RSP-0290

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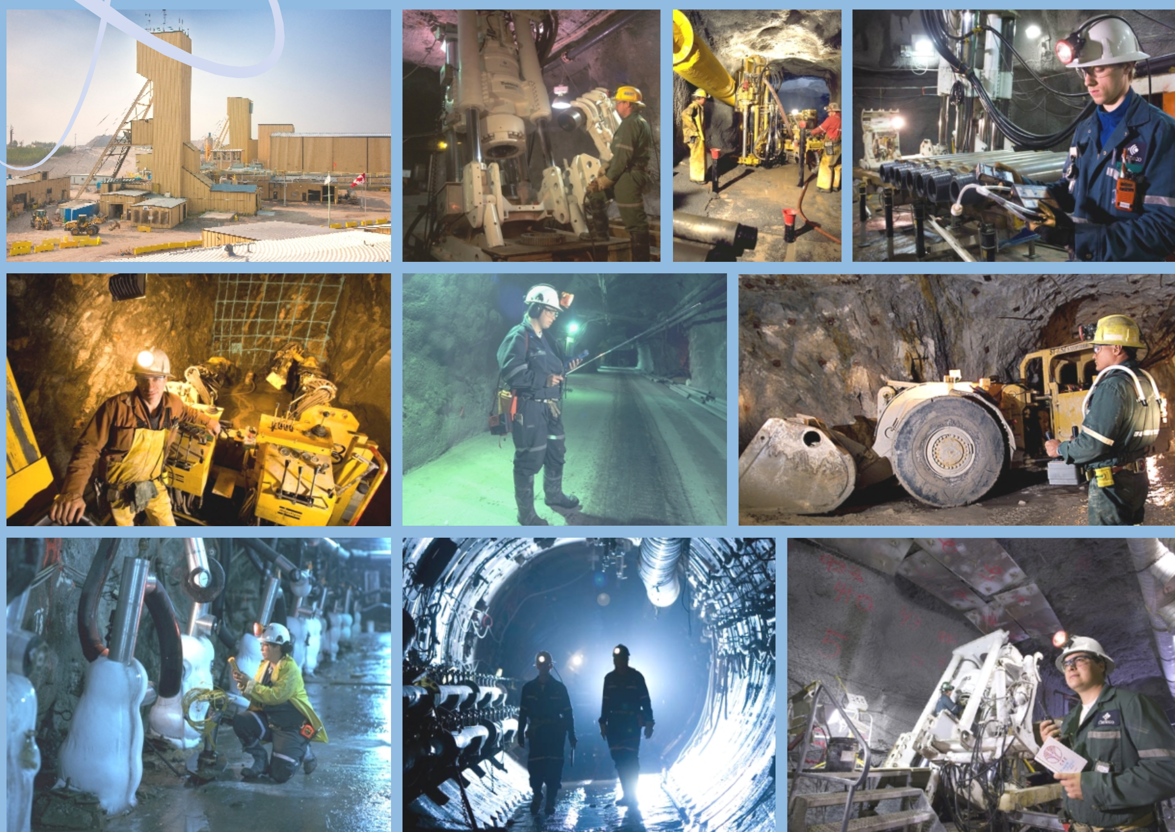

Prepared For:

Canadian Nuclear Safety Commission

Prepared By:

SENES Consultants Limited

March 2013

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SUMMARY

The traditional metric for exposure to uranium miners has been the working level month (WLM), a measure of exposure to radon progeny. This has been the approach used internationally to manage and regulate exposures of miners to radon and its short-lived decay products.

For the purpose of developing a system of radiological protection, it has been necessary to compare doses from radon and its short-lived decay product to doses from other sources of radiation exposure; hence, a dose conversion convention (DCC) is required. The International Commission on Radiological Protection (ICRP) developed guidance in this regard and in ICRP 65 (1993) proposed a convention to convert radon exposure (in WLM) to effective dose by dividing the risk of lung cancer derived from epidemiological studies of miners by the detriment from external radiation based primarily on data from follow-up of Japanese atomic bomb survivors.

In addition to the epidemiological approach, a dosimetric approach (i.e., one relying on biokinetic and dosimetric modelling) can also be used to estimate dose to the lungs (or regions of the lungs) and with the help of subjective weighting factors, the corresponding effective dose can be estimated and used for radiation protection purposes. In its 2009 statement on radon, the ICRP proposed to move from its current epidemiologically based approach (i.e., DCCs) to treat radon and progeny in the same way as other radionuclides and to publish dose coefficients calculated using dosimetric models for use within the ICRP's system of protection.

The primary objective of the study is to understand how and to what degree environmental factors within a mine affect the conversion of airborne concentrations in radon decay products (RDP) in working levels to dose estimation.

The dosimetry-based dose from radon decay products depends on the characteristics of the mine environment including, combinations of several aerosol inputs including alpha energy (typically measured via WL), the particle size distribution of the mine workplace aerosols, including the unattached fraction, and if radon gas is measured instead of radon progeny, the equilibrium factor (F) between radon and its progeny is important. Thus, this study

- looked for dosimetrically relevant information on mine environments and concluded that relevant data is very limited;
- looked at currently available methods and equipment for measuring dosimetrically relevant parameters and concluded that at this time, off-the-shelf equipment is not available;

- estimated the range of dosimetrically relevant parameters for conditions in modern underground uranium mines; radon progeny doses per WLM (provided by the Health Protection Agency (HPA) using the HPA's implementation of the ICRP's HRTM model); and
- simulations were performed to provide an estimation of the variation in absorbed dose conversion factor for hypothetical mine environments and exposure scenarios.

In mines, all the parameters mentioned above vary widely within just a single mine. Parameters vary from place to place with mining activity and ventilation and over time. Due to the changing characteristics of a mine atmosphere, the parameters can not only vary between mines, but also between different work stations, and as operations and conditions change within a single mine site. Coming up with standard values of atmospheric parameters that can be applied across all jobs in uranium mines is therefore extremely difficult.

The simulations described in this report consider picking an average WL and associated particle size distribution for each of three hypothetical work places. The particle size determines the workplace-specific dose conversion factors. The dosimetric factors used in the current simulations are presented in units of mGy/WLM and the effect of radiation and tissue weighting factors used to convert from absorbed dose to lung to effective dose are considered separately.

The DCFs (as a function of particle size) were combined with workplace WL and the time a miner spends in each workplace to predict the dose received (WLM) in each work place. The WL and WLM are summed across the workplaces and a weighted DCF is determined. For the hypothetical mine environments and worker exposure scenarios considered in this report, the DCFs for annual doses were estimated to range from about 6 to 10 mGy/WLM for both of the two different worker types considered.

Our overall conclusions are that:

- dosimetrically relevant data for modern uranium mines is very limited;
- suitable commercial (off-the shelf) equipment for measuring dosimetrically relevant parameters required for modelling is not currently available; and,
- there are considerable uncertainties associated with the implementation of a fully dosimetric approach.

In broad terms, further research, advancements in current measuring practices and relevant data on modern mine environments is needed and thus, until such time as such data is available, we recommend continuing with current practice for monitoring, reporting and regulating miner's exposure to radon progeny.

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ACKNOWLEDGEMENTS

SENES would like to thank the staff of the Canadian Nuclear Safety Commission for the opportunity to work on this challenging project. The lead investigators for SENES were Dr. Douglas Chambers and Mr. Ronald Stager, supported by Mr. Ryan Das.

Dr. James Marsh of the UK Health Protection Agency provided the basic dose conversion factors and through telephonic and electronic interchanges much useful input to the study. The advice provided by Dr. Naomi Harley is gratefully acknowledged and very much appreciated.

Notwithstanding the contributions from Drs. Marsh and Harley, the views expressed in this report and responsibility for any inadvertent errors or omissions lie with the lead author Dr. Chambers.

1.0 INTRODUCTION

Our understanding of the health risks from exposure to ionizing radiation are strongly based on epidemiological studies, in particular, until recently, epidemiological studies of miners provided the main basis for estimating the risks from exposure to radon. Today, case-control studies of residential exposure to radon also show a risk of lung cancer increasing with increasing exposure to radon[1]. The traditional metric for exposure to uranium miners has been the working level month (WLM), a measure of exposure to radon progeny. This has been the approach used internationally to manage and regulate exposures of miners to radon and its short-lived decay products.

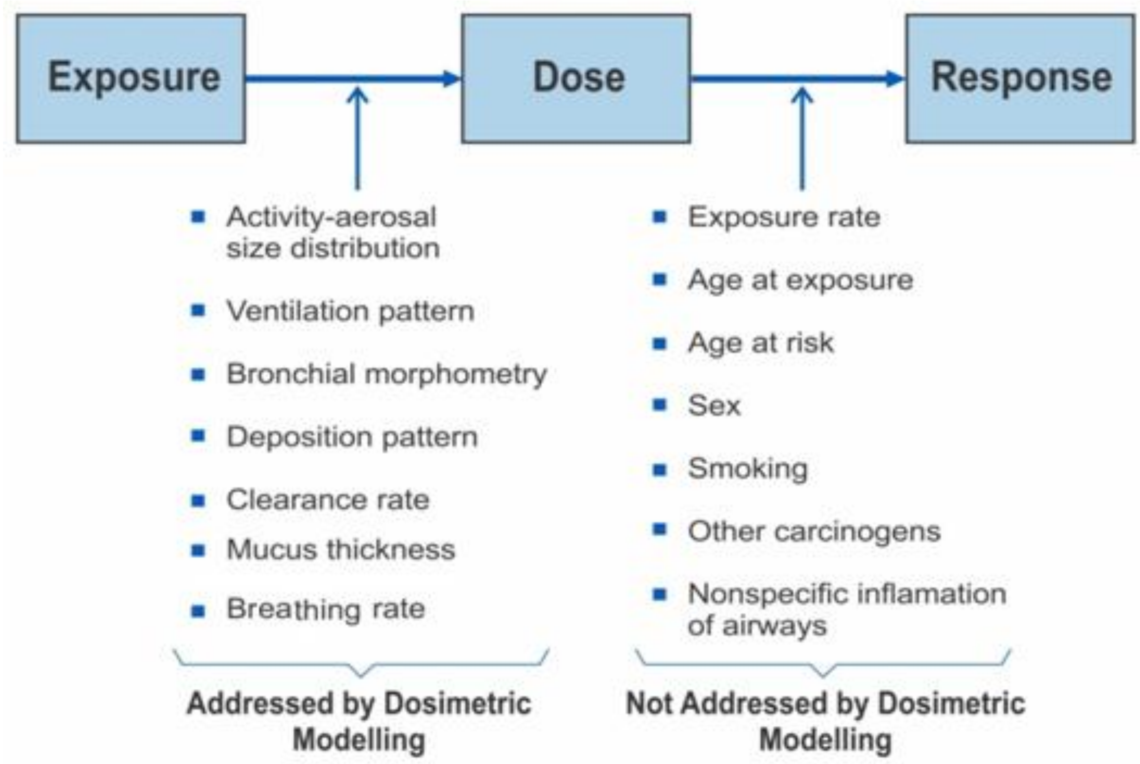
For the purpose of developing a system of radiological protection, it has been necessary to compare doses from radon and its short-lived decay product to doses from other sources of radiation exposure; hence, a dose conversion convention (DCC) is required. The International Commission on Radiological Protection (ICRP) developed guidance in this regard and in ICRP 65 (1993) proposed a convention to convert radon exposure (in WLM) to effective dose by dividing the risk of lung cancer derived from epidemiological studies of miners by the detriment from external radiation based on data from follow-up of Japanese atomic bomb survivors.

In addition to the epidemiological approach, a dosimetric approach (i.e., one relying on biokinetic and dosimetric modelling) can also be used to estimate dose to the lungs (or regions of the lungs) and with the help of subjective weighting factors, the corresponding effective dose can be estimated and used for radiation protection purposes. In its 2009 statement on radon, the ICRP proposed to move from its current epidemiologically based approach (i.e., DCCs) to treat radon and progeny in the same way as other radionuclides and to publish dose coefficients calculated using dosimetric models for use within the ICRP's system of protection and is developing dosimetric conversion factors (DCFs).

In broad terms, as illustrated in Figure 1.1, several factors affect the dosimetric based dose conversion factor (DCF) including total alpha activity, particle size distribution, the unattached fraction of radon decay products, the breathing rate, relative nasal-oral filtration airway characteristics, and the target cell depth (i.e., distance from alpha decay). However, not all of factors can be addressed by current dosimetric models, in particular, smoking which is of special importance as it is the primary cause of lung cancer.

