Annex 3:Appendix 2

Dose coefficients

I INTRODUCTION

Dose coefficients for occupational exposure may be found in the publications [IC94b] and databases from the International Commission on Radiation Protection (ICRP) [IC01] for three default rates of absorption (Fast, Moderate and Slow) and a limited set of Activity Median Aerodynamic Diameters (AMAD) and Geometric Standard Deviations (GSD).

Values for other absorption rates and particle size characteristics may be calculated with dedicated software such as IMBA [IM02 and IM03] or PLEIADES [PL03] that both incorporate the most recent Human Respiratory Tract Model (HRTM) published in the ICRP 66 [IC94a], and the most recent biokinetic models. The main difference between these two codes is that in IMBA the decay products of the incorporated radionuclide follow the same biokinetic model, while in PLEIADES (that implements the most recent ICRP dose coefficients calculation scheme) the decay products of Pb, Ra, Th and U follow their own biokinetic models.

Within the scope of the SMOPIE project, it became apparent that dose coefficients for the main radionuclides belonging to the two ^{238}U and ^{232}Th natural chains had to be calculated for a wider range of particle size distributions (AMAD = 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20 µm ; GSD=1.5 and 2.5) than are available in the ICRP databases, and for default rates of absorption that were not considered by ICRP for occupational exposure.

Dose coefficients presented in this appendix have been calculated with the help of both IMBA and PLEIADES codes. In the retained calculation sequence, the deposition values in the respiratory tract were calculated by the IMBA deposition module and were later used as inputs to the PLEIADES code that performed the committed effective dose calculation. Where the absorption rate was not originally considered by ICRP for occupational exposure, the gastrointestinal absorption fraction f1 taken into account in the PLEIADES calculation was the one used by ICRP for the exposure of adult members of the public.

While the dose coefficients based on the older ICRP 30 HRTM [IC79] had to be applied to the inhalable fraction of the ambient aerosol, the dose coefficients presented below, based on the most recent ICRP 66 HRTM [IC94a], must be applied [IC02] to the true (total) activity concentration of the aerosol, i.e. the measured airborne activity concentration corrected for the sampling efficiency of the sampler.

An additional consideration when calculating DCs for the U-238 decay series is the rate of radon-222 emanation. ICRP assumed a high emanation rate, such as would be appropriate for purified radium-226 compounds. But many NORM materials, such as mineral sands, are known to have low radon emanation rates. The effect of this difference on the calculated dose coefficients is also considered in this Appendix.

II CALCULATED DOSE COEFFICIENTS

Table 1 and Figure 1 present the variation with absorption rate and radionuclide of the workers dose coefficients for default particle size dispersion characteristics (AMAD 5 µm, GSD 2.5). Tables 2 to 4 and Figure 2 present, for each Type of absorption rate, the variation with radionuclide of the contribution of the main organs to the public (adult) dose coefficients, extracted from the ICRP database.

The results indicate the significant variability of the dose coefficients with both the considered radionuclide and absorption rate. Examples in terms of a number of key radioelements are given below (comparisons are based on 5 μm AMAD and a 2.5 GSD):

Uranium

For U-238 and U-234 , the effective dose from inhalation is inversely dependent on the absorption rate and is always the lowest for compounds of absorption Type Fast and the highest for compounds of absorption Type Slow. Moreover, while for Type Fast compounds almost half of the effective dose is received by the bone surface and the red bone marrow; for Moderate and Slow compounds the major part of the effective dose is received by the lung.

This is consistent with the characteristics of the uranium biokinetic mode, described in ICRP publication 69, in which the transfer rate of uranium from blood to the urinary path is relatively high, and the transfer rate of uranium from blood to bones is smaller but higher than the corresponding rates for thorium. As a consequence, around 10% of the uranium in the blood is transferred to bones within the next day and only 1% remains there after 30 years.

Thorium

Dose coefficients for thorium compounds are significantly higher than those for uranium compounds. Compounds of thorium of absorption Type Fast give rise to substantially higher effective doses than compounds of Type M or S. A significant proportion of the effective dose is due to the exposure of the bone surfaces and red bone marrow.

This is consistent with the Thorium biokinetic mode, described in the ICRP publication 69, in which the transfer rate of thorium from blood to the urinary path is relatively small, and the transfer rate of thorium from blood to bones is much higher. As a consequence, around 70% of the thorium in the blood is transferred to bones within the next 10 days and remains there during the next 30 years.

In the case of Th-228 , which has a much shorter half life, the effective dose resulting from inhalation of Fast compounds is still the highest. However the effective dose associated with Slow compounds is slightly higher than that from Moderate compounds, and the difference between the effective doses associated with the different compounds absorption rate is much reduced.

Radium

For Ra-226 and Ra-228, the radium biokinetic model described in ICRP publication 67 applies. Like uranium isotopes, the effective dose from inhalation is inversely dependent on the absorption rate and is always smallest for compounds of Type Fast and highest for compounds of Type M and S. Again, the difference in dose coefficients for different absorption rates is less for the shorter half life radionuclide (Ra-228).

Lead

For Pb-210, while the effective dose associated with the Slow compounds is the highest, the effective dose associated with Moderate compounds is slightly smaller than the one associated with Fast compounds.

The exposure of the bone surface, red bone marrow and liver account for most of the effective dose. This is consistent with the lead biokinetic model (described in the ICRP publication 67), which is characterised by high transfer rates from blood to bones and liver.

Tables 5 to 14 and Figures 2 to 10 present, for each considered radionuclide, the variation with absorption rate, AMAD and GSD of the dose coefficients calculated in this study for occupational exposures.

From these figures and tables, that the ranking between the three absorption rate Types (Fast, Moderate, Slow) for a given radionuclide does not depend generally on the considered AMAD, with the exception of:

- U-234 and U-238 for which the Fast dose coefficients become slightly higher than the Moderate dose coefficients for any AMAD above approximately 15 µm (GSD 1.5);
- Ra-228, for which the Fast dose coefficients become higher than the Moderate dose coefficients for any AMAD above 7 µm (GSD 1.5) and 10 µm (GSD 2.5); and
- Po-210, for which the Fast dose coefficients become higher than the Moderate dose coefficients for any AMAD above 12 µm (GSD 1.5), and higher than the Slow dose coefficients for any AMAD above 14 µm (GSD 1.5).

III LOW RADON EMANATING PARTICLES

The current ICRP biokinetic model for radium assumes that radon-222, which is formed by radioactive decay of radium-226, emanates very efficiently from the inhaled particle. An escape rate of 100 d^{-1} from the respiratory tract is assumed. This means that radon, and consequently the short-lived daughters of radon do not contribute to the dose to the lungs, even when the particle is poorly soluble.

Many NORM materials, however, show a very low radon emanation fraction of only a few percent. It is not expected that when such a particle is inhaled the emanation will change significantly. Since a large part of the potential alpha energy of radon and the short-lived radon daughters is not taken into account, the dose to the lungs is underestimated by a factor of 5 to 6 for these materials.

The biokinetic model for radium further assumes that radon entering the blood is removed from the body at a rate of 1 min^{-1}. This means that radon and the short-lived radon daughters cannot be transported to the tissues at risk and do not contribute significantly to the effective dose Therefore the doses to organs other than the respiratory tract do not depend on the emanation rate of the inhaled particles of absorption Type F that are rapidly removed from the respiratory tract. However, the dose coefficients for Ra-226 in Type S and M aerosols need to be reconsidered, since these are determined for over 95% by the doses to the respiratory tract. Radon and its short-lived daughters contribute significantly to that dose when they remain trapped in the particles.

To determine the upper bound of the dose coefficients it is assumed that the inhaled particles have zero radon emanation as long as they are retained in the respiratory tract.

The results of the calculations are presented in Table 12, and these may be compared with the (high emanation rate) values in table 11. As might be expected the effective dose for Type M and S compounds are approximately five times higher.

