




Chapter 7: External Radiation Protection

Table of Contents

- ☞ Basic principles for external radiation protection
- ☞ Gamma ray shielding
 - ☞ General concepts
 - ☞ Buildup factor
 - ☞ Broad beam considerations
- ☞ X-ray shielding design
- ☞ Shielding for isotopic beta sources
- ☞ Neutron shielding

Basic Principle for Radiation Protection

Basic Principles

-  Maximizing distance
-  Minimizing exposure time
-  Shielding the radiation source

So How Much Shielding is Needed?

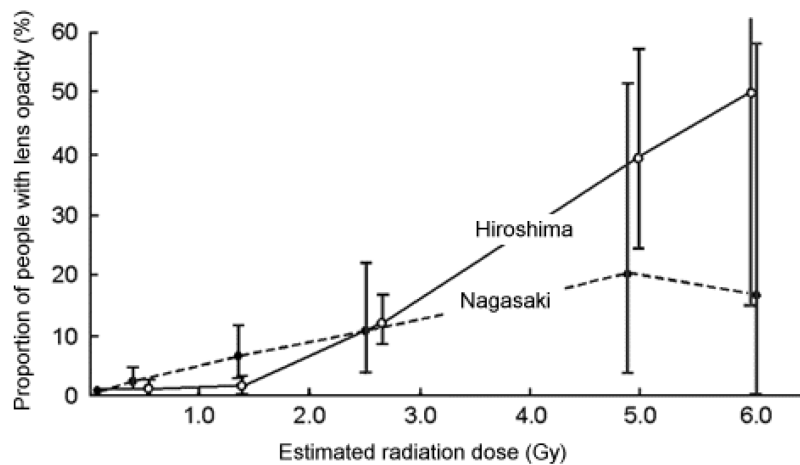
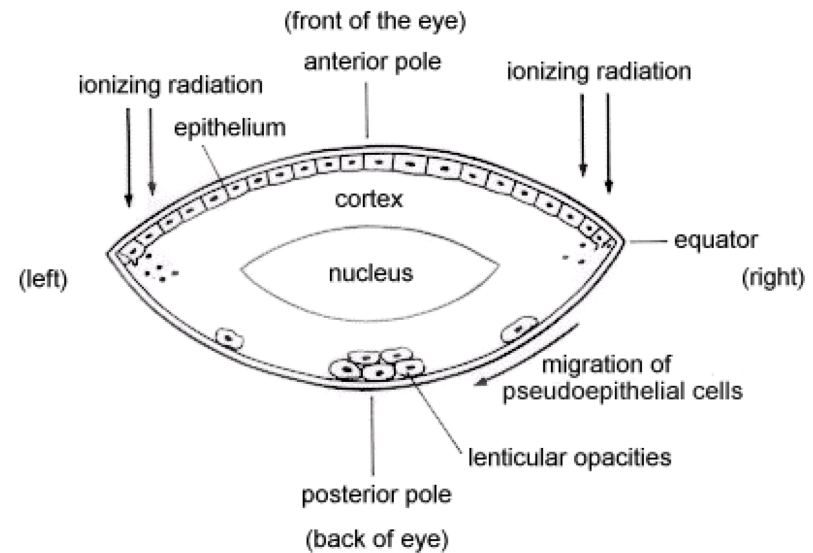
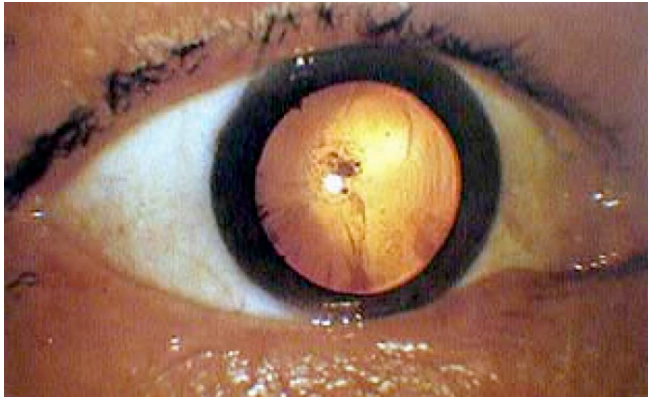
- ☞ To determine the shielding requirement, we need to compute the **dose equivalent** and **effective dose equivalent (EDE)**.

Deterministic and Stochastic Effects

The biological effects of radiation differs widely depending on the dose, kind of radiation. They can be divided into two general categories, stochastic and deterministic.

- ☞ **Stochastic effect** are those that occur in a statistical manner, such as cancer.
- ☞ **Deterministic effect** are those that show (a) a clear relationship between dose and effect in a given individual, and (b) a clear threshold for inducing the effect. Skin reddening and radiation-induced cataracts are examples of deterministic effects of radiation.

Delayed Effects – Cataracts



- ➡ Radiation damage to epithelial cells.
- ➡ Damaged cells move to the back of the eye and cause lens opacity by blocking light.
- ➡ Occurs with 50% chance for people with dose of ~500 rad.

Effective Dose, Weighting Factor (or Quality Factor)

Effective dose is absorbed dose modified by weighting factors for radiation type and exposed organs

Radiation type

- X-rays and gamma radiation
- beta, electrons
- neutrons
- alpha radiation

Weighting factor

1
1
3-20
20

Quality Factor

$$\text{Effective dose} = \sum_{organ} w_{organ} (w_R \times D_{organ})$$

whole body dose

Dose equivalent

Effective Dose

whole body

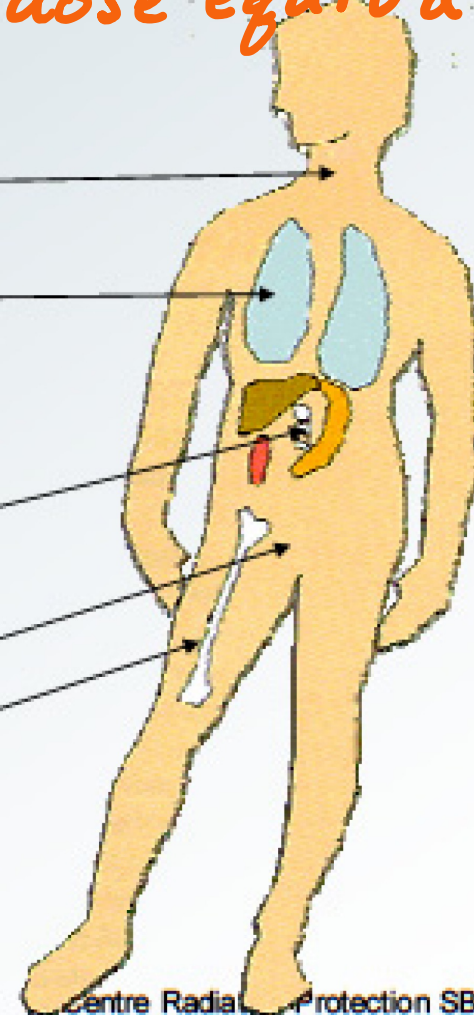
organ dose

$$Effective\ dose = \sum_{organ} w_{organ} (w_R \times D_{organ})$$

dose equivalent

For calculation of effective dose:

