Division of Compensation Analysis and Support

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TABLE OF CONTENTS

SECTION **TITLE** **PAGE**

1.0 Introduction 4
1.1 Purpose 4

2.0 Background 4

3.0 Working Level Definition 4

4.0 Calculation Method 5
4.1 Absorption rate 5
4.2 Particle size 5

5.0 Radon-222 6
5.1 Unattached Fraction 6
5.2 Equilibrium 7
5.3 Radon-222 Results 7

6.0 Radon-220 7
6.1 Unattached Fraction 8
6.2 Equilibrium 8
6.3 Radon-220 Results 9

7.0 Radon-219 10
7.1 Unattached Fraction 10
7.2 Equilibrium 10
7.3 Radon-219 Results 10

8.0 Dose to Organs Outside the Respiratory Tract 11
8.1 Model Parameters 11
8.2 Organ Dose Conversion Factor Results 11

References 13

LIST OF TABLES

TABLE **TITLE** **PAGE**

Table 5-1. Equilibrium Factors for Radon 222. 7

Table 5-2. Dose Conversion Factors for Radon 222. 7

Table 6-1. Dose Conversion Factors for Radon 220. 9

Table 7-1. Dose Conversion Factors for Radon 219. 11

Table 8-1. Dose Conversion Factors for Organs outside the Respiratory Tract 12

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historical background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document, the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy (DOE) facility” as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. § 7384l(5) and (12)].

1.1 PURPOSE

This Technical Information Bulletin provides the conversion factors for calculating organ dose from Rn-222, Rn-220 and Rn-219 decay products measured in working level months (WLM).

2.0 BACKGROUND

The Interactive RadioEpidemiological Program (IREP) is used to determine the Probability of Causation (POC) that a cancer was caused by occupationally related radiation exposure. Annual radiation dose is the normal IREP input but in the case of Rn-222, a direct exposure model is also included for lung cancers. The exposure model was based on studies performed at uranium mines and thus applies to Rn-222 and its associated decay products. Rn-220 (also known as thoron) and Rn-219 (also known as actinon) decay products have characteristics that are sufficiently different from Rn-222 so that the exposure model is not applicable to Rn-220 and Rn-219. However, decay products of these two isotopes are often measured in units of working levels. This requires the development of a conversion factor to express Rn-220 and Rn-219 working level exposures in terms of lung dose in rem. For completeness, conversion factors for all organs for Rn-222, Rn-220 and Rn-219 have been included.

3.0 WORKING LEVEL DEFINITION

The majority of dose received from radon is actually derived from energy emitted by the decay products rather than the gas itself. Because of this, the dose per unit radon gas activity is greatly dependent on the state of equilibrium of the decay products. To better describe the hazard associated with radon, worker exposure has historically been expressed in terms of the decay product activity. The unit developed for this is the Working Level. A Working Level is described as the amount of short lived radon decay products in one liter of air that will ultimately decay with 1.3E5 MeV of alpha energy.

When the decay chain reaches 100% equilibrium, one Working Level is equivalent to approximately 100 pCi/L of Rn-222, 7.5 pCi/L of Rn-220 or 162 pCi/L of Rn-219. While this is a significant difference in the gas concentrations, by definition of the working level, the decay products will ultimately emit the same amount of alpha energy. This, however, does not lead to the same lung dose. This is caused largely by the difference in the half-lives of the decay products. Since Rn-220 products have longer half-lives, the body has longer to transport the activity from one compartment to another and thus deliver dose to different areas of the lung.

Since the working level is an air concentration, it is analogous to an exposure rate. To describe exposure, the unit working level month (WLM) is normally used. A WLM is described as the exposure equivalent to breathing one WL for 170 hours (one working month).

4.0 CALCULATION METHOD

The ICRP publication 66 (ICRP 1994) lung model was used to determine the proper conversion factor of dose per WLM for each isotope of radon. Each isotope of radon decays to several decay products creating a decay chain. Since most of the decay products are relatively short lived, all will decay in hours or days and most of that energy will be absorbed in the body. Therefore, the dose from the inhalation of a particular isotope is related most closely to the number of atoms inhaled from each isotope rather than activity inhaled.

Some of the isotopes have a branching ratio. That is the isotope decays to one isotope some percentage of the time and to a different isotope the rest of the time. To simplify the calculations, branching ratios representing less than 1% of the decays are ignored.

