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# Air-Kerma-Rate Coefficients for Selected Photon-Emitting Radionuclide Sources

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## ABSTRACT

Calculations have been done to provide estimates of the air-kerma rate, as a function of distance in air, that can be expected from the photons emerging from sealed sources containing pure $^{241}$Am, $^{57}$Co, $^{133}$Ba, $^{137}$Cs, $^{228}$Th (and daughters, in secular equilibrium), and $^{60}$Co. A number of encapsulation geometries are considered, including those planned for possible deployment in support of newly developed standards for the routine testing of radiological detection and measuring instruments to meet homeland-security requirements.

**Key Words:** air kerma; encapsulated sources; gamma constant; photons; radionuclides;

## Introduction

This report describes calculations to estimate the air-kerma rate from selected photon-emitting radionuclide sources, sealed in a number of geometries, to address recommendations in newly developed standards for the routine testing of radiological detection and measuring instruments to meet homeland-security requirements. Although detailed Monte Carlo calculations would provide the most definitive results, a much simpler calculation was deemed sufficient for estimates to guide the design and use of these sources.

## Schematization

We start with the assumption that the source is a mathematical point, so that no self-absorption and scattering of the emitted photons in the source material are taken into account. Only photon emission is considered; any beta- or alpha-particle emission is ignored, assumed to be eventually absorbed in intervening material(s) present in a real case. Note, however, that the small contributions of bremsstrahlung produced by charged particles is also ignored, assumed negligible compared to primary photon emission. The simple schematization also ignores backscattering from the relatively massive backing material that is part of the construction of a realistic, rugged, sealed source

For the point source in vacuum, the fluence rate $\dot{\Phi}_i$ of photons with energy $E_i$ at a radial distance $r$ is simply $AP_i/(4\pi r^2)$, where $A$ is the source activity, and $P_i$ is the probability per disintegration that a photon of energy $E_i$ is emitted. Assuming charged-particle equilibrium, the air-kerma rate $\dot{K}_i$ from photons of energy $E_i$ is then $\dot{\Phi}_i E_i \frac{\mu_{tr}(E_i)}{\rho_{air}}$, where $\frac{\mu_{tr}(E_i)}{\rho_{air}}$ is the mass energy-transfer coefficient for air. In general, for the in-vacuo case,

$$\dot{K} = \sum_i \frac{AP_i E_i}{4\pi r^2} \frac{\mu_{tr}(E_i)}{\rho_{air}}, \tag{1}$$

and the air-kerma-rate *constant* [1] is

$$\Gamma_\delta = \frac{r^2 \dot{K}_\delta}{A} = \sum_i \frac{P_i E_i}{4\pi} \frac{\mu_{tr}(E_i)}{\rho_{air}}, \tag{2}$$

where δ denotes the minimum photon energy included.

Now consider the point source surrounded by spherical shell(s) of encapsulating material in an infinite air medium. An estimate of the air-kerma rate at a radial distance $r$ in air is

$$\dot{K} = \sum_i \frac{AP_i E_i}{4\pi r^2} \frac{\mu_{tr}(E_i)}{\rho_{air}} \exp\left[-\sum_j \mu_j(E_i) z_j\right] \exp[-\mu_{air}(E_i) r] B[\mu_{air}(E_i) r], \tag{3}$$

where $z$ is the thickness of the encapsulating layer, $\mu_j$ the linear total attenuation coefficient for the encapsulating-layer material and $\mu_{air}$ that for air, and $B$ the air-kerma (exposure) buildup factor for $\mu_{air}(E_i)r$ mean-free paths of air. We then define the air-kerma-rate *coefficient* for the practical case of the encapsulated source in air as the analog to the air-kerma-rate constant of Eq.(2):

$$\Lambda_\delta = \sum_i \frac{P_i E_i}{4\pi} \frac{\mu_{tr}(E_i)}{\rho_{air}} \exp\left[-\sum_j \mu_j(E_i) z_j\right] \exp[-\mu_{air}(E_i) r] B[\mu_{air}(E_i) r]. \tag{4}$$

## Data Used in the Evaluations

Values of the mass energy-transfer coefficient for air, $\frac{\mu_{tr}}{\rho_{air}}$, are taken from Seltzer [2, 3]; values of the total attenuation coefficients are those of Berger and Hubbell [4]. The buildup factors are those of Seltzer [5], calculated for water but assumed to apply to the fairly similar composition of air at the same values of the mean-free path. This choice of buildup-factor data was made because (a) they covered photon energies down to lower energies than standard tables, and (b) they include the effects of coherent scattering in a manner consistent with the use of total attenuation coefficients for air that include coherent scattering, whereas available standard tables do not. Note that buildup due to scattering in the encapsulation layer(s) is not included in our simplified model; the values selected for the total attenuation coefficients for the encapsulating materials do not include coherent scattering, as that process was assumed to mimic no scattering for these estimates.

