

Engineering Compendium on Radiation Shielding

Prepared by numerous specialists

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Notation and Units (Continued)

Symbol	Name or definition	Units	Where used
$-\Delta\kappa_n^{DBM}$	Davies-Bethe-Maximon Coulomb correction to κ_n^{BH} (Born)	b/atom	Table 4.2-9b; Eqs. (4.2-21), (-24)
σ_R	Rayleigh ("coherent") scattering cross section per atom	b/atom	Sec. 4.2.6.; Tables 4.2-11, -12; Fig. 4.2-1; Eq. (4.2-31)
$F(q, Z)$	atomic form factor	dimensionless	Eq. (4.2-31)
θ_c	criterion angle for assessing importance of Rayleigh scattering	degrees or radians	Eq. (4.2-32)
σ_{pn}	total photonuclear cross section $= \sigma(\gamma, n) + \sigma(\gamma, p) + \dots$	b/atom or mb/atom	Sec. 4.2.7.; Table 4.2-13
E_m	energy at which the maximum of the σ_{pn} resonance peak occurs	MeV	Table 4.2-13

4.1.3. DEFINITION AND SIGNIFICANCE OF NARROW-BEAM ATTENUATION COEFFICIENT

The most important quantity characterizing the penetration and diffusion of gamma radiation in extended media is the attenuation coefficient, μ . This quantity depends on the photon energy E and on the atomic number Z of the medium, and may be defined as the probability per unit pathlength that a photon will interact with the medium.

Consider, as a typical situation, a slab of material of thickness t located between a narrowly collimated source of monoenergetic gamma ray photons and a narrowly collimated detector, as indicated in Fig. 4.1-1. In a layer dx within the slab there will occur a reduction of the intensity, I , of the gamma ray beam, due to:

- (1) outright absorption, or
- (2) scattering out of the beam.

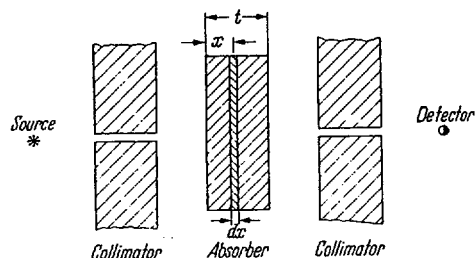


Fig. 4.1-1. Arrangement for experimental determination of narrow-beam attenuation coefficients.

The resulting fractional reduction of the beam intensity, $-dI/I$, is proportional to the "narrow beam" attenuation coefficient, μ , and to the layer thickness, dx , i.e.,

$$-dI/I = \mu dx. \quad (4.1-1)$$

Integrating this equation and assuming that the beam intensity incident on the slab has the value I_0 , one obtains for the intensity transmitted through the slab the value

$$I(t) = I_0 \exp \left\{ - \int_0^t \mu(x) dx \right\}. \quad (4.1-2)$$

For a homogeneous medium this reduces to

$$I(t) = I_0 e^{-\mu t}. \quad (4.1-3)$$

For situations more complicated than the narrow-beam experiment, the attenuation is still basically exponential but is modified by two additional factors. The first of these, sometimes called a "geometry factor", depends essentially on the source geometry and involves, for example, the insertion of the inverse square law in Eq. (4.1-3) for a point isotropic source. The other factor, often called the "buildup factor", takes into account secondary photons produced in the absorber (mainly as the result of one or more Compton scatters) which reach the detector. The determination of such buildup factors constitutes a large part of gamma ray transport theory and is discussed further in Sec. 4.3. on "broad beam attenuation".

In the narrow-beam equation (4.1-3), the absorber thickness t in which the beam intensity is reduced by a factor e (i.e., $I/I_0 = 1/e = 0.36788$), is called the mean-free-path. One mean-free-path (mfp) also represents the average distance traveled by a photon between successive interactions. Analogous quantities are the half-value layer and one-tenth-value layer, $t_{1/2}$ and $t_{1/10}$, in which the

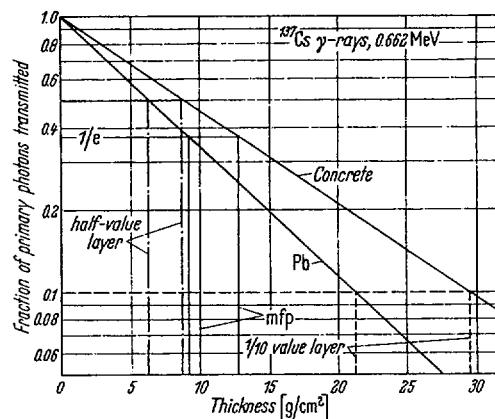


Fig. 4.1-2. Semi-log plot of narrow-beam attenuation of ^{137}Cs (0.662 MeV) gamma rays in lead and concrete. Graphical determinations of the mean-free-path and of the $1/2$ and $1/10$ -value layers are indicated.