IV DOSE COEFFICIENTS FOR CHAINS AND CHAIN SEGMENTS

The dose coefficients for individual radionuclides have been combined to produce dose coefficients for complete chains in secular equilibrium, and for chain segments. An example is provided in table 15 for inhalation of particles with AMAD 5 µm and GSD 2.5. From these table several observations can be made with respect to the ratio’s between the dose coefficients for particles with absorption Type Slow and Fast respectively, i.e.:

- the S/F ratio is particularly high for Ra-226 (16) and even higher (87) for Ra-226 with low emanation rate;
- the SF ratio is about 10 for U-238, U-234 and Ra-228 and about 4 for Pb-210 and Po-210;
- the S/F ratio is particularly low for Th-232 and Th-230;
- for the U-238 decay chain in secular equilibrium the S/F ratio is less than 1 (0.28 or 0.53 depending on the radon emanation rate of the material considered);
- for the chain segment Ra-226+ the S/F ratio is about 6 or 20, depending on the radon emanation rate of the material considered;
- for the Th-232 decay chain in secular equilibrium the S/F ratio is 0.3;
- a choice of default absorption Type S for dose calculations is not conservative for materials containing the U-238 and/or Th-232 decay chain radionuclides is secular equilibrium; and
- a choice of default absorption Type F when the true absorption Type would be S results in underestimates of exposures ranging from a factor of 4 for Pb-210 and Po-210 to a factor of about 90 for Ra-226 containing particles with low radon emanation rate.

V REFERENCES

IC79 International Commission on Radiological Protection. Limits for Intakes of Radionuclides by Workers. ICRP Publication 30 part 1. Annals of the ICRP 2 (3/4). Pergamon Press Oxford (1979)

IC94a International Commission on Radiological Protection: Human respiratory tract model for radiological protection. ICRP publication 66. Annals of the ICRP 24 (1-3). Pergamon Press, Oxford. (1994)

IC94b International Commission on Radiological Protection: Dose coefficients for intakes of radionuclides by workers. ICRP publication 68. Annals of the ICRP 24 (4). Pergamon Press, Oxford. (1994)

IC01 International Commission on Radiological Protection: ICRP Database of Dose Coefficients: Workers and Members of the Public, Version 1.0 (2001)

IC02 International Commission on Radiological Protection: Supporting guidance 3, Guide for the Practical Application of the ICRP Human Respiratory Tract Model. ICRP publication 83. Annals of the ICRP 32 (1-2). Pergamon Press, Oxford. (2002)

IM02 Marsh, J W, Jarvis, N S, Birchall, A, James, A C, Peace M S, Davis, K E, Dorrian M D, Phipps, A W, Smith, A and Smith, F M G. Validation of IMBA and IMBA EXPERT. Proceedings of the European IRPA Congress 2002: 'Towards harmonisation of radiation protection in Europe', Florence, Italy, 8-11 October 2002.

IM03 A. Birchall, M Puncher, A C James, J W Marsh, N S Jarvis, M S Peace and K Davis. IMBA ExpertTM: Internal dosimetry made simple. Proceedings of a Workshop on Internal Dosimetry of Radionuclides: Occupational, Public and Medical Exposure, Oxford, UK, September 9 -12, 2002. Radiat. Prot. Dosim., 105(1-4), 421-425 (2003).

PL03 NRPB's code for producing compilations of dose coefficients, used to contribute to the work of the ICRP Task Group on Dose Calculations. J. Marsh, NRPB, personal communication, (2003).

VI TABLES AND FIGURES

Table 1 : Dependence of the workers inhalation dose coefficient on lung absorption Type (AMAD 5 μm, GSD 2.5)

Inhalation dose coefficients, e(50), worker, Sv/Bq (AMAD 5 μm, GSD 2.5) *			
	Fast	**Moderate**	**Slow**
U238	5.87E-07	1.66E-06	5.73E-06
U234	6.53E-07	2.11E-06	6.83E-06
Th232	**1.28E-04**	2.92E-05	1.20E-05
Th230	**1.18E-04**	2.77E-05	7.19E-06
Th228	**3.42E-05**	2.21E-05	2.52E-05
Ra228	**1.10E-06**	1.69E-06	**1.14E-05**
Ra226	**4.40E-07**	2.19E-06	**6.91E-06**
Po210	7.29E-07	2.16E-06	**2.69E-06**
Pb210	1.11E-06	**7.43E-07**	**4.26E-06**

* Dose coefficients in bold were not considered in the ICRP [IC94b] calculation for occupational exposure

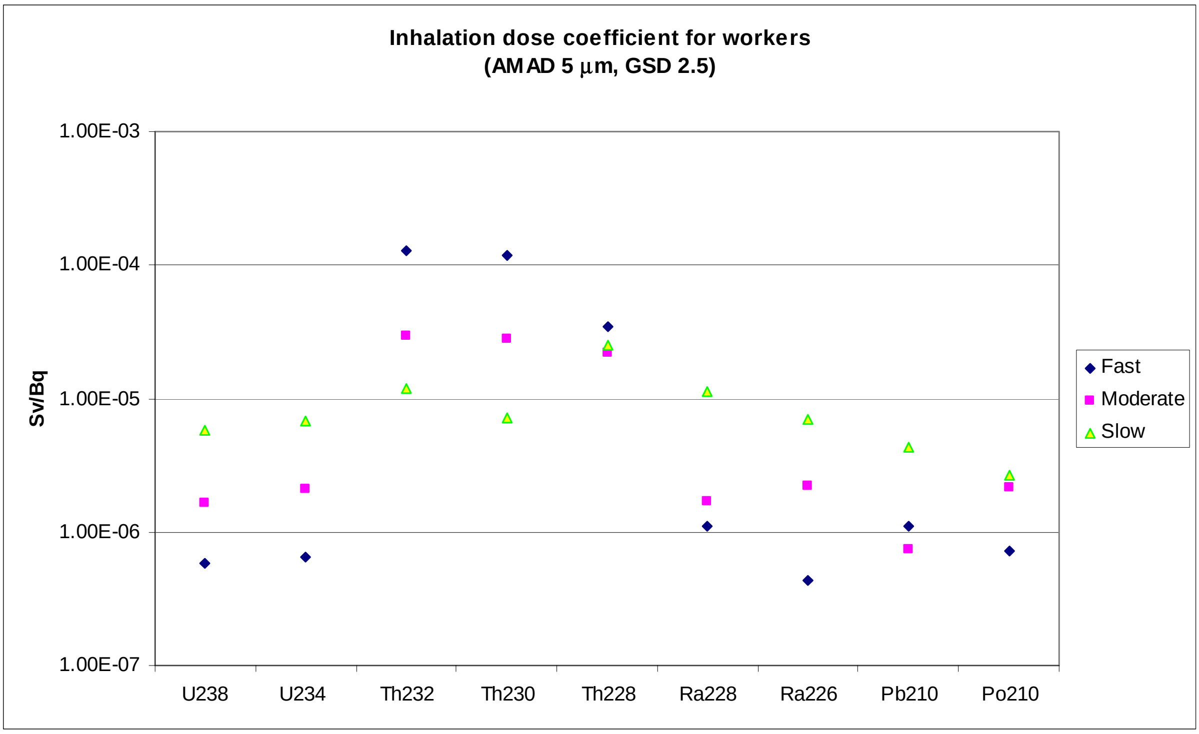


Figure 1: Workers' inhalation dose coefficients e(50) for absorption Type F, M and S, AMAD 5 μm and GSD 2.5. Gut transfer factors according to Table 5 – Table 13.

Table 2: Relative contributions of the main organ doses to the effective inhalation dose coefficients for adult members of the public (Fast compounds, AMAD 5 µm, GSD 2.5)

Nuclide	Bone surface	Colon	Liver	Red Marrow	Lungs	Remainders
U238	**17%**	7%	**12%**	**22%**	7%	3%
U234	**18%**	7%	**12%**	**21%**	7%	3%
Th232	**52%**	2%	4%	**25%**	2%	1%
Th230	**58%**	1%	4%	**25%**	1%	0%
Th228	**40%**	2%	8%	**37%**	1%	1%
Ra228	**33%**	3%	7%	**40%**	3%	1%
Ra226	**47%**	3%	3%	**37%**	2%	1%
Pb210	**32%**	2%	**14**%	**43%**	1%	1%
Po210	1%	3%	**28%**	**26%**	3%	**28%**

Table 3: Relative contributions of the main organ doses to the effective inhalation dose coefficients for adult members of the public (Moderate compounds, AMAD 5 µm, GSD 2.5)

Nuclide	Bone surface	Colon	Liver	Red Marrow	Lungs	Remainders
U238	1%	1%	1%	2%	**92%**	0%
U234	1%	1%	1%	1%	**94%**	0%
Th232	**49%**	2%	4%	**24%**	7%	1%
Th230	**54%**	1%	4%	**23%**	8%	0%
Th228	12%	1%	3%	11%	**70%**	0%
Ra228	**20%**	1%	4%	**21%**	**46%**	0%
Ra226	3%	0%	0%	2%	**94%**	0%
Pb210	**14%**	1%	7%	**20%**	**54%**	1%
Po210	0%	0%	2%	2%	**94%**	0%

