

***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.

Note that this edition supersedes publication NISTIR 7092 by including corrections to Table 2 (in the earlier version, the lines at 356 keV and 384 keV in the source spectrum for ^{133}Ba were inadvertently left off), and to the date of publication.

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,

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

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

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

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

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

where z is the thickness of the encapsulating layer, μ_j the linear total attenuation coefficient for the encapsulating-layer material and μ_{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):

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

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 Mylar¹ 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

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.

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 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 δ 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 its daughters; results are given in terms of the activity of the parent radionuclide; 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
				356.015	0.6205
				383.850	0.0894

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, Γ_δ , for $\delta = 3, 5, 10, 15, 20, 25,$ 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, Γ_δ , in units of $\text{m}^2\mu\text{Gy/h/GBq}$, 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, A_δ , for a cut-off value of $\delta = 3$ 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.

²⁴¹Am

attenuator:	bare	0.06 mm Mylar tape	0.1 mm Al + 0.06 mm Mylar tape	0.6 mm Pyrex + 7.65 mm H ₂ O	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, A_3 (m ² μGy/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

⁵⁷Co

attenuator:	bare	0.06 mm Mylar tape	0.1 mm Al + 0.06 mm Mylar tape	0.6 mm Pyrex + 7.65 mm H ₂ O	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, A_3 (m ² μGy/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

¹³³Ba

attenuator:	bare	0.06 mm Mylar tape	0.1 mm Al + 0.06 mm Mylar tape	0.6 mm Pyrex + 7.65 mm H ₂ O	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, A_3 (m ² μGy/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

¹³⁷Cs

attenuator:	bare	0.06 mm Mylar tape	0.1 mm Al + 0.06 mm Mylar tape	0.6 mm Pyrex + 7.65 mm H ₂ O	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, A_3 (m ² μGy/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

²²⁸Th (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 ₂ O	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, A_3 (m ² μGy/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

⁶⁰Co

attenuator:	bare	0.06 mm Mylar tape	0.1 mm Al + 0.06 mm Mylar tape	0.6 mm Pyrex + 7.65 mm H ₂ O	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, A_3 (m ² μGy/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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