APPROVED PROCEDURE FOR DOSE ASSESSMENT

GUIDELINE RSG05

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CONTENTS

FOREWORD

Department of Industry and Resources radiation safety guidelines are issued to describe methods for implementing specific regulations under Part 16 of the Mine Safety and Inspection Regulations 1995 which are acceptable to the State Mining Engineer. The guidelines are not a substitute for regulations and compliance with them is not mandatory. Methods and solutions different from those set out in the guidelines may also be acceptable to the State Mining Engineer. However, to the extent practicable, industry is encouraged to follow the guidelines to ensure uniformity in radiation safety management.

Comments on, and suggestions for improvements to, this guideline are encouraged. The guideline will be revised, as appropriate, to accommodate industry and inspectorate comments, and to reflect new information, regulatory amendments, improvements in technology and operational experience.

This is an UNCONTROLLED DOCUMENT. Its publication on floppy disk means the contents may be subject to amendment and therefore can not be guaranteed.

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1.0 OBJECTIVE

The purpose of this guideline is:

To explain and outline the approved methodology for radiation dose assessment.

2.0 DEFINITIONS

'**Absorbed Dose**' means the quotient dE by dm, where dE is the mean energy imparted by ionising radiation to matter of mass dm. In these guidelines the absorbed dose means the average dose over a tissue or organ.

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

'Activity median aerodynamic diameter (AMAD)' means the diameter of a unit density sphere with the same terminal velocity in air as that of an aerosol particle whose activity is the median for the entire aerosol.

'**Collective effective dose**' means the sum, over all subgroups i in a population, of the product of the average effective dose, $\overline{E_i}$, received by the members of each subgroup and the number of people in the subgroup N_i, and is given by the expression:

$$S = \sum_i \overline{E_i} N_i$$

Unit: man-sievert (symbol man-Sv)

'**Committed effective dose**' means the effective dose which an individual is committed to receive from an intake of radioactive material over the fifty years subsequent to that intake and is given by the expression:

$$E(50) = \int_{to}^{to+50} \dot{E}(t)at$$

Where E(t) is the effective dose at time t and t_0 is the time at which intake commences.
Unit: sievert (symbol Sv)

Effective dose' means the sum of weighted equivalent doses in all organs or tissues of the body. It is given by the expression:

$$E = \sum_{T} w_T H_T$$

Where H_T is the equivalent dose in an organ or tissue T and w_T is the weighting factor for the organ or tissue.

Unit: sievert (Sv)

'**Equivalent dose**' means the radiation weighted dose in an organ or tissue, with the radiation weighting factor(s) determined by the type and energy of the radiation to which the organ or tissue is exposed. The equivalent dose is given by the expression:

$$H_T = \sum_{R} W_R D_{T,R}$$

Where $D_{T,R}$ is the absorbed dose averaged over the organ or tissue T due to radiation R and w_R is the radiation weighting factor for that radiation. Radiation Weighting Factors are listed in Table 1.

Unit: sievert (symbol Sv)

'**Radiation weighting factor**' means 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 1.

'**Tissue weighting factors**' means a factor which modifies equivalent dose in an organ or tissue to yield tissue effective dose. Tissue weighting factors are listed in Table 2.

3.0 INTRODUCTION

REGULATORY REFERENCE

Assessment of Doses

16.23 (1) The following doses of radiation are not to be included in assessing the doses referred to in regulation 16.18 or 16.19 -

(a) doses due to natural background radiation; and

(b) doses received as a patient undergoing radiological examinations, radiotherapy or nuclear medicine investigations.

(2) The manager of a mine must ensure that any assessment of doses of radiation -

(a) takes into account the results obtained from the monitoring program contained in the radiation management plan for the mine;

(b) does not, without the approval of the State mining engineer, take into account any protection factor for the use of protective clothing or respiratory protective equipment; and

(c) is done in accordance with a procedure approved by the State mining engineer.

Penalty: see Regulation 17.1.

(3) If the assessed annual effective dose to a person exceeds 10 millisieverts, the manager of the mine must, so far as is practicable, re-assess the effective dose using more appropriate data as approved by the State mining engineer.

The objectives of radiation protection have remained essentially unchanged since standards were first promulgated. Namely:

(i) to prevent acute radiation effects; and

(ii) to limit the risk of chronic effects to an acceptable level.