Table 4: Relative contributions of the main organ doses to the effective inhalation dose coefficients for adult members of the public (Slow compounds, AMAD 5 µm, GSD 2.5)

Nuclide	Bone surface	Colon	Liver	Red Marrow	Lungs	Remainders
U238	0%	0%	0%	0%	**76%**	**24%**
U234	0%	0%	0%	0%	**77%**	**23%**
Th232	**12%**	0%	1%	6%	**77%**	0%
Th230	**19%**	0%	1%	8%	**67%**	0%
Th228	1%	0%	0%	0%	**99%**	0%
Ra228	1%	0%	0%	1%	**70%**	**28%**
Ra226	0%	0%	0%	0%	**77%**	**23%**
Pb210	0%	0%	0%	0%	**68%**	**31%**
Po210	0%	0%	0%	0%	**100%**	0%

Table 5: U-238 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

U-238	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.02 *)**	**f_1=0.02**	**f_1=0.002**	**f_1=0.02**	**f_1=0.02**	**f_1=0.00**
1	4.78E-07	2.29E-06	7.15E-06	5.02E-07	2.58E-06	7.36E-06
2	7.07E-07	3.11E-06	8.44E-06	5.94E-07	2.42E-06	6.59E-06
3	7.32E-07	2.95E-06	9.02E-06	6.13E-07	2.18E-06	7.20E-06
4	6.96E-07	2.36E-06	7.34E-06	6.05E-07	1.91E-06	6.43E-06
5	6.49E-07	1.75E-06	5.80E-06	**5.87E-07**	**1.66E-06**	**5.73E-06**
6	6.05E-07	1.57E-06	4.61E-06	5.66E-07	1.44E-06	5.12E-06
8	5.33E-07	9.45E-07	3.12E-06	5.26E-07	1.36E-06	4.17E-06
10	4.80E-07	6.35E-07	2.35E-06	4.90E-07	1.10E-06	3.49E-06
12	4.39E-07	4.76E-07	1.94E-06	4.61E-07	9.17E-07	3.00E-06
14	4.07E-07	3.88E-07	1.69E-06	4.36E-07	7.80E-07	2.64E-06
16	3.81E-07	3.37E-07	1.53E-06	4.16E-07	6.76E-07	2.36E-06
18	3.61E-07	3.05E-07	1.43E-06	3.99E-07	5.96E-07	2.15E-06
20	3.45E-07	2.83E-07	1.35E-06	3.85E-07	5.33E-07	1.98E-06

*) f_1: gut transfer factor

Table 6: U-234 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

U-234	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.02 *)**	**f_1=0.02**	**f_1=0.002**	**f_1=0.02**	**f_1=0.02**	**f_1=0.002**
1	5.31E-07	2.80E-06	8.35E-06	5.57E-07	3.15E-06	8.61E-06
2	7.85E-07	3.92E-06	1.01E-05	6.59E-07	3.03E-06	7.82E-06
3	8.13E-07	3.77E-06	1.08E-05	6.81E-07	2.76E-06	8.55E-06
4	7.73E-07	3.04E-06	8.82E-06	6.72E-07	2.42E-06	7.66E-06
5	7.21E-07	2.26E-06	6.97E-06	**6.53E-07**	**2.11E-06**	**6.83E-06**
6	6.72E-07	1.99E-06	5.53E-06	6.29E-07	1.84E-06	6.11E-06
8	5.92E-07	1.19E-06	3.73E-06	5.84E-07	1.70E-06	4.97E-06
10	5.33E-07	7.87E-07	2.79E-06	5.45E-07	1.38E-06	4.16E-06
12	4.87E-07	5.81E-07	2.28E-06	5.12E-07	1.15E-06	3.57E-06
14	4.52E-07	4.68E-07	1.98E-06	4.85E-07	9.71E-07	3.13E-06
16	4.23E-07	4.01E-07	1.79E-06	4.62E-07	8.38E-07	2.80E-06
18	4.01E-07	3.60E-07	1.66E-06	4.43E-07	7.35E-07	2.54E-06
20	3.83E-07	3.32E-07	1.57E-06	4.27E-07	6.55E-07	2.34E-06

*) f_1: gut transfer factor

Table 7 : Th-232 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

Th-232	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.0005 *)**	**f_1=0.0005**	**f_1=0.0002**	**f_1=0.0005**	**f_1=0.0005**	**f_1=0.0002**
1	1.04E-04	4.30E-05	2.33E-05	1.09E-04	4.27E-05	2.29E-05
2	1.54E-04	5.09E-05	2.56E-05	1.29E-04	4.07E-05	2.01E-05
3	1.59E-04	4.45E-05	2.07E-05	1.33E-04	3.68E-05	1.70E-05
4	1.51E-04	3.59E-05	1.52E-05	1.32E-04	3.28E-05	1.43E-05
5	1.41E-04	2.87E-05	1.08E-05	**1.28E-04**	**2.92E-05**	**1.20E-05**
6	1.31E-04	2.33E-05	1.06E-05	1.23E-04	2.62E-05	1.02E-05
8	1.16E-04	1.66E-05	6.65E-06	1.14E-04	2.15E-05	1.00E-05
10	1.04E-04	1.30E-05	4.71E-06	1.06E-04	1.82E-05	8.09E-06
12	9.49E-05	1.09E-05	3.69E-06	9.99E-05	1.58E-05	6.74E-06
14	8.80E-05	9.63E-06	3.11E-06	9.45E-05	1.40E-05	5.76E-06
16	8.25E-05	8.78E-06	2.76E-06	9.01E-05	1.26E-05	5.03E-06
18	7.81E-05	8.17E-06	2.53E-06	8.64E-05	1.16E-05	4.47E-06
20	7.46E-05	7.73E-06	2.38E-06	8.33E-05	1.07E-05	4.04E-06

*) f_1: gut transfer factor

Table 8 : Th-230 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

Th-230	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.0005 *)**	**f_1=0.0005**	**f_1=0.0002**	**f_1=0.0005**	**f_1=0.0005**	**f_1=0.0002**
1	9.67E-05	4.05E-05	1.28E-05	1.01E-04	4.03E-05	1.29E-05
2	1.43E-04	4.82E-05	1.48E-05	1.20E-04	3.85E-05	1.15E-05
3	1.48E-04	4.23E-05	1.25E-05	1.24E-04	3.49E-05	9.97E-06
4	1.40E-04	3.42E-05	9.43E-06	1.22E-04	3.11E-05	8.47E-06
5	1.30E-04	2.73E-05	6.79E-06	**1.18E-04**	**2.77E-05**	**7.19E-06**
6	1.22E-04	2.21E-05	4.83E-06	1.14E-04	2.48E-05	6.13E-06
8	1.07E-04	1.56E-05	4.48E-06	1.06E-04	2.03E-05	4.54E-06
10	9.62E-05	1.22E-05	3.24E-06	9.85E-05	1.71E-05	5.23E-06
12	8.79E-05	1.02E-05	2.58E-06	9.25E-05	1.49E-05	4.41E-06
14	8.15E-05	8.96E-06	2.20E-06	8.76E-05	1.32E-05	3.81E-06
16	7.64E-05	8.16E-06	1.97E-06	8.35E-05	1.19E-05	3.36E-06
18	7.24E-05	7.59E-06	1.81E-06	8.00E-05	1.08E-05	3.01E-06
20	6.91E-05	7.18E-06	1.70E-06	7.71E-05	1.01E-05	2.74E-06

