Managing naturally occurring radioactive material (NORM) in mining and mineral processing — guideline

NORM–5

Dose assessment

Government of **Western Australia**
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1. General information

1.1. Purpose

To provide guidance on methods of the assessment of radiation exposure of employees and members of the general public.

1.2. Scope

This guideline applies to all exploration, mining and mineral processing operations in Western Australia that use or handle naturally occurring radioactive material (NORM) and come within the scope of Part 16 of the Mines Safety and Inspection Regulations 1995 [1].

1.3. Definitions

Activity The activity of a radionuclide A is the number of spontaneous nuclear transformations dN taking place in the relevant number of radionuclides N in a time interval dt, divided by this time interval:

$$A = \frac{dN}{dt}$$

The SI unit for the activity is the Becquerel (Bq).

Activity Concentration / Specific Activity The activity concentration C is the activity A of a radioactive substance in a liquid or air, divided by the volume V of the liquid or air:

$$C = \frac{A}{V}$$

The specific activity of the solid material is determined in a similar way, by the division of the activity of the radionuclide by the measure of weight.

The units for the activity concentration and specific activity vary, most commonly used are Becquerel per cubic metre (Bq/m^3), Becquerel per litre (Bq/L), and Becquerel per gram (Bq/g).

Absorbed Dose The absorbed dose D is the mean energy $d\bar{\varepsilon}$ imparted by ionising radiation to a mass element dm in the matter, divided by this mass element:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

The absorbed dose means the average dose over a tissue or organ.

Unit: gray (symbol Gy), 1 Gy = 1 joule per kilogram.

Equivalent Dose The equivalent dose $H_{T,R}$ of a tissue or organ T is the average absorbed dose $D_{T,R}$ in the tissue or organ, multiplied by the radiation weighting factor w_R:

$$H_{T,R} = w_R D_{T,R}$$

where:

w_R is the radiation weighting factor for the radiation quality R; and

$D_{T,R}$ is the average absorbed dose in the tissue T caused by the radiation quality R.

If the radiation is composed of several radiation qualities with different w_R values, the equivalent dose H_T is:

$$H_T = \sum_R w_R D_{T,R}$$

Unit: Sievert (symbol Sv)

Radiation Weighting Factor Radiation weighting factor (w_R) is a factor, which modifies absorbed dose in an organ or tissue to yield equivalent dose and which is determined by the type and energy of the radiation to which the organ or tissue is exposed. Radiation weighting factors are listed in Table B.1 on page 22 .

Effective Dose The effective dose E is the sum of the equivalent doses H_T, multiplied by tissue weighting factors w_T:

$$E = \sum_T w_T H_T = \sum_T w_T \sum_R w_R D_{T,R}$$

Unit: Sievert (symbol Sv)

Tissue Weighting Factor Tissue weighting factor is a factor, which modifies equivalent dose in an organ or tissue to yield tissue effective dose. Tissue weighting factors are listed in Table B.2 on page 23.

Committed Equivalent Dose The committed equivalent dose $H_T\left(\tau\right)$ of a tissue T is the equivalent dose caused to this tissue as a result of an intake:

$$H_T\left(\tau\right) = \int\limits_{t_0}^{t_0+\tau} H_T\left(t\right) dt$$

where:

$H_T\left(t\right)$ is the equivalent dose rate in a tissue T at time t; and

t_0 is the time of the intake.

Unit: Sievert (symbol Sv)

The integration time τ starting from the time of the intake is expressed in years. If no integration time is given, it should be assumed that it is 50 years for adults and the number of years remaining until the age of 70 for children.

Committed Effective Dose The committed effective dose $E\left(\tau\right)$ is the sum of the committed equivalent doses $HT\left(\tau\right)$, multiplied by the tissue weighting factors w_T: Unit:

$$E\left(\tau\right) = \sum_{T} w_T H_T\left(\tau\right)$$

Sievert (symbol Sv)

Collective Effective Dose Collective effective dose is the sum, over all subgroups i in a population, of the product of the average effective dose, E_i, received by the members of each subgroup and the number of people in the subgroup N_i:

$$S = \sum_{i} E_i N_i$$

Unit: man-Sievert (symbol man-Sv)

Intake Intake is, according to the context, either the process of a radioactive substance entering the body or the activity of the radioactive substance, which has entered the body.

When a radioactive substance enters the body through inhalation, the intake means the inhaled activity, irrespective of the activity that is exhaled. When a substance enters the body through ingestion, the intake means the swallowed activity.

Unit: Becquerel (Bq)

Annual Limit of Intake The Annual Limit of Intake (ALI) is the intake, which will cause a committed effective dose equal to the annual dose limit. The ALI value of a radionuclide j is calculated as follows:

$$ALI = \frac{D_{AL}}{h_j}$$

where:

$D_{AL}$is the annual dose limit; and

$h_j$is the dose conversion factor of the radionuclide in question (the committed effective dose per unit activity).

The unit for the Annual Limit on Intake is the Becquerel.

The values of the dose conversion factors h_j and ALI are given in the Tables in Appendices C, D, F, G and H.

Derived Air Concentration The Derived Air Concentration of a radionuclide (DAC) is the average activity concentration of the radionuclide in air in which it is possible to work for 2000 hours per year without exceeding the dose limit. When only internal radiation is considered, the Derived Air Concentration DAC is calculated from the ALI value as follows:

$$DAC = \frac{ALI}{V}$$

where:

V is the volume of the inhaled air during working hours.

The unit for the Derived Air Concentration is Bq/m^3.

When the inhalation rate of a person engaged in light work is about 1.2 m^3/hour, the value obtained for V is approximately 2400 m^3. In the case of the members of the general public, the assumptions of 8760 hours in a year and 0.96 m^3/hour breathing rate result in the value of $V = 8410$ m^3.

The values of the dose conversion factors h_j and DAC are given in the Tables 13–26 in the Appendix.

Potential alpha energy The potential alpha energy of radon progeny and thoron progeny is the total alpha energy ultimately emitted in the decay of radon progeny and thoron progeny through the decay chain, up to but not including ^{210}Pb for progeny of ^{222}Rn and up to stable ^{208}Pb for progeny of ^{220}Rn.

Potential alpha energy exposures to radon progeny and thoron progeny may be determined from the concentrations of radon and thoron gas in the air by using the following formula's derived from Table A.1 of ICRP–47 [6] and paragraph 15 of ICRP–65 [7]:

$$P_{RnP} = 5.56 \times 10^{-6} \times t \times F_{RnP} \times C_{Rn}$$

$$P_{TnP} = 7.57 \times 10^{-5} \times t \times F_{TnP} \times C_{Tn}$$

where:

P_{RnP}, P_{TnP} are the potential alpha energy exposures to radon progeny and thoron progeny, respectively (mJh/m^3);

t is the exposure time (hours);

F_{RnP} is the equilibrium factor for radon progeny (typically taken as 0.4 for indoor areas and 0.2 for the outdoors);

F_{TnP} is the equilibrium factor for thoron progeny (typically taken as 0.1 for indoor areas and 0.02 for the outdoors);

C_{Rn} is the radon gas concentration (Bq/m^3); and

C_{Tn} is the thoron gas concentration (Bq/m^3).

The SI unit of potential alpha energy is the joule (J).

Owing to the short half-life of thoron (55.6 s), the equilibrium between thoron and its progeny can be extremely variable. It is therefore preferable to measure the thoron progeny concentration rather than the thoron gas concentration. Where the measurements of radon and thoron progeny are carried out, a calculation of exposure from the inhalation of radon and thoron progeny is carried out as follows:

$$E_{Rn} = EEC_{Rn} \times f_{Rn} \times T,$$

$$E_{Tn} = EEC_{Tn} \times f_{Tn} \times T,$$

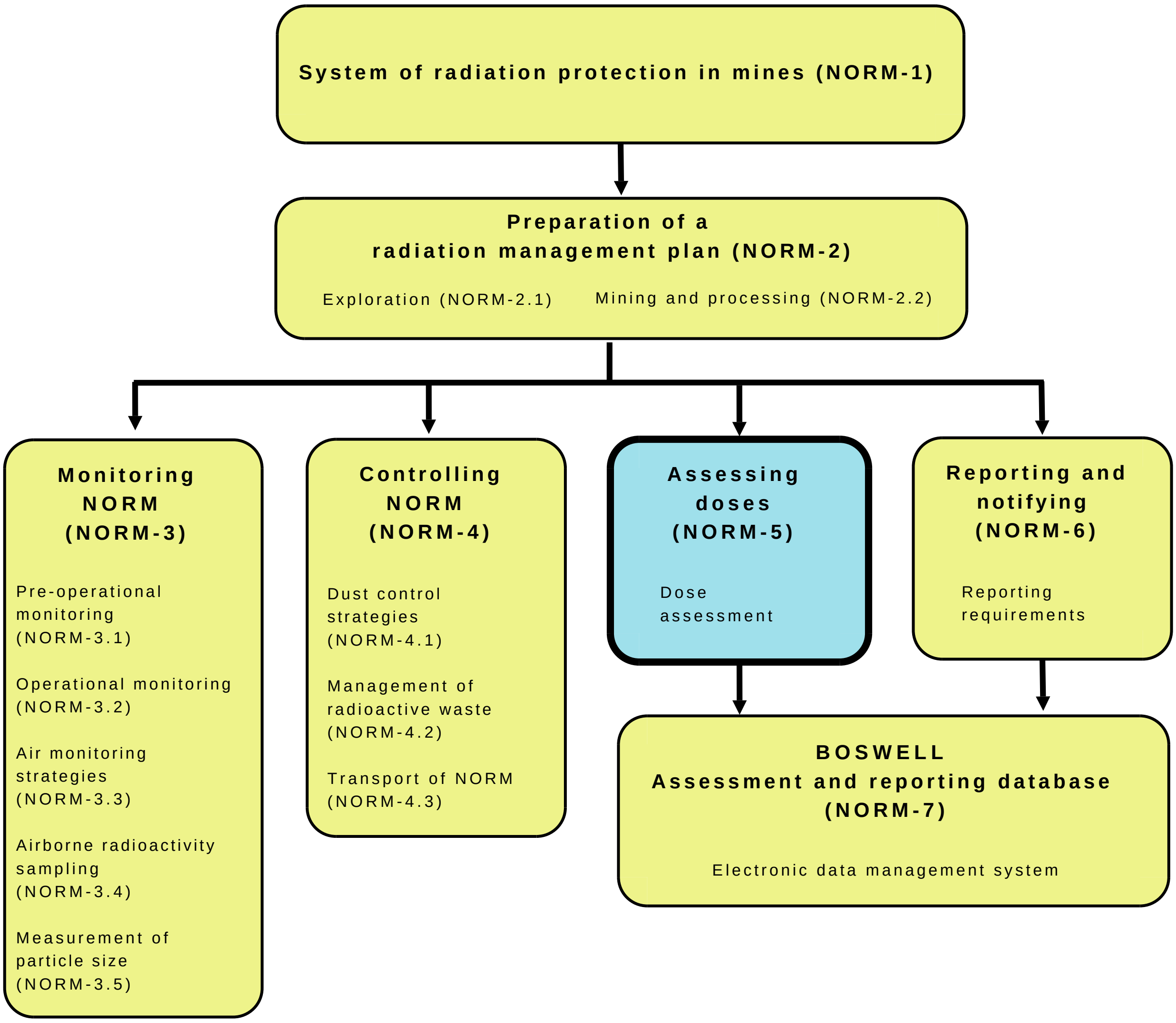
where:

the conversion factors f_{Rn} and f_{Tn} were adopted as 9 and 40 [nSv/(Bq·h·m^{-3})] for radon and thoron, respectively[17, 18].

1.4. Relationship to other NORM guidelines

The flowchart in Figure 1.1 shows the arrangement of the Radiation Safety Guidelines.

Figure 1.1.: Relationship to other NORM guidelines



2. Guidance

2.1. Introduction

The objectives of radiation protection are:

- to prevent acute radiation effects; and
- to limit the risk of chronic effects to an acceptable level.

To achieve the objectives listed above it is essential for the mining and mineral processing industry to observe accepted radiation protection standards and practices.

The International Commission on Radiological Protection (ICRP) has been studying radiological data and formulating appropriate recommendations on radiation dose standards since 1928. In general, their recommendations are universally accepted by the regulators of radiation protection and adopted into relevant legislation. The ICRP's latest radiation exposure standard recommendations were published in ICRP–103 [3] in 2007. In this publication the effects of ionising radiation on tissue have been divided into stochastic and deterministic effects.

Deterministic harmful effects of radiation are radiation sickness, burns, grey cataract and foetal abnormalities.

Stochastic harmful effects include cancer and damage, which takes place in human cells and is passed on to descendants (genetic damage).

The relationship between the probability of stochastic effects and absorbed dose depends on:

1. the type of radiation; and
2. the organ or tissue irradiated.

The factors by which the radiation type and tissues or organs are weighted are called the radiation weighting factor w_R (Appendix B.1 on page 22) and the tissue weighting factor w_T (Table B.2 on page 23), respectively.

Many other ICRP publications, which have an affect on dose assessment procedures, have also been published. Of greatest interest are publications dealing with radon, new biokinetic models for uranium and thorium and a new respiratory tract model. Numerous guidance documents were also issued by the International Atomic Energy Agency (IAEA).

This Guideline sets out the mathematical definitions and principles involved in the calculation of the effective dose based on the dose assessment procedures are based on the ICRP and IAEA documents.

The applicability of the following pathways of radiation exposure should be considered for a particular operation:

1. External radiation exposure – gamma radiation (γ).
2. Inhalation of resuspended dust – alpha radiation (α).
3. Inhalation of radon and decay products – alpha radiation (α).
4. Ingestion of drinking water – alpha and beta radiation (α, β).
5. Incidental ingestion of food, dust and soil – alpha and beta radiation (α, β).

2.2. External radiation exposure

2.2.1. Designated employees

The external dose component is obtained directly from the results of a radiation badge (TLD) monitoring program. The doses for an employee for each monitoring period are added together to give an annual dose for that employee and no further calculations on this component are required.

Example 1: The employee was monitored for the external radiation exposure by the use of TLD badges.

The quarterly results were:

1. 0.32 mSv;
2. 0.21 mSv;
3. 0.43 mSv; and
4. 0.25 mSv.

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

$0.32 + 0.21 + 0.23 + 0.25 = 1.01$ mSv

Additional information is available in Guideline NORM–3.2 Operational monitoring requirements.

2.2.2. Non-designated employees

Typically, only a cross-section of *non-designated* employees is monitored individually with TLD badges. The exposure of these employees to the external gamma-radiation is estimated on the basis of assigning of the average of individual results for a particular work category to all members of this work category.

Example 2: The employee was not monitored for the external radiation exposure by the use of TLD badges. He is a part of the work category consisting of 12 people out of which five were monitored with TLD badges. The annual average for an employee in this work category is 0.27 mSv. The annual external exposure of this employee is estimated at 0.27 mSv.

2.2.3. Other employees and members of the general public

The exposure of these employees and the members of the general public to the external gamma-radiation is estimated on the basis of regular radiation surveys carried out in a particular area as follows:

1. ‘Default’ number of hours is assumed as 2000 for employees and 8760 for members of the general public.
2. Average dose rate from the last survey (μGy/hour or μSv/hour) is multiplied by the number of hours to calculate the total external radiation exposure.
3. Average ‘background’ dose rate (μGy/hour or μSv/hour) for the particular site is multiplied by the same number of hours to calculate the external exposure due to the natural background in the area.
4. The actual exposure is calculated by subtracting the exposure from natural sources from the total radiation exposure.

Example 3: An employee working in the office but occasionally visits the production area. The average dose rates are: in the office of an employee 0.23 μGy/hour, in the production area 1.12 μGy/hour. 'Background' dose rate for the site is 0.15 μGy/hour.

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

1. 1800 hours at 0.23 μGy/hour = 414 μGy = 0.41 mSv
2. 200 hours at 1.12 μGy/hour = 224 μGy = 0.22 mSv

$\therefore$ the sum of external exposure is: 0.41 mSv + 0.22 mSv = 0.63 mSv

The 'background' exposure is: 2000 hours at 0.15 μGy/hour = 300 μGy = 0.30 mSv

$\therefore$ total external exposure is: 0.63 mSv – 0.30 mSv = 0.33 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 0.19 μGy/hour; 'background' dose rate for the site prior to operations taking place was 0.15 μGy/hour.

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

1. 8760 hours at 0.19 μGy/hour = 1664 μGy = 1.66 mSv
2. The 'background' exposure is 8760 hours at 0.15 μGy/hour = 1314 μGy = 1.31 mSv

$\therefore$ total external exposure is: 1.66 mSv – 1.31 mSv = 0.35 mSv.

In examples 3 and 4 above, 1 mSv is assumed to be equal to 1 mGy for simplicity. As this may not be always the case, please refer to Appendix B2 of NORM–3.1 Pre-operational monitoring requirements for additional information.

2.2.4. Data interpretation

As detailed in Appendix B – Note on survey instruments and data interpretation in the Appendix of Guideline NORM–3.1 Pre-operational monitoring requirements, there is a vast variety of radiation monitoring instruments that are calibrated for the *dose rate*, which can be expressed differently on different monitors: in μSv/hour, μGy/hour and μR/hour.

In many cases the following approximate interpretation is used:

100 Roentgens = 100 Rem = 1 Gray = 1 Sievert, as in examples 3 and 4 above.

There are several coefficients that can be used for the conversion between different units, such as 0.7 Sv/Gy. However, due to the potential complexity involved in the interpretation of data obtained with a particular instrument and calibration uncertainties the use of any conversion factors should be avoided without prior approval from the appropriate authority.

2.3. Internal radiation exposure (dust inhalation)

2.3.1. Inhalation

When radioactive aerosols are inhaled, parts of the respiratory system are irradiated both by radiation originating from the material in lungs and as a result of trans-location of inhaled material to body tissue from the respiratory system.

It is recognised that after inhalation of radioactive aerosols the doses received by various regions of the respiratory system will differ widely, depending on the size distribution of the inhaled material.

ICRP–66 [4] describes a revision of the respiratory tract model used in ICRP–30 [5]. The revision was necessary, as increased knowledge had become available of the anatomy and physiology of the respiratory tract as well as of the deposition, clearance and biological effects of inhaled radioactive particles.

The new model has been extended to apply explicitly to all members of the population, giving reference values for 3 month old infants, 1, 5, 10 and 15 year old children and adults. The main difference between the two models is that the ICRP–30 [5] model calculates the average dose to the lungs, whilst the new model calculates doses to specific tissues. A diagram of the respiratory tract is given in Figure A.1 on page 20.

