Table 4: Committed effective dose, inhalation of thorium ore dust, AMAD = 10 µm, lung absorption Class S (where applicable)

Radionuclide	Decay	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
			Alpha	Beta	
^{232}Th	alpha	2.6×10^{-5}	1		2.6×10^{-5}
^{228}Ra	beta	1.3×10^{-5}		1	1.3×10^{-5}
^{228}Ac	beta	5.1×10^{-9}		1	5.1×10^{-9}
^{228}Th	alpha	1.4×10^{-5}	1		1.4×10^{-5}
^{224}Ra	alpha	6.5×10^{-7}	1		6.5×10^{-7}
^{220}Rn*	alpha	–	1		–
^{216}Po*	alpha	–	1		–
^{212}Pb*	beta	6.2×10^{-8}		1	6.2×10^{-8}
^{212}Bi*	64.1% beta 35.9% alpha	2.1×10^{-8}	0.359	0.641	2.1×10^{-8}
^{212}Po*	alpha	–	0.641	0.359	–
^{208}Tl*	beta	–			–
Total			**6**	**4**	**5.37×10^{-5}**

* ^{220}Rn and short-lived decay products

Committed effective dose per unit intake of alpha activity (DCF):

$$DCF_{10\,\mu m\,Th\,dust} = \frac{5.37 \times 10^{-5}\,Sv}{6\,Bq_{\alpha}} = 0.90 \times 10^{-5}\,\frac{Sv}{Bq_{\alpha}} = 0.0090\,mSv/Bq$$

Table 5: Committed effective dose, inhalation of thorium ore dust, AMAD = 20 μ, lung absorption Class S (where applicable)

Radionuclide	Decay	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
			Alpha	Beta	
^{232}Th	alpha	1.1×10^{-5}	1		1.1×10^{-5}
^{228}Ra	beta	6.4×10^{-6}		1	6.4×10^{-6}
^{228}Ac	beta	2.9×10^{-9}		1	2.9×10^{-9}
^{228}Th	alpha	7.7×10^{-6}	1		7.7×10^{-6}
^{224}Ra	alpha	3.0×10^{-7}	1		3.0×10^{-7}
^{220}Rn*	alpha	–	1		–
^{216}Po*	alpha	–	1		–
^{212}Pb*	beta	3.4×10^{-8}		1	3.4×10^{-8}
^{212}Bi*	64.1% beta 35.9% alpha	1.3×10^{-8}	0.359	0.641	1.3×10^{-8}
^{212}Po*	alpha	–	0.641	0.359	–
^{208}Tl*	beta	–			–
Total			**6**	**4**	$\mathbf{2.54 \times 10^{-5}}$

* ^{220}Rn and short-lived decay products

Committed effective dose per unit intake of alpha activity (DCF):

$$DCF_{20\,\mu m\,Th\,dust} = \frac{2.54 \times 10^{-5}\,Sv}{6\,Bq_{\alpha}} = 0.42 \times 10^{-5}\,\frac{Sv}{Bq_{\alpha}} = 0.0042\,mSv/Bq$$

Table 6: Committed effective dose, inhalation of uranium ore dust, AMAD = 1 µm, lung absorption Class S (where applicable)

Radionuclide	Decay	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
			Alpha	Beta	
^{238}U	alpha	2.0×10^{-5}	1		2.0×10^{-5}
^{234}Th	beta	4.9×10^{-9}		1	4.9×10^{-9}
^{234}Pa$_m$	beta	1.7×10^{-10}		1	1.7×10^{-10}
^{234}U	alpha	2.3×10^{-5}	1		2.3×10^{-5}
^{230}Th	alpha	2.5×10^{-5}	1		2.5×10^{-5}
^{226}Ra	alpha	2.3×10^{-5}	1		2.3×10^{-5}
^{222}Rn*	alpha	–	1		–
^{218}Po*	alpha	–	1		–
^{214}Pb*	beta	1.1×10^{-8}		1	1.1×10^{-8}
^{214}Bi*	beta	1.0×10^{-8}		1	1.0×10^{-8}
^{214}Po*	alpha	–	1		–
^{210}Pb	beta	1.5×10^{-5}		1	1.5×10^{-5}
^{210}Bi (Class M)	beta	8.7×10^{-8}		1	8.7×10^{-8}
^{210}Po	alpha	2.8×10^{-6}	1		2.8×10^{-6}
^{235}U	alpha	2.1×10^{-5}	0.046		9.7×10^{-7}
^{231}Th	beta	1.7×10^{-10}		0.046	7.8×10^{-12}
^{231}Pa	alpha	8.4×10^{-5}	0.046		3.9×10^{-6}
^{227}Ac	beta	1.1×10^{-4}		0.046	5.1×10^{-6}
^{227}Th	alpha	3.3×10^{-6}	0.046		1.5×10^{-7}
^{223}Ra	alpha	3.2×10^{-6}	0.046		1.5×10^{-7}
^{219}Rn*	alpha	–	0.046		–
^{215}Po*	alpha	–	0.046		–
^{211}Pb* (Class F)	beta	1.1×10^{-8}		0.046	5.1×10^{-10}
^{211}Bi*	alpha	–	0.046		–
^{207}Tl*	beta	–		0.046	–
Total			**8.322**	**6.184**	**1.19×10^{-4}**

* ^{222}Rn, ^{219}Rn, short-lived decay products

Committed effective dose per unit intake of alpha activity (DCF):

$$DCF_{1\,\mu m\,U\,dust} = \frac{1.19 \times 10^{-4}\,Sv}{8.322\,Bq_{\alpha}} = 1.43 \times 10^{-5}\,\frac{Sv}{Bq_{\alpha}} = 0.0143\,mSv/Bq$$