A number of encapsulation geometries were considered: (a) none (bare point source), (b) 0.06 mm Mylar[1] tape, (c) 0.06 mm Mylar tape + 0.1 mm Al, (d) Pyrex vial (7.65 mm water + 0.6 mm Pyrex glass), (e) 0.125 mm stainless-steel (type 304) foil, and (f) 0.25 mm type-304 stainless-steel foil. A number of these might be more useful in the development and testing of the source design, while a steel-window construction would provide for a more rugged source for safe, routine use. In addition, calculations for a 0.30 mm type-304 stainless-steel foil window are included to cover deviations in the thickness of the manufactured foils. The assumed compositions of the materials involved are listed in Table 1.

Table 1. Assumed composition of materials used in calculations.

| attenuator: | air | water | Mylar tape | Pyrex glass | Al | stainless steel |
|---|---|---|---|---|---|---|
| density(g/cm$^3$): | 0.0012 | 1.0 | 1.38 | 2.23 | 2.699 | 7.93 |
| atomic number, *Z* | fractions by weight | | | | | |
| 1 | | 0.111898 | 0.041960 | | | |
| 5 | | | | 0.040066 | | |
| 6 | 0.000124 | | 0.625016 | | | 0.0004 |
| 7 | 0.755268 | | | | | |
| 8 | 0.231781 | 0.888102 | 0.333024 | 0.539559 | | |
| 11 | | | | 0.028191 | | |
| 13 | | | | 0.011644 | 1.000000 | |
| 14 | | | | 0.377220 | | 0.0050 |
| 18 | 0.012827 | | | | | |
| 19 | | | | 0.003321 | | |
| 24 | | | | | | 0.1850 |
| 25 | | | | | | 0.0100 |
| 26 | | | | | | 0.7046 |
| 28 | | | | | | 0.0950 |

Source-emission data were taken from NuDat, a web-based database maintained by the National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY, USA, and from Lund/LBNL Nuclear Data Search, 2.0, providing the WWW Table of Radioactive Isotopes, maintained by the Lawrence Berkeley Laboratory, Berkeley, USA, and the Department of Physics, Lund University, Sweden. Data for gamma-ray emission were selected mainly from the National Nuclear Data Center tables, with confirmation

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[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

and some augmentation from the Lund/LBNL Nuclear Data Search table. Data for x-ray emission by the daughter radionuclide were taken from the Lund/LBNL Nuclear Data Search tables, which include more detail. All energies given in these tables have been included, implying a cut-off value of, say, 3 keV for $\delta$ in Eqs.(2) and (4). The use of such a low cut-off is perhaps a bit unusual, but has little effect for sources with substantial encapsulation and at realistic distances in air. It can, however, result in values of the air-kerma-rate constant and of the air-kerma-rate coefficient for bare sources different from those from other calculations.

The radionuclides so far considered are $^{241}$Am, $^{57}$Co, $^{133}$Ba, $^{137}$Cs, $^{228}$Th, and $^{60}$Co. Secular equilibrium is assumed for $^{228}$Th and it daughters; in-growth ratios of from 1.00527 to 1.00597 for the daughter radionuclides were supplied by Larry Lucas (private communication). The evaluations of Eqs. (2) and (4) were based on 160 photon energies from about 11.9 keV to 945.7 keV for $^{241}$Am, 16 photon energies from 6.3 keV to 706.5 keV for $^{57}$Co, 28 photon energies from 3.8 keV to 383.8 keV for $^{133}$Ba, 22 photon energies from 4.0 keV to 661.7 keV for $^{137}$Cs, 211 photon energies from 9.0 keV to 2614.5 keV for $^{228}$Th, and 12 photon energies from 7.3 keV to 2505.7 keV for $^{60}$Co. A complete listing of all these input data for $E_i$ and $P_i$ is too voluminous for inclusion here, but can be requested from the author. Instead, Table 2 gives the photon lines with emission probabilities greater than 1 %.