*) f_1: gut transfer factor

Table 9 : Th-228 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

Th-228	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.0005 *)**	**f_1=0.0005**	**f_1=0.0002**	**f_1=0.0005**	**f_1=0.0005**	**f_1=0.0002**
1	2.80E-05	2.78E-05	3.44E-05	2.94E-05	2.98E-05	3.67E-05
2	4.13E-05	3.95E-05	4.80E-05	3.47E-05	3.03E-05	3.64E-05
3	4.27E-05	3.79E-05	4.54E-05	3.58E-05	2.80E-05	3.32E-05
4	4.05E-05	3.10E-05	3.62E-05	3.53E-05	2.50E-05	2.91E-05
5	3.78E-05	2.37E-05	3.29E-05	**3.42E-05**	**2.21E-05**	**2.52E-05**
6	3.52E-05	1.78E-05	2.53E-05	3.30E-05	1.94E-05	2.71E-05
8	3.10E-05	1.03E-05	1.55E-05	3.06E-05	1.52E-05	2.17E-05
10	2.79E-05	6.50E-06	1.05E-05	2.85E-05	1.22E-05	1.77E-05
12	2.55E-05	4.56E-06	7.91E-06	2.68E-05	9.96E-06	1.48E-05
14	2.36E-05	3.51E-06	6.47E-06	2.54E-05	8.31E-06	1.26E-05
16	2.21E-05	2.91E-06	5.61E-06	2.42E-05	7.07E-06	1.10E-05
18	2.10E-05	2.54E-06	5.06E-06	2.32E-05	6.11E-06	9.69E-06
20	2.00E-05	2.31E-06	4.69E-06	2.23E-05	5.37E-06	8.69E-06

*) f_1: gut transfer factor

Table 10: Ra-228 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

Ra-228	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.2 *)**	**f_1=0.2**	**f_1=0.01**	**f_1=0.2**	**f_1=0.2**	**f_1=0.01**
1	8.56E-07	2.53E-06	1.53E-05	9.01E-07	2.54E-06	1.49E-05
2	1.29E-06	3.09E-06	2.01E-05	1.09E-06	2.43E-06	1.60E-05
3	1.35E-06	2.73E-06	1.74E-05	1.14E-06	2.18E-06	1.44E-05
4	1.30E-06	2.17E-06	1.39E-05	1.13E-06	1.92E-06	1.28E-05
5	1.22E-06	1.68E-06	1.11E-05	**1.10E-06**	**1.69E-06**	**1.14E-05**
6	1.15E-06	1.30E-06	8.95E-06	1.07E-06	1.49E-06	1.02E-05
8	1.02E-06	8.27E-07	6.35E-06	9.99E-07	1.18E-06	8.35E-06
10	9.27E-07	5.86E-07	4.99E-06	9.36E-07	9.63E-07	7.06E-06
12	8.51E-07	4.58E-07	4.22E-06	8.84E-07	8.08E-07	6.13E-06
14	7.92E-07	3.84E-07	3.75E-06	8.40E-07	6.93E-07	5.44E-06
16	7.44E-07	3.39E-07	3.43E-06	8.03E-07	6.07E-07	4.92E-06
18	7.06E-07	3.09E-07	3.21E-06	7.72E-07	5.40E-07	4.51E-06
20	6.75E-07	2.88E-07	3.05E-06	7.45E-07	4.89E-07	4.19E-06

*) f_1: gut transfer factor

Table 11: Ra-226 ; dependence of workers inhalation dose coefficients on solubility Type, AMAD and GSD

Ra-226	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(µm)	**f_1=0.2 *)**	**f_1=0.2**	**f_1=0.01**	**f_1=0.2**	**f_1=0.2**	**f_1=0.01**
1	3.42E-07	2.81E-06	8.45E-06	3.60E-07	3.17E-06	8.72E-06
2	5.16E-07	3.98E-06	1.02E-05	4.35E-07	3.09E-06	7.92E-06
3	5.41E-07	3.86E-06	1.09E-05	4.54E-07	2.82E-06	8.66E-06
4	5.19E-07	3.13E-06	8.94E-06	4.51E-07	2.50E-06	7.75E-06
5	4.89E-07	2.36E-06	7.07E-06	**4.40E-07**	**2.19E-06**	**6.91E-06**
6	4.59E-07	2.08E-06	5.61E-06	4.26E-07	1.91E-06	6.18E-06
8	4.08E-07	1.28E-06	3.77E-06	3.99E-07	1.78E-06	5.04E-06
10	3.70E-07	8.66E-07	2.83E-06	3.74E-07	1.46E-06	4.21E-06
12	3.39E-07	6.53E-07	2.31E-06	3.53E-07	1.22E-06	3.62E-06
14	3.16E-07	5.35E-07	2.01E-06	3.35E-07	1.04E-06	3.17E-06
16	2.96E-07	4.65E-07	1.81E-06	3.20E-07	9.04E-07	2.83E-06
18	2.81E-07	4.20E-07	1.68E-06	3.08E-07	8.00E-07	2.57E-06
20	2.69E-07	3.90E-07	1.59E-06	2.97E-07	7.18E-07	2.36E-06

*) f_1: gut transfer factor

Table 12 : Ra-226 (low radon emanation); variation with absorption Type, AMAD and GSD of the workers dose coefficients

Ra-226	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(µm)	**f1=0.2**	**f1=0.2**	**f1=0.01**	**f1=0.2**	**f1=0.2**	**f1=0.01**
1	3.42E-07	1.46E-05	4.26E-05	3.60E-07	1.63E-05	4.39E-05
2	5.16E-07	2.38E-05	5.73E-05	4.35E-07	1.80E-05	4.41E-05
3	5.41E-07	2.41E-05	5.24E-05	4.54E-07	1.70E-05	4.67E-05
4	5.19E-07	1.99E-05	5.04E-05	4.51E-07	1.53E-05	4.28E-05
5	4.89E-07	1.50E-05	3.96E-05	**4.40E-07**	**1.35E-05**	**3.82E-05**
6	4.59E-07	1.09E-05	3.10E-05	4.26E-07	1.18E-05	3.41E-05
8	4.08E-07	5.62E-06	1.99E-05	3.99E-07	9.43E-06	2.75E-05
10	3.70E-07	2.98E-06	1.42E-05	3.74E-07	7.39E-06	2.27E-05
12	3.39E-07	3.11E-06	1.11E-05	3.53E-07	6.93E-06	1.92E-05
14	3.16E-07	2.36E-06	9.40E-06	3.35E-07	5.78E-06	1.66E-05
16	2.96E-07	1.93E-06	8.34E-06	3.20E-07	4.91E-06	1.46E-05
18	2.81E-07	1.68E-06	7.64E-06	3.08E-07	4.24E-06	1.31E-05
20	2.69E-07	1.51E-06	7.16E-06	2.97E-07	3.71E-06	1.19E-05

*) f_1: gut transfer factor

Table 13: Pb-210 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

Pb-210	**Inhalation dose coefficients, e(50), worker, Sv**					
	GSD = 1.5			**GSD = 2.5/Bq**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.2 *)**	**f_1=0.1**	**f_1=0.01**	**f_1=0.2**	**f_1=0.1**	**f_1=0.01**
1	8.60E-07	9.96E-07	5.32E-06	9.05E-07	1.03E-06	5.19E-06
2	1.30E-06	1.28E-06	7.25E-06	1.09E-06	1.01E-06	5.80E-06
3	1.36E-06	1.17E-06	6.40E-06	1.14E-06	9.28E-07	5.30E-06
4	1.31E-06	9.62E-07	5.21E-06	1.13E-06	8.33E-07	4.75E-06
5	1.23E-06	7.64E-07	4.21E-06	**1.11E-06**	**7.43E-07**	**4.26E-06**
6	1.15E-06	6.08E-07	3.46E-06	1.07E-06	6.65E-07	3.84E-06
8	1.03E-06	4.11E-07	2.52E-06	1.00E-06	5.42E-07	3.19E-06
10	9.31E-07	3.07E-07	2.01E-06	9.40E-07	4.53E-07	2.73E-06
12	8.55E-07	2.49E-07	1.73E-06	8.87E-07	3.88E-07	2.39E-06
14	7.95E-07	2.15E-07	1.54E-06	8.43E-07	3.40E-07	2.14E-06
16	7.47E-07	1.93E-07	1.42E-06	8.06E-07	3.03E-07	1.95E-06
18	7.08E-07	1.78E-07	1.33E-06	7.75E-07	2.75E-07	1.80E-06
20	6.77E-07	1.67E-07	1.27E-06	7.48E-07	2.52E-07	1.68E-06

*) f_1: gut transfer factor

Table 14: Po-210 ; dependence of workers inhalation dose coefficients on absorption Type, AMAD and GSD