To obtain the objectives listed above it is incumbent on operators/managers to observe accepted radiation protection standards and practices.

The International Commission on Radiological Protection (ICRP) have 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 Publication 60 in 1990. In this publication the effects of ionising radiation on tissue have been divided into stochastic and deterministic effects.

Stochastic effects are those effects which occur with a probability associated with dose. i.e. cancer. The severity of the cancer is related to the type and location of the cancer.

Deterministic effects vary with the dose and a threshold may occur ie. erythema.

The relationship between the probability of stochastic effects and absorbed dose is found to depend on:

(a) the type of radiation, and
(b) 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 (Table 1) and the tissue weighting factor W_T (Table 2) respectively.

Other ICRP publications which have an affect on dose assessment procedures have been published since ICRP 60. Of greatest interest are publications dealing with radon, new biokinetic models for uranium and thorium and a new respiratory tract model.

The following dose assessment procedures are based on the above mentioned documents.

4.0 INTERNAL DOSE ASSESSMENT

4.1 Inhalation

When radioactive aerosols are inhaled, parts of the respiratory system are irradiated both by radiations originating from the lungs and as a result of translocation 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 describes a revision of the respiratory tract model used in ICRP publication 30. The revision was necessary as increased knowledge had become available of the anatomy and physiology of the respiratory tracts as well as 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 Publication 30 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 1.

The ICRP 30 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 model is more complex and hence a computer program (LUDEP) is required to generate dose conversion factors for AMAD's which have not been listed. Dose conversion factors for radionuclides in the thorium and uranium decay chains as well as for the thorium and uranium series are given in Table 4.

4.1.1 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 wing. Different areas of the wing have different clearance mechanisms which will therefore impact on dose assessment.

ICRP 66 recommend 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 AMAD's in dose assessment. Approval may be given by the State Mining Engineer after review and assessment of a companies particle size measuring program.

4.2 Ingestion

The model used to describe the behaviour of radionuclides in the gastrointestinal (GI) tract is the model described in ICRP publication 30. However, where more recent information has been published these values have been incorporated in the formulation of dose conversion factors for ingestion. The dose conversion factors for the ingestion of radionuclides in the thorium and uranium decay chains as well as for the thorium and uranium series are listed in Table 5.

4.3 Radon

The existence of a high mortality rate among miners in central Europe was recognised before 1600, and the main cause of death was identified as lung cancer in the late nineteenth century. In 1925 is was suggested that the cancers could be attributed to radon exposure.

The two significant isotopes of radon are radon 222, 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. 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 condensation nuclei and dust particles present in air. The problems posed by radon-220 (thoron) are much less widespread than those posed by radon -222.

Units

The potential alpha energy of an atom of radon 222 is the total alpha energy emitted during the decay of the atom to stable Pb-210. 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}

1 mJh m^{-3} = 0.282 WLM

The factors used in assessing internal dose from inhalation of radon 222 are given in Table 6.

5.0 DETERMINATION OF INTAKE

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 programme is necessary which should conform with the Guideline: Air Monitoring Strategies, which has been approved by the Appropriate Authority.

For both inhalation and ingestion the annual intake (in Bq) is multiplied by the appropriate dose conversion factor to yield annual dose (mSv).

6.0 EXTERNAL DOSE ASSESSMENT

The external dose component is obtained directly from the results of the TLD monitoring program. The dose for an employee for each monitoring period is added together to give a yearly dose for the employee. No further calculations on this component are required.

7.0 DOSE CALCULATIONS

The dose to a worker over a year is the dose from inhaled or ingested radionuclides added to the dose from external radiation.

The internal component is not absolute but estimated with a considerable degree of uncertainty. Important assumptions used in the assessment of internal dose are listed in Table 3. Consistent with contemporary health physics practice the estimates are made using conservative assumptions, to limit the likelihood of understating dose.

8.0 APPROVED METHOD FOR THE ASSESSMENT OF DOSES

1. The assessments of effective dose received by employees shall take into account the results obtained from the monitoring program, as approved by the appropriate authority and shall use the data given in Table 4 and 5.

2. Components of the effective dose equivalent shall be assessed quarterly.

3. The effective dose for each specified period of time shall be taken as the sum of the external and internal dose for that period and the annual effective dose equivalent shall be the sum of the values determined for each specified period over twelve months.