The ICRP–30 [5] publication model gave dose conversion factors for a 1 μm AMAD but provided a formula to generate dose conversion factors for different AMAD's. The ICRP–66 [4] model is more complex and therefore a computer program is required to generate dose conversion factors for AMAD's, which have not been listed.

Dose conversion factors (DCF – in mSv/Bq$_\alpha$), annual limits of intake (ALI – in Bq) and derived air concentrations (DAC – in Bq/m^3) were calculated using the computer program (ICRP–68 [8] and ICRP–72 [9]), for:

- radionuclides in the thorium and uranium decay chains;
- thorium and uranium decay series; and
- the materials containing thorium and uranium in different weight ratios.

Calculation results are presented in the Tables in Appendix C on page 24 and Appendix D on page 34, and are also plotted on Charts in Appendix I on page 59.

Activity Mean Aerodynamic Diameter (AMAD) The AMAD of airborne dusts is the equivalent aerodynamic diameter (EAD) such that 50% of the mass of the dust is associated with smaller particles. Two particles of different densities are said to have equivalent aerodynamic diameters if their densities and diameters are such that their terminal settling velocities are equal.

The AMAD is an important parameter in dose assessment as different particle sizes result in different depositions within the lung. Different areas of the lung have different clearance mechanisms, which will therefore impact on dose assessment. Figure A.2 on page 21 illustrates the influence of particle size on deposition in the various regions of the respiratory tract.

ICRP–66 [4] recommends that a default AMAD of 5 μm is used for occupational exposures whilst for environmental exposures the default AMAD is taken to be 1 μm.

Approval may be granted for the use of other values of AMAD in dose assessments. The State Mining Engineer may give approval for a site-specific AMAD value after the review and assessment of data from the particle size characterisation program for the particular site. More detailed information is available in the Guideline NORM–3.5 Measurement of particle size.

2.3.2. Dose assessment

To determine the dose to any organ or tissue or to the whole body it is necessary to determine the amount of radioactive material inhaled or ingested. To assess the amount of radioactive material inhaled an appropriate monitoring program is necessary — detailed information is provided in Guidelines NORM–3.1 through to NORM–3.5 dealing with the different aspects of radiation monitoring.

An annual intake (in Bq) is multiplied by the appropriate dose conversion factor to calculate the annual dose (mSv).

The first step in the assessment of the internal dose is to calculate the arithmetic mean of α-activity concentration for each identified work category during the specified monitoring period.

Next, the internal dose assessment using an arithmetic mean is then calculated as follows:

Individual Internal Dose $= \sum_i [AM_i \times HW_i \times BR] \, DCF_i$

where:

AM_i– arithmetic mean of gross α-activity concentration for the work category i (Bq/m^3);

HW_i– hours worked by an employee for the period of assessment in the work category i;

BR – assumed breathing rate of an employee (1.2 m^3/hour);

$[AM_i \times HW_i \times BR]$ – personal intake for the period of assessment for the work category i (Bq); and

DCF_i – dose conversion factor in mSv/Bq$_\alpha$ for different AMAD sizes and different uranium and thorium weight ratios (Tables in Appendix C and D).

Example 5: The employee was working in the plant processing mineral containing thorium for a period of three months. Time spent in different work categories was:

‘Shift coordinator’ 200 hours;

‘Plant operator’ 100 hours; and

‘Wet concentrator operator’ 200 hours.

Mean α-activity concentrations in the period were:

‘Shift coordinator’ 0.039 Bq/m^3;

‘Plant operator’ 0.213 Bq/m^3 ; and

‘Wet concentrator operator’ 0.021 Bq/m^3.

A ‘Special exposure’ was declared for the employee during work in the ‘Plant operator’ work category: 8 hours exposure to the α-activity concentration of 1.435 Bq/m^3;

Assuming a default particle size value of 5 μm (using a dose conversion factor of 0.0080 mSv/Bq$_\alpha$ taken from Table C.4 on page 27), the internal dose from dust inhalation is calculated by calculating the intake for each work category:

1. ‘Shift coordinator’: 200 hours × 0.039 Bq/m^3 × 1.2 m^3/hour = 9.36 Bq
2. ‘Plant operator’: (100 – 8) hours × 0.213 Bq/m^3 × 1.2 m^3/hour = 19.61 Bq
3. ‘Wet concentrator operator’: 200 hours × 0.021 Bq/m^3 × 1.2 m^3/hour = 5.04 Bq
4. ‘Special exposure’: 8 hours × 1.435 Bq/m^3 × 1.2 m^3/hour = 13.78 Bq
5. All intakes associated are summarised: 9.36 + 19.61 + 5.04 + 13.78 = 47.8 Bq

   $\therefore$ internal dose due to dust inhalation is: 47.8 Bq × 0.0080 mSv/Bq$_\alpha$ = 0.38 mSv

Example 6: The scale from the internal surface of the processing vessel is being removed by grinding. Monitoring results indicate that dust contains 27 Bq/m^3 of predominantly ^{226}Ra and the size of dust particles is 5 μm. The duration of the task is 10 hours. The internal dose from dust inhalation is calculated as follows:

1. The intake of ^{226}Ra is: 10 hours × 27 Bq/m^3 × 1.2 m^3/hour = 324 Bq
2. Dose conversion factor for 5 μm dust containing ^{226}Ra is: 0.0022 mSv/Bq$_\alpha$ (Table C.9 on page 32)

   ∴ internal dose due to dust inhalation is: 324 × 0.0022 = 0.71 mSv

Example 7: An operator of a zircon mill is exposed to 3 μm dust containing 0.069 Bq/m^3 for 800 hours in a year. Zircon contains 200 ppm thorium and 250 ppm uranium (weight ratio of Th:U = 1:1.25). The internal dose from dust inhalation is calculated as follows:

1. The intake is: 800 hours × 0.069 Bq/m^3 × 1.2 m^3/hour = 66.2 Bq
2. Dose conversion factor for 3 μm dust containing thorium and uranium in the weight ratio of 1:1.25 is: 0.0054 mSv/Bq$_\alpha$ (Table D.6 on page 40, Table D.7 on page 41 and Table D.8 on page 42)

   ∴ internal dose due to dust inhalation is: 66.2 × 0.0054 = 0.36 mSv

Example 8: Members of the critical group of the members of the public can be potentially exposed to the dust from a rehabilitated uranium mining and processing operation.

Results of the monitoring indicate that dust contains, on average, 400 ppm uranium and 20 ppm thorium and an average alpha-activity level in the dust is 0.0045Bq/m^3.

The 'background' concentration of radioactivity in the dust is 0.0004 Bq/m^3.

The exposure for members of the public is estimated using the default 8760 hours/year, breathing rate of 0.96 m^3/hour, and dose conversion factor for 1 μm dust containing uranium and thorium in the weight ratio of 20:1 is 0.0070 mSv/Bq$_\alpha$ (Table D.1 on page 35).

Potential intake is:

8760 hours × 0.0045 Bq/m^3 × 0.96 m^3/hour = 37.8 Bq

'Background' intake is:

8760 hours × 0.0004 Bq/m^3 × 0.96 m^3/hour = 3.4 Bq

∴ potential annual internal dose due to dust inhalation is:

(37.8 – 3.4) × 0.0070 = 0.24 mSv

If dust inhalation is the only pathway of radiation exposure, measures should be taken to ensure that the dose continue to be below the constraint of 0.3 mSv/year. Derived air concentration for the exposure of 0.3 mSv/year to this particular type of dust is 0.005 Bq/m^{3}and the level of radioactivity in the dust should be kept below this value.

2.3.3. Correction factors

During the monitoring of workplace atmosphere for airborne radionuclides a sample of airborne dust representative of that inhaled by a worker is collected on a filter and, after a delay of some days (during which some radon or thoron escapes), is analysed by gross alpha counting; the loss of radon or thoron from the dust particles on the filter is accompanied by a corresponding loss of short lived progeny of radon or thoron, due to the rapid decay of these progeny.

In the calculation of the dose conversion factors in Table 1 of the ARPANSA Code [10] this is not taken into account and *"it is assumed that no loss of radon occurs"*. As specified in the Guideline NORM–3.4 Airborne radioactivity sampling, six or seven days are allowed to elapse before alpha counting to allow for the decay of short-lived radon (^{222}Rn) and thoron (^{220}Rn) daughter products trapped on the filter. This decay time also provides for the build-up of radon/thoron daughters from ^{226}Ra/^{224}Ra in the event of radon/thoron emanation from the airborne dust particles. The assumption used when determining gross alpha activity is that all alpha particles emitted from the ^{238}U and ^{232}Th radioactive decay chains are registered by the counter.

However, in the situation when samples are analysed some weeks or months after the date of sampling (for example, in the course of a quality control procedure when several dust filters are analysed using another alpha-counter), correction factors may need to be used. As it is shown in Table E.1 on page 49 and Table E.2 on page 50, correction factors for thorium ore dust would be in range between 1.14 and 1.33 and for uranium ore dust — in the range between 1.10 and 1.23.

2.4. Internal radiation exposure (inhalation of radon/thoron and decay products)

The two significant isotopes of radon are radon–222 (^{222}Rn), the immediate decay product of radium–226, deriving from the uranium series of natural radionuclides; and radon–220, the immediate decay product of radium–224, deriving from the thorium series. The relevant radon progeny are ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po and the relevant thoron progeny are ^{216}Po, ^{212}Pb, ^{212}Bi, ^{212}Po and ^{208}Tl.

Because of their origins, the two isotopes are commonly known as radon and thoron. Radon is a noble gas and both isotopes decay to isotopes of solid elements, the atoms of which attach themselves to the dust particles present in air. The problems posed by radon–220 (thoron) are much less widespread than those posed by radon–222.

The inhalation limits of intake for short-lived progeny of radon and thoron may be expressed in terms of potential alpha energy. The potential alpha energy intake can be determined from measurements of the potential alpha energy concentration in the air (PAEC) and the volume of air inhaled. Potential alpha energy exposures to radon progeny and thoron progeny may be determined by integrating the PAEC over the exposure time; they may also be determined from the concentrations of radon and thoron in the air by using the formula's presented in Section 1.3 on page 1.

Variations in concentrations of radon or thoron over a period of time may be taken into account by expressing such concentrations as time weighted averages.

The potential alpha energy exposure of workers is often expressed in the historical unit Working Level Month (WLM). The equivalent SI unit is the mJh/m^3. The conversion is as follows:

1 WLM = 3.54 mJh/m^3; and

1 mJh/m^3 = 0.282 WLM.

The factors used in assessing internal dose from inhalation of radon–222 are given in Table F.1 on page 51; derived air concentrations and annual limits of intake — in Table F.2 on page 51.

Example 9: An employee works in an underground mine where radon (^{222}Rn) measurements have been taken on a quarterly basis using radon caps. The monitoring results were as follows:

1st quarter = 580 Bq/m^3

2nd quarter = 750 Bq/m^3

3rd quarter = 690 Bq/m^3

4th quarter = 520 Bq/m^3

$\therefore$annual average = 635 Bq/m^3

From Table F.2 on page 51: conversion factor:

4.45x10^{-3} mJh/m^3 per 1 Bq/m^3 (assuming 2000 working hours per year and an equilibrium factor of 0.4)

$\therefore$ 635 Bq/m^3 = 2.83 mJh/m^3

Using the dose conversion factor from Table F.1 on page 51 (1.4 mSv per 1 mJh/m^3):

2.83 mJh/m^3 × 1.4 (mSv / [mJh/m^3]) = 3.95 mSv

2.5. Internal radiation exposure (ingestion of drinking water)

In accordance with Australian Drinking Water Guidelines (www.nhmrc.gov.au) [11], drinking water should be analysed for gross α and gross β-activity concentrations (in Bq per litre). The naturally occurring radioisotope potassium–40 (^{40}K) is present in all drinking water, and its contribution for gross β–activity value should be subtracted from the total value in accordance with the Guidelines.

DMP recommends limit values slightly different from the drinking water guidelines:

Gross α–activity = 0.2 Bq/l

Gross β–activity = 0.5 Bq/l, after subtracting the contribution from ^{40}K

The reason for this variation is to make allowance for all other pathways of exposure that may not have been considered during the development of the 2004 drinking water guideline. If either of these activity concentrations is exceeded, specific radionuclides should be identified and their activity concentrations determined.

At many mining and processing sites all drinking and washing water is provided from an outside source (for example, town water supplies, etc.). In these cases any radiation exposure of employees from the ingestion of drinking water could not be attributed to mining and processing activities, and radiation exposure from this pathway is assumed to be negligible. If, however, the drinking water is provided from on-site bores and Guideline values are exceeded, the dose assessment should be carried out. Also, the potential radiation exposure of the members of the critical group of the members of the public via the ingestion of drinking water should be assessed, particularly in cases where chemical and/or thermal processing of a mineral takes place.

The ingestion model used in the development of the IAEA Basic Safety Standards [12] to describe the behaviour of radionuclides ingested by workers is that given in ICRP–30 [5]. It has four compartments, representing the stomach, the small intestine, the upper large intestine and the lower large intestine. The mean residence times in the gastrointestinal tract compartments are 1, 4, 13, and 24 hours respectively. The uptake to blood takes place from the small intestine and is specified by fractional uptake (f_1) values. Dose conversion factors and other relevant data are presented in Tables (G.1)–(G.4) beginning on page 52.

When the exact concentrations of radionuclides are unknown, the highest potential exposure is associated with the following radionuclides:

Thorium decay chain: ^{232}Th, ^{228}Ra, ^{228}Th and ^{224}Ra; and

Uranium decay chain: ^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po.

Additional consultation with the appropriate authority is required prior to undertaking the dose assessment in complex situations, where radionuclides present in water are suspected not to be in a secular equilibrium, or where only data for gross alpha and gross beta concentrations in water are available.

Typically, the dose assessment for employees is carried out as follows:

1. The level of water consumption is generally assumed to be 2 litres per day (500 litres per year for 250 'default' working days).
2. The 'background' concentrations of radionuclides in local drinking water are typically determined during the site 'baseline' survey (prior to the commencement of operations) for the radionuclides listed above (at least for ^{226}Ra and ^{228}Ra for the cases where it is expected that both thorium and uranium decay chains are in secular equilibrium).
3. Intake of radioactivity (in Bq) is calculated separately for different radionuclides by multiplying the concentration in drinking water (in Bq/L) by the water consumption level (in litres/year).
4. The dose (in mSv) is calculated separately for each radionuclide using dose conversion factors (Tables (G.1)–(G.4) beginning on page 52). The total dose due to ingestion is calculated as a sum of values for each radionuclide.
5. The internal dose from the intake of radioactivity based on 'background' concentrations for different radionuclides is calculated in the same manner, resulting in the total 'background' dose.
6. Actual radiation exposure is calculated by subtracting the exposure from natural background sources from the total radiation exposure.

Example 10: Radionuclides concentrations in the drinking water are:

^{226}Ra=0.267 Bq/L; and

^{228}Ra=0.764 Bq/L.

Radionuclide concentrations in the 'background' drinking 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 drinking water ingestion is calculated as follows:

Intake of radioactivity is calculated separately for different radionuclides:

for ^{226}Ra = 0.267 Bq/l × 500 l = 133.5 Bq; and

for ^{228}Ra = 0.764 Bq/l × 500 l = 382.0 Bq.

Dose is calculated separately for each radionuclide (Table G.2 on page 53 and Table G.4 on page 55):

for ^{226}Ra = 133. 5 Bq × 0.00024 mSv/Bq = 0.032 mSv; and

for ^{228}Ra = 382.0 Bq × 0.00067 mSv/Bq = 0.256 mSv.

Total dose from water ingestion is:

0.032 mSv + 0.256 mSv = 0.288 mSv.

Intake of radioactivity based on 'background' concentrations is calculated for different radionuclides:

for ^{226}Ra = 0.107 Bq/l × 500 l = 53.5 Bq; and

for ^{228}Ra = 0.096 Bq/l × 500 l = 48.0 Bq.

Dose is calculated separately for each radionuclide similarly to (3.2.):

for ^{226}Ra = 53.5 Bq × 0.00024 mSv/Bq = 0.013 mSv; and

for ^{228}Ra = 48.0 Bq × 0.00066 mSv/Bq = 0.032 mSv.

Total 'background' dose is:

0.013 mSv + 0.032 mSv = 0.045 mSv.

Total dose form drinking water ingestion is 0.288 mSv – 0.045 mSv = 0.24 mSv.

2.6. Internal radiation exposure (ingestion of food, dust and soil)

This pathway of exposure is considered to be of a much less importance, particularly for workers. The assessment of potential radiation exposure via this pathway may sometimes be necessary in complex studies of the exposure of members of the general public, particularly in remote areas of Western Australia, and should be carried out in accordance with the advice from the appropriate authority.

For more information please refer to the following Safety Reports issued by the International Atomic Energy Agency:

No.27 – Monitoring and surveillance of residues from the mining and milling of uranium and thorium (2002) [13];

No.37 – Methods for assessing occupational radiation doses due to intakes of radionuclides (2004) [14];

No.44 – Derivation of activity concentration values for exclusion, exemption and clearance (2005) [15] – appendices in particular; and

No.49 – Assessing the need for radiation protection measures in work involving minerals and raw materials (2006) [16].

These reports contain most information necessary for the assessment of doses via this pathway, but an adjustment for Australian conditions is almost always necessary — particularly for the reference data in regards to the annual consumption of meat, milk and vegetables.

2.7. Complex dose assessments

It is very important to ensure that the first step in any dose assessment is always the analysis of all possible pathways of radiation exposure and their applicability for the particular situation.

Example 11: Conditions:

An employee was working in a mineral processing plant (Site A) for five months:

1. 520 hours as dry plant operator (average dust activity concentration = 0.305 Bq/m^3);
2. 300 hours as control room operator (average dust activity concentration = 0.027 Bq/m^3); and
3. 140 hours as wet plant operator (average dust activity concentration = 0.066 Bq/m^3).

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

TLD badges results for two monitoring periods are 0.19 and 0.28 mSv.

Two months in a year (∼380 hours) the employee spent at a remote uranium exploration site (Site B), in the area with gamma-radiation level of 0.49 μGy/hour (background radiation level for this site is 0.14 μGy/hour), the 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 employee 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) concentrations are 63 Bq/m^3 above the natural background levels observed at the site prior to exploration activities taking place.