The LNet and LNth compartments were determined but not listed in the respiratory dose sections. Due to the fact that there is no direct deposition in the lymph nodes and the short half-life of the radon progeny, no significant dose is received by the lymph nodes. The progeny undergoes significant decay before any of the material can reach the lymph nodes. LNet and LNth doses are included in section 8.

4.1 ABSORPTION RATE

The rate material is absorbed from the lungs to the bloodstream is an important parameter. The ICRP 66 (ICRP 1994) lung model defines three default categories for particulate lung absorption. These defaults are to be used unless more specific information is known about the situation at hand. In the case of radon decay products, a number of references are available indicating an absorption half-life of approximately 10 hours. Marsh and Birchall (Marsh 1994) describe an evaluation while Nikezic (Nikezic 2002) lists four separate references to this value. Therefore, the 10 hour half-life is used in this calculation for each of the isotopes of radon.

4.2 PARTICLE SIZE

The particle size of the inhaled material is another important parameter for these calculations. The ICRP recommends a default particle size of 5 micron for a working environment and 1 micron for members of the public exposed to environmental releases. In both cases, these particle sizes are the median of a lognormal distribution of particle sizes. The default geometric standard deviation (GSD) is 2.5, the default density is 3 g/cc and the default shape factor is 1.5. This calculation uses all of these defaults with the exception of the particle size and GSD. GSD is calculated based on particle size using equation 16 of ICRP publication 66 (ICRP 1994).

The particle size distribution affects the regional deposition of the aerosol in the lungs. This size is greatly affected by the unattached fraction. The fraction that is attached to other particulates can exhibit the aerodynamic characteristics of the larger particle to which it is attached. The unattached fraction, on the other hand, represents very small particles produced from the noble gas (radon).

Nikezic et. al. (Nikezic 2002) indicated a particle size distribution for the attached fraction of 0.2 micron with a GSD of 2.35 while the unattached fraction was 0.0015 micron with a GSD of 1.1.

Porstendorfer (Porstendorfer 2001) indicated particle sizes for various environments. The unattached median particle sizes ranged from 0.00013 micron to 0.0013 micron with GSDs ranging from 1.1 to 1.3. For the attached fraction, the major contribution (~86%) exhibited median particle sizes of 0.33 micron for outdoor air and 0.217 micron for indoor air. Most of the remaining distribution exhibited a median size of ~0.040 micron. The GSD for these distributions varied from 1.5 to 2.2.

Birchall and James (Birchall 1994) indicated that the available data of attached aerosol size in underground uranium mines indicates a particle size between 0.15 micron and 0.5 micron with Samet et. al. (Samet 1991) considering the best estimate to be 0.25 micron.

ICRP 32 (ICRP 1981) indicates the value between 0.2 and 0.3 micron.

Based on the references above, for each of the isotopes of radon, these calculations will use a median particle size of 0.25 micron for the attached fraction. A size of 0.0015 micron will be used for the unattached fraction.

Two additional important parameters are the unattached fraction and the degree of equilibrium between members of the decay chain. These parameters vary with the different radon isotopes and will be discussed in the sections specific to each isotopes.

5.0 <u>RADON-222</u>

Rn-222 is historically known as Radon. The decay chain for Rn-222 and its short lived decay products is shown below.

Rn-222	3.8235 day	Alpha decay
Po-218	3.10 min	Alpha decay
Pb-214	27 min	Beta decay
Bi-214	19.9 min	Beta decay
Po-214	163.7 µsec	Alpha decay

(GE 1989)

The half-life of Po-214 is very short and thus will represent only a small number of atoms inhaled. Therefore, to simplify calculations, inhaled Po-214 will be ignored. Also, for dose calculations, it will be assumed that each decay of Bi-214 will include one decay of Po-214.

A direct risk-based Rn-222 exposure model is available for lung cancer cases in NIOSH-IREP. However the chronic lymphocytic leukemia (CLL) model requires the calculation of a lung dose from all sources including Rn-222. Table 5-2 provides the conversion factor but it should only be used for CLL dose calculations. This direct exposure model should continue to be used for Rn-222 exposures for lung cases.

The Po-214 decay was not modeled separately. The energy emitted from this decay was added to the Bi-214 decays. This is due to the very short half-life of Po-214 (approximately 0.16 msec).

5.1 UNATTACHED FRACTION

Rn-222 decay products are normally electrically charged. This causes the products to quickly attach to particles normally in the air. This greatly affects the aerodynamic characteristics of these particles which in turn affects the deposition of the particles in the lungs. While the unattached fraction is not specifically a parameter of the ICRP 66 lung model, the aerodynamic parameters are.