0.05	thyroid
0.05	breast tissue
0.12	lungs
0.05	esophagus
0.12	stomach
0.05	liver
0.12	colon
0.05	urinary bladder
0.20	reproductive organs
0.01	skin
0.12	red bone marrow
0.01	bone surface
0.05	<u>rest of body</u>
1.00	total



Basic Limits - Occupational Exposure

- ☞ The ICRP 26 basic annual limits recommended for exposure to workers
 - ☞ To limit nonstochastic effects
 - ☞ 0.5 Sv to all tissues except the lens of the eye
 - ☞ 0.15 Sv to the lens of the eye
 - ☞ To limit stochastic effects
 - ☞ 0.05 Sv per year

Gamma Ray Shielding Designs

Radiation Dose Induced by Gamma Radiation

Radiation Dose from a Gamma-Ray Point Source

Considering an I-131 point-source of 1 MBq, how do we evaluate the exposure it delivers at a distance of 1 m?

☞ The decay of ^{131}I produces gamma rays of various energies as shown below,

Quantum Energy, MeV	Photons per Transformation	Energy Absorption Coefficient for Air, m^{-1}
0.723	0.016	3.8×10^{-3}
0.637	0.069	3.9×10^{-3}
0.503	0.003	3.8×10^{-3}
0.326	0.002	3.8×10^{-3}
0.177	0.002	3.4×10^{-3}
0.365	0.853	3.8×10^{-3}
0.284	0.051	3.7×10^{-3}
0.080	0.051	3.2×10^{-3}
0.164	0.006	3.3×10^{-3}

Radiation Dose from a Gamma-Ray Point Source

For the 0.080-MeV gamma ray, we have

$$\dot{X} = \frac{5.1 \times 10^{-2} \times 8 \times 10^{-2} \times 1.6 \times 10^{-13} \times 1 \times 10^6 \times 3.6 \times 10^3 \times 3.2 \times 10^{-3}}{4\pi(1)^2 \times 1.293 \times 34}$$

$$= 1.36 \times 10^{-11} \frac{\text{C}/(\text{kg} \cdot \text{h})}{\text{MBq}}$$

☞ Repeating the calculation, we get the following results:

Quantum Energy, MeV	(C/kg)/h at 1 m
0.723	4.583×10^{-11}
0.637	17.787×10^{-11}
0.503	0.598×10^{-11}
0.326	0.258×10^{-11}
0.177	0.126×10^{-11}
0.365	123.400×10^{-11}
0.284	5.569×10^{-11}
0.080	1.361×10^{-11}
0.164	0.339×10^{-11}
Total = $1.540 \times 10^{-9} \frac{\text{C}/(\text{kg})/\text{h}}{\text{MBq}}$ at 1 m	

Specific Gamma-Ray Constant

- ☞ In a more generic case, considering a gamma-ray point-source of activity A (MBq), the exposure rate it will deliver to a distance d (m) away in air is given by

$$\dot{X} \left(\frac{C/kg}{h} \right) = \sum_{i=1}^I \left[\frac{A \times 10^6 (t/s) \times 3600 (s/h) \cdot f_i (p/t) \cdot E_i (J/p)}{4\pi [d (m)]^2} \cdot \mu_i (m^{-1}) / \rho_a (kg/m^3) \right] \cdot \frac{1}{34 \frac{J/kg}{C/kg}}$$

where

\dot{X} : exposure rate, $\left(\frac{C/kg}{h} \right)$

f_i : fraction of transformation that result in a photon of the i 'th energy

E_i : energy carried by each photon of the i 'th group, (J)

μ_i : linear energy absorption coefficient for photons of the i 'th group, (m^{-1})

ρ_a : the density of air, (kg/m^3)

- ☞ The specific gamma-ray constant, Γ , , for this gamma-ray source, is given by

$$\Gamma \left(\frac{C/kg \cdot m^2}{h \cdot MBq} \right) = \frac{\dot{X} \left(\frac{C/kg}{h} \right) \cdot [d(m)]^2}{A(MBq)}$$

- ☞ The specific gamma-ray constant numerically equal to the exposure rate that a source of a unit activity delivers to a unit distance away in air.

Specific Gamma-Ray Constant

- ☞ Substitute all known constants into the generic equation, the specific Gamma-Ray Constant can be given by

$$\Gamma = 1.043 \times 10^{-6} \sum_i f_i \times E_i \times \mu_i \frac{(\text{C/kg}) \text{ m}^2}{\text{MBq} \cdot \text{h}},$$

where f_i is the fraction of the transformations that yield a photon whose energy is E_i and μ_i is the linear energy absorption coefficient in air of the i th photon.

- ☞ For many practical situations, when photon energy is ranging from 60keV to 2MeV, the linear absorption coefficient varies little with energy, over this energy range, μ is about 3.5×10^{-3} per meter. Therefore, we can simplify the above equation as

$$\Gamma = 3.65 \times 10^{-9} \sum_i f_i \times E_i \frac{(\text{C/kg}) \text{ m}^2}{\text{MBq} \cdot \text{h}}$$

Specific Gamma-Ray Constant

- ☞ Specific Gamma Ray Constant (Γ): The **exposure rate** from a gamma ray point source of unit activity and positioned at a unit distance. It is given in the unit of coulombs per kilogram per hour at a distance of 1 m from a 1 MBq point source, or (coulombs/kg/h/MBq at 1m).

TABLE 6.3. Specific Gamma-ray Constant of Some Radioisotopes

Isotope	Γ	
	$\frac{R \cdot m^2}{Ci \cdot h}^a$	$\frac{X \cdot m^2}{MBq \cdot h}^b$
Antimony 122	0.24	1.67E-09
Cesium 137	0.33	2.30E-09
Chromium 51	0.016	1.11E-10
Cobalt 60	1.32	9.19E-09
Gold 198	0.23	1.60E-09
Iodine 125	0.07	4.87E-10
Iodine 131	0.22	1.53E-09
Iridium 192	0.48	3.34E-09
Mercury 203	0.13	9.05E-10
Potassium 42	0.14	1.39E-09
Radium 226	0.825	5.75E-09
Sodium 22	1.20	8.36E-09
Sodium 24	1.84	12.80E-09
Zinc 65	0.27	1.88E-09

^aFrom *Radiological Health Handbook*, rev. ed., U.S. Public Health Service, Bureau of Radiological Health, Rockville, MD, 1970.