Four months in a year (~700 hours) employee spent 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 ration of Th:U = 1:1.25), thoron concentrations above background 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 μGy/hour, in the storage shed – 0.53 μGy/hour, background in the surrounding area – 0.16 μGy/hour.

Dose assessment:

External dose 1 (Site A):

$$0.19 \text{ mSv} + 0.28 \text{ mSv} = 0.47 \text{ mSv}$$

External dose 2 (Site B):

$$(0.49\ \mu\text{Gy/hour} \times 380 \text{ hours}) – (0.14\ \mu\text{Gy/hour} \times 380 \text{ hours}) = 133\ \mu\text{Gy} = 0.13 \text{ mSv}$$

External dose 3 (Site C):

$$(0.32\ \mu\ \text{Gy/hour} \times 500 \text{ hours}) – (0.16\ \mu\text{Gy/hour} \times 500 \text{ hours}) = 80\ \mu\text{Gy} = 0.08 \text{ mSv}$$

$$(0.53\ \mu\text{Gy/hour} \times 200 \text{ hours}) – (0.16\ \mu\text{Gy/hour} \times 200 \text{ hours}) = 74\ \mu\text{Gy} = 0.07 \text{ mSv};$$

Sum of external doses:

$$0.47 + 0.13 + 0.08 + 0.07 = 0.75 \text{ mSv}$$

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

$$[0.305 \text{ Bq/m}^3 \times 1.2 \text{ m}^3\text{/hour} \times 520 \text{ hours}] \times 0.0075 \text{ mSv/Bq}_\alpha = 1.43 \text{ mSv}$$

$$[0.027 \text{ Bq/m}^3 \times 1.2 \text{ m}^3\text{/hour} \times 300 \text{ hours}] \times 0.0075 \text{ mSv/Bq}_\alpha = 0.07 \text{ mSv}$$

$$[0.066 \text{ Bq/m}^3 \times 1.2 \text{ m}^3\text{/hour} \times 140 \text{ hours}] \times 0.0075 \text{ mSv/Bq}_\alpha = 0.08 \text{ mSv}$$

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

$$[0.117 \text{ Bq/m}^3 \times 1.2 \text{ m}^3\text{/hour} \times 380 \text{ hours}] \times 0.0035 \text{ mSv/Bq}_\alpha = 0.19 \text{ mSv}$$

$$[3.692 \text{ Bq/m}^3 \times 1.2 \text{ m}^3\text{/hour} \times 10 \text{ hours}] \times 0.0035 \text{ mSv/Bq}_\alpha = 0.08 \text{ mSv}$$

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

$$5.56 \times 10^{-6} \times 380 \text{ hours} \times 0.4 \times 63 \text{ Bq/m}^3 = 0.05 \text{ mJh/m}^3;$$

$$\therefore 0.05 \text{ mJh/m}^3 \times 1.4 \text{ (mSv [mJh/m}^3\text{])} = 0.07 \text{ mSv}$$

Internal dose 4 (Site B – ingestion):

$$[0.72 \text{ Bq/L} \times 125 \text{ L} – 0.15 \text{ Bq/L} \times 125 \text{ L}] \times 0.00024 \text{ mSv/Bq} = 0.02 \text{ mSv}$$

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

$$[0.089 \text{ Bq/m}^3 \times 1.2 \text{ m}^3\text{/hour} \times 200 \text{ hours}] \times 0.0044 \text{ mSv/Bq} = 0.09 \text{ mSv}$$

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

$7.57 \times 10^{-5} \times 200$ hours $\times\ 0.1\times\ 105$ Bq/m^3 = 0.16 mJh/m^3;

$\therefore$0.16 mJh/m^3 × 0.48 (mSv / [mJh/m^3]) = 0.08 mSv

$7.57 \times 10^{-5} \times 500$ hours $\times\ 0.1\times\ 25$ Bq/m^3 = 0.09 mJh/m^3;

$\therefore$0.09 mJh/m^3 × 0.48 (mSv / [mJh/m^3]) = 0.04 mSv

Sum of internal doses:

1.43 + 0.07 + 0.19 + 0.08 + 0.07 + 0.02 + 0.09 + 0.31 + 0.18 = 2.07 mSv

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

0.75 + 2.07 = 2.82 mSv

Example 12: Conditions:

A processing site has been rehabilitated and there is a possibility of an industrial or residential development:

Gamma-dose rate is 0.19 ± 0.02 μSv/hour; and

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). The modelling indicates that if tailings are brought to the surface, concentration of radon in the air is expected to be around 18 Bq/m^3.

Note on the estimation of the external dose Background gamma-radiation levels may vary significantly; statistical (random and systematic) errors (Appendix A of the Guideline NORM–6 Reporting requirements) could also be significant, particularly when relatively low levels of exposure are being measured (below 0.40 μGy/hour). Therefore, it is recommended that the background value be considered to be an average value plus one or two standard deviations. Otherwise, some parts of the site where background levels were marginally higher than in other parts may be erroneously classified as having being unsuccessfully rehabilitated, whilst the gamma-radiation levels are, in fact, not different from the pre-mining ones. An additional consultation with the appropriate authority is required prior to the calculation of the potential external dose in these cases.

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

[0.19 μGy/hour – 0.13 μGy/hour] × 8760 hours = 0.53 mSv

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

[0.19 μGy/hour – 0.17 μGy/hour] × 8760 hours = 0.17 mSv

Potential internal dose – ingestion:

[0.45 Bq/L – 0.22 Bq/L] × 500 L × 0.00024 mSv/Bq = 0.03 mSv

Potential internal dose – inhalation:

18 Bq/m^3 = 0.08 mJh/m^3

$\therefore$ 0.08 mJh/m^3 × 1.4 (mSv / [mJh/m^3]) = 0.11 mSv

If the appropriate authority approved the use of the background level plus two standard deviations (Case 2), the exposure of a member of the public will be 0.31 mSv/year — which is significantly below the exposure limit of 1 mSv/year and is comparable with the dose constraint of 0.3 mSv/year, at which a classification of a site as ‘contaminated’ may be considered (please see NORM–4.2. Management of radioactive waste for more information).

If such approval has not been obtained, the estimated exposure is 0.67 mSv/year — which is above the dose constraint of 0.3 mSv/year, site will need to be registered as contaminated and it is possible that certain restrictions will be placed on the land use.

A. Appendix defining the ICRP lung model

Respiratory tract regions defined in the ICRP model shown in A.1 on the next page (reproduced with permission from ICRP–66 [4]). The ET airways are divided into ET_1, the anterior nasal passage, and ET_2, which consists of the posterior nasal and oral passages, the pharynx and the larynx. The thoracic regions are bronchial (BB: trachea and main bronchi), bronchiolar (bb: bronchioles) and alveolar–interstitial (AI: the gas exchange region). Lymphatic tissue is associated with the ET and thoracic airways (LN_{ET} and LN_{TH}, respectively).

A.1. Lung absorption types

Type F 100% absorbed with a biological half-life of ten minutes. There is rapid absorption of almost all material deposited in BB, bb and AI. Half of the material deposited in ET_2 is cleared to the gastrointestinal tract by particle transport and half is absorbed.

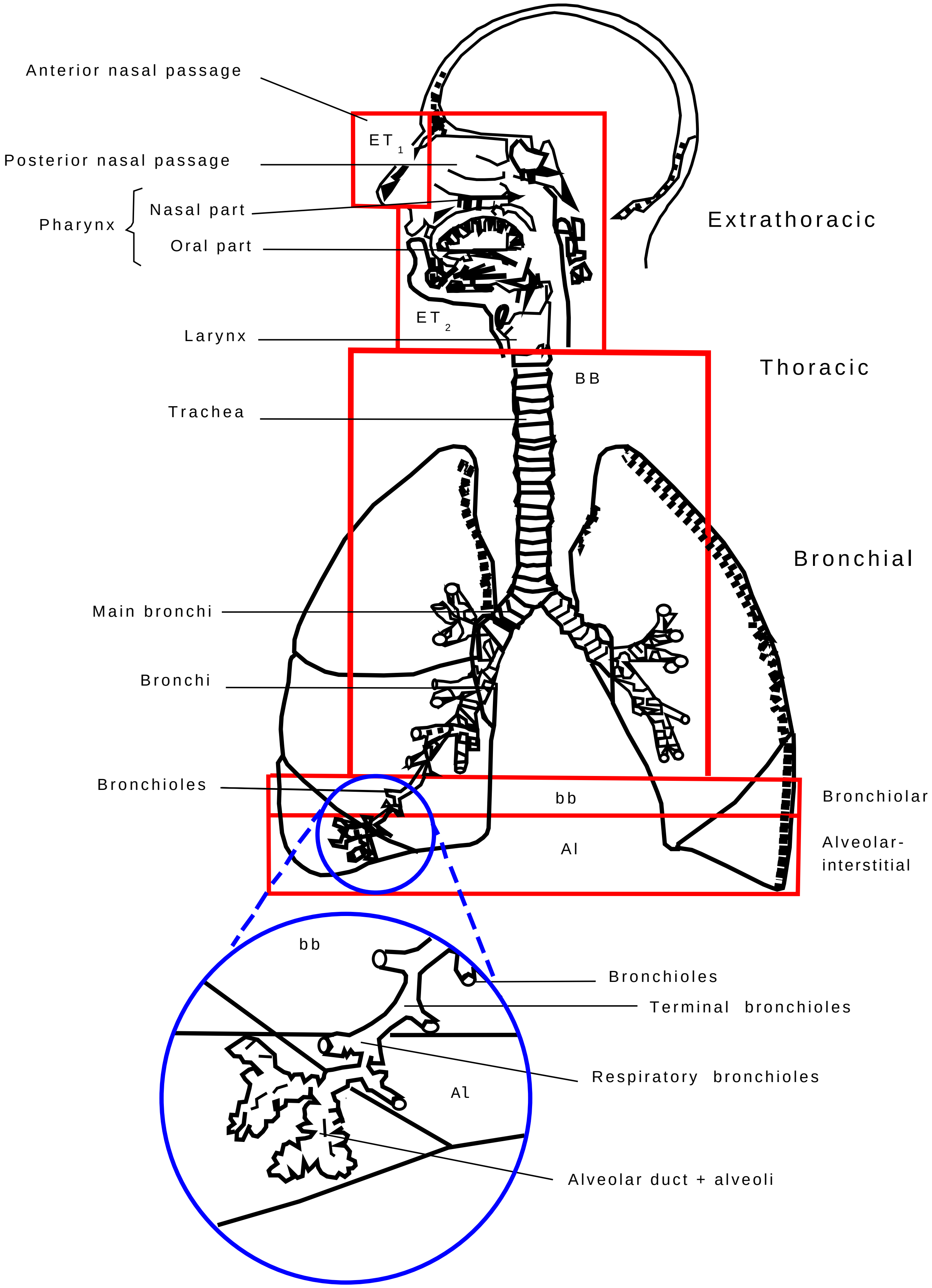
Type M 10% absorbed with a biological half-life of ten minutes and 90% with a biological half-life of 140 days. There is rapid absorption of about 10% of the deposit in BB and bb; and 5% of material deposited in ET_2. About 70% of the deposit in AI eventually reaches body fluids by absorption.

Type S 0.1% absorbed with a biological half-life of ten minutes and 99.9% with a biological half-life of 7000 days. There is little absorption from ET, BB or bb, and about 10% of the deposit in AI eventually reaches body fluids by absorption.

The slowest lung class Type S has been used in the calculations. This is appropriate for the vast majority of minerals but not necessarily for some of the materials subsequently produced. Contact an appropriate authority for clarification.

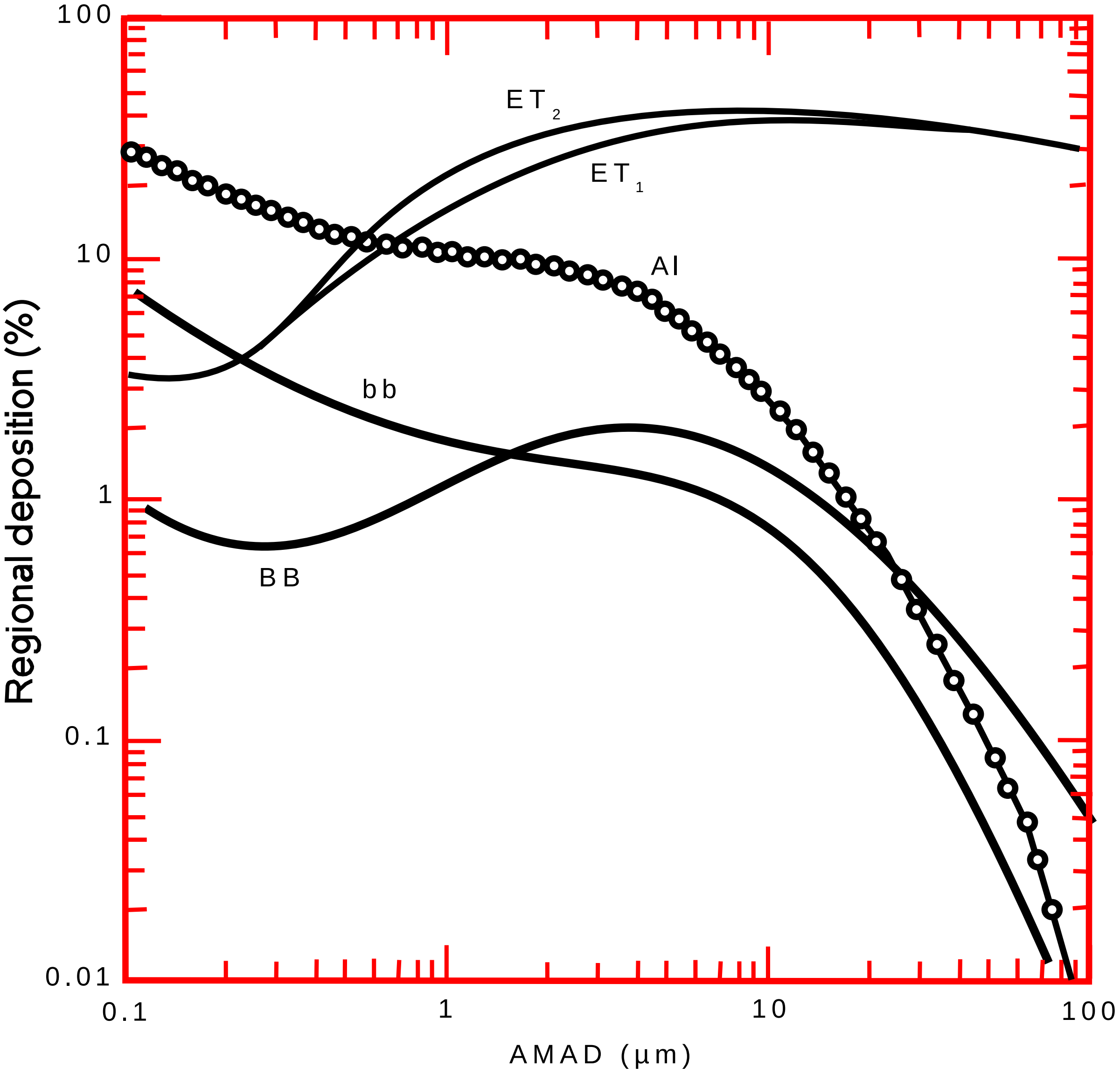
On the basis of the new respiratory tract model A.1 on the following page, deposition in the thorax of aerosols of occupational concern is highest in the AI region, but progressively decreases with increasing particle size as shown in A.2 on page 21 (reproduced with permission from ICRP–66 [4]).

Figure A.1.: Human respiratory tract model



Reproduced with permission from ICRP–66 [4]

Figure A.2.: Influence of particle size on deposition in the various regions of the respiratory tract



Fractional deposition in each region of respiratory tract for reference worker (normal nose breather) shown as the activity median aerodynamic diameter, AMAD. Deposition is expressed as a fraction of activity present in the volume of ambient air that is inspired, and activity is assumed to be log-normally distributed as a function of particle size (for particles of density 3.0 g cm^{-3} and shape factor 1.5). Reproduced with permission from ICRP–66 [4]

B. Appendix listing the radiation weighting factors

Table B.1.: Radiation weighting factors (IAEA Basic Safety Standards)

Type and Energy Range	Radiation weighting factor w_R
Photons, all energies	1
Electrons and muons, all energies	1
Neutrons, energy <10 keV	5
10 keV to 100 keV	10
>100 keV to 2 MeV	20
>2 MeV to 20 MeV	10
>20 MeV	5
Protons, other than recoil protons, energy >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

Table B.2.: Tissue and organ weighting factors (IAEA Basic Safety Standards)

Tissue or organ	Tissue weighting factor w_R
Gonads	0.20
Bone Marrow (red)	0.12
Colon[1]	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone Surface	0.01
Remainder[2]	0.05

[1] The weighting factor for the colon is applied to the mass average of the equivalent dose in the walls of the upper and lower large intestine.

[2] For the purposes of calculation, the remainder is composed of adrenal glands, brain, extrathoracic region, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus. In those exceptional cases in which the most exposed remainder tissue receives the highest committed equivalent dose of all organs, a weighting factor of 0.025 shall be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the rest of the remainder as defined here.

C. Appendix listing the thorium/uranium radionuclide activities and committed effective dose

Table C.1.: Radionuclide activities and committed effective dose for the inhalation of thorium ore dust (AMAD = 1 μm) by members of the general public

				Quantity inhaled (Bq)		
Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Alpha	Beta	Dose (Sv)
^{232}Th	α	S	2.5×10^{-5}	1		2.5×10^{-5}
^{228}Ra	β	M	1.6×10^{-5}		1	1.6×10^{-5}
^{228}Ac	β	S	1.6×10^{-8}		1	1.6×10^{-8}
^{228}Th	α	S	4.0×10^{-5}	1		4.0×10^{-5}
^{224}Ra	α	M	3.4×10^{-6}	1		3.4×10^{-6}
^{220}Rn^{a}	α	–	–	1		–
^{216}Po^{a}	α	–	–	1		–
^{212}Pb^{a}	β	F	1.9×10^{-7}		1	1.9×10^{-7}
^{212}Bi^{a}	64.1% β 35.9% α	M	3.1×10^{-8}	0.359	0.641	3.1×10^{-8}
^{212}Po^{a}	α	–	–	0.61		–
^{208}Tl^{a}	β	–	–		0.359	–
			Total	6	4	8.46×10^{-5}

[a]– Rn–220 and short lived progeny.