Table 7: Committed effective dose, inhalation of uranium ore dust, AMAD = 3 µm, lung absorption Class S (where applicable)

Radionuclide	Decay	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
			Alpha	Beta	
^{238}U	alpha	1.6×10^{-5}	1		1.6×10^{-5}
^{234}Th	beta	3.8×10^{-9}		1	3.8×10^{-9}
$^{234}Pa_m$	beta	2.1×10^{-10}		1	2.1×10^{-10}
^{234}U	alpha	1.8×10^{-5}	1		1.8×10^{-5}
^{230}Th	alpha	2.0×10^{-5}	1		2.0×10^{-5}
^{226}Ra	alpha	1.8×10^{-5}	1		1.8×10^{-5}
^{222}Rn*	alpha	–	1		–
^{218}Po*	alpha	–	1		–
^{214}Pb*	beta	1.4×10^{-8}		1	1.4×10^{-8}
^{214}Bi*	beta	1.4×10^{-8}		1	1.4×10^{-8}
^{214}Po*	alpha	–	1		–
^{210}Pb	beta	1.2×10^{-5}		1	1.2×10^{-5}
^{210}Bi (Class M)	beta	7.3×10^{-8}		1	7.3×10^{-8}
^{210}Po	alpha	2.3×10^{-6}	1		2.3×10^{-6}
^{235}U	alpha	1.6×10^{-5}	0.046		7.4×10^{-7}
^{231}Th	beta	1.6×10^{-10}		0.046	7.4×10^{-12}
^{231}Pa	alpha	6.4×10^{-5}	0.046		2.9×10^{-6}
^{227}Ac	beta	8.7×10^{-5}		0.046	4.0×10^{-6}
^{227}Th	alpha	2.7×10^{-6}	0.046		1.2×10^{-7}
^{223}Ra	alpha	2.7×10^{-6}	0.046		1.2×10^{-7}
^{219}Rn*	alpha	–	0.046		–
^{215}Po*	alpha	–	0.046		–
^{211}Pb* (Class F)	beta	1.4×10^{-8}		0.046	6.4×10^{-10}
^{211}Bi*	alpha	–	0.046		–
^{207}Tl*	beta	–		0.046	–
Total			**8.322**	**6.184**	**9.43×10^{-5}**

* ^{222}Rn, ^{219}Rn, short-lived decay products

Committed effective dose per unit intake of alpha activity (DCF):

$$DCF_{3\,\mu m\,U\,dust} = \frac{9.43 \times 10^{-5}\,Sv}{8.322\,Bq_\alpha} = 1.13 \times 10^{-5}\,\frac{Sv}{Bq_\alpha} = 0.0113\,mSv/Bq$$

Table 8: Committed effective dose, inhalation of uranium ore dust, AMAD = 5 µm (DEFAULT), lung absorption Class S (where applicable)

Radionuclide	Decay	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
			Alpha	Beta	
^{238}U	alpha	1.2×10^{-5}	1		1.2×10^{-5}
^{234}Th	beta	2.9×10^{-9}		1	2.9×10^{-9}
$^{234}Pa_m$	beta	2.0×10^{-10}		1	2.0×10^{-10}
^{234}U	alpha	1.3×10^{-5}	1		1.3×10^{-5}
^{230}Th	alpha	1.5×10^{-5}	1		1.5×10^{-5}
^{226}Ra	alpha	1.3×10^{-5}	1		1.3×10^{-5}
^{222}Rn*	alpha	–	1		–
^{218}Po*	alpha	–	1		–
^{214}Pb*	beta	1.4×10^{-8}		1	1.4×10^{-8}
^{214}Bi*	beta	1.4×10^{-8}		1	1.4×10^{-8}
^{214}Po*	alpha	–	1		–
^{210}Pb	beta	9.2×10^{-6}		1	9.2×10^{-6}
^{210}Bi (Class M)	beta	5.7×10^{-8}		1	5.7×10^{-8}
^{210}Po	alpha	1.8×10^{-6}	1		1.8×10^{-6}
^{235}U	alpha	1.2×10^{-5}	0.046		5.5×10^{-7}
^{231}Th	beta	1.3×10^{-10}		0.046	6.0×10^{-12}
^{231}Pa	alpha	4.6×10^{-5}	0.046		2.1×10^{-6}
^{227}Ac	beta	6.5×10^{-5}		0.046	3.0×10^{-6}
^{227}Th	alpha	2.1×10^{-6}	0.046		9.7×10^{-8}
^{223}Ra	alpha	2.2×10^{-6}	0.046		1.0×10^{-7}
^{219}Rn*	alpha	–	0.046		–
^{215}Po*	alpha	–	0.046		–
^{211}Pb* (Class F)	beta	1.3×10^{-8}		0.046	6.0×10^{-10}
^{211}Bi*	alpha	–	0.046		–
^{207}Tl*	beta	–		0.046	–
Total			**8.322**	**6.184**	**6.99×10^{-5}**

* ^{222}Rn, ^{219}Rn, short-lived decay products

Committed effective dose per unit intake of alpha activity (DCF):

$$DCF_{5\,\mu m\,U\,dust} = \frac{6.99 \times 10^{-5}\,Sv}{8.322\,Bq_{\alpha}} = 0.84 \times 10^{-5}\frac{Sv}{Bq_{\alpha}} = 0.0084\,mSv/Bq$$