^b1 X unit = 1 C/kg.

Specific Gamma-Ray Constant

Given the specific gamma ray constant, Γ , for an isotope, the exposure rate at a location at a distance, r , is simply

$$\dot{X} = \Gamma \frac{A}{r^2}$$

← activity
← distance

Example

(a) Estimate the specific gamma-ray constant for ^{137}Cs . (b) Estimate the exposure rate at a distance of 1.7 m from a 100-mCi point source of ^{137}Cs .

Solution

(a) The isotope emits only a 0.662-MeV gamma ray in 85% of its transformations (Appendix D). The average energy per disintegration released as gamma radiation is therefore $0.85 \times 0.662 = 0.563$ MeV. The estimated specific gamma-ray constant for ^{137}Cs is therefore $\Gamma = 0.28 \text{ R m}^2 \text{ Ci}^{-1} \text{ h}^{-1}$.

(b) From Eq. (12.28), the exposure rate at a distance $r = 1.7$ m from a point source of activity $C = 100 \text{ mCi} = 0.1 \text{ Ci}$ is

$$\dot{X} = 0.28 \frac{\text{R m}^2}{\text{Ci h}} \times \frac{0.1 \text{ Ci}}{(1.7 \text{ m})^2} = 9.7 \times 10^{-3} \text{ R h}^{-1} = 9.7 \text{ mR h}^{-1}. \quad (12.29)$$

Internally Deposited Radioisotope (IV) Gamma Ray Emitters

- ☞ For a uniformly distributed gamma-ray-emitting isotope, the dose rate from the isotope in an infinitesimal volume dV to a point p at a distance r away is

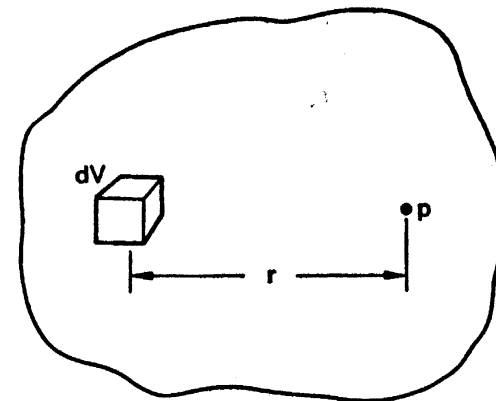
$$d\dot{D} = C(\text{MBq}/\text{m}^3) \cdot \Gamma\left(\frac{\text{C}/\text{kg}\cdot\text{m}^2}{\text{MBq}\cdot\text{hr}}\right) \cdot \frac{e^{-\mu(\text{m}^{-1})r(\text{m})}}{r^2(\text{m}^2)} \cdot dV(\text{m}^3) \cdot \left(34 \frac{\text{J}/\text{kg}}{\text{C}/\text{kg}}\right) \cdot \left(\frac{\mu_m/\rho_m}{\mu_a/\rho_a}\right)$$

Mass energy absorption coefficient
of the dose-receiving media
↓

↑
Mass energy absorption
coefficient of the air

where C is the concentration of the isotope, Γ is the specific gamma-ray emission, and μ is the linear energy absorption coefficient.

FIGURE 6.8. Diagram for calculating dose at point p from the gamma rays emitted from the volume element dV in a tissue mass containing a uniformly distributed isotope.



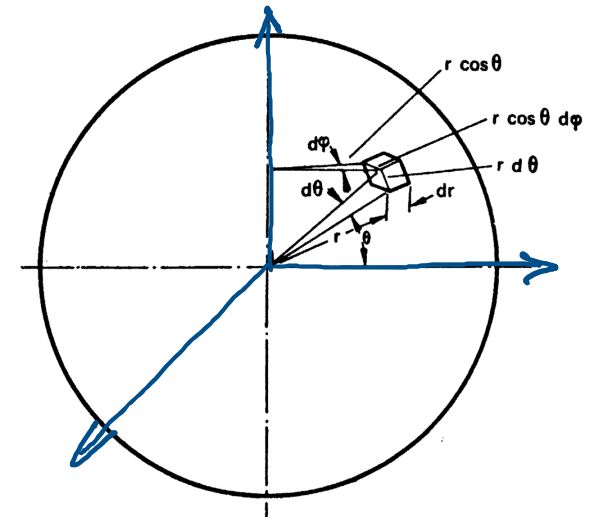
Internally Deposited Radioisotope (IV) Gamma Ray Emitters

☞ For a uniform spherical source, the **dose rate at the center** is given by

$$\begin{aligned} \dot{D} &= 4C\Gamma \int_{r=0}^{r=R} \int_{\theta=0}^{\theta=\pi/2} \int_{\varphi=0}^{\varphi=\pi} \frac{e^{-\mu r}}{r^2} \cdot r \, d\theta \cdot r \cos\theta \, d\varphi \cdot dr \cdot \left(34 \frac{J/kg}{\text{Coulomb/kg}}\right) \cdot \left(\frac{\mu_m/\rho_m}{\mu_a/\rho_a}\right) \\ &= C\Gamma \cdot \frac{4\pi}{\mu} (1 - e^{-\mu R}) \cdot \left(34 \frac{J/kg}{\text{Coulomb/kg}}\right) \cdot \left(\frac{\mu_m/\rho_m}{\mu_a/\rho_a}\right) \end{aligned}$$

☞ And the **dose rate at the surface** of the spherical source volume is given by

$$\dot{D}_{\text{surface}} = 0.5 \dot{D}_{\text{center}}$$



$$dV = r d\theta \cdot r \cos\theta d\varphi \cdot dr = r^2 \cos\theta d\varphi d\theta dr$$

The Buildup Factor

Scattered Gamma Rays and Characteristic X-rays

- ☞ The linear attenuation equation only accounts for how many photons passing through the shielding without interaction ...

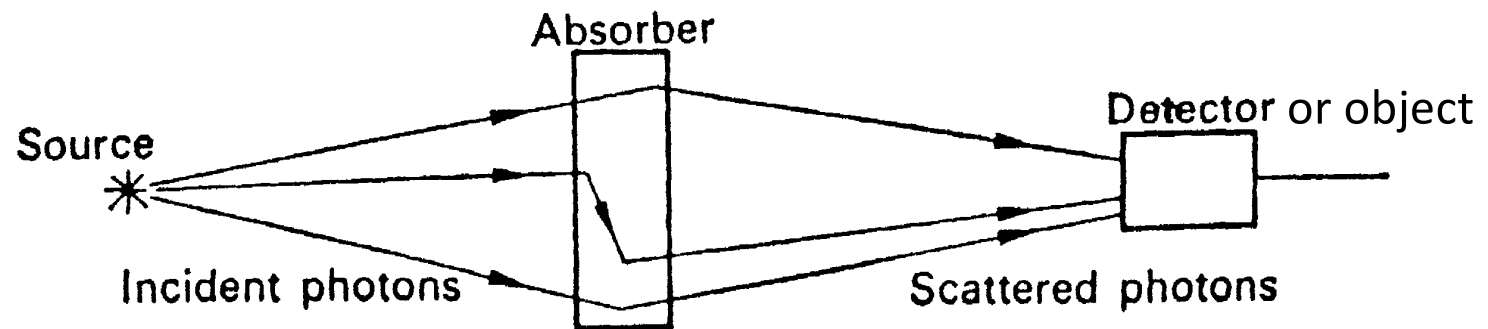


FIGURE 10.5. Gamma-ray absorption under conditions of *broad beam* geometry, showing the effect of photons scattered into the detector.