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

$$DCF_{1\mu m,Th,public} = \frac{8.46 \times 10^{-5} Sv}{6 Bq_{\alpha}} = 1.41 \times 10^{-5} Sv/Bq_{\alpha} = 0.0141\, mSv/Bq_{\alpha}$$

Table C.2.: Radionuclide activities and committed effective dose for the inhalation of thorium ore dust (AMAD = 1 μm) by workers

Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq) Alpha	Quantity inhaled (Bq) Beta	Dose (Sv)
^{232}Th	α	S	2.3×10^{-5}	1		2.3×10^{-5}
^{228}Ra	β	M	2.6×10^{-6}		1	2.6×10^{-6}
^{228}Ac	β	S	1.4×10^{-8}		1	1.4×10^{-8}
^{228}Th	α	S	3.9×10^{-5}	1		3.9×10^{-5}
^{224}Ra	α	M	2.9×10^{-6}	1		2.9×10^{-6}
^{220}Rn^{a}	α	–	–	1		–
^{216}Po^{a}	α	–	–	1		–
^{212}Pb^{a}	β	F	1.9×10^{-8}		1	1.9×10^{-7}
^{212}Bi^{a}	64.1% β 35.9% α	M	3.0×10^{-8}	0.359	0.641	3.0×10^{-8}
^{212}Po^{a}	α	–	–	0.641		–
^{208}Tl^{a}	β	–	–		0.359	–
			Total	6	4	6.76×10^{-5}

[a] – ^{220}Rn and short lived progeny.

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

$$DCF_{1\mu m,Th,worker} = \frac{6.76 \times 10^{-5} Sv}{6 Bq_{\alpha}} = 1.13 \times 10^{-5} Sv/Bq_{\alpha} = 0.0113\, mSv/Bq_{\alpha}$$

Table C.3.: Radionuclide activities and committed effective dose for the inhalation of thorium ore dust (AMAD = 3 μm) by workers

Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		
				Alpha	Beta	Dose (Sv)
^{232}Th	α	S	1.7×10^{-5}	1		1.7×10^{-5}
^{228}Ra	β	M	2.2×10^{-6}		1	2.2×10^{-6}
^{228}Ac	β	S	1.3×10^{-8}		1	1.3×10^{-8}
^{228}Th	α	S	3.3×10^{-5}	1		3.3×10^{-5}
^{224}Ra	α	M	3.1×10^{-6}	1		3.1×10^{-6}
^{220}Rn^{a}	α	–	–	1		–
^{216}Po^{a}	α	–	–	1		–
^{212}Pb^{a}	β	F	3.1×10^{-8}		1	3.1×10^{-8}
^{212}Bi^{a}	64.1% β 35.9% α	M	4.1×10^{-8}	0.359	0.641	4.1×10^{-8}
^{212}Po^{a}	α	–	–	0.641		–
^{208}Tl^{a}	β	–	–		0.359	–
			Total	6	4	5.54×10^{-5}

^{a}– Rn–220 and short lived progeny.

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

$$DCF_{3\mu m,Th,worker} = \frac{5.54 \times 10^{-5} Sv}{6 Bq_{\alpha}} = 9.23 \times 10^{-6} Sv/Bq_{\alpha} = 0.0092\, mSv/Bq_{\alpha}$$

Table C.4.: Radionuclide activities and committed effective dose for the inhalation of thorium ore dust (AMAD = 5 μm) by workers

Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
				Alpha	Beta	
^{232}Th	α	S	1.2×10^{-5}	1		1.2×10^{-5}
^{228}Ra	β	M	1.7×10^{-6}		1	1.7×10^{-6}
^{228}Ac	β	S	1.2×10^{-8}		1	1.2×10^{-8}
^{228}Th	α	S	3.2×10^{-5}	1		3.2×10^{-5}
^{224}Ra	α	M	2.4×10^{-6}	1		2.4×10^{-6}
^{220}Rn^{a}	α	–	–	1		–
^{216}Po^{a}	α	–	–	1		–
^{212}Pb^{a}	β	F	3.3×10^{-8}		1	3.3×10^{-8}
^{212}Bi^{a}	64.1% β 35.9% α	M	3.9×10^{-8}	0.359	0.641	3.9×10^{-8}
^{212}Po^{a}	α	–	–	0.641		–
^{208}Tl^{a}	β	–	–		0.359	–
			Total	6	4	4.82×10^{-5}

[a] – ^{220}Rn and short lived progeny.

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

$$DCF_{5\mu m,Th,worker} = \frac{4.82 \times 10^{-5} Sv}{6 Bq_{\alpha}} = 8.03 \times 10^{-6} Sv/Bq_{\alpha} = 0.0080\, mSv/Bq_{\alpha}$$

Table C.5.: Radionuclide activities and committed effective dose for the inhalation of thorium ore dust (AMAD = 10 μm) by workers

Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq) Alpha	Quantity inhaled (Bq) Beta	Dose (Sv)
^{232}Th	α	S	8.1×10^{-6}	1		8.1×10^{-6}
^{228}Ra	β	M	9.8×10^{-7}		1	9.8×10^{-7}
^{228}Ac	β	S	7.2×10^{-9}		1	7.2×10^{-9}
^{228}Th	α	S	1.8×10^{-5}	1		1.8×10^{-5}
^{224}Ra	α	M	1.3×10^{-6}	1		1.3×10^{-6}
^{220}Rn^{a}	α	–	–	1		–
^{216}Po^{a}	α	–	–	1		–
^{212}Pb^{a}	β	F	3.2×10^{-8}		1	3.2×10^{-8}
^{212}Bi^{a}	64.1% β 35.9% α	M	3.1×10^{-8}	0.359	0.641	3.1×10^{-8}
^{212}Po^{a}	α	–	–	0.641		–
^{208}Tl^{a}	β	–	–		0.359	–
			Total	6	4	2.85×10^{-5}

[a] – ^{220}Rn and short lived progeny.

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

$$DCF_{10\mu m,Th,worker} = \frac{2.85 \times 10^{-5} Sv}{6 Bq_{\alpha}} = 4.74 \times 10^{-6} Sv/Bq_{\alpha} = 0.0047\, mSv/Bq_{\alpha}$$

Table C.6.: Radionuclide activities and committed effective dose for the inhalation of uranium ore dust (AMAD = 1 μm) by members of the general public

Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
				Alpha	Beta	
$^{238}\mathrm{U}$	α	S	8.0×10^{-6}	1		8.0×10^{-6}
$^{234}\mathrm{Th}$	β	S	7.7×10^{-9}		1	7.7×10^{-9}
$^{234}\mathrm{Pa}_m$	β	–	–		1	–
$^{234}\mathrm{U}$	α	S	9.4×10^{-6}	1		9.4×10^{-6}
$^{230}\mathrm{Th}$	α	S	1.4×10^{-5}	1		1.4×10^{-5}
$^{226}\mathrm{Ra}$	α	M	9.5×10^{-6}	1		9.5×10^{-6}
$^{222}\mathrm{Rn}^{a}$	α	–	–	1		–
$^{218}\mathrm{Po}^{a}$	α	–	–	1		–
$^{214}\mathrm{Pb}^{a}$	β	F	8.0×10^{-6}		1	1.5×10^{-8}
$^{214}\mathrm{Bi}^{a}$	β	M	1.4×10^{-8}		1	1.4×10^{-8}
$^{214}\mathrm{Po}^{a}$	α	–	–	1		–
$^{210}\mathrm{Pb}$	β	F	5.6×10^{-6}		1	5.6×10^{-6}
$^{210}\mathrm{Bi}$	β	M	9.3×10^{-8}		1	9.3×10^{-8}
$^{210}\mathrm{Po}$	α	M	4.3×10^{-6}	1		4.3×10^{-6}
$^{235}\mathrm{U}$	α	S	8.5×10^{-6}	0.046		3.9×10^{-7}
$^{231}\mathrm{Th}$	β	S	3.3×10^{-10}		0.046	1.5×10^{-11}
$^{231}\mathrm{Pa}$	α	S	3.4×10^{-5}	0.046		1.6×10^{-6}
$^{227}\mathrm{Ac}$	β	S	7.2×10^{-5}		0.046	3.3×10^{-6}
$^{227}\mathrm{Th}$	α	S	1.0×10^{-5}	0.046		4.6×10^{-7}
$^{223}\mathrm{Ra}$	α	M	8.7×10^{-6}	0.046		4.0×10^{-7}
$^{219}\mathrm{Rn}^{a}$	α	–	–	0.046		–
$^{215}\mathrm{Po}^{a}$	α	–	–	0.046		–
$^{211}\mathrm{Pb}^{a}$	β	F	1.2×10^{-8}		0.046	5.5×10^{-10}
$^{211}\mathrm{Bi}^{a}$	α	–	–	0.046		
$^{207}\mathrm{Tl}^{a}$	β	–	–		0.046	
			Total	8.322	6.184	5.71×10^{-5}

^{a}– ^{220}Rn, ^{219}Rn and short lived progeny.

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

$$DCF_{1\mu m,U,public} = \frac{5.71 \times 10^{-5} Sv}{8.322 Bq_\alpha} = 6.86 \times 10^{-6} Sv/Bq_\alpha = 0.0069\, mSv/Bq_\alpha$$

Table C.7.: Radionuclide activities and committed effective dose for the inhalation of uranium ore dust (AMAD = 1 μm) by workers

				Quantity inhaled (Bq)		
Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Alpha	Beta	Dose (Sv)
^{238}U	α	S	7.6×10^{-6}	1		7.3×10^{-6}
^{234}Th	β	S	7.3×10^{-9}		1	7.3×10^{-9}
^{234}Pa$_m$	β	–	–		1	–
^{234}U	α	S	8.5×10^{-6}	1		8.5×10^{-6}
^{230}Th	α	S	1.3×10^{-5}	1		1.3×10^{-5}
^{226}Ra	α	M	3.2×10^{-6}	1		3.2×10^{-6}
^{222}Rn^a	α	–	–	1		–
^{218}Po^a	α	–	–	1		–
^{214}Pb^a	β	F	2.9×10^{-9}		1	2.9×10^{-9}
^{214}Bi^a	β	M	1.4×10^{-8}		1	1.4×10^{-8}
^{214}Po^a	α	–	–	1		–
^{210}Pb	β	F	8.9×10^{-7}		1	8.9×10^{-7}
^{210}Bi	β	M	8.4×10^{-8}		1	8.4×10^{-8}
^{210}Po	α	M	3.0×10^{-6}	1		3.0×10^{-6}
^{235}U	α	S	7.7×10^{-6}	0.046		3.5×10^{-7}
^{231}Th	β	S	3.2×10^{-10}		0.046	1.5×10^{-11}
^{231}Pa	α	S	3.2×10^{-5}	0.046		1.5×10^{-6}
^{227}Ac	β	S	6.6×10^{-5}		0.046	3.0×10^{-6}
^{227}Th	α	S	9.6×10^{-6}	0.046		4.4×10^{-7}
^{223}Ra	α	M	6.9×10^{-6}	0.046		3.2×10^{-7}
^{219}Rn^a	α	–	–	0.046		–
^{215}Po^a	α	–	–	0.046		–
^{211}Pb^a	β	F	3.9×10^{-9}		0.046	1.8×10^{-10}
^{211}Bi^a	α	–	–	0.046		
^{207}Tl^a	β	–	–		0.046	
			Total	8.322	6.184	4.16×10^{-5}

^{a}– ^{220}Rn, ^{219}Rn and short lived progeny.

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

$$DCF_{1\mu m,U,worker} = \frac{4.16 \times 10^{-5} Sv}{8.322 Bq_\alpha} = 5.00 \times 10^{-6} Sv/Bq_\alpha = 0.0050\, mSv/Bq_\alpha$$

Table C.8.: Radionuclide activities and committed effective dose for the inhalation of uranium ore dust (AMAD = 3 μm) by workers

				Quantity inhaled (Bq)		
Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Alpha	Beta	Dose (Sv)
^{238}U	α	S	7.1×10^{-6}	1		7.1×10^{-6}
^{234}Th	β	S	7.2×10^{-9}		1	7.2×10^{-9}
^{234}Pa$_m$	β	–	–		1	–
^{234}U	α	S	8.5×10^{-6}	1		8.5×10^{-6}
^{230}Th	α	S	1.0×10^{-5}	1		1.0×10^{-5}
^{226}Ra	α	M	2.8×10^{-6}	1		2.8×10^{-6}
^{222}Rn^a	α	–	–	1		–
^{218}Po^a	α	–	–	1		–
^{214}Pb^a	β	F	4.6×10^{-9}		1	4.6×10^{-9}
^{214}Bi^a	β	M	2.1×10^{-8}		1	2.1×10^{-8}
^{214}Po^a	α	–	–	1		–
^{210}Pb	β	F	1.1×10^{-6}		1	1.1×10^{-6}
^{210}Bi	β	M	8.4×10^{-8}		1	8.4×10^{-8}
^{210}Po	α	M	2.8×10^{-6}	1		2.8×10^{-6}
^{235}U	α	S	7.6×10^{-6}	0.046		3.5×10^{-7}
^{231}Th	β	S	3.8×10^{-10}		0.046	1.8×10^{-11}
^{231}Pa	α	S	2.4×10^{-5}	0.046		1.1×10^{-6}
^{227}Ac	β	S	5.2×10^{-5}		0.046	2.4×10^{-6}
^{227}Th	α	S	9.7×10^{-6}	0.046		4.5×10^{-7}
^{223}Ra	α	M	7.1×10^{-6}	0.046		3.3×10^{-7}
^{219}Rn^a	α	–	–	0.046		–
^{215}Po^a	α	–	–	0.046		–
^{211}Pb^a	β	F	5.6×10^{-9}		0.046	2.6×10^{-10}
^{211}Bi^a	α	–	–	0.046		
^{207}Tl^a	β	–	–		0.046	
			Total	8.322	6.184	3.70×10^{-5}

^{a}– ^{220}Rn, ^{219}Rn and short lived progeny.

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

$$DCF_{3\mu m,U,worker} = \frac{3.70 \times 10^{-5} Sv}{8.322 Bq_\alpha} = 4.45 \times 10^{-6} Sv/Bq_\alpha = 0.0045\, mSv/Bq_\alpha$$

Table C.9.: Radionuclide activities and committed effective dose for the inhalation of uranium ore dust (AMAD = 5 μm) by workers

Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
				Alpha	Beta	
^{238}U	α	S	5.7×10^{-6}	1		5.7×10^{-6}
^{234}Th	β	S	5.8×10^{-9}		1	5.8×10^{-9}
^{234}Pa$_m$	β	–	–		1	–
^{234}U	α	S	6.8×10^{-6}	1		6.8×10^{-6}
^{230}Th	α	S	7.2×10^{-6}	1		7.2×10^{-5}
^{226}Ra	α	M	2.2×10^{-6}	1		2.2×10^{-6}
^{222}Rn[a]	α	–	–	1		–
^{218}Po[a]	α	–	–	1		–
^{214}Pb[a]	β	F	4.8×10^{-9}		1	4.8×10^{-9}
^{214}Bi[a]	β	M	2.1×10^{-8}		1	2.1×10^{-8}
^{214}Po[a]	α	–	–	1		–
^{210}Pb	β	F	1.1×10^{-6}		1	1.1×10^{-6}
^{210}Bi	β	M	6.0×10^{-8}		1	6.0×10^{-8}
^{210}Po	α	M	2.2×10^{-6}	1		2.2×10^{-6}
^{235}U	α	S	6.1×10^{-6}	0.046		2.8×10^{-7}
^{231}Th	β	S	4.0×10^{-10}		0.046	1.8×10^{-11}
^{231}Pa	α	S	1.7×10^{-5}	0.046		7.8×10^{-6}
^{227}Ac	β	S	4.7×10^{-5}		0.046	2.2×10^{-6}
^{227}Th	α	S	7.6×10^{-6}	0.046		3.5×10^{-7}
^{223}Ra	α	M	5.7×10^{-6}	0.046		2.6×10^{-7}
^{219}Rn[a]	α	–	–	0.046		–
^{215}Po[a]	α	–	–	0.046		–
^{211}Pb[a]	β	F	5.6×10^{-9}		0.046	2.6×10^{-10}
^{211}Bi[a]	α	–	–	0.046		
^{207}Tl[a]	β	–	–		0.046	
			Total	8.322	6.184	2.91×10^{-5}

[a] – ^{220}Rn, ^{219}Rn and short lived progeny.

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

$$DCF_{5\mu m,U,worker} = \frac{2.91 \times 10^{-5} Sv}{8.322 Bq_{\alpha}} = 3.50 \times 10^{-6} Sv/Bq_{\alpha} = 0.0035\, mSv/Bq_{\alpha}$$

Table C.10.: Radionuclide activities and committed effective dose for the inhalation of uranium ore dust (AMAD = 10 μm) by workers

Radionuclide	Decay	Slowest lung absorption class	Dose coefficient (Sv/Bq)	Quantity inhaled (Bq)		Dose (Sv)
				Alpha	Beta	
^{238}U	α	S	3.5×10^{-6}	1		3.5×10^{-6}
^{234}Th	β	S	3.5×10^{-9}		1	3.5×10^{-9}
^{234}Pa$_m$	β	–	–		1	–
^{234}U	α	S	4.1×10^{-6}	1		4.1×10^{-6}
^{230}Th	α	S	5.2×10^{-6}	1		5.2×10^{-6}
^{226}Ra	α	M	1.5×10^{-6}	1		1.5×10^{-6}
^{222}Rn^a	α	–	–	1		–
^{218}Po^a	α	–	–	1		–
^{214}Pb^a	β	F	4.4×10^{-9}		1	4.4×10^{-9}
^{214}Bi^a	β	M	1.8×10^{-8}		1	1.8×10^{-8}
^{214}Po^a	α	–	–	1		–
^{210}Pb	β	F	9.4×10^{-7}		1	9.4×10^{-7}
^{210}Bi	β	M	3.0×10^{-8}		1	3.0×10^{-8}
^{210}Po	α	M	1.1×10^{-6}	1		1.1×10^{-6}
^{235}U	α	S	3.7×10^{-6}	0.046		1.7×10^{-7}
^{231}Th	β	S	3.0×10^{-10}		0.046	1.4×10^{-11}
^{231}Pa	α	S	8.3×10^{-6}	0.046		3.8×10^{-7}
^{227}Ac	β	S	2.7×10^{-5}		0.046	1.2×10^{-6}
^{227}Th	α	S	3.9×10^{-6}	0.046		1.8×10^{-7}
^{223}Ra	α	M	3.0×10^{-6}	0.046		1.4×10^{-7}
^{219}Rn^a	α	–	–	0.046		–
^{215}Po^a	α	–	–	0.046		–
^{211}Pb^a	β	F	4.8×10^{-9}		0.046	2.2×10^{-10}
^{211}Bi^a	α	–	–	0.046		
^{207}Tl^a	β	–	–		0.046	
			Total	8.322	6.184	2.15×10^{-5}

^{a}– ^{220}Rn, ^{219}Rn and short lived progeny.