[1] See, for example, the discussions of epidemiology in Annex E, UNSCEAR 2006.

Figure 1.1 Represents the Various Factors Involved in Radon Exposure and Lung Dosimetry



Dosimetric models[2], as for example described in **Chapter 2**, consider that the dose per unit intake of radon decay products depends on the site of deposition in the respiratory tract. In turn, the site of deposition depends strongly on the particle size distribution of the radon decay products, especially small sized (ultra-fine) particles in the range of 2-5 nanometer (nm) or commonly referred to as the "unattached fraction". Key environmental factors for radon dosimetry that are important to future measurement programs include:

[2] It should be understood that current epidemiological models of radon risk are relative risk models and hence depend directly on the baseline risk. In turn, smoking is by far the dominant cause of lung cancer and thus smoking prevalence is an important consideration in discussions of risk from exposure to radon and its progeny. Current dosimetric models do not adequately address smoking and hence there is there is uncertainty in how the risk of lung cancer derived through dosimetric models compares to those derived from epidemiology and further work is need to benchmark the results of dosimetric models to those from epidemiology.

- ✓ Total alpha activity;
- ✓ Fraction of unattached radon decay products (i.e., ^{218}Po, ^{214}Pb; and
- ✓ Particle activity size distribution in the mine atmosphere[3].

The combination of these environmental parameters affects the calculation of dose. These parameters can vary widely from place to place within a single mine, over time and between mines, because of the changing characteristics of the mine atmosphere. The current practice in Canadian mines is to measure WL in all these areas, estimate exposure (WLM) and convert to "dose" using a dose conversion convention of 5 mSv/WLM. In view of the ICRP's recommendation for an approximate doubling[4] of the Dose Conversion Coefficient (DCC) for radon and to move to a dosimetric approach for radon exposure, it is important for the CNSC to fully understand the dosimetric approach and the requirements for measuring mine environment characteristics that are needed to support dose calculation.

The primary objective of the study is to investigate how and to what degree environmental factors within a mine affect the dosimetric model based dose assessment. Thus, this study:

- looked for dosimetrically relevant information on mine environments;
- looked at currently available methods and equipment for measuring dosimetrically relevant parameters;
- estimated the range of dosimetrically relevant parameters for conditions in modern underground uranium mines;
- reports radon progeny doses per WLM [provided by the Health Protection Agency (HPA) using the HPA's implementation of the ICRP's HRTM model]; and
- Performed simulations to estimate the variation in absorbed dose conversion factor for hypothetical mine environments and exposure scenarios.

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[3] In reality, the unattached fraction is the fraction of the potential alpha energy concentration (PAEC) of the short-lived progeny that is not attached to the ambient aerosol and depends primarily on the concentration of particles in the air. The unattached fraction is the smallest portion of the particle size distribution. Potential alpha energy concentration (PAEC) of the short-lived progeny that is not attached to the ambient aerosol is dependent upon the number concentration of aerosol (Z) as illustrated by Porstendörfer, (2001)for radon decay products (a similar formula applies for thoron decay products):

Porstendörfer used a single screen diffusion battery to measure the unattached fraction of radon progeny. Z can also be defined as the concentration of particles of ambient aerosol.

$$f_p = \frac{414}{Z\ (cm^{-3})}$$

[4] ICRPs Statement of November 2009, ICRP Ref 00/92/09.

Chapter 3 and Annex A provide a summary of relevant mine aerosol data for modern uranium mines, which turns out to be very limited. Moreover, also as described in Chapter 3, suitable operationally viable equipment for making such measurements suitable for use in mines is not available at this time. The lack of relevant measurements and measurement devices is further compounded by the variability in mine aerosols which are known to vary widely within just a single mine. The characteristics of mine environments depend on local sources of radon, local work activities and local ventilation, all of which change over time. As discussed in Chapter 3, coming up with standard values of mine aerosol characteristics that atmospheric parameters that can be applied across all uranium mines is extremely difficult.

The simulations described in **Chapter 4** of this report present a preliminary approach to estimating the range of DCFs based on a range of hypothetical mine environments and worker exposure scenarios. In general terms, the approach is to pick an average WL and associated particle size distribution for each of three hypothetical work places. The particle size determines the workplace-specific dose conversion factors. As discussed in Chapter 4, the dosimetric factors used in the current simulations are presented in units of mGy/WLM and the effect of radiation and tissue weighting factors used to convert from absorbed dose to lung to effective dose are considered separately.

Chapter 5 provides an overall discussion along with conclusions and recommendations.

Chapter 6 identifies the references cited in the main text and a fuller **bibliography** is provided as **Annex B**.

2.0 DOSIMETRIC MODELLING

2.1 INTRODUCTION

Various radon dosimetry models are available. UNSCEAR (2006, Annex E) provides a tabulation of dose factors for the 13 published models. ICRP Report 115 (2010, Table B.1) provides a similar table. To convert from absorbed dose (mGy) to effective dose (mSv) two weighting factors[5] are used. The first is a radiation weighting factor (w_R) and the second is a tissue weighting factor (w_T). For lung cancers of interest here, the bronchial dose is of prime interest and is related to the deposition of the short-lived decay products with little contribution to dose from radon gas.

The nominal radiation weighting factor of 20 used by the ICRP and for this evaluation is an important factor for the dosimetric approach. Brenner *et al.* (1995) suggest that a radiation-weighting factor of 20 may be too large for radon and recommended a value of 10 for residential exposure. According to ICRP (11/07/2011), *"it is possible that the dosimetric estimates are generally higher because they include a radiation weighting factor of 20 for alpha particles, chosen for use in the calculation of the ICRP quantities, equivalent and effective dose. It may be that the relative biological effectiveness (RBE) of alpha particles compared to gamma rays for lung cancer induction, included implicitly in the dose conversion convention is closer to 10 than 20."*

Values of tissue weighting factors used to calculate effective dose are chosen by ICRP to represent the contributions of individual organs to the overall radiation detriment from stochastic effects. They are rounded values averaged over both sexes and all ages across Asian and Euro-American populations; only four different w_T values are assigned to the various organs and tissues to represent the range of relative detriment (ICRP, 2007). The w_T value for lung is 0.12, compared with values of relative detriment for lung of 0.16 for the whole population and 0.22 for adults (ICRP, 2007).

Dosimetric calculations in this assessment have been performed with the ICRP Publication 66, Human Respiratory tract model (HRTM). Revisions made to the model (see Section 2.2.2) include changes to the particle transport model of the extra thoracic (ET) region, the bronchial (BB) and (bb) regions (Section 2.5). However, these changes have little effect on the dosimetry of the inhaled radon progeny because of their short radioactive half-lives.

[5] In the ICRP's system of radiological protection, the effective dose (E) is used as a "*protection quantity*". The effective dose[5] depends on the absorbed dose (a physical quantity) adjusted by a radiation-weighting factor (w_R) to account for relative biological effectiveness of different radiations and a tissue-weighting factor (w_T) to account for the different radiosensitivities of various organs and tissues. These factors were most recently reviewed by the ICRP in Publication 103.

2.2 DOSIMETRIC MODEL

The International Commission on Radiological Protection's Human Respiratory Tract Model (HRTM) is described in detail in ICRP Publication 66 (ICRP, 1994). The HRTM considers both the extrathoracic airways and the thoracic airways (lung). The extrathoracic region (ET) comprises of the anterior nose (ET_1) and the posterior nasal passages, larynx, and mouth (ET_2). The lung is divided into three regions; the bronchial region (BB), the bronchiolar region (bb) and the alveolar-interstitial (AI) region.

The HRTM treats clearance as a competitive process between absorption into blood and particle transport to the alimentary tract and lymph nodes. It is assumed that particle transport rates are the same for all materials, whereas absorption into blood is material specific. The model assumes that the rate of absorption is the same in all respiratory tract regions except in the anterior nose where none occurs. Absorption is regarded as a two stage process: dissociation of the particles into a material that can be absorbed into blood (dissolution); and absorption into blood of soluble material or material dissociated from particles (uptake).

Dissolution can be considered as the process in which the inhaled material dissolves in the lung fluid. To represent time dependent dissolution, a fraction (f_r) dissolves rapidly at a rate s_r while the remaining fraction (1-f_r) dissolves more slowly at a rate s_s (Figure 2.1). Dissolution depends upon the chemical form of the inhaled material. Uptake can be usually treated as instantaneous, however, for some elements a significant fraction of the dissolved material is absorbed more slowly as a result of binding to the respiratory tract components. To represent time dependent uptake a fraction, f_b of the dissolved material is assumed to be retained in a bound state, from which it is transferred into blood at a rate s_b, while the remaining fraction (1-f_b) transfers to blood instantaneously (Figure 2.1).

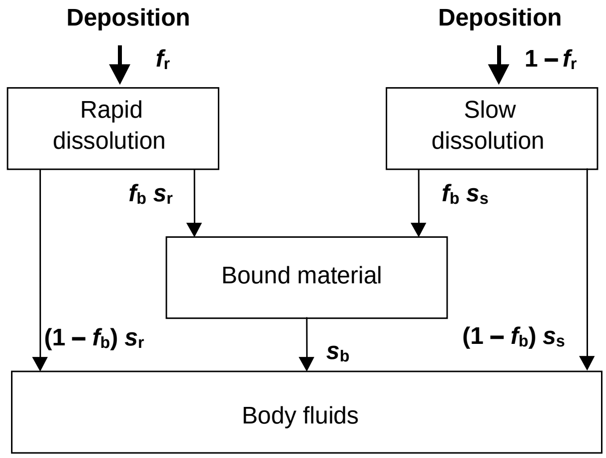
For radon progeny dosimetry, the absorption parameters given in Table 2.1 have been assumed.

Table 2.1 Absorption Parameter Values for Inhaled Radon Progeny

Inhaled Radon Progeny	Dissolution Parameter Values			Uptake Parameter Values		Absorption from the Alimentary Tract, f_A*
	f_r	s_r (d^{-1})	s_s (d^{-1})	f_b	S_b (d^{-1})	
Polonium	1	3	–	–	–	0.1
Lead	0.1	100	1.7	0.5	1.7	0.02*
Bismuth	1	1	–	–	–	0.05

* f_A is the value for absorption from the alimentary tract for lead arising as a decay product of radon.

Figure 2.1 Compartment Model Representing Time-Dependent Absorption to Body Fluids (dissolution and uptake), from ICRP Publication 66 (ICRP, 1994)



For the purposes of dosimetry, radiosensitive cells in each of the three regions of the lung have been identified. These are basal (BB_{bas}) and secretory (BB_{sec}) cells in the bronchial epithelium; clara cells (a type of secretory cell) in the bronchiolar epithelium; and endothelial cells such as those of capillary walls and type II epithelial cells in the AI region. The radiosensitive targets of the BB and bb regions are assumed to be restricted to tissue layers of given depths and thicknesses whereas in the AI region it is assumed the sensitive cells are distributed homogenously throughout its mass. The absorbed dose to each target region is calculated. For example, the absorbed dose to the BB region is taken as the average dose to the two target cell layers in that region: $D_{BB} = 0.5D_{bas} + 0.5D_{sec}$.

To calculate the equivalent dose to the lung, it is assumed that each of the three regions (BB, bb, AI) is equally sensitive to radiation-induced cancer and is therefore assigned 1/3 of the total radiation detriment in the lung. The equivalent dose to lung has been revised and is defined as follows:

$$H_{lung} = (A_{BB} \times H_{BB}) + (A_{BB} \times H_{bb}) + (A_{BB} \times H_{AI}) = ⅓ \times (H_{BB} + H_{bb} + H_{AI}) \qquad (2\text{-}1)$$

Where, H_X is the equivalent dose to each region and A_X is the apportionment factor representing the partition of the total radiation detriment in the lung for region X. (A_X is also referred to as assigned fractions of w_T).

For radon dosimetry, where the doses are dominated by the alpha particles, the equivalent dose to lung is given by:

$$H_{lung} = w_R \times ⅓ \times ([0.5 \times (D_{bas} + D_{sec})] + D_{bb} + D_{AI}) \qquad (2\text{-}2)$$

Where, D_X is the absorbed dose to each target region, and w_R is the radiation weighting factor for alpha particles (w_R=20).