(Ed. note: It is common practice to call "mass thickness", which is linear thickness times density, simply "thickness". The units g/cm^2 used here make it obvious that mass thickness is the abscissa for this figure.)

Table 4.1.-3. (Continued)

Photon energy [MeV]	¹⁴ Si	¹⁵ P	¹⁶ S	¹⁸ Ar	¹⁹ K	²⁰ Ca	²⁶ Fe	²⁹ Cu
0.01	33.6	40.2	50.3	63.8	80.1	95.6	172.0	223.0
0.015	9.97	12.0	15.2	19.5	24.6	29.6	55.7	73.3
0.02	4.20	5.10	6.42	8.27	10.5	12.6	25.1	33.0
0.03	1.31	1.55	1.95	2.48	3.14	3.82	7.88	10.6
0.04	0.635	0.731	0.891	1.11	1.39	1.67	3.46	4.71
0.05	0.396	0.441	0.524	0.630	0.777	0.925	1.84	2.50
0.06	0.292	0.318	0.367	0.420	0.512	0.595	1.13	1.52
0.08	0.207	0.215	0.238	0.252	0.296	0.334	0.550	0.718
0.10	0.173	0.175	0.189	0.189	0.216	0.237	0.342	0.427
0.15	0.140	0.138	0.145	0.136	0.150	0.159	0.184	0.208
0.2	0.125	0.122	0.127	0.117	0.128	0.133	0.139	0.148
0.3	0.107	0.104	0.108	0.0979	0.106	0.109	0.107	0.108
0.4	0.0954	0.0928	0.0958	0.0868	0.0938	0.0966	0.0921	0.0919
0.5	0.0870	0.0846	0.0873	0.0789	0.0852	0.0877	0.0829	0.0821
0.6	0.0804	0.0781	0.0806	0.0729	0.0786	0.0809	0.0761	0.0752
0.8	0.0706	0.0685	0.0707	0.0639	0.0689	0.0709	0.0664	0.0654
1.0	0.0634	0.0617	0.0635	0.0574	0.0619	0.0636	0.0596	0.0586
1.5	0.0517	0.0502	0.0517	0.0468	0.0505	0.0519	0.0486	0.0478
2	0.0447	0.0436	0.0448	0.0406	0.0439	0.0451	0.0425	0.0419
3	0.0367	0.0358	0.0371	0.0338	0.0366	0.0377	0.0361	0.0359
4	0.0324	0.0317	0.0329	0.0302	0.0328	0.0340	0.0331	0.0332
5	0.0297	0.0292	0.0304	0.0280	0.0306	0.0318	0.0315	0.0318
6	0.0279	0.0275	0.0287	0.0267	0.0292	0.0304	0.0306	0.0309
8	0.0257	0.0255	0.0268	0.0252	0.0277	0.0289	0.0299	0.0307
10	0.0246	0.0245	0.0259	0.0245	0.0270	0.0284	0.0299	0.0310
15	0.0235	0.0237	0.0252	0.0242	0.0269	0.0284	0.0309	0.0324
20	0.0234	0.0236	0.0253	0.0246	0.0274	0.0291	0.0322	0.0341
30	0.0239	0.0243	0.0262	0.0257	0.0287	0.0308	0.0347	0.0370
40	0.0246	0.0251	0.0271	0.0267	0.0300	0.0321	0.0367	0.0393
50	0.0252	0.0258	0.0279	0.0276	0.0311	0.0333	0.0384	0.0412
60	0.0256	0.0264	0.0286	0.0284	0.0319	0.0343	0.0397	0.0426
80	0.0268	0.0275	0.0299	0.0297	0.0335	0.0359	0.0418	0.0449
100	0.0276	0.0283	0.0308	0.0307	0.0346	0.0371	0.0432	0.0466

4.1.-3 through the experimental points for each measured element. Values of μ/ρ were read from these curves at 200, 300, ..., 10 000 MeV, and they are as listed in Table 4.1.-6 without parentheses. These values were then converted to b/atom using Table 4.1.-1, and the values in parentheses (converted back to cm²/g) were filled in by smooth interpolation vs. Z . We estimate the accuracy of Table 4.1.-6, considering consistency between authors, their stated experimental uncertainties, and density of data-points, to be ~2 to 3% at 1 GeV and ~5 to 10% at 10 GeV.