Table 2. Photon emission spectra for the radionuclides of interest. These data include only those photons of energy *E* whose probability of emission per disintegration, *P*, is larger than 0.01.

| $^{241}$Am | | $^{57}$Co | | $^{133}$Ba | |
|---|---|---|---|---|---|
| *E* (keV) | *P* | *E* (keV) | *P* | *E* (keV) | *P* |
| 13.761 | 0.0107 | 6.391 | 0.1640 | 4.286 | 0.0600 |
| 13.976 | 0.0960 | 6.404 | 0.3260 | 4.620 | 0.0380 |
| 16.816 | 0.0250 | 7.058 | 0.0587 | 4.934 | 0.0119 |
| 17.061 | 0.0150 | 14.413 | 0.0916 | 30.625 | 0.3490 |
| 17.751 | 0.0570 | 122.061 | 0.8560 | 30.973 | 0.6450 |
| 17.992 | 0.0137 | 136.474 | 0.1068 | 34.920 | 0.0599 |
| 20.784 | 0.0139 | | | 34.987 | 0.1160 |
| 26.345 | 0.0240 | | | 35.818 | 0.0358 |
| 59.541 | 0.3590 | | | 79.614 | 0.0262 |
| | | | | 80.997 | 0.3408 |
| | | | | 276.399 | 0.0716 |
| | | | | 302.820 | 0.1833 |

| $^{137}$Cs | | $^{228}$Th (equilibrium) | | $^{60}$Co | |
|---|---|---|---|---|---|
| *E* (keV) | *P* | *E* (keV) | *P* | *E* (keV) | *P* |
| 31.817 | 0.0204 | 10.268 | 0.0273 | 1173.233 | 0.9991 |
| 32.194 | 0.0376 | 10.839 | 0.0589 | 1332.497 | 0.9984 |
| 661.657 | 0.8510 | 12.213 | 0.0124 | | |
| | | 12.339 | 0.0283 | | |
| | | 12.967 | 0.0147 | | |
| | | 13.023 | 0.0369 | | |
| | | 15.236 | 0.0378 | | |
| | | 39.858 | 0.0108 | | |
| | | 74.815 | 0.1047 | | |
| | | 74.969 | 0.0128 | | |
| | | 77.107 | 0.1760 | | |
| | | 84.373 | 0.0122 | | |
| | | 86.830 | 0.0210 | | |
| | | 87.349 | 0.0403 | | |
| | | 89.784 | 0.0147 | | |
| | | 238.632 | 0.4356 | | |
| | | 240.986 | 0.0412 | | |
| | | 277.355 | 0.0228 | | |
| | | 300.087 | 0.0330 | | |
| | | 510.770 | 0.0818 | | |
| | | 583.191 | 0.3186 | | |
| | | 727.330 | 0.0666 | | |
| | | 785.370 | 0.0111 | | |
| | | 860.564 | 0.0449 | | |
| | | 1620.500 | 0.0150 | | |
| | | 2614.533 | 0.3755 | | |

## Results

Table 3 gives results for the air-kerma-rate constant, $\Gamma_\delta$, for δ = 3, 5, 10, 15, 20, 25, and 30 keV. Clearly, the choice of cut-off can have a significant effect on this quantity for the radionuclides other than $^{60}$Co.

Table 3. Values of the air-kerma-rate constant, $\Gamma_\delta$, in units of m$^2$μGy/h/GBq, for various values of the cut-off energy δ.

| δ (keV) | $^{241}$Am | $^{57}$Co | $^{133}$Ba | $^{137}$Cs | $^{228}$Th | $^{60}$Co |
|---|---|---|---|---|---|---|
| 3 | 25.50 | 31.76 | 231.9 | 85.86 | 215.2 | 306.9 |
| 5 | 25.50 | 31.76 | 78.21 | 78.26 | 215.2 | 306.9 |
| 10 | 25.50 | 22.39 | 71.14 | 77.28 | 213.9 | 306.9 |
| 15 | 13.06 | 13.23 | 71.14 | 77.28 | 174.3 | 306.9 |
| 20 | 5.02 | 13.23 | 71.14 | 77.28 | 169.1 | 306.9 |
| 25 | 3.72 | 13.23 | 71.14 | 77.28 | 169.1 | 306.9 |
| 30 | 3.61 | 13.23 | 71.14 | 77.28 | 169.1 | 306.9 |