It is noted that the equally partitioning of the total lung detriment to each of the three regions of the lung was assumed by ICRP in the absence of adequate quantitative information about the relative sensitivities of different respiratory tract tissues in the thorax. However, a higher weighting factor to the BB and bb regions compared with the AI region maybe more appropriate for smokers. For example, based on the estimated regional distribution of spontaneous lung cancers in the general population (consisting of smokers and non-smokers), the factors for apportionment of radiation detriment would be A_{BB} = 0.6, A_{bb} = 0.3 and A_{AI} = 0.1 (ICRP, 1994). Using these values instead of the ICRP default values (A_{BB} = ⅓, A_{bb} = ⅓ and A_{AI} = ⅓) would give higher equivalent doses to the lung by about a factor of 1.3 (Marsh and Birchall, 2000).

The effective dose arising from the inhalation of radon progeny is dominated by the dose to the lung. However, the equivalent dose to the extrathoracic region (H_{ET}) is not small but its contribution to the effective dose is quite small as it is one of the remainder organs (ICRP, 2007).

In comparison, the doses to systemic organs and the gastrointestinal tract regions are low, in part since the short half-life of the progeny (~30 min) eliminates much of the removal to blood, and can be ignored in the calculation of effective doses. The effective dose (E) arising from the inhalation of radon progeny can be approximated by:

$$E = 0.12 \times H_{lung} + (0.12 \times H_{ET}/13) \qquad (2\text{-}3)$$

In this document the 'absorbed dose to lung' is given as $H_{lung}/w_R = H_{lung}/20$ and the tissue weighted lung dose ($w_T H_{lung}$) = $0.12 \times H_{lung}$.

The dose calculations were performed for an adult male; no sex-averaging was carried in the calculation of effective dose.

For the average breathing rate, the ICRP default value for a reference worker of 1.2 m^3 h^{-1} (ICRP, 1994) was assumed in the current calculations. This value is similar to the average breathing rate of 1.3 m^{-3} h^{-1} estimated from a study of 620 underground miners carrying out heavy work in a gold mine in South Africa (ICRP Publication 66, para. B76, ICRP, 1994). It is also consistent with the breathing rates derived by Ruzer *et al*. (1995) for personnel (0.9 ± 0.4 m^{-3} h^{-1}), assistant drillers (1.1 ± 0.5 m^{-3} h^{-1}) and drillers (1.4 ± 0.5 m^{-3} h^{-1}) working underground in a metal mine in Tajikistan.

2.2.1 Dose Calculations

The tissue weighted lung dose (w_T H_{lung}) and effective dose per WLM as a function of particle size has been calculated for purposes of this study. In some exposure situations, the attached size distribution can have a multi-modal size distribution. For example, a trimodal activity size distribution can be described by a sum of three lognormal distributions (Porstendörfer, 2001). These size distributions considered by Porstendörfer (2001) comprise the nucleation mode with an activity median thermodynamic diameter (AMTD) between 10 nm and 100 nm, the accumulation mode with AMTD values of 100 – 450 nm and a coarse mode with activity median aerodynamic diameter, AMAD > 1 μm. As discussed in Chapter 3, generally, the greatest activity fraction is in the accumulation mode.

The dose calculations for the current assessment were developed as a function of particle size. Three sets of calculations were analysed with the following assumptions:

A. Monodisperse aerosol (i.e. GSD = 1.0) with unit density (ρ) and shape factor (χ);
B. Poly-disperse aerosol (with GSD = 1.3 for unattached mode, GSD=2.0 for nucleation and accumulation modes and GSD=2.5 for coarse mode);
C. Same as B but with:
    - unit density (ρ) and shape factor (χ) for unattached mode, effective density, ρ/χ = 0.7 g cm^{-3} for nucleation and accumulation modes assuming the aerosol mainly consists of diesel exhaust particles;
    - density, ρ = 3.0 g cm^{-3} and shape factor, χ=1.5 for coarse mode (ICRP defaults);
    - The activity median diameters (AMD) are expressed in terms of thermodynamic diameters for the unattached, nucleation and accumulation modes but for the coarse mode expressed in terms of aerodynamic diameter.

Several authors have calculated the effective density of diesel exhaust particles from measurements of the thermodynamic diameter (d_{th}) and aerodynamic diameter (d_{ae}) of the exhaust particles (Park *et al*. 2003; Olfert *et al*. 2007). The effective density is the ratio of the particle density (ρ) and shape factor (χ). Results indicate that the effective density decreases with increasing d_{th} in the size range from 50 – 300 nm. This mainly occurs because particles become more highly agglomerated as size increases. The smaller particles are more compact than the larger particles and therefore have a higher effective density. Typically, the effective density varies from 1.2 to about 0.3 g cm^{-3} depending on size and fuel composition; higher effective densities are observed for high sulphur fuel. In our calculations, an effective density of 0.7 g cm^{-3} was assumed for the nucleation and accumulation modes for a diesel powered mine, which is based on the measurements of Park *et al*. (2003) and Olfert *et al.* (2007).

The relative activity size distribution of unattached radon progeny clusters depends on the concentration of water vapour, trace gases and the electrical charge distribution of the radionuclides in the air. Porstendörfer (2001) found that under 'normal' conditions of humidity and radon concentration, the activity size distribution of the unattached progeny can be approximated with three lognormal distributions. The AMTD values measured were 0.6 nm, 0.85 nm, and 1.3 nm with geometric standard deviations (σ_g) of about 1.2. In places with high radon concentrations, the fraction with the greatest AMTD value (1.3 nm) was not observed.

The neutralisation rate of the unattached clusters increases with radon concentration and so it is likely that modes below 1 nm are mainly associated with neutral clusters, whereas modes above 1 nm are charged clusters (Porstendörfer *et al*. 2005). Huet *et al*. (2001) also measured the size distribution for the unattached radon progeny and found a unimodal distribution with median diameters between 0.5 and 1.5 nm and values of σ_g between 1.2 and 1.4. Other workers have also measured a unimodal distribution in the range 0.7 – 1.7 nm (Cheng *et al*. 1997; El-Hussein, *et al*. 1998; Mohammed 1999; El-Hussein, 2005). For the purposes of dose calculation and for simplicity, a unimodal distribution with an AMTD of 1.0 nm and a σ_g of 1.3 can be used. Alternatively, an AMTD[6] of 0.9 nm with a σ_g of 1.3 could be assumed, as this gives doses that are closer to the ones calculated for bi-modal or tri-modal distributions as measured by Porstendörfer (2001).

In practice, the activity concentrations of radon progeny will vary with particular environmental conditions of exposure. However, the equivalent dose to the lung per WLM is relatively insensitive to the activity ratios of the radon progeny (Marsh and Birchall, 2000). This is because the WL is defined in terms of the PAEC and because the fraction of alpha energy absorbed by the target tissues in the lung is similar for ^{218}Po and ^{214}Po per disintegration. Based on measurements of the activity concentration of ^{218}Po, ^{214}Pb, and ^{214}Bi carried out indoors (Reineking and Porstendörfer, 1990; Kojima and Abe, 1988) the following activity ratios of ^{222}Rn progeny were assumed in our calculations:

Unattached: ^{214}Pb /^{218}Po = 0.1 and ^{214}Bi/^{218}Po = 0

Attached: ^{214}Pb /^{218}Po = 0.75 and ^{214}Bi/^{218}Po = 0.6.

[6] The ICRPs draft assumes an AMTD of 0.9 nm with a σ_g of 1.3 for the unattached.

More recently, El-Hussein, *et al*. 1999 measured a higher activity ratio of unattached ^{214}Pb: ^{218}Po of about 0.5 in closed room air as pointed. As expected this makes little difference (< 2%) in the lung dose from inhaled unattached progeny.

Figure 2.2 shows the effective dose as a function of AMD for mono-disperse particles and Figure 2.3 shows the effective dose per WLM as a function of AMD for poly-disperse particles.

Figure 2.2 Effective and Tissue Weighted Lung Dose (mSv per WLM) as a Function of AMD of a Unimodal Poly-Disperse Aerosol. Assumptions are the Ones Given in Case "C" Above

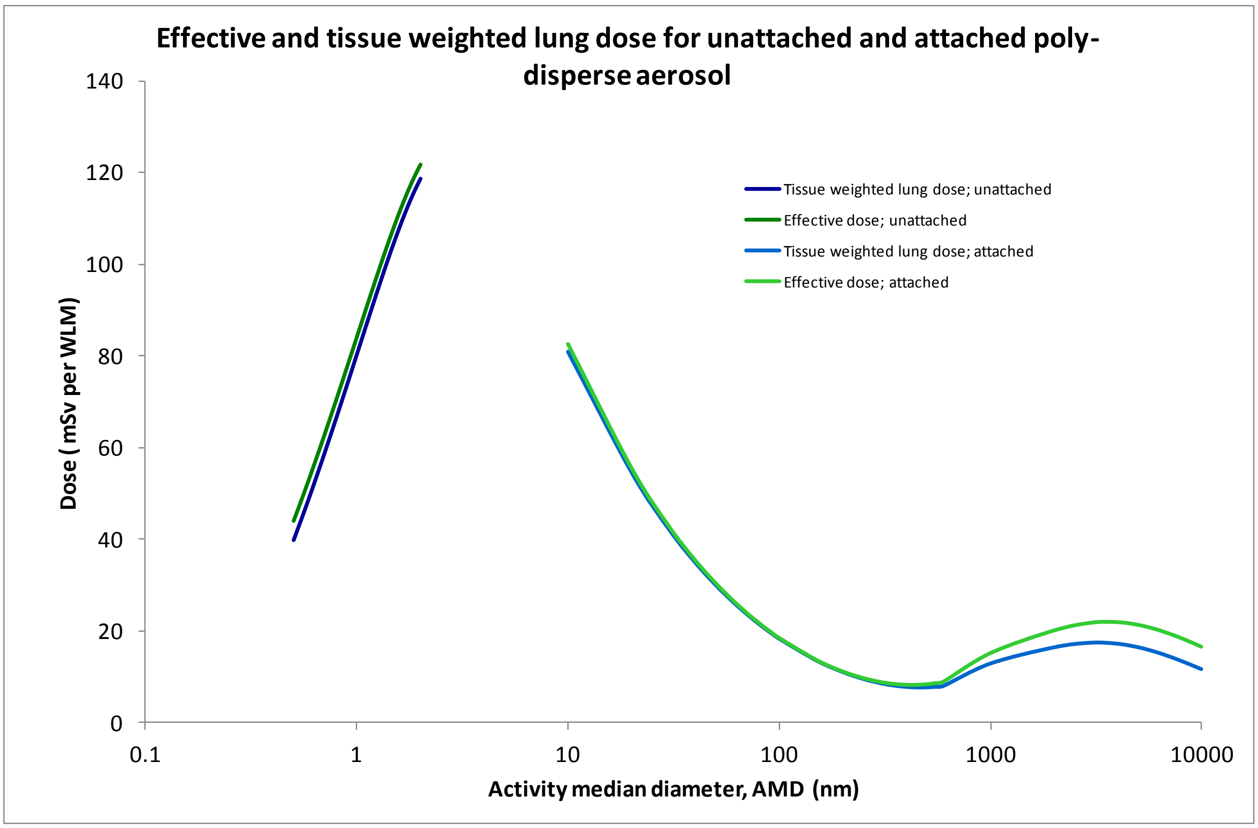
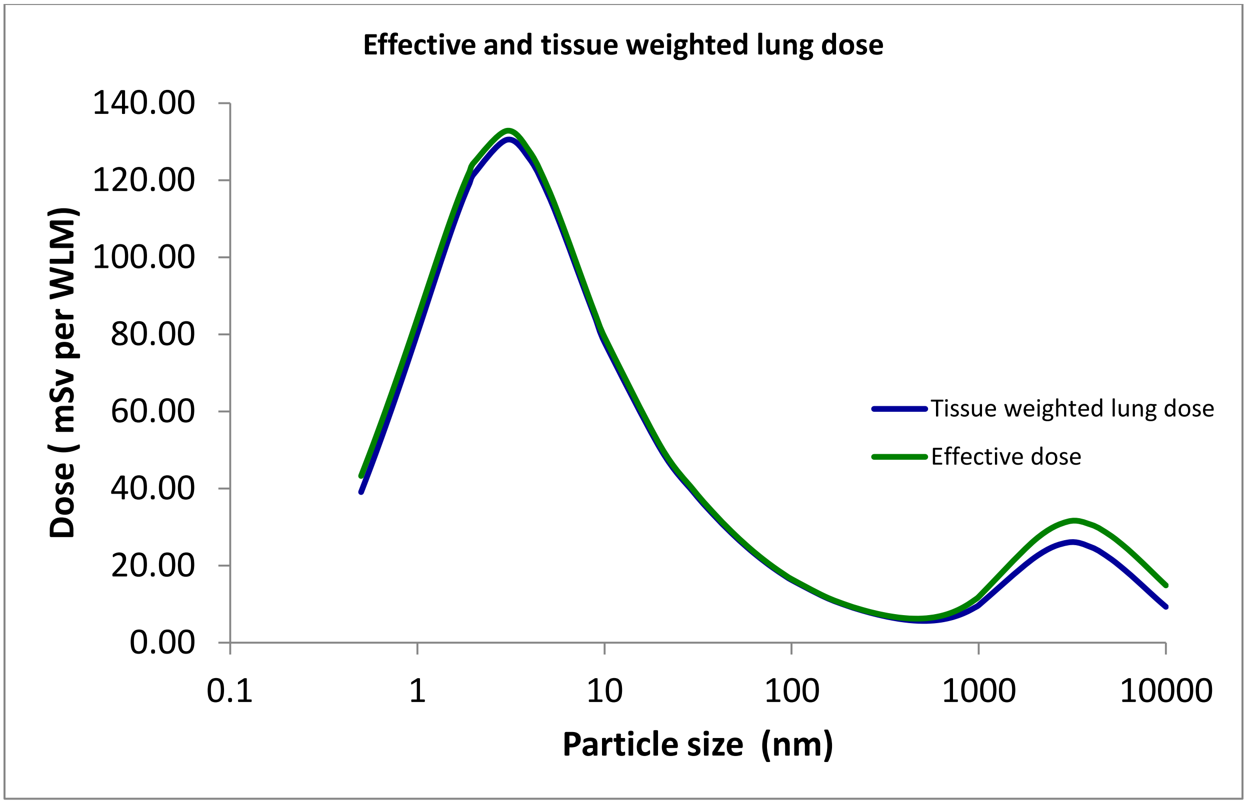