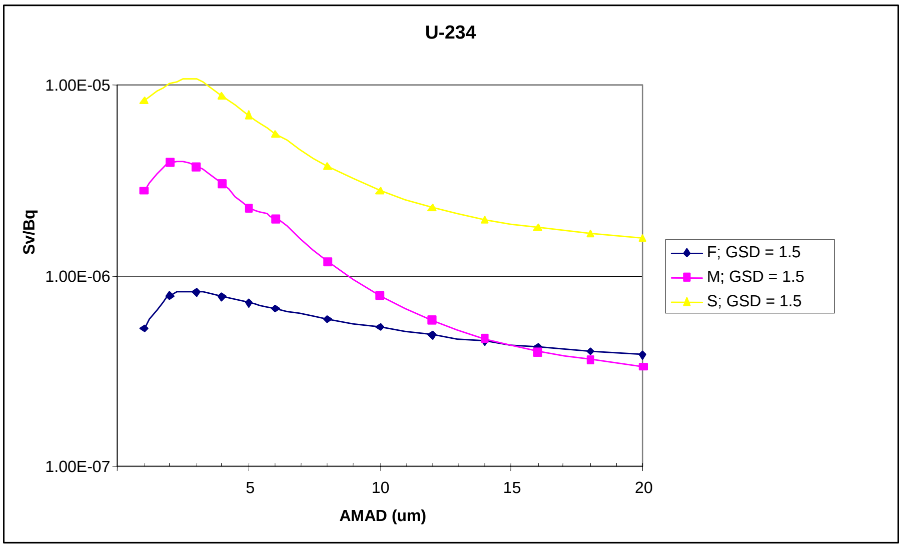
Po-210	**Inhalation dose coefficients, e(50), worker, Sv/Bq**					
	GSD = 1.5			**GSD = 2.5**		
AMAD	**Fast**	**Moderate**	**Slow**	**Fast**	**Moderate**	**Slow**
(μm)	**f_1=0.1 *)**	**f_1=0.1**	**f_1=0.01**	**f_1=0.1**	**f_1=0.1**	**f_1=0.01**
1	5.80E-07	2.61E-06	3.43E-06	6.10E-07	2.98E-06	3.88E-06
2	8.66E-07	3.89E-06	4.99E-06	7.28E-07	2.98E-06	3.82E-06
3	9.02E-07	3.84E-06	4.88E-06	7.56E-07	2.76E-06	3.50E-06
4	8.61E-07	3.15E-06	3.95E-06	7.49E-07	2.46E-06	3.09E-06
5	8.07E-07	2.38E-06	2.94E-06	**7.29E-07**	**2.16E-06**	**2.69E-06**
6	7.55E-07	1.74E-06	2.11E-06	7.04E-07	1.89E-06	2.34E-06
8	6.68E-07	1.13E-06	1.47E-06	6.56E-07	1.46E-06	1.78E-06
10	6.03E-07	7.20E-07	9.33E-07	6.13E-07	1.14E-06	1.72E-06
12	5.53E-07	5.09E-07	6.61E-07	5.77E-07	1.08E-06	1.41E-06
14	5.13E-07	3.96E-07	5.14E-07	5.48E-07	9.09E-07	1.18E-06
16	4.81E-07	3.31E-07	4.30E-07	5.23E-07	7.76E-07	1.01E-06
18	4.56E-07	2.91E-07	3.78E-07	5.02E-07	6.73E-07	8.75E-07
20	4.36E-07	2.65E-07	3.44E-07	4.84E-07	5.93E-07	7.71E-07

*) f_1: gut transfer factor

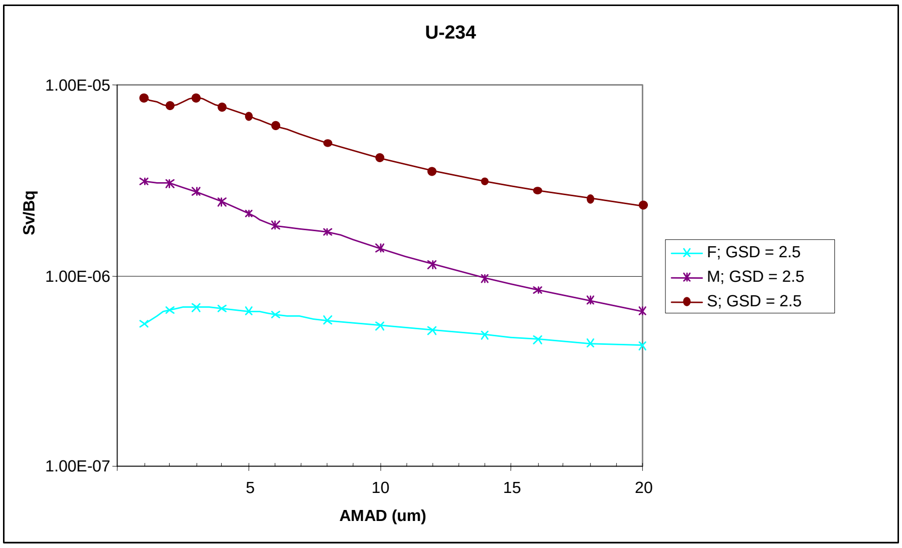
Table 15 : Workers dose inhalation coefficients (Sv/Bq) and their ratios for individual radionuclides and chain segments. AMAD 5 µm, GSD 2.5.

Nuclide, chain or chain segment	Fast	Moderate	Slow	Ratio S/F	Ratio S/M
U-238	5.9E-07	1.7E-06	5.7E-06	**9.8**	3.5
U-234	6.5E-07	2.1E-06	6.8E-06	**10**	3.2
Th-230	1.2E-04	2.8E-05	7.2E-06	**0.06**	0.26
Ra-226	4.4E-07	2.2E-06	6.9E-06	**16**	3.2
Ra-226 *)	4.4E-07	1.4E-05	3.8E-05	**87**	2.8
Pb-210	1.1E-06	7.4E-07	4.3E-06	**3.8**	5.7
Po-210	7.3E-07	2.2E-06	2.7E-06	**3.7**	1.25
U-238sec	1.2E-04	3.7E-05	3.4E-05	**0.28**	0.92
U-238sec *)	1.2E-04	4.8E-05	6.5E-05	**0.53**	1.36
Ra-226+	2.3E-06	5.1E-06	1.4E-05	**6.1**	2.7
Ra-226+ *)	2.3E-06	1.6E-05	4.5E-05	**20**	2.8
*) Low Rn emanation rate					
	Fast	Moderate	Slow	**Ratio S/F**	Ratio S/M
Th-232	1.3E-04	2.9E-05	1.2E-05	**0.09**	0.41
Ra-228	1.1E-06	1.7E-06	1.1E-05	**10**	6.7
Th-228*)	3.4E-05	2.2E-05	2.5E-05	**0.74**	1.14
Th-232sec	1.6E-04	5.3E-05	4.9E-05	**0.30**	0.92

*) Exclusive a contribution of ≤ 10% from Ra-224 in secular equilibrium with Th-228