Scattered Gamma Rays and Characteristic X-rays

- ☞ When considering scattered photons and characteristic x-rays following photoelectric, the total response of the detector is now the sum of two components:

Response due to photons penetrating the shielding without interaction

Energy-dependent response function of the detector/object

Energy-dependent response function

$$R = R^o + R^s = \mathcal{R}(E_o)\phi^o + \int_0^\infty dE \mathcal{R}(E)\phi^s(E).$$

Total response of the receiver (e.g., the dose received by an object)

Response due to photons that interacted in the shielding but still reached the detector/object

The photon flux reaching the object without interaction in the shielding

The flux of secondary photons of energy E reaching the object (scattered photons, fluorescence x-rays, bremsstrahlung X-rays, etc.)

☞ **R is always greater than or equal to R^o !**

The Buildup Factor

$$B \equiv 1 + \frac{R^s}{R^o} = 1 + \frac{1}{\mathcal{R}(E_o)\phi^o(r)} \int_0^\infty dE \mathcal{R}(E)\phi^s(r, E).$$

Extra response due to the scattered photons and characteristic X-rays

Distance traveled in shielding

The response due to the primary photons penetrating the shielding

Energy-dependent response function

Energy dependent response function

The photon flux reaching the object without interaction in the shielding

Flux of photons of energy E reaching the object (scattered photons, x-rays etc.)

- ☞ The buildup factor depends on
 - ☞ the source energy,
 - ☞ the distance traveled, and
 - ☞ the nature of the medium

The Buildup Factor

TABLE E.1 Gamma-Ray Buildup Factors for Air-Kerma Response to an Isotropic Point Source in an Infinite Air Medium. Also Given is the Total Mass Interaction Coefficient Used to Calculate the Mean-Free-Path Length.

MEAN FREE PATHS	ENERGY (MeV)										
	0.04	0.06	0.08	0.1	0.2	0.5	1	2	5	10	15
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.5	2.20	2.58	2.52	2.35	1.90	1.60	1.47	1.38	1.29	1.20	1.15
1	<u>3.38</u>	<u>4.76</u>	<u>4.83</u>	<u>4.46</u>	<u>3.28</u>	<u>2.44</u>	<u>2.08</u>	<u>1.83</u>	<u>1.57</u>	<u>1.37</u>	<u>1.28</u>
2	5.85	10.8	12.0	11.4	7.74	4.84	3.60	2.81	2.09	1.68	1.49
3	8.47	18.9	22.9	22.5	15.00	8.21	5.46	3.86	2.60	1.97	1.70
4	11.2	29.1	37.9	38.4	25.6	12.6	7.60	4.96	3.11	2.26	1.90
5	14.1	41.5	57.4	59.9	40.0	17.9	10.0	6.13	3.61	2.54	2.11
6	17.0	56.1	82	87.8	58.9	24.2	12.7	7.35	4.12	2.82	2.30
7	20.1	73.2	112	123	82.8	31.6	15.6	8.61	4.62	3.10	2.50
8	23.3	92.7	148	166	112	40.1	18.8	9.92	5.12	3.37	2.70
10	<u>30.0</u>	<u>140</u>	<u>242</u>	<u>282</u>	<u>192</u>	<u>60.6</u>	<u>25.8</u>	<u>12.6</u>	<u>6.13</u>	<u>3.92</u>	<u>3.08</u>
15	49.0	316	636	800	545	134	47.0	20.0	8.63	5.25	4.03
20	71.4	596	1350	1810	1220	241	72.8	27.9	11.1	6.55	4.96
25	97.2	1010	2540	3570	2360	385	103	36.2	13.6	7.84	5.87
30	126	1600	4390	6430	4150	567	136	45.0	16.1	9.11	6.75
35	159	2410	7140	10600	6770	788	173	54.0	18.5	10.4	7.58
40	195	3480	11100	15700	10500	1050	212	63.2	21.0	11.6	8.31
μ/ρ (cm ² /g)	.2486	.1875	.1662	.1541	.1234	.08712	.06358	.04447	.02751	.02045	.01810

Source: Extracted from American National Standard ANSI/ANS-6.4.3-1991 with permission of the publisher, the American Nuclear Society.

The Buildup Factor

TABLE E.2 Gamma-Ray Buildup Factors for Air-Kerma Response to an Isotropic Point Source in an Infinite Water Medium. Data are for Air Kerma Response, but Apply within a Few Percent to Water Kerma Response as Well. Also Given is the Total Mass Interaction Coefficient Used to Calculate the Mean-Free-Path Length.

MEAN FREE PATHS	ENERGY (MeV)											
	0.04	0.06	0.08	0.1	0.2	0.5	1	2	5	10	15	
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.5	2.22	2.62	2.55	2.37	1.92	1.60	1.47	1.38	1.28	1.20	1.15	1.15
1	3.47	4.90	4.95	4.55	3.42	2.44	2.08	1.83	1.56	1.37	1.28	1.28
2	6.18	11.4	12.6	11.8	8.31	4.88	3.62	2.81	2.08	1.68	1.49	1.49
3	9.14	20.4	24.5	23.8	16.0	8.35	5.50	3.87	2.58	1.97	1.70	1.70
4	12.3	32.0	41.1	41.3	27.0	12.8	7.68	4.98	3.08	2.25	1.90	1.90
5	15.7	46.4	63.3	65.2	42.2	18.4	10.1	6.15	3.58	2.53	2.10	2.10
6	19.2	63.6	91.4	96.7	62.5	25.0	12.8	7.38	4.08	2.80	2.30	2.30
7	22.9	83.9	126	137	88.5	32.7	15.8	8.65	4.58	3.07	2.49	2.49
8	26.8	107	169	187	121	41.5	19.0	9.97	5.07	3.34	2.68	2.68
10	35.1	165	281	321	208	62.9	26.1	12.7	6.05	3.86	3.05	3.05
15	59.2	386	762	938	600	139	47.7	20.1	8.49	5.14	3.96	3.96
20	88.5	751	1660	2170	1350	252	74.0	28.0	10.9	6.38	4.84	4.84
25	123	1310	3200	4360	2670	403	104	36.5	13.3	7.59	5.69	5.69
30	163	2110	5630	7970	4810	594	139	45.2	15.7	9.96	6.51	6.51
35	208	3240	9300	13500	8170	828	177	54.4	18.0	11.2	7.26	7.26
40	259	4740	14600	21100	13300	1110	218	63.7	20.4	11.3	7.91	7.91
μ/ρ (cm^2/g)	.2683	.2058	.1836	.1707	.1370	.09687	.07072	.04941	.03031	.02219	.01941	.01941

Source: Extracted from American National Standard ANSI/ANS-6.4.3-1991 with permission of the publisher, the American Nuclear Society.