Figure 2.3 Effective and Tissue Weighted Lung Dose (mSv per WLM) as a Function of AMD of a Mono-Disperse Aerosol



2.2.2 Revisions to the ICRP Publication 66 HRTM

ICRP is in the process of publishing revised dose coefficients for occupational intakes of radionuclides (OIR) by inhalation and ingestion. In the revision of the dose coefficient, ICRP has taken the opportunity to update its biokinetic and dosimetric models. ICRP will also provide information on absorption to blood following inhalation or ingestion of different chemical forms of elements.

An important aspect of these revisions is changes to the HRTM (Bailey, 2009). Changes relate to particle transport from the nasal passages, bronchial tree (slow phase) and alveolar region. The HTRM assumes that of the material deposited in the ET airways, about 50% deposits in ET_1, which is cleared by nose blowing at a rate of 1 d^{-1}. The rest deposits in ET_2, which clears to the GI tract at a rate of 100 d^{-1}. Recent volunteer studies on clearance of inhaled particles from nose suggest greater deposition in ET_1 and transfer from ET_1 to ET_2 (Smith *et al*., 2011). Based on this work a new model of ET clearance is to be adopted by ICRP (Bailey, 2009). In the revised model, about 65% of the deposit in ET, is assumed to be deposited in ET_1 and is cleared at a rate of 2.1 d^{-1} ($t_{½}$ ~ 8 h): about one-third is cleared by nose blowing and two-thirds by transfer to ET_2. This has the effect of increasing the fraction of material deposited in the nose that is available for clearance to the GI tract. Also for very soluble materials a greater fraction will be absorbed to blood.

The HRTM includes a slow phase of clearance of particles deposited in the BB and bb regions. However, new data suggests that slow clearance in the bronchial tree is only associated with particles deposited in the bronchioles (Falk, *et al*. 1999, Bailey, 2009). The revised model assumes no slow clearance in the BB region but assumes particles deposited in the bb region are cleared to the BB region with a rate of 0.2 d^{-1} ($t_{½}$ ~ 3.5 d), except for the small sequestered fraction.

Since the publication of ICRP 66, additional data were published that showed greater long-term retention in the AI region than was previous assumed (Gregoratto, 2010). Kuempel *et al.* (2001) developed a model for particle transport in the AI region, which was physiologically more realistic and simpler than that in the HRTM. In this model particles deposited in the alveolar region either clear to the ciliated airways or penetrate to the interstitium from which they clear very slowly to the lymph nodes. New parameter values for the Kuempel model have been derived based on the previous experimental data in which the HRTM parameter values were based and on recent long term studies (Gregoratto *et al.* 2010). Based on this work a new model of AI clearance is to be adopted by ICRP (Bailey, 2009). In this model a significant fraction is sequestered in the interstitium; about a third of the AI deposit (neglecting absorption). These changes mean greater retention in the AI region for insoluble particles. Furthermore, long term studies showed no clear difference in the AI retention between smokers and non-smokers (Gregoratto *et al.* 2010) and therefore the modifying factors for the particle transport rates of a smoker given in ICRP Publication 66 are no longer considered applicable in the revised model.

The thoracic Lymphatic Tissue (LT) is now included in the tissue ‘lymphatic nodes’ which is one of the remainder tissues of the body in the calculation of the effective dose (ICRP, 2007). Because of this, the thoracic LT is no longer included in the calculation of equivalent dose to lung and the apportionment factor assigned to each of the three regions of the lung (BB, bb, AI) is one-third: $H_{lung} = ⅓ \times (H_{BB} + H_{bb} + H_{AI})$.

The absorbed fractions for the BB and bb source regions are derived as the thickness-weighted sum of the slow and fast clearing source regions as tabulated in Publication 66.

3.0 RANGE OF MINE AEROSOL CONDITIONS RELEVANT TO MODERN MINES

3.1 INTRODUCTION

To characterize and "get a sense" of the range of mine aerosols in modern uranium mines, the first step was to conduct a literature search to identify potentially applicable information. The initial literature search process involved the review of publisher databases such as *Elsevier, IOPScience, Oxford Journals, and Scholars Portal.* Specific attention was given to databases such as *Radiation Protection Dosimetry, Health Physics, and Environment International.*

The literature search focused around key words such as: Particle Deposition, Particle Size Distribution, Attached and Unattached Fractions, Aerosol Size, Dosimetry, Respiratory Health Effects, Aerosol Distribution and Inhalation Exposure.

In addition, data from CANMET – Elliot Lake Laboratories (ELL), the International Commission on Radiological Protection (ICRP), National Radiological Protection Board (NRPB) and previous reports of the CNSC (then the Atomic Energy Control Board (AECB)) and Australian Radiation Laboratory (ARL) were also reviewed.

In addition, major mining companies in Canada were asked whether relevant data for modern Canadian mines was available beyond that available through the open literature.

The literature[7] and associated data that were retrieved was then assessed based on relevance to factors that govern uranium mine environments, including current practice and methods under development. Parameters such as mine locations/work stations, time, measurement methods, data variance, and the type of studies conducted were also assessed. For information relevant to radon dosimetry, the review focussed on three key factors:

- ✓ Particle size distribution in the mine atmosphere;
- ✓ Radon gas and total alpha activity; and
- ✓ Fraction of unattached radon decay products (i.e., ^{218}Po, ^{214}Pb).

The kinds of data available are illustrated in Table 3.1 for selected publications and reports.

[7] More than 200 potentially useful data sources were identified. These papers and reports were scanned for application to the present study and the most relevant 80 odd papers were examined in more detail. These papers are identified in the Bibliography provided in Annex B of this report. In the end, very few papers were identified as having data potentially relevant to modern underground uranium mines. In selecting papers for detailed review, consideration was given to likely relevance to modern mining in Canada, and clarity of paper concerning methods of measurement and locations where measurements were made. Priority was given to peer reviewed articles; research papers prepared for government agencies, and recognized research laboratories such as EML.

In addition to a review of available literature concerning measurement radon and its progeny and the activity size distribution of the progeny, a review of particle size measurements per se was performed and considered:

- Cascade Impactors - rely on change on air velocity directed through sequential plates.
- Mobility Analyzers - depend upon differing electrical mobility for particle size separation.
- Graded Screen Arrays - Graded screen arrays (GSA) use the same air flow rate through screens of different mesh size, usually 60 to 600mesh. The size separation is based on differing diffusion coefficients with diameter.
- Multi element – with both impactors and 4 fine mesh screens.

In the end, very few data for modern mines, in Canada or elsewhere are available. Most measurements in the past have been made with cascade impactors or diffusion batteries or combinations of both.

Particle size plays a key role in the determination of the behaviour of radon progeny in the lung as deposition of radioactive particles, unattached or attached, is very sensitive to particle size (see discussions in Chapter 2). For instance, particles with higher diffusion coefficients (unattached progeny) will tend to deposit in the upper portion of the respiratory tract (bronchi) when inhaled. The smaller the inhaled particle, the likelihood of the particle depositing itself into the upper airways increases, due to the roughly inversely proportional relationship between a particle's diameter and its diffusivity. The regional deposition of particulates depends on the degree of attachment of the particles (see for example, Townsend, 1984), thus making the measurement of both the particle size and the unattached/attached fraction of airborne radon progeny important considerations.

Based on the literature reviewed, while some data suggest multiple modes, much of the data suggest that the attached progeny can be described broadly as having a bimodal activity size distribution[8] which can be illustrated by a sum of two lognormal distributions. It is made up of the nucleation mode with an activity median diameter usually around 1% or up to (about) 10 nm and an accumulation mode usually between 60 - 300 nm. The highest activity fraction was usually found in the accumulation mode. From the limited data on activity-size distributions made in uranium mines, based on our review of accessible literature, the AMAD values ranged between 60 to 300 nm for both diesel and electric powered mines. The unattached fraction in majority of the cases was very small. The majority of the activity size measurements seem to have been performed in mines using diesel powered equipment. A difference in aerosol size distribution between homes and mines was also observed. In indoor air, it was noted that the unattached fraction is weakly correlated to equilibrium factor.

[8] It is acknowledged that the distribution of particle size can be quite complex and depends on the nature of the work activity, local ventilation and the use or otherwise, of diesel equipment amongst other factors. Notwithstanding, the majority of data found from our literature review suggested a bimodal distribution.

Table 3.1 Data Summary of Selected Publications for Uranium Mines

Publication	**Device Used**	**Location of Mine**	**Nominal Particle Size Range (Activity Median Diameter, AMD)**	**Average Geometric Standard Deviation ($\sigma_{(g)}$)**	**Equipment Used**	**Comments on Unattached Fraction and Other Parameters**
Cavallo, Hutter, A., & Shebell, P. (1999).	Graded Screen Array, Gardner Condensation Nuclei Counter (CNC)	Northern Saskatchewan, Canada	85 nm	2	Diesel Power	Unattached fraction was 6% Equilibrium factor, F was reported to be 0.078. Measurements were made in the summer.
Busgin *et al*. 1981	Diffusion Battery	Elliot Lake Canada	65 – 110 nm.	1.45-2.73	Diesel Power	Aerosol Concentration = 9 x 10^4 – 1.4 x 10^5 (cm^{-3})
Cavallo, A. J. (1998).	Low-pressure Impactor	Two Southern United States mines (Colorado, New Mexico)	72 nm - 303 nm	2.24.	Diesel Power	-
Khan *et al*. 1987	Diffusion Battery	Elliot Lake Canada	50-90 nm	1.8	Diesel and Electrical Power	Unattached mode was noted to be extremely small.
Solomon *et al*. 1993	Diffusion Battery and serial graded screen array	Olympic Dam, Australia	200-300 nm,	2.5	Diesel Power	DCF were 8.2 and 7.9 mSv/WLM. Unattached fraction was at about 3-4%.
Cavallo, et al. 1997.	An impactor with a graded screen array	Eagle Point, Saskatchewan, Canada	70-100 nm	1.8	Diesel Power	Unattached fraction was estimated to be approximately 1%

Table 3.1 Data summary of Selected Publications for Uranium Mines (Cont'd)

Publication	Device Used	Location of Mine	Nominal Particle Size Range (Activity Median Diameter, AMD)	Average Geometric Standard Deviation ($\sigma_{(g)}$)	Equipment Used	Comments on Unattached Fraction and Other parameters
Butterweck et al. 1992	Low Pressure Cascade Impactor and a High Volume Impactor. Plus a Wire Screen	Germany	180-270 nm	2.0	Diesel Power	Unattached fraction was at about 0.7% (0.1%-2.5%) during working hours. Mean Equilibrium Factor of 0.45 Outside working hours fp=3% (0.5%-7%). The tourist cave had a higher fp value 10% (6%-16%) because of the lower particle concentration.
Tokonami et al. 2005	Cascade impactor with ten stages and a graded screen array	Gifu, Japan	162-222 nm	3.1	Not Specified	The median diameter of the unattached progeny was less than 1 nm.
Boulaud, D., & Chouard, J. C. (1992).	Cascade impactors and diffusion batteries	France, Bellezane Mining Centre	150-210 nm	1.8-2.0	Not Specified	Unattached fraction was estimated to be <1% from Porstendorfer's equation (2001)
J. Bigu (1988).	For WL(Rn), alpha-particle scalers model Tri-Met 372A by Tri-Met was used. Fluxmeters were used for Radon flux measurements	Elliot Lake Canada	-	-	-	Equilibrium factor was 0.8.