Table 9: Committed effective dose, inhalation of uranium ore dust, AMAD = 10 μm, lung absorption Class S (where applicable)

Radionuclide	Decay	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
			Alpha	Beta	
^{238}U	alpha	6.3×10^{-6}	1		6.3×10^{-6}
^{234}Th	beta	1.6×10^{-9}		1	1.6×10^{-9}
$^{234}Pa_m$	beta	1.6×10^{-10}		1	1.6×10^{-10}
^{234}U	alpha	7.2×10^{-6}	1		7.2×10^{-6}
^{230}Th	alpha	7.8×10^{-6}	1		7.8×10^{-6}
^{226}Ra	alpha	7.2×10^{-6}	1		7.2×10^{-6}
^{222}Rn*	alpha	–	1		–
^{218}Po*	alpha	–	1		–
^{214}Pb*	beta	1.0×10^{-8}		1	1.0×10^{-8}
^{214}Bi*	beta	1.1×10^{-8}		1	1.1×10^{-8}
^{214}Po*	alpha	–	1		–
^{210}Pb	beta	5.1×10^{-6}		1	5.1×10^{-6}
^{210}Bi (Class M)	beta	3.4×10^{-8}		1	3.4×10^{-8}
^{210}Po	alpha	1.1×10^{-6}	1		1.1×10^{-6}
^{235}U	alpha	6.6×10^{-6}	0.046		3.0×10^{-7}
^{231}Th	beta	8.6×10^{-11}		0.046	4.0×10^{-12}
^{231}Pa	alpha	2.3×10^{-5}	0.046		1.1×10^{-6}
^{227}Ac	beta	3.6×10^{-5}		0.046	1.7×10^{-6}
^{227}Th	alpha	1.2×10^{-6}	0.046		5.5×10^{-8}
^{223}Ra	alpha	1.3×10^{-6}	0.046		6.0×10^{-8}
^{219}Rn*	alpha	–	0.046		–
^{215}Po*	alpha	–	0.046		–
^{211}Pb* (Class F)	beta	9.2×10^{-9}		0.046	4.2×10^{-10}
^{211}Bi*	alpha	–	0.046		–
^{207}Tl*	beta	–		0.046	–
Total			**8.322**	**6.184**	**3.79×10^{-5}**

* ^{222}Rn, ^{219}Rn, short-lived decay products

Committed effective dose per unit intake of alpha activity (DCF):

$$DCF_{10\ \mu m\ U\ dust} = \frac{3.79 \times 10^{-5}\ Sv}{8.322\ Bq_\alpha} = 0.46 \times 10^{-5} \frac{Sv}{Bq_\alpha} = 0.0046\ mSv/Bq$$

Table 10: Committed effective dose, inhalation of uranium ore dust, AMAD = 20 μm, lung absorption Class S (where applicable)

Radionuclide	Decay	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
			Alpha	Beta	
^{238}U	alpha	3.1×10^{-6}	1		3.1×10^{-6}
^{234}Th	beta	7.8×10^{-10}		1	7.8×10^{-10}
$^{234}Pa_m$	beta	1.2×10^{-10}		1	1.2×10^{-10}
^{234}U	alpha	3.5×10^{-6}	1		3.5×10^{-6}
^{230}Th	alpha	3.7×10^{-6}	1		3.7×10^{-6}
^{226}Ra	alpha	3.6×10^{-6}	1		3.6×10^{-6}
^{222}Rn*	alpha	–	1		–
^{218}Po*	alpha	–	1		–
^{214}Pb*	beta	5.9×10^{-9}		1	5.9×10^{-9}
^{214}Bi*	beta	6.8×10^{-9}		1	6.8×10^{-9}
^{214}Po*	alpha	–	1		–
^{210}Pb	beta	2.6×10^{-6}		1	2.6×10^{-6}
^{210}Bi (Class M)	beta	1.9×10^{-8}		1	1.9×10^{-8}
^{210}Po	alpha	5.8×10^{-7}	1		5.8×10^{-7}
^{235}U	alpha	3.2×10^{-6}	0.046		1.5×10^{-7}
^{231}Th	beta	4.6×10^{-11}		0.046	2.1×10^{-12}
^{231}Pa	alpha	9.4×10^{-6}	0.046		4.3×10^{-7}
^{227}Ac	beta	1.8×10^{-5}		0.046	8.3×10^{-7}
^{227}Th	alpha	6.1×10^{-7}	0.046		2.8×10^{-8}
^{223}Ra	alpha	6.1×10^{-7}	0.046		2.8×10^{-8}
^{219}Rn*	alpha	–	0.046		-
^{215}Po*	alpha	–	0.046		-
^{211}Pb* (Class F)	beta	5.2×10^{-9}		0.046	2.4×10^{-10}
^{211}Bi*	alpha	–	0.046		–
^{207}Tl*	beta	–		0.046	–
Total			**8.322**	**6.184**	**1.86×10^{-5}**

* ^{222}Rn, ^{219}Rn, short-lived decay products

Committed effective dose per unit intake of alpha activity (DCF):

$$DCF_{20\,\mu m\,U\,dust} = \frac{1.86 \times 10^{-5}\,Sv}{8.322\,Bq_\alpha} = 0.22 \times 10^{-5}\,\frac{Sv}{Bq_\alpha} = 0.0022\,mSv/Bq$$

Table 11: Dose Conversion Factors in mSv/Bq$_{\alpha}$, for dust containing both thorium and uranium in different weight ratios

