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Gamma-Ray Buildup Factors for Heavy Concretes

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Gamma-Ray Buildup Factors for Heavy Concretes

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Buildup factors up to 40 mean free path in ranging from 0.015 MeV to 15 MeV photon energy were evaluated by using the Monte Carlo simulation code, EGS4 for two typical heavy concretes. One is iron-contained and the other is barium-contained heavy concretes. The parameters of Geometrical Progression approximation for buildup factors were also presented for simplified calculations such as using the point kernel method.

Keywords: Buildup Factor, Heavy Concrete, EGS4, Geometrical Progression Approximation.

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重コンクリートのγ線ビルドアップ係数

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2 種類の重コンクリートについて、0.015MeV から 15MeV の範囲内でガンマ線再生係数（ビルドアップ係数）をモンテカルロ計算コード EGS4 で 40 平均自由行程（mfp）まで求めた。重コンクリートの種類は１つは鉄充填、もう１つはバリウム充填の重コンクリートである。点減衰核法等の簡易計算でビルドアップ係数を用いて線量率を算出するために、GP 法のパラメーターも合わせて示した。

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1. Introduction

The point kernel methods are quite useful in shielding design calculations with deep penetration, and widely used as a practical tool to make a quick estimation of gamma-ray dose in a variety of shielding configurations. In the calculations, buildup factors are quite important data and many investigations[1-4] were performed for various shield materials. However, the data of mixed materials such as heavy concrete are very few with the consideration of Bremsstrahlung and fluorescence until now. Recently, the shielding design is strongly required with economical restriction and space saving so that the partial usage of heavy concrete increases more and more, especially for accelerator shielding.

The buildup factor is defined by the ratio of the total radiation quantity at any point to the radiation quantity of radiation reaching the point without any collision. Many empirical formula[5-7] of buildup factors were presented for the interpolation at arbitrary thickness of shielding materials. In the formula, the Geometrical Progression approximation[8] is well known to reproduce the buildup factors in the wide energy range of various materials and thicknesses with good accuracy.

This report presents the buildup factors for heavy concretes up to 40 mean free path (mfp) in ranging from 15 keV to 15 MeV photon energy by using the Monte Carlo code, EGS4[9] with a particle splitting method[10]. In chapter 2, the buildup factors for ordinary concrete obtained by using EGS4 code are firstly compared with existing data to examine the difference of production code. The buildup factors for heavy concretes are also compared with those for ordinary concrete and main element of heavy concretes with same density. For the practical use of the data to desired photon energy and shielding thickness in shielding calculations, the fitting parameters of the Geometrical Progression approximation are presented in chapter 3.

2. Calculation of Buildup Factors

The buildup factor is defined as follows,

$$B(E_0, X) = R / R_0 \cdot \exp(-X) \tag{1}$$

where $B(E_0,X)$ is the buildup factor at the response of the detector with a radiation quantity, R, to γ-rays transmitted through materials with thickness of X mfp for the unscattered γ-rays with the incident energy, E_0. R_0 is the response that would occur without the attenuation medium. In this report, we consider the radiation quantities of exposure[11], effective dose with anterior-posterior (AP) geometry[12], and ambient dose equivalent[12]. The buildup factors in this report were basically presented with coherent scattering and incoherent scattering to obtain the practical doses such as exposure, ambient dose and effective dose, directly. On the other hand, the ANSI/ANS-6.4.3[13] data are based on the calculations with neglecting coherent scattering and assuming free electron Compton scattering, and the correction factors are provided to obtain the exposure and the doses.

In the EGS4 calculations, we employed PHOTX data[14] and the low energy photon scattering expansion code[15] with considering the Bremsstrahlung and fluorescence. The cylindrical geometries with isotropic photon sources and 10^6 histories were employed in the calculations. The compositions which we employed in the calculations of ordinary Portland cement concrete[16], iron-contained heavy concrete (heavy concrete (Fe))[17], and barium-contained heavy concrete (heavy concrete (Ba))[18] are shown in Table 1, including the data of the ANSI/ANS-6.4.3. In the calculations, isotropic irradiation is employed for the calculation. The data up to 40 mfp of the concretes in the infinite geometry were estimated based on the 42 mfp thickness calculations in a spherical geometry. The splitting point was set at each five mfp, and 10^6 histories were employed to ensure the consistency of the previous calculations[10] for other materials. The mean free path is indicated in Table 2 as a function of the photon energy.

2.1 Ordinary concrete

The buildup factors for ordinary concretes as functions of the mean free path and photon energy are shown in Figs. 1 to 4, including the data of the ANSI/ANS-6.4.3. In these figures, the buildup factors of the present works (triangle and circle symbols) are the calculation results by using the EGS4 code with the material compositions of the ordinary concretes as indicated in Table 1. The broken line shows the ANSI/ANS-6.4.3 data with neglecting coherent scattering and assuming free electron Compton scattering. As shown in these figures, the difference between the calculation results of the buildup factors of the ANSI/ANS and Portland cement ordinary concretes is due to the difference of the compositions. On the other hand, the slight differences between the calculation results of the ANSI/ANS ordinary concrete and the data are assumed to be due to two reasons. One is the different calculation methods between the two. The ANSI/ANS data are based on the calculation result data by using the moments method[19] with parallel beam source, and the present work is by using the Monte Carlo code, EGS4 with isotropic emission photons. The other is the development of the low energy photon treatments in EGS4 such as K-X ray, L-X ray and Bremsstrahlung. Besides, ANSI/ANS-6.4.3 data in Figs.1 to 4 are shown without corrections for the neglect of coherent scattering.

2.2 Heavy concrete

The calculation results of the buildup factors for heavy concretes are summarized in Tables A1 to A6 in Appendix. Figures 5 to 8 show the buildup factors including data of the Portland cement ordinary concrete for the exposure of radiation quantity as a function of mean free path for the photon energy, and Figures 9 to 12 show those as a function of photon energy, respectively. These calculations are performed with considering coherent and incoherent scattering. As shown in these figures, the specific features can be found at the energy of around 40 keV for the heavy concrete (Ba), and the buildup factors grow up more than 10^{10} at 40 mfp. The K-edge of photo-electric cross section of barium is 37.44 keV so that the specific features around 40 keV are recognized. On the other hand, the K edges of photo-electric cross section of iron and silicon are less than 10 keV so that the pointy-shaped features disappear in heavy concrete (Fe) and ordinary concrete.

The ratios of the ambient dose equivalent to the exposure are shown in Figs 13 to 16. In these calculation results except for 15 MeV photons, the ratios of the heavy concrete (Fe), the heavy concrete (Ba) and ordinary concrete are in ranging from about 1.0 to 1.1, 0.7 to 1.05, and 0.9 to 1.2, respectively. At 15 MeV, the ratios for each concrete are up to 1.4. The ratios of the effective dose with AP geometry to the exposure are shown in Figs 17 to 20. In the calculations, the ratios of the heavy concrete (Fe), the heavy concrete (Ba) and ordinary concrete are in ranging from about 1.0 to 1.1, 0.55 to 1.05, and 0.9 to 1.2, respectively. In both results of the ambient dose equivalent and the effective dose, the tendencies of the ratios to the exposure are not changed so much with the mean free path, except for the heavy concrete (Ba) with around 40 keV photon energy.

In order to investigate the effect of the composition, the buildup factors of each concrete were compared with that of the main component. The calculation results are shown in Figs. 21 and 22 as the ratios of the exposure buildup factors, Figs. 23 and 24 are for the ambient dose equivalent, and Figs.25 and 26 are for the equivalent dose as the functions of photon energy and the mean free path. As shown in these figures, the tendencies of the distributions are the same between the doses. For the buildup factor ratios of iron and heavy concrete (Fe), the variations are small, in ranging from 0.5 to 1.0 below 2 MeV, and the variations are growing up as increasing the thickness and photon energy over about 2 MeV. For the ratios of barium and heavy concrete (Ba), the tendencies are the same as the cases of iron and heavy concrete (Fe) over the photon energy of 0.1 MeV, and the paces of the growing over about 2 MeV are much larger than that of iron and heavy concrete (Ba). At around 40 keV, the ratios grow up to 10^5 as increasing the thickness.

Table 1 Compositions of the Ordinary and Heavy Concretes

	Ordinary Concrete		Heavy Concrete	
	ANSI/ANS-6.4.3[13)]	Portland[16)]	HCON(Fe)[17)]	HCON(Ba)[18]
Density (g/cm^3)	2.3	2.3	3.7	3.35
Composition(w/o)				
Hydrogen (H)	0.0056	0.01	0.004	0.0036
Carbon (C)	-	0.001	-	-
Oxygen (O)	0.4983	0.53	0.345	0.3116
Sodium (Na)	0.0171	0.016	-	-
Magnesium (Mg)	0.0024	-	0.019	0.0012
Aluminum (Al)	0.0456	0.036	0.010	0.0042
Silicon (Si)	0.3158	0.3367	0.069	0.0105
Fluorine (F)	-	-	-	0.1079
Sulfur (S)	0.0012	-	-	-
Potassium (K)	0.0192	-	-	-
Calcium (Ca)	0.0826	0.0564	0.048	0.0502
Iron (Fe)	0.0122	0.0139	0.505	0.0475
Barium (Ba)	-	-	-	0.4633

Table 2 The Shield Thickness Corresponding to One Mean Free Path.

(unit:cm)

Photon Energy (MeV)	Ordinary Concrete		Heavy Concrete	
	ANSI/ANS-6.4.3	Portland	HCON (Fe)	HCON (Ba)
0.015	0.054	0.062	0.009	0.009
0.020	0.125	0.143	0.019	0.020
0.030	0.389	0.371	0.061	0.063
0.040	0.787	0.868	0.138	0.027
0.050	1.23	1.325	0.252	0.048
0.060	1.635	1.725	0.398	0.078
0.080	2.232	2.292	0.745	0.167
0.10	2.609	2.642	1.087	0.294
0.15	3.15	3.152	1.710	0.749
0.20	3.506	3.497	2.081	1.281
0.30	4.069	4.051	2.546	2.200
0.40	4.55	4.528	2.887	2.852
0.50	4.985	4.960	3.180	3.341
0.60	5.389	5.361	3.447	3.740
0.80	6.134	6.102	3.932	4.402
1.0	6.822	6.787	4.377	4.969
1.5	8.369	8.328	5.364	6.142
2.0	9.698	9.655	6.179	7.019
3.0	11.90	11.86	7.437	8.217
4.0	13.62	13.61	8.339	8.947
5.0	15.01	15.02	8.991	9.388
6.0	16.12	16.16	9.459	9.647
8.0	17.73	17.84	10.04	9.840
10.0	18.80	18.97	10.32	9.811
15.0	20.17	20.47	10.49	9.442

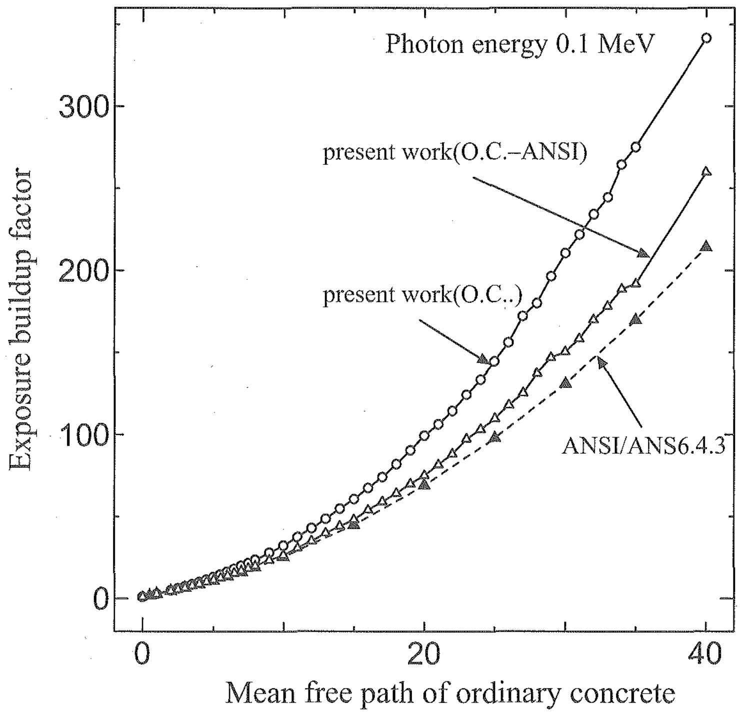

Fig.1 Buildup Factors of Ordinary Concretes at the Photon Energy of 0.1 MeV. Solid lines with open circles and triangles are the calculation results by using the data of the material compositions of ANSI/ANS-6.4.3 and Portland cement, respectively. The dotted line with full triangles indicates the ANSI/ANS-6.4.3 data.

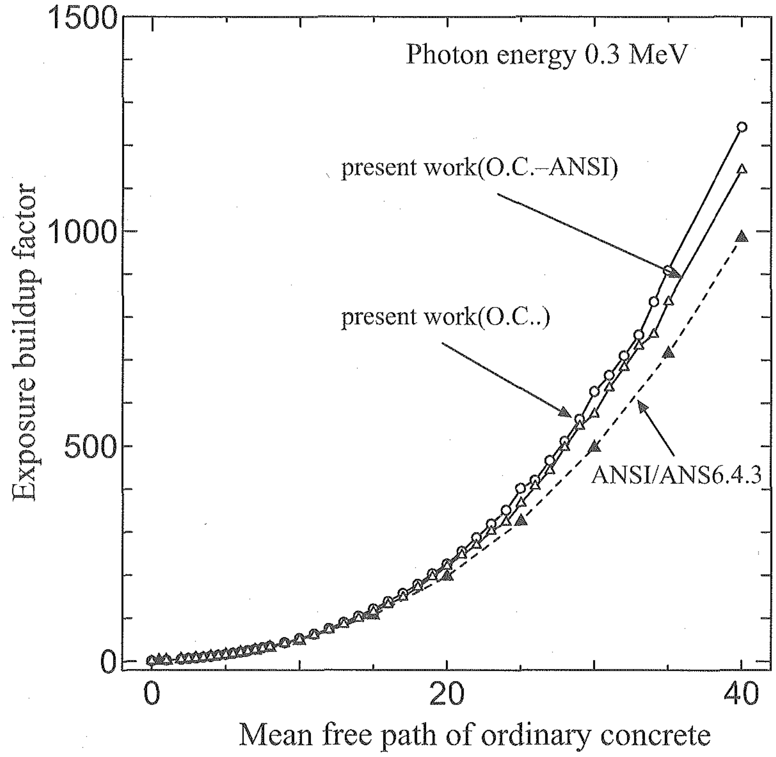

Fig.2 Buildup Factors of Ordinary Concretes at the Photon Energy of 0.3 MeV. The lines are shown same as Fig. 1.

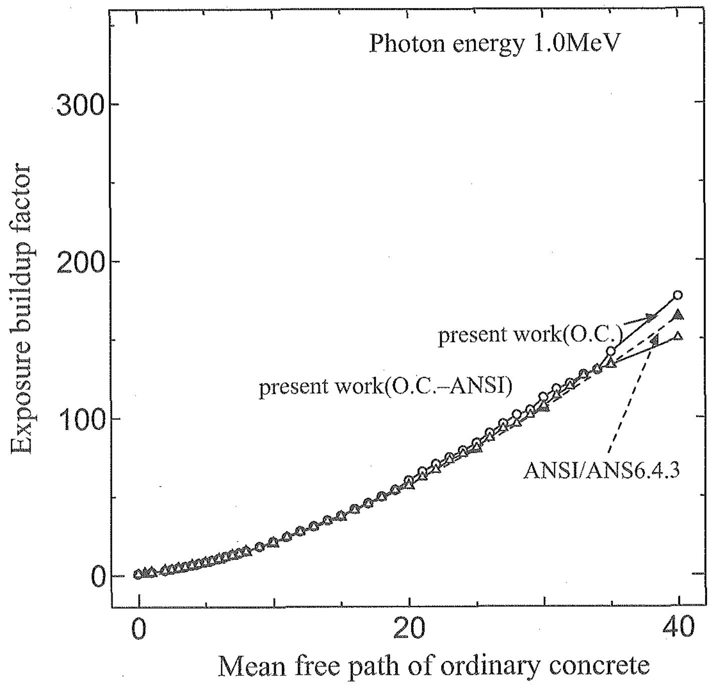

Fig.3 Buildup Factors of Ordinary Concretes at the Photon Energy of 1.0 MeV. The lines are shown same as Fig. 1.

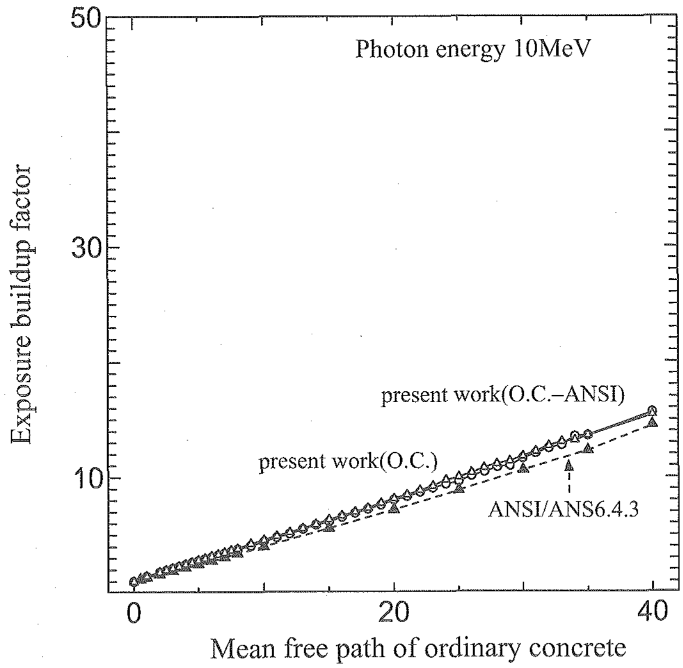

Fig.4 Buildup Factors of Ordinary Concretes at the Photon Energy of 10 MeV. The lines are shown same as Fig. 1.

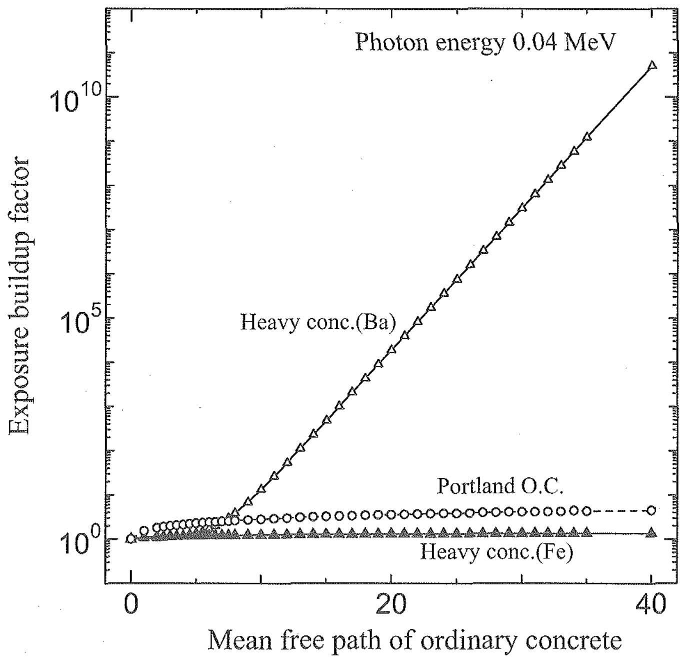

Fig.5 Exposure Buildup Factors at 0.04 MeV Photon Energy for Heavy Concretes and the Ordinary Concrete (Portland Cement) as a Function of Penetration Length. Solid lines with open and full triangles indicate the buildup factors for Barium and iron contained heavy concretes, respectively. dotted line with open circles shows the factors for the ordinary concrete (Portland cement).