Table 3.1 Data summary of Selected Publications for Uranium Mines (Cont'd)

Publication	Device Used	Location of Mine	Nominal Particle Size Range (Activity Median Diameter, AMD)	Average Geometric Standard Deviation ($\sigma_{(g)}$)	Equipment Used	Comments on Unattached Fraction and Other parameters
Ito, Kimio, Yuu Ishimori, and Sada-aki Furuta. (2002).	Diffusion Batteries	Japan	110-260 nm	2.0-2.6	The Mine was Closed During Measurement	Unattached fraction was less than 1%.
Wu-Tu et al. 1997		Rabbit Lake, Canada Stopes and drilling area Bolt storage bay next to major mine exhaust	0.5-300 nm	-	Diesel Powered	Three Peaks were reported. Unattached mode (0.5-2 nm), Accumulation Mode and Coarse mode. Winter measurements Biomodal: About 65% of the attached PAEC[(a)] at 60 nm and 35% at 330 nm About 97% of the attached PAEC[(a)] at 66 nm and 3% at 5 µm.

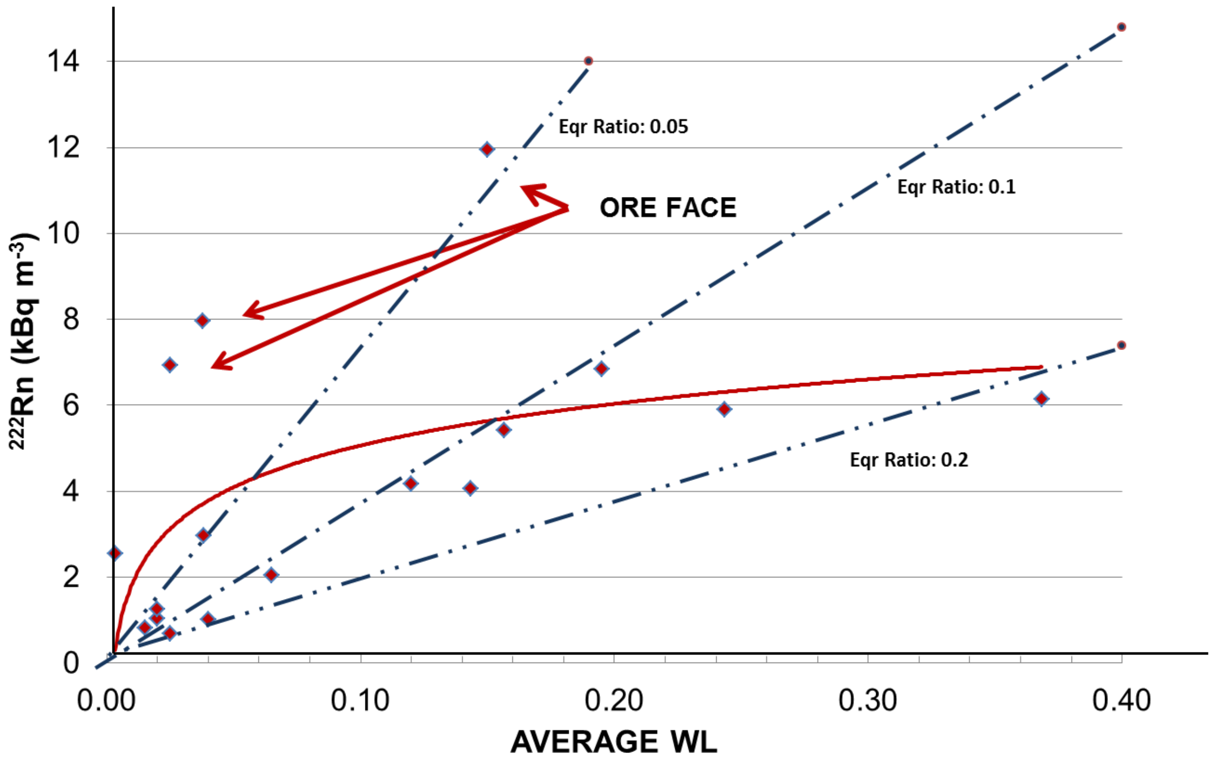
3.2 CANADIAN MINE ENVIRONMENTS

The available data for Canadian Mines have been investigated. It is evident from the research that very few recent relevant measurement data are available for Canadian Mines. Further, these results may not be representative of the actual worker conditions as mining environments vary rapidly with distance from the working face, with local activity, with local ventilation and other factors. The papers describing the few available data are typically unclear about precisely where the measurements were made relative to where men actually worked. Given that mine aerosols can change within a few meters (see for example Figure 3.1), this introduces a further level of uncertainty about the applicability of the available data. An example of key data identified includes:

- ✓ A paper by Wu-Tu (EML 589, 1997) which reported winter time measurements and noted the results were different from previous (summer) values.
- ✓ Cavallo, Alfred (1999) is also a good source for discussions on attached and unattached fractions, specifically for Canadian mines.
- ✓ Dr. N. Harley has performed a few made measurements in the Rabbit Lake mine (September 1996), during which time, quite high unattached fractions were observed near the working face as illustrated in the following Figure 3.1.

Our overall "synthesis" of a hypothetical modern mine environment is reflected in Table 4.1. For comparison, the ICRPs synthesis of mine environments is summarized in the next Section.

Figure 3.1 Variation in Rn and WL for Eagle Point Mine in Saskatchewan and estimated values of equilibrium factor (*F*)



3.3 ICRP'S SYNTHESIS

The ICRP (115 and draft OIR, 2011) have observed similarly, that there is no recent published measurement data on aerosol activity size distribution in Canadian mines. However, in the draft OIR document, ICRP has calculated an effective dose per WLM for a mine with assumed aerosol parameter values based on the measurement data of Solomon et al. 1993, 1994; Bouland and Chouland, 1992; and Butterweck *et al.* 1992. A preliminary value of 12 mSv per WLM was reported in the draft OIR document for consultation. However, we have calculated effective doses per WLM for specific exposure scenarios based on the data of Solomon et al. 1993; Wu-Tu *et al.* 1997; and Cavallo, 1999, 2000 as illustrated in Table 3.2 below.

Table 3.2 Effective Doses per WLM for Specific Exposure Scenarios

Exposure scenario and reference	Unattached[(a,b)]		Attached [(c)]			Dose from ^{222}Rn progeny	
	f_p	AMTD (nm)	Mode	f_{pi}	AMD (nm)	w_T H_{lung} (mSv/WLM)	E (mSv/WLM)
Solomon, *et al*. (1994), Olympic Dam, Australia	0.01	1.0	a	1.0	250	11.7	12.1
Saskatchewan, Canada							
Wu-Tu *et al.* 1997,							
• Stopes & drilling area, Winter	0.01	1.0	n a	0.65 0.35	60 350	20.6	21.1
• Bolt storage bay next to major exhaust; Winter	0.01	1.0	n c	0.97 0.03	70 5000	24.1	24.7
• 120 m, in front of water pond	0.01	1.0	a	1.0	70	24.3	24.7
Cavallo, 2000, Summer	0.06		a	1.0	90	23.4	24.0
Examples, Stager & Chamber, 12 July, 2012							
• Stope	0.05	2.0	a c	0.84 0.16	200 2000	17.2	18.2
• Travelways	0.01	2.0	a c	0.96 0.04	200 2000	12.3	12.8

(a) f_p = unattached fraction in terms of the potential alpha energy concentration (PAEC).
(b) The unattached progeny are assumed to have a lognormal activity size distribution characterised by an activity median thermodynamic diameter (AMTD) with a σ_g of 1.3. Unit density and shape factor are also assumed for the unattached progeny.
(c) Indices i = n, a and c represent the nucleation, accumulation, and coarse modes. f_{pi} = fraction of attached PAEC associated with mode, i.
(d) The activity median diameters (AMD) of the attached modes are expressed in terms of thermodynamic diameters for the nucleation and accumulation modes but for the coarse mode expressed in terms of aerodynamic diameter. The σ_g = 2.0 for the nucleation and accumulation modes but σ_g = 2.5 for the coarse mode.
(e) The values chosen for the density (ρ) and shape factor (χ) for the nucleation and accumulation modes are based on the measurements of the effective density, (i.e. ρ/χ) of diesel exhaust particles and is assumed to be $\rho/\chi = 0.7$ g cm^{-3} (Park *et al*. 2003; Olfert *et al*. 2007). The ICRP defaults are chosen for the coarse mode: $\rho = 3.0$ g cm^{-3} and χ=1.5.

The following points should be noted:

- If the ventilation rate is high, and the radon progeny is far from equilibrium, then the unattached fraction (f_p) is higher than the expected value based on particle concentration (Cavallo, 1999). In the wet underground uranium mine in northern Saskatchewan, Canada, Cavallo *et al*. 1999 measured an average value of f_p of about 6% whereas the expected value based on particle concentration was 0.3%. The average value of the equilibrium factor was 0.08.
- NRC, 1991 recommended a f_p value of 0.03 for haulage drifts.
- Outdoor air has an f_p = 0.03 (Porstendörfer and Gründel, 2005).

- A nucleation mode with AMTD between 50 – 120 nm has been measured in a Canadian mine both during winter months (Wu-Tu *et al.* 1997) and summer months (Cavallo *et al*. 1999). The nucleation mode was thought to mainly arise from burning propane gas to heat the mine air during winter (Wu-Tu *et al*. 1997). However, Cavallo *et al.* 1999 measured an average AMD of 85 nm in summer (Cavallo 2000).

3.4 MEASUREMENT CHALLENGES

One of the other major challenges associated with radon exposure in literature is the actual representation and meaning of radon dose. There are different approaches when establishing a radon dose conversion factor and it has typically been based on two main criteria, the dose based on dosimetry and the dose based on epidemiological considerations. The radon dose based on epidemiological considerations (used by ICRP previously) does not depend on radiation or tissue weighting factor whereas the dose model based on physical dosimetry is heavily reliant on conceptual models for estimation of absorbed dose (a physical quantity) which is subject to a number of uncertainties, and effective dose which involves several judgments. However, it must be emphasised that the effective dose is a radiation protection quantity that is used for regulatory purposes.

Over time, mining methods and ventilation practices have changed greatly in response to addressing health concerns with quartz, radon and diesel exhaust amongst other factors. In effect, modern mines are better ventilated and much “cleaner” with lower dust levels than mines in the past. It should also be noted that the ventilation and mining practices in modern high-grade mines where remote mining is practiced from those in past mines. Also, in the future, as lower grade deposits (in the order of 1% uranium) are mined, the radiation protection and ventilation practices will be revisited again to suit the characteristics of the deposit and entry mining.

Based on findings to date, relevant data on mine aerosols is very limited and interpretation of available data requires considerable judgment on the part of the investigators. Overall, more measurements need to be taken in modern day mines; however, operationally, off the shelf, measurement equipment is not available at this time, adding further challenges to the implementation of a fully dosimetric approach at this time.

There are many different types of radon and airborne particle monitoring instruments available today[9]. Many of the commonly available monitoring instruments used in homes and laboratories may not be adequately designed for use in mines, since factors such as portability, accuracy and "ruggedness", are essential for relatively harsh conditions in mines. Very few manufacturers have been found that specifically configure instruments for mining environments. Factors such as sensitivity, power, mode of operation, size weight, etc. have been used to categorize the instruments reviewed.