4.1.5. DEFINITION AND SIGNIFICANCE OF ENERGY-ABSORPTION COEFFICIENTS AND RELATED QUANTITIES

4.1.5.1. MODES OF ENERGY TRANSFER

The effects of gamma rays on irradiated media are largely indirect, i.e., they occur via electrons (or positrons) which are set in motion as a result of gamma ray interactions with matter, and then dissipate their energy as they are brought to rest. The relation between electron (or positron) energy deposition in a medium and the various physical, chemical, and biological effects is complicated and,

in most cases, not well understood. However, it is commonly assumed that the amount of energy absorbed per unit mass of the medium (absorbed dose) is a significant parameter which provides a basis for discussing radiation effects.

The transfer of energy from photons to electrons, and vice versa, takes place in a complex chain of events with feedbacks as indicated in the flow diagram in Fig. 4.1.-3 (p. 176)¹⁾. Following this flow diagram, a complete treatment of an energy deposition problem should take into account all indicated energy transfer routes leading to electron collision losses and associated typical effects such as are listed in the bottom right triangle²⁾.

¹⁾ Although the diagram in Fig. 4.1.-3 treats electrons and positrons alike, there are actually small differences in the rates by which they lose energy (see NELMS [67] and BERGER and SELTZER [68]).

²⁾ Additional energy transfer routes, not shown in Fig. 4.1.-3, occur in the case of nuclear absorption, shown simply as an "energy sink" in the lower left triangle. The neutrons, charged particles and gamma rays resulting from such an event will, in turn, either directly or indirectly transfer additional kinetic energy to electrons. These additional routes were disregarded by R. BERGER [49], ALLISON [50] and in the present work.

These notes with page 77
of
"An Industrial Gamma Irradiation
for Medical Supplies"

Interpolate 0.662 to 0.0729
1/0.0729 = 13.7

This table * density = linear Attenuation coef.

tors very closely over the whole range of distances involved (out to 15 or 20 mean-free-path lengths), and for energies from 0.5 to 10 MeV. These are given in Tables 4.3.-9 and 4.3.-10. Note that the formula provides polynomial expansions in terms of both distance and source photon energy. This avoids the necessity of interpolation with respect to energy as well as with respect to distance.

Table 4.3.-9 also includes coefficients provided by BUSCAGLIONE and MANZINI [14] for exposure buildup in concrete covering point sources of energy from 0.5 to 10.0 MeV and distances out to 20 mean-free-path lengths. The concrete types included are ordinary, magnetite, ferrophosphorus, and barytes. They were calculated by interpolation from known buildup factor data for elementary materials on the assumption that these concretes behave like elementary materials of atomic numbers 11, 17, 21, and 27, respectively. Since the use of the "average atomic number" concept for composite materials is

to some extent an approximation, buildup factors obtained from these coefficients tabulated for concrete must be considered as probably somewhat less accurate than those provided by CAPO for more elemental materials. In addition, there is some degree of variability in the composition of concrete, even for a certain specific type, so that one should not expect high precision in practice by use of such tabulations. Unpublished Monte Carlo calculations based directly on concrete attenuation factors rather than on average atomic number have been carried out by the present author for ordinary concrete, and they confirm that the data presented here, although giving results a little high, especially at lower energies, are valid within perhaps about 20% overall.

TAYLOR's formula is well known, but its accuracy is not always comparable to that of the original data, as shown, for example, by BIBERGAL and LESHCHINSKII in the case of water [15]. Values of

Table 4.3.-6. Values of parameters in BERGER's formula for exposure buildup factors — Point isotropic source, infinite medium