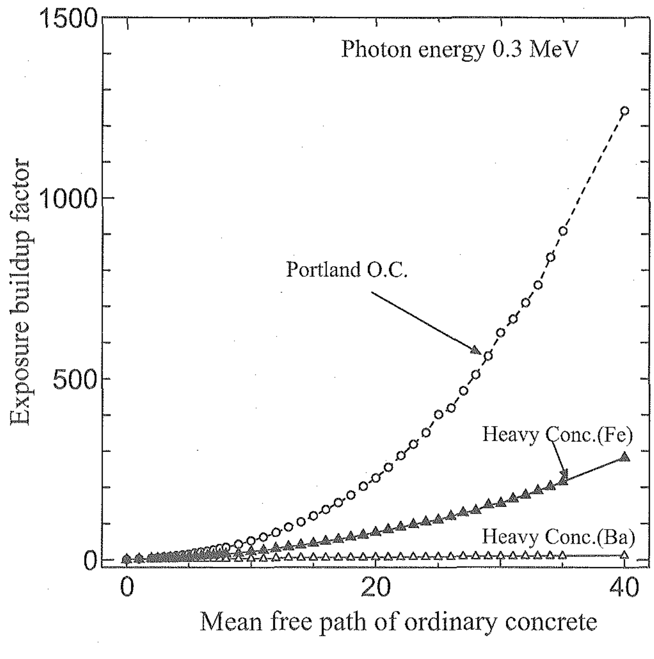

Fig.6 Exposure Buildup Factors at 0.04 MeV Photon Energy for Heavy Concretes and the Ordinary Concrete (Portland Cement) as a Function of Penetration Length. The lines are shown same as Fig. 5.

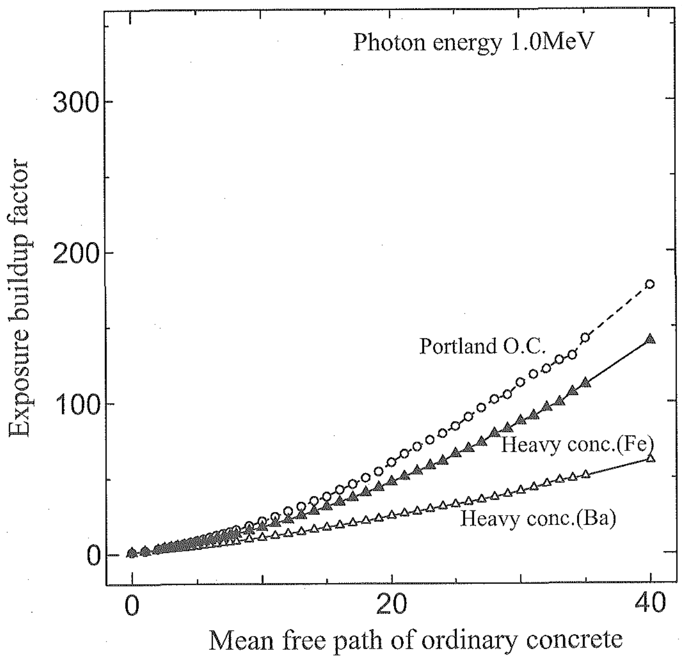

Fig.7 Exposure Buildup Factors at 1 MeV Photon Energy for Heavy Concretes and the Ordinary Concrete (Portland Cement) as a Function of Penetration Length. The lines are shown same as Fig. 5.

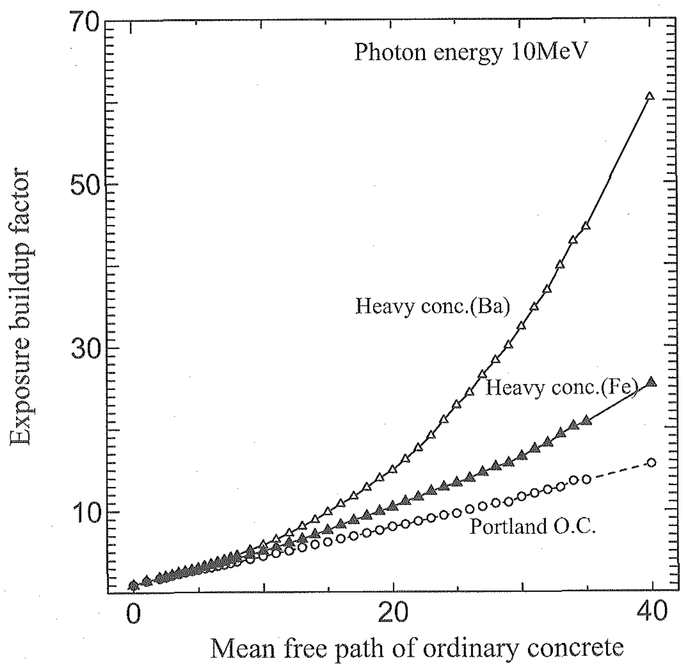

Fig.8 Exposure Buildup Factors at 10 MeV Photon Energy for Heavy Concretes and the Ordinary Concrete (Portland Cement) as a Function of Penetration Length. The lines are shown same as Fig. 5.

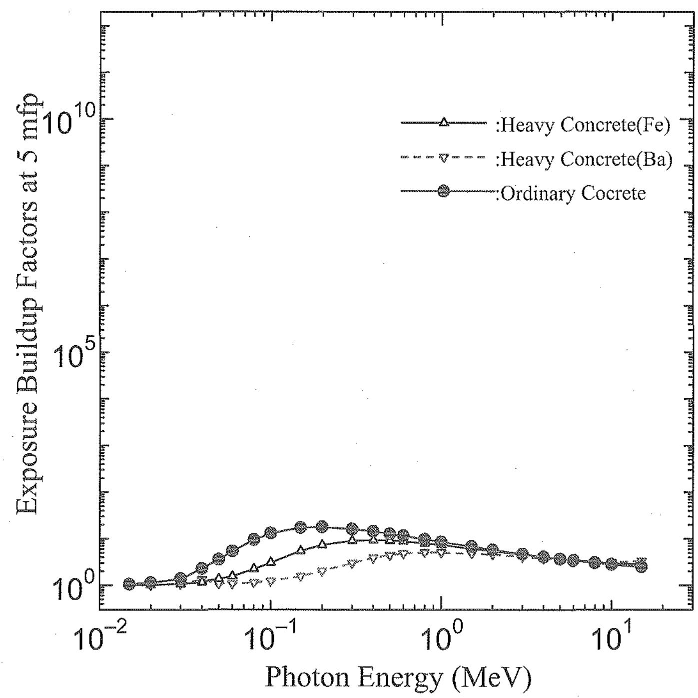

Fig. 9 Exposure Buildup Factors at 5 mfp for Heavy Concretes and Ordinary Concrete. Solid line with triangle, dotted line with upside-down triangle, and solid line with full circle show the buildup factors for iron contained heavy concrete, barium contained heavy concrete, and ordinary concrete, respectively.

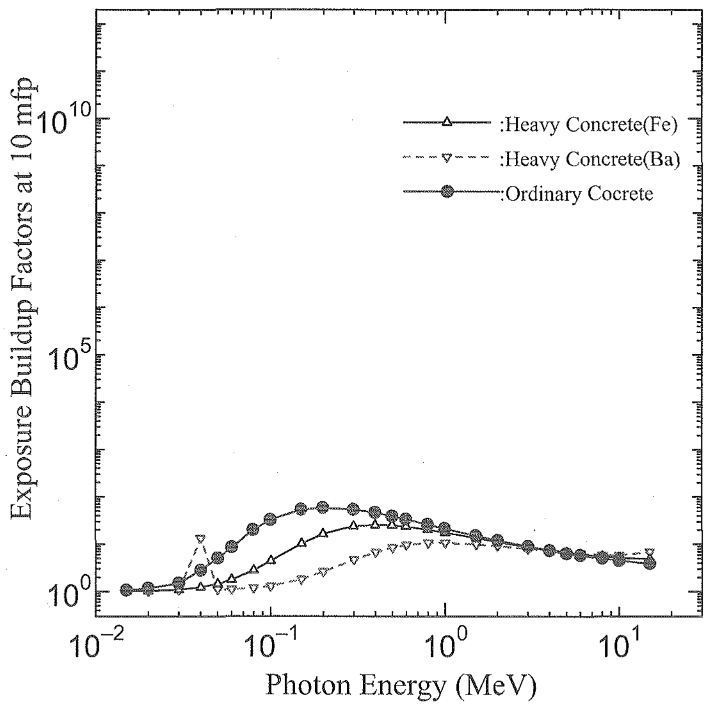

Fig. 10 Exposure Buildup Factors at 10 mfp for Heavy Concretes and Ordinary Concrete. The lines are shown same as Fig.9

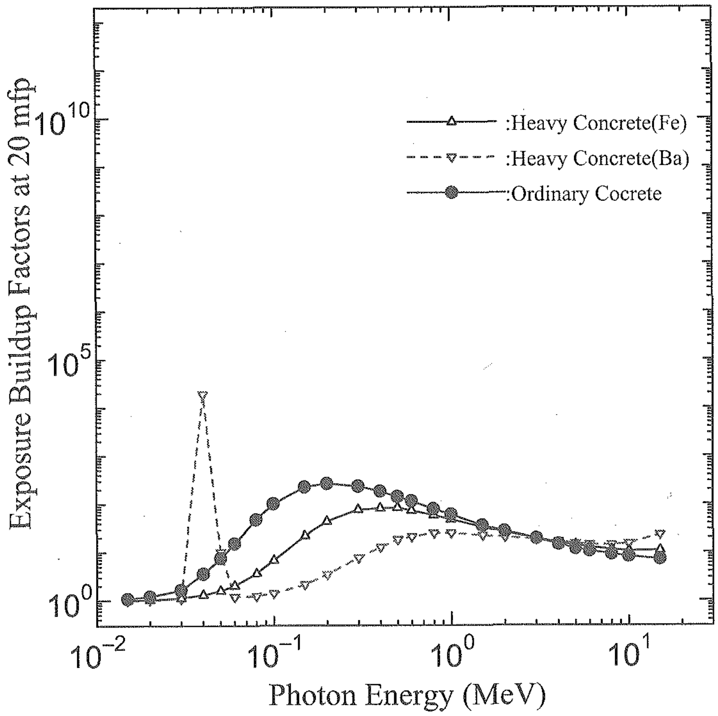

Fig. 11 Exposure Buildup Factors at 20 mfp for Heavy Concretes and Ordinary Concrete. The lines are shown same as Fig.9

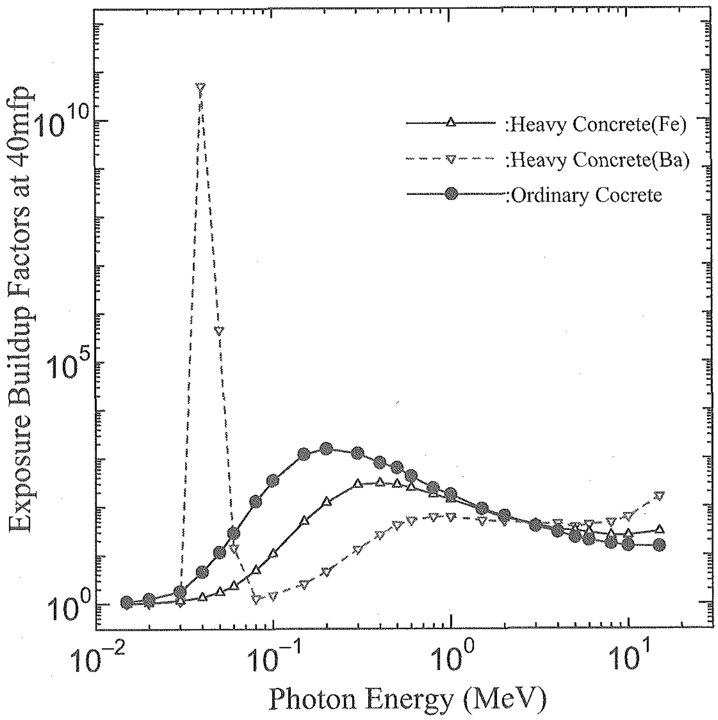

Fig. 12 Exposure Buildup Factors at 40 mfp for Heavy Concretes and Ordinary Concrete. The lines are shown same as Fig.9

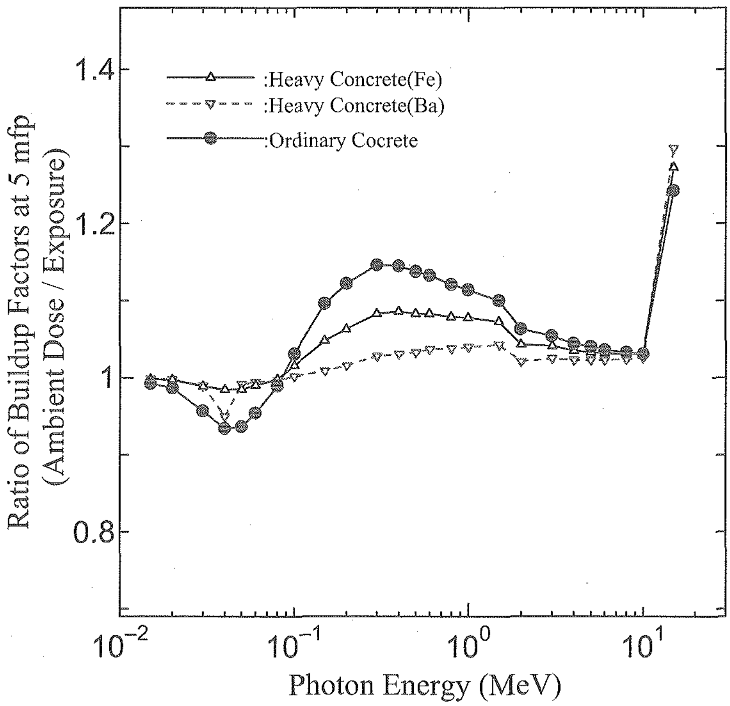

Fig.13 Dependencies of Radiation Quantity for Ambient Dose Equivalent and Exposure Buildup Factors of Concretes at 5 mfp. Solid line with triangle, dotted line with upside-down triangle, and solid line with full circle show the buildup factors for iron contained heavy concrete, barium contained heavy concrete, and ordinary concrete, respectively.

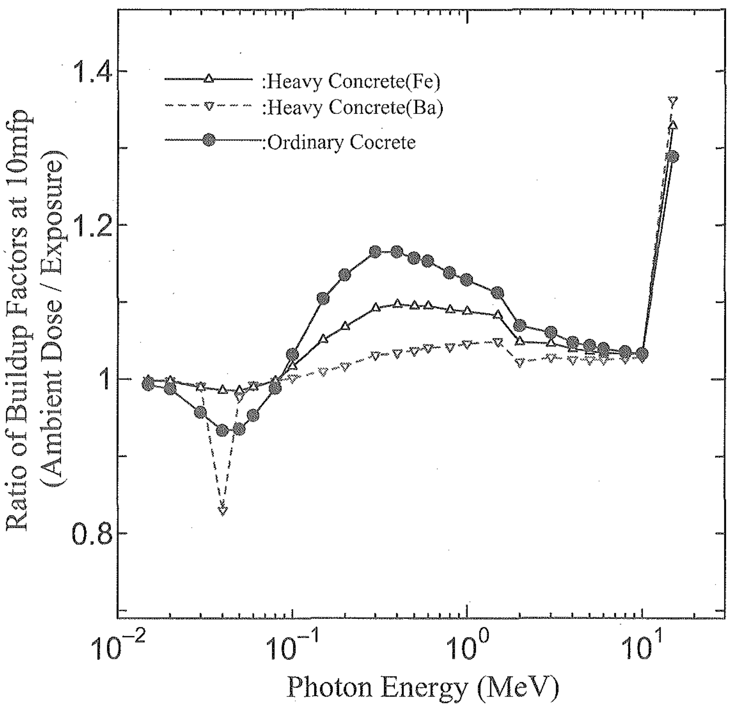

Fig.14 Dependencies of Radiation Quantity for Ambient Dose Equivalent and Exposure Buildup Factors of Concretes at 10 mfp. Lines show the same as in Fig.13

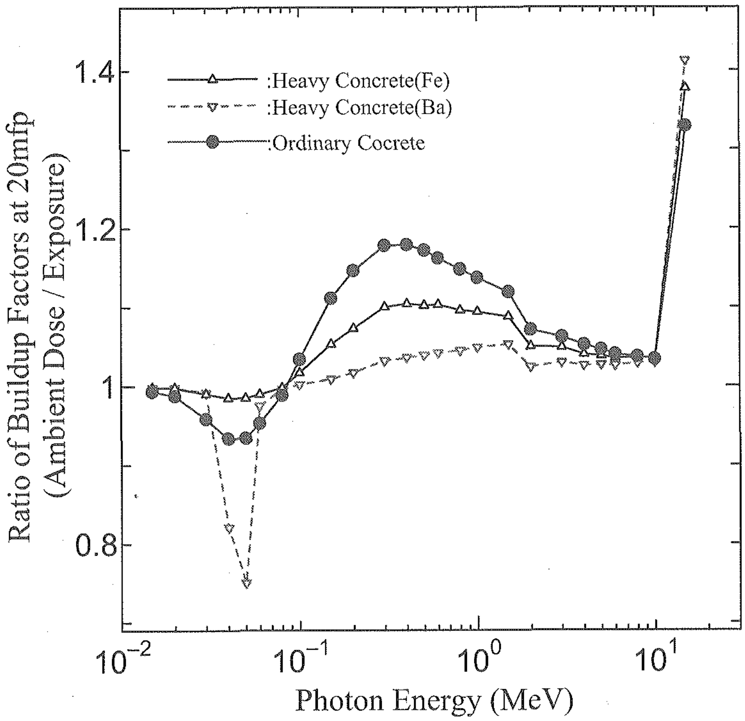

Fig.15 Dependencies of Radiation Quantity for Ambient Dose Equivalent and Exposure Buildup Factors of Concretes at 20 mfp. Lines show the same as in Fig.13

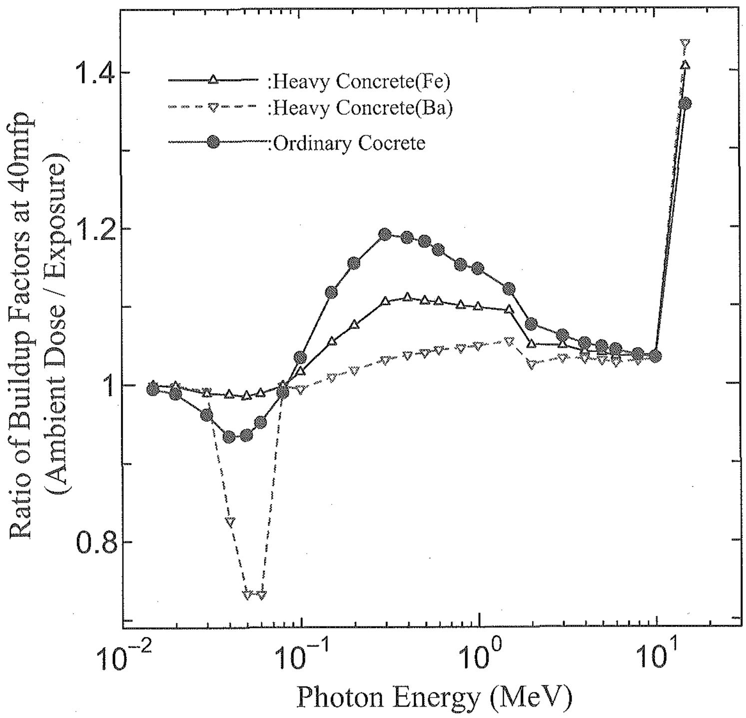

Fig.16 Dependencies of Radiation Quantity for Ambient Dose Equivalent and Exposure Buildup Factors of Concretes at 40 mfp. Lines show the same as in Fig.13

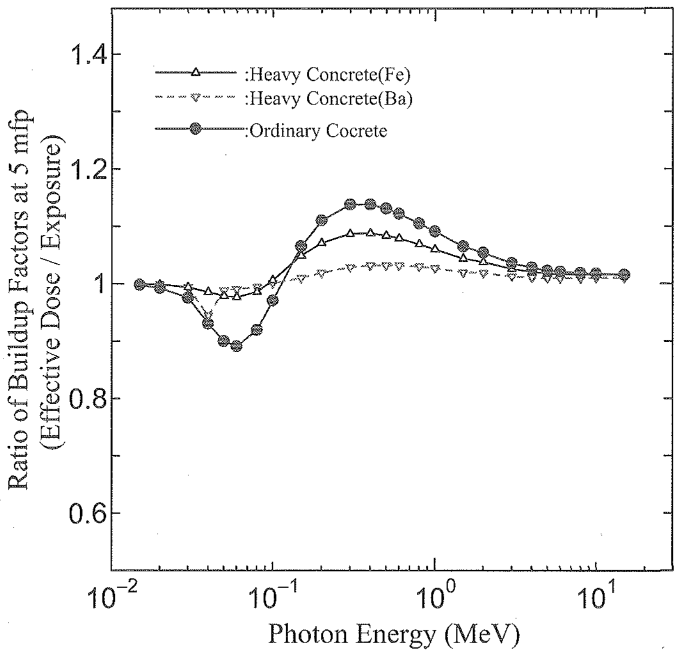

Fig.17 Dependencies of Radiation Quantity for Effective Dose with AP Geometry and Exposure Buildup Factors of Concretes at 5 mfp. Solid line with triangle, dotted line with upside-down triangle, and solid line with full circle show the buildup factors for iron contained heavy concrete, barium contained heavy concrete, and ordinary concrete, respectively.