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

$$DCF_{10\mu m,U,worker} = \frac{2.15 \times 10^{-5} Sv}{8.322 Bq_\alpha} = 2.58 \times 10^{-6} Sv/Bq_\alpha = 0.026\, mSv/Bq_\alpha$$

D. Appendix listing the thorium/uranium dose conversion factors

Table D.1.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 1 μm containing both thorium and uranium in different ratios, for members of the general public (dose constraint = 0.3 mSv/year

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0141	21	0.003
50:1	0.0137	22	0.003
40:1	0.0136	22	0.003
30:1	0.0134	22	0.003
25:1	0.0133	23	0.003
20:1	0.0131	23	0.003
15:1	0.0129	23	0.003
10:1	0.0124	24	0.003
9:1	0.0123	24	0.003
8:1	0.0121	25	0.003
7:1	0.0119	25	0.003
6:1	0.0117	26	0.003
5:1	0.0114	26	0.003
4:1	0.0110	27	0.003
3:1	0.0105	29	0.003
2:1	0.0097	31	0.004
1.75:1	0.0095	32	0.004
1.5:1	0.0092	32	0.004
1.25:1	0.0090	33	0.004
1:1	0.0086	35	0.004
1:1.25	0.0084	36	0.004
1:1.5	0.0082	37	0.004
1:1.75	0.0080	37	0.004
1:2	0.0079	38	0.005
1:3	0.0076	40	0.005
1:4	0.0074	41	0.005
1:5	0.0073	41	0.005
1:6	0.0072	41	0.005
1:7	0.0072	42	0.005
1:8	0.0071	42	0.005
1:9	0.0071	42	0.005
1:10	0.0071	42	0.005
1:15	0.0070	43	0.005
1:20	0.0070	43	0.005
1:25	0.0069	43	0.005
1:30	0.0069	43	0.005
1:40	0.0069	43	0.005
1:50	0.0069	43	0.005
All uranium	0.0069	44	0.005

Table D.2.: Dose conversion factors (DCF – mSv/Bq_α), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 1 μm containing both thorium and uranium in different ratios, for members of the general public (exposure limit = 1 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq_α)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0141	71	0.008
50:1	0.0137	73	0.009
40:1	0.0136	74	0.009
30:1	0.0134	74	0.009
25:1	0.0133	75	0.009
20:1	0.0131	76	0.009
15:1	0.0129	78	0.009
10:1	0.0124	81	0.010
9:1	0.0123	81	0.010
8:1	0.0121	83	0.010
7:1	0.0119	84	0.010
6:1	0.0117	86	0.010
5:1	0.0114	88	0.010
4:1	0.0110	91	0.011
3:1	0.0105	96	0.011
2:1	0.0097	103	0.012
1.75:1	0.0095	105	0.013
1.5:1	0.0092	108	0.013
1.25:1	0.0090	112	0.013
1:1	0.0086	116	0.014
1:1.25	0.0084	120	0.014
1:1.5	0.0082	123	0.015
1:1.75	0.0080	125	0.015
1:2	0.0079	127	0.015
1:3	0.0076	132	0.016
1:4	0.0074	135	0.016
1:5	0.0073	137	0.016
1:6	0.0072	138	0.016
1:7	0.0072	139	0.017
1:8	0.0071	140	0.017
1:9	0.0071	141	0.017
1:10	0.0071	141)	0.017
1:15	0.0070	143	0.017
1:20	0.0070	143	0.017
1:25	0.0069	144	0.017
1:30	0.0069	144	0.017
1:40	0.0069	145	0.017
1:50	0.0069	145	0.017
All uranium	0.0069	146	0.017

Table D.3.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 1 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 1 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0113	89	0.037
50:1	0.0109	92	0.038
40:1	0.0108	92	0.039
30:1	0.0107	94	0.039
25:1	0.0106	95	0.039
20:1	0.0104	96	0.040
15:1	0.0102	98	0.041
10:1	0.0098	102	0.043
9:1	0.0097	103	0.043
8:1	0.0095	105	0.044
7:1	0.0094	107	0.045
6:1	0.0092	109	0.046
5:1	0.0089	112	0.047
4:1	0.0086	117	0.049
3:1	0.0081	123	0.051
2:1	0.0075	134	0.056
1.75:1	0.0073	137	0.057
1.5:1	0.0071	142	0.059
1.25:1	0.0068	147	0.061
1:1	0.0065	153	0.064
1:1.25	0.0063	159	0.066
1:1.5	0.0061	163	0.068
1:1.75	0.0060	167	0.070
1:2	0.0059	170	0.071
1:3	0.0056	178	0.074
1:4	0.0055	183	0.076
1:5	0.0054	186	0.077
1:6	0.0053	188	0.078
1:7	0.0053	189	0.079
1:8	0.0052	191	0.079
1:9	0.0052	192	0.080
1:10	0.0052	192	0.080
1:15	0.0051	195	0.081
1:20	0.0051	196	0.082
1:25	0.0051	197	0.082
1:30	0.0051	197	0.082
1:40	0.0051	198	0.082
1:50	0.0050	198	0.083
All uranium	0.0050	200	0.083

Table D.4.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 1 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 5 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0113	444	0.185
50:1	0.0109	459	0.191
40:1	0.0108	462	0.193
30:1	0.0107	468	0.195
25:1	0.0106	473	0.197
20:1	0.0104	479	0.200
15:1	0.0102	490	0.204
10:1	0.0098	510	0.213
9:1	0.0097	517	0.215
8:1	0.0095	524	0.219
7:1	0.0094	534	0.223
6:1	0.0092	546	0.228
5:1	0.0089	562	0.234
4:1	0.0086	585	0.244
3:1	0.0081	617	0.257
2:1	0.0075	668	0.278
1.75:1	0.0073	686	0.286
1.5:1	0.0071	708	0.295
1.25:1	0.0068	733	0.305
1:1	0.0065	764	0.318
1:1.25	0.0063	793	0.331
1:1.5	0.0061	816	0.340
1:1.75	0.0060	835	0.348
1:2	0.0059	850	0.354
1:3	0.0056	890	0.371
1:4	0.0055	913	0.380
1:5	0.0054	928	0.387
1:6	0.0053	939	0.391
1:7	0.0053	947	0.394
1:8	0.0052	953	0.397
1:9	0.0052	958	0.399
1:10	0.0052	962	0.401
1:15	0.0051	974	0.406
1:20	0.0051	980	0.408
1:25	0.0051	984	0.410
1:30	0.0051	986	0.411
1:40	0.0051	990	0.412
1:50	0.0050	992	0.413
All uranium	0.0050	1000	0.417

Table D.5.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 1 μm containing both thorium and uranium in different ratios, for workers (exposure limit = 20 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0113	1776	0.740
50:1	0.0109	1835	0.764
40:1	0.0108	1849	0.770
30:1	0.0107	1872	0.780
25:1	0.0106	1890	0.788
20:1	0.0104	1917	0.799
15:1	0.0102	1960	0.817
10:1	0.0098	2041	0.850
9:1	0.0097	2067	0.861
8:1	0.0095	2098	0.874
7:1	0.0094	2136	0.890
6:1	0.0092	2185	0.911
5:1	0.0089	2250	0.937
4:1	0.0086	2338	0.974
3:1	0.0081	2467	1.028
2:1	0.0075	2674	1.114
1.75:1	0.0073	2746	1.144
1.5:1	0.0071	2831	1.179
1.25:1	0.0068	2932	1.222
1:1	0.0065	3055	1.273
1:1.25	0.0063	3173	1.322
1:1.5	0.0061	3266	1.361
1:1.75	0.0060	3339	1.391
1:2	0.0059	3400	1.417
1:3	0.0056	3560	1.483
1:4	0.0055	3653	1.522
1:5	0.0054	3713	1.547
1:6	0.0053	3756	1.565
1:7	0.0053	3787	1.578
1:8	0.0052	3811	1.588
1:9	0.0052	3831	1.596
1:10	0.0052	3846	1.603
1:15	0.0051	3895	1.623
1:20	0.0051	3920	1.633
1:25	0.0051	3935	1.640
1:30	0.0051	3946	1.644
1:40	0.0051	3959	1.650
1:50	0.0050	3967	1.653
All uranium	0.0050	3999	1.666

Table D.6.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 3 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 1 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0092	108	0.045
50:1	0.0090	112	0.047
40:1	0.0089	112	0.047
30:1	0.0088	114	0.047
25:1	0.0087	115	0.048
20:1	0.0086	116	0.048
15:1	0.0084	119	0.049
10:1	0.0081	123	0.051
9:1	0.0080	125	0.052
8:1	0.0079	126	0.053
7:1	0.0078	129	0.054
6:1	0.0076	131	0.055
5:1	0.0074	135	0.056
4:1	0.0072	140	0.058
3:1	0.0068	147	0.061
2:1	0.0063	158	0.066
1.75:1	0.0062	161	0.067
1.5:1	0.0060	166	0.069
1.25:1	0.0058	171	0.071
1:1	0.0056	178	0.074
1:1.25	0.0054	184	0.077
1:1.5	0.0053	188	0.079
1:1.75	0.0052	192	0.080
1:2	0.0051	195	0.081
1:3	0.0049	203	0.085
1:4	0.0048	208	0.087
1:5	0.0047	211	0.088
1:6	0.0047	213	0.089
1:7	0.0047	214	0.089
1:8	0.0046	216	0.090
1:9	0.0046	217	0.090
1:10	0.0046	217	0.091
1:15	0.0046	220	0.092
1:20	0.0045	221	0.092
1:25	0.0045	222	0.092
1:30	0.0045	222	0.093
1:40	0.0045	223	0.093
1:50	0.0045	223	0.093
All uranium	0.0044	225	0.094

Table D.7.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/mμ) for the dust with AMAD = 3 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 5 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0092	542	0.226
50:1	0.0090	558	0.233
40:1	0.0089	562	0.234
30:1	0.0088	569	0.237
25:1	0.0087	574	0.239
20:1	0.0086	581	0.242
15:1	0.0084	594	0.247
10:1	0.0081	616	0.257
9:1	0.0080	623	0.260
8:1	0.0079	632	0.263
7:1	0.0078	643	0.268
6:1	0.0076	656	0.273
5:1	0.0074	674	0.281
4:1	0.0072	698	0.291
3:1	0.0068	733	0.305
2:1	0.0063	788	0.328
1.75:1	0.0062	807	0.336
1.5:1	0.0060	830	0.346
1.25:1	0.0058	856	0.357
1:1	0.0056	888	0.370
1:1.25	0.0054	919	0.383
1:1.5	0.0053	942	0.393
1:1.75	0.0052	961	0.400
1:2	0.0051	976	0.407
1:3	0.0049	1016	0.423
1:4	0.0048	1039	0.433
1:5	0.0047	1054	0.439
1:6	0.0047	1065	0.444
1:7	0.0047	1072	0.447
1:8	0.0046	1078	0.449
1:9	0.0046	1083	0.451
1:10	0.0046	1087	0.453
1:15	0.0046	1099	0.458
1:20	0.0045	1105	0.460
1:25	0.0045	1108	0.462
1:30	0.0045	1111	0.463
1:40	0.0045	1114	0.464
1:50	0.0045	1116	0.465
All uranium	0.0044	1124	0.468

Table D.8.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 3 μm containing both thorium and uranium in different ratios, for workers (exposure limit = 20 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0092	2167	0.903
50:1	0.0090	2233	0.930
40:1	0.0089	2249	0.937
30:1	0.0088	2275	0.948
25:1	0.0087	2296	0.957
20:1	0.0086	2326	0.969
15:1	0.0084	2374	0.989
10:1	0.0081	2465	1.027
9:1	0.0080	2493	1.039
8:1	0.0079	2528	1.053
7:1	0.0078	2571	1.071
6:1	0.0076	2625	1.094
5:1	0.0074	2696	1.123
4:1	0.0072	2792	1.163
3:1	0.0068	2932	1.222
2:1	0.0063	3153	1.314
1.75:1	0.0062	3230	1.346
1.5:1	0.0060	3319	1.383
1.25:1	0.0058	3425	1.427
1:1	0.0056	3552	1.480
1:1.25	0.0054	3674	1.531
1:1.5	0.0053	3769	1.570
1:1.75	0.0052	3843	1.601
1:2	0.0051	3904	1.627
1:3	0.0049	4065	1.694
1:4	0.0048	4157	1.732
1:5	0.0047	4216	1.757
1:6	0.0047	4258	1.774
1:7	0.0047	4289	1.787
1:8	0.0046	4313	1.797
1:9	0.0046	4332	1.805
1:10	0.0046	4347	1.811
1:15	0.0046	4394	1.831
1:20	0.0045	4419	1.841
1:25	0.0045	4434	1.847
1:30	0.0045	4444	1.852
1:40	0.0045	4456	1.857
1:50	0.0045	4464	1.860
All uranium	0.0044	4495	1.873

Table D.9.: Dose conversion factors (DCF – mSv/Bq_α), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 5 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 1 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq_α)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0080	125	0.052
50:1	0.0078	129	0.054
40:1	0.0077	130	0.054
30:1	0.0076	131	0.055
25:1	0.0075	133	0.055
20:1	0.0074	135	0.056
15:1	0.0073	138	0.057
10:1	0.0070	143	0.060
9:1	0.0069	145	0.061
8:1	0.0068	147	0.061
7:1	0.0067	150	0.063
6:1	0.0065	154	0.064
5:1	0.0063	158	0.066
4:1	0.0061	165	0.069
3:1	0.0057	174	0.072
2:1	0.0053	189	0.079
1.75:1	0.0052	194	0.081
1.5:1	0.0050	200	0.083
1.25:1	0.0048	208	0.086
1:1	0.0046	216	0.090
1:1.25	0.0044	225	0.094
1:1.5	0.0043	232	0.097
1:1.75	0.0042	237	0.099
1:2	0.0041	242	0.101
1:3	0.0039	253	0.106
1:4	0.0038	260	0.108
1:5	0.0038	265	0.110
1:6	0.0037	268	0.112
1:7	0.0037	270	0.113
1:8	0.0037	272	0.113
1:9	0.0037	273	0.114
1:10	0.0036	274	0.114
1:15	0.0036	278	0.116
1:20	0.0036	280	0.117
1:25	0.0036	281	0.117
1:30	0.0035	282	0.117
1:40	0.0035	283	0.118
1:50	0.0035	283	0.118
All uranium	0.0035	286	0.119

Table D.10.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 5 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 5 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0080	623	0.259
50:1	0.0078	643	0.268
40:1	0.0077	648	0.270
30:1	0.0076	657	0.274
25:1	0.0075	663	0.276
20:1	0.0074	673	0.280
15:1	0.0073	688	0.287
10:1	0.0070	717	0.299
9:1	0.0069	726	0.303
8:1	0.0068	737	0.307
7:1	0.0067	751	0.313
6:1	0.0065	769	0.320
5:1	0.0063	792	0.330
4:1	0.0061	824	0.343
3:1	0.0057	870	0.362
2:1	0.0053	944	0.393
1.75:1	0.0052	970	0.404
1.5:1	0.0050	1001	0.417
1.25:1	0.0048	1038	0.432
1:1	0.0046	1082	0.451
1:1.25	0.0044	1126	0.469
1:1.5	0.0043	1159	0.483
1:1.75	0.0042	1186	0.494
1:2	0.0041	1208	0.503
1:3	0.0039	1267	0.528
1:4	0.0038	1301	0.542
1:5	0.0038	1323	0.551
1:6	0.0037	1339	0.558
1:7	0.0037	1350	0.563
1:8	0.0037	1359	0.566
1:9	0.0037	1366	0.569
1:10	0.0036	1372	0.572
1:15	0.0036	1390	0.579
1:20	0.0036	1399	0.583
1:25	0.0036	1405	0.585
1:30	0.0035	1409	0.587
1:40	0.0035	1414	0.589
1:50	0.0035	1417	0.590
All uranium	0.0035	1429	0.595

Table D.11.: Dose conversion factors (DCF – mSv/Bq_α), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 5 μm containing both thorium and uranium in different ratios, for workers (exposure limit = 20 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq_α)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0080	2490	1.038
50:1	0.0078	2574	1.072
40:1	0.0077	2594	1.081
30:1	0.0076	2627	1.095
25:1	0.0075	2653	1.105
20:1	0.0074	2691	1.121
15:1	0.0073	2753	1.147
10:1	0.0070	2868	1.195
9:1	0.0069	2905	1.210
8:1	0.0068	2950	1.229
7:1	0.0067	3005	1.252
6:1	0.0065	3075	1.281
5:1	0.0063	3167	1.320
4:1	0.0061	3294	1.373
3:1	0.0057	3480	1.450
2:1	0.0053	3777	1.574
1.75:1	0.0052	3882	1.617
1.5:1	0.0050	4005	1.669
1.25:1	0.0048	4152	1.730
1:1	0.0046	4330	1.804
1:1.25	0.0044	4503	1.876
1:1.5	0.0043	4637	1.932
1:1.75	0.0042	4745	1.977
1:2	0.0041	4833	2.014
1:3	0.0039	5068	2.112
1:4	0.0038	5204	2.168
1:5	0.0038	5292	2.205
1:6	0.0037	5355	2.231
1:7	0.0037	5401	2.251
1:8	0.0037	5437	2.265
1:9	0.0037	5465	2.277
1:10	0.0036	5489	2.287
1:15	0.0036	5560	2.317
1:20	0.0036	5597	2.332
1:25	0.0036	5620	2.342
1:30	0.0035	5635	2.348
1:40	0.0035	5655	2.356
1:50	0.0035	5666	2.361
All uranium	0.0035	5714	2.381