E_0 [MeV]	a	b	E_0 [MeV]	a	b
Water			Tungsten		
0.255	2.2887	0.2035	0.5	0.2828	-0.0609
0.5	1.4386	0.1772	1.0	0.4358	-0.0198
1.0	1.1046	0.0907	2.0	0.4233	0.0026
2.0	0.8229	0.0346	3.0	0.3460	0.0338
3.0	0.6913	0.0105	4.0	0.2711	0.0665
4.0	0.5801	0.0024	6.0	0.1751	0.1092
6.0	0.4633	-0.0109	8.0	0.1232	0.1261
8.0	0.3819	-0.0174	10.0	0.0954	0.1317
10.0	0.3298	-0.0208	Lead		
Aluminum			0.5	0.2425	-0.0696
0.5	1.2874	0.1121	1.0	0.3701	-0.0326
1.0	0.9886	0.0751	2.0	0.3836	-0.0007
2.0	0.7417	0.0410	3.0	0.3193	0.0283
3.0	0.6345	0.0197	4.0	0.2520	0.0562
4.0	0.5273	0.0113	5.11	0.1928	0.0854
6.0	0.4165	0.0072	6.0	0.1603	0.1060
8.0	0.3363	0.0060	8.0	0.1181	0.1200
10.0	0.2739	0.0072	10.0	0.0915	0.1264
Iron			Uranium		
0.5	0.9214	0.0698	0.5	0.1740	-0.0774
1.0	0.8359	0.0619	1.0	0.3113	-0.0492
2.0	0.6976	0.0342	2.0	0.3284	-0.0121
3.0	0.5378	0.0346	3.0	0.2796	0.0220
4.0	0.4390	0.0337	4.0	0.2275	0.0471
6.0	0.3294	0.0430	6.0	0.1465	0.0944
8.0	0.2564	0.0463	8.0	0.1064	0.1132
10.0	0.1882	0.0581	10.0	0.0781	0.1244
Tin					
0.5	0.5552	-0.0109			
1.0	0.6237	0.0233			
2.0	0.5531	0.0316			
3.0	0.4405	0.0457			
4.0	0.3601	0.0583			
6.0	0.2372	0.0920			
8.0	0.1685	0.1120			
10.0	0.1220	0.1227			

this formula's parameters are available to the interested reader in the GOLDSTEIN-WILKINS report or in TAYLOR's original paper [16].

Example: The exposure buildup factor for 3 MeV photons from a point source in water at a distance of 2 mean-free-path lengths, according to Table 4.3.-3, is 2.42. By the use of the linear formula, k would be 0.69 and thus one would get $B = 1 + 0.69 \cdot 2 = 2.38$. By the use of BERGER's formula and CHILTON's parameter values from Table 4.3.-6, one calculates the buildup factor as $B = 1 + 0.6913 \cdot 2 \cdot e^{0.0105 \cdot 2}$, or 2.41. By the use of CAPO's formula and the parameter values from Table 4.3.-9, the buildup factor is calculated as follows:

$$\beta_0 = 1.01094 - \frac{0.0600394}{3} + \frac{0.0720778}{3^2} - \frac{0.0301498}{3^3} + \frac{0.00394733}{3^4} = 0.9979,$$

$$\beta_1 = 0.116772 + \frac{2.32125}{3} - \frac{2.12801}{3^2} + \frac{0.767783}{3^3} - \frac{0.0908139}{3^4} = 0.6814,$$

$$\beta_2 = -0.00765869 - \frac{0.0179023}{3} + \frac{0.241735}{3^2} - \frac{0.0434443}{3^3} - \frac{0.00134203}{3^4} = 0.01161,$$

$$\beta_3 = 0.000167068 + \frac{0.000569295}{3} - \frac{0.00796332}{3^2} + \frac{0.00723758}{3^3} - \frac{0.000987237}{3^4} = -0.000272,$$

$$B = 0.9979 + 0.6814 \cdot 2 + 0.01161 \cdot 2^2 - 0.000272 \cdot 2^3 = 2.40.$$

Then, if the exposure rate 1 cm from a point source of 3 MeV photons is 100 R/h, the dose rate at 50.5 cm (number of mean-free-path lengths, μr , is $0.0396 \cdot 50.5$, or 2.00) is given by $D = 2.42 \cdot 100 \cdot e^{-2/(50.5)^2}$, or 0.0128 R/h, where the directly tabulated buildup factor value is used.

