of γ rays in the medium is expressed in terms of the energy absorption coefficient μ_e. It is noted that μ_e is smaller than the total attenuation coefficient μ, because the energy of the photon is not entirely absorbed in the medium.

The new systematic compilation of photon cross sections, total attenuation coefficients, and energy absorption coefficients was done by Hubbell.$^{3)}$ In the table, he listed values of μ_e of air for 25 γ-ray energies over the energy range 10 keV-10 MeV.

The values of μ_e were obtained by interpolation from the table of Hubbell. Using the nuclear parameters in Ref. 1 and the μ_e values thus estimated, we have computed the Rhm values of the nuclides listed in Table I. The results obtained are shown in Table I.

In Table III, we have listed the values of μ_e of air for the γ-ray energies given in Table II.

Table III. Linear Energy Absorption Coefficients for air ($\times 10^{-5}$ cm^{-1})

γ-ray energy (MeV)	μ_e	γ-ray energy (MeV)	μ_e
0.12194	2.90	0.6984	3.52
0.1426	2.98	0.740	3.51
0.14543	2.99	0.7769	3.49
0.159	3.05	0.8276	3.47
0.173	3.12	0.8353	3.46
0.247	3.37	1.0440	3.32
0.28431	3.45	1.115	3.28
0.31980	3.50	1.17323	3.24
0.36447	3.53	1.2746	3.18
0.41180	3.56	1.3171	3.16
0.510976	3.58	1.33245	3.15
0.5541	3.58	1.36853	3.13
0.6187	3.56	1.4753	3.07
0.63700	3.56	2.7539	2.55
0.6616	3.55		

The Rhm values in Table I are smaller than the previous literature values.$^{4)}$ There are several reasons for this. Some authors used the old values of μ_e,$^{5)}$ which are larger than the values tabulated by Hubbell. Some other authors used the values of absorption coefficient, μ_a, instead of μ_e.$^{6)}$ The absorption coefficient is approximate and only the escape of Compton-scattered photons is taken into account. On the other hand, the energy absorption coefficient is estimated by taking into account the escape of all types of secondary photons, such as Compton-scattered, fluorescence, annihilation, and bremsstrahlung photons. The values of μ_e are less than or equal to those of μ_a.

Furthermore, various authors calculated the Rhm values under the approximation that the values of μ_e is constant in the energy region between 0.07 and 3 MeV. The constant value is taken to be 3.5×10^{-5} cm^{-1}. It is clear from Table III that this approximation overestimates the Rhm values.

2. Total Attenuation Coefficient

The total attenuation coefficients μ were estimated for six materials of interest in shielding; water, aluminum, iron, lead, ordinary concrete, and air. The table of μ for various materials from 10 keV to 100 MeV was published by White-Grodstein,[7] and revised in the 10–100 keV region by McGinnies.[8] Recently Hubbell[3] revised and extended previous NBS tabulations, based on a new analysis of all available information.

Interpolation was made for six materials with respect to the energies in Table

Table IV. Total Attenuation Coefficients (cm^{-1})

γ-ray energy (MeV)	H_2O	Al	Fe	Pb	Concrete	Air ($\times10^{-4}$)
0.12194	0.159	0.397	1.93	33.7	0.361	1.72
0.1426	0.151	0.370	1.54	23.6	0.336	1.64
0.14543	0.150	0.367	1.50	22.7	0.333	1.63
0.159	0.146	0.353	1.35	19.1	0.321	1.59
0.173	0.142	0.342	1.24	15.8	0.311	1.55
0.247	0.127	0.299	0.939	6.05	0.271	1.38
0.28431	0.120	0.284	0.865	4.68	0.257	1.30
0.31980	0.115	0.271	0.813	3.94	0.245	1.25
0.36447	0.110	0.258	0.759	3.06	0.233	1.19
0.41180	0.105	0.246	0.713	2.35	0.223	1.14
0.510976	0.0958	0.225	0.645	1.70	0.203	1.04
0.5541	0.0927	0.217	0.622	1.52	0.196	1.00
0.6187	0.0882	0.207	0.590	1.30	0.187	0.957
0.63700	0.0869	0.204	0.582	1.25	0.185	0.945
0.6616	0.0852	0.201	0.572	1.19	0.182	0.929
0.6984	0.0827	0.196	0.558	1.12	0.177	0.907
0.740	0.0801	0.191	0.543	1.05	0.173	0.883
0.7769	0.0780	0.187	0.530	0.999	0.169	0.864
0.8276	0.0756	0.182	0.514	0.939	0.164	0.839
0.8353	0.0753	0.181	0.512	0.930	0.163	0.835
1.0440	0.0696	0.162	0.458	0.752	0.147	0.750
1.115	0.0678	0.157	0.444	0.710	0.142	0.726
1.17323	0.0662	0.153	0.432	0.680	0.138	0.708
1.2746	0.0634	0.147	0.415	0.639	0.132	0.679
1.3171	0.0622	0.144	0.408	0.625	0.130	0.667
1.33245	0.0618	0.143	0.406	0.620	0.130	0.664
1.36853	0.0608	0.141	0.400	0.609	0.128	0.654
1.4753	0.0581	0.136	0.386	0.584	0.123	0.630
2.7539	0.0417	0.0995	0.293	0.475	0.0894	0.451