Table D.12.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 10 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 1 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0047	211	0.088
50:1	0.0046	217	0.090
40:1	0.0046	218	0.091
30:1	0.0045	220	0.092
25:1	0.0045	222	0.092
20:1	0.0045	224	0.094
15:1	0.0044	228	0.095
10:1	0.0042	236	0.098
9:1	0.0042	238	0.099
8:1	0.0041	241	0.101
7:1	0.0041	245	0.102
6:1	0.0040	249	0.104
5:1	0.0039	255	0.106
4:1	0.0038	263	0.109
3:1	0.0037	274	0.114
2:1	0.0034	291	0.121
1.75:1	0.0034	297	0.124
1.5:1	0.0033	304	0.127
1.25:1	0.0032	312	0.130
1:1	0.0031	321	0.134
1:1.25	0.0030	330	0.138
1:1.5	0.0030	337	0.140
1:1.75	0.0029	342	0.143
1:2	0.0029	347	0.144
1:3	0.0028	358	0.149
1:4	0.0027	364	0.152
1:5	0.0027	368	0.154
1:6	0.0027	371	0.155
1:7	0.0027	373	0.156
1:8	0.0027	375	0.156
1:9	0.0027	376	0.157
1:10	0.0026	377	0.157
1:15	0.0026	381	0.159
1:20	0.0026	382	0.159
1:25	0.0026	383	0.160
1:30	0.0026	384	0.160
1:40	0.0026	385	0.160
1:50	0.0026	385	0.161
All uranium	0.0026	387	0.161

Table D.13.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 10 μm containing both thorium and uranium in different ratios, for workers (dose constraint = 5 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0047	1054	0.439
50:1	0.0046	1083	0.451
40:1	0.0046	1090	0.454
30:1	0.0045	1101	0.459
25:1	0.0045	1109	0.462
20:1	0.0045	1122	0.468
15:1	0.0044	1142	0.476
10:1	0.0042	1180	0.492
9:1	0.0042	1192	0.497
8:1	0.0041	1206	0.503
7:1	0.0041	1224	0.510
6:1	0.0040	1246	0.519
5:1	0.0039	1274	0.531
4:1	0.0038	1313	0.547
3:1	0.0037	1369	0.570
2:1	0.0034	1455	0.606
1.75:1	0.0034	1484	0.618
1.5:1	0.0033	1518	0.633
1.25:1	0.0032	1558	0.649
1:1	0.0031	1605	0.669
1:1.25	0.0030	1650	0.688
1:1.5	0.0030	1684	0.702
1:1.75	0.0029	1711	0.713
1:2	0.0029	1733	0.722
1:3	0.0028	1790	0.746
1:4	0.0027	1822	0.759
1:5	0.0027	1842	0.768
1:6	0.0027	1857	0.774
1:7	0.0027	1867	0.778
1:8	0.0027	1875	0.781
1:9	0.0027	1882	0.784
1:10	0.0026	1887	0.786
1:15	0.0026	1903	0.793
1:20	0.0026	1911	0.796
1:25	0.0026	1916	0.799
1:30	0.0026	1920	0.800
1:40	0.0026	1924	0.802
1:50	0.0026	1927	0.803
All uranium	0.0026	1937	0.807

Table D.14.: Dose conversion factors (DCF – mSv/Bq$_\alpha$), annual limits of intake (ALI – Bq/year) and derived air concentrations (DAC – Bq/m^3) for the dust with AMAD = 10 μm containing both thorium and uranium in different ratios, for workers (exposure limit = 20 mSv/year)

Th:U weight ratio	Dose conversion factor (mSv/Bq$_\alpha$)	Annual limit of intake (Bq/year)	Derived air concentration (Bq/m^3)
All thorium	0.0047	4218	1.757
50:1	0.0046	4331	1.805
40:1	0.0046	4358	1.816
30:1	0.0045	4403	1.834
25:1	0.0045	4437	1.849
20:1	0.0045	4488	1.870
15:1	0.0044	4569	1.904
10:1	0.0042	4720	1.967
9:1	0.0042	4767	1.986
8:1	0.0041	4824	2.010
7:1	0.0041	4894	2.039
6:1	0.0040	4983	2.076
5:1	0.0039	5098	2.124
4:1	0.0038	5253	2.189
3:1	0.0037	5475	2.281
2:1	0.0034	5819	2.425
1.75:1	0.0034	5936	2.473
1.5:1	0.0033	6072	2.530
1.25:1	0.0032	6232	2.597
1:1	0.0031	6421	2.675
1:1.25	0.0030	6600	2.750
1:1.5	0.0030	6737	2.807
1:1.75	0.0029	6844	2.852
1:2	0.0029	6931	2.888
1:3	0.0028	7158	2.983
1:4	0.0027	7287	3.036
1:5	0.0027	7369	3.070
1:6	0.0027	7427	3.094
1:7	0.0027	7469	3.112
1:8	0.0027	7502	3.126
1:9	0.0027	7527	3.136
1:10	0.0026	7548	3.145
1:15	0.0026	7613	3.172
1:20	0.0026	7646	3.186
1:25	0.0026	7666	3.194
1:30	0.0026	7679	3.200
1:40	0.0026	7697	3.207
1:50	0.0026	7707	3.211
All uranium	0.0026	7749	3.229

E. Appendix listing air sampling alpha activities and their correction factors

Table E.1.: Alpha activities and correction factors for thorium ore dust residing on an air sampling filter (reproduced from IAEA RS–G–1.6)

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

	Realistic range			Hypothetical extreme case
Alpha emitting radionuclide	100%	75%	50%	0%
^{232}Th	1	1	1	1
^{228}Th	1	1	1	1
^{224}Ra	1	1	1	1
^{220}Rn^{a}	1	0.75	0.5	-
^{216}Po^{a}	1	0.75	0.5	-
^{214}Bi^{a}	0.359	0.269	0.1795	-
^{212}Po^{a}	0.641	0.481	0.3205	-
Total (gross) alpha activity on the filter	6	5.25	4.5	3
Correction factor for determining intake of alpha activity	1	1.14	1.33	2

^{a}– ^{220}Rn and short lived progeny

Table E.2.: Alpha activities and correction factors for uranium ore dust residing on an air sampling filter (reproduced from IAEA RS–G–1.6)

Alpha activity residing on the filter for various retention fractions of Rn–220 (Bq)				
	Realistic range			Hypothetical extreme case
Alpha emitting radionuclide	100%	75%	50%	0%
^{238}U	1	1	1	1
^{234}U	1	1	1	1
^{230}Th	1	1	1	1
^{226}Ra	1	1	1	-
^{222}Rn[a]	1	0.75	0.5	-
^{218}Po[a]	1	0.75	0.5	-
^{214}Po[a]	1	0.75	0.5	-
^{210}Po	1	1	1	1
^{235}U	0.046	0.046	0.046	0.046
^{231}Pa	0.046	0.046	0.046	0.046
^{227}Th	0.046	0.046	0.046	0.046
^{223}Ra	0.046	0.046	0.046	0.046
^{219}Rn[a]	0.046	0.035	0.023	-
^{215}Po[a]	0.046	0.035	0.023	-
^{211}Bi[a]	0.046	0.035	0.023	-
Total (gross) alpha activity on the filter	8.322	7.538	6.753	5.184
Correction factor for determining intake of alpha activity	1	1.10	1.23	1.61

[a] – ^{220}Rn, ^{219}Rn and short lived progeny

Alpha self-absorption effects should also be accounted for. Please refer to section 2.4.1 in guideline NORM–3.4 Airborne radioactivity sampling.

F. Appendix listing radon/thoron intakes

Table F.1.: Dose conversion factors for inhaled radon decay products for workers (reproduced from ARPANSA 'Mining Code', 2005)

Radionuclides	Factor (mSv/mJ)	Factor (mSv/[mJh/m^3])
Radon–222 decay products	1.2	1.4
Radon–220 decay products	0.39	0.48

Assuming breathing rate of 1.2 m^3/hour

Table F.2.: Annual limits of intake and derived air concentrations for radon and thoron progeny for workers

	Derived air concentration (mJh/m^3)		Annual limit of intake (mJ)	
Annual exposure (mSv)	Radon progeny	Thoron progeny	Radon progeny	Thoron progeny
1	0.7	2.2	0.8	2.6
5	3.5	10.7	4.2	12.8
20	13.9	42.8	16.7	51.3
50	34.7	106.8	41.7	128.2
	Derived air concentration (kBq/m^3)		Annual limit of intake (kBq)	
Annual exposure (mSv)	Radon progeny	Thoron progeny	Radon progeny	Thoron progeny
1	0.16	0.49	380	1180
5	0.79	2.40	1900	5760
20	3.12	9.62	7490	23090
50	7.80	24.00	18720	57600

Conversion factor: 4.45×10^{-3} mJh/m^3 per 1 Bq/m^3
Assuming breathing rate of 1.2 m^3/hour and 2000 working hours in a year
Annual limit of intake (kBq) rounded to the nearest 10 kBq

G. Appendix listing ingestion radionuclide activities and committed effective dose

Table G.1.: Radionuclide activities and committed effective dose for the ingestion of radionuclides from thorium decay chain by members of the general public

Radionuclide	Decay	$f_1$value	Dose coefficient	Quantity ingested (Bq)		Dose (Sv)
			(Sv/Bq)	Alpha	Beta	
^{232}Th	α	0.0005	1.1×10^{-7}	1		1.1×10^{-7}
^{228}Ra	β	0.2	6.7×10^{-7}		1	6.7×10^{-7}
^{228}Ac	β	0.0005	4.3×10^{-10}		1	4.3×10^{-10}
^{228}Th	α	0.0005	7.2×10^{-8}	1		7.2×10^{-8}
^{224}Ra	α	0.2	6.5×10^{-8}	1		6.5×10^{-8}
^{220}Rn[a]	α		-	1		-
^{216}Po[a]	α		-	1		-
^{212}Pb[a]	β	0.2	6.0×10^{-9}		1	6.0×10^{-9}
^{212}Bi[a]	64.1% β 35.9% α	0.05	2.6×10^{-10}	0.359	0.641	2.6×10^{-10}
^{212}Po[a]	α	-	-	0.641		-
^{208}Tl[a]	β	-	-		0.359	-
			Total	6	4	9.24×10^{-7}

[a]– ^{220}Rn and short lived progeny

Table G.2.: Radionuclide activities and committed effective dose for the ingestion of radionuclides from thorium decay chain by workers

Radionuclide	Decay	$f_1$value	Dose coefficient (Sv/Bq)	Quantity ingested (Bq) Alpha	Beta	Dose (Sv)
^{232}Th	α	0.0005 0.0002	1.1×10^{-7} 4.6×10^{-8}	1		1.1×10^{-7}
^{228}Ra	β	0.2	6.7×10^{-7}		1	6.7×10^{-7}
^{228}Ac	β	0.0005	4.3×10^{-10}		1	4.3×10^{-10}
^{228}Th	α	0.0005 0.0002	7.2×10^{-8} 3.5×10^{-8}	1		7.2×10^{-8}
^{224}Ra	α	0.2	6.5×10^{-8}	1		6.5×10^{-8}
^{220}Rn^{a}	α	-	-	1		-
^{216}Po^{a}	α	-	-	1		-
^{212}Pb^{a}	β	0.2	5.9×10^{-9}		1	5.9×10^{-9}
^{212}Bi^{a}	64.1% β 35.9% α	0.05	2.6×10^{-10}	0.359	0.641	2.6×10^{-10}
^{212}Po^{a}	α	-	-	0.641		-
^{208}Tl^{a}	β	-	-		0.359	-
			Total	6	4	9.24×10^{-7}

Note: the lowest f_1 value is used in the assessment of the dose (last column)

^{a}– ^{220}Rn and short lived progeny

Table G.3.: Radionuclide activities and committed effective dose for the ingestion of radionuclides from uranium decay chain by members of the general public

Radionuclide	Decay	$f_1$value	Dose coefficient (Sv/Bq)	Quantity ingested (Bq)		Dose (Sv)
				Alpha	Beta	
^{238}U	α	0.02	2.9×10^{-8}	1		2.9×10^{-8}
^{234}Th	β	0.0005	3.4×10^{-9}		1	3.4×10^{-9}
^{234}Pa$_m$	β	-	-		1	-
^{234}U	α	0.02	3.2×10^{-8}	1		3.2×10^{-8}
^{230}Th	α	0.0005	1.1×10^{-7}	1		1.1×10^{-7}
^{226}Ra	α	0.2	2.4×10^{-7}	1		2.4×10^{-7}
^{222}Rn^a	α	-	-	1		-
^{218}Po^a	α	-	-	1		-
^{214}Pb^a	β	0.2	1.4×10^{-10}		1	1.4×10^{-10}
^{214}Bi^a	β	0.05	1.1×10^{-10}		1	1.1×10^{-10}
^{214}Po^a	α	-	-	1		-
^{210}Pb	β	0.2	6.4×10^{-7}		1	6.4×10^{-7}
^{210}Bi	β	0.05	1.3×10^{-9}		1	1.3×10^{-9}
^{210}Po	α	0.5	1.2×10^{-6}	1		1.2×10^{-6}
^{235}U	α	0.02	3.1×10^{-8}	0.046		1.4×10^{-9}
^{231}Th	β	0.0005	3.4×10^{-10}		0.046	1.6×10^{-11}
^{231}Pa	α	0.0005	2.1×10^{-7}	0.046		9.7×10^{-9}
^{227}Ac	β	0.0005	7.3×10^{-7}		0.046	3.4×10^{-8}
^{227}Th	α	0.0005	8.8×10^{-9}	0.046		4.0×10^{-10}
^{223}Ra	α	0.2	1.0×10^{-7}	0.046		4.6×10^{-9}
^{219}Rn^a	α	-	-	0.046		-
^{215}Po^a	α	-	-	0.046		-
^{211}Pb^a	β	0.2	1.8×10^{-10}		0.046	8.3×10^{-12}
^{211}Bi^a	α	-	-	0.046		
^{207}Tl^a	β	-	-		0.046	
			Total	8.322	6.184	2.31×10^{-6}

^{a}– ^{220}Rn, ^{219}Rn and short lived progeny

Table G.4.: Radionuclide activities and committed effective dose for the ingestion of radionuclides from uranium decay chain by workers

Radionuclide	Decay	$f_1$value	Dose coefficient (Sv/Bq)	Quantity ingested (Bq)		Dose (Sv)
				Alpha	Beta	
^{238}U	α	0.02 0.002	2.9×10^{-8} 6.1×10^{-9}	1		2.9×10^{-8}
^{234}Th	β	0.0005 0.002	3.4×10^{-9} 3.4×10^{-9}		1	3.4×10^{-9}
^{234}Pa$_m$	β	-	-		1	-
^{234}U	α	0.02 0.002	3.2×10^{-8} 6.7×10^{-9}	1		3.2×10^{-8}
^{230}Th	α	0.0005 0.0002	1.1×10^{-7} 4.7×10^{-8}	1		1.1×10^{-7}
^{226}Ra	α	0.2	2.4×10^{-7}	1		2.4×10^{-7}
^{222}Rn^{a}	α	-	-	1		-
^{218}Po^{a}	α	-	-	1		-
^{214}Pb^{a}	β	0.2	1.4×10^{-10}		1	1.4×10^{-10}
^{214}Bi^{a}	β	0.05	1.1×10^{-10}		1	1.1×10^{-10}
^{214}Po^{a}	α	-	-	1		-
^{210}Pb	β	0.2	6.3×10^{-7}		1	6.3×10^{-7}
^{210}Bi	β	0.05	1.3×10^{-9}		1	1.3×10^{-9}
^{210}Po	α	0.1	2.4×10^{-7}	1		2.4×10^{-7}
^{235}U	α	0.02 0.002	3.0×10^{-8} 6.8×10^{-9}	0.046		1.4×10^{-9}
^{231}Th	β	0.0005 0.0002	3.4×10^{-10} 3.4×10^{-10}		0.046	1.6×10^{-11}
^{231}Pa	α	0.0005	2.1×10^{-7}	0.046		9.7×10^{-9}
^{227}Ac	β	0.0005	7.2×10^{-7}		0.046	3.3×10^{-8}
^{227}Th	α	0.0005 0.0002	8.8×10^{-9} 8.4×10^{-9}	0.046		4.1×10^{-10}
^{223}Ra	α	0.2	1.0×10^{-7}	0.046		4.6×10^{-9}
^{219}Rn^{a}	α	-	-	0.046		-
^{215}Po^{a}	α	-	-	0.046		-
^{211}Pb^{a}	β	0.2	1.8×10^{-10}		0.046	8.3×10^{-12}
^{211}Bi^{a}	α	-	-	0.046		
^{207}Tl^{a}	β	-	-		0.046	
			Total	8.322	6.184	1.34×10^{-6}

^{a}– ^{220}Rn, ^{219}Rn and short lived progeny

H. Appendix listing drinking water dose conversion factors

Table H.1.: Dose conversion factors (DCF – mSv/Bq), theoretical annual limits of intake (ALI – Bq/year) and derived water concentrations (DWC – Bq/m^3) for the radionuclides of radiological significance in drinking water, for members of the general public (exposure limit = 1 mSv/year)

Radionuclide	Dose conversion factor (mSv/Bq)	Annual limit of intake (Bq/year)	Derived water concentration (kBq/L)
^{232}**Th**	**0.00011**	9.09	0.013
^{228}**Ra**	**0.00067**	1.49	0.002
^{228}Th	0.00007	13.89	0.020
^{224}Ra	0.00007	15.38	0.022
^{238}U	0.00003	34.48	0.049
^{234}U	0.00003	31.25	0.045
^{230}**Th**	**0.00011**	9.09	0.013
^{226}**Ra**	**0.00024**	4.17	0.006
^{210}**Pb**	**0.00063**	1.59	0.002
^{210}**Po**	**0.00024**	4.17	0.006

Notes: Applicable only for individual radionuclides, decay should be taken into account — particularly for values of annual limits of intake and derived water concentrations, Most important radionuclides highlighted by **bold font**, Assumed water consumption per year: 700 L.

Table H.2.: Dose conversion factors (DCF – mSv/Bq), theoretical annual limits of intake (ALI – Bq/year) and derived water concentrations (DWC – Bq/m^3) for the radionuclides of radiological significance in drinking water, for workers (dose constraint = 5 mSv/year)

Radionuclide	Dose conversion factor (mSv/Bq)	Annual limit of intake (kBq/year)	Derived water concentration (kBq/L)
^{232}Th	**0.00011**	45.45	0.091
^{228}Ra	**0.00067**	7.46	0.015
^{228}Th	0.00007	69.44	0.139
^{224}Ra	0.00007	76.92	0.154
^{238}U	0.00003	172.41	0.345
^{234}U	0.00003	156.25	0.313
^{230}Th	**0.00011**	45.45	0.091
^{226}Ra	**0.00024**	20.83	0.042
^{210}Pb	**0.00063**	7.94	0.016
^{210}Po	**0.00024**	20.83	0.042

Notes: Applicable only for individual radionuclides, decay should be taken into account – particularly for values of annual limits of intake and derived water concentrations, Most important radionuclides highlighted by **bold font**, Assumed water consumption per year: 500 L.