BERGER [17] has recently provided new moment calculations for point sources in light media. Although calculated and presented as energy deposition buildup factors, they will serve approximately (Continued p. 218)

Table 4.3.-7. Values of parameters in BERGER's formula for energy fluence buildup factors - Point isotropic source, infinite medium

E_0 [MeV]	a	b	E_0 [MeV]	a	b
Water			Tungsten		
0.255	1.9716	0.1996	0.5	0.2753	-0.0593
0.5	1.4763	0.1599	1.0	0.4182	-0.0199
1.0	1.0751	0.0853	2.0	0.3800	0.0070
2.0	0.7239	0.0334	3.0	0.2989	0.0356
3.0	0.5779	0.0099	4.0	0.2264	0.0667
4.0	0.4705	0.0032	6.0	0.1424	0.1060
6.0	0.3635	-0.0083	8.0	0.0997	0.1200
8.0	0.2957	-0.0121	10.0	0.0786	0.1216
10.0	0.2620	-0.0157	Lead		
Aluminum			0.5	0.2394	-0.0693
0.5	1.3592	0.1139	1.0	0.3513	-0.0304
1.0	0.9796	0.0749	2.0	0.3437	0.0009
2.0	0.6619	0.0394	3.0	0.2797	0.0287
3.0	0.5292	0.0203	4.0	0.2179	0.0529
4.0	0.4342	0.0105	5.11	0.1629	0.0815
6.0	0.3303	0.0091	6.0	0.1344	0.1000
8.0	0.2668	0.0066	8.0	0.0954	0.1161
10.0	0.2189	0.0099	10.0	0.0763	0.1147
Iron			Uranium		
0.5	0.9632	0.0690	0.5	0.1719	-0.0767
1.0	0.8100	0.0625	1.0	0.2999	-0.0488
2.0	0.5872	0.0410	2.0	0.3005	-0.0115
3.0	0.4658	0.0337	3.0	0.2434	0.0240
4.0	0.3721	0.0330	4.0	0.1977	0.0445
6.0	0.2693	0.0399	6.0	0.1258	0.0880
8.0	0.2032	0.0471	8.0	0.0885	0.1060
10.0	0.1616	0.0546	10.0	0.0689	0.1113
Tin					
0.5	0.5529	-0.0118			
1.0	0.5969	0.0237			
2.0	0.4889	0.0318			
3.0	0.3714	0.0454			
4.0	0.2966	0.0571			
6.0	0.1929	0.0867			
8.0	0.1362	0.1050			
10.0	0.1002	0.1142			

Capo - Cesium @ .662 = $1.001 + .941\mu r + .36\mu r^2 + .003\mu r^3$

Table 4.3.-8. Values of parameters in BERGER's formula for energy deposition buildup factors — Point isotropic source, infinite medium

E_0 [MeV]	a	b	E_0 [MeV]	a	b
Water			Tin		
0.255	1.8632	0.2213	0.5	1.2392	-0.0174
0.5	1.3782	0.1728	1.0	1.0735	0.0149
1.0	1.1007	0.0958	2.0	0.7171	0.0347
2.0	0.8411	0.0363	3.0	0.4713	0.0466
3.0	0.7409	0.0097	4.0	0.3265	0.0585
4.0	0.5879	0.0022	6.0	0.1918	0.0837
6.0	0.4587	-0.0099	8.0	0.1266	0.0972
8.0	0.3825	-0.0164	10.0	0.0976	0.1029
10.0	0.3113	-0.0194	Lead		
Aluminum			0.5	0.4991	-0.1000
0.5	1.5207	0.1204	1.0	0.7544	-0.0449
1.0	1.1347	0.0728	2.0	0.5662	-0.0080
2.0	0.7967	0.0420	3.0	0.3528	0.0214
3.0	0.6560	0.0203	4.0	0.2235	0.0522
4.0	0.5349	0.0107	5.11	0.1707	0.0728
6.0	0.3977	0.0070	6.0	0.1227	0.0938
8.0	0.3070	0.0066	8.0	0.0862	0.1032
10.0	0.2487	0.0078	10.0	0.0672	0.1005
Iron					
0.5	1.6865	0.0689			
1.0	1.1406	0.0626			
2.0	0.7583	0.0368			
3.0	0.5662	0.0332			
4.0	0.4413	0.0329			
6.0	0.2901	0.0413			
8.0	0.2032	0.0471			
10.0	0.1542	0.0564			