4. In the event that the assessed effective dose equivalent in any one quarter exceeds values in the Guideline: Treatment of Special Exposures, Dose Constraints and Reporting Levels, the appropriate authority shall be notified.

5. The components of effective dose for an employee shall be assessed as follows:

   (a) The effective dose from external exposure for a monitoring period shall be taken to be numerically equal to the dose reported after assessment of personal monitors worn throughout that period.

   (b) The committed effective dose for a monitoring period from the inhaled intake of radioactive materials other than radon daughters, shall be taken to be equal to the mean contamination levels in the air inhaled multiplied by the factors given in Table 4 and by the quantity of air inhaled in each period. A breathing rate of 1.2 $m^3 h^{-1}$ shall be assumed for normal working conditions.

Hence for inhalation:

Committed Effective Dose = E.R.F..(8.1)

Where E = individual's exposure (i.e. mean airborne radioactivity concentration x hours worked) in $Bq.h.m^{-3}$.

R = breathing rate in $m^3 h^{-1}$.

F = dose conversion factor given in Table 4, in $mSv\ Bq^{-1}$ or $mSv/\ \alpha\ dps^{-1}$.

Note: E.R = Annual intake in Bq.

The committed effective dose from the inhalation of radon 222 and radon 220 daughters may not normally need to be assessed for employee dose unless it is requested by the appropriate authority, or company monitoring shows that this pathway may give rise to a non negligible dose.

(c) The committed effective dose from the intake of radioactive materials from ingestion, will only need to be assessed if required by the regulatory authority.

The dose can be assessed by measuring the concentration of radionuclides in food or water, multiplying by the amount of material ingested in the monitoring period and finally multiplying by the ingestion factors listed in Table 5.

Hence for ingestion:

Committed Effective Dose = I.R.F..(8.2)

Where I = individuals exposure (i.e. mean concentration in food and/or water (Bq gm^{-1} or Bq l^{-1}))

R = quantity of material ingested (gms or l)

F = dose conversion factor given in Table 5, in mSv Bq^{-1}.

Note: I.R = Annual Intake in Bq.

9.0 EXAMPLE DOSE CALCULATIONS

EXAMPLE 1

A mineral sands employee has worked in the following categories in the preceding 12 months. The mean airborne activity in each of the areas is stated. The dust consists of thorium 232 in equilibrium with its daughters with a 5 μm AMAD.

CATEGORY	HOURS	MEAN AIRBORNE ACTIVITY
A	1685	4×10^{-3} Bq m^{-3}
B	11	23×10^{-3} Bq m^{-3}
C	308	74×10^{-3} Bq m^{-3}

INTERNAL DOSE

Using the formula 8.1 where Committed Effective Dose = E.R.F. the internal dose component is (using Table 4):

$$(1685h)(1.2\ m^{3}\ h^{-1})(4 \times 10^{-3}\ Bq\ m^{-3})(9.7 \times 10^{-3}\ mSv\ \ \alpha dps^{-1}) = 0.08\ mSv$$

(11h)(1.2 m^3 hr^{-1})(23 x 10^{-3} Bq m^{-3})(9.7 x 10^{-3} mSv αdps^{-1}) = 0.003 mSv

(308h)(1.2 m^3 hr^{-1})(74 x 10^{-3} Bq m^{-3})(9.7 x 10^{-3} mSv αdps^{-1}) = 0.26 mSv

Therefore, the total internal dose component is 0.08 + 0.003 + 0.26 = 0.34 mSv

EXTERNAL DOSE

The employees quarterly TLD badge results were 200, 50, 180 and 220 μSv resulting in annual effective dose from gamma radiation of 650 μSv (rounded to 0.7 mSv).

EFFECTIVE DOSE

The Total Effective Dose for the preceding 12 months is 0.34 + 0.7 = 1.0 mSv.

EXAMPLE 2

A mineral sands employee has worked in the following categories in the preceding 12 months. The mean airborne activity concentration for each of the areas is also stated. The dust consists of the thorium 232 series in equilibrium with a 5 μm AMAD. The employee has also ingested during 10 days, water contaminated with 0.6 Bq l^{-1} of Ra-226.