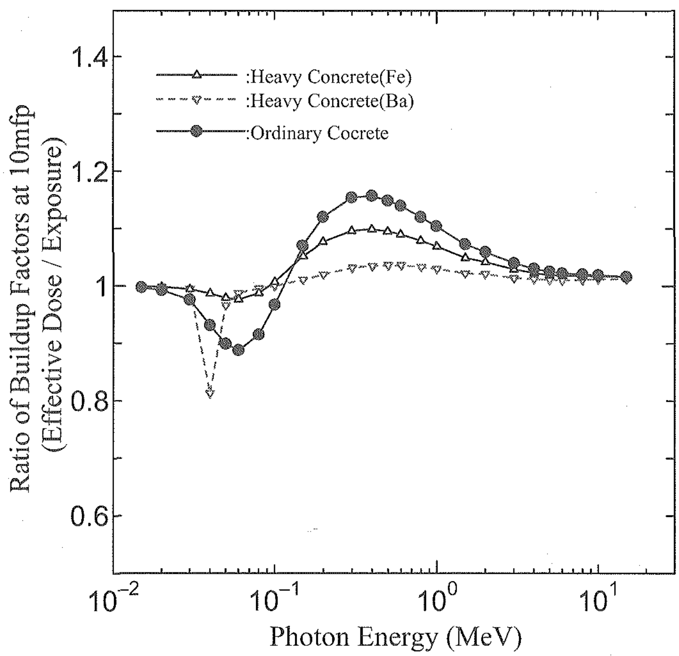

Fig.18 Dependencies of Radiation Quantity for Effective Dose with AP Geometry and Exposure Buildup Factors of Concretes at 10 mfp. Lines show the same as Fig.17

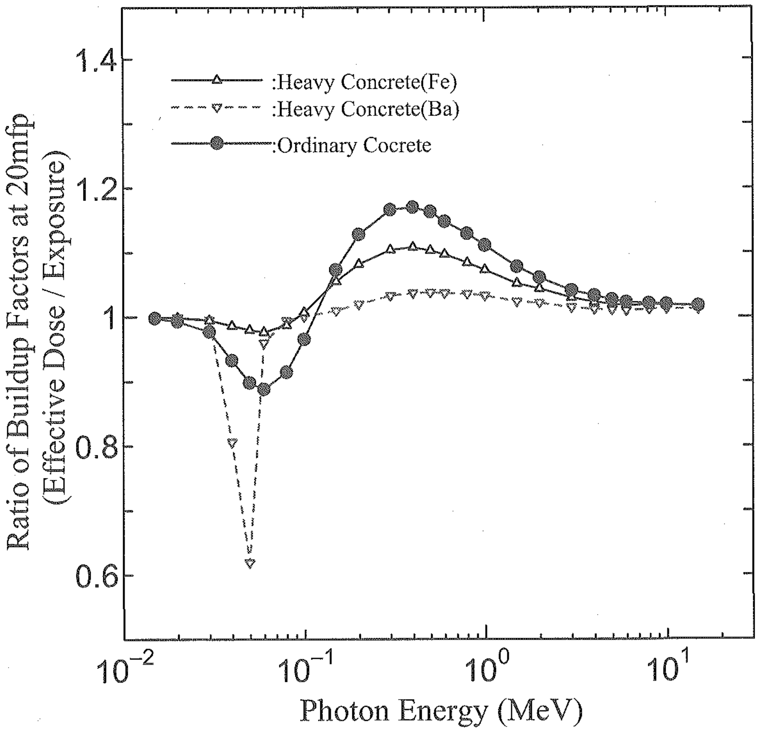

Fig.19 Dependencies of Radiation Quantity for Effective Dose with AP Geometry and Exposure Buildup Factors of Concretes at 20 mfp. Lines show the same as Fig.17

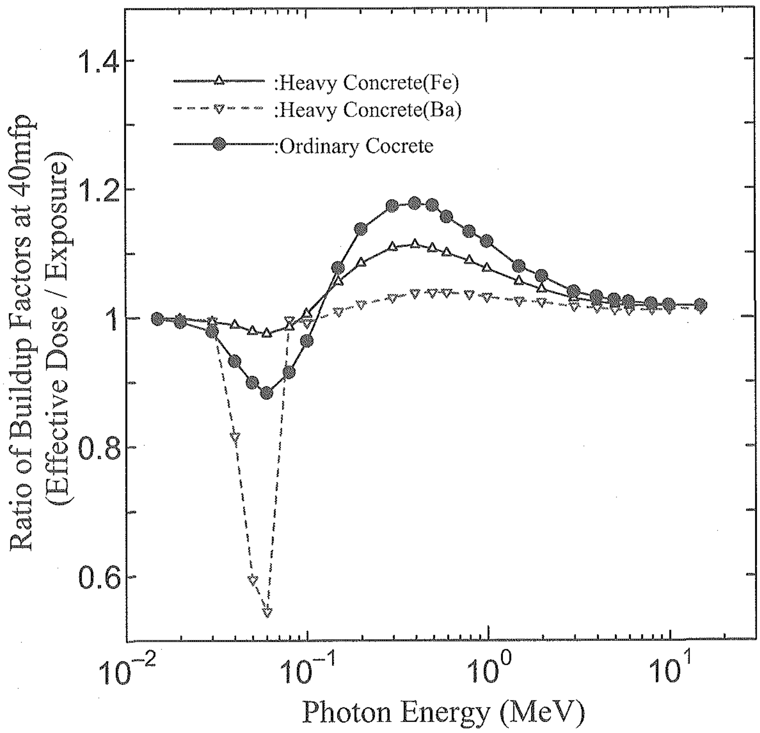

Fig.20 Dependencies of Radiation Quantity for Effective Dose with AP Geometry and Exposure Buildup Factors of Concretes at 40 mfp. Lines show the same as Fig.17

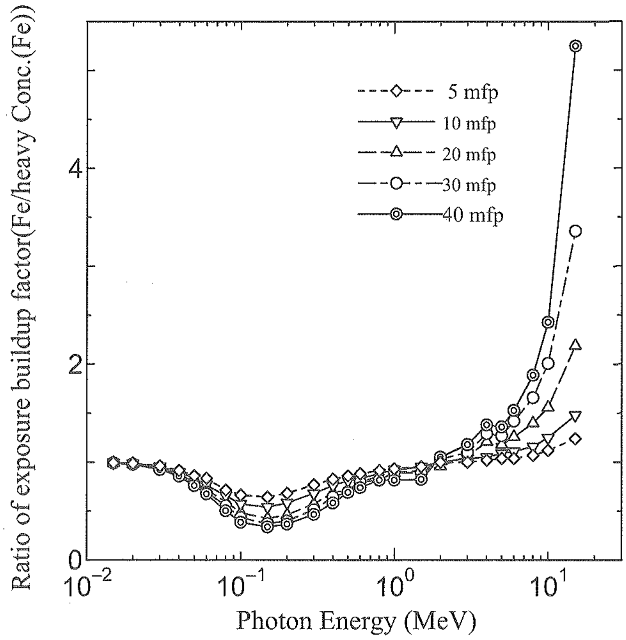

Fig.21 Energy Dependence of the Ratio of Exposure Buildup Factors between the Iron and Heavy Concrete (Fe) on the Assumption of the Fixed Density, 3.7 g/cm³. Dotted line with diamonds, solid line with upside-down triangles, dashed line with triangles, dot-dashed line with open circles, and solid line with double circles show the ratios at the thickness of 5, 10, 20,30 and 40 mfp.

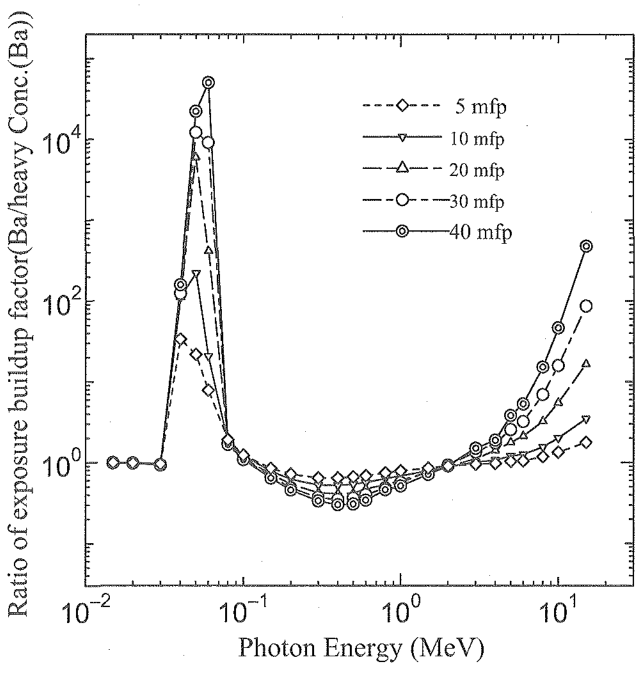

Fig.22 Energy Dependence of the Ratio of Exposure Buildup Factors between the Barium and Heavy Concrete (Ba) on the Assumption of the Fixed Density, 3.35 g/cm³. Lines show the same as Fig.21.

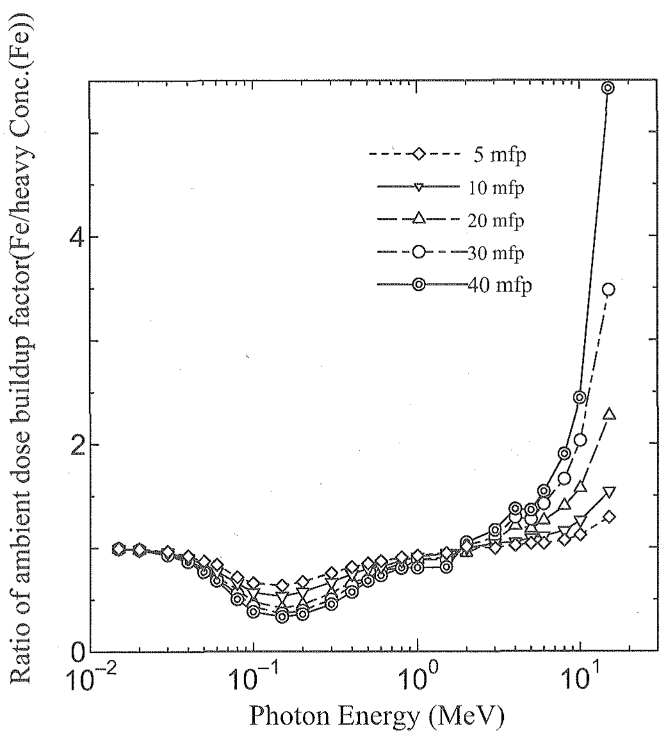

Fig.23 Energy Dependence of the Ratio of the Ambient Dose Equivalent Buildup Factors between the Iron and Heavy concrete (Fe) on the Assumption of the Fixed Density, 3.7 g/cm^3. Lines are the same as Fig.21.

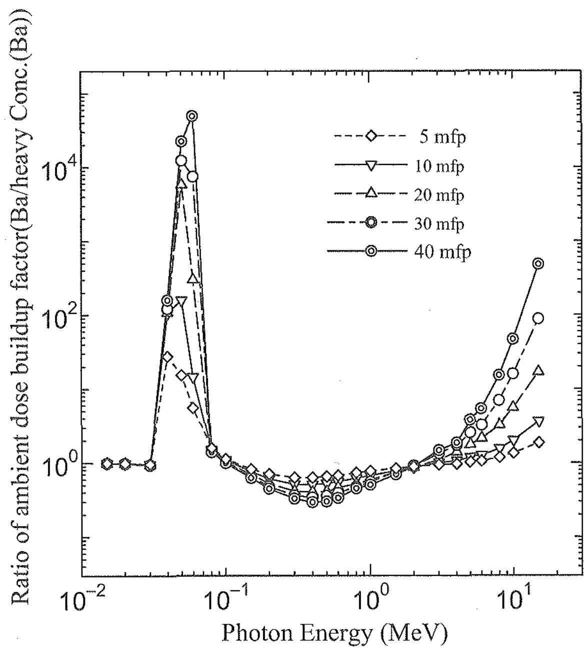

Fig.24 Energy Dependence of the Ratio of the Ambient Dose Equivalent Buildup Factors between the Barium and Heavy Concrete (Ba) on the Assumption of the Fixed Density, 3.35 g/cm^3. Lines are the same as Fig.21.

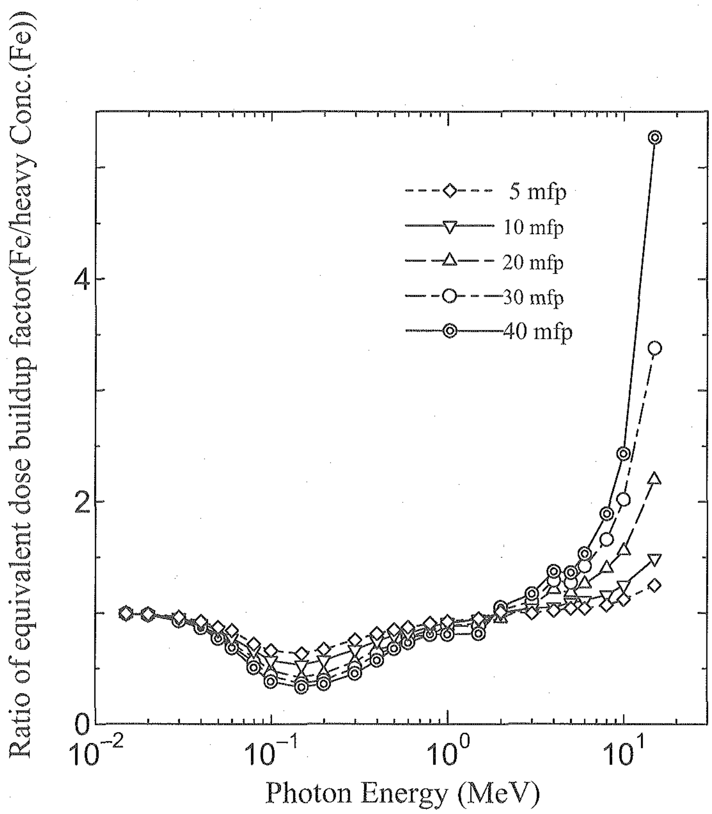

Fig.25 Energy Dependence of the Ratio of the Effective Dose Buildup Factors between the Iron and Heavy Concrete (Fe) on the Assumption of the Fixed Density, 3.7 g/cm^3. Lines are the same as Fig.21.

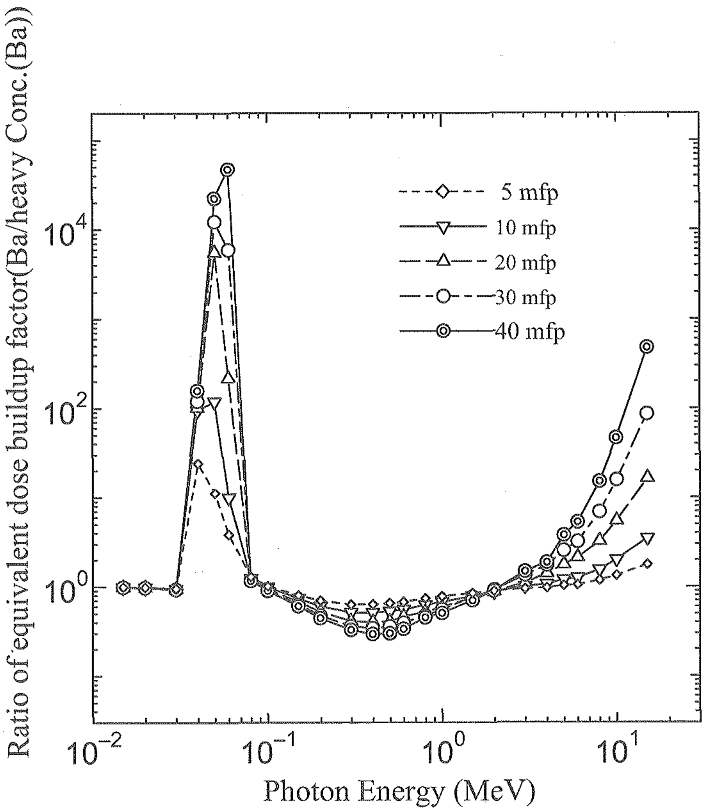

Fig.26 Energy Dependence of the Ratio of the Effective Dose Buildup Factors between the Barium and Heavy Concrete (Ba) on the Assumption of the Fixed Density, 3.35 g/cm^3. Lines are the same as Fig.21.

3. Geometrical Progression approximation

In the shielding calculations by using the point kernel method, the buildup factors are needed for desired photon energy and shielding thickness. For the interpolation of buildup factors by shielding thickness, there are many empirical formulae. The geometrical progression approximation is the most reliable one which has been adopted in ANSN-ANS-6.4.3. The formula of the geometrical progression approximation is defined as follows[20),

$$B(E,X) = 1 + \frac{B-1}{K-1}(K^X - 1) \qquad K \neq 1$$

$$= 1 + (B-1)X \qquad K = 1 \tag{2}$$

$$K = c \cdot X^a + d \cdot f(\frac{X}{X_k}) \tag{3}$$

$$f(t) = \frac{\tanh(t-2) - \tanh(-2)}{1 - \tanh(-2)} \tag{4}$$

where $B(E,X)$, E and X are the buildup factor, photon energy and the thickness of the shield material in mfp unit, respectively. The B, c, a, X_k *and* d are the fitting parameters of the G-P approximation. The fitting by G-P approximation was executed to the smoothed data of buildup factors, $\hat{B}_{(X)}$, obtained by using of the following equation for elimination of statistical errors in buildup factor data,

$$\hat{B}_{(X)} = \frac{1}{35}\left\{-3B_{(X-2\Delta X)} + 12B_{(X-\Delta X)} + 17B_{(X)} + 12B_{(X+\Delta X)} - 3B_{(X+2\Delta X)}\right\} \tag{5}$$

where $B_{(X)}$ is the buildup factor at X mfp calculated by using of the EGS4 code, and ΔX is the mesh interval, 0.5 mfp or 1 mfp in this case.