II from the table compiled by Hubbell.³⁾ The data in the energy region between 0.01 and 10 MeV were used in the calculations. The density of each material was taken from the Hubbell's table. The composition of the ordinary concrete is the same as that given in the table of McGinnies.⁸⁾ The results of the interpolation are given in Table IV. Since these values are based on the table of Hubbell, they are consistent with the energy absorption coefficients for air in Table III.

3. Buildup Factor

The dose buildup factor is defined as the ratio of the total dose rate at a given point in a given medium to the dose rate at that point due to the unscattered γ-ray flux. Calculations so far been made for various shapes of sources and for several types of attenuating medium configurations. However, the most useful buildup factors are for point isotropic sources in infinite homogeneous media.

Most of the tabulations of the buildup factors in current use are derived from results of moments-method calculations reported by Goldstein and Wilkins.⁹⁾ Various efforts have been made to express by empirical formulas buildup data of Goldstein and Wilkins for isotropic point source. Recently, Trubey¹⁰⁾ reviewed several simple functions to estimate buildup factors and showed that the best fitting form is

Table V. Values of Parameter *a* in Berger's Formula for Dose Buildup Factors

γ-ray energy (MeV)	H_2O	Al	Fe	Pb	Concrete
0.284	1.69	(1.38)	(0.948)	(0.191)	(1.64)
0.320	1.63	(1.35)	(0.941)	(0.201)	(1.61)
0.364	1.54	(1.33)	(0.933)	(0.213)	(1.57)
0.412	1.46	(1.30)	(0.925)	(0.227)	(1.53)
0.511	1.31	1.24	0.906	0.256	1.44
0.554	1.26	1.21	0.898	0.268	1.40
0.619	1.20	1.17	0.886	0.287	1.34
0.637	1.18	1.16	0.883	0.292	1.33
0.662	1.17	1.14	0.878	0.299	1.30
0.698	1.15	1.12	0.872	0.309	1.27
0.740	1.13	1.10	0.864	0.320	1.24
0.777	1.11	1.08	0.858	0.330	1.21
0.828	1.10	1.05	0.849	0.342	1.16
0.835	1.09	1.04	0.848	0.344	1.16
1.044	1.05	0.939	0.815	0.385	1.02
1.115	1.04	0.910	0.806	0.394	0.984
1.173	1.03	0.889	0.798	0.400	0.958
1.275	1.00	0.855	0.786	0.407	0.922
1.317	0.991	0.843	0.781	0.409	0.909
1.333	0.987	0.839	0.779	0.410	0.905
1.369	0.978	0.829	0.775	0.411	0.895
1.475	0.948	0.804	0.764	0.411	0.872
2.754	0.709	0.654	0.572	0.342	0.661

the 4–term polynomial formula obtained by Capo.[11] For most purpose, however, he recommended a function proposed by Berger[12] because of its simplicity and reasonable accuracy.

A two-parameter formula first proposed by Berger[12] and reintroduced by Chilton[13] is written by

$$B(E, \mu x) = 1 + a(E)\mu x \exp\left[b(E)\mu x\right], \tag{5}$$

where E is the γ-ray energy, $a(E)$ and $b(E)$ are the parameters as a function of E, μ is the total attenuation coefficient, and x is the thickness of the attenuating medium.

Trubey determined parameters a and b by a least-squares method, based on data of Goldstein and Wilkins and on data for concrete.[14] Two sets of parameters are presented; one is based on data for $\mu x \leq 7$ and the other $\mu x \leq 20$.