INTERNAL DOSE

Inhalation

CATEGORY	HOURS	MEAN AIRBORNE ACTIVITY
A	1080	54 x 10^{-3} Bq m^{-3}
B	350	120 x 10^{-3} Bq m^{-3}
C	225	229 x 10^{-3} Bq m^{-3}

The internal inhaled dose component is (using Table 4) and formula 8.1:

$(1080h)(1.2\ m^{3}\ hr^{-1})(54 \times 10^{-3}\ Bq\ m^{-3})(9.7 \times 10^{-3}\ mSv\ \alpha dps^{-1}) = 0.68\ mSv$

$(350h)(1.2\ m^{3}\ hr^{-1})(120 \times 10^{-3}\ Bq\ m^{-3})(9.7 \times 10^{-3}\ mSv\ \alpha dps^{-1}) = 0.49\ mSv$

$(225h)(1.2\ m^{3}\ hr^{-1})(229 \times 10^{-3}\ Bq\ m^{-3})(9.7 \times 10^{-3}\ mSv\ \alpha dps^{-1}) = 0.6\ mSv$

Total inhaled internal dose component is 0.68 + 0.49 + 0.6 = 1.8 mSv

INGESTION

Assume a fluid intake of 2 litres per day (Table 3) and a factor of $2.8 \times 10m^{-4}$ Sv Bq^{-1} (Table 5).

Therefore: $10\ days \times 2\ litres\ day^{-1} \times 0.6\ Bq\ l^{-1} \times 2.8 \times 10^{-4}\ Sv\ Bq^{-1}$

= 0.003 mSv.

TOTAL INTERNAL DOSE

Therefore total internal component is 1.8 mSv + 0.003 mSv = 1.8 mSv.

EXTERNAL DOSE

The workers external dose was 0.8 mSv for the preceding year. The TLD quarterly results were 390, 60, 150, 200 μSv.

EFFECTIVE DOSE

The Total Effective Dose for the preceding 12 months is 1.8 mSv + 0.8 mSv = 2.6 mSv.

EXAMPLE 3

An employee has worked on a mine site as an operator for some time during the preceding 12 months. Exposure has been to a mixture of thorium and uranium bearing ore dust of an AMAD of 5 μm. An analysis of the feedstock to the tin shed indicated thorium and uranium concentrations of 500 ppm and 1000 ppm respectively.

CATEGORY	HOURS	MEAN AIRBORNE ACTIVITY
Tin shed operator	1920	780 mBq m^{-3}

INTERNAL DOSE

As the activity is expressed in terms of gross alpha activity, the dose conversion factor for this mixture needs to be derived accounting for the relative alpha activity contributed by each series. The specific alpha activity contributed by the thorium series is 12.6 Bq g^{-1} (2.1 Bq g^{-1} x 6 α) and by the uranium series is 98.4 Bq/g (12.3 Bq g^{-1} x 8 α). The specific activity for Th-232 is taken to be 3100 Bq g^{-1} and the specific activity of U-238 is taken to be 12300 Bq g^{-1}. Hence, the fraction contributed by the thorium series is 11% ([12.6 x 100]/[98.4 + 12.6]).

Therefore, the dose conversion factor for this particular mixture is $[0.11 \times 9.7 \times 10^{-3}] + [0.89 \times 4.4 \times 10^{-3}] = 5.1 \times 10^{-3}$ mSv αdps^{-1}.

Therefore total inhaled component is

$(1920h)(1.2m^3h^{-1})(780 \times 10^{-3}\ Bq\ m^{-3})(5.1 \times 10^{-3}\ mSv\ \alpha dps^{-1}) = 9.2\ mSv$.

EXTERNAL DOSE

The employees quarterly TLD badge results were 200, 90, 130 and 290 resulting in annual effective dose from gamma radiation of 710 μSv.

EFFECTIVE DOSE

The Total Effective Dose for the preceding 12 months is 9.2 + 0.7 = 9.9 mSv.