There are two fitting methods for G-P approximation, one is the Min Max method in which the maximum fitting error is minimized, and the other is the least square method in which the sum for squares of fitting errors is minimized. Different fitting parameter sets obtained by the Min Max method sometimes show the almost same fitting errors, and the fitting parameter is depended upon the ambiguous data such as data with large statistical errors. In the least square method, the influence by the ambiguous data is migrated and the fitting parameter is determined almost uniquely.

As the fitting parameters in G-P approximation are non-linear ones for buildup factors, the fitting procedures in GPFIT code are executed as follows.

Step1: By the introduction of trial *B*-parameter, B_0, which is corresponding to the buildup factor at 1 mfp, the *K*-parameters which satisfied Eq.(2) are obtained numerically.

Step 2: If the parameters *a* and X_k were postulated, the fitting procedure of *K*-parameters in the least square method would be a linear problem for *c* and *d* parameters. As the sensitivity of *K*-parameters to buildup factors gets larger with the increase of shielding thickness, the buildup factors, themselves are considered as the weighing factors in the fitting procedure.

Step3: The *a* parameter which shows the minimum of sum of error square is determined by the procedure that the sums of the fitting errors corresponding to *a*-parameters of a_0-Δa, a_0 and a_0+Δa are approximated by the parabolic line. Next, the same procedure for the X_k parameter is executed by using of the sum of error squares corresponding to X_{k0}-ΔX_k, X_{k0} and X_{k0}+ΔX_k. By the reduction of Δa for *a*-parameter and ΔX_k for X_k-parameter mutually, four parameters, *c*, *a*, X_k and *d* will be determined for the trial B_0. Its method is generally called "brutal method".

Step 4: The *B* parameter which shows the minimum of sum of error square is determined by the procedure that the sums of the fitting errors corresponding to *B*-parameters of B_0-ΔB, B_0 and B_0+ΔB via three steps mentioned before are approximated by the parabolic line. A final *B*-parameter is determined by the search of the minimum sum of error squares for the stepwise change of *B*-parameter with 0.001 within 0.01 width.

Tables 3 to 8 show the fitting parameters of G-P approximation (B,c,a,X_k and d), maximum error, standard error and mfp where the maximum error appeared, for exposure, ambient dose equivalent and effective dose buildup factors in two type heavy concretes. The G-P approximation can obtain the buildup factors within 5% accuracy. The interpolation of buildup factors by photon energy is done by the energy interpolation of G-P parameters.

Table 3. Fitting Parameters of the Geometrical Progression Approximation for Exposure Buildup Factor of Heavy Concrete (Fe)

Energy (MeV)	*B*	*c*	*a*	X_k	*d*	*Max. error*	*At mfp*	*St.error*
15	1.399	0.947	0.011	5.00	0.0434	3.06%	1	1.27%
10	1.438	0.875	0.052	12.39	-0.0471	2.11%	1	0.95%
8	1.461	0.917	0.035	14.79	-0.0378	2.34%	1	0.88%
6	1.516	0.946	0.024	15.25	-0.0248	1.85%	1	0.85%
5	1.553	0.970	0.018	12.76	-0.0231	1.72%	1	0.76%
4	1.596	1.032	-0.006	5.00	0.0055	1.70%	1	0.86%
3	1.663	1.067	-0.014	5.00	0.0077	1.94%	35	0.76%
2	1.754	1.118	-0.020	10.50	-0.0088	1.80%	35	0.60%
1.5	1.803	1.205	-0.041	29.48	0.0385	2.77%	25	0.99%
1	1.895	1.294	-0.058	17.61	0.0247	0.69%	1	0.30%
0.8	1.948	1.320	-0.060	29.14	0.0459	2.18%	30	0.86%
0.6	1.991	1.382	-0.071	29.21	0.0668	4.06%	35	1.59%
0.5	2.077	1.317	-0.051	8.74	-0.0107	1.37%	30	0.69%
0.4	2.105	1.325	-0.056	26.52	0.0166	1.64%	25	0.76%
0.3	2.148	1.237	-0.033	9.72	-0.0172	1.27%	1	0.54%
0.2	2.079	1.101	-0.009	12.63	-0.0200	2.44%	1	0.82%
0.15	1.933	0.938	0.027	15.55	-0.0308	2.21%	1	0.94%
0.1	1.609	0.682	0.103	12.73	-0.0593	1.61%	1	0.79%
0.08	1.431	0.572	0.138	12.11	-0.0645	1.25%	1	0.55%
0.06	1.242	0.467	0.176	13.59	-0.0868	0.67%	25	0.38%
0.05	1.162	0.430	0.189	11.62	-0.0801	0.62%	4	0.33%
0.04	1.093	0.397	0.200	15.17	-0.1095	0.69%	35	0.30%
0.03	1.043	0.385	0.201	10.31	-0.0704	0.17%	1	0.08%
0.02	1.011	0.485	0.130	34.23	-0.2751	0.10%	35	0.06%
0.015	1.005	0.431	0.170	28.68	-0.4604	0.09%	20	0.04%

Table 4. Fitting Parameters of the Geometrical Progression Approximation for Ambient Dose Equivalent Buildup Factor of Heavy Concrete (Fe)

Energy (MeV)	*B*	*c*	*a*	X_k	*d*	*Max. error*	*At mfp*	*St.error*
15	1.604	0.844	0.065	14.68	-0.0576	2.83%	1	1.37%
10	1.463	0.866	0.055	12.40	-0.0489	2.64%	1	1.05%
8	1.497	0.889	0.045	14.42	-0.0460	2.22%	1	0.94%
6	1.548	0.931	0.029	14.89	-0.0285	1.99%	1	0.95%
5	1.587	0.957	0.022	12.92	-0.0259	1.82%	1	0.81%
4	1.625	1.031	-0.006	5.01	0.0060	2.16%	1	0.92%
3	1.700	1.066	-0.014	5.18	0.0086	1.73%	35	0.80%
2	1.793	1.118	-0.020	10.59	-0.0089	1.75%	35	0.61%
1.5	1.870	1.209	-0.042	28.89	0.0405	2.92%	25	1.03%
1	1.969	1.299	-0.059	17.58	0.0252	0.86%	1	0.31%
0.8	2.018	1.334	-0.063	29.08	0.0534	2.34%	30	0.92%
0.6	2.079	1.387	-0.072	31.00	0.0794	3.60%	35	1.63%
0.5	2.177	1.318	-0.051	8.99	-0.0111	1.46%	30	0.71%
0.4	2.209	1.326	-0.056	27.50	0.0166	1.66%	25	0.76%
0.3	2.252	1.241	-0.034	9.68	-0.0163	1.49%	1	0.57%
0.2	2.170	1.086	-0.004	12.51	-0.0257	2.25%	1	0.86%
0.15	1.997	0.929	0.030	15.38	-0.0333	2.21%	1	0.99%
0.1	1.620	0.686	0.101	12.71	-0.0576	2.13%	1	0.82%
0.08	1.428	0.574	0.137	12.02	-0.0636	1.41%	1	0.55%
0.06	1.231	0.483	0.166	13.88	-0.0807	0.65%	1	0.38%
0.05	1.148	0.452	0.177	11.64	-0.0735	0.65%	4	0.31%
0.04	1.078	0.454	0.167	15.88	-0.0891	0.54%	1	0.27%
0.03	1.035	0.422	0.184	10.85	-0.0640	0.15%	3	0.07%
0.02	1.008	0.634	0.059	6.57	0.0166	0.15%	1	0.05%
0.015	1.004	0.450	0.170	29.44	-0.4487	0.07%	15	0.03%

Table 5. Fitting Parameters of the Geometrical Progression Approximation for Effective Dose Buildup Factor with A-P Geometry of Heavy Concrete (Fe)

Energy (MeV)	*B*	*c*	*a*	X_k	*d*	*Max. error*	*At mfp*	*St.error*
15	1.447	0.823	0.073	14.54	-0.0643	2.63%	15	1.35%
10	1.454	0.864	0.056	12.42	-0.0503	2.25%	1	1.00%
8	1.485	0.892	0.044	14.41	-0.0454	2.01%	1	0.90%
6	1.532	0.940	0.026	14.99	-0.0262	2.04%	1	0.90%
5	1.572	0.963	0.020	12.95	-0.0242	1.81%	1	0.79%
4	1.614	1.031	-0.006	5.25	0.0061	1.98%	1	0.90%
3	1.689	1.063	-0.013	5.00	0.0077	1.70%	35	0.79%
2	1.782	1.125	-0.022	10.13	-0.0074	1.68%	35	0.65%
1.5	1.845	1.205	-0.041	29.62	0.0396	2.84%	25	1.02%
1	1.951	1.299	-0.059	17.71	0.0255	0.91%	1	0.31%
0.8	2.019	1.325	-0.061	28.42	0.0453	2.24%	30	0.88%
0.6	2.074	1.387	-0.072	31.06	0.0802	3.78%	35	1.62%
0.5	2.165	1.327	-0.053	8.31	-0.0102	1.46%	30	0.74%
0.4	2.213	1.326	-0.056	26.80	0.0158	1.61%	25	0.76%
0.3	2.257	1.241	-0.034	9.69	-0.0163	1.50%	1	0.57%
0.2	2.175	1.092	-0.006	12.56	-0.0234	2.48%	1	0.86%
0.15	1.995	0.932	0.029	15.44	-0.0324	2.34%	1	0.99%
0.1	1.614	0.682	0.103	12.72	-0.0594	1.67%	1	0.79%
0.08	1.412	0.588	0.130	12.03	-0.0591	1.38%	1	0.52%
0.06	1.218	0.497	0.159	14.00	-0.0765	0.57%	5	0.36%
0.05	1.141	0.470	0.166	11.72	-0.0664	0.65%	4	0.32%
0.04	1.080	0.435	0.181	15.04	-0.0979	0.56%	35	0.26%
0.03	1.038	0.413	0.187	10.64	-0.0655	0.15%	3	0.07%
0.02	1.009	0.575	0.091	30.36	-0.1078	0.13%	1	0.05%
0.015	1.005	0.394	0.197	34.45	-0.7499	0.08%	2	0.04%

Table 6. Fitting Parameters of the Geometrical Progression Approximation for Exposure Buildup Factor of Heavy Concrete (Ba)

Energy (MeV)	*B*	*c*	*a*	X_k	*d*	*Max. error*	*At mfp*	*St.error*
15	1.425	1.058	-0.002	6.20	0.0443	3.72%	1	1.83%
10	1.408	1.011	0.002	5.06	0.0395	3.78%	1	1.49%
8	1.455	0.899	0.052	14.19	-0.0554	2.11%	4	1.17%
6	1.472	0.967	0.025	14.61	-0.0295	2.52%	25	1.44%
5	1.498	0.977	0.022	13.76	-0.0358	2.01%	1	0.78%
4	1.538	1.000	0.016	10.73	-0.0288	1.80%	25	0.87%
3	1.588	1.022	0.009	11.75	-0.0314	1.14%	25	0.63%
2	1.643	1.073	-0.007	9.33	-0.0157	0.41%	1	0.26%
1.5	1.667	1.098	-0.012	9.08	-0.0208	0.48%	10	0.29%
1	1.689	1.124	-0.018	8.07	-0.0152	0.73%	1	0.37%
0.8	1.700	1.111	-0.016	9.22	-0.0122	1.26%	35	0.59%
0.6	1.669	1.112	-0.023	13.67	0.0105	1.79%	1	0.77%
0.5	1.669	1.008	0.008	10.90	-0.0190	0.64%	15	0.39%
0.4	1.611	0.943	0.020	11.23	-0.0139	0.80%	30	0.48%
0.3	1.500	0.839	0.045	12.06	-0.0196	1.40%	1	0.60%
0.2	1.316	0.683	0.089	13.52	-0.0389	1.02%	15	0.64%
0.15	1.203	0.588	0.118	12.71	-0.0472	0.60%	1	0.29%
0.1	1.096	0.485	0.163	11.84	-0.0794	0.50%	4	0.21%
0.08	1.066	0.444	0.174	15.72	-0.1001	0.33%	1	0.17%
0.06	1.042	0.350	0.215	11.52	0.3311	0.92%	30	0.51%
0.05	1.020	0.542	0.217	7.49	0.2949	4.38%	35	1.93%
0.04	1.015	1.769	0.029	5.02	0.0919	1.97%	2	1.22%
0.03	1.036	0.391	0.189	13.82	-0.0708	0.27%	3	0.13%
0.02	1.010	0.413	0.177	33.39	-0.4877	0.24%	4	0.08%
0.015	1.004	0.493	0.102	7.40	0.0507	0.12%	2	0.05%

Table 7. Fitting Parameters of the Geometrical Progression Approximation for Ambient Dose Equivalent Buildup Factor of Heavy Concrete (Ba)

Energy (MeV)	*B*	*c*	*a*	X_k	*d*	*Max. error*	*At mfp*	*St.error*
15	1.665	0.916	0.059	16.64	-0.0697	2.83%	25	1.52%
10	1.469	0.883	0.060	14.89	-0.0606	2.29%	15	1.43%
8	1.468	0.906	0.049	14.33	-0.0518	2.12%	1	1.12%
6	1.509	0.938	0.034	14.69	-0.0366	2.62%	3	1.60%
5	1.515	0.974	0.023	13.68	-0.0366	2.50%	1	0.86%
4	1.562	0.990	0.019	10.89	-0.0304	1.60%	25	0.90%
3	1.617	1.009	0.013	11.89	-0.0344	1.06%	25	0.66%
2	1.663	1.067	-0.005	9.47	-0.0178	0.52%	30	0.30%
1.5	1.703	1.098	-0.012	9.05	-0.0206	0.62%	1	0.33%
1	1.727	1.120	-0.017	8.42	-0.0155	0.74%	15	0.39%
0.8	1.716	1.148	-0.029	28.29	0.0213	1.77%	1	0.72%
0.6	1.706	1.102	-0.020	13.93	0.0077	1.76%	1	0.82%
0.5	1.701	1.002	0.010	11.00	-0.0209	0.68%	7	0.40%
0.4	1.638	0.940	0.021	11.31	-0.0148	1.09%	1	0.50%
0.3	1.525	0.831	0.048	12.11	-0.0222	1.60%	1	0.66%
0.2	1.328	0.681	0.089	13.63	-0.0376	1.08%	1	0.66%
0.15	1.212	0.575	0.124	12.80	-0.0513	0.60%	2	0.30%
0.1	1.096	0.499	0.151	12.91	-0.0705	0.56%	1	0.25%
0.08	1.064	0.451	0.170	15.72	-0.0947	0.26%	1	0.15%
0.06	1.025	0.679	0.042	13.26	0.3422	1.12%	1	0.55%
0.05	1.011	0.628	0.192	7.88	0.2390	2.65%	25	1.52%
0.04	1.010	1.882	0.020	5.43	0.0458	2.06%	3	1.09%
0.03	1.035	0.422	0.184	10.85	-0.0640	0.15%	3	0.07%
0.02	1.008	0.634	0.059	6.57	0.0166	0.15%	1	0.05%
0.015	1.004	0.450	0.170	29.44	-0.4487	0.07%	15	0.03%

Table 8. Fitting Parameters of the Geometrical Progression Approximation for Effective Dose Buildup Factor with A-P Geometry of Heavy Concrete (Ba)

Energy (MeV)	*B*	*c*	*a*	X_k	*d*	*Max. error*	*At mfp*	*St.error*
15	1.435	1.052	-0.001	6.11	0.0460	3.83%	1	1.88%
10	1.460	0.876	0.063	14.59	-0.0643	2.66%	15	1.45%
8	1.430	1.008	0.000	5.00	0.0378	3.72%	1	1.40%
6	1.497	0.946	0.031	14.95	-0.0337	2.67%	3	1.59%
5	1.506	0.974	0.023	13.68	-0.0367	2.24%	1	0.81%
4	1.548	0.999	0.016	10.76	-0.0277	1.71%	30	0.88%
3	1.599	1.024	0.008	11.80	-0.0295	1.14%	25	0.67%
2	1.660	1.070	-0.006	9.40	-0.0168	0.50%	30	0.29%
1.5	1.689	1.091	-0.010	9.29	-0.0220	0.52%	7	0.31%
1	1.715	1.120	-0.017	8.36	-0.0155	0.74%	1	0.39%
0.8	1.730	1.107	-0.015	9.55	-0.0124	1.46%	35	0.60%
0.6	1.703	1.102	-0.020	13.92	0.0078	1.68%	1	0.80%
0.5	1.698	1.003	0.010	10.88	-0.0216	0.83%	15	0.40%
0.4	1.639	0.940	0.021	11.36	-0.0149	1.07%	1	0.51%
0.3	1.528	0.828	0.049	12.23	-0.0227	1.46%	1	0.67%
0.2	1.330	0.679	0.090	13.52	-0.0386	1.12%	1	0.66%
0.15	1.211	0.581	0.121	12.79	-0.0494	0.66%	1	0.29%
0.1	1.096	0.487	0.160	12.75	-0.0799	0.50%	35	0.23%
0.08	1.062	0.463	0.164	15.79	-0.0913	0.31%	25	0.14%
0.06	1.035	0.399	0.165	12.54	0.3683	0.74%	25	0.40%
0.05	1.012	0.586	0.205	7.98	0.2532	3.54%	35	1.54%
0.04	1.010	1.869	0.021	5.36	0.0519	1.91%	3	1.02%
0.03	1.031	0.432	0.170	13.85	-0.0643	0.23%	1	0.10%
0.02	1.008	0.516	0.124	33.46	-0.3162	0.18%	4	0.08%
0.015	1.004	0.431	0.139	5.00	0.0491	0.12%	30	0.05%

4. Summary

Buildup factors of two typical heavy concretes were evaluated to improve the capability of the various materials for the shielding wall by using the calculation of the EGS4 Monte Carlo code in ranging from 0.015 MeV to 15 MeV, and up to 40 mfp. One is iron-contained and the other is barium-contained heavy concretes. The data of these buildup factors were compared with that of the element of the main component of the heavy concretes on the assumption of the same densities. Using these data, the fitting parameters of the Geometrical Progression approximation were derived. As the results, we can use easily the code of the point kernel method with good accuracy for the case of the shield material of heavy concretes.