The unattached fractions used were 18%, 2.1%, and 0.07% for Po-218, Pb-214, and Bi-214 respectively. This was taken from a formula in NCRP Report 78 (NCRP 1984) that equates unattached fractions to dust particle concentrations in the air. The particle concentration used was $1x10^4$ particles per cm^3, which equates to an overall unattached fraction of 8%. This fraction is the same reported by Nikezic et. al. (Nikezic 2002) for indoor air. By comparison, Birchall and James (Birchall 1994) reported an unattached fraction of 1% for mine air. The dose conversion factor was determined to be higher for higher unattached fractions. Since the dust concentration is difficult to determine and the difference is not large (~15%) the 8% assumption was used. This should be an overestimate for most work sites.

5.2 EQUILIBRIUM

The equilibrium of the various Rn-222 progeny also affects the conversion factor. However, this also affects the number of working levels the activity in the air will represent. These tend to be competing factors and cause the effect on this conversion factor to be relatively small. Three equilibrium fractions were investigated. Two from NCRP Report 78 (NCRP 1984) and the third from Domanski (Domanski 1979). The factors along with the associated overall equilibrium factor are shown in the table below.

Table 5-1. Equilibrium Factors for Radon 222.

	NCRP 78 outdoor	**NCRP 78 indoor**	**Domanski**
Po-218	0.9	0.5	0.656
Pb-214	0.7	0.3	0.446
Bi-214	0.7	0.2	0.259
Overall	0.72	0.28	0.40

The highest conversion factor for the ET2 compartment was produced by the NCRP 78 outdoor factors. Given the small difference in factors, these fractions will be used as a slightly favorable assumption for all values of equilibrium.

5.3 RADON-222 RESULTS

As a result of these parameters, the Rn-222 conversion factors are listed in the table below.

Table 5-2. Dose Conversion Factors for Radon 222.

	Conversion Factor (Rem/WLM)
ET1 compartment	1793
ET2 compartment	6.09
Lungs[a]	15.69

a. Direct exposure model in NIOSH-IREP should be used for lung cases. The lung conversion factor should only be used for CLL cases.

6.0 RADON-220

Rn-220 is historically known as Thoron. The decay chain for Rn-220 and its short lived decay products is shown below.

Rn-220	55.6 sec	Alpha decay
Po-216	0.15 sec	Alpha decay
Pb-212	10.64 hours	Beta decay
Bi-212	60.6 min	Alpha decay (36%), Beta decay (64%)
Po-212	304 nsec	Alpha decay
Tl-208	3 min	Beta decay

(GE 1989)

The half-life of Po-216 and Po-212 are very short and thus will represent only a small number of atoms inhaled. Also, Tl-208 has a relatively short half-life but more importantly is a beta emitter. As such, it does not contribute to the working level calculation and represents an insignificant dose compared to other isotopes in the chain. Therefore, to simplify calculations, inhaled Po-216, Po-212 and Tl-208 will be ignored. For dose calculations, it will be assumed that each decay of Bi-212 will include one decay of Po-212 (64% of the time) and one decay of Tl-208 the remaining 36% of the time.

6.1 UNATTACHED FRACTION

Birchall and James (Birchall 1994) used an unattached fraction of 1% based on a report by Samet et. al. (Samet 1991) Nikezic et. al. (Nikezic 2002) used 8% apparently based on the same report. The largest difference appears to be that Birchall and James attempted to describe typical mine air while Nikezic attempted to describe typical household air. It should also be noted that both reports were describing Rn-222 decay products. The unattached fraction of Rn-220 decay products can be different due to the greatly different half-lives of the products. The Rn-220 products have longer half-lives and thus a longer period of time for the attachment to occur.

Yamasaki et. al. (Yamasaki 1995) performed a theoretical calculation that showed the unattached fraction for Rn-220 decay products to be approximately 1.6% for indoor air.

Porstendorfer (Porstendorfer 2001) demonstrated that the unattached fraction depends on the concentration of particulates in the air. He also showed that the unattached fraction of Rn-220 decay products is smaller than that of Rn-222 decay products. His values match well with each of the references above; therefore, this calculation will use a value of 2%. It is likely that the dust concentration in a work environment is higher than in a dwelling and thus the unattached fraction should be lower for the work environment. Therefore, when Yamasaki's value of 1.6% is considered, the 2% unattached fraction should be slightly high for a standard work environment. This can be shown to be a slight overestimate of dose conversion factors but with the percentages so low, it appears to be reasonable.