For the more practical case of the source in air, Table 4 gives results for the air-kerma-rate coefficient, $\Lambda_\delta$, for a cut-off value of δ = 3 keV. Note the interplay between attenuation and buildup displayed in the tables, most notable for the lightly encapsulated sources with significant low-energy photon emission. For the more rugged encapsulation of stainless steel, the air-kerma-rate coefficient for distances from 0 to 6 m is fairly constant, varying by less than 1 % for the high-energy sources ($^{60}$Co, $^{228}$Th, and $^{137}$Cs), by less than 3 % for $^{133}$Ba, by no more than 8 % for $^{57}$Co, but by as much as 18 % for $^{241}$Am.

The uncertainty in the results of these evaluations is difficult to estimate, involving the accuracy of the source emission spectra, the photon-interaction cross sections, and the simplified model employed. At present, our estimate is that the relative expanded uncertainty is about 5 % at the 90 % to 95% confidence level (a coverage factor, *k*, of about 1.6 to 2).

Table 4. Air-kerma-rate coefficients for various encapsulation geometries, at distances of up to 6 m in air from the radionuclide source. The average energy given is that of the photons emerging from the encapsulation, taking into account only simple attenuation. The results for 0.25 mm and for 0.30 mm of stainless steel are given in a single column, separated by a virgule (slash) for demarcation, not to indicate division.

$^{241}$Am

| attenuator: | bare | 0.06 mm Mylar tape | 0.1 mm Al + 0.06 mm Mylar tape | 0.6 mm Pyrex + 7.65 mm $H_2O$ | 0.125 mm stainless steel | 0.25/0.30 mm stainless steel |
|---|---|---|---|---|---|---|
| avg. E (keV): | 40.78 | 40.84 | 42.61 | 51.89 | 57.97 | 59.25/59.40 |
| r (cm) in air | air-kerma coefficient, $\Lambda_3$ ($m^2\mu Gy/h/GBq$) | | | | | |
| 0 | 25.50 | 25.31 | 21.28 | 6.793 | 3.341 | 2.538/2.390 |
| 1 | 25.47 | 25.28 | 21.26 | 6.791 | 3.342 | 2.539/2.390 |
| 2 | 25.44 | 25.26 | 21.24 | 6.788 | 3.343 | 2.539/2.391 |
| 5 | 25.35 | 25.17 | 21.17 | 6.779 | 3.345 | 2.542/2.394 |
| 10 | 25.21 | 25.03 | 21.06 | 6.765 | 3.349 | 2.546/2.398 |
| 20 | 24.93 | 24.75 | 20.85 | 6.737 | 3.356 | 2.555/2.406 |
| 50 | 24.10 | 23.93 | 20.21 | 6.655 | 3.378 | 2.580/2.430 |
| 100 | 22.78 | 22.63 | 19.20 | 6.523 | 3.414 | 2.621/2.470 |
| 150 | 21.57 | 21.42 | 18.25 | 6.397 | 3.449 | 2.662/2.509 |
| 200 | 20.42 | 20.29 | 17.37 | 6.277 | 3.483 | 2.702/2.548 |
| 225 | 19.88 | 19.75 | 16.94 | 6.219 | 3.500 | 2.722/2.567 |
| 250 | 19.36 | 19.24 | 16.54 | 6.163 | 3.517 | 2.742/2.586 |
| 300 | 18.37 | 18.26 | 15.77 | 6.056 | 3.550 | 2.781/2.624 |
| 400 | 16.60 | 16.50 | 14.38 | 5.858 | 3.615 | 2.858/2.698 |
| 450 | 15.81 | 15.72 | 13.76 | 5.768 | 3.646 | 2.895/2.734 |
| 500 | 15.08 | 14.99 | 13.19 | 5.683 | 3.678 | 2.932/2.770 |
| 600 | 13.78 | 13.70 | 12.15 | 5.529 | 3.738 | 3.004/2.840 |