The Buildup Factor

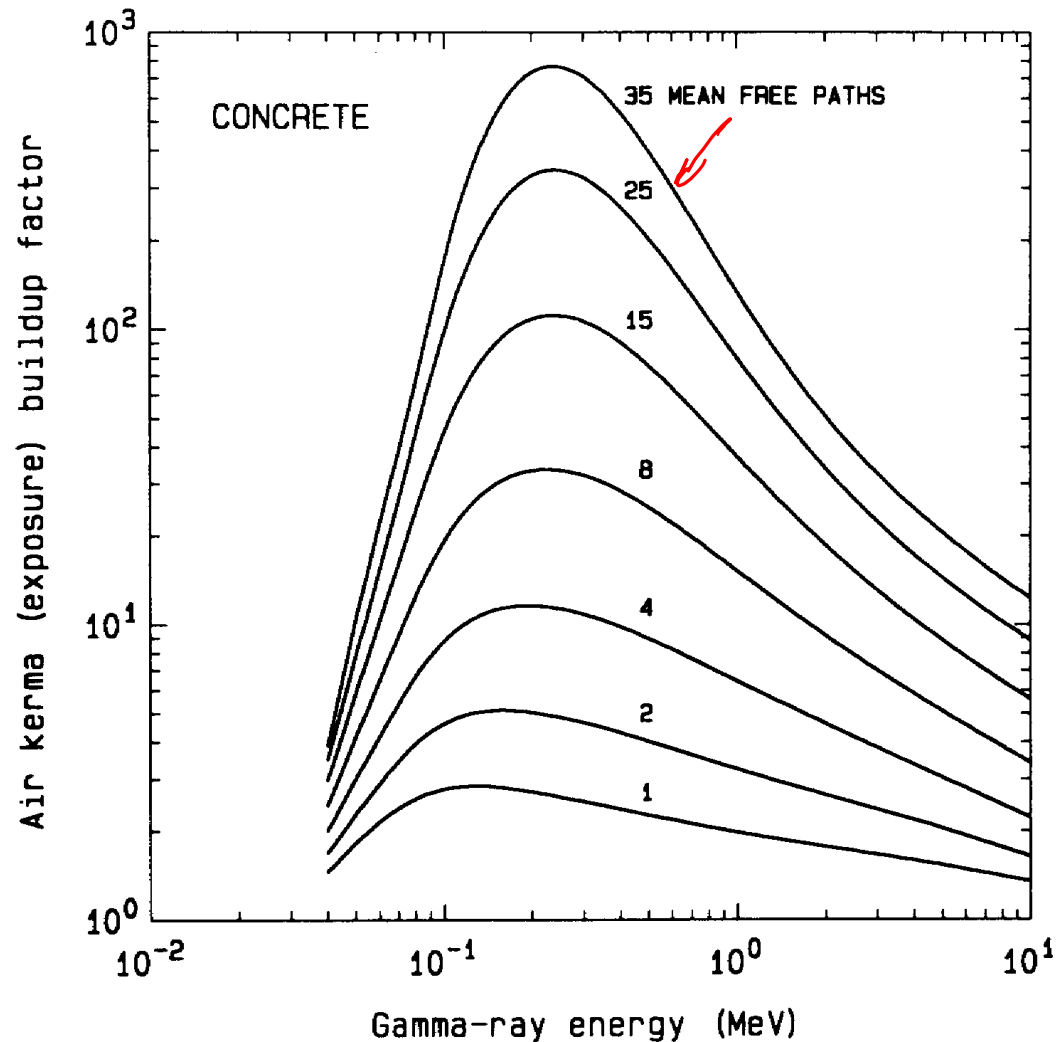


Figure 6.15 Air kerma (exposure) buildup factors for gamma-ray attenuation in concrete. [Data are from Eisenhauser and Simmons (1975).]

The Buildup Factor

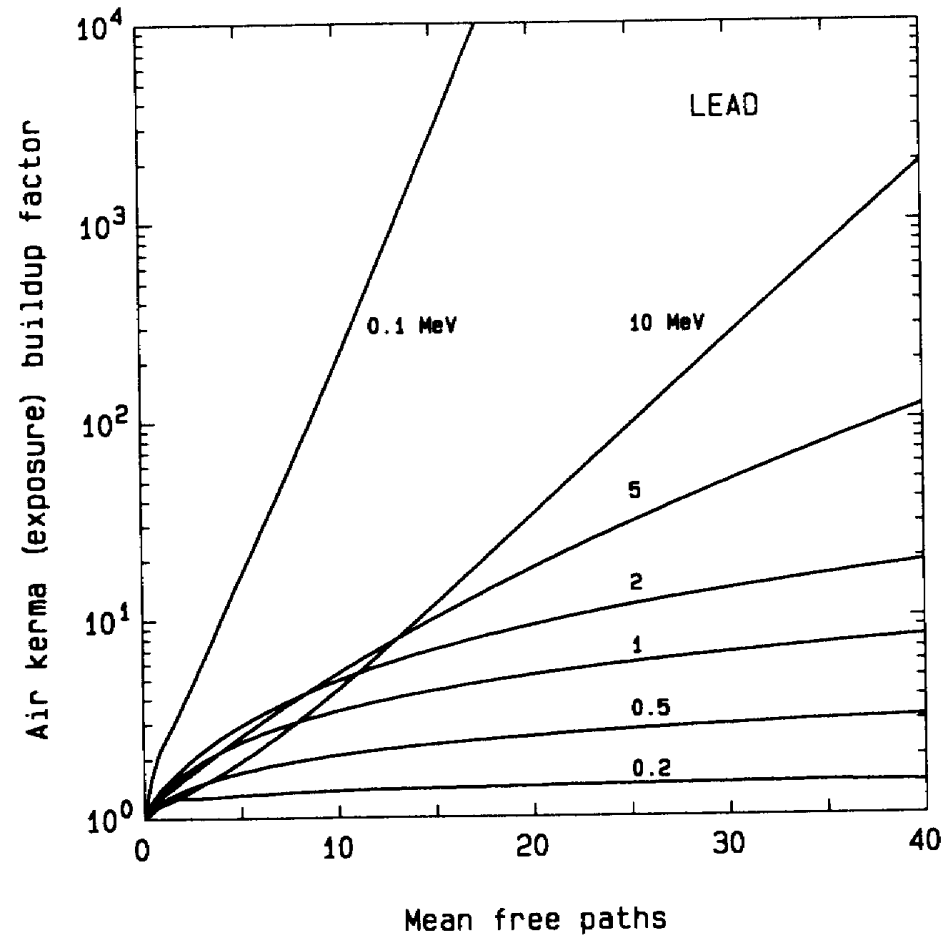


Figure 6.16 Air kerma (exposure) buildup factors for gamma-ray attenuation in lead. [Data are from Simmons and Eisenhauer, as reported in Chilton, Shultis, and Faw (1984).]