Diffusion batteries, graded screen arrays, cascade impactors, multi element instruments and mobility analyzers are common types of particle size samplers that have been used to make measurements in the past. The laser based instruments have generally been designed for lab environments. Combinations of instruments – cascade impactors and diffusion batteries for example are needed to develop the full range of particles size distribution needed to support dosimetry.

Under field sampling conditions the requirements for a practical instrument are substantial and include "ruggedness", and factors such as humidity, dust, and temperature are important to finding instruments that can withstand relatively operation underground. Appendix C provides a comparison of some the instruments reviewed.

A few additional comments on current capability for activity/particle size measurement is appropriate. There are many inconsistencies that still exist with respect to the activity distribution, especially in the smaller (low nm) particle size range and with respect to characterizing the full distribution of activity size. Some of the desireaber characteristics of such devices are ability to measure activity size distributions to low nm size range, to measure the full activity/particle size distribution, ruggedness of operation in a mine, proven experience in a mining or similar environment, ease of operation for routine measurements (rather than research), ability to integrate over a working day, and additional factors.

We are currently unaware of standard methods that can readily characterize personal exposures to nanoparticles for determining exposures in a mine[10]. For example impaction is used for aerosol sampling and low-pressure techniques are used for collecting nanoparticels. These techniques are not currently feasible for personal sampling and are not practical for regular use in

[9] Various commercially available air particle and radon monitors were reviewed, among them, selected products from TSI Incorporated, MSP Corp. (MOUDI), GRIMM Aerosol Technik GmbH & Co., CessTech and Phillips Aerasense, SARAD, Pylon Electronics, Inc., Durridge Company Inc., Saphymo GmbH (formerly Genitron Instruments), Gammadata Instruments AB, *femto*-TECH Inc., Environmental Instruments Canada Inc., alphaNUCLEAR Products, Sun Nuclear Corporation, and RadonAway/AccuStar Labs.

[10] Although personal nm size monitoring devices are under development (Thayer et al. 2011) and with further development, such devices may offer promise in the future for personal; radon progeny size distribution monitors

mines. Moreover the flow rate throughout the sampling duration must be known and the measurement of the radioactivity usually requires significant counting time since the activity concentrations are low.

Overall, of all the instruments and methods identified and reviewed to measure particle size and activity size of radon progeny, no off the shelf equipment was found that can be easily utilized for routine measurements for measuring the necessary activity particle size distribution to support radon dosimetry in mining environments. However, as noted below there are some measurement devices that can help advance knowledge in this area.

Previously much of the work has been done with "homemade" systems such as the one developed by US DOE at EML *(*Environmental Measurements Laboratory) and at ARPANSA (The Australian Radiation Protection and Nuclear Safety Agency)) and at University Gottingen, Germany (Reineking, *et al.* 1994). The instruments we have identified and shortlisted for potential use and development is a time integrating measurement instrumentation (IMP) developed at New York University (NYU Medical Center), a two stage system used by ARPANSA (really a protype and not commercially available), and an instrument developed by a German company known as EQF3220 developed by SARAD GmbH. These instruments based on information we have are capable of measuring fractions down to the nanometre range, are portable, can self-power and seem suitable for area measurements of at two particle sizes. As discussed later, variability from workplace to workplace is a concern and such devices could be useful in understanding such variability.

The time integrating measurement instrumentation (IMP[11]) developed at New York University (NYU Medical Center) was chosen as it has previously been used to make measurements in an actual uranium mine (Rabbit Lake) around ten years ago where high unattached fractions were observed near the working face. This instrument has been used successfully and it is one of very few instruments that can measure parameters in a working mine without the use of several sampling devices or elements[12].

The instrument developed by SARAD GmbH was selected, specifically the EQF3220, because the instrument has the capacity to sample free and attached decay products and cluster

[11] The IMP is a miniature design of screen arrays – diffusion battery-relying on detection of the long lived ^{210}Pb/Po decay products produced from decay of the short lived species deposited on the screens. The sampler head fits in the palm of a hand and contains an inlet impactor followed by 4 stacked fine mesh screens and an exit Millipore filter. All entry aerosol particles are captured on the 6 filtration stages. A small linear pump draws air through the sampler and a Magnehelic shows the pressure drop across the sampler head to avoid excessive sampling time and overloading due to normal background aerosol mass. Alpha counting of the filters is usually delayed by several weeks and can be done on multiple counters or a single counter because the measurement is of the alpha emitting ^{210}Po that builds up from ^{210}Pb on the stages. Usually, low background ZnS alpha scintillation counters are used. The entire IMP sampling system fits in a space about the size of a shoebox.

[12] The instrument is currently available for testing and use upon request from Dr. Harley at NYU Medical Centre.

components with ranges of 20-100nm. It is the only practical instrument that we could find with respect to portability and durability that can measure radon & thoron concentrations and their decay products in relation with the volume of particles of the aerosol. It can provide EEC, PAEC for both attached and unattached radon daughter products and is relatively simple to use. It comes with a transportation case and has a internal power system. Additionally it can also be connected to a 12v car battery for longer use. This instrument is commercially available and there are other similar lines of products which SARAD (and possibly others) is currently developing.

Figure 3.2 NYU IMP Miniature Particle Size Sampler

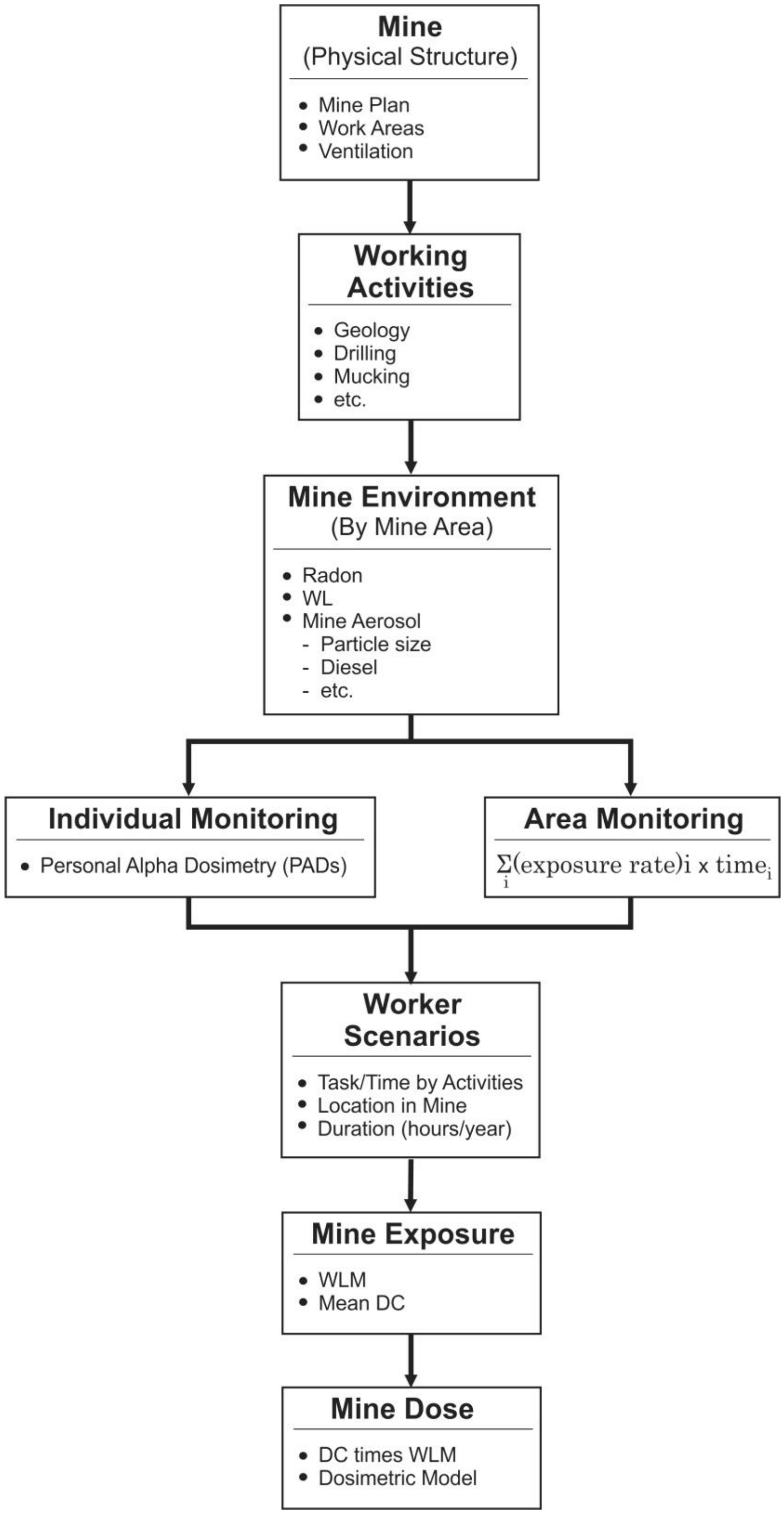
Figure 3.3 SARAD-Radon/Thoron Gas & Decay Product – Monitor for attached and unattached decay products (EQF3220)

4.0 RANGE OF DOSE CONVERSION FACTOR

A simulation approach was used to investigate the range of DCFs for a modern underground uranium mine based on a range of hypothetical mine environments and worker exposure scenarios. In general terms, the approach is to pick an average WL and associated particle size distribution for each of three hypothetical work places. The particle size determines the workplace-specific dose conversion factors as described in Chapter 2. As previously indicated, the dosimetric factors used in the current simulations are presented in units of mGy/WLM and the effect of radiation and tissue weighting factors used to convert from absorbed dose to lung to effective dose are considered separately.

The factors, and hopefully the complexities, involved in estimating mine environments and consequently dose are illustrated conceptually in the following Figure 4.1.

Figure 4.1 Absorbed Dose by Hypothetical Mine Environment



4.1 APPROACH TO SIMULATION

An uncertainty analyses was used to provide an estimation of the DCF for use to convert WL to WLM for time spent, illustrative worker, in work places of varying WL and varying distribution of the activity by particle size assuming a uniform distribution for present purposes.

The simulation approach considers picking an average WL and associated particle size distribution for each of the three work places. The particle size determines the workplace-specific DCF and the combination of this DCF, the workplace WL and the time spent is used to calculate the total exposure (WLM) and dose received in each work place. The dose and WLM are summed across the workplaces and a weighted DCF (mGy/WLM) is determined.

4.1.1 Modelled Scenario

For the present analysis, three workplaces were considered, namely travelways and two active mining areas within a stope – the first near to the face and the second a more general location in the stope but away from the face. The notional assumptions of time spent in each area and the corresponding assumptions of mine aerosols, and WL are shown in Table 4.1.

These data are considered reasonable based on recent assessments performed by the authors but are quite simplistic and must be understood to be quite hypothetical and developed for illustrative purposes.

Table 4.1 Data Summary of Uranium Mine Environment, Based on Hypothetical Scenarios* of potential alpha energy

Activity	WL (Rn)	Time (hrs/day)	Unattached Fraction*		Accumulation Mode		Hours Per Day	
			%	(Size nm)	%	(Size nm)	Worker A	Worker B
Travel Way	0.005 – 0.015	148 hours (20 hours spent on surface)	0.5-1%	0.5-2	99%	150-300	9	3
StopeNear	0.05-0.25	62 hours (9 hours in, 3 hours out)	2-6%	0.5-2	94-98%	60-100	1.5	4.5
StopeGeneral)	0.02-0.1	62 hours (3 hours in, 9 hours out)	0.5-2%	0.5-2	98-99%	60-300	1.5	4.5

4.1.2 Results

Table 4.2 shows the variation of WL, particle size and the associated conversion from WL to absorbed doses. The absorbed dose factor (mGy/WLM) is highest in the StopeNear workplace due to the generally higher unattached fraction and the smaller agglomerate particle sizes. compared to the other two workplaces. The proportion of the absorbed dose factor from the unattached fraction is higher in the StopeNear workplace indicating that the model range of unattached fraction is an important factor. The mean absorbed dose factor ranges from 4.7 mGy/WLM for the travelways to 10 mGy/WLM within in the StopeNear workplace (see Figure 4.2).