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Appendix: Data of Buildup Factors for Heavy Concrete

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Table A1. Exposure Buildup Factors of Heavy Concrete (Fe)

Photon Energy (MeV)	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.2	0.3	0.4	0.5
1.0 mfp	1.01	1.01	1.04	1.10	1.17	1.25	1.45	1.64	1.98	2.13	2.18	2.14	2.09
2.0 mfp	1.01	1.02	1.06	1.13	1.24	1.36	1.70	2.05	2.82	3.26	3.55	3.52	3.44
2.5 mfp	1.01	1.02	1.07	1.15	1.27	1.42	1.80	2.23	3.24	3.87	4.29	4.32	4.22
3.0 mfp	1.01	1.02	1.07	1.16	1.29	1.45	1.89	2.40	3.65	4.50	5.11	5.18	5.06
3.5 mfp	1.01	1.02	1.08	1.17	1.31	1.50	1.99	2.58	4.10	5.15	6.00	6.12	5.99
4.0 mfp	1.01	1.02	1.08	1.17	1.32	1.51	2.06	2.73	4.51	5.86	6.98	7.12	6.96
4.5 mfp	1.01	1.03	1.09	1.19	1.34	1.56	2.13	2.87	4.97	6.59	7.99	8.24	8.05
5.0 mfp	1.01	1.02	1.09	1.19	1.36	1.56	2.24	3.05	5.45	7.35	9.09	9.38	9.19
5.5 mfp	1.01	1.03	1.09	1.20	1.37	1.59	2.30	3.19	5.90	8.15	10.2	10.6	10.5
6.0 mfp	1.01	1.03	1.09	1.21	1.39	1.62	2.36	3.33	6.36	8.94	11.5	11.9	11.8
6.5 mfp	1.01	1.03	1.09	1.21	1.40	1.64	2.43	3.48	6.84	9.80	12.7	13.4	13.2
7.0 mfp	1.01	1.03	1.10	1.22	1.41	1.66	2.47	3.62	7.35	10.7	14.1	14.8	14.6
7.5 mfp	1.01	1.03	1.10	1.23	1.42	1.69	2.55	3.78	7.76	11.6	15.6	16.4	16.1
8.0 mfp	1.01	1.03	1.10	1.23	1.44	1.71	2.61	3.89	8.29	12.6	17.0	18.0	17.8
9.0 mfp	1.01	1.03	1.11	1.24	1.46	1.75	2.71	4.19	9.25	14.6	20.2	21.5	21.4
10.0 mfp	1.01	1.03	1.11	1.25	1.47	1.78	2.81	4.44	10.3	16.5	24.0	25.3	25.0
11.0 mfp	1.01	1.03	1.11	1.26	1.49	1.82	2.92	4.69	11.3	18.6	27.6	29.4	29.1
12.0 mfp	1.01	1.03	1.11	1.27	1.50	1.86	3.03	4.94	12.4	21.0	31.8	33.9	33.6
13.0 mfp	1.01	1.03	1.12	1.27	1.52	1.88	3.09	5.16	13.5	23.4	36.2	38.9	38.6
14.0 mfp	1.01	1.03	1.12	1.28	1.53	1.90	3.17	5.41	14.6	26.0	41.0	43.5	43.7
15.0 mfp	1.02	1.03	1.12	1.29	1.54	1.92	3.28	5.69	15.6	28.4	45.8	48.7	49.4
16.0 mfp	1.01	1.04	1.12	1.29	1.55	1.96	3.37	5.91	16.8	31.1	51.4	54.1	55.2
17.0 mfp	1.01	1.04	1.13	1.30	1.56	1.98	3.46	6.11	18.0	33.9	56.9	60.3	62.4
18.0 mfp	1.02	1.04	1.13	1.30	1.58	2.01	3.51	6.27	19.2	36.8	63.0	66.3	68.8
19.0 mfp	1.02	1.04	1.13	1.31	1.59	2.03	3.61	6.55	20.5	39.9	69.0	73.9	75.1
20.0 mfp	1.02	1.04	1.13	1.31	1.60	2.04	3.64	6.76	21.9	43.4	76.1	81.2	83.4
21.0 mfp	1.02	1.04	1.13	1.31	1.60	2.06	3.71	6.93	23.1	46.4	83.5	89.5	88.7
22.0 mfp	1.02	1.04	1.14	1.32	1.61	2.08	3.75	7.15	24.3	49.4	90.6	97.3	96.2
23.0 mfp	1.02	1.04	1.14	1.32	1.62	2.10	3.88	7.30	25.5	53.0	97.8	106.	105.
24.0 mfp	1.02	1.04	1.14	1.33	1.61	2.11	3.94	7.68	27.0	56.7	106.	117.	111.
25.0 mfp	1.02	1.04	1.14	1.33	1.63	2.12	3.96	7.68	28.6	60.0	111.	126.	120.
26.0 mfp	1.02	1.04	1.14	1.33	1.64	2.14	4.00	7.90	29.9	62.6	121.	133.	133.
27.0 mfp	1.02	1.04	1.14	1.34	1.65	2.17	4.06	8.04	30.9	66.9	129.	142.	141.
28.0 mfp	1.02	1.04	1.15	1.34	1.67	2.15	4.16	8.36	32.5	69.1	136.	149.	150.
29.0 mfp	1.02	1.04	1.14	1.34	1.67	2.20	4.20	8.43	34.2	73.7	152.	161.	160.
30.0 mfp	1.02	1.04	1.14	1.34	1.67	2.20	4.25	8.63	34.8	79.3	156.	172.	170.
31.0 mfp	1.02	1.04	1.15	1.35	1.68	2.22	4.32	8.85	36.9	82.5	169.	183.	183.
32.0 mfp	1.02	1.04	1.14	1.35	1.69	2.24	4.34	9.12	37.7	87.0	179.	191.	193.
33.0 mfp	1.02	1.04	1.15	1.36	1.69	2.24	4.36	9.17	39.4	90.9	191.	207.	205.
34.0 mfp	1.02	1.04	1.15	1.36	1.69	2.23	4.51	9.41	41.8	97.0	203.	215.	214.
35.0 mfp	1.02	1.04	1.15	1.36	1.71	2.26	4.51	9.60	42.9	98.6	216.	232.	221.
40.0 mfp	1.02	1.04	1.16	1.36	1.76	2.33	4.94	10.7	49.3	121.	283.	303.	285.

Table A1. (Continued) Exposure Buildup Factors of Heavy Concrete (Fe)

Photon Energy (MeV)	0.6	0.8	1	1.5	2	3	4	5	6	8	10	15
1.0 mfp	2.04	1.97	1.91	1.81	1.75	1.68	1.62	1.58	1.54	1.50	1.47	1.44
2.0 mfp	3.33	3.15	2.99	2.75	2.58	2.36	2.21	2.10	2.01	1.90	1.84	1.80
2.5 mfp	4.08	3.83	3.62	3.26	3.01	2.72	2.51	2.36	2.25	2.10	2.02	1.97
3.0 mfp	4.90	4.55	4.28	3.79	3.47	3.07	2.81	2.63	2.48	2.31	2.21	2.14
3.5 mfp	5.76	5.35	5.00	4.36	3.94	3.44	3.12	2.89	2.73	2.52	2.39	2.31
4.0 mfp	6.69	6.17	5.75	4.94	4.43	3.82	3.45	3.17	2.97	2.72	2.58	2.48
4.5 mfp	7.79	7.07	6.54	5.57	4.94	4.20	3.75	3.44	3.21	2.94	2.77	2.65
5.0 mfp	8.90	8.03	7.40	6.19	5.47	4.63	4.08	3.72	3.47	3.15	2.95	2.83
5.5 mfp	10.0	9.04	8.28	6.83	5.99	5.03	4.42	4.03	3.73	3.36	3.15	3.03
6.0 mfp	11.3	10.1	9.19	7.52	6.52	5.43	4.77	4.34	3.99	3.59	3.36	3.23
6.5 mfp	12.6	11.2	10.2	8.23	7.07	5.86	5.12	4.62	4.25	3.81	3.57	3.41
7.0 mfp	14.0	12.4	11.1	8.91	7.62	6.26	5.46	4.94	4.51	4.02	3.76	3.61
7.5 mfp	15.4	13.5	12.1	9.66	8.23	6.69	5.82	5.22	4.77	4.25	3.98	3.82
8.0 mfp	16.9	14.8	13.2	10.3	8.78	7.09	6.18	5.53	5.04	4.50	4.19	4.03
9.0 mfp	20.3	17.5	15.4	12.0	10.0	7.92	6.85	6.19	5.62	5.00	4.63	4.47
10.0 mfp	23.6	20.4	17.6	13.6	11.3	8.81	7.69	6.76	6.13	5.52	5.10	4.90
11.0 mfp	27.5	23.5	20.2	15.4	12.5	9.82	8.32	7.50	6.79	6.05	5.58	5.40
12.0 mfp	31.5	26.7	22.5	17.2	13.7	10.8	9.11	8.11	7.44	6.62	6.09	5.91
13.0 mfp	36.1	30.0	25.4	18.9	15.0	11.7	9.86	8.85	7.95	7.20	6.56	6.41
14.0 mfp	40.2	33.5	28.2	20.9	16.3	12.7	10.5	9.51	8.65	7.71	7.08	7.01
15.0 mfp	44.7	37.3	31.2	22.6	18.1	13.7	11.3	10.3	9.20	8.21	7.61	7.56
16.0 mfp	49.9	41.1	34.2	24.4	19.6	14.7	12.1	11.0	9.89	8.80	8.27	8.23
17.0 mfp	55.2	45.3	37.2	26.2	21.0	15.7	12.9	11.7	10.5	9.40	8.82	8.89
18.0 mfp	60.8	49.3	40.4	28.4	22.4	16.8	13.7	12.5	11.3	10.0	9.34	9.49
19.0 mfp	66.6	53.6	43.7	30.3	23.9	17.9	14.4	13.3	12.0	10.6	9.91	10.0
20.0 mfp	72.9	58.3	47.4	33.0	25.8	19.3	15.3	13.9	12.6	11.2	10.4	10.8
21.0 mfp	79.9	63.6	51.0	35.1	27.5	20.1	16.1	14.7	13.3	11.8	11.1	11.4
22.0 mfp	85.3	68.3	54.3	37.3	28.9	21.2	16.9	15.7	13.9	12.6	11.6	12.2
23.0 mfp	92.5	75.9	58.1	39.6	30.5	22.1	17.9	16.2	14.6	13.4	12.3	13.0
24.0 mfp	100.	77.4	61.0	43.4	31.8	23.4	18.6	17.1	15.4	14.1	12.8	13.7
25.0 mfp	109.	83.5	65.9	45.2	33.4	24.1	19.9	18.0	16.2	14.6	13.3	14.4
26.0 mfp	116.	90.0	69.4	48.3	35.2	25.1	20.6	18.9	16.9	15.2	13.9	15.3
27.0 mfp	123.	98.7	73.3	50.8	36.4	26.3	21.3	19.8	17.5	16.1	14.6	16.3
28.0 mfp	129.	100.	79.2	51.9	37.7	27.3	22.3	20.6	18.6	16.9	15.3	17.4
29.0 mfp	136.	106.	82.4	54.6	40.1	28.9	23.0	21.0	19.6	17.4	15.8	18.2
30.0 mfp	145.	115.	87.5	55.8	41.1	29.9	23.7	22.5	20.1	18.0	16.6	19.5
31.0 mfp	150.	118.	90.9	58.1	43.0	31.5	25.0	23.3	21.0	18.6	17.5	20.3
32.0 mfp	159.	125.	96.0	60.6	44.2	32.2	26.0	24.2	21.9	19.3	18.2	21.3
33.0 mfp	168.	131.	99.5	63.7	46.9	33.3	26.8	25.0	22.8	20.3	19.2	22.1
34.0 mfp	176.	136.	106.	65.1	47.5	34.1	27.8	26.0	23.8	21.1	20.1	23.5
35.0 mfp	180.	140.	112.	68.2	48.5	36.7	28.8	26.1	24.6	21.5	20.7	24.4
40.0 mfp	245.	179.	140.	85.1	58.3	41.7	32.9	31.5	28.6	25.1	25.4	30.4

Table A2. Ambient Dose Equivalent Buildup Factors of Heavy Concrete (Fe)

Photon Energy (MeV)	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.2	0.3	0.4	0.5
1.0 mfp	1.00	1.01	1.04	1.08	1.15	1.24	1.45	1.66	2.04	2.22	2.29	2.24	2.19
2.0 mfp	1.01	1.01	1.05	1.12	1.22	1.35	1.69	2.08	2.94	3.43	3.78	3.76	3.66
2.5 mfp	1.01	1.02	1.06	1.13	1.25	1.40	1.79	2.27	3.37	4.09	4.60	4.63	4.51
3.0 mfp	1.01	1.02	1.06	1.14	1.27	1.44	1.89	2.44	3.81	4.75	5.49	5.57	5.42
3.5 mfp	1.01	1.02	1.07	1.15	1.29	1.48	1.98	2.61	4.29	5.45	6.46	6.61	6.45
4.0 mfp	1.01	1.02	1.07	1.15	1.30	1.49	2.06	2.77	4.71	6.21	7.54	7.70	7.51
4.5 mfp	1.01	1.02	1.07	1.17	1.32	1.54	2.13	2.92	5.20	6.99	8.64	8.92	8.70
5.0 mfp	1.01	1.02	1.08	1.17	1.34	1.55	2.24	3.10	5.71	7.81	9.84	10.2	9.96
5.5 mfp	1.01	1.02	1.08	1.18	1.35	1.58	2.30	3.24	6.18	8.68	11.1	11.5	11.4
6.0 mfp	1.01	1.02	1.08	1.19	1.37	1.60	2.35	3.38	6.66	9.53	12.4	12.9	12.8
6.5 mfp	1.01	1.02	1.08	1.20	1.38	1.63	2.43	3.54	7.18	10.4	13.8	14.6	14.3
7.0 mfp	1.01	1.03	1.08	1.20	1.39	1.65	2.47	3.68	7.71	11.4	15.3	16.1	15.9
7.5 mfp	1.01	1.03	1.09	1.21	1.40	1.67	2.55	3.84	8.14	12.3	17.0	17.9	17.6
8.0 mfp	1.01	1.03	1.09	1.22	1.42	1.70	2.60	3.95	8.71	13.4	18.5	19.6	19.5
9.0 mfp	1.01	1.03	1.10	1.22	1.43	1.73	2.71	4.26	9.72	15.6	22.0	23.5	23.4
10.0 mfp	1.01	1.03	1.10	1.23	1.45	1.76	2.81	4.52	10.8	17.6	26.2	27.8	27.4
11.0 mfp	1.01	1.03	1.10	1.24	1.46	1.81	2.91	4.77	11.9	19.9	30.2	32.2	31.9
12.0 mfp	1.01	1.03	1.10	1.25	1.48	1.84	3.03	5.03	13.0	22.5	34.9	37.2	36.9
13.0 mfp	1.01	1.03	1.10	1.25	1.50	1.86	3.08	5.25	14.2	25.0	39.6	42.8	42.3
14.0 mfp	1.01	1.03	1.11	1.26	1.51	1.88	3.16	5.50	15.3	27.8	44.9	47.9	48.0
15.0 mfp	1.01	1.03	1.11	1.27	1.52	1.91	3.27	5.78	16.5	30.4	50.2	53.5	54.3
16.0 mfp	1.01	1.03	1.11	1.27	1.53	1.94	3.36	6.01	17.6	33.4	56.4	59.6	60.7
17.0 mfp	1.01	1.03	1.11	1.28	1.54	1.96	3.45	6.21	18.9	36.4	62.5	66.5	68.7
18.0 mfp	1.01	1.03	1.12	1.28	1.55	1.99	3.50	6.37	20.2	39.5	69.2	73.1	75.9
19.0 mfp	1.01	1.03	1.12	1.29	1.56	2.00	3.60	6.66	21.6	42.9	75.9	81.6	82.8
20.0 mfp	1.01	1.04	1.12	1.29	1.57	2.02	3.64	6.88	23.1	46.6	83.7	89.7	91.9
21.0 mfp	1.01	1.04	1.12	1.30	1.58	2.04	3.70	7.05	24.3	49.8	92.0	98.8	97.8
22.0 mfp	1.01	1.04	1.12	1.30	1.59	2.06	3.74	7.28	25.6	53.0	99.7	107.	106.
23.0 mfp	1.01	1.04	1.12	1.30	1.59	2.08	3.88	7.43	26.9	56.9	108.	117.	116.
24.0 mfp	1.01	1.04	1.12	1.31	1.59	2.09	3.93	7.82	28.4	60.9	116.	130.	122.
25.0 mfp	1.02	1.04	1.13	1.31	1.61	2.10	3.95	7.80	30.1	64.5	122.	139.	132.
26.0 mfp	1.02	1.04	1.13	1.31	1.62	2.12	3.99	8.03	31.5	67.2	133.	147.	147.
27.0 mfp	1.02	1.04	1.13	1.32	1.62	2.15	4.05	8.18	32.6	71.9	142.	157.	155.
28.0 mfp	1.02	1.04	1.14	1.32	1.64	2.13	4.15	8.50	34.2	74.2	150.	165.	166.
29.0 mfp	1.02	1.04	1.13	1.32	1.64	2.18	4.19	8.58	36.1	79.2	168.	179.	177.
30.0 mfp	1.02	1.04	1.13	1.32	1.64	2.18	4.24	8.78	36.7	85.2	172.	191.	188.
31.0 mfp	1.02	1.04	1.13	1.33	1.65	2.20	4.28	9.00	38.9	88.6	186.	203.	203.
32.0 mfp	1.02	1.04	1.13	1.33	1.67	2.22	4.33	9.27	39.8	93.5	197.	212.	213.
33.0 mfp	1.02	1.04	1.14	1.34	1.66	2.22	4.35	9.32	41.6	97.6	211.	230.	227.
34.0 mfp	1.02	1.04	1.14	1.34	1.67	2.21	4.50	9.57	44.0	104.	224.	239.	237.
35.0 mfp	1.02	1.04	1.14	1.34	1.69	2.23	4.50	9.76	45.3	106.	238.	257.	244.
40.0 mfp	1.02	1.04	1.15	1.34	1.73	2.30	4.93	10.8	52.0	131.	313.	337.	315.