EXAMPLE 4

An employee works in an area of a plant where thorium concentrate is being processed for 2000 hrs per year. Measurements taken in the area revealed the following:

Parameter	Concentrations		
	Units	Range	Mean
^{232}Th	mBq m^{-3}	3.5 - 160	34.5
^{220}Rn gas conc.	Bq m^{-3}	10 - 700	50

INTERNAL DOSE

1. Dose due to ^{232}Th

The thorium concentration will contain ^{228}Th and ^{232}Th in equilibrium and the dose contribution from ^{228}Th should therefore also be taken into account. From Table 4, the intake to dose conversion factor for Type S 1μm Th concentrate is 0.031 mSv Bq^{-1}, the committed effective dose is:

$$(2000h)(1.2\ m^3\ h^{-1})(34.6 \times 10^{-3}\ Bq\ m^{-3})(0.031\ mSv\ Bq^{-1}) = 2.6\ mSv$$

2. Dose Due to ^{220}Rn progeny

From Table 6 the exposure to dose conversion factor is 32 nSv per Bq h m^{-3} for indoors. Exposure to a concentration of ^{220}Rn gas of 50 Bq m^{-3} for a normal working year results in an exposure of 1 x 10^5 Bq h m^{-3}. Therefore, the effective dose from ^{220}Rn progeny is:

$(1 \times 10^5$ Bq h $m^{-3})(32$ nSv/Bq h $m^{-3}) = 3.2$ mSv

Therefore total internal component is:

(2.6 mSv)+(3.2 mSv) = 5.8 mSv

EXTERNAL DOSE

The employees quarterly TLD badge results were 150, 70, 210 and 260 microsieverts resulting in an annual effective dose from gamma radiation of 690 μSv.

EFFECTIVE DOSE

The Total Effective Dose for the preceding 12 months is 5.8 + 0.7 = 6.5 mSv.

EXAMPLE 5

An employee works on a mine site where radon (^{222}Rn) measurements have been taken on a quarterly basis using radon cups. The measurements obtained are listed below.

Measurement period	Result	Mean
1 Jan - 31 Mar	580 Bq m^{-3}	
1 Apr - 30 Jun	750 Bq m^{-3}	
1 Jul - 30 Sep	690 Bq m^{-3}	
1 Oct - 31 Dec	520 Bq m^{-3}	
		635 ± 104 Bq m^{-3}

From Table 6 the conversion from Bq m^{-3} to mJh m^{-3} is given as 4.45 x 10^{-3} mJh m^{-3} per Bqm^{-3}. This conversion assumes 2000 hours per year at work and an equilibrium factor of 0.4. Therefore 635 Bqm^{-3} is equivalent to 2.8 $mJhm^{-3}$.

The dose conversion factor from Table 6 is 1.4 mSv per $mJhm^{-3}$ therefore 635 Bq m^{-3} gives rise to 4 mSv.

Therefore, a mine employee may receive up to 4 mSv per year from exposure to these radon concentrations.