Th : U weight ratio	Dose coefficient (mSv/Bq$_{\alpha}$), for an AMAD of:				
	1 µm	3 µm	5 µm	10 µm	20 µm
All thorium	0.0290	0.0226	0.0167	0.0090	0.0042
50:1	0.0282	0.0219	0.0162	0.0087	0.0041
40:1	0.0280	0.0218	0.0161	0.0087	0.0041
30:1	0.0276	0.0216	0.0159	0.0086	0.0040
20:1	0.0271	0.0211	0.0156	0.0084	0.0039
15:1	0.0265	0.0207	0.0153	0.0083	0.0039
10:1	0.0256	0.0200	0.0148	0.0080	0.0037
9:1	0.0253	0.0197	0.0146	0.0079	0.0037
8:1	0.0249	0.0195	0.0144	0.0078	0.0036
7:1	0.0245	0.0192	0.0142	0.0077	0.0036
6:1	0.0240	0.0188	0.0139	0.0075	0.0035
5:1	0.0234	0.0183	0.0136	0.0073	0.0034
4:1	0.0226	0.0177	0.0131	0.0071	0.0033
3:1	0.0216	0.0169	0.0125	0.0068	0.0032
2:1	0.0201	0.0158	0.0117	0.0063	0.0030
1.75:1	0.0197	0.0154	0.0114	0.0062	0.0029
1.5:1	0.0191	0.0150	0.0111	0.0060	0.0029
1:1	0.0179	0.0141	0.0104	0.0057	0.0027
1:1.5	0.0169	0.0133	0.0099	0.0054	0.0026
1:1.75	0.0166	0.0131	0.0097	0.0053	0.0025
1:2	0.0164	0.0129	0.0096	0.0052	0.0025
1:3	0.0157	0.0124	0.0092	0.0050	0.0024
1:4	0.0154	0.0122	0.0090	0.0049	0.0024
1:5	0.0152	0.0120	0.0089	0.0049	0.0023
1:6	0.0151	0.0119	0.0088	0.0048	0.0023
1:7	0.0150	0.0118	0.0088	0.0048	0.0023
1:8	0.0149	0.0117	0.0087	0.0048	0.0023
1:9	0.0148	0.0117	0.0087	0.0048	0.0023
1:10	0.0148	0.0117	0.0087	0.0047	0.0023
1:15	0.0146	0.0115	0.0086	0.0047	0.0022
1:20	0.0145	0.0115	0.0085	0.0047	0.0022
1:30	0.0145	0.0114	0.0085	0.0046	0.0022
1:40	0.0144	0.0114	0.0085	0.0046	0.0022
1:50	0.0144	0.0114	0.0085	0.0046	0.0022
All uranium	0.0143	0.0113	0.0084	0.0046	0.0022

Table 12: Dose Conversion Factors for a default AMAD of 5 µm for dusts typically generated from processing of WA minerals

Relevant mineral or material (typical Th : U weight ratio)	DC (mSv/Bq$_\alpha$)
Bauxite (1.5:1)	0.0111
Coal (all U)	0.0084
Copper concentrate (all U)	0.0084
Heavy mineral sands concentrate (10:1)	0.0148
Ilmenite (15:1)	0.0153
Iron ore (all U)	0.0084
Monazite (30:1)	0.0159
Phosphate ore and fertilisers (1:20 – 1:25)	0.0085
Rare earth concentrate (25:1)	0.0158
Red mud (1.5 to 1)	0.0111
Rutile (1.25:1)	0.0108
Silica fume (1:4)	0.0090
Tantalum concentrate (1:10 to 1:25)	0.0086
Uranium ore (all U)	0.0084
Zircon and zirconia (1:1.25)	0.0101

Note: For preliminary assessments only, the Th:U weight ratio is to be confirmed where regular dust monitoring may need to be carried out

Table 13: Dose coefficients for the inhalation of ^{210}Po and ^{210}Pb dusts

Radionuclide	Slowest lung absorption class	DC (Sv/Bq), for AMAD of:				
		0.03 µm	0.1 µm	0.3 µm	1 µm	3 µm
^{210}Po	S	5.6×10^{-5}	2.8×10^{-5}	2.0×10^{-5}	1.5×10^{-5}	1.2×10^{-5}
^{210}Pb	S	1.1×10^{-5}	5.5×10^{-6}	3.9×10^{-6}	2.8×10^{-6}	2.3×10^{-6}

Table 14: Dose coefficients for the inhalation of dust containing ^{40}K and ^{87}Rb

Radionuclide	Slowest lung absorption class	DC (Sv/Bq), for AMAD of:	
		1 µm	5 µm
^{40}K	F	2.1×10^{-9}	3.0×10^{-9}
^{87}Rb	F	5.1×10^{-10}	7.6×10^{-10}
^{147}Sm	M	8.9×10^{-6}	6.1×10^{-6}

Table 15: Coefficients between content of NORs and activity concentration

Element	From oxide to element (µg/g, ppm)		Activity concentration (Bq/µg)
Uranium	U_3O_8 to U	× 0.848	1.2384 × 10^{-2}
Thorium	ThO_2 to Th	× 0.879	4.055 × 10^{-3}
Potassium	K_2O to K	× 0.879	8.68 × 10^{-4} (*)
Rubidium	Rb_2O to Rb	× 0.914	3.2 × 10^{-5} (*)
Samarium	Sm_2O_3 to Sm	× 0.862	1.25 × 10^{-4} (*)

* Taking into account that:

- 0.012% of potassium is ^{40}K
- 28% of rubidium is ^{87}Rb
- 15% of samarium is ^{147}Sm

Table 16: Alpha activities and correction factors for thorium ore dust residing on an air sampling filter (reproduced from IAEA RS-G-1.6 p. 84)