Table A2. (Continued) Ambient Dose Equivalent Buildup Factors of Heavy Concrete (Fe)

Photon Energy (MeV)	0.6	0.8	1	1.5	2	3	4	5	6	8	10	15
1.0 mfp	2.14	2.05	1.99	1.88	1.79	1.72	1.66	1.62	1.58	1.53	1.50	1.65
2.0 mfp	3.54	3.34	3.17	2.90	2.66	2.44	2.28	2.16	2.07	1.95	1.89	2.15
2.5 mfp	4.36	4.07	3.85	3.46	3.12	2.82	2.59	2.43	2.31	2.16	2.08	2.39
3.0 mfp	5.25	4.87	4.57	4.03	3.60	3.19	2.90	2.71	2.55	2.37	2.27	2.64
3.5 mfp	6.20	5.74	5.35	4.65	4.09	3.58	3.22	2.98	2.81	2.59	2.46	2.87
4.0 mfp	7.21	6.62	6.17	5.28	4.60	3.97	3.57	3.27	3.06	2.81	2.65	3.11
4.5 mfp	8.43	7.62	7.03	5.97	5.15	4.37	3.88	3.55	3.31	3.03	2.86	3.35
5.0 mfp	9.64	8.66	7.98	6.65	5.70	4.82	4.22	3.85	3.58	3.24	3.04	3.61
5.5 mfp	10.9	9.76	8.93	7.34	6.25	5.25	4.58	4.16	3.85	3.47	3.25	3.88
6.0 mfp	12.2	10.9	9.92	8.09	6.80	5.66	4.94	4.48	4.12	3.71	3.47	4.17
6.5 mfp	13.7	12.1	11.0	8.86	7.39	6.11	5.31	4.78	4.39	3.93	3.68	4.43
7.0 mfp	15.2	13.4	12.0	9.61	7.96	6.54	5.66	5.11	4.66	4.15	3.88	4.69
7.5 mfp	16.7	14.7	13.1	10.4	8.60	6.99	6.03	5.41	4.93	4.39	4.10	5.00
8.0 mfp	18.4	16.1	14.3	11.2	9.18	7.40	6.42	5.72	5.21	4.64	4.32	5.28
9.0 mfp	22.2	19.0	16.8	12.9	10.5	8.28	7.11	6.41	5.82	5.16	4.78	5.91
10.0 mfp	25.9	22.3	19.1	14.8	11.8	9.21	7.98	7.00	6.34	5.71	5.27	6.51
11.0 mfp	30.2	25.7	22.0	16.7	13.1	10.3	8.64	7.77	7.02	6.25	5.77	7.22
12.0 mfp	34.5	29.1	24.6	18.6	14.4	11.3	9.46	8.41	7.70	6.85	6.30	7.94
13.0 mfp	39.6	32.8	27.7	20.5	15.7	12.2	10.2	9.18	8.22	7.45	6.78	8.64
14.0 mfp	44.1	36.7	30.7	22.7	17.1	13.2	10.9	9.85	8.95	7.98	7.32	9.51
15.0 mfp	49.1	40.8	34.1	24.6	19.0	14.4	11.8	10.7	9.52	8.49	7.86	10.3
16.0 mfp	54.9	45.0	37.3	26.6	20.6	15.4	12.5	11.4	10.2	9.10	8.55	11.2
17.0 mfp	60.8	49.6	40.6	28.5	22.0	16.4	13.4	12.2	10.9	9.73	9.13	12.2
18.0 mfp	67.0	54.0	44.2	30.8	23.5	17.6	14.2	13.0	11.7	10.4	9.67	13.0
19.0 mfp	73.3	58.8	47.8	32.9	25.1	18.7	15.0	13.8	12.4	11.0	10.2	13.7
20.0 mfp	80.4	63.9	51.9	35.9	27.1	20.2	15.9	14.4	13.0	11.6	10.8	14.8
21.0 mfp	88.0	69.8	55.7	38.2	28.8	21.1	16.7	15.2	13.8	12.2	11.5	15.7
22.0 mfp	94.1	75.0	59.5	40.6	30.3	22.2	17.6	16.3	14.4	13.0	12.0	16.9
23.0 mfp	102.	83.6	63.6	43.0	32.1	23.2	18.6	16.8	15.2	13.8	12.8	18.1
24.0 mfp	111.	84.8	66.8	47.3	33.4	24.6	19.4	17.8	15.9	14.6	13.3	19.0
25.0 mfp	121.	91.7	72.2	49.1	35.1	25.2	20.7	18.7	16.7	15.1	13.8	19.9
26.0 mfp	128.	98.9	76.0	52.6	37.0	26.3	21.4	19.6	17.5	15.8	14.4	21.3
27.0 mfp	135.	109.	80.3	55.3	38.3	27.5	22.1	20.6	18.1	16.6	15.1	22.6
28.0 mfp	143.	110.	86.9	56.5	39.7	28.7	23.2	21.4	19.3	17.5	15.8	24.2
29.0 mfp	150.	117.	90.3	59.5	42.2	30.3	23.9	21.8	20.4	18.0	16.3	25.3
30.0 mfp	160.	126,	96.0	60.7	43.2	31.4	24.6	23.3	20.8	18.7	17.1	27.2
31.0 mfp	166.	130.	99.6	63.3	45.2	33.1	26.0	24.1	21.7	19.3	18.1	28.3
32.0 mfp	176.	137.	105.	66.0	46.4	33.8	27.0	25.1	22.8	20.0	18.8	29.7
33.0 mfp	186.	144.	109.	69.6	49.3	34.9	27.9	26.0	23.6	21.1	19.9	30.9
34.0 mfp	194.	150.	117.	70.9	50.0	35.8	28.9	27.0	24.7	21.8	20.9	32.8
35.0 mfp	199.	153.	122.	74.3	50.9	38.6	30.0	27.1	25.5	22.3	21.5	34.2
40.0 mfp	271.	197.	154.	93.1	61.2	43.7	34.2	32.7	29.6	26.0	26.3	42.7

Table A3. Effective Dose (AP) Buildup Factors of Heavy Concrete (Fe)

Photon Energy (MeV)	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.2	0.3	0.4	0.5
1.0 mfp	1.01	1.01	1.04	1.08	1.15	1.22	1.43	1.64	2.04	2.23	2.29	2.25	2.19
2.0 mfp	1.01	1.01	1.06	1.12	1.21	1.33	1.67	2.06	2.94	3.45	3.79	3.77	3.66
2.5 mfp	1.01	1.02	1.06	1.13	1.24	1.38	1.77	2.24	3.38	4.11	4.61	4.64	4.52
3.0 mfp	1.01	1.02	1.07	1.14	1.26	1.42	1.87	2.42	3.82	4.79	5.51	5.58	5.43
3.5 mfp	1.01	1.02	1.07	1.15	1.28	1.46	1.96	2.59	4.29	5.49	6.48	6.62	6.45
4.0 mfp	1.01	1.02	1.07	1.16	1.29	1.47	2.03	2.75	4.72	6.26	7.56	7.72	7.51
4.5 mfp	1.01	1.02	1.08	1.17	1.31	1.52	2.10	2.89	5.21	7.04	8.67	8.95	8.70
5.0 mfp	1.01	1.02	1.08	1.17	1.34	1.52	2.21	3.07	5.72	7.87	9.88	10.2	9.96
5.5 mfp	1.01	1.02	1.08	1.18	1.34	1.56	2.27	3.21	6.19	8.74	11.1	11.5	11.4
6.0 mfp	1.01	1.02	1.09	1.19	1.36	1.58	2.33	3.35	6.67	9.60	12.5	13.0	12.8
6.5 mfp	1.01	1.03	1.09	1.20	1.37	1.61	2.40	3.51	7.19	10.5	13.9	14.6	14.3
7.0 mfp	1.01	1.03	1.09	1.20	1.38	1.63	2.44	3.64	7.72	11.5	15.4	16.1	15.9
7.5 mfp	1.01	1.03	1.09	1.21	1.39	1.65	2.52	3.80	8.15	12.4	17.1	17.9	17.6
8.0 mfp	1.01	1.03	1.10	1.22	1.41	1.67	2.57	3.91	8.72	13.5	18.6	19.7	19.5
9.0 mfp	1.01	1.03	1.10	1.22	1.43	1.71	2.68	4.21	9.73	15.7	22.1	23.6	23.4
10.0 mfp	1.01	1.03	1.10	1.23	1.44	1.74	2.78	4.47	10.9	17.7	26.3	27.8	27.4
11.0 mfp	1.01	1.03	1.11	1.24	1.46	1.78	2.88	4.72	11.9	20.0	30.3	32.3	31.9
12.0 mfp	1.01	1.03	1.11	1.25	1.47	1.81	2.99	4.98	13.0	22.7	35.0	37.3	36.9
13.0 mfp	1.01	1.03	1.11	1.25	1.49	1.84	3.05	5.20	14.2	25.2	39.8	43.0	42.3
14.0 mfp	1.01	1.03	1.11	1.26	1.50	1.86	3.13	5.45	15.3	28.0	45.1	48.1	48.1
15.0 mfp	1.02	1.03	1.11	1.27	1.51	1.88	3.24	5.72	16.5	30.6	50.4	53.7	54.3
16.0 mfp	1.01	1.03	1.12	1.27	1.52	1.91	3.33	5.95	17.7	33.6	56.6	59.7	60.7
17.0 mfp	1.01	1.03	1.12	1.28	1.53	1.93	3.41	6.15	18.9	36.7	62.8	66.6	68.7
18.0 mfp	1.01	1.03	1.12	1.29	1.54	1.96	3.47	6.31	20.3	39.8	69.5	73.3	75.9
19.0 mfp	1.01	1.03	1.13	1.29	1.55	1.97	3.56	6.59	21.7	43.2	76.2	81.9	82.8
20.0 mfp	1.02	1.04	1.12	1.29	1.56	1.99	3.60	6.81	23.1	47.0	84.0	90.0	91.9
21.0 mfp	1.02	1.04	1.13	1.30	1.57	2.02	3.66	6.98	24.3	50.2	92.4	99.1	97.9
22.0 mfp	1.02	1.04	1.13	1.30	1.58	2.04	3.71	7.21	25.6	53.4	100.	108.	106.
23.0 mfp	1.02	1.04	1.13	1.31	1.59	2.05	3.84	7.35	26.9	57.4	108.	118.	116.
24.0 mfp	1.02	1.04	1.13	1.31	1.58	2.07	3.89	7.74	28.4	61.4	117.	130.	122.
25.0 mfp	1.02	1.04	1.13	1.31	1.60	2.07	3.91	7.72	30.1	65.0	123.	139.	132.
26.0 mfp	1.02	1.04	1.13	1.31	1.61	2.09	3.95	7.95	31.6	67.8	134.	148.	147.
27.0 mfp	1.02	1.04	1.13	1.32	1.62	2.12	4.01	8.10	32.6	72.5	143.	158.	155.
28.0 mfp	1.02	1.04	1.14	1.33	1.64	2.11	4.10	8.42	34.3	74.8	150.	166.	166.
29.0 mfp	1.02	1.04	1.14	1.32	1.64	2.15	4.15	8.49	36.1	79.8	169.	179.	177.
30.0 mfp	1.02	1.04	1.14	1.33	1.64	2.15	4.19	8.68	36.8	85.9	173.	191.	188.
31.0 mfp	1.02	1.04	1.14	1.33	1.65	2.17	4.24	8.91	38.9	89.3	187.	203.	203.
32.0 mfp	1.02	1.04	1.14	1.33	1.66	2.19	4.29	9.18	39.8	94.3	198.	212.	213.
33.0 mfp	1.02	1.04	1.14	1.34	1.66	2.19	4.30	9.23	41.6	98.5	212.	230.	227.
34.0 mfp	1.02	1.04	1.14	1.34	1.66	2.18	4.45	9.48	44.1	105.	225.	239.	237.
35.0 mfp	1.02	1.04	1.15	1.35	1.68	2.21	4.45	9.66	45.4	107.	239.	258.	244.
40.0 mfp	1.02	1.04	1.16	1.35	1.72	2.27	4.87	10.7	52.1	132.	314.	338.	315.

Table A3. (Continued) Effective Dose (AP) Buildup Factors of Heavy Concrete (Fe)

Photon Energy (MeV)	0.6	0.8	1	1.5	2	3	4	5	6	8	10	15
1.0 mfp	2.13	2.04	1.97	1.85	1.79	1.70	1.65	1.60	1.56	1.52	1.49	1.46
2.0 mfp	3.53	3.31	3.13	2.84	2.65	2.41	2.25	2.13	2.04	1.93	1.87	1.82
2.5 mfp	4.34	4.04	3.79	3.38	3.10	2.78	2.56	2.40	2.28	2.14	2.05	2.00
3.0 mfp	5.23	4.83	4.51	3.93	3.58	3.15	2.86	2.67	2.52	2.34	2.24	2.17
3.5 mfp	6.18	5.69	5.28	4.53	4.07	3.53	3.18	2.94	2.77	2.56	2.43	2.34
4.0 mfp	7.18	6.57	6.08	5.15	4.58	3.91	3.52	3.23	3.01	2.77	2.62	2.52
4.5 mfp	8.40	7.55	6.92	5.81	5.12	4.31	3.83	3.50	3.26	2.98	2.82	2.69
5.0 mfp	9.60	8.58	7.85	6.47	5.67	4.75	4.17	3.79	3.53	3.20	3.00	2.88
5.5 mfp	10.8	9.67	8.79	7.13	6.22	5.17	4.52	4.10	3.79	3.42	3.20	3.07
6.0 mfp	12.2	10.8	9.76	7.86	6.77	5.57	4.87	4.42	4.06	3.65	3.42	3.28
6.5 mfp	13.6	12.0	10.8	8.60	7.35	6.02	5.23	4.71	4.33	3.87	3.62	3.47
7.0 mfp	15.2	13.3	11.8	9.33	7.92	6.43	5.57	5.03	4.59	4.09	3.82	3.66
7.5 mfp	16.7	14.6	12.9	10.1	8.55	6.88	5.95	5.32	4.85	4.32	4.04	3.89
8.0 mfp	18.3	15.9	14.1	10.8	9.13	7.28	6.32	5.63	5.13	4.57	4.26	4.09
9.0 mfp	22.1	18.8	16.5	12.5	10.5	8.15	7.00	6.31	5.72	5.08	4.71	4.54
10.0 mfp	25.7	22.0	18.8	14.3	11.7	9.06	7.86	6.89	6.24	5.62	5.19	4.98
11.0 mfp	30.0	25.4	21.6	16.2	13.0	10.1	8.51	7.65	6.91	6.15	5.68	5.48
12.0 mfp	34.4	28.8	24.1	18.0	14.3	11.1	9.31	8.27	7.58	6.74	6.20	6.01
13.0 mfp	39.4	32.4	27.2	19.9	15.6	12.0	10.1	9.03	8.09	7.33	6.67	6.51
14.0 mfp	43.9	36.3	30.2	22.0	17.0	13.0	10.7	9.70	8.80	7.85	7.21	7.13
15.0 mfp	48.8	40.4	33.4	23.8	18.9	14.2	11.6	10.5	9.36	8.36	7.74	7.69
16.0 mfp	54.6	44.5	36.6	25.7	20.5	15.1	12.3	11.2	10.1	8.96	8.42	8.37
17.0 mfp	60.5	49.1	39.9	27.5	21.9	16.2	13.1	12.0	10.7	9.57	8.98	9.03
18.0 mfp	66.6	53.4	43.3	29.8	23.4	17.3	14.0	12.8	11.5	10.2	9.51	9.66
19.0 mfp	72.9	58.2	46.9	31.8	24.9	18.4	14.8	13.5	12.2	10.8	10.1	10.2
20.0 mfp	80.0	63.2	50.9	34.7	26.9	19.9	15.6	14.2	12.8	11.4	10.6	11.0
21.0 mfp	87.6	69.0	54.7	36.9	28.7	20.7	16.5	15.0	13.5	12.0	11.3	11.6
22.0 mfp	93.6	74.2	58.4	39.3	30.2	21.8	17.3	16.0	14.2	12.8	11.8	12.5
23.0 mfp	101.	82.7	62.4	41.6	31.9	22.8	18.3	16.5	14.9	13.6	12.6	13.3
24.0 mfp	110.	83.9	65.5	45.7	33.2	24.1	19.1	17.5	15.7	14.3	13.1	13.9
25.0 mfp	120.	90.7	70.8	47.5	34.9	24.8	20.4	18.4	16.5	14.8	13.6	14.6
26.0 mfp	127.	97.8	74.5	50.9	36.8	25.8	21.0	19.2	17.2	15.5	14.2	15.6
27.0 mfp	135.	108.	78.8	53.5	38.1	27.1	21.8	20.2	17.8	16.4	14.9	16.5
28.0 mfp	142.	109.	85.2	54.6	39.4	28.2	22.8	21.1	18.9	17.2	15.6	17.7
29.0 mfp	149.	116.	88.6	57.5	42.0	29.8	23.5	21.5	20.0	17.7	16.1	18.5
30.0 mfp	159.	125.	94.1	58.7	42.9	30.8	24.2	22.9	20.4	18.3	16.9	19.8
31.0 mfp	165.	129.	97.7	61.2	44.9	32.5	25.6	23.7	21.4	19.0	17.8	20.6
32.0 mfp	175.	135.	103.	63.8	46.1	33.2	26.6	24.7	22.4	19.7	18.5	21.6
33.0 mfp	185.	142.	107.	67.2	49.0	34.3	27.5	25.6	23.2	20.7	19.6	22.5
34.0 mfp	193.	148.	114.	68.6	49.7	35.1	28.4	26.6	24.2	21.5	20.5	23.9
35.0 mfp	198.	152.	120.	71.8	50.6	37.9	29.5	26.6	25.1	21.9	21.1	24.8
40.0 mfp	269.	195.	151.	89.9	60.9	43.0	33.7	32.1	29.1	25.6	25.9	30.9

Table A4. Exposure Buildup Factors of Heavy Concrete (Ba)

Photon Energy (MeV)	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.2	0.3	0.4	0.5
1.0 mfp	1.00	1.01	1.04	1.03	1.03	1.04	1.07	1.10	1.21	1.33	1.52	1.62	1.68
2.0 mfp	1.01	1.02	1.05	1.06	1.04	1.06	1.10	1.15	1.33	1.54	1.93	2.19	2.33
2.5 mfp	1.01	1.02	1.06	1.08	1.05	1.06	1.11	1.17	1.38	1.64	2.13	2.47	2.69
3.0 mfp	1.01	1.02	1.06	1.11	1.05	1.07	1.12	1.19	1.42	1.72	2.31	2.75	3.03
3.5 mfp	1.01	1.02	1.06	1.15	1.05	1.07	1.13	1.19	1.47	1.81	2.50	3.04	3.37
4.0 mfp	1.01	1.02	1.07	1.19	1.05	1.08	1.13	1.21	1.51	1.88	2.69	3.31	3.74
4.5 mfp	1.01	1.02	1.07	1.27	1.06	1.07	1.14	1.22	1.54	1.95	2.86	3.59	4.11
5.0 mfp	1.01	1.02	1.08	1.37	1.06	1.08	1.15	1.23	1.57	2.03	3.02	3.88	4.47
5.5 mfp	1.01	1.02	1.08	1.51	1.07	1.08	1.15	1.24	1.60	2.10	3.21	4.17	4.87
6.0 mfp	1.01	1.02	1.08	1.71	1.07	1.09	1.16	1.25	1.63	2.16	3.38	4.47	5.25
6.5 mfp	1.01	1.02	1.08	2.01	1.07	1.09	1.16	1.26	1.66	2.23	3.55	4.74	5.63
7.0 mfp	1.01	1.02	1.08	2.43	1.08	1.09	1.17	1.27	1.69	2.28	3.72	5.04	6.06
7.5 mfp	1.01	1.02	1.08	3.04	1.08	1.10	1.17	1.28	1.71	2.35	3.89	5.30	6.46
8.0 mfp	1.01	1.02	1.09	3.92	1.09	1.10	1.18	1.29	1.73	2.39	4.07	5.62	6.83
9.0 mfp	1.01	1.03	1.09	6.98	1.11	1.12	1.18	1.30	1.78	2.52	4.38	6.18	7.60
10.0 mfp	1.01	1.03	1.09	13.4	1.13	1.11	1.19	1.31	1.81	2.63	4.70	6.74	8.54
11.0 mfp	1.01	1.03	1.09	26.7	1.17	1.11	1.20	1.32	1.85	2.73	5.01	7.37	9.40
12.0 mfp	1.01	1.03	1.09	54.4	1.23	1.12	1.21	1.34	1.90	2.83	5.33	7.95	10.2
13.0 mfp	1.01	1.03	1.10	112.	1.33	1.12	1.21	1.34	1.93	2.93	5.62	8.58	11.2
14.0 mfp	1.01	1.03	1.10	232.	1.49	1.13	1.22	1.36	1.96	3.01	5.99	9.11	12.2
15.0 mfp	1.01	1.03	1.10	483.	1.76	1.13	1.22	1.37	1.99	3.10	6.20	9.85	13.0
16.0 mfp	1.01	1.03	1.10	1.01E+3	2.22	1.14	1.23	1.37	2.02	3.18	6.47	10.4	13.9
17.0 mfp	1.01	1.03	1.11	2.10E+3	2.98	1.15	1.23	1.38	2.05	3.24	6.76	11.0	15.1
18.0 mfp	1.02	1.03	1.11	4.38E+3	4.26	1.16	1.24	1.39	2.09	3.32	7.05	11.5	16.1
19.0 mfp	1.01	1.03	1.11	9.15E+3	6.41	1.17	1.24	1.40	2.11	3.35	7.28	12.2	17.0
20.0 mfp	1.01	1.03	1.11	1.91E+4	10.1	1.19	1.24	1.40	2.13	3.43	7.62	12.7	18.2
21.0 mfp	1.01	1.03	1.11	4.00E+4	16.4	1.21	1.25	1.41	2.15	3.51	7.86	13.2	19.1
22.0 mfp	1.01	1.03	1.11	8.36E+4	27.1	1.23	1.25	1.42	2.17	3.57	8.17	13.9	20.1
23.0 mfp	1.02	1.03	1.11	1.75E+5	45.5	1.26	1.26	1.42	2.19	3.63	8.41	14.4	21.1
24.0 mfp	1.01	1.03	1.11	3.66E+5	76.9	1.30	1.26	1.42	2.21	3.70	8.64	15.3	22.4
25.0 mfp	1.02	1.03	1.12	7.65E+5	131.	1.36	1.26	1.42	2.23	3.77	8.87	15.7	23.1
26.0 mfp	1.01	1.03	1.12	1.60E+6	222.	1.42	1.26	1.44	2.25	3.82	9.24	16.4	23.9
27.0 mfp	1.01	1.03	1.12	3.35E+6	394.	1.52	1.26	1.44	2.26	3.89	9.50	16.9	25.0
28.0 mfp	1.01	1.03	1.12	7.00E+6	647.	1.63	1.26	1.45	2.29	3.94	9.62	17.5	26.4
29.0 mfp	1.02	1.04	1.12	1.46E+7	1.11E+3	1.77	1.27	1.45	2.34	4.02	9.92	18.0	27.4
30.0 mfp	1.02	1.04	1.12	3.08E+7	1.90E+3	2.00	1.28	1.45	2.32	4.11	10.3	19.2	28.0
31.0 mfp	1.02	1.03	1.12	6.44E+7	3.36E+3	2.23	1.28	1.45	2.33	4.13	10.6	19.9	29.3
32.0 mfp	1.02	1.04	1.12	1.35E+8	5.66E+3	2.59	1.29	1.46	2.37	4.17	10.8	20.4	30.7
33.0 mfp	1.02	1.03	1.12	2.83E+8	9.74E+3	3.06	1.28	1.46	2.38	4.27	11.1	21.3	31.3
34.0 mfp	1.02	1.04	1.12	5.93E+8	1.68E+4	3.75	1.28	1.46	2.40	4.25	11.4	22.0	32.9
35.0 mfp	1.02	1.04	1.13	1.25E+9	2.92E+4	4.45	1.28	1.48	2.39	4.30	11.6	22.3	34.2
40.0 mfp	1.02	1.04	1.13	5.08E+10	4.54E+5	14.5	1.29	1.50	2.52	4.59	13.1	26.4	41.4