Similar derivations of the parameters for the Berger formula have been made by Rudloff[15] based on data for $\mu x \leq 15$ and by Chilton based on data for $\mu x \leq 10$.[16] Because of the difference in the range of distances involved, the parameters determined by these authors are not the same.

In the present work, we used the parameters determined by Trubey, based on data over the range out to 7 mean-free-path lengths. The parameters corresponding

Table VI. Values of Parameter b in Berger's Formula for Dose Buildup Factors

γ-ray energy (MeV)	H_2O	Al	Fe	Pb	Concrete
0.284	0.255	(0.143)	(0.0770)	(−0.105)	(0.185)
0.320	0.247	(0.140)	(0.0766)	(−0.102)	(0.180)
0.364	0.237	(0.136)	(0.0762)	(−0.0978)	(0.175)
0.412	0.227	(0.132)	(0.0759)	(−0.0933)	(0.169)
0.511	0.205	0.124	0.0751	−0.0837	0.157
0.554	0.196	0.121	0.0748	−0.0796	0.152
0.619	0.181	0.115	0.0743	−0.0734	0.144
0.637	0.177	0.114	0.0742	−0.0717	0.142
0.662	0.172	0.112	0.0739	−0.0694	0.139
0.698	0.164	0.109	0.0736	−0.0659	0.135
0.740	0.155	0.105	0.0731	−0.0621	0.130
0.777	0.147	0.102	0.0727	−0.0588	0.126
0.828	0.137	0.0984	0.0719	−0.0543	0.120
0.835	0.135	0.0979	0.0718	−0.0536	0.119
1.044	0.0985	0.0837	0.0672	−0.0371	0.0971
1.115	0.0887	0.0796	0.0649	−0.0323	0.0904
1.173	0.0818	0.0765	0.0628	−0.0286	0.0852
1.275	0.0716	0.0717	0.0588	−0.0228	0.0769
1.317	0.0679	0.0699	0.0570	−0.0206	0.0737
1.333	0.0667	0.0692	0.0564	−0.0198	0.0726
1.369	0.0640	0.0678	0.0548	−0.0180	0.0700
1.475	0.0574	0.0638	0.0502	−0.0133	0.0629
2.754	0.0188	0.0280	0.0354	0.0195	0.0307

to the γ-ray energies in Table II were interpolated as a function of energy for five usual shielding materials. The results are shown in Tables V and VI. The values in parentheses are estimated by extrapolation. Since long-range extrapolation often is a deceptive process, calculations were limited to the energy region greater than 0.25 MeV.

ACKNOWLEDGMENTS

The author wishes to express his thanks to Professor S. Shimizu and Professor T. Hyodo for their helpful discussions. It is also a pleasure to thank the members of the Radiation Protection Committee of Kyoto University for valuable comments.

REFERENCES

(1) C. M. Lederer, J.M. Hollander, and I. Perlman, "Table of Isotopes," 6th ed., Wiley, New York, 1967.
(2) T. N. E. Greville, in "Mathematical Methods for Digital Computer," Vol. II, ed. by A. Ralston and H.S. Wilf, John Wiley & Sons, New York, 1967, p. 156.
(3) J. H. Hubbell, HSRDS-NBS 29, Nat. Bur. Stand., Washington D.C., 1969.
(4) For example, "The Radiochemical Manual," 2nd ed., ed. by B.J. Wilson, The Radiochemical Center, Amersham, 1966.
(5) H. Goldstein, "Fundamental Aspects of Reactor Shielding," Pergamon Press, London, 1959, p. 17.
(6) R. D. Evans, "The Atomic Nucleus, "McGraw-Hill, New York, 1955, p. 713.
(7) G. White Grodstein, NBS Circular 583 (1957).
(8) R. T. McGinnies, Suppl. to NBS Circ. 583 (1959).
(9) H. Goldstein and J.E. Wilkins, Jr., NYO-3075 (1954).
(10) D. K. Trubey, ORNL-RSIC-10 (1966).
(11) M. A. Capo, APEX-510 (1958).
(12) M. J. Berger, USNRDL Reviews and Lectures No. 29, p. 47 (1956).
(13) A. B. Chilton, D. Holoviak, and L. K. Donovan, USNCEL-TN-389 (AD-24915) (1960).
(14) R. L. Walker and M. Grotenhuis, ANL-6443 (1961).
(15) A. Rudloff, *Atomkernenergie*, **9**, 451 (1964).
(16) A. B. Chilton, *Nucleonics*, **23**, No. 8, 119 (1965).