Alpha activity residing on the filter for various retention fractions of ^{220}Rn (Bq)

Alpha-emitting radionuclide		Realistic range		Hypothetical extreme case
	100%	**75%**	**50%**	**0%**
^{232}Th	1	1	1	1
^{228}Th	1	1	1	1
^{224}Ra	1	1	1	1
^{220}Rn*	1	0.75	0.5	-
^{216}Po*	1	0.75	0.5	-
^{212}Bi*	0.359	0.269	0.180	-
^{212}Po*	0.641	0.481	0.321	-
Total (gross) alpha activity on the filter	6	5.25	4.5	3
Correction factor for determining alpha activity	**1**	**1.14**	**1.33**	**2**

* ^{220}Rn and short-lived decay products

Appendix 3. Calculation examples

Example 1

A worker was monitored for the external radiation exposure by the use of OSL badges. The quarterly monitoring results were: 0.19, <MDL, 0.23, and 0.15 mSv. The laboratory certificate states that the MDL for this type of OSL is 0.02 mSv.

The annual external dose is calculated as a sum of TLD badges results:

0.19 + 0.02 + 0.23 + 0.15 = **0.59 mSv**

Example 2

A worker is a part of a SEG of workers consisting of 12 people. Although the worker was not individually monitored for external radiation exposure, five other workers in the SEG were monitored with OSL badges.

The annual average for a worker in this work category is 0.27 mSv.

Therefore, the annual external exposure of this worker is estimated at **0.27 mSv**.

Example 3

A worker works in the office but occasionally visits a production area where NORMs are processed. The average dose rates are: in the worker's office 0.22 μSv/h; in the production area 1.12 μSv/h; background dose rate for the site is 0.15 μSv/h.

Exposure is estimated on the basis of a 'time and motion' study for the worker:

- 1800 hours at 0.22 μSv/hour = 396 μSv,
- 200 hours at 1.12 μSv/hour = 224 μSv;

The sum of external exposure is: 396 μSv + 224 μSv = 620 μSv = 0.62 mSv;

The \`background' exposure is: 2000 hours at 0.15 μSv/h = 300 μSv = 0.30 mSv;

The total external exposure is: 0.62 mSv – 0.30 mSv = 0.32 mSv.

Example 4

A parcel of land has been rehabilitated and it is expected that it will be used for residential development. The average result of the post-mining radiation survey is 0.18 μSv/h; natural background gamma dose rate for the site prior to operations was 0.15 μSv/h.

Potential maximum exposure of the member of the general public to the external gamma-radiation is estimated as follows:

- 8760 hours at 0.18 μSv/h = 1577 μSv = 1.58 mSv,
- the \`background' exposure is 8760 hours at 0.15 μSv/h = 1314 μSv = 1.31 mSv;

The total external exposure is: 1.58 mSv – 1.31 mSv = 0.27 mSv.

Example 5

A worker worked for three months in a plant where thorium-containing mineral is processed. The worker worked in several SEGs and the corresponding average dust activity concentrations were:

- shift coordinator: 200 hours, 0.039 Bq/m^3;
- dry plant operator: 100 hours, 0.213 Bq/m^3 ; and
- wet concentrator operator: 200 hours, 0.021 Bq/m^3.

A ‘special exposure’ was declared for this worker during work in the ‘dry plant operator’ SEG and an incident investigation was undertaken: 8 hours’ exposure to the alpha-activity concentration of 1.435 Bq/m^3; heavy workload – the BR was assumed to have been 1.6 m^3/hour.

Assuming a default particle size value of 5 μm (using a DC of 0.0167 mSv/Bq taken from Table 11), the internal dose from dust inhalation is calculated by calculating the intake for each work category:

- shift coordinator: 200 hours × 0.039 Bq/m^3 × 1.2 m^3/hour = 9.36 Bq
- plant operator: (100 – 8) hours × 0.213 Bq/m^3 × 1.2 m^3/hour = 23.51 Bq
- wet plant operator: 200 hours × 0.021 Bq/m^3 × 1.2 m^3/hour = 5.04 Bq
- special exposure: 8 hours × 1.435 Bq/m^3 × 1.6 m^3/hour = 18.37 Bq

All intakes are summed: 9.36 + 23.51 + 5.04 + 18.37 = 56.28 Bq

The internal dose due to dust inhalation for the three-month period is: 56.28 Bq × 0.0167 mSv/Bq = **0.94 mSv**.

Example 6

After consultation with the workforce, it is decided that the most appropriate method to remove scale from the internal surface of a processing vessel is by grinding the contaminated surface. As well as the introduction of non-radiation hazards such as noise and musculoskeletal stress, the descaling operation has the potential to liberate large amounts of dust into the workplace atmosphere. As a result, it is mandated that respiratory protection is to be worn in the work area.

Because this is a one-off exercise it is decided to not apply to the regulator for approval of the use of a respiratory program protection factor, and that the dose estimate will not consider the use of respiratory protection.

Monitoring results indicate that dust contains 7 Bq/m^3 of predominantly ^{226}Ra and the size of dust particles is 5 μm. The duration of the task was 10 hours. The (potential) internal dose from dust inhalation is calculated as follows:

- the (potential) intake of ^{226}Ra is: 10 hours × 7 Bq/m^3 × 1.2 m^3/hour = 84 Bq
- the DC for 5 μm dust containing ^{226}Ra is 0.0130 mSv/Bq (Table 8)
- the (potential) internal dose due to dust inhalation is: 84 Bq × 0.0130 mSv/Bq = **1.09 mSv**.
  - A note is to be made in the dose assessment record that respiratory protection was worn.