Table A4. (Continued) Exposure Buildup Factors of Heavy Concrete (Ba)

Photon Energy (MeV)	0.6	0.8	1	1.5	2	3	4	5	6	8	10	15
1.0 mfp	1.70	1.71	1.70	1.67	1.65	1.60	1.56	1.53	1.50	1.47	1.46	1.48
2.0 mfp	2.41	2.46	2.45	2.39	2.32	2.18	2.08	1.99	1.93	1.86	1.84	1.90
2.5 mfp	2.78	2.86	2.87	2.77	2.68	2.49	2.34	2.23	2.15	2.06	2.03	2.11
3.0 mfp	3.16	3.29	3.28	3.16	3.05	2.81	2.62	2.48	2.37	2.26	2.22	2.33
3.5 mfp	3.55	3.71	3.72	3.58	3.43	3.14	2.91	2.73	2.61	2.46	2.43	2.56
4.0 mfp	3.95	4.16	4.18	4.01	3.81	3.47	3.20	2.98	2.85	2.67	2.64	2.81
4.5 mfp	4.43	4.64	4.64	4.44	4.22	3.79	3.50	3.25	3.10	2.90	2.85	3.07
5.0 mfp	4.84	5.13	5.11	4.87	4.61	4.13	3.83	3.51	3.36	3.13	3.08	3.33
5.5 mfp	5.28	5.63	5.63	5.35	5.04	4.51	4.16	3.80	3.63	3.38	3.32	3.62
6.0 mfp	5.75	6.15	6.15	5.81	5.48	4.88	4.47	4.09	3.91	3.62	3.56	3.92
6.5 mfp	6.19	6.65	6.67	6.32	5.92	5.26	4.81	4.40	4.20	3.87	3.81	4.22
7.0 mfp	6.67	7.22	7.22	6.81	6.36	5.65	5.15	4.69	4.49	4.12	4.07	4.55
7.5 mfp	7.15	7.73	7.76	7.34	6.84	6.07	5.50	5.01	4.79	4.38	4.33	4.91
8.0 mfp	7.64	8.24	8.37	7.79	7.31	6.47	5.86	5.34	5.09	4.69	4.62	5.27
9.0 mfp	8.66	9.49	9.63	8.85	8.23	7.32	6.60	5.98	5.72	5.26	5.23	6.02
10.0 mfp	9.67	10.7	10.8	9.97	9.19	8.09	7.36	6.61	6.37	5.88	5.83	6.88
11.0 mfp	10.7	11.9	12.1	11.2	10.2	8.97	8.11	7.39	7.04	6.51	6.50	7.86
12.0 mfp	11.8	13.2	13.3	12.4	11.3	9.88	8.96	8.17	7.75	7.21	7.26	8.95
13.0 mfp	12.8	14.5	14.5	13.6	12.4	10.9	9.84	8.92	8.44	7.93	8.10	10.1
14.0 mfp	14.1	15.9	16.1	14.9	13.7	11.8	10.7	9.68	9.24	8.68	8.89	11.5
15.0 mfp	15.2	17.2	17.4	16.1	14.7	12.8	11.6	10.5	9.98	9.46	9.82	12.9
16.0 mfp	16.2	18.6	18.8	17.4	15.8	13.8	12.4	11.4	10.8	10.3	10.8	14.5
17.0 mfp	17.6	20.1	20.3	18.5	16.9	14.9	13.4	12.2	11.7	11.1	11.7	16.3
18.0 mfp	18.8	21.6	21.6	19.7	18.2	16.0	14.3	13.2	12.6	12.2	12.8	18.3
19.0 mfp	19.9	23.1	23.2	21.2	19.4	17.1	15.4	14.1	13.4	13.2	13.9	20.4
20.0 mfp	20.9	24.7	25.0	22.1	20.5	18.4	16.3	14.9	14.2	14.2	14.9	23.1
21.0 mfp	22.6	26.2	26.5	23.4	21.7	19.5	17.5	16.0	15.4	15.2	16.2	25.7
22.0 mfp	23.6	27.7	27.7	24.6	23.0	20.6	18.5	16.9	16.4	16.3	17.6	28.4
23.0 mfp	24.7	29.4	29.4	26.2	24.0	21.7	19.8	18.1	17.6	17.6	19.1	31.9
24.0 mfp	26.1	30.5	31.1	27.4	25.0	22.8	20.9	18.9	18.6	19.0	21.0	35.6
25.0 mfp	27.3	32.6	32.5	28.4	26.5	24.1	22.2	20.3	19.5	20.3	22.8	38.9
26.0 mfp	29.1	34.4	34.0	30.1	28.3	25.2	23.0	21.2	20.8	21.8	24.4	42.9
27.0 mfp	30.5	35.9	35.7	31.0	29.9	26.3	24.1	22.3	22.0	23.3	26.5	47.6
28.0 mfp	32.2	37.3	37.3	33.1	31.3	27.1	24.9	23.7	23.7	24.9	28.3	53.2
29.0 mfp	34.1	39.3	39.2	34.3	32.7	28.0	26.0	24.8	25.1	25.9	30.1	59.9
30.0 mfp	35.0	41.4	41.3	35.4	32.9	28.9	27.2	25.5	26.9	27.4	32.4	65.0
31.0 mfp	36.9	42.7	43.5	36.7	35.1	30.1	28.2	26.6	28.3	29.5	34.8	72.6
32.0 mfp	38.1	44.1	45.9	38.4	36.9	31.3	29.5	27.6	29.5	31.2	36.9	79.4
33.0 mfp	40.2	45.6	48.1	39.2	38.6	32.2	30.7	28.6	30.7	33.4	39.8	87.3
34.0 mfp	41.3	47.9	49.3	41.1	39.8	32.8	32.2	29.4	32.1	34.9	42.8	96.3
35.0 mfp	44.1	49.6	51.0	42.7	41.1	34.9	35.1	31.0	33.2	36.2	44.5	107.
40.0 mfp	52.0	61.1	61.5	51.2	49.5	42.6	44.4	37.5	41.9	46.9	60.3	159.

Table A5. Ambient Dose Equivalent Buildup Factors of Heavy Concrete (Ba)

Photon Energy (MeV)	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.2	0.3	0.4	0.5
1.0 mfp	1.00	1.01	1.03	1.02	1.02	1.04	1.07	1.10	1.22	1.34	1.55	1.66	1.71
2.0 mfp	1.01	1.01	1.04	1.05	1.04	1.05	1.10	1.15	1.34	1.56	1.98	2.25	2.40
2.5 mfp	1.01	1.01	1.05	1.07	1.04	1.06	1.11	1.17	1.39	1.66	2.18	2.54	2.76
3.0 mfp	1.01	1.02	1.05	1.09	1.04	1.06	1.12	1.19	1.44	1.75	2.36	2.83	3.12
3.5 mfp	1.01	1.01	1.05	1.12	1.04	1.07	1.12	1.19	1.48	1.84	2.57	3.13	3.48
4.0 mfp	1.01	1.01	1.06	1.16	1.05	1.07	1.13	1.21	1.52	1.91	2.76	3.41	3.86
4.5 mfp	1.01	1.02	1.06	1.21	1.05	1.07	1.14	1.22	1.56	1.98	2.94	3.70	4.24
5.0 mfp	1.01	1.02	1.06	1.30	1.06	1.08	1.14	1.24	1.58	2.06	3.11	4.00	4.62
5.5 mfp	1.01	1.02	1.07	1.42	1.06	1.08	1.15	1.25	1.62	2.13	3.30	4.30	5.03
6.0 mfp	1.01	1.02	1.07	1.58	1.06	1.08	1.16	1.25	1.65	2.20	3.48	4.61	5.43
6.5 mfp	1.01	1.02	1.07	1.82	1.06	1.09	1.16	1.26	1.67	2.26	3.66	4.90	5.83
7.0 mfp	1.01	1.02	1.07	2.17	1.07	1.09	1.17	1.27	1.71	2.32	3.84	5.21	6.27
7.5 mfp	1.01	1.02	1.07	2.66	1.07	1.09	1.17	1.28	1.72	2.38	4.01	5.48	6.69
8.0 mfp	1.01	1.02	1.08	3.38	1.07	1.09	1.17	1.29	1.75	2.43	4.20	5.81	7.08
9.0 mfp	1.01	1.02	1.08	5.89	1.09	1.10	1.18	1.30	1.79	2.56	4.51	6.39	7.88
10.0 mfp	1.01	1.02	1.08	11.1	1.11	1.10	1.19	1.31	1.83	2.68	4.84	6.97	8.85
11.0 mfp	1.01	1.02	1.08	22.0	1.13	1.10	1.20	1.33	1.87	2.78	5.17	7.63	9.75
12.0 mfp	1.01	1.03	1.08	44.6	1.18	1.11	1.21	1.34	1.91	2.88	5.49	8.23	10.6
13.0 mfp	1.01	1.03	1.09	91.9	1.25	1.11	1.21	1.35	1.95	2.98	5.80	8.88	11.6
14.0 mfp	1.01	1.03	1.09	190.	1.36	1.12	1.22	1.36	1.98	3.07	6.18	9.43	12.7
15.0 mfp	1.01	1.03	1.09	396.	1.56	1.12	1.22	1.37	2.01	3.15	6.39	10.2	13.5
16.0 mfp	1.01	1.03	1.09	825.	1.89	1.13	1.22	1.37	2.04	3.23	6.67	10.7	14.5
17.0 mfp	1.01	1.03	1.09	1.72E+3	2.43	1.13	1.23	1.38	2.07	3.30	6.97	11.4	15.7
18.0 mfp	1.01	1.03	1.10	3.59E+3	3.36	1.14	1.23	1.39	2.11	3.37	7.28	12.0	16.7
19.0 mfp	1.01	1.03	1.10	7.51E+3	4.92	1.15	1.24	1.40	2.13	3.41	7.51	12.6	17.7
20.0 mfp	1.01	1.03	1.10	1.57E+4	7.61	1.16	1.24	1.40	2.15	3.48	7.86	13.1	18.9
21.0 mfp	1.01	1.03	1.10	3.28E+4	12.1	1.18	1.25	1.41	2.17	3.57	8.11	13.7	19.8
22.0 mfp	1.01	1.03	1.10	6.87E+4	19.8	1.19	1.25	1.42	2.19	3.63	8.44	14.4	20.9
23.0 mfp	1.01	1.03	1.10	1.44E+5	33.3	1.22	1.25	1.42	2.21	3.69	8.68	15.0	21.9
24.0 mfp	1.01	1.03	1.10	3.00E+5	56.1	1.24	1.25	1.43	2.23	3.76	8.92	15.8	23.3
25.0 mfp	1.01	1.03	1.11	6.29E+5	95.4	1.28	1.25	1.43	2.26	3.83	9.15	16.2	24.1
26.0 mfp	1.01	1.03	1.11	1.32E+6	161.	1.33	1.26	1.44	2.27	3.88	9.54	17.0	24.9
27.0 mfp	1.01	1.03	1.11	2.75E+6	287.	1.40	1.26	1.44	2.29	3.96	9.80	17.5	26.0
28.0 mfp	1.01	1.03	1.11	5.76E+6	471.	1.48	1.26	1.45	2.31	4.01	9.93	18.1	27.5
29.0 mfp	1.02	1.03	1.11	1.21E+7	811.	1.58	1.27	1.45	2.36	4.10	10.2	18.6	28.5
30.0 mfp	1.02	1.03	1.11	2.54E+7	1.39E+3	1.74	1.27	1.45	2.35	4.17	10.6	19.9	29.1
31.0 mfp	1.01	1.03	1.11	5.31E+7	2.41E+3	1.90	1.27	1.46	2.36	4.20	10.9	20.7	30.4
32.0 mfp	1.01	1.03	1.11	1.11E+8	4.13E+3	2.16	1.29	1.46	2.40	4.25	11.2	21.2	31.9
33.0 mfp	1.01	1.03	1.12	2.34E+8	7.12E+3	2.49	1.28	1.47	2.40	4.35	11.5	22.1	32.5
34.0 mfp	1.02	1.03	1.12	4.89E+8	1.23E+4	2.98	1.28	1.46	2.42	4.33	11.7	22.9	34.2
35.0 mfp	1.02	1.03	1.12	1.03E+9	2.13E+4	3.48	1.28	1.48	2.42	4.37	12.0	23.1	35.5
40.0 mfp	1.02	1.03	1.12	4.20E+10	3.33E+5	10.6	1.28	1.49	2.54	4.67	13.5	27.4	43.1

Table A5.(Continued) Ambient Dose Equivalent Buildup Factors of Heavy Concrete (Ba)

Photon Energy (MeV)	0.6	0.8	1	1.5	2	3	4	5	6	8	10	15
1.0 mfp	1.74	1.75	1.74	1.71	1.67	1.63	1.58	1.55	1.53	1.50	1.49	1.70
2.0 mfp	2.48	2.53	2.53	2.47	2.36	2.23	2.11	2.03	1.97	1.90	1.88	2.29
2.5 mfp	2.87	2.95	2.96	2.87	2.72	2.55	2.39	2.28	2.19	2.10	2.07	2.60
3.0 mfp	3.26	3.39	3.40	3.28	3.10	2.88	2.67	2.53	2.42	2.31	2.27	2.91
3.5 mfp	3.67	3.84	3.85	3.72	3.50	3.21	2.97	2.79	2.66	2.51	2.49	3.23
4.0 mfp	4.09	4.30	4.34	4.17	3.88	3.55	3.27	3.04	2.91	2.74	2.70	3.58
4.5 mfp	4.60	4.81	4.82	4.63	4.31	3.89	3.58	3.33	3.17	2.97	2.92	3.95
5.0 mfp	5.02	5.33	5.31	5.08	4.70	4.24	3.91	3.60	3.44	3.21	3.16	4.32
5.5 mfp	5.48	5.84	5.86	5.59	5.15	4.63	4.25	3.89	3.71	3.46	3.41	4.73
6.0 mfp	5.97	6.39	6.41	6.07	5.59	5.00	4.57	4.18	4.00	3.71	3.66	5.16
6.5 mfp	6.42	6.92	6.95	6.61	6.04	5.40	4.93	4.50	4.30	3.97	3.91	5.59
7.0 mfp	6.93	7.50	7.53	7.13	6.50	5.80	5.28	4.80	4.60	4.23	4.17	6.06
7.5 mfp	7.43	8.05	8.10	7.69	6.99	6.23	5.64	5.13	4.91	4.49	4.45	6.57
8.0 mfp	7.94	8.57	8.74	8.16	7.47	6.64	6.00	5.47	5.22	4.81	4.74	7.08
9.0 mfp	9.00	9.89	10.1	9.28	8.42	7.52	6.76	6.13	5.86	5.40	5.38	8.15
10.0 mfp	10.1	11.2	11.3	10.5	9.39	8.31	7.54	6.78	6.53	6.04	5.99	9.37
11.0 mfp	11.1	12.4	12.6	11.7	10.5	9.22	8.32	7.58	7.22	6.68	6.68	10.8
12.0 mfp	12.2	13.7	13.9	13.0	11.6	10.2	9.19	8.38	7.95	7.41	7.46	12.3
13.0 mfp	13.4	15.1	15.2	14.3	12.7	11.2	10.1	9.15	8.66	8.15	8.34	14.0
14.0 mfp	14.7	16.5	16.8	15.7	14.0	12.1	11.0	9.93	9.49	8.92	9.14	16.0
15.0 mfp	15.8	17.9	18.2	16.9	15.0	13.2	11.9	10.8	10.2	9.73	10.1	18.0
16.0 mfp	16.9	19.4	19.7	18.3	16.2	14.2	12.7	11.7	11.1	10.6	11.1	20.3
17.0 mfp	18.3	20.9	21.2	19.5	17.3	15.4	13.7	12.6	12.0	11.5	12.1	22.8
18.0 mfp	19.6	22.6	22.6	20.7	18.6	16.5	14.7	13.5	12.9	12.5	13.2	25.7
19.0 mfp	20.7	24.1	24.3	22.4	19.8	17.6	15.8	14.4	13.7	13.6	14.4	28.7
20.0 mfp	21.8	25.8	26.2	23.3	21.0	18.9	16.7	15.3	14.6	14.6	15.4	32.6
21.0 mfp	23.6	27.4	27.8	24.7	22.3	20.1	18.0	16.4	15.8	15.6	16.7	36.3
22.0 mfp	24.6	29.0	29.1	25.9	23.5	21.2	19.0	17.3	16.8	16.8	18.1	40.2
23.0 mfp	25.8	30.8	30.9	27.6	24.6	22.4	20.3	18.6	18.1	18.1	19.7	45.2
24.0 mfp	27.3	31.8	32.6	28.9	25.6	23.5	21.4	19.4	19.1	19.5	21.6	50.5
25.0 mfp	28.5	34.1	34.1	29.9	27.1	24.8	22.9	20.8	20.0	20.9	23.5	55.4
26.0 mfp	30.3	36.0	35.7	31.7	29.0	26.0	23.7	21.8	21.4	22.4	25.1	61.1
27.0 mfp	31.8	37.5	37.4	32.7	30.6	27.1	24.8	22.9	22.6	23.9	27.3	67.8
28.0 mfp	33.6	39.0	39.2	34.9	32.0	27.9	25.6	24.3	24.4	25.6	29.2	75.9
29.0 mfp	35.5	41.1	41.1	36.0	33.5	28.9	26.7	25.5	25.8	26.7	31.0	85.6
30.0 mfp	36.6	43.3	43.4	37.2	33.7	29.8	27.9	26.1	27.6	28.3	33.4	92.8
31.0 mfp	38.5	44.6	45.6	38.6	36.0	31.1	29.0	27.3	29.1	30.4	35.9	104.
32.0 mfp	39.7	46.1	48.2	40.5	37.8	32.3	30.3	28.3	30.3	32.1	38.0	114.
33.0 mfp	42.0	47.6	50.5	41.4	39.6	33.2	31.5	29.4	31.5	34.4	41.0	125.
34.0 mfp	43.1	50.1	51.8	43.4	40.8	33.8	33.0	30.2	33.0	36.0	44.2	138.
35.0 mfp	46.1	51.9	53.6	45.0	42.0	36.0	36.1	31.8	34.1	37.3	45.9	153.
40.0 mfp	54.3	63.9	64.5	54.0	50.8	43.9	45.8	38.6	43.0	48.3	62.2	228.