Analytical Approximations to Buildup Factor

☞ The Taylor form

$$B(E_0, \mu r) \simeq \sum_i A_i e^{-\alpha_i \mu r},$$

A and α are model parameters
depends on E_0
(see Radiation assessment:
sources and doses, p627)

☞ The Berger form

$$B(E_0, \mu r) \simeq 1 + a \mu r e^{+b \mu r}$$

a, b and e are mode parameters
depends on E_0

Analytical Approximations to Buildup Factor

- ☞ An extraordinarily precise formulation is the geometrical progression (GP) approximation:

$$B(E_o, \mu r) \cong \begin{cases} 1 + \frac{(b-1)(K^{\mu r} - 1)}{K - 1}, & K \neq 1 \\ 1 + (b-1)\mu r, & K = 1, \end{cases}$$

where

$$K(\mu r) = c(\mu r)^a + d \frac{\tanh(\mu r/\xi - 2) - \tanh(-2)}{1 - \tanh(-2)}$$

in which a , b , c , d , and ξ are parameters dependent on the gamma-ray energy, the attenuating medium, and the nature of the response.

The model parameters are pre-calculated and listed in Radiation Assessment: Sources and Doses, p628-630.

Internally Deposited Radioisotope (IV) Gamma Ray Emitters

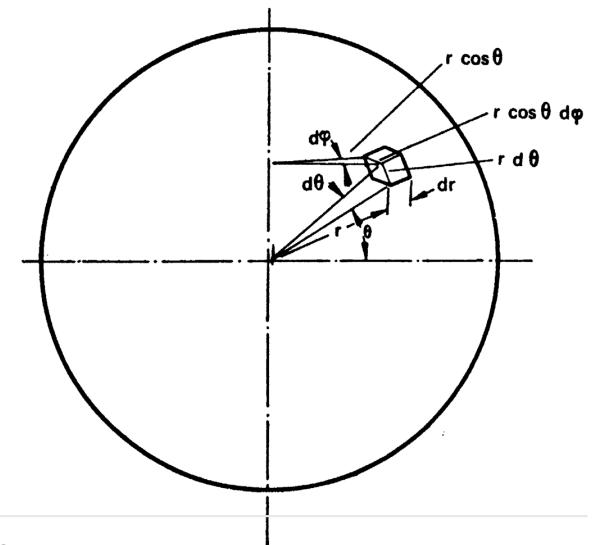
- ☞ The dose rate due to the gamma ray emitter uniformly distributed through the entire source volume is therefore

$$\dot{D} = C\Gamma \int_0^V \frac{e^{-\mu r}}{r^2} dV \cdot 34 \frac{J/kg}{c/kg} \cdot \frac{\mu_m/\rho_m}{\mu_{air}/\rho_{air}}$$

- ☞ In case of spherical source, the dose rate (after considering the build-up factor) at the center is

$$\dot{D} = 4C\Gamma \int_{r=0}^{r=R} \int_{\theta=0}^{\theta=\pi/2} \int_{\varphi=0}^{\varphi=\pi} \frac{e^{-\mu r}}{r^2} \cdot r \cdot r \cos \theta \cdot r \, d\theta \cdot r \cos \theta \, d\varphi \cdot dr \cdot 34 \frac{J/kg}{c/kg} \cdot \frac{\mu_m/\rho_m}{\mu_{air}/\rho_{air}}$$

$B(\epsilon_0, r)$



Shielding Factor (or Attenuation Factor)

Broad Beam Consideration for Shielding Design

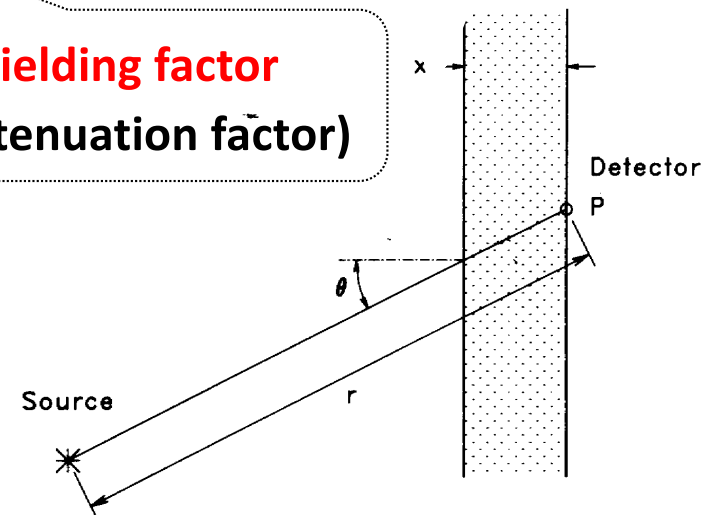
- ☞ For situations in which the radiation source is far away from the shielding slab, the photons of incident are traveling in almost parallel directions. Addressed by NCRP 49 (1976).
- ☞ For gamma rays from a point source

$$R(P) = R_o(P)A_f$$

Dose or exposure rate at point P.