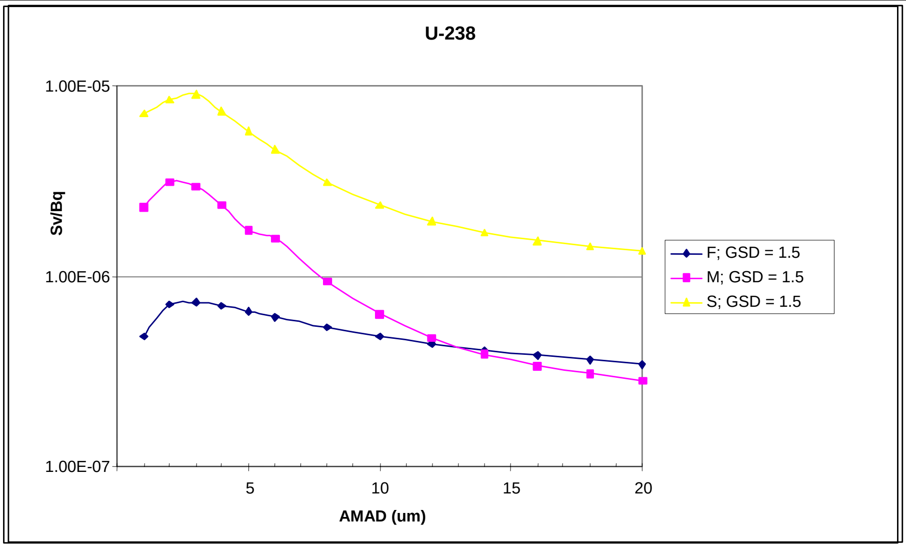


GSD = 1.5

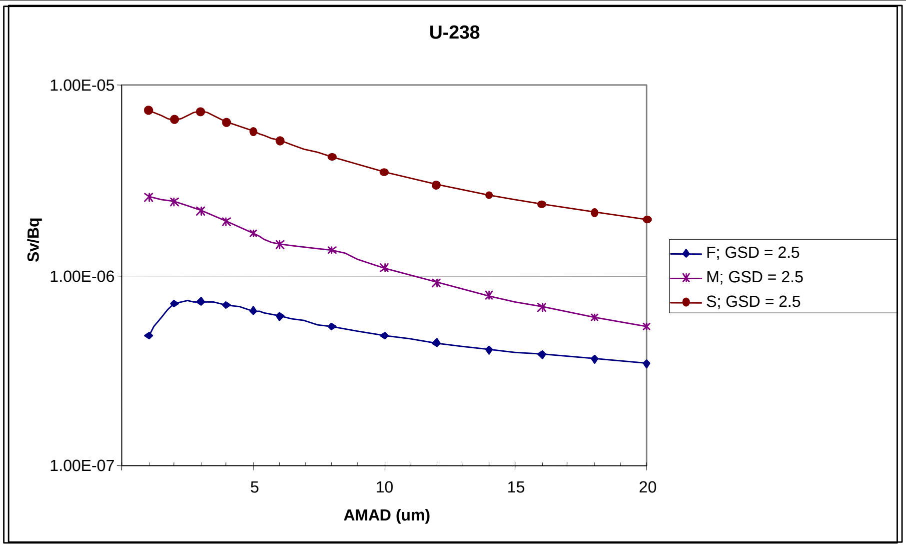


GSD = 2.5

Figure 2: U-234: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 6.

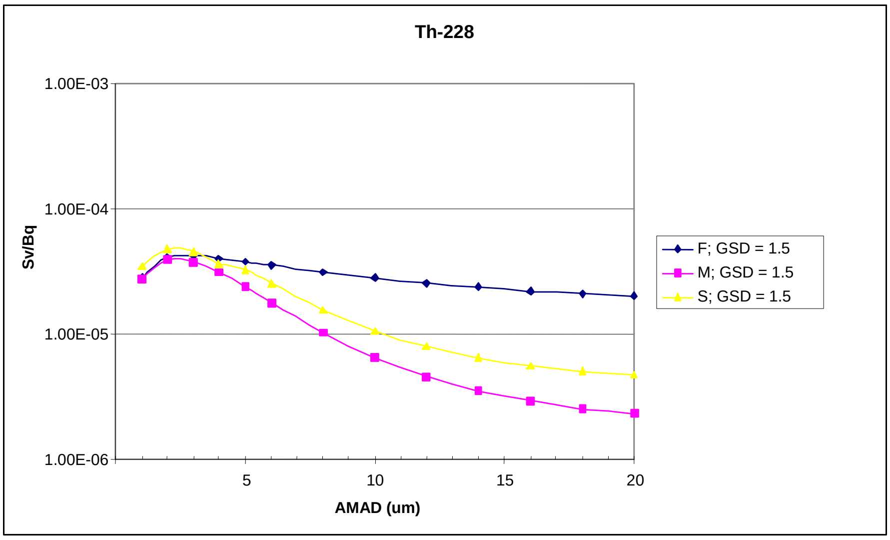


GSD = 1.5

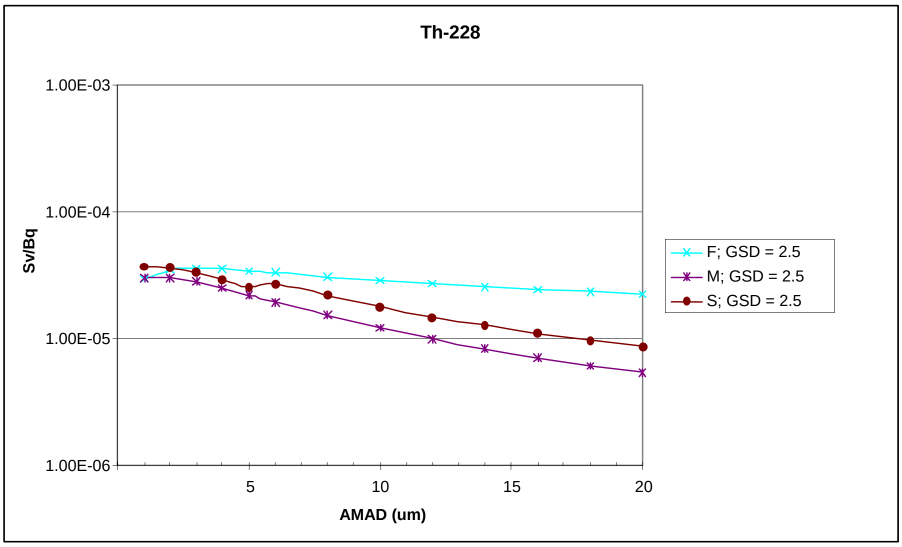


GSD = 2.5

Figure 3: U-238: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 5.

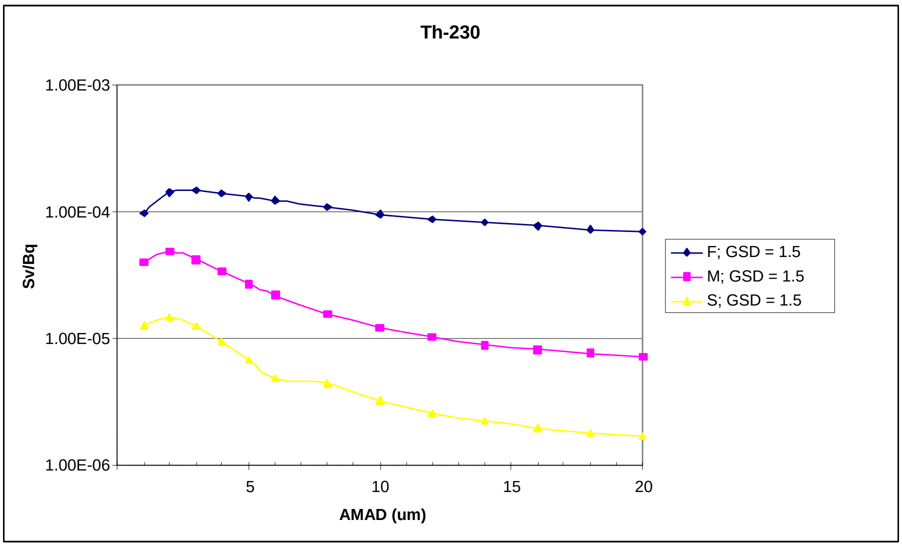


GSD = 1.5

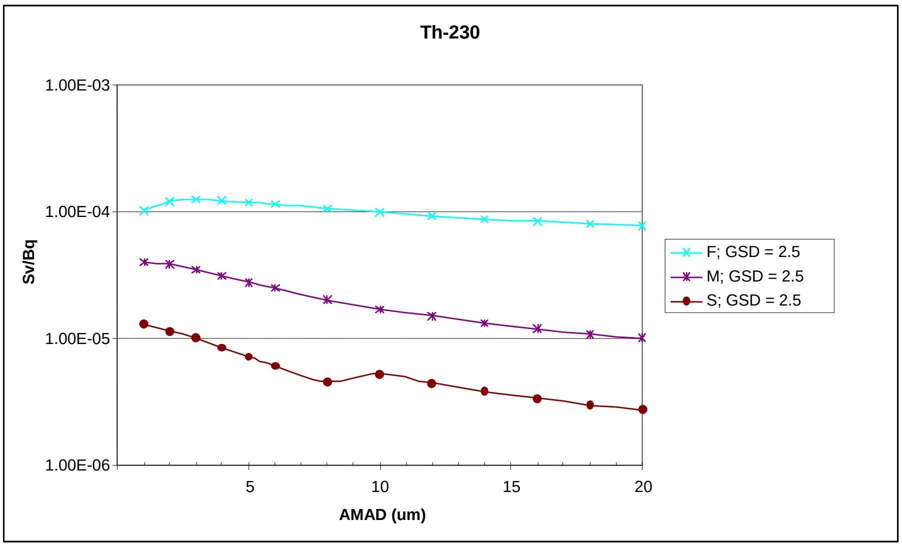


GSD = 2.5

Figure 4: Th-228: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 9.