Example 7

In one year an operator in a zircon processing plant is exposed to 5 μm zirconia dust containing 0.039 Bq/m^3 for 800 hours, and to 3 μm silica fume dust containing 0.054 Bq/m^3 for 400 hours. The internal dose from dust inhalation is calculated as follows:

- the intake from inhalation of zirconia dust is: 800 hours × 0.039 Bq/m^3 × 1.2 m^3/hour = 37.44 Bq
- the intake from inhalation of silica fume dust is: 400 hours × 0.054 Bq/m^3 × 1.2 m^3/hour = 25.92 Bq
- the DCs are (Table 11):
  - for 5 μm zirconia dust (Th : U = 1:1.25) is 0.0101 mSv/Bq
  - for 3 μm silica fume dust (Th : U = 1:4) is 0.0122 mSv/Bq
- the internal dose due to dust inhalation is: 37.44 Bq × 0.0101 mSv/Bq + 25.92 mSv/Bq × 0.0122 mSv/Bq = 0.378+ 0.316 = **0.69 mSv**.

Example 8

Members of the public can be potentially exposed to the dust from a rehabilitated mining and processing operation.

Monitoring results indicate that the dust contains, on average, 400 ppm uranium and 20 ppm thorium and an average alpha-activity level in the dust of 0.0045 Bq/m^3. The natural background concentration of alpha-activity in the dust prior to the commencement of operations was 0.0004 Bq/m^3.

It is estimated that in the worst case, a member of the public would spend 6,500 hours per year at this particular location. Assuming a BR of 0.96 m^3/hour, and a DC for 1 μm dust containing thorium to uranium in the weight ratio of 1:20 is 0.0145 mSv/Bq (Table 11).

The estimated possible internal exposure is calculated as follows:

- potential intake is: 6500 hours × 0.0045 Bq/m^3 × 0.96 m^3/hour = 28.08 Bq
- 'background' intake is: 6500 hours × 0.0004 Bq/m^3 × 0.96 m^3/hour = 2.50 Bq
- potential annual internal dose due to dust inhalation is:
  - (28.08 – 2.50) Bq × 0.0145 mSv/Bq = 0.37 mSv.

Example 9

Two workers work in a workplace where radon (^{222}Rn) measurements have been taken on a quarterly basis using radon cups. The monitoring results were as follows:

- 1st quarter = 180 Bq/m^3
- 2nd quarter = 250 Bq/m^3
- 3rd quarter = 190 Bq/m^3
- 4th quarter = 220 Bq/m^3
- Annual average = 210 Bq/m^3.

The first worker was employed for the whole year (2000 hours).

The second worker was at this site only during the first quarter (500 hours) and also worked for the rest of the year (1500 hours) in a workplace where thoron (^{220}Rn) concentrations were measured at 780 Bq/m^3. The site-specific F for thoron was established at 0.003, the F for radon is assumed to be at the default value, 0.4.

As individual dose records are required to be kept at the site, the background concentrations of radon and thoron were not taken into account in dose calculations.

For the first worker:

- the conversion factor is 4.45 × 10^{-3} mJh/m^3 per 1 Bq/m^3
  - 210 Bq/m^3 = 0.93 mJh/m^3
- using the DC from Table 18 (3.14 mSv per 1 mJh/m^3):
  - 0.93 mJh/m^3 × 3.14 mSv/[mJh/m^3] = 2.93 mSv.

For the second worker:

- exposure to radon (^{222}Rn):

$$P_{RnP} = 5.56 \times 10^{-6} \times t \times F_{RnP} \times C_{Rn} = 5.56 \times 10^{-6} \times 500 \times 0.4 \times 180 = 0.20\, mJh/m^3$$

Then, using the DC from Table 18 (3.14 mSv per 1 mJh/m^3):

- 0.20 mJh/m^3 × 3.14 mSv/[mJh/m^3] = 0.63 mSv.

- exposure to thoron (^{220}Rn):

$$P_{TnP} = 7.56 \times 10^{-5} \times t \times F_{TnP} \times C_{Tn} = 7.56 \times 10^{-5} \times 1500 \times 0.003 \times 650 = 0.22\ mJh/m^3$$

Then, using the DC from Table 18 (1.36 mSv per 1 mJh/m^3):

- 0.22 mJh/m^3 × 1.36 mSv/[mJh/m^3] = 0.30 mSv.

The total exposure due to inhalation of radon and thoron is 0.63 + 0.30 = **0.93 mSv/year**.

Example 10

The concentrations of NORs in drinking water extracted from ground water bores on site are: ^{226}Ra=0.267 Bq/L and ^{228}Ra=0.764 Bq/L. The consumption of drinking water by workers is estimated to be 600 L/year.

The concentration prior to the commencement of mining and processing operations in this water were: ^{226}Ra=0.107 Bq/L and ^{228}Ra=0.096 Bq/L.

Detailed analysis of drinking water indicates that only isotopes of radium are present in relatively significant quantities. The internal dose from ingestion of drinking water is calculated as follows:

Intake of radioactivity is calculated separately for different NORs:

- for ^{226}Ra = 0.267 Bq/L × 600 L = 160.2 Bq
- for ^{228}Ra = 0.764 Bq/L × 600 L = 458.4 Bq.

Dose is calculated separately for each NOR (Tables 19 and 20):

- for ^{226}Ra = 160.2 Bq × 0.00013 mSv/Bq = 0.021 mSv
- for ^{228}Ra = 382.0 Bq × 0.00034 mSv/Bq = 0.130 mSv.