Table 4.3.-10. Values of parameter C_{ij} in CAPO's formula for energy deposition buildup factors — Point isotropic source, infinite medium

j	$i = 0$	1	2	3
Water				
0	$1.00935 \cdot 10^0$	$6.75909 \cdot 10^{-2}$	$-2.88512 \cdot 10^{-3}$	$3.54158 \cdot 10^{-5}$
1	$-5.05187 \cdot 10^{-2}$	$2.73952 \cdot 10^0$	$-7.11806 \cdot 10^{-2}$	$1.98272 \cdot 10^{-3}$
2	$5.93863 \cdot 10^{-2}$	$-2.82306 \cdot 10^0$	$3.98796 \cdot 10^{-1}$	$-1.19564 \cdot 10^{-2}$
3	$-2.43717 \cdot 10^{-2}$	$1.11668 \cdot 10^0$	$-1.50948 \cdot 10^{-1}$	$9.52922 \cdot 10^{-3}$
4	$3.14779 \cdot 10^{-3}$	$-1.41350 \cdot 10^{-1}$	$1.65266 \cdot 10^{-2}$	$-1.36541 \cdot 10^{-3}$
Aluminum				
0	$9.97130 \cdot 10^{-1}$	$-3.85219 \cdot 10^{-2}$	$1.27816 \cdot 10^{-2}$	$-3.39093 \cdot 10^{-4}$
1	$6.54640 \cdot 10^{-2}$	$3.27946 \cdot 10^0$	$-1.64393 \cdot 10^{-1}$	$5.04304 \cdot 10^{-3}$
2	$-2.68716 \cdot 10^{-1}$	$-4.74349 \cdot 10^0$	$7.45795 \cdot 10^{-1}$	$-2.38346 \cdot 10^{-2}$
3	$2.84908 \cdot 10^{-1}$	$3.39495 \cdot 10^0$	$-6.26720 \cdot 10^{-1}$	$2.53658 \cdot 10^{-2}$
4	$-8.33177 \cdot 10^{-2}$	$-8.37392 \cdot 10^{-1}$	$1.66032 \cdot 10^{-1}$	$-7.07268 \cdot 10^{-3}$
Iron				
0	$1.00009 \cdot 10^0$	$-9.76981 \cdot 10^{-2}$	$3.07480 \cdot 10^{-3}$	$5.43036 \cdot 10^{-4}$
1	$-2.69391 \cdot 10^{-2}$	$2.81567 \cdot 10^0$	$5.47069 \cdot 10^{-2}$	$-3.05850 \cdot 10^{-3}$
2	$1.06797 \cdot 10^{-1}$	$-3.14590 \cdot 10^0$	$-1.33763 \cdot 10^{-4}$	$2.43681 \cdot 10^{-3}$
3	$-1.11725 \cdot 10^{-1}$	$1.91566 \cdot 10^0$	$1.03003 \cdot 10^{-1}$	$-1.57016 \cdot 10^{-3}$
4	$3.27028 \cdot 10^{-2}$	$-4.17820 \cdot 10^{-1}$	$-4.79248 \cdot 10^{-2}$	$5.35111 \cdot 10^{-4}$
Lead				
0	$9.99305 \cdot 10^{-1}$	$-3.49764 \cdot 10^{-1}$	$2.89886 \cdot 10^{-2}$	$1.28555 \cdot 10^{-3}$
1	$1.13017 \cdot 10^{-2}$	$2.79914 \cdot 10^0$	$-7.10002 \cdot 10^{-2}$	$-4.75607 \cdot 10^{-3}$
2	$-3.44367 \cdot 10^{-3}$	$-2.20399 \cdot 10^0$	$-1.11108 \cdot 10^{-2}$	$7.04843 \cdot 10^{-3}$
3	$2.04092 \cdot 10^{-3}$	$5.02301 \cdot 10^{-1}$	$1.45444 \cdot 10^{-2}$	$-2.31052 \cdot 10^{-3}$

Table 4.3.-9. Values of parameters C_{ij} in CAPO's formula for exposure buildup factors — Point isotropic source, infinite medium