$^{57}$Co

| attenuator: | bare | 0.06 mm Mylar tape | 0.1 mm Al + 0.06 mm Mylar tape | 0.6 mm Pyrex + 7.65 mm $H_2O$ | 0.125 mm stainless steel | 0.25/0.30 mm stainless steel |
|---|---|---|---|---|---|---|
| avg. E (keV): | 78.03 | 80.46 | 112.8 | 123.5 | 124.8 | 124.8/124.8 |
| r (cm) in air | air-kerma coefficient, $\Lambda_3$ ($m^2\mu Gy/h/GBq$) | | | | | |
| 0 | 317.62 | 289.08 | 42.60 | 12.53 | 12.99 | 12.65/12.53 |
| 1 | 311.25 | 283.32 | 42.12 | 12.53 | 12.99 | 12.65/12.53 |
| 2 | 305.01 | 277.69 | 41.65 | 12.53 | 12.99 | 12.65/12.54 |
| 5 | 287.10 | 261.50 | 40.30 | 12.53 | 12.99 | 12.65/12.54 |
| 10 | 259.69 | 236.75 | 38.23 | 12.53 | 13.00 | 12.66/12.55 |
| 20 | 213.01 | 194.57 | 34.67 | 12.53 | 13.01 | 12.68/12.57 |
| 50 | 120.77 | 111.21 | 27.53 | 12.53 | 13.05 | 12.73/12.62 |
| 100 | 54.27 | 51.05 | 22.08 | 12.53 | 13.13 | 12.82/12.70 |
| 150 | 31.75 | 30.63 | 19.97 | 12.54 | 13.21 | 12.90/12.78 |
| 200 | 23.92 | 23.50 | 19.01 | 12.55 | 13.29 | 12.98/12.87 |
| 225 | 22.13 | 21.85 | 18.70 | 12.55 | 13.34 | 13.02/12.91 |
| 250 | 21.00 | 20.81 | 18.46 | 12.56 | 13.38 | 13.07/12.95 |
| 300 | 19.74 | 19.64 | 18.08 | 12.58 | 13.46 | 13.15/13.03 |
| 400 | 18.62 | 18.56 | 17.50 | 12.62 | 13.63 | 13.31/13.19 |
| 450 | 18.27 | 18.21 | 17.27 | 12.65 | 13.71 | 13.39/13.27 |
| 500 | 17.97 | 17.92 | 17.06 | 12.68 | 13.79 | 13.47/13.35 |
| 600 | 17.47 | 17.43 | 16.71 | 12.75 | 13.95 | 13.63/13.51 |

$^{133}$Ba

| attenuator: | bare | 0.06 mm Mylar tape | 0.1 mm Al + 0.06 mm Mylar tape | 0.6 mm Pyrex + 7.65 mm $H_2O$ | 0.125 mm stainless steel | 0.25/0.30 mm stainless steel |
|---|---|---|---|---|---|---|
| avg. E (keV): | 148.55 | 150.7 | 158.1 | 172.6 | 194.5 | 225.2/235.0 |
| r (cm) in air | air-kerma coefficient, $\Lambda_3$ ($m^2\mu Gy/h/GBq$) | | | | | |
| 0 | 231.93 | 188.64 | 70.57 | 59.42 | 59.11 | 52.73/51.08 |
| 1 | 221.65 | 181.21 | 70.57 | 59.43 | 59.12 | 52.74/51.08 |
| 2 | 212.06 | 174.26 | 70.56 | 59.43 | 59.12 | 52.74/51.09 |
| 5 | 186.88 | 156.01 | 70.55 | 59.45 | 59.13 | 52.75/51.09 |
| 10 | 154.69 | 132.61 | 70.55 | 59.47 | 59.15 | 52.76/51.10 |
| 20 | 115.10 | 103.71 | 70.56 | 59.52 | 59.19 | 52.78/51.12 |
| 50 | 78.32 | 76.58 | 70.68 | 59.65 | 59.30 | 52.86/51.19 |
| 100 | 72.18 | 72.00 | 70.95 | 59.87 | 59.48 | 52.98/51.29 |
| 150 | 72.06 | 71.97 | 71.22 | 60.08 | 59.65 | 53.09/51.39 |
| 200 | 72.29 | 72.20 | 71.47 | 60.27 | 59.81 | 53.20/51.49 |
| 225 | 72.41 | 72.32 | 71.59 | 60.36 | 59.89 | 53.26/51.54 |
| 250 | 72.53 | 72.43 | 71.71 | 60.45 | 59.97 | 53.31/51.59 |
| 300 | 72.75 | 72.66 | 71.93 | 60.62 | 60.11 | 53.41/51.67 |
| 400 | 73.15 | 73.06 | 72.32 | 60.92 | 60.37 | 53.60/51.84 |
| 450 | 73.33 | 73.24 | 72.50 | 61.05 | 60.49 | 53.69/51.92 |
| 500 | 73.49 | 73.40 | 72.66 | 61.18 | 60.60 | 53.77/52.00 |
| 600 | 73.78 | 73.68 | 72.94 | 61.40 | 60.81 | 53.93/52.15 |