Total dose from water ingestion is: 0.021 mSv + 0.130 mSv = 0.151 mSv.

Intake of radioactivity based on background' concentrations is also calculated separately:

- for ^{226}Ra = 0.107 Bq/L × 600 L = 64.2 Bq
- for ^{228}Ra = 0.096 Bq/L × 600 L = 57.6 Bq.

Dose is calculated separately for each NOR, as above:

- for ^{226}Ra = 64.2 Bq × 0.00013 mSv/Bq = 0.008 mSv
- for ^{228}Ra = 57.6 Bq × 0.00034 mSv/Bq = 0.020 mSv.

Total `background' dose is: 0.008 mSv + 0.020 mSv = 0.028 mSv.

Thus, the total dose from drinking water ingestion is 0.151 mSv – 0.028 mSv = **0.12 mSv**.

Example 11

Conditions

1. A worker was working in a mineral processing plant (Site A) for five months:
   - 520 hours as dry plant operator (average dust activity concentration = 0.305 Bq/m^3)
   - 300 hours as control room operator (average dust activity concentration = 0.027 Bq/m^3)
   - 140 hours as wet plant operator (average dust activity concentration = 0.066 Bq/m^3).

   Particle size characterisation program is not carried out. The mineral contains both thorium and uranium in an approximate ratio of Th:U = 25:1.

   The results of TLD badges worn by the worker for two monitoring periods are 0.19 and 0.28 mSv.

2. The worker spent two months in the year (380 hours) at a remote uranium exploration site (Site B):
   - the area in which the worker worked has a gamma-radiation level of 0.49 μSv/hour (background radiation level for this site is 0.14 μSv/hour)
   - drinking water was supplied from an on-site bore and ^{226}Ra concentration in the water was on average 0.72 Bq/L (background level is 0.15 Bq/L)
   - average dust activity concentration of uranium dust was 0.117 Bq/m^3 and on one occasion the worker was exposed to the dust with activity concentration of 3.692 Bq/m^3 for 10 hours (this was treated as a special exposure)
   - the average radon (^{222}Rn) concentration is 63 Bq/m^3.

3. The worker spent four months in the year (700 hours) working in a mineral storage area at the wharf (Site C):
   - 500 hours were spent working in the office
   - 200 hours were spent inside the product storage shed (dust activity concentration = 0.089 Bq/m^3, material contains both thorium and uranium in an approximate ratio of Th:U = 1:1.25), thoron concentrations were measured at 105 Bq/m^3 in the product storage shed and 25 Bq/m^3 inside the office
   - gamma-radiation level in the office was 0.32 μSv/hour, in the storage shed – 0.53 μSv/hour, background in the surrounding area – 0.16 μSv/hour.

Dose assessment

External dose 1 (Site A):

0.19 mSv + 0.28 mSv = 0.47 mSv

External dose 2 (Site B):

(0.49 μSv/hour × 380 hours) – (0.14 μSv/hour × 380 hours) = 133 μSv = 0.13 mSv

External dose 3 (Site C):

(0.32 μSv/hour × 500 hours) – (0.16 μSv/hour × 500 hours) = 80 μSv = 0.08 mSv

(0.53 μSv/hour × 200 hours) – (0.16 μSv/hour × 200 hours) = 74 μSv = 0.07 mSv

Sum of external doses

0.47 + 0.13 + 0.08 + 0.07 = 0.75 mSv

Internal dose 1 (Site A – inhalation – dust):

(0.305 Bq/m^3 × 1.2 m^3/hour × 520 hours) × 0.0158 mSv/Bq = 3.01 mSv

(0.027 Bq/m^3 × 1.2 m^3/hour × 300 hours) × 0.0158 mSv/Bq = 0.15 mSv

(0.066 Bq/m^3 × 1.2 m^3/hour × 140 hours) × 0.0158 mSv/Bq = 0.18 mSv

Internal dose 2 (Site B – inhalation – dust):

(0.117 Bq/m^3 × 1.2 m^3/hour × 380 hours) × 0.0084 mSv/Bq = 0.45 mSv

(3.692 Bq/m^3 × 1.2 m^3/hour × 10 hours] × 0.0084 mSv/Bq = 0.37 mSv

Internal dose 3 (Site B – inhalation – radon):

5.56 × 10^{-6} × 380 hours × 0.4 × 63 Bq/m^3 = 0.05 mJh/m^3

0.05 mJh/m^3 × 3.14 (mSv [mJh/m^3]) = 0.16 mSv

Internal dose 4 (Site B – ingestion):

(0.72 Bq/L × 125 L – 0.15 Bq/L × 125 L) × 0.00013 mSv/Bq = 0.01 mSv

Internal dose 5 (Site C – inhalation – dust):

(0.089 Bq/m^3 × 1.2 m^3/hour × 200 hours) × 0.0101 mSv/Bq = 0.22 mSv

Internal dose 6 (Site C – inhalation – thoron):

7.56 × 10^{-5} × 200 hours × 0.04 × 105 Bq/m^3 = 0.06 mJh/m^3

0.06 mJh/m^3 × 1.5 (mSv/[mJh/m^3]) = 0.09 mSv

7.56 × 10^{-5} × 500 hours × 0.04 × 25 Bq/m^3 = 0.04 mJh/m^3

0.04 mJh/m^3 × 1.36 (mSv/[mJh/m^3]) = 0.05 mSv

Sum of internal doses

3.01 + 0.15 + 0.18 + 0.45 + 0.37 + 0.16 + 0.01 + 0.22 + 0.09 + 0.05 = 4.69 mSv

The annual radiation exposure of the worker is estimated to be:

0.75 + 4.69 = **5.44 mSv**

Example 12

Conditions

There is a possibility of an industrial or residential development to be established on a rehabilitated processing site. The gamma-dose rate is 0.19±0.02 μSv/hour; background in the area was 0.13±0.02 μSv/hour.