j	$i = 0$	1	2	3
Water				
0	$1.01094 \cdot 10^0$	$1.16772 \cdot 10^{-1}$	$-7.65869 \cdot 10^{-3}$	$1.67068 \cdot 10^{-4}$
1	$-6.00394 \cdot 10^{-2}$	$2.32125 \cdot 10^0$	$-1.79023 \cdot 10^{-2}$	$5.69295 \cdot 10^{-4}$
2	$7.20778 \cdot 10^{-2}$	$-2.12801 \cdot 10^0$	$2.41735 \cdot 10^{-1}$	$-7.96332 \cdot 10^{-3}$
3	$-3.01498 \cdot 10^{-2}$	$7.67783 \cdot 10^{-1}$	$-4.34443 \cdot 10^{-2}$	$7.23758 \cdot 10^{-3}$
4	$3.94733 \cdot 10^{-3}$	$-9.08139 \cdot 10^{-2}$	$-1.34203 \cdot 10^{-3}$	$-9.87237 \cdot 10^{-4}$
Aluminum				
0	$1.00768 \cdot 10^0$	$-1.03807 \cdot 10^{-2}$	$1.30705 \cdot 10^{-2}$	$-3.29348 \cdot 10^{-4}$
1	$-4.98085 \cdot 10^{-2}$	$3.32216 \cdot 10^0$	$-1.58167 \cdot 10^{-1}$	$4.60315 \cdot 10^{-3}$
2	$7.23425 \cdot 10^{-2}$	$-5.52427 \cdot 10^0$	$6.89496 \cdot 10^{-1}$	$-2.04255 \cdot 10^{-2}$
3	$-3.93841 \cdot 10^{-2}$	$4.16700 \cdot 10^0$	$-5.59836 \cdot 10^{-1}$	$2.00554 \cdot 10^{-2}$
4	$7.35778 \cdot 10^{-3}$	$-1.04638 \cdot 10^0$	$1.41308 \cdot 10^{-1}$	$-5.29934 \cdot 10^{-3}$
Iron				
0	$1.01460 \cdot 10^0$	$-4.12104 \cdot 10^{-2}$	$1.88074 \cdot 10^{-3}$	$1.20198 \cdot 10^{-3}$
1	$-1.88657 \cdot 10^{-1}$	$2.72752 \cdot 10^0$	$1.00217 \cdot 10^{-1}$	$-9.83313 \cdot 10^{-3}$
2	$6.38649 \cdot 10^{-1}$	$-3.76728 \cdot 10^0$	$-1.31988 \cdot 10^{-1}$	$2.06002 \cdot 10^{-2}$
3	$-6.55159 \cdot 10^{-1}$	$2.42384 \cdot 10^0$	$1.68976 \cdot 10^{-1}$	$-1.75251 \cdot 10^{-2}$
4	$1.90742 \cdot 10^{-1}$	$-5.54657 \cdot 10^{-1}$	$-5.80710 \cdot 10^{-2}$	$4.75673 \cdot 10^{-3}$
Ordinary concrete ^{a)}				
0	$9.3368 \cdot 10^{-1}$	$1.2046 \cdot 10^{-1}$	$-4.1739 \cdot 10^{-3}$	$1.0626 \cdot 10^{-4}$
1	$3.2095 \cdot 10^0$	$1.3049 \cdot 10^0$	$4.5191 \cdot 10^{-2}$	$-1.4593 \cdot 10^{-3}$
2	$-1.2066 \cdot 10^1$	$1.0892 \cdot 10^0$	$7.9888 \cdot 10^{-2}$	$-2.3189 \cdot 10^{-3}$
3	$1.1583 \cdot 10^1$	$-1.1306 \cdot 10^0$	$-1.1193 \cdot 10^{-1}$	$7.3120 \cdot 10^{-3}$
4	$-3.1406 \cdot 10^0$	$2.3122 \cdot 10^{-1}$	$4.5724 \cdot 10^{-2}$	$-1.7597 \cdot 10^{-3}$
Magnetite concrete ^{a)}				
0	$1.1552 \cdot 10^0$	$-4.2798 \cdot 10^{-2}$	$1.3402 \cdot 10^{-2}$	$-1.0598 \cdot 10^{-4}$
1	$-1.4852 \cdot 10^0$	$3.3548 \cdot 10^0$	$-1.1491 \cdot 10^{-1}$	$1.3261 \cdot 10^{-3}$
2	$4.1211 \cdot 10^0$	$-5.0124 \cdot 10^0$	$4.5050 \cdot 10^{-1}$	$-6.4846 \cdot 10^{-3}$
3	$-4.8274 \cdot 10^0$	$3.9411 \cdot 10^0$	$-3.3907 \cdot 10^{-1}$	$5.2485 \cdot 10^{-3}$