Table 4.2 Variation in Workplace Conditions Modelled

Workplace Variations						
Attribute	**Units**	**Number of Sims**	**2nd**	**Mean**	**98th**	**CV**
StopeGen						
WL	WL	1000	0.021	0.059	0.099	40
Unattached Fraction	%	1000	0.53	1.2	2	35
Unattached Size	nm	1000	0.55	1.2	2	34
Agglomerated Size	nm	1000	63	180	290	38
Absorbed Dose Factor	mGy/WLM	1000	3.8	6	11	32
Proportion from Unattached	%	1000	2.1	8.2	17	49
StopeNear						
WL	WL	1000	0.053	0.15	0.25	39
Unattached Fraction	%	1000	2.1	4	5.9	29
Unattached Size	nm	1000	0.54	1.3	2	34
Agglomerated Size	nm	1000	61	79	99	14
Absorbed Dose Factor	mGy/WLM	1000	8.4	10	13	11
Proportion from Unattached	%	1000	5.2	14	25	35
Travelway						
WL	WL	1000	0.0053	0.01	0.015	29
Unattached Fraction	%	1000	0.51	0.74	0.99	19
Unattached Size	nm	1000	0.54	1.2	2	35
Agglomerated Size	nm	1000	150	220	300	19
Absorbed Dose Factor	mGy/WLM	1000	3.8	4.7	6	14
Proportion from Unattached	%	1000	2.3	5.9	10	34

Annual doses were calculated for the two worker types and the summary of these is provided in Table 4.3 based on 200 days of 12 hour shifts (See also Figure 4.3). As would be expect, the worker spending more time in the travelways (Worker A) has lower exposure and dose compared to the worker who spends more time within the stopes (Worker A)).

Table 4.3 Summary of Annual Absorbed Doses

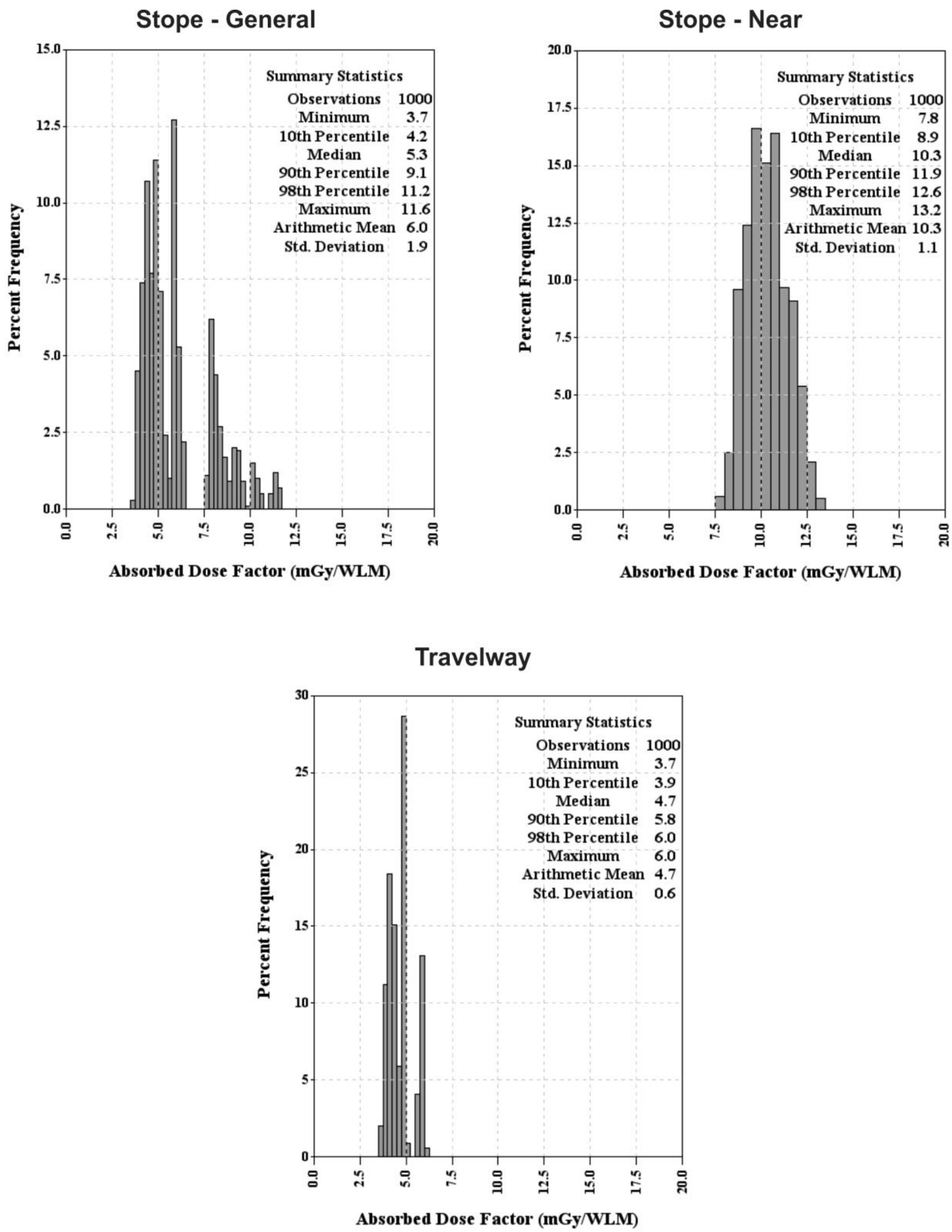
Attribute	Units	Num Sims	2nd	Mean	98th	CV
WorkerA						
Annual WLM	WLM	1000	0.25	0.48	0.69	24
Annual Absorbed Dose	mGy	1000	1.8	3.9	6.1	30
Absorbed Dose Factor	mGy/WLM	1000	6.1	8	10	12
WorkerB						
Annual WLM	WLM	1000	0.52	1.1	1.7	29
Annual Absorbed Dose	mGy	1000	4.3	10	17	33
Absorbed Dose Factor	mGy/WLM	1000	6.8	8.9	11	12

There is not much difference in the overall observed dose factor determined by dividing the annual dose by the annual WLM. These range from 6.1 to 10 mGy/WLM with a mean of 8.0 mGy/WLM for Worker A who spends a large proportion of time in the travelways to a similar range of 6.8 to 11 mGy/WLM with a mean of 8.9 mGy/WLM for Worker B. This likely arises because the majority of the dose for both worker types is typically received in the StopeNear workplaces and therefore the overall factor is dominated by the larger unattached fraction at that location and the unattached fraction. The annual conversion approaches the conversion factor, 10 mGy/WLM, observed in the StopeNear workplace as this has both the highest conversion factor and highest WL.

4.1.3 Discussion

The illustrative calculation indicates that two worker experience an averaging of exposure conditions as they work underground that a locations with variation in WL and the conversion from WL to dose. The example shown tends to demonstrate that the highest exposure rate (WL) tend to occur with the highest dose conversion factor due to the presence of high unattached fraction and smaller agglomeration size in locations with “fresh” radon.

Figure 4.2 Absorbed Dose by Hypothetical Mine Environment (Histograms)



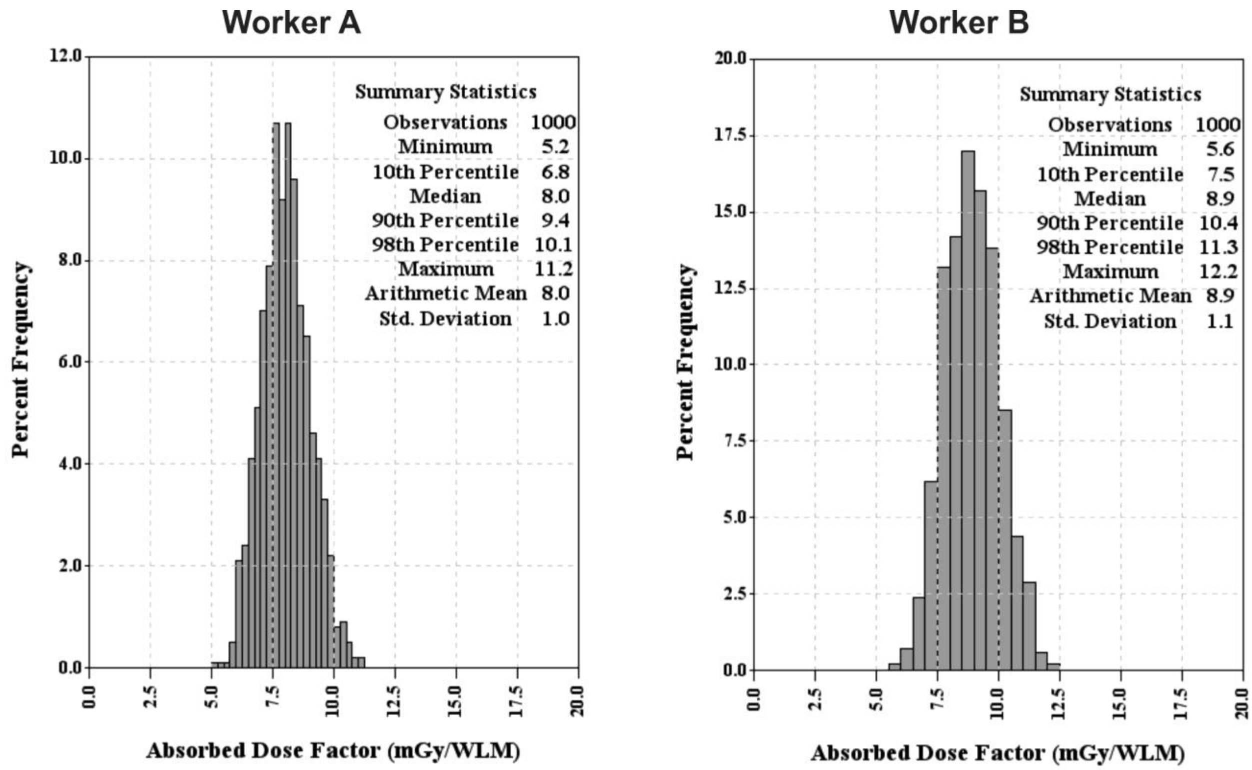
The overall dose conversion factors representing the multiple workplaces are similar to two worker types who spend very different amounts of time within the high exposure areas. The modelled difference in factors is small between the two worker types and the variation within a worker type is less than a factor of two.

This is an illustrative example and may be biased towards the StopeNear condition (as fairly high – for modern mines - WLs were used). Until detailed measurements can be collected to support the conditions in varying workplaces, it seems reasonable to use a single dose conversion factor for all underground employees.

The absorbed doses can be converted to effective doses by the application of ICRP weighting factors namely radiation weighting factor (w_R) and tissue weighting factor (w_T). Although effective dose is used as a risk-related quantity for the optimisation of protection below constraints and reference levels it cannot provide a quantitative measure of risk to individuals or particular population groups. Simplifying assumptions, including age- and sex- averaging are made in the calculation of effective dose. The effective dose is defined for a sex-average reference person (ICRP, 2007).

Values of w_R are chosen as a simplified representation of the different effectiveness of radiations per unit absorbed dose in causing cancer. The w_R value for alpha particles is 20, despite the fact that the relative biological effectiveness (RBE) of alpha particles compared to gamma rays depends on the disease under consideration. For example, the RBE of alpha particles for leukaemia is likely to be closer to 1 than to 20 (Harrison and Muirhead, 2003). Also, for induced lung cancer arising from exposure to radon progeny, the RBE of alpha particles may be closer to 10 than 20 (Hofmann et al. 2004). Values of w_T are chosen to represent the contributions of individual organs to the overall radiation detriment from stochastic effects. They are rounded values averaged over both sexes and all ages across Asian and Euro-American populations; only four different w_T values are assigned to the various organs and tissues to represent the range of relative detriment (ICRP, 1991, 2007). The w_T value for lung is 0.12, compared with values of relative detriment for lung of 0.16 for the whole population and 0.29 for adults (ICRP, 2007).

Figure 4.3 Estimated Doses from Radon Progeny for Two Hypothetical Worker Scenarios



For an 'absorbed dose to lung' of 8.9 mGy/WLM, the effective dose is approximately, 8.9 × 20 × 0.12 = 21 mSv/WLM[13]. However, if instead of using the specified alpha particle w_R of 20 and the lung w_T of 0.12, an RBE value of 10 is used as a best estimate of alpha-induced lung cancer and the relative detriment for adult males of 0.22 is also used (ICRP, 2007), then the "effective dose" per unit exposure becomes 20 mSv per WLM, similar to the previous value.