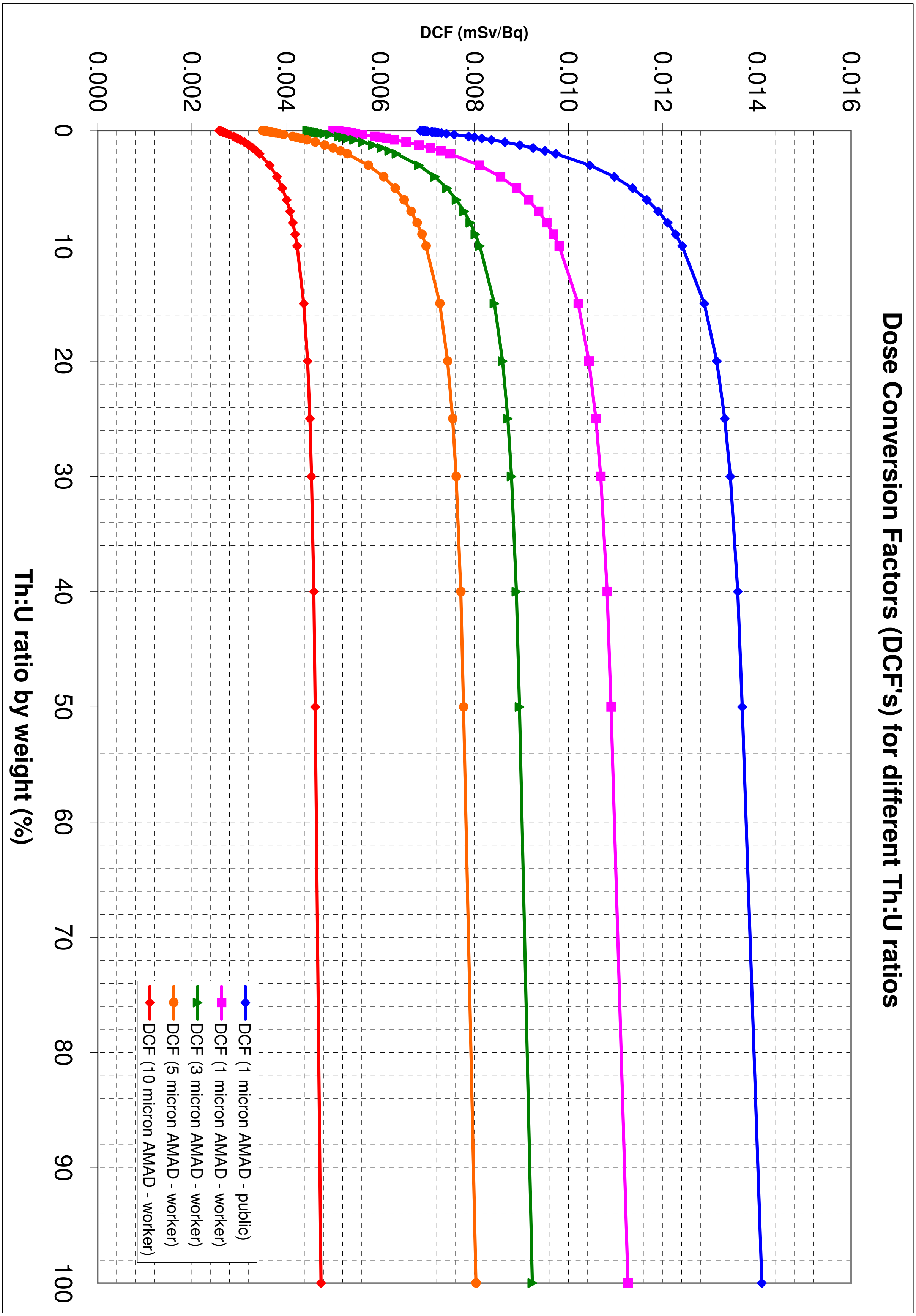
Table H.3.: Dose conversion factors (DCF – mSv/Bq), theoretical annual limits of intake (ALI – Bq/year) and derived water concentrations (DWC – Bq/m^3) for the radionuclides of radiological significance in drinking water, for workers (exposure limit = 20 mSv/year)

Radionuclide	Dose conversion factor (mSv/Bq)	Annual limit of intake (Bq/year)	Derived water concentration (kBq/L)
^{232}Th	**0.00011**	181.82	0.364
^{228}Ra	**0.00067**	29.85	0.060
^{228}Th	0.00007	277.78	0.556
^{224}Ra	0.00007	307.69	0.615
^{238}U	0.00003	689.66	1.379
^{234}U	0.00003	625.00	1.250
^{230}Th	**0.00011**	181.82	0.364
^{226}Ra	**0.00024**	83.33	0.167
^{210}Pb	**0.00063**	31.75	0.064
^{210}Po	**0.00024**	83.33	0.167

Notes: Applicable only for individual radionuclides, decay should be taken into account — particularly for values of annual limits of intake and derived water concentrations, Most important radionuclides highlighted by **bold font**, Assumed water consumption per year: 500 L.

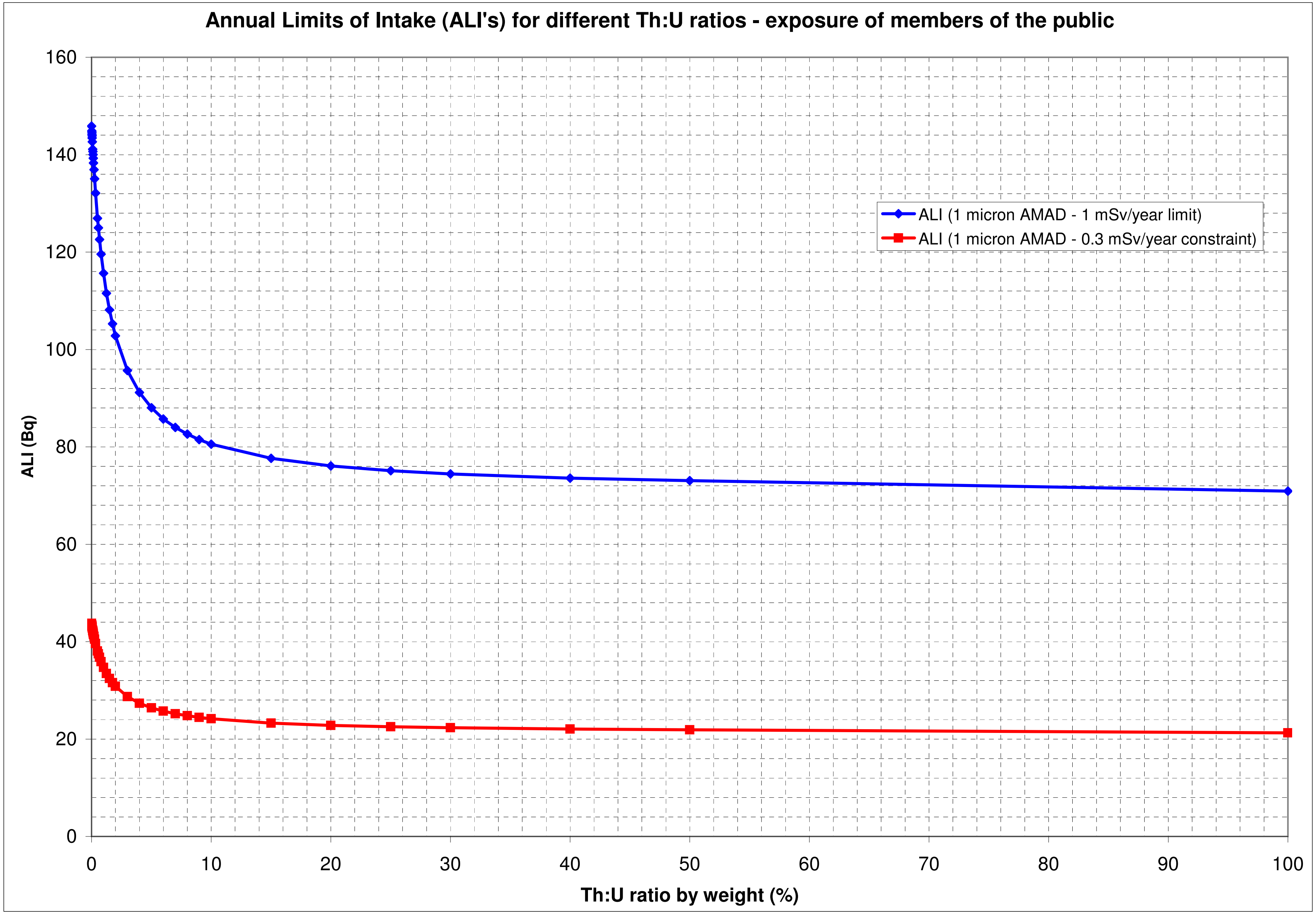
I. Appendix with dose conversion factor charts

Figure I.1.: Chart 1



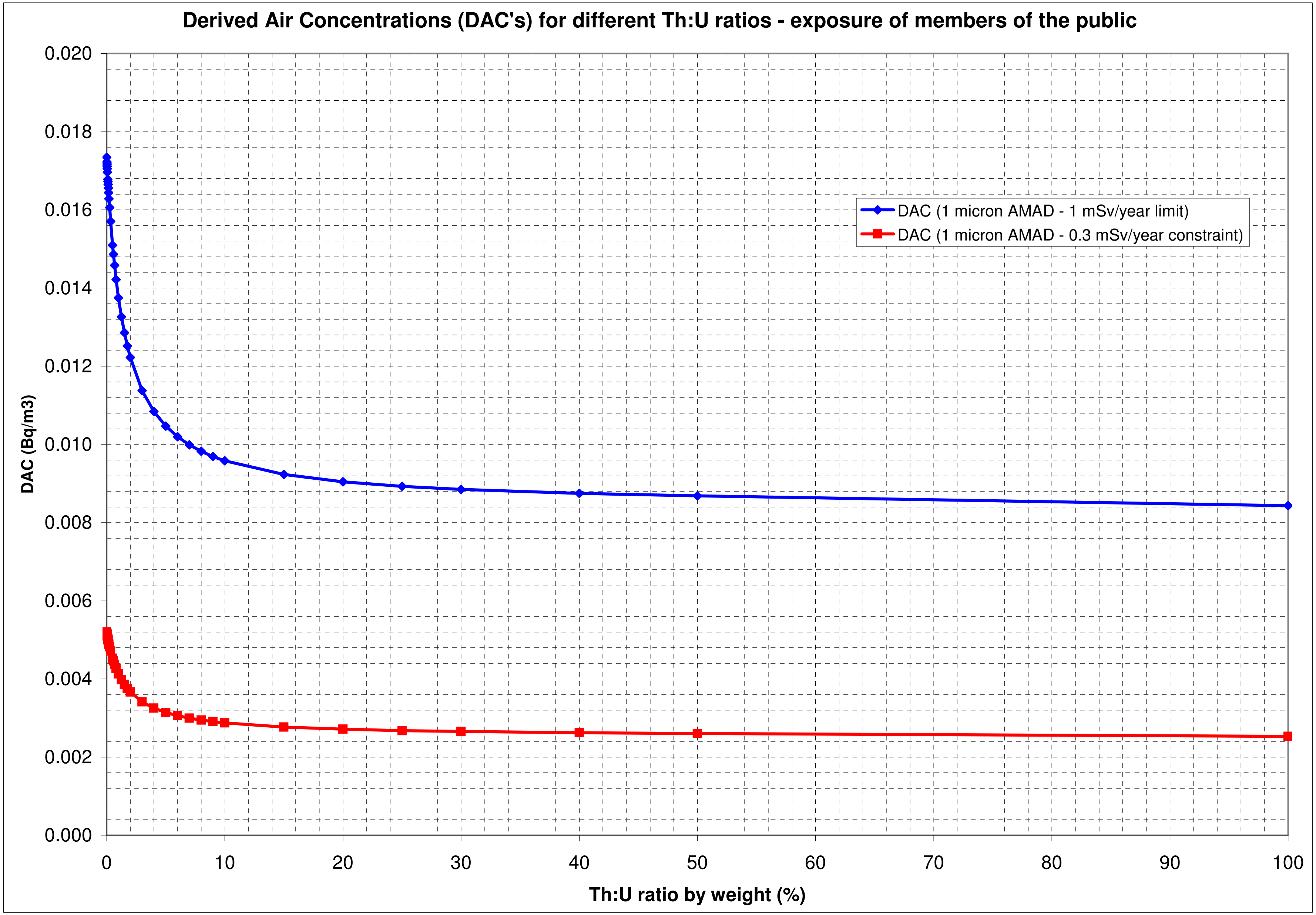
Dose conversion factors for different particle sizes and different Th:U ratios.

Figure I.2.: Chart 2



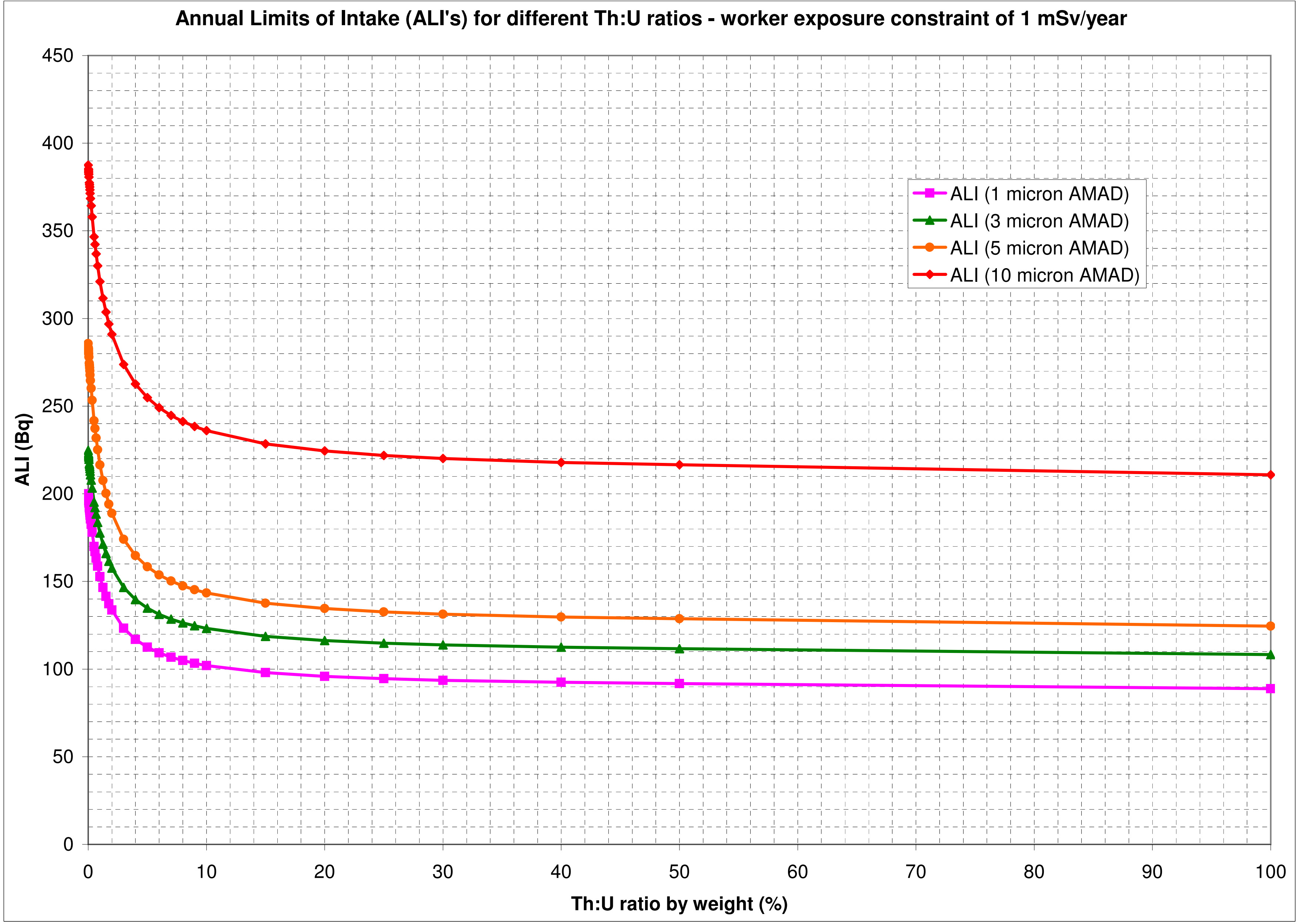
Annual limits of intake for different exposure levels and different Th:U ratios, members of the general public.