Dose or exposure rate without the shielding

Shielding factor
(or attenuation factor)



Broad Beam Consideration for Shielding Design

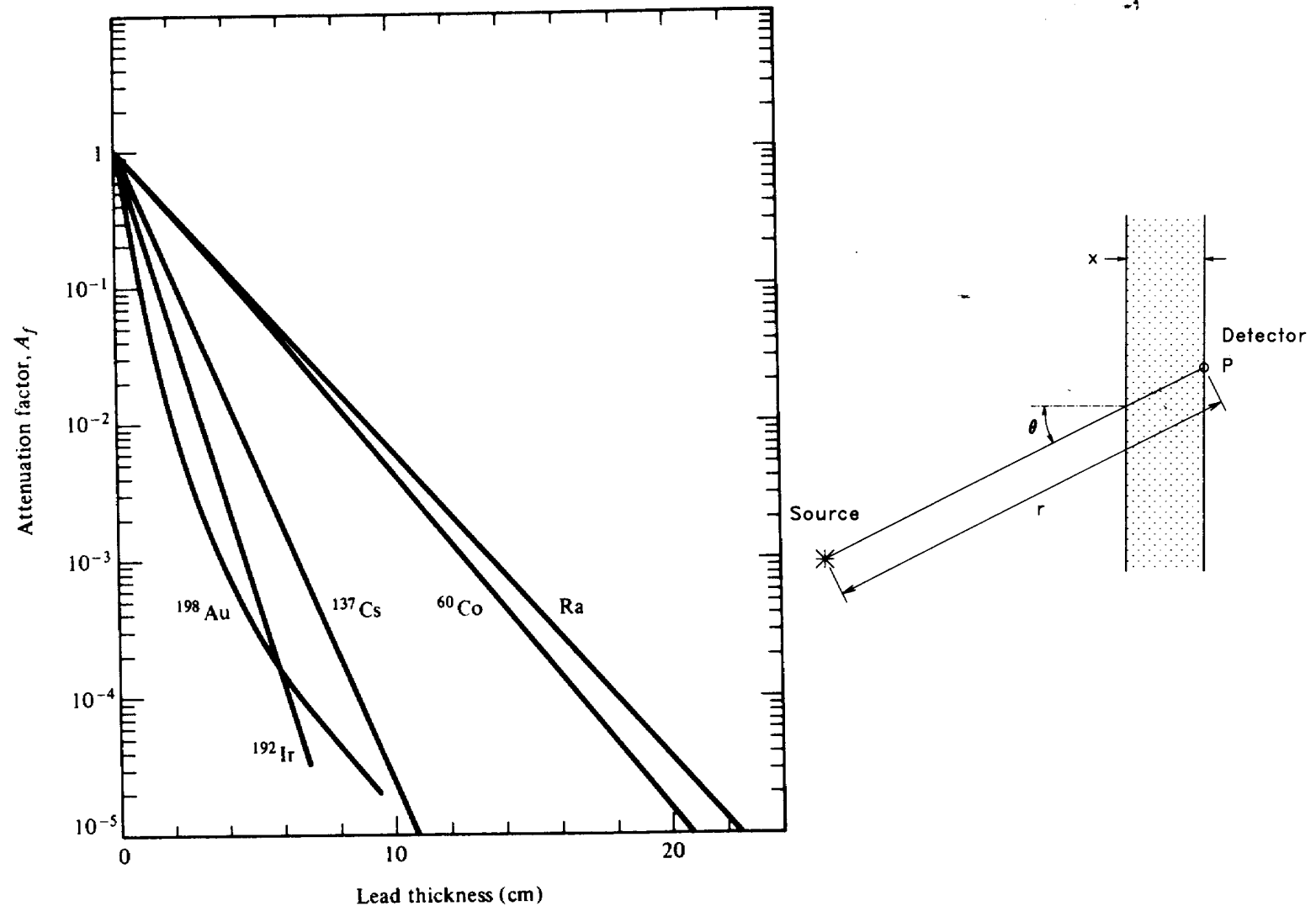


Figure 6.19 Attenuation factor A_f for gamma photons from several radionuclides normally incident on lead slabs. [From NCRP (1976); by permission of the NCRP.]

Broad Beam Consideration for Shielding Design

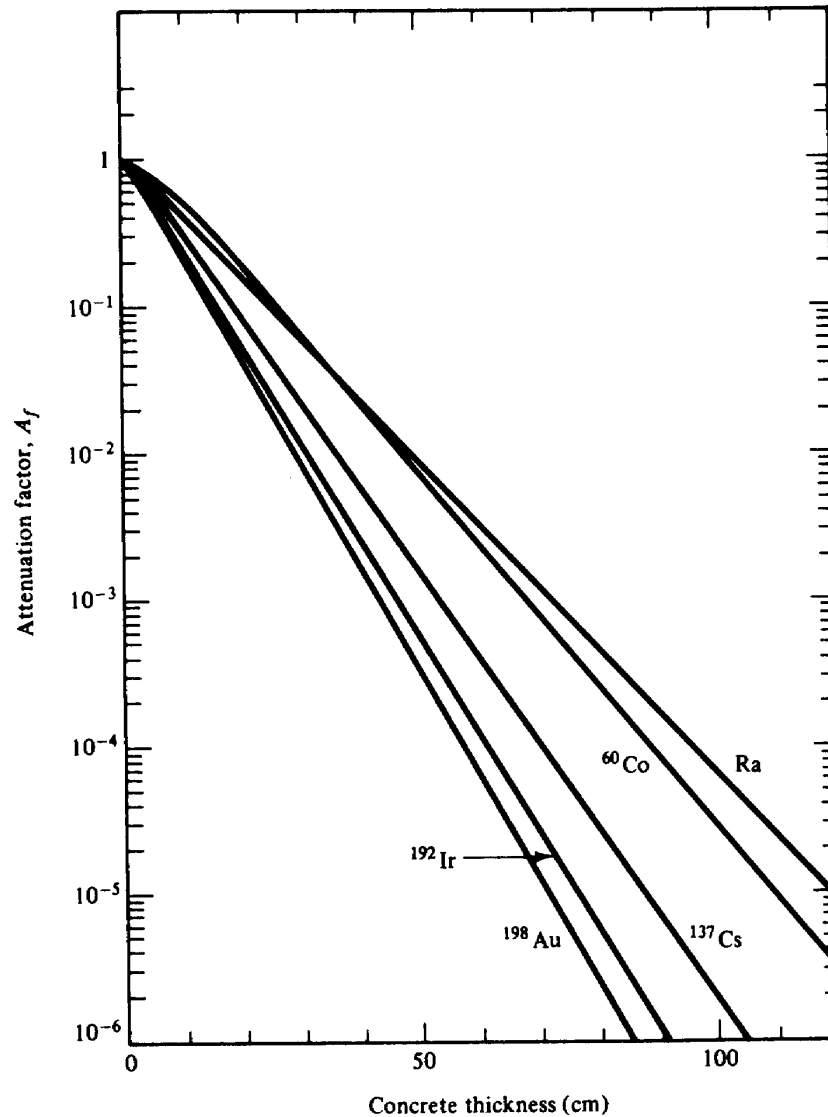


Figure 6.20 Attenuation factor A_f for gamma photons from several radionuclides normally incident on concrete slabs of density 2.25 g/cm^3 . [From NCRP (1976); by permission of the NCRP.]