$^{137}$Cs

| attenuator: | bare | 0.06 mm Mylar tape | 0.1 mm Al + 0.06 mm Mylar tape | 0.6 mm Pyrex + 7.65 mm $H_2O$ | 0.125 mm stainless steel | 0.25/0.30 mm stainless steel |
|---|---|---|---|---|---|---|
| avg. E (keV): | 607.8 | 609.1 | 614.1 | 623.5 | 633.8 | 645.7/648.9 |
| r (cm) in air | air-kerma coefficient, $\Lambda_3$ ($m^2\mu Gy/h/GBq$) | | | | | |
| 0 | 85.86 | 83.73 | 77.07 | 71.36 | 76.16 | 75.31/75.01 |
| 1 | 85.37 | 83.36 | 77.07 | 71.36 | 76.16 | 75.31/75.01 |
| 2 | 84.91 | 83.01 | 77.07 | 71.36 | 76.16 | 75.31/75.01 |
| 5 | 83.68 | 82.09 | 77.06 | 71.36 | 76.16 | 75.31/75.01 |
| 10 | 82.07 | 80.88 | 77.06 | 71.36 | 76.16 | 75.30/75.01 |
| 20 | 79.97 | 79.29 | 77.05 | 71.36 | 76.15 | 75.30/75.00 |
| 50 | 77.77 | 77.61 | 77.03 | 71.34 | 76.14 | 75.28/74.98 |
| 100 | 77.28 | 77.22 | 77.01 | 71.32 | 76.11 | 75.25/74.95 |
| 150 | 77.23 | 77.17 | 76.99 | 71.30 | 76.09 | 75.22/74.92 |
| 200 | 77.20 | 77.15 | 76.97 | 71.28 | 76.06 | 75.19/74.89 |
| 225 | 77.19 | 77.14 | 76.96 | 71.27 | 76.05 | 75.18/74.88 |
| 250 | 77.18 | 77.13 | 76.95 | 71.26 | 76.03 | 75.16/74.86 |
| 300 | 77.16 | 77.10 | 76.92 | 71.23 | 76.00 | 75.13/74.83 |
| 400 | 77.11 | 77.05 | 76.87 | 71.18 | 75.95 | 75.07/74.77 |
| 450 | 77.08 | 77.03 | 76.85 | 71.16 | 75.92 | 75.04/74.74 |
| 500 | 77.05 | 77.00 | 76.82 | 71.13 | 75.89 | 75.01/74.71 |
| 600 | 77.00 | 76.94 | 76.76 | 71.08 | 75.83 | 74.94/74.64 |