Figure I.3.: Chart 3



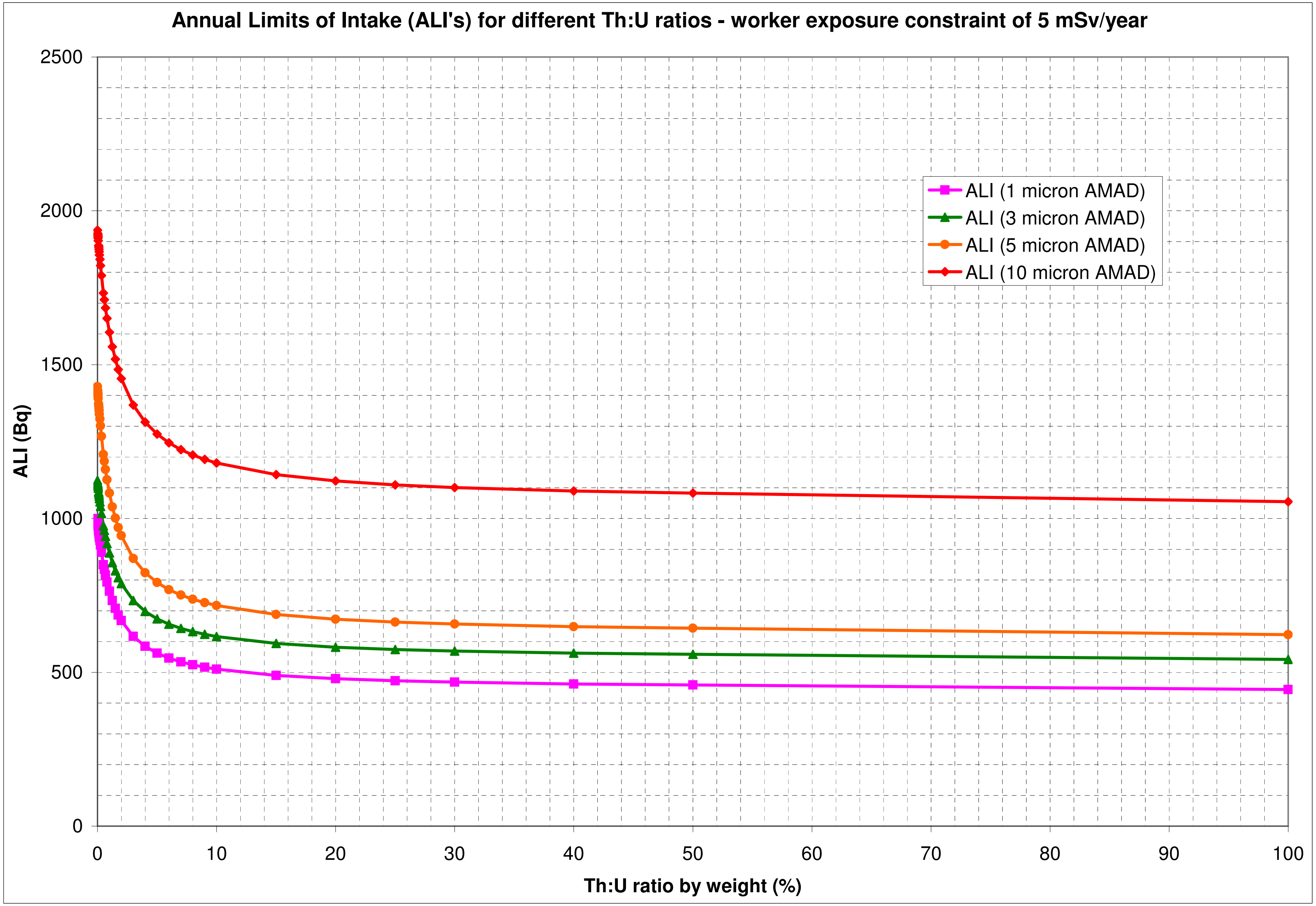
Derived air concentrations of intake for different exposure levels and different Th:U ratios, members of the general public.

Figure I.4.: Chart 4



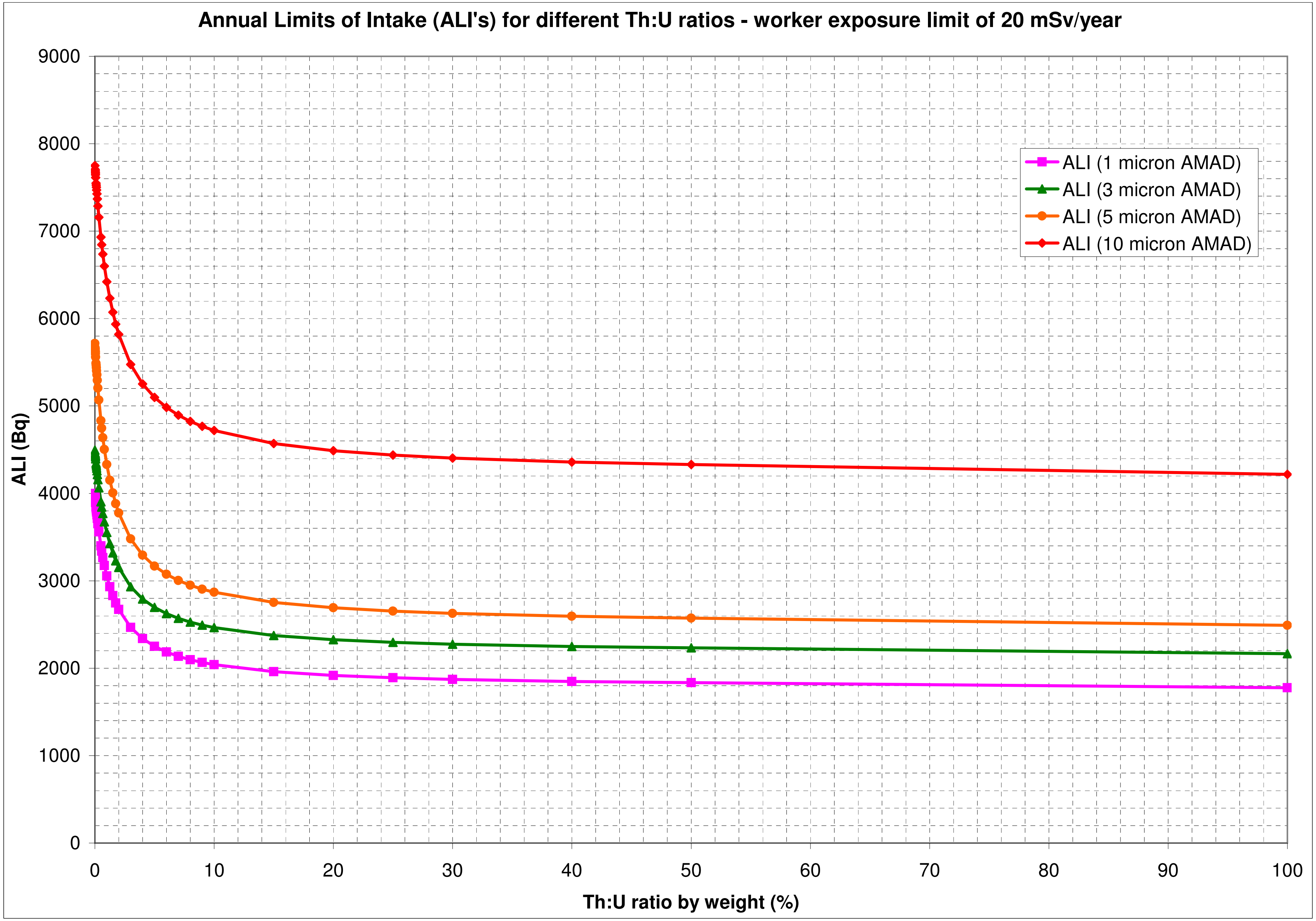
Annual limits of intake for different particle sizes levels and different Th:U ratios, members of the general public, worker – dose constraint of 1 mSv/year.

Figure I.5.: Chart 5



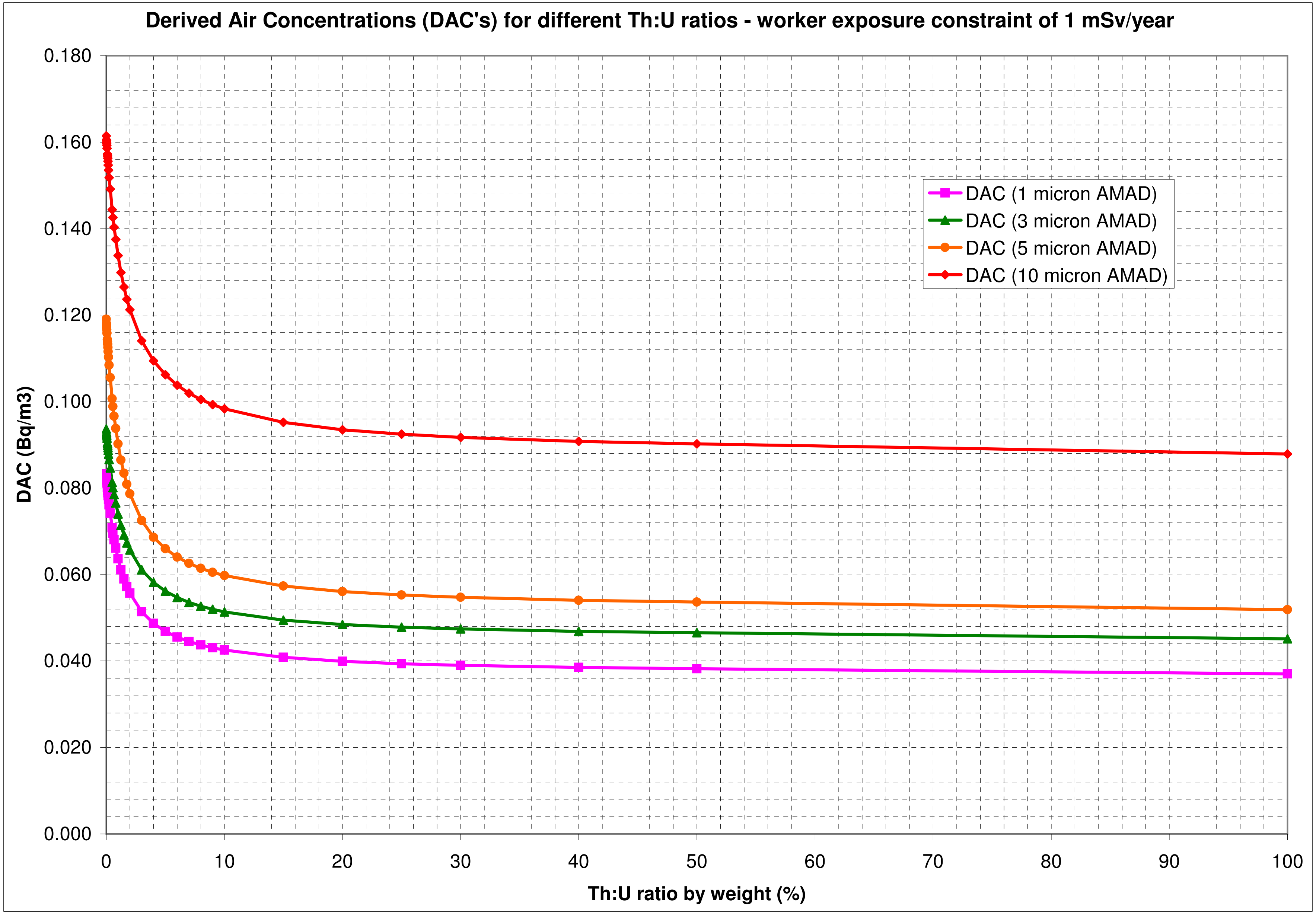
Annual limits of intake for different particle sizes levels and different Th:U ratios, members of the general public, worker – dose constraint of 5 mSv/year.

Figure I.6.: Chart 6



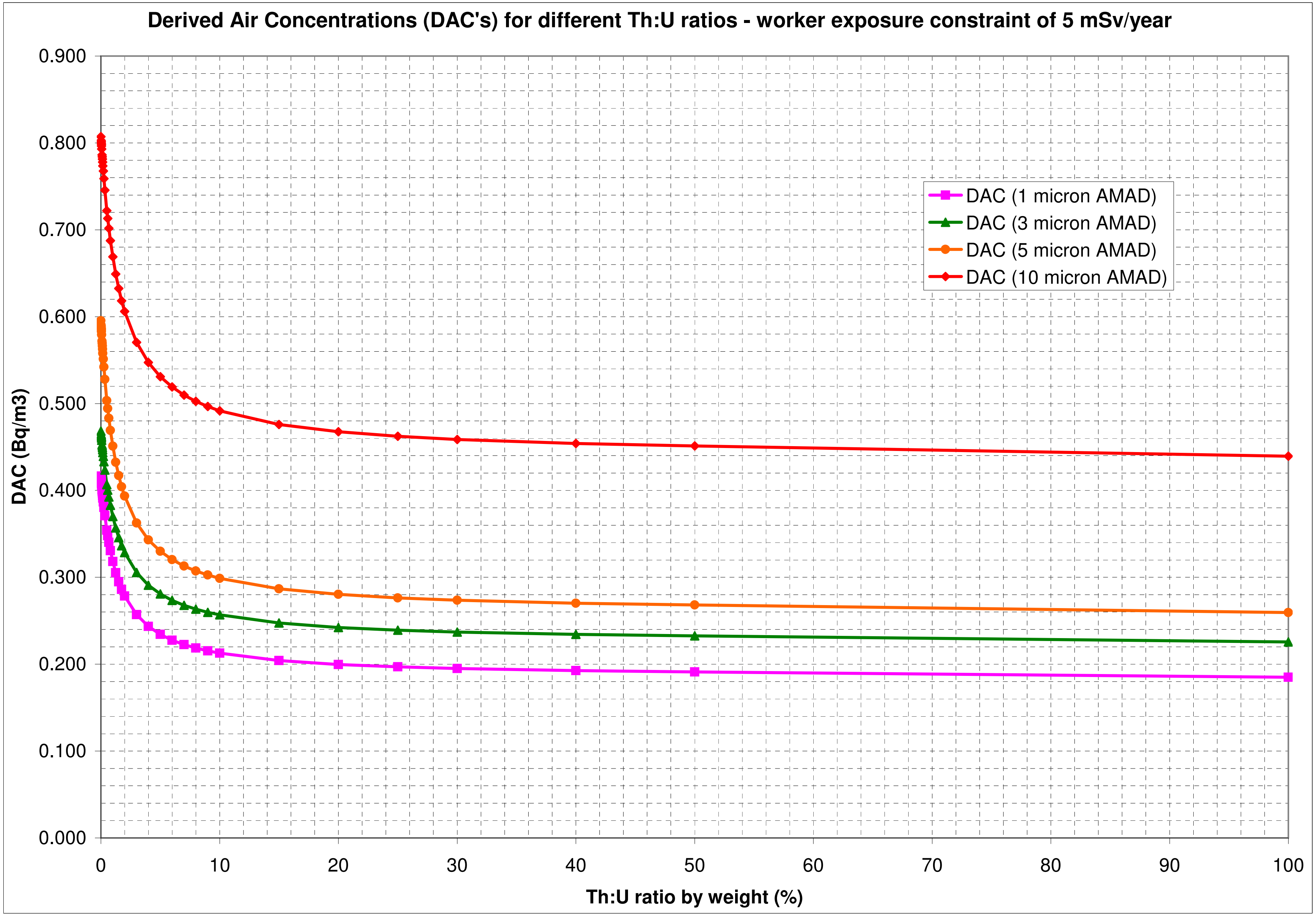
Annual limits of intake for different particle sizes levels and different Th:U ratios, members of the general public, worker – exposure limit of 20 mSv/year.

Figure I.7.: Chart 7



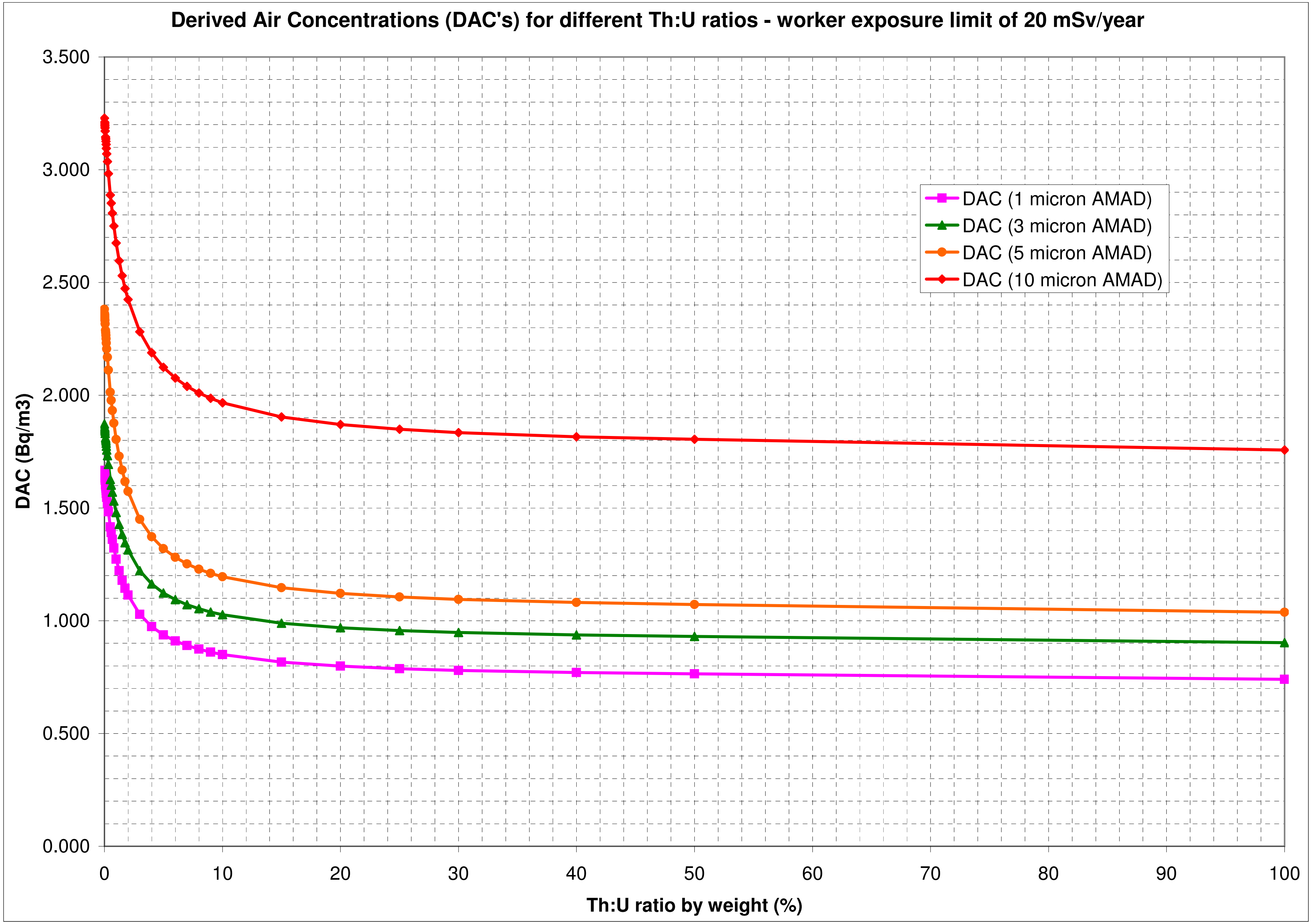
Derived air concentrations of intake for different particle sizes levels and different Th:U ratios, worker – dose constraint of 1 mSv/year.

Figure I.8.: Chart 8



Derived air concentrations of intake for different particle sizes levels and different Th:U ratios, worker – dose constraint of 5 mSv/year.

Figure I.9.: Chart 9



Derived air concentrations of intake for different particle sizes levels and different Th:U ratios, worker – exposure limit of 20 mSv/year.

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