Broad Beam Consideration for Shielding Design

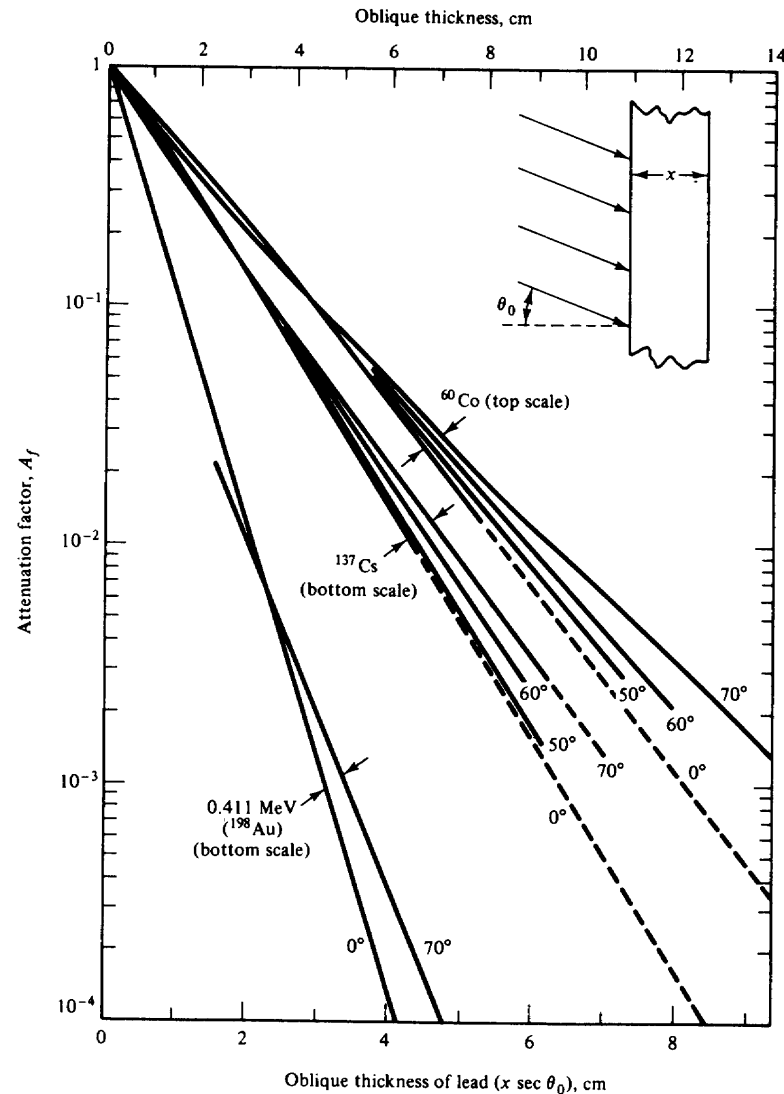


Figure 6.21 Attenuation factors for the transmission of gamma photons from three radionuclide sources through a lead slab. The slab is uniformly illuminated at several angles of incidence with respect to the slab normal. Results for ^{198}Au have been corrected so that only the transmission of the 0.411-MeV photon is shown. [After Kirn, Kennedy, and Wycoff (1954).]

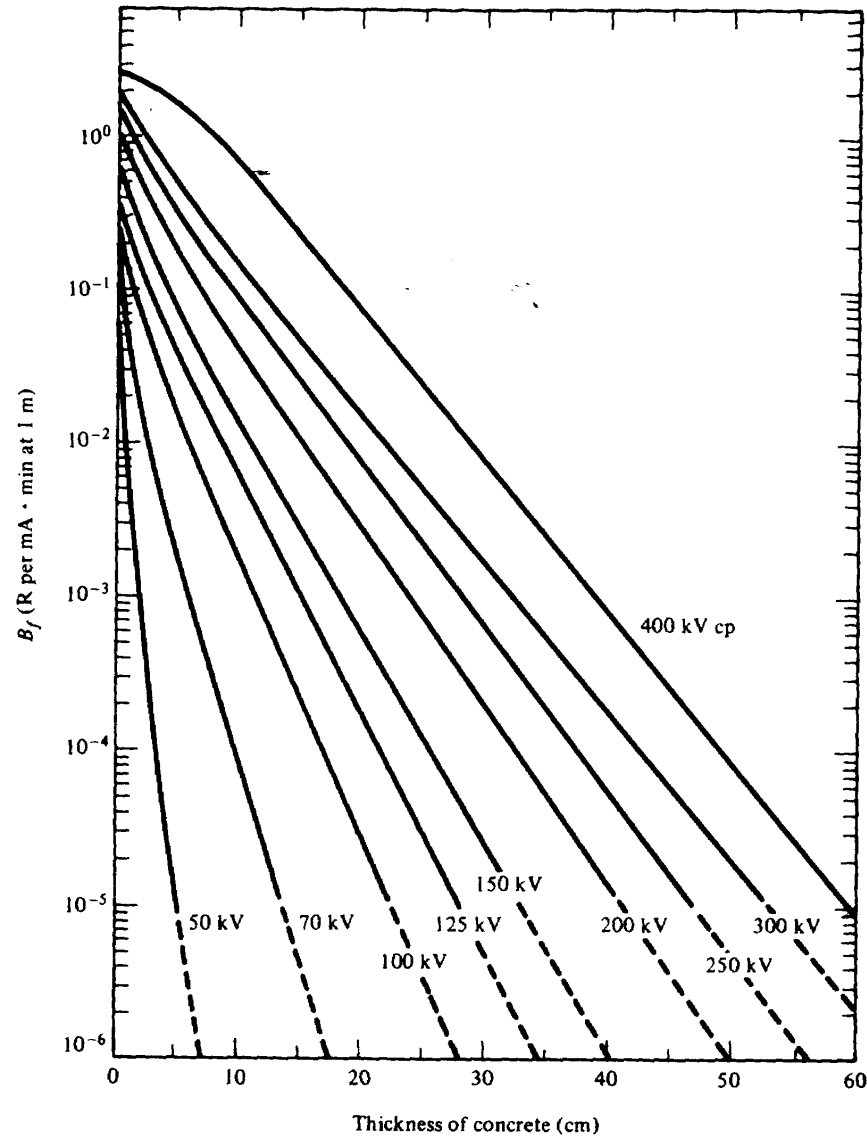


Figure 6.23 Attenuation in concrete (2.35 g/cm^3 density) of x-rays produced by various peak potentials (kVp) with a 90° angle between the electron beam and the axis of the x-ray beam. Pulsed waveforms assumed except for the 400 kV cp curve which is for a constant potential generator. The x-ray beam filtrations are: 1 mm of Al for 50 kV, 1.5 for 70 kV, 2 mm for 100 kV, 3 mm for 100 to 300 kV, and 3 mm of Cu for 400 kV cp. [From NCRP (1976); by permission of the NCRP]