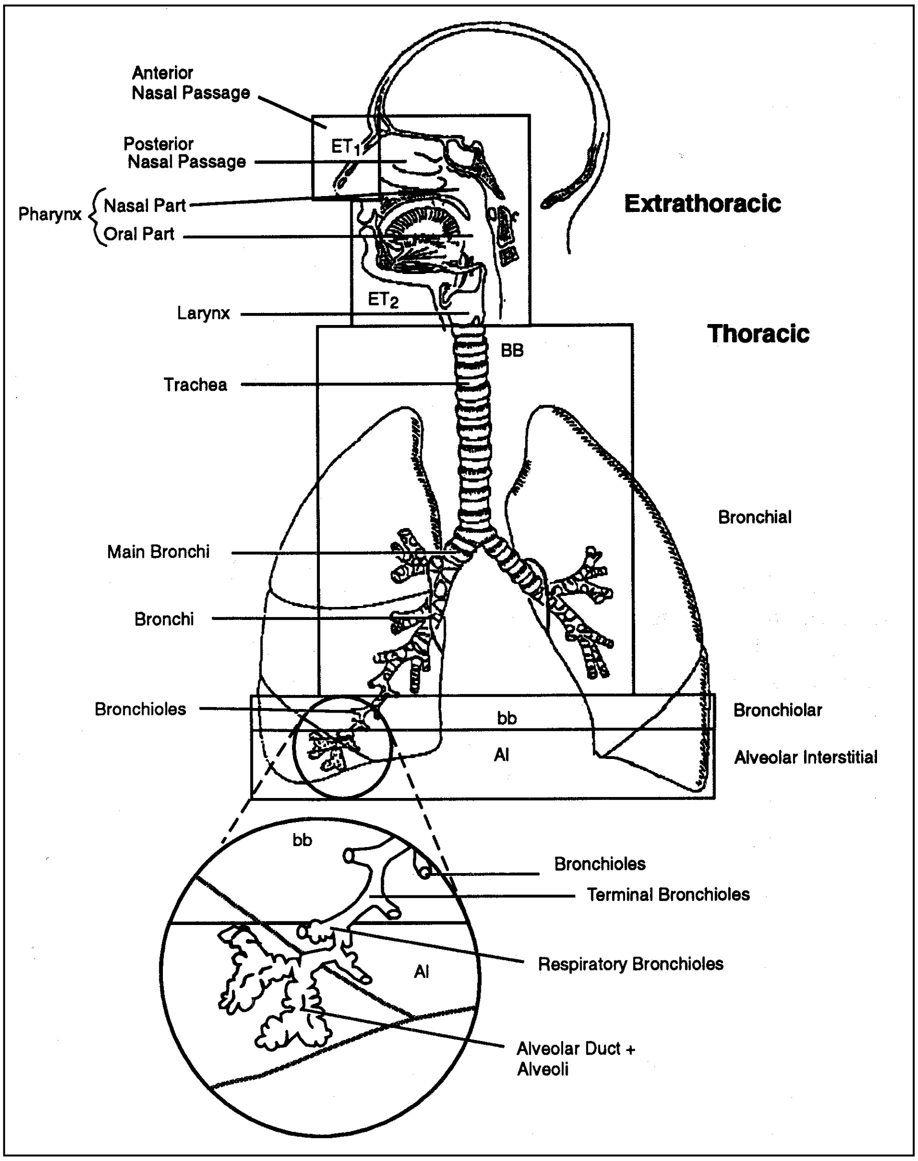

Figure 1: The Human Respiratory Tract Model

TABLE 1. Radiation Weighting Factors

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 2. Weighting Factors for Individual Organs and Tissues(1)

Tissue or organ	Weighting Factor w_T
Gonads	0.20
Bone Marrow (red)	0.12
Colon	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	0.05(2)(3)

1 The values have been developed from a reference population of equal numbers of both sexes and a wide range of ages.

2 The "remainder" is comprised of the following organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus.

3 In the cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the twelve organs for which a weighting factor is specified, a weighting factor of 0.025 should 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 above.

TABLE 3. Assumptions used in the calculation of committed effective dose following inhalation/ingestion of thorium ore (monazite) dust

Parameter	Assumed Value
Radionuclide content	All thorium series present in secular equilibrium, no uranium series present.
Particle size (AMAD) (a)	5 μm
Lung clearance	Slow
Gut transfer factor	0.0002
Rn 220 emanation (b)	< 1%
Breathing rate	1.2 cubic metres per hour
Respiratory protection data (c)	1
Fluid Intake	2 litres per day

(a) In the absence of measurements a default of 5 μm is assumed for mining and mineral processing operations and 1 μm is assumed when calculating doses to the public.

(b) Negligible Rn 220 emission means that the Th 232 decay chain is in secular equilibrium (i.e., six alpha emissions accompany decay of Th-232).

(c) Specific authorisations would be required for a protection factor other than 1. An authorised protection factor may vary from > 2 for half-mask respirator used intermittently in the workplace to 50 or more for filtered, air supplied helmets used continuously.

TABLE 4. Inhalation Conversion Factors for Individual Radionuclides Plus Uranium and Thorium Series for Different AMADs[(1)] (Taken from IAEA Guide-Document Nens-78)