### $^{228}$Th (equilibrium)

| attenuator: | bare | 0.06 mm Mylar tape | 0.1 mm Al + 0.06 mm Mylar tape | 0.6 mm Pyrex + 7.65 mm $H_2O$ | 0.125 mm stainless steel | 0.25/0.30 mm stainless steel |
|---|---|---|---|---|---|---|
| avg. E (keV): | 681.7 | 683.3 | 715.5 | 820.1 | 804.8 | 815.2/819.2 |
| r (cm) in air | air-kerma coefficient, $\Lambda_3$ ($m^2\mu Gy/h/GBq$) | | | | | |
| 0 | 215.2 | 214.4 | 198.4 | 161.4 | 168.0 | 166.8/166.4 |
| 1 | 215.1 | 214.2 | 198.3 | 161.4 | 168.0 | 166.8/166.4 |
| 2 | 214.9 | 214.1 | 198.2 | 161.4 | 168.0 | 166.8/166.4 |
| 5 | 214.5 | 213.6 | 197.9 | 161.4 | 168.0 | 166.8/166.4 |
| 10 | 213.7 | 212.9 | 197.5 | 161.4 | 168.0 | 166.8/166.4 |
| 20 | 212.3 | 211.5 | 196.6 | 161.3 | 168.0 | 166.8/166.4 |
| 50 | 208.2 | 207.5 | 194.2 | 161.2 | 168.0 | 166.8/166.4 |
| 100 | 202.3 | 201.7 | 190.6 | 161.1 | 168.0 | 166.8/166.4 |
| 150 | 197.4 | 196.9 | 187.6 | 161.0 | 168.0 | 166.9/166.4 |
| 200 | 193.3 | 192.9 | 185.1 | 160.8 | 168.1 | 166.9/166.4 |
| 225 | 191.5 | 191.1 | 183.9 | 160.8 | 168.1 | 166.9/166.4 |
| 250 | 189.9 | 189.5 | 182.9 | 160.7 | 168.1 | 166.9/166.4 |
| 300 | 187.0 | 186.7 | 181.1 | 160.6 | 168.1 | 166.9/166.4 |
| 400 | 182.5 | 182.2 | 178.2 | 160.5 | 168.1 | 166.9/166.5 |
| 450 | 180.8 | 180.5 | 177.0 | 160.4 | 168.1 | 166.9/166.5 |
| 500 | 179.3 | 179.1 | 176.1 | 160.3 | 168.1 | 166.9/166.5 |
| 600 | 177.0 | 176.8 | 174.5 | 160.2 | 168.2 | 167.0/166.5 |

### $^{60}$Co

| attenuator: | bare | 0.06 mm Mylar tape | 0.1 mm Al + 0.06 mm Mylar tape | 0.6 mm Pyrex + 7.65 mm $H_2O$ | 0.125 mm stainless steel | 0.25/0.30 mm stainless steel |
|---|---|---|---|---|---|---|
| avg. E (keV): | 1252.7 | 1252.7 | 1252.8 | 1252.8 | 1252.8 | 1252.8 |
| r (cm) in air | air-kerma coefficient, $\Lambda_3$ ($m^2\mu Gy/h/GBq$) | | | | | |
| 0 | 306.9 | 306.8 | 306.3 | 304.5 | 305.2 | 303.6/303.0 |
| 1 | 306.9 | 306.7 | 306.3 | 304.5 | 305.2 | 303.6/303.0 |
| 2 | 306.9 | 306.7 | 306.3 | 304.5 | 305.2 | 303.6/303.0 |
| 5 | 306.9 | 306.7 | 306.2 | 304.5 | 305.2 | 303.6/303.0 |
| 10 | 306.9 | 306.7 | 306.2 | 304.5 | 305.2 | 303.6/303.0 |
| 20 | 306.8 | 306.7 | 306.2 | 304.5 | 305.2 | 303.6/302.9 |
| 50 | 306.7 | 306.5 | 306.1 | 304.4 | 305.1 | 303.5/302.8 |
| 100 | 306.5 | 306.3 | 305.9 | 304.2 | 304.9 | 303.3/302.6 |
| 150 | 306.3 | 306.2 | 305.7 | 304.0 | 304.7 | 303.1/302.4 |
| 200 | 306.1 | 306.0 | 305.5 | 303.8 | 304.5 | 302.9/302.3 |
| 225 | 306.0 | 305.9 | 305.4 | 303.7 | 304.4 | 302.8/302.2 |
| 250 | 305.9 | 305.8 | 305.3 | 303.6 | 304.3 | 302.7/302.1 |
| 300 | 305.7 | 305.6 | 305.1 | 303.4 | 304.1 | 302.5/301.9 |
| 400 | 305.3 | 305.2 | 304.7 | 303.0 | 303.7 | 302.1/301.5 |
| 450 | 305.1 | 305.0 | 304.6 | 302.8 | 303.5 | 301.9/301.3 |
| 500 | 305.0 | 304.8 | 304.4 | 302.7 | 303.3 | 301.8/301.1 |
| 600 | 304.6 | 304.4 | 304.0 | 302.3 | 303.0 | 301.4/300.7 |

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