The dust activity concentration is the same as it was prior to the construction of a plant. Some tailings have been buried on site and concentrations of ^{226}Ra in the ground water are slightly elevated (0.45 Bq/L in comparison with background value of 0.22 Bq/L). Modelling indicates that if tailings are brought to the surface, concentration of radon in the air is expected to be of the order of 18 Bq/m^3.

Residential development case

Potential external dose (Case 1 – exact background value):

[0.19 μSv/hour – 0.13 μSv/hour) × 8760 hours = 0.526 mSv

Potential external dose (Case 2 – background value plus two GSDs):

(0.19 μSv/hour – 0.17 μSv/hour) × 8760 hours = 0.175 mSv

Potential internal dose – ingestion:

(0.45 Bq/L – 0.22 Bq/L) × 500 L × 0.00013 mSv/Bq = 0.015 mSv

Potential internal dose – inhalation:

$5.56 \times 10^{-6} \times 8760$ hours × 0.2 × 18 Bq/m^3 = 0.175 mJh/m^3

0.17 mJh/m^3 × 3.14 (mSv [mJh/m^3]) = 0.534 mSv

The determination of whether exposure to radon is taken into account in the assessment of the site or not is made by the regulator. In this case it is assumed that the exposure is excluded from dose calculations for members of the general public, as it is close to general background levels in WA.

The potential exposure level for the member of the general public in the area is:

- 0.19 mSv/year if the use of the background level plus two GSDs was approved by the regulator
- 0.54 mSv/year if the use of the “background level plus two GSDs” was not approved.

In the first case, the site does not need to be classified in any way and any development of the land will be permissible. However, in the second case, the exposure of a member of the public is above the dose constraint of 0.3 mSv/year, at which a classification of a site as ‘radiologically contaminated’ may be required.

Industrial development case

Potential external dose:

[0.19 μSv/hour – 0.13 μSv/hour) × 2000 hours = 0.120 mSv

Potential internal dose – ingestion:

(0.45 Bq/L – 0.22 Bq/L) × 500 L × 0.00013 mSv/Bq = 0.015 mSv

Potential internal dose – inhalation:

$5.56 \times 10^{-6} \times 2000$ hours $\times 0.4 \times 18$ Bq/m^3 = 0.08 mJh/m^3

0.08 mJh/m^3 × 3.14 (mSv [mJh/m^3]) = 0.251 mSv

It is estimated that an industrial worker will receive a dose of approximately 0.39 mSv/year, which may require the classification of the site as 'radiologically contaminated'.

Appendix 4: Glossary and Abbreviations

ADWG	*Australian Drinking Water Guidelines*
AED	Aerodynamic equivalent diameters
AMAD	Activity median aerodynamic diameter
ARPANSA	Australian Radiation Protection And Nuclear Safety Agency
BR	Breathing rate
DC	Dose coefficient
DCF	Dose conversion factor
Designated worker	A worker who works, or may work, under conditions so that the effective dose of radiation the worker receives may exceed 5 millisievert per year (r. 641S(1)(a))
EEC	Equilibrium equivalent concentrates
F	Equilibrium factor
GM	Geometric mean
GSD	Geometric standard deviation
IAEA	International Atomic Energy Agency
ICRP	International Commission On Radiological Protection
MAD	Median aerodynamic diameter
MDL	Minimum detectable limit
MMAD	Mass median aerodynamic diameter
NOR	Naturally occurring radionuclide
OSL	Optically stimulated luminescence
PAEC	Potential alpha energy concentration
PED	Personal electronic dosimeter
Pre-operational monitoring program	A program submitted to the regulator for the mining operation for the monitoring of radiation and dose levels at the mine (r. 641M(1))
Radioactive material	Material that has an activity concentration that exceeds 1 Bqg-1 and either: • exhibits radioactivity; or (ii) • emits ionising radiation or particles, or • contains radionuclides of natural origin (r. 641K)

Relevant mines	A mine is considered a relevant mine if minerals or radioactive materials that have an activity concentration of radioactivity of 1 Bqg-1 or more are mined at the mine, and either: • workers at the mine are likely to receive doses of radiation over 1 millisievert per year, arising from mining operations at the mine, or • members of the public at, or in the vicinity of, the mine are likely to receive doses of radiation, arising from mining operations at the mine, in excess of one-half of the effective dose as above (r. 641L)
RnP	Radon progeny
RPS-9	The *Radiation Protection Series 9 – Code of practice and safety guide for radiation protection and radiative waste management in mining and mineral processing (2005)* published by the Chief Executive officer of the Australian Radiation protection and Nuclear Safety Agency in August 2005 and updated in January and December 2015
SEG	Similar exposure group
TLD	Thermo-luminescent dosimeter
TnP	Thoron progeny
WLM	Working level month

Radionuclides	
^{40}K	Potassium-40
^{210}Pb	Lead-210
^{210}Po	Polonium-210
^{228}Ra and ^{226}Ra	Radium-228 and Radium-226
^{87}Rb	Rubidium-87
^{222}Rn ^{220}Rn	Radon-222 and Radon-220
^{147}Sm	Samarium-147
^{238}U and ^{235}U	Uranium-238 and Uranium-235
^{232}Th	Thorium-232

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