Radionuclides	Type(2)	AMAD		
		1 μm	**5 μm**	**10 μm**
Thorium series				
Th-232	S	2.3×10^{-2}	1.2×10^{-2}	8.1×10^{-3}
Ra-228	M	2.6×10^{-3}	1.7×10^{-3}	9.7×10^{-4}
Th-228	S	3.9×10^{-2}	3.2×10^{-2}	1.8×10^{-2}
Ra-224	M	2.9×10^{-3}	2.4×10^{-3}	1.2×10^{-3}
Uranium series				
U-238	S	7.3×10^{-3}	5.7×10^{-3}	3.5×10^{-3}
U-234	S	8.5×10^{-3}	6.8×10^{-3}	4.2×10^{-3}
Th-230	S	1.3×10^{-2}	7.2×10^{-3}	5.2×10^{-3}
Ra-226	M	3.2×10^{-3}	2.2×10^{-3}	1.5×10^{-3}
Pb-210	F	8.9×10^{-4}	1.1×10^{-3}	9.4×10^{-4}
Po-210	M	3.0×10^{-3}	2.2×10^{-3}	1.1×10^{-3}
Th concentrate(3)	M	3.6×10^{-2}	2.6×10^{-2}	1.5×10^{-2}
Th concentrate(3)	S	3.1×10^{-2}	2.2×10^{-2}	1.3×10^{-2}
Th Dust				
Th-232 series		1.3×10^{-2}	9.7×10^{-3}	5.7×10^{-3}
Uranium Dust				
U-238 series		6.2×10^{-3}	4.5×10^{-3}	2.9×10^{-3}

(1) The committed effective dose is given in mSv Bq^{-1} for each individual radionuclide, but for both the thorium and uranium series the committed effective dose is given in millisieverts per alpha disintegration per second (αdps).

(2) Where F is fast rate of absorption into blood from the respiratory tract,

M is moderate rate of absorption into blood from the respiratory tract, and

S is materials that are relatively insoluble in the respiratory tract (slow rate of absorption).

(3) Assuming freshly separated thorium (^{232}Th + ^{228}Th).

TABLE 5. Ingestion Conversion Factors for Individual Radionuclides Plus Uranium and Thorium Series(1)(2)

Radionuclides	Ingestion Dose Conversion Factor
Thorium series	
Th-232	2.3×10^{-4}
Ra-228	6.6×10^{-4}
Th-228	7.2×10^{-5}
Ra-224	6.3×10^{-5}
Uranium series	
U-238	4.5×10^{-5}
U-234	5.0×10^{-5}
Th-230	2.1×10^{-4}
Ra-226	2.8×10^{-4}
Pb-210	7.0×10^{-4}
Po-210	1.2×10^{-3}
Th-232 series	1.0×10^{-3}
U-238 series	2.5×10^{-3}

(1) The committed effective dose is given in mSv Bq^{-1} for each individual radionuclide plus for each series.

(2) The most restrictive value for the ingestion dose conversion factor was chosen for each individual radionuclide.

TABLE 6. Conversion Factors for Radon and Thoron Progeny(1)(2)

Quantity	Conversion Factor
Radon (^{222}Rn)	
Effective dose per unit exposure at work to radon progeny	1.4 mSv per 1 mJh m^{-3} or 5 mSv per WLM
Annual exposure to radon progeny per unit radon concentration (parent only) at work	4.45 x 10^{-3} mJhm^{-3} per 1 Bq m^{-3}
Thoron (^{220}Rn) Progeny	
Effective dose per unit exposure at work	32 nSv per Bq h m^{-3}

(1) Assuming 2000 hours per year for work.

(2) Assuming an equilibrium factor of 0.4.

REFERENCES:

1. International Commission on Radiological Protection (ICRP). Recommendations of the Commission 1991. ICRP Publication 60, Pergamon Press, Oxford, 1991.

2. International Commission on Radiological Protection (ICRP). Protection Against Radon-222 at Home and at Work. ICRP Publication 65, Pergamon Press, Oxford, 1993.

3. International Commission on Radiological Protection (ICRP). Human Respiratory Tract Model for Radiological Protection. ICRP Publication 66, Pergamon Press, Oxford. 1994.

4. International Commission on Radiological Protection (ICRP). Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 2 Ingestion Dose Co-efficients. ICRP Publication 67, Pergamon Press, Oxford 1993.

5. International Commission of Radiological Protection (ICRP). Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 3 Ingestion Dose Coefficients. ICRP Publication 69, Pergamon Press, Oxford. 1995.

6. International Atomic Energy Agency (IAEA). Radiation Protection from Occupational Sources of Thoron and Thorium. IAEA Safety Practice/Guide Document NENS-78. (DRAFT). February 1996.

7. International Atomic Energy Agency (IAEA). International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources. Interim Edition. Safety Series No. 115 - I. International Atomic Energy Agency. Vienna 1994.

8. United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR 1993 Report to the General Assembly, with Scientific Annexes. Sources and Effects of Ionizing Radiation. United Nations New York, 1993.