Table A6. Effective Dose Buildup Factors of Heavy Concrete (Ba)

Photon Energy (MeV)	0.015	0.02	0.03	0.04	0.05	0.06	0.08	0.1	0.15	0.2	0.3	0.4	0.5
1.0 mfp	1.00	1.01	1.03	1.02	1.02	1.03	1.06	1.10	1.22	1.35	1.55	1.66	1.71
2.0 mfp	1.01	1.01	1.05	1.05	1.03	1.05	1.09	1.15	1.34	1.57	1.98	2.25	2.40
2.5 mfp	1.01	1.01	1.05	1.06	1.04	1.05	1.10	1.16	1.39	1.67	2.18	2.54	2.76
3.0 mfp	1.01	1.02	1.05	1.09	1.04	1.06	1.11	1.19	1.44	1.75	2.37	2.83	3.11
3.5 mfp	1.01	1.02	1.06	1.11	1.04	1.06	1.12	1.19	1.48	1.84	2.57	3.13	3.48
4.0 mfp	1.01	1.02	1.06	1.15	1.04	1.07	1.13	1.21	1.53	1.91	2.76	3.41	3.85
4.5 mfp	1.01	1.02	1.07	1.21	1.05	1.07	1.14	1.22	1.56	1.98	2.94	3.70	4.24
5.0 mfp	1.01	1.02	1.07	1.29	1.05	1.07	1.14	1.23	1.59	2.07	3.11	4.00	4.62
5.5 mfp	1.01	1.02	1.07	1.41	1.05	1.07	1.15	1.24	1.62	2.14	3.31	4.31	5.03
6.0 mfp	1.01	1.02	1.07	1.57	1.06	1.08	1.15	1.25	1.65	2.20	3.48	4.61	5.42
6.5 mfp	1.01	1.02	1.07	1.80	1.06	1.08	1.16	1.26	1.68	2.27	3.66	4.90	5.82
7.0 mfp	1.01	1.02	1.08	2.14	1.06	1.08	1.16	1.27	1.71	2.33	3.84	5.21	6.27
7.5 mfp	1.01	1.02	1.08	2.62	1.06	1.09	1.17	1.28	1.73	2.39	4.01	5.48	6.69
8.0 mfp	1.01	1.02	1.08	3.33	1.07	1.09	1.17	1.29	1.75	2.44	4.20	5.81	7.08
9.0 mfp	1.01	1.02	1.08	5.77	1.08	1.09	1.18	1.30	1.80	2.57	4.52	6.40	7.87
10.0 mfp	1.01	1.02	1.08	10.9	1.09	1.10	1.19	1.31	1.84	2.68	4.85	6.98	8.84
11.0 mfp	1.01	1.03	1.09	21.5	1.11	1.10	1.19	1.32	1.87	2.79	5.17	7.63	9.74
12.0 mfp	1.01	1.03	1.09	43.7	1.15	1.10	1.20	1.34	1.92	2.88	5.50	8.24	10.6
13.0 mfp	1.01	1.03	1.09	90.0	1.20	1.10	1.21	1.34	1.95	2.99	5.80	8.89	11.6
14.0 mfp	1.01	1.03	1.09	187.	1.30	1.11	1.21	1.36	1.99	3.08	6.18	9.43	12.6
15.0 mfp	1.01	1.03	1.10	388.	1.45	1.11	1.22	1.37	2.01	3.16	6.40	10.2	13.5
16.0 mfp	1.01	1.03	1.10	809.	1.71	1.12	1.22	1.37	2.04	3.24	6.68	10.7	14.5
17.0 mfp	1.01	1.03	1.10	1.69E+3	2.15	1.12	1.23	1.38	2.07	3.31	6.98	11.4	15.7
18.0 mfp	1.01	1.03	1.10	3.53E+3	2.88	1.13	1.23	1.39	2.11	3.38	7.28	12.0	16.7
19.0 mfp	1.01	1.03	1.10	7.37E+3	4.13	1.14	1.23	1.40	2.14	3.42	7.52	12.6	17.6
20.0 mfp	1.01	1.03	1.10	1.54E+4	6.28	1.15	1.24	1.40	2.15	3.49	7.87	13.1	18.8
21.0 mfp	1.01	1.03	1.11	3.22E+4	9.91	1.16	1.24	1.41	2.17	3.59	8.11	13.7	19.8
22.0 mfp	1.01	1.03	1.11	6.75E+4	16.1	1.17	1.24	1.42	2.19	3.64	8.44	14.5	20.9
23.0 mfp	1.01	1.03	1.11	1.41E+5	26.9	1.19	1.25	1.42	2.21	3.70	8.69	15.0	21.9
24.0 mfp	1.01	1.03	1.11	2.95E+5	45.2	1.21	1.25	1.42	2.24	3.77	8.92	15.8	23.3
25.0 mfp	1.01	1.03	1.11	6.19E+5	76.8	1.23	1.25	1.43	2.26	3.84	9.15	16.2	24.0
26.0 mfp	1.01	1.03	1.11	1.30E+6	130.	1.27	1.26	1.44	2.27	3.89	9.54	17.0	24.8
27.0 mfp	1.01	1.03	1.11	2.71E+6	231.	1.31	1.26	1.44	2.29	3.97	9.81	17.5	25.9
28.0 mfp	1.01	1.03	1.11	5.67E+6	380.	1.37	1.26	1.45	2.32	4.02	9.94	18.1	27.4
29.0 mfp	1.02	1.03	1.11	1.19E+7	654.	1.45	1.27	1.45	2.36	4.11	10.2	18.7	28.5
30.0 mfp	1.02	1.03	1.12	2.50E+7	1.12E+3	1.56	1.27	1.45	2.35	4.18	10.6	19.9	29.1
31.0 mfp	1.02	1.03	1.12	5.23E+7	1.94E+3	1.68	1.27	1.45	2.36	4.22	10.9	20.7	30.4
32.0 mfp	1.02	1.03	1.12	1.10E+8	3.34E+3	1.86	1.28	1.46	2.40	4.26	11.2	21.2	31.9
33.0 mfp	1.02	1.03	1.12	2.30E+8	5.76E+3	2.10	1.27	1.46	2.40	4.36	11.5	22.1	32.5
34.0 mfp	1.02	1.04	1.12	4.83E+8	9.91E+3	2.44	1.27	1.46	2.42	4.34	11.7	22.9	34.2
35.0 mfp	1.02	1.03	1.12	1.02E+9	1.73E+4	2.80	1.28	1.48	2.42	4.39	12.0	23.1	35.5
40.0 mfp	1.02	1.03	1.13	4.14E+10	2.70E+5	7.91	1.28	1.49	2.54	4.68	13.5	27.4	43.0

Table A6. (Continued) Effective Dose Buildup Factors of Heavy Concrete (Ba)

Photon Energy (MeV)	0.6	0.8	1	1.5	2	3	4	5	6	8	10	15
1.0 mfp	1.73	1.74	1.73	1.69	1.67	1.62	1.57	1.54	1.51	1.49	1.48	1.49
2.0 mfp	2.47	2.52	2.50	2.43	2.36	2.21	2.10	2.01	1.95	1.88	1.86	1.92
2.5 mfp	2.86	2.93	2.93	2.82	2.72	2.52	2.36	2.25	2.17	2.08	2.05	2.13
3.0 mfp	3.25	3.37	3.36	3.22	3.10	2.85	2.64	2.50	2.39	2.28	2.24	2.36
3.5 mfp	3.66	3.82	3.81	3.64	3.49	3.17	2.94	2.75	2.63	2.48	2.46	2.59
4.0 mfp	4.07	4.28	4.29	4.09	3.88	3.51	3.23	3.01	2.88	2.70	2.67	2.84
4.5 mfp	4.58	4.77	4.76	4.53	4.30	3.84	3.54	3.29	3.13	2.93	2.88	3.10
5.0 mfp	5.00	5.29	5.24	4.97	4.69	4.19	3.87	3.55	3.39	3.17	3.11	3.36
5.5 mfp	5.45	5.80	5.78	5.46	5.14	4.58	4.20	3.84	3.66	3.41	3.36	3.66
6.0 mfp	5.94	6.34	6.32	5.94	5.59	4.94	4.52	4.13	3.95	3.66	3.60	3.96
6.5 mfp	6.40	6.86	6.86	6.46	6.04	5.33	4.87	4.44	4.24	3.91	3.86	4.27
7.0 mfp	6.90	7.44	7.43	6.96	6.49	5.73	5.21	4.73	4.54	4.17	4.11	4.60
7.5 mfp	7.40	7.98	7.99	7.50	6.98	6.15	5.57	5.06	4.84	4.43	4.38	4.96
8.0 mfp	7.90	8.50	8.62	7.97	7.46	6.56	5.93	5.40	5.14	4.74	4.67	5.33
9.0 mfp	8.96	9.81	9.93	9.05	8.41	7.42	6.68	6.05	5.78	5.32	5.29	6.09
10.0 mfp	10.0	11.1	11.1	10.2	9.38	8.20	7.45	6.68	6.43	5.94	5.90	6.96
11.0 mfp	11.1	12.3	12.4	11.4	10.5	9.10	8.21	7.47	7.11	6.58	6.58	7.96
12.0 mfp	12.2	13.6	13.7	12.7	11.6	10.0	9.07	8.26	7.83	7.29	7.34	9.05
13.0 mfp	13.3	15.0	15.0	13.9	12.7	11.1	9.96	9.02	8.53	8.02	8.20	10.3
14.0 mfp	14.6	16.4	16.6	15.3	14.0	11.9	10.9	9.78	9.34	8.78	8.99	11.6
15.0 mfp	15.8	17.8	18.0	16.5	15.0	13.0	11.7	10.6	10.1	9.57	9.94	13.1
16.0 mfp	16.8	19.2	19.4	17.8	16.2	14.0	12.6	11.5	10.9	10.4	10.9	14.7
17.0 mfp	18.2	20.8	20.9	19.0	17.3	15.2	13.5	12.4	11.8	11.3	11.9	16.5
18.0 mfp	19.5	22.4	22.3	20.1	18.6	16.2	14.5	13.3	12.7	12.3	13.0	18.5
19.0 mfp	20.6	23.9	24.0	21.8	19.8	17.4	15.6	14.2	13.5	13.3	14.1	20.6
20.0 mfp	21.7	25.6	25.8	22.6	21.0	18.6	16.5	15.0	14.4	14.3	15.1	23.3
21.0 mfp	23.5	27.1	27.4	24.0	22.2	19.8	17.7	16.1	15.6	15.3	16.4	26.0
22.0 mfp	24.5	28.7	28.6	25.2	23.5	20.9	18.8	17.1	16.5	16.5	17.8	28.8
23.0 mfp	25.7	30.5	30.4	26.9	24.6	22.1	20.0	18.3	17.8	17.8	19.4	32.3
24.0 mfp	27.1	31.5	32.1	28.1	25.6	23.2	21.1	19.1	18.8	19.2	21.3	36.0
25.0 mfp	28.3	33.8	33.5	29.1	27.1	24.5	22.5	20.5	19.7	20.5	23.1	39.4
26.0 mfp	30.2	35.6	35.1	30.8	29.0	25.6	23.3	21.5	21.1	22.0	24.7	43.5
27.0 mfp	31.7	37.2	36.8	31.8	30.6	26.7	24.4	22.6	22.2	23.5	26.8	48.2
28.0 mfp	33.4	38.7	38.6	33.9	32.0	27.5	25.2	23.9	24.0	25.2	28.7	53.8
29.0 mfp	35.3	40.7	40.5	35.1	33.4	28.4	26.4	25.1	25.4	26.3	30.5	60.7
30.0 mfp	36.4	42.9	42.7	36.2	33.7	29.3	27.5	25.7	27.2	27.8	32.8	65.8
31.0 mfp	38.3	44.2	44.9	37.6	36.0	30.6	28.5	26.9	28.6	29.9	35.2	73.5
32.0 mfp	39.5	45.7	47.4	39.3	37.8	31.8	29.9	27.9	29.8	31.6	37.4	80.4
33.0 mfp	41.8	47.2	49.7	40.2	39.5	32.7	31.1	28.9	31.0	33.8	40.3	88.4
34.0 mfp	42.9	49.6	51.0	42.2	40.7	33.3	32.6	29.7	32.5	35.4	43.3	97.5
35.0 mfp	45.8	51.4	52.8	43.7	42.0	35.5	35.6	31.3	33.5	36.7	45.1	108.
40.0 mfp	54.0	63.3	63.5	52.5	50.7	43.3	45.0	38.0	42.3	47.5	61.1	161.

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	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

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m-1
密度（質量密度）	キログラム毎立法メートル	kg/m^3
質量体積（比体積）	立法メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
（物質量の）濃度	モル毎立方メートル	mol/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率	（数の）1	1

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	μ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表３．固有の名称とその独自の記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[a]	rad		$m \cdot m^{-1}=1$ [b]
立体角	ステラジアン[a]	sr[c]		$m^2 \cdot m^{-2}=1$ [b]
周波数	ヘルツ	Hz		s^{-1}
力	ニュートン	N		$m \cdot kg \cdot s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N・m	$m^2 \cdot kg \cdot s^{-2}$
工率，放射束	ワット	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
電荷，電気量	クーロン	C		s・A
電位差（電圧），起電力	ボルト	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
電気抵抗	オーム	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
磁束	ウエーバ	Wb	V・s	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
セルシウス温度	セルシウス度[d]	℃		K
光束	ルーメン	lm	cd・sr[c]	$m^2 \cdot m^{-2} \cdot cd=cd$
照度	ルクス	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd=m^{-2} \cdot cd$
（放射性核種の）放射能	ベクレル	Bq		s^{-1}
吸収線量，質量エネルギー分与，カーマ	グレイ	Gy	J/kg	$m^2 \cdot s^{-2}$
線量当量，周辺線量当量，方向性線量当量，個人線量当量，組織線量当	シーベルト	Sv	J/kg	$m^2 \cdot s^{-2}$

(a) ラジアン及びステラジアンの使用は、同じ次元であっても異なった性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表４に示されている。
(b) 実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“1”は明示されない。
(c) 測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。
(d) この単位は、例としてミリセルシウス度m℃のようにSI接頭語を伴って用いても良い。

表４．単位の中に固有の名称とその独自の記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa・s	$m^{-1} \cdot kg \cdot s^{-1}$
力のモーメント	ニュートンメートル	N・m	$m^2 \cdot kg \cdot s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg \cdot s^{-2}$
角速度	ラジアン毎秒	rad/s	$m \cdot m^{-1} \cdot s^{-1}=s^{-1}$
角加速度	ラジアン毎平方秒	rad/s^2	$m \cdot m^{-1} \cdot s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg \cdot s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
質量熱容量（比熱容量），質量エントロピー	ジュール毎キログラム毎ケルビン	J/(kg・K)	$m^2 \cdot s^{-2} \cdot K^{-1}$
質量エネルギー（比エネルギー）	ジュール毎キログラム	J/kg	$m^2 \cdot s^{-2} \cdot K^{-1}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m・K)	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
体積電荷	クーロン毎立方メートル	C/m^3	$m^{-3} \cdot s \cdot A$
電気変位	クーロン毎平方メートル	C/m^2	$m^{-2} \cdot s \cdot A$
誘電率	ファラド毎メートル	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
透磁率	ヘンリー毎メートル	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
モルエントロピー，モル熱容量	ジュール毎モル毎ケルビン	J/(mol・K)	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1} \cdot s \cdot A$
吸収線量率	グレイ毎秒	Gy/s	$m^2 \cdot s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4 \cdot m^{-2} \cdot kg \cdot s^{-3}=m^2 \cdot kg \cdot s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2 \cdot sr)$	$m^2 \cdot m^{-2} \cdot kg \cdot s^{-3}=kg \cdot s^{-3}$

表６．国際単位系と併用されるが国際単位系に属さない単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86400 s
度	°	1° =(π/180) rad
分	'	1' =(1/60)° =(π/10800) rad
秒	"	1" =(1/60)' =(π/648000) rad
リットル	l、L	1l=1 $dm^3=10^{-3}m^3$
トン	t	1t=10^3 kg
ネーパ	Np	1Np=1
ベル	B	1B=(1/2)ln10(Np)

表７．国際単位系と併用されこれに属さない単位で
SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位であらわされる数値
電子ボルト	eV	1eV=1.60217733(49)$\times10^{-19}$J
統一原子質量単位	u	1u=1.6605402(10)$\times10^{-27}$kg
天文単位	ua	1ua=1.49597870691(30)$\times10^{11}$m

表８．国際単位系に属さないが国際単位系と
併用されるその他の単位

名称	記号	SI 単位であらわされる数値
海里		1海里=1852m
ノット		1ノット=1海里毎時=(1852/3600)m/s
アール	a	1 a=1 $dam^2=10^2m^2$
ヘクタール	ha	1 ha=1 $hm^2=10^4m^2$
バール	bar	1 bar=0.1MPa=100kPa=1000hPa=10^5Pa
オングストローム	Å	1 Å=0.1nm=10^{-10}m
バーン	b	1 b=100$fm^2=10^{-28}m^2$

表９．固有の名称を含むCGS組立単位

名称	記号	SI 単位であらわされる数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn・s/cm^2=0.1Pa・s
ストークス	St	1 St =1cm^2/s=$10^{-4}m^2$/s
ガウス	G	1 G ^10^{-4}T
エルステッド	Oe	1 Oe ^(1000/4π)A/m
マクスウェル	Mx	1 Mx ^10^{-8}Wb
スチルブ	sb	1 sb =1cd/cm^2=10^4cd/m^2
ホト	ph	1 ph=10^4lx
ガル	Gal	1 Gal =1cm/s^2=10^{-2}m/s^2

表10．国際単位に属さないその他の単位の例

名称	記号	SI 単位であらわされる数値
キュリー	Ci	1 Ci=3.7$\times10^{10}$Bq
レントゲン	R	1 R = 2.58$\times10^{-4}$C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
X線単位		1X unit=1.002$\times10^{-4}$nm
ガンマ	γ	1γ=1 nT=10^{-9}T
ジャンスキー	Jy	1 Jy=$10^{-26}W \cdot m^{-2} \cdot Hz^{-1}$
フェルミ		1 fermi=1 fm=10^{-15}m
メートル系カラット		1 metric carat = 200 mg = 2$\times10^{-4}$kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	
ミクロン	μ	1 μ =1μm=10^{-6}m

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