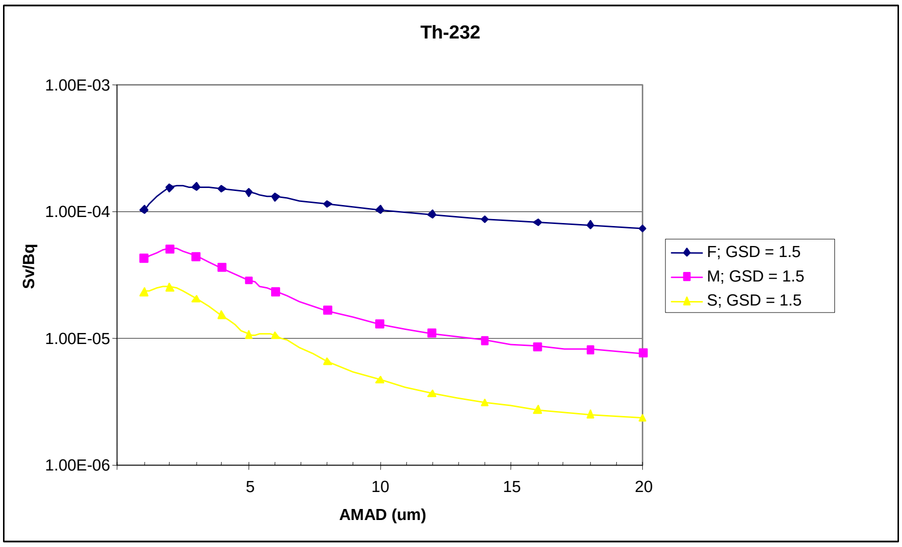


GSD = 1.5

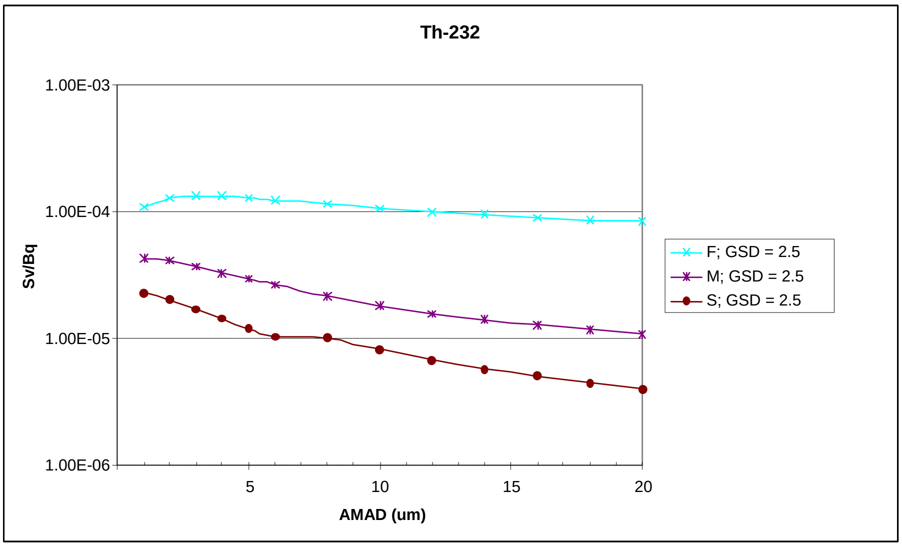


GSD = 2.5

Figure 5: Th-230: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 8.

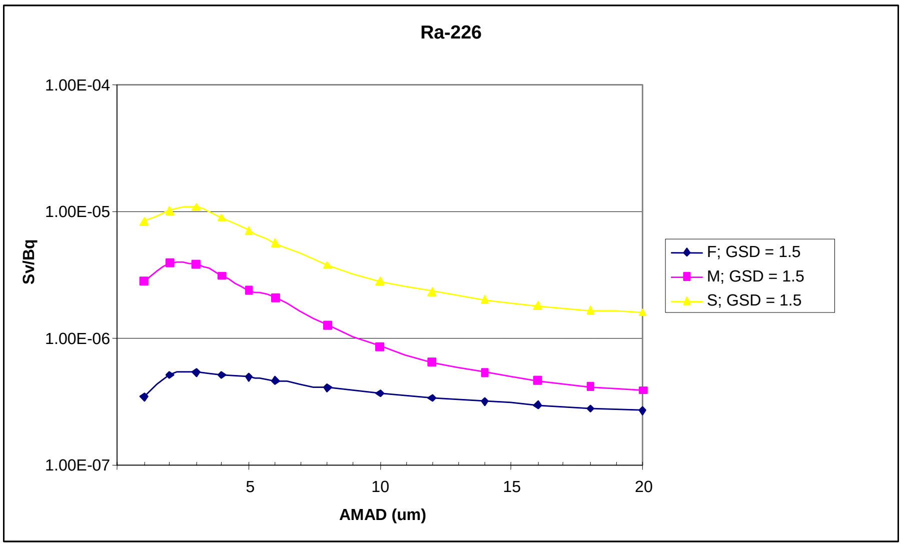


GSD = 1.5

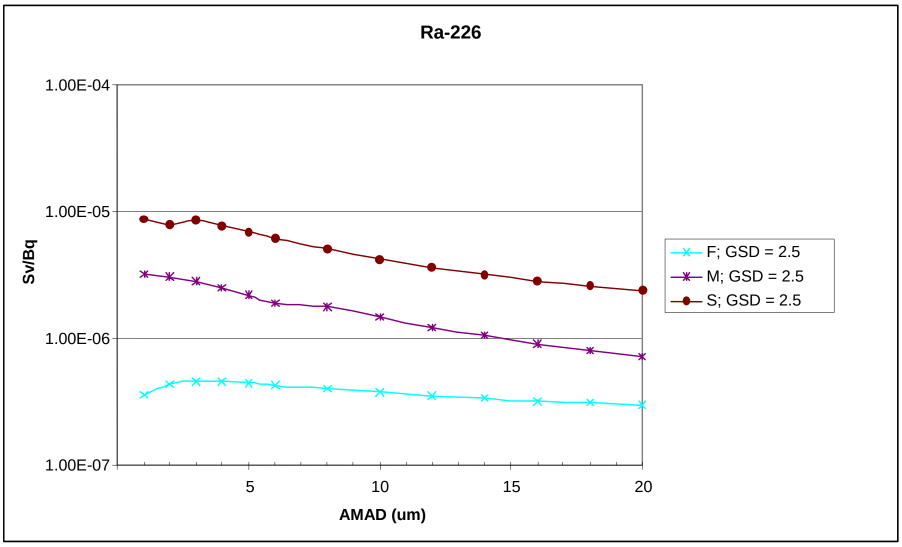


GSD = 2.5

Figure 6:Th-232: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 7.