4	$1.5641 \cdot 10^0$	$-1.0845 \cdot 10^0$	$8.8020 \cdot 10^{-2}$	$-1.3924 \cdot 10^{-3}$
Ferrophosphorus concrete ^{a)}				
0	$9.1266 \cdot 10^{-1}$	$6.9926 \cdot 10^{-2}$	$-4.2108 \cdot 10^{-3}$	$8.2296 \cdot 10^{-4}$
1	$7.4394 \cdot 10^{-1}$	$2.3276 \cdot 10^0$	$4.5025 \cdot 10^{-2}$	$-4.6242 \cdot 10^{-3}$
2	$-1.9041 \cdot 10^0$	$-2.3910 \cdot 10^0$	$1.4831 \cdot 10^{-2}$	$8.0834 \cdot 10^{-3}$
3	$8.1771 \cdot 10^{-1}$	$1.5490 \cdot 10^0$	$2.2113 \cdot 10^{-2}$	$-6.1558 \cdot 10^{-3}$
4	$-4.5739 \cdot 10^{-2}$	$-3.9851 \cdot 10^{-1}$	$-1.1561 \cdot 10^{-2}$	$1.6045 \cdot 10^{-3}$
Barytes concrete ^{a)}				
0	$9.2229 \cdot 10^{-1}$	$5.6213 \cdot 10^{-2}$	$-1.5123 \cdot 10^{-2}$	$2.2190 \cdot 10^{-3}$
1	$-2.2516 \cdot 10^{-1}$	$2.5211 \cdot 10^0$	$1.7424 \cdot 10^{-1}$	$-1.6242 \cdot 10^{-2}$
2	$6.6842 \cdot 10^{-1}$	$-2.9568 \cdot 10^0$	$-3.5783 \cdot 10^{-1}$	$3.7158 \cdot 10^{-2}$
3	$4.7302 \cdot 10^{-1}$	$6.7814 \cdot 10^{-1}$	$5.1702 \cdot 10^{-1}$	$-3.6732 \cdot 10^{-2}$
4	$-3.5229 \cdot 10^{-1}$	$1.2320 \cdot 10^{-1}$	$-1.8144 \cdot 10^{-1}$	$1.0835 \cdot 10^{-2}$
Lead				
0	$9.59342 \cdot 10^{-1}$	$6.78254 \cdot 10^{-2}$	$-2.26626 \cdot 10^{-2}$	$6.39872 \cdot 10^{-4}$
1	$1.13722 \cdot 10^{-1}$	$4.50412 \cdot 10^{-1}$	$7.55191 \cdot 10^{-3}$	$1.52094 \cdot 10^{-4}$
2	$-7.39816 \cdot 10^{-2}$	$-2.15037 \cdot 10^{-1}$	$5.10254 \cdot 10^{-3}$	$-6.04837 \cdot 10^{-4}$
3	$1.87767 \cdot 10^{-2}$	$4.05189 \cdot 10^{-2}$	$-1.89332 \cdot 10^{-3}$	$2.42263 \cdot 10^{-4}$
4	$-2.04254 \cdot 10^{-3}$	$-3.40802 \cdot 10^{-3}$	$1.93415 \cdot 10^{-4}$	$-2.93865 \cdot 10^{-5}$
5	$7.93621 \cdot 10^{-5}$	$1.06510 \cdot 10^{-4}$	$-6.24306 \cdot 10^{-6}$	$1.13914 \cdot 10^{-6}$
Uranium				
0	$1.01765 \cdot 10^0$	$4.24238 \cdot 10^{-2}$	$-1.42252 \cdot 10^{-2}$	$5.93162 \cdot 10^{-4}$
1	$-1.65482 \cdot 10^{-2}$	$3.31303 \cdot 10^{-1}$	$-2.90268 \cdot 10^{-3}$	$-1.84501 \cdot 10^{-4}$
2	$5.84308 \cdot 10^{-3}$	$-1.24381 \cdot 10^{-1}$	$6.06091 \cdot 10^{-3}$	$-7.15165 \cdot 10^{-5}$
3	$-8.56681 \cdot 10^{-4}$	$1.62433 \cdot 10^{-2}$	$-1.24102 \cdot 10^{-3}$	$3.86282 \cdot 10^{-5}$
4	$4.03127 \cdot 10^{-5}$	$-7.01931 \cdot 10^{-4}$	$6.59820 \cdot 10^{-5}$	$-2.68878 \cdot 10^{-6}$

^{a)} These coefficients have been provided by BUSCAGLIONE and MANZINI [14]. (Those not marked with an ^{a)} were originally calculated by CAPO [13].)