[13] Alternative conversions to the ICRPs are also used. For example, factor could be used to convert absorbed dose to the **bronchial tree** to effective dose is $(A_{bb}+A_{BB}) \times w_T$, where $A_{bb} = ⅓$ and $A_{BB} = ⅓$ and are apportionment factors of the radiation detriment of the lung for BB and bb regions respectively. Since, $w_T = 0.12$ for the lung, the 'tissue weighting factor' for the **bronchial and bronchiolar region t**hat are used in this case would be = (⅓ + ⅓) × 0.12 = 0.08. In this case, the effective dose is estimated by multiplying the absorbed dose to **bronchial tree** by $w_R \times 0.08$. The convention outlined in the foregoing text includes the apportionment factors ($A_{BB} = ⅓$, $A_{bb} = ⅓$ and $A_{AI} = ⅓$); see equation 2-1. So to convert to effective dose, the 'absorbed dose to **lung is multiplied** by $w_R \times w_T$, where $w_R = 20$ and $w_T = 0.12$.

5.0 DISCUSSION AND CONCLUSIONS

The traditional metric for exposure to uranium miners has been the working level month (WLM), a measure of exposure to radon progeny. This has been the approach used internationally to manage and regulate exposures of miners to radon and its short-lived decay products. However, the ICRP has proposed to move toward a fully dosimetric approach for radon progeny.

The dosimetry-based dose from radon decay products depends on the characteristics of the mine environment including, combinations of several aerosol inputs including alpha energy (typically measured via WL), the particle size distribution of the mine workplace aerosols, including the unattached fraction. (See for example, Figure 4.1.). In considering the use of dosimetric conversion factors, it is important to understand that mine environments vary widely not only between mines but also within mines and with time. In mines, all the parameters mentioned above vary widely within just a single mine. Parameters vary from place to place and change with time. Due to the changing characteristics of a mine atmosphere, the parameters can not only vary between mines, but also between different work stations, and with time, within a single mine site. Coming up with standard values of atmospheric parameters that can be applied across all uranium mines is therefore extremely difficult.

In this report, hypothetical mine environments and exposure patterns were simulated based on choosing an average WL and associated particle size distribution for each of three hypothetical work places. The particle size and unattached fraction determines the workplace-specific dose conversion factors. The dosimetric factors used in the current simulations are presented in units of mGy/WLM and the effect of radiation and tissue weighting factors used to convert from absorbed dose to lung to effective dose are considered separately.

The DCFs (as a function of particle size) were combined with workplace WL and the time a miner spends in each workplace to predict the dose received for the calculated exposure (WLM) in each work place. The dose and WLM are summed across the workplaces and a weighted DCF (mGy/WLM) is determined. For the hypothetical mine environments and worker exposure scenarios considered in this report, the DCFs for annual doses were estimated to range from about 6 to 10 mGy/WLM for both of the two different worker types considered. Applying the ICRP radiation and tissue weighting factors ($w_R = 20$ for alpha particles and $w_T = 0.12$ for lung), gives effective doses in the range 14 to 24 mSv/WLM.

Our overall conclusions are that dosimetrically relevant data available for modern uranium mines is very limited, that suitable commercial (off-the shelf) equipment for measuring dosimetrically relevant parameters is not currently available and that there are considerable uncertainties associated with the implementation of a fully dosimetric approach. In broad terms, further research, advancements in current measuring practices and relevant data on modern mine environments is needed and thus, until such time as such data is available, we recommend continuing with current practice for monitoring, reporting and regulating miner's exposure to radon progeny.

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APPENDIX B: INSTRUMENT COMPARISON

B.1 Comparison of Airborne Particle Monitors/Air Samplers Reviewed

Model/ Specifications	AeroTrak 9000™	Model 3550	Model 3007	Model 3091	Model 3788	Model 3936
Manufacturer	TSI					
Length	27 cm	13 cm	29 cm	70 cm	31 cm	Varied (dependant on combination of instruments used)
Width	22 cm	38 cm	14 cm	34 cm	16 cm	
Height	9 cm	28 cm	14 cm	44 cm	36 cm	
Weight	7.2 kg	7.2 kg	1.7 kg	32 kg	8.2 kg	
Sensor Type	Diffusion charger + electrometer	Diffusion charger + electrometer	CPC	Diffusion charger + electrometer	CPC	SMPS
Particle Size Range	10nm to 1μm	10nm to 1μm	10nm to 1μm	5.6nm to 560nm	2.5nm to > 3μm	2.5nm to 1μm
Aerosol Concentration Range (μm^2/cc or specified otherwise)	1 to 2,500 (TB/A)	1 to 2,500 (TB) 1 to 10,000 (A)	0 to 100,000 particles/cm^3	-	0 to 400,000 particles/cm^3	0 to 10,000,000 particles/cm^3
Condensing Source	-	-	99%+ Isopropyl Alcohol	-	Distilled Water	Distilled Water/ Butanol
Type of Instrument	Portable	Non-portable	Portable	Non-portable	Non-portable	Non-portable
Operating Range	T: 10 to 35°C	T: 10 to 35°C	T: 10 to 35°C	T: 0 to 40°C	T: 10 to 35°C	T: 10 to 35°C

B.1 Comparison of Airborne Particle Monitors/Air Samplers Reviewed (Cont'd)

Model/ Specifications	CPC 5.403	Advanced CPC 5.416	HCT CPC 4322/4323	HCT CPC 4312	Model 1110	NanoMonitor	NanoTracer
Manufacturer	**GRIMM – Aerosol**		**CessTech**		**MSP Corp.**	**Phillips Aerasense**	
Length	22 cm	40 cm	31 cm	32 cm	26 cm	-	-
Width	26 cm	25 cm	16 cm	32 cm	38 cm	9.5 cm	9.5 cm
Height	30 cm	22 cm	36 cm	26 cm	25 cm	16.5 cm	16.5 cm
Weight	13 kg	variable	12 kg	13.2 kg	11 kg	-	-
Sensor Type	CPC	CPC/SMPS	CPC	CPC	CPC	Diffusion charger + electrometer	Diffusion charger + electrometer
Particle Size Range	4.5 nm to > 3μm	4nm to > 3μm	> 7nm	> 5nm	> 10nm	10nm to 300nm	10nm to 300nm
Aerosol Concentration Range (particles/cm^3)	0 to 14,000 (s) 0 to 10^7 (p)	0 to 150,000 (s) 0 to 10^7 (p)	0 to 10,000/ 0 to 1,000	0 to 10,000	0 to 20,000	0 to 1,000,000	0 to 1,000,000
Condensing Source	1-butanol	1-butanol	Distilled Water	n-butyl alcohol	Distilled Water	-	-
Type of Instrument	Portable	Non-portable	Non-portable	Non-portable	Non-portable	Non-portable	Portable
Operating Range	T: 10 to 35°C	T: 10 to 40°C	-	-	-	T: 0 to 35°C	T: 0 to 35°C

Note: (s) – single counting mode, (p) – photometric counting mode, (TB) – Tracheobronchial region of lung, (A) – Alveolar region of lung

B.2 Comparison of Radon Monitors/Radon Detectors

Model Name/ Specification	CRM-1 (Active)	CRM-2 (Passive)	WLx	AB-4/ AB-4A	AB-5/ AB-5R	AB-6	RAD7	AlphaGUARD P30	AlphaGUARD PQ2000 PRO
Manufacturer	Pylon Electronics Ltd.						Durridge Company Inc.	Saphymo GmbH	
Length	22.25 cm	17.22 cm	25.4 cm	29.21 cm	26.67 cm	19.685 cm	24.13 cm	34.00 cm	34.00 cm
Width	40.64 cm	40.64 cm	45.1 cm	26.67 cm	25.4 cm	22.86 cm	19.05 cm	23.00 cm	23.00 cm
Height	57.15 cm	57.15 cm	22.9 cm	17.78 cm	9.906 cm	30.48 cm	26.67 cm	11.6 cm	11.6 cm
Weight	14 kg	14 kg	6 kg	5.5 kg	5 kg	6 kg	5 kg	4.5 kg	4.5 kg
Measurement Type	Radon conc.	Radon conc.	WL	Radon conc.	Radon conc.	Radon conc.	Radon conc.	Radon conc.	Radon conc.& WL
Type of Instrument	Area Monitor	Area Monitor	Portable	Portable	Portable	Portable	Portable	Portable	Portable
Principle of Detection	Scintillation cell	Scintillation cell	Solid State	Scintillation cell	Scintillation cell	Scintillation cell	Solid State	Pulse-counting ionization chamber	Pulse-counting ionization chamber
Sensitivity (cpm/pCi/L)	0.85	0.85	n/a	1.25	0.76 or 1.36 or 0.85	Lucas cell dependant	0.5	1.818	1.818
Operating Range	T: 0 to 50°C H: 0 to 90%	T: 0 to 50°C H: 0 to 90%	T: 0 to 50°C H: 0 to 90%	T: 0 to 50°C H: 0 to 90%	T: 0 to 50°C H: 0 to 90%	T: 0 to 50°C H: 0 to 90%	T: 0 to 40°C H: 0 to 95%	T: -10 to 40°C H: 0 to 99%	T: -10 to 40°C H: 0 to 99%
Minimum Detection Limit	1.18 pCi/L	1.18 pCi/L	0.001 WL	0.8 pCi/L	1.3 or 0.74 or 1.18 pCi/L	0.67 or 0.8 or 1.18 pCi/L	0.5 (monitor) 0.25 (sniffer)	-	-
Detection Range	-	-	0.001 to 50WL	-	-	-	0.1 to 10,000 pCi/L	2 to 2,000,000 Bq/m^3	2 to 2,000,000 Bq/m^3

B.2 Comparison of Radon Monitors/Radon Detectors (Cont'd)

Model Name/ Specification	ATMOS 12 DPX	CRM-510LP	VS472 Radon Sniffer	TM372 Sample Counter	Model 565	Model 595	Model 1000 CWLM	Model 1027CRM	Model 1028CRM	Model 1029CRM
Manufacturer	**Gammadata Instruments AB**	**femto-TECH Inc.**	**Environmental Instruments Canada Inc.**		**Alpha NUCLEAR Products**			**Sun Nuclear Corporation**		
Length	-	-	-	-	n/a	n/a	n/a	20.32 cm	11.68 cm	11.68 cm
Depth	22.10 cm	13.72 cm	10.80 cm	10.80 cm	-	-	-	-	-	-
Width	50.04 cm	16.76 cm	21.59 cm	21.59 cm	n/a	n/a	n/a	11.97 cm	20.83 cm	20.83 cm
Height	38.61 cm	13.72 cm	20.32 cm	20.32 cm	n/a	n/a	n/a	6.35 cm	9.91 cm	9.91 cm
Weight	14 kg	1.8 kg	2.2 kg	2.2 kg	2.25 kg	2.25 kg	2.25 kg	0.91 kg	1.36 kg	1.36 kg
Measurement Type	Radon conc.	Radon conc.	Radon conc.	WL	WL	WL	WL	Radon conc.	Radon conc.	Radon conc.
Type of Instrument	Portable	Portable	Portable	Portable	Area Monitor	Area Monitor	Area Monitor	Portable	Portable	Portable
Principle of Detection	Pulsed-ionization chamber	Pulsed-ionization chamber	Scintillation cell	Solid State	Diffused junction silicon	Diffused junction silicon	Diffused junction silicon	Diffused junction silicon	Diffused junction silicon	Diffused junction silicon
Sensitivity (cpm/pCi/L)*	0.82	0.3	0.75	1000 cpm/1WL	666-750 cpm/1 WL	n/a	n/a	2.5	2.5	5
Operating Range	T: 0 to 50°C H: 0 to 99%	T: 10 to 40°C H: 10 to 90%	-	-	T: -10 to 40°C	T: -10 to 40°C	T: -10 to 40°C	T: 7 to 35°C	T: 7 to 35°C	T: 7 to 35°C
Minimum Detection Limit	-	-	-	-	-	-	-	-	-	-
Detection Range	1 to 100,000 Bq/m^3	0.5 to 2000 pCi/L	-	-	-	-	-	0.1 to 999 pCi/L	0.1 to 999 pCi/L	0.1 to 1000 pCi/L