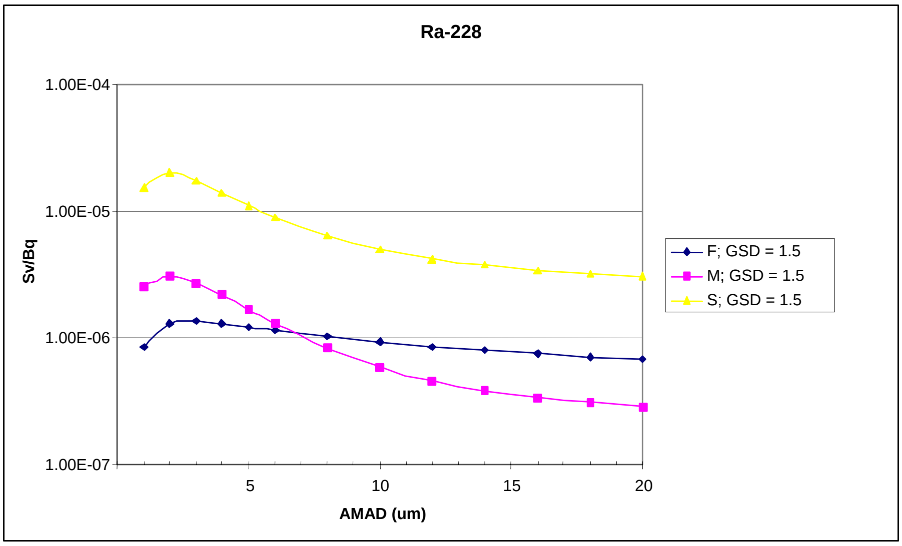


GSD = 1.5

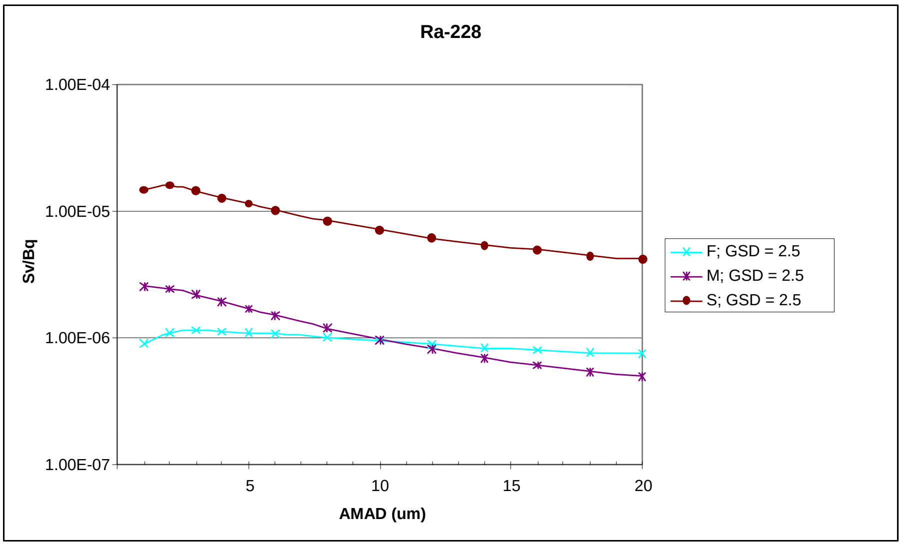


GSD = 2.5

Figure 7: Ra-226: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 11.

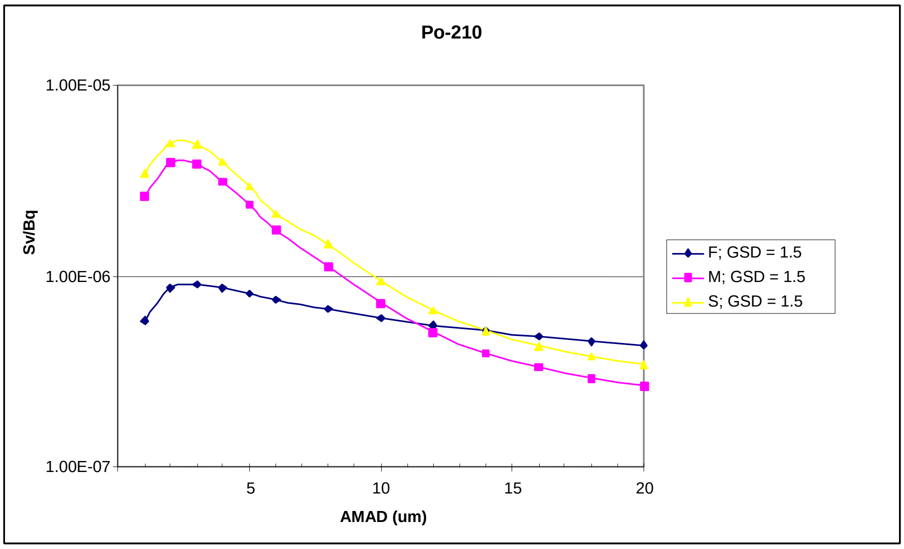


GSD = 1.5

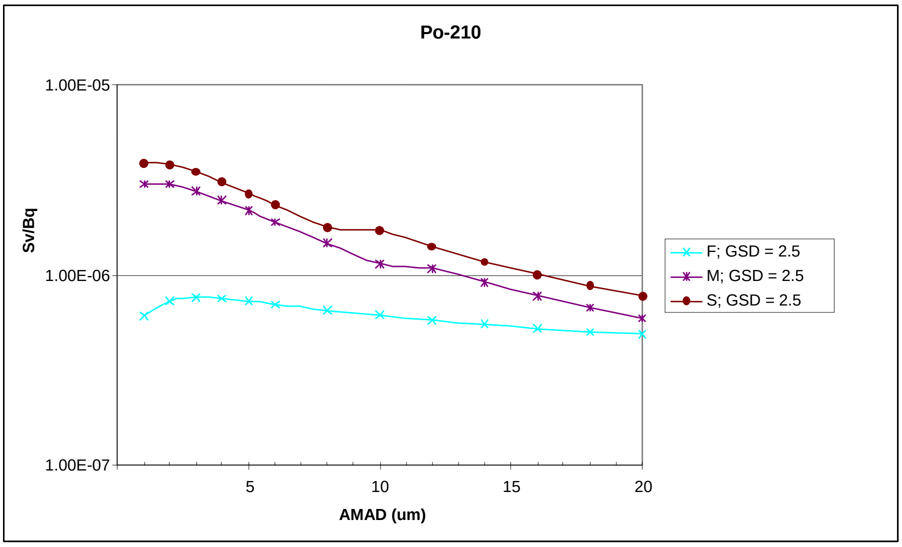


GSD = 2.5

Figure 8: Ra-228: Workers inhalation dose coefficients e(50) or absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 10.

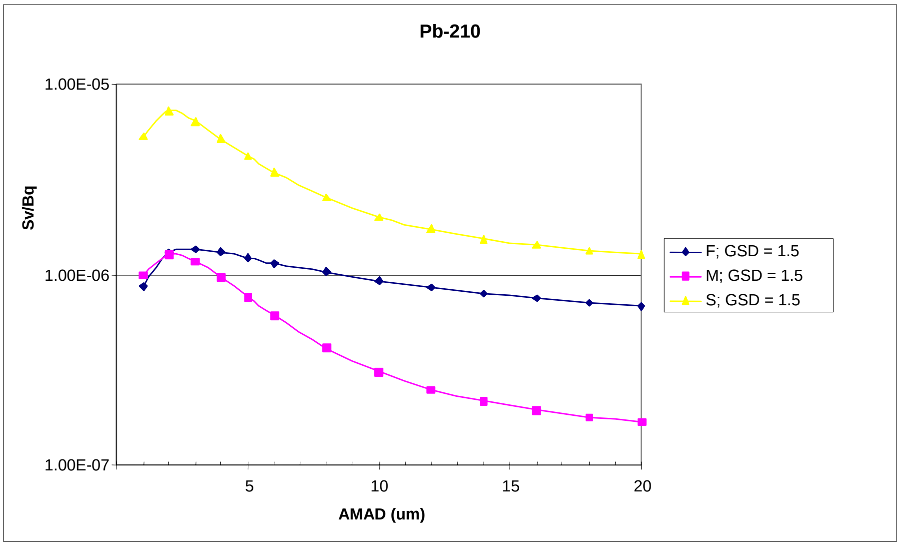


GSD = 1.5

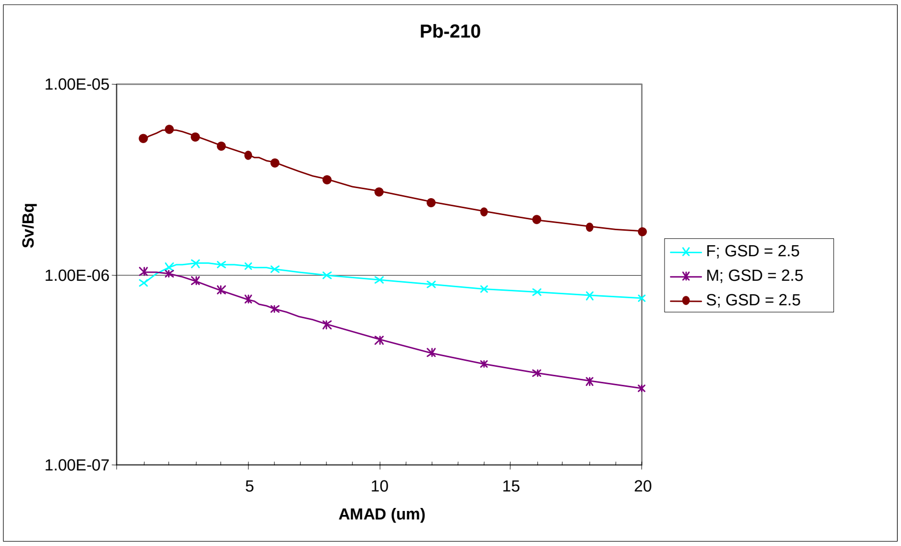


GSD = 2.5

Figure 9: Po-210: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 14.



GSD = 1.5



GSD = 2.5

Figure 10: Pb-210: Workers inhalation dose coefficients e(50) for absorption Types F, M and S, AMAD up to 20 µm and GSD 1.5 and 2.5. Gut transfer factors according to Table 13.