6.2 EQUILIBRIUM

The last major factor to consider is the state of equilibrium exhibited by the decay chain inhaled. The decay chain of Rn-220 is shown below.

Rn-220	55.6 sec	Alpha decay
Po-216	0.15 sec	Alpha decay
Pb-212	10.64 hours	Beta decay
Bi-212	60.6 min	Alpha decay (36%), Beta decay (64%)
Po-212	304 nsec	Alpha decay
Tl-208	3 min	Beta decay

(GE 1989)

When the chain is in 100% equilibrium, the activity of each generation is equal. However, the number of atoms required to reach this equilibrium activity varies depending on the half-life. Since the working level is defined by the ultimate energy released, it is affected by the number of atoms more than the total activity in a mixture. The alpha energy is emitted only by Po-216 and essentially Bi-212. In reality Bi-212 emits an alpha only 36% of the time but the other 64% of the time it emits a beta then an alpha almost immediately through the decay of Po-212 (304 nsec half-life). The average alpha energy released by a Bi-212 decay is then 7.8 MeV (6.07 Mev * 0.36 + 8.785 MeV * 0.64). Since Po-216 ultimately decays by two alphas (Po-216 and Bi-212) the alpha energy released per Po-216 atom is 14.6 MeV. Pb-212 and Bi-212 both decay with an effective alpha energy of 7.8 MeV. Po-212 decays with an energy of 8.785 MeV and Tl208 decays by beta decay only.

The largest number of atoms associated with the chain in equilibrium are Pb-212 and Bi-212 due to the relatively long half-lives. The remaining nuclides contribute little to the WL measurement or the lung dose. Therefore, in order to simplify the calculations, dose from inhaled Po-216, Po-212 and Tl-208 will be ignored. Also, for each Bi-212 decay, it is assumed there is an immediate decay of Po-212 64% of the time and Tl-208 the remaining 36% of the time.

Since Pb-212 has a half-life approximately 10 times larger than Bi-212, the number of Pb-212 atoms in a 100% equilibrium mixture is approximately 10 times that of Bi-212. This causes Pb-212 to be the primary contributor to the WL measurement regardless of the degree of equilibrium. On the other hand, Pb-212 atoms inhaled have more time to be removed from the lungs prior to emitting all energy that will ultimately be emitted by the remainder of the decay chain. Therefore, while the amount of Pb-212 in air drives the WL measurement, the amount of Bi-212 in air is a large contributor to lung dose. This causes the degree of equilibrium to be an important parameter. A good measurement of this degree of disequilibrium is the ratio of Bi-212 to Pb-212.

The degree of equilibrium depends entirely on the circumstances surrounding the production and movement of the Rn-220 gas in the breathing zone. This cannot be easily predetermined but a range of likely values can.

ICRP 32 (ICRP 1981) indicates this ratio (Bi-212 to Pb-212) is between 20% and 80%. Pillai and Paul (Pillai 1999) indicate the ratio is between 11% and 37% in a monazite mine and 24% to 84% in open air. This calculation will use 80% as a default value but also provide values for a range of equilibrium values. This will allow the most appropriate value to be used for the particular circumstances.

6.3 RADON-220 RESULTS

The ICRP 66 lung model was solved using the assumptions described above. Under the default assumptions used in this report, a dose of 6.20 rem to the lungs will be assigned per WLM of Rn-220 decay products inhaled. Similarly, the default doses to the ET1 region will be 943.83 rem and 0.45 rem to ET2. This value should be considered to be received entirely in the year the material was inhaled.

The values for different degrees of equilibrium were also calculated and are provided in the table below. The degree of equilibrium is specified by the ratio of Bi-212 activity to Pb-212 activity. These values can be used if information for the specific situation is available.

Table 6-1. Dose Conversion Factors for Radon 220.

% Equilibrium (Bi212/Pb-212)	Lung dose (rem) per WLM	ET1 dose (rem) per WLM	ET2 dose (rem) per WLM
20%	5.77	913.92	0.23
40%	5.92	924.25	0.31
60%	6.06	934.21	0.38
80%	6.20	943.83	0.45

7.0 <u>RADON-219</u>

Rn-219 is historically known as Actinon. The decay chain for Rn-219 and its short lived decay products is shown below.

Rn-219	3.96 sec	Alpha decay
Po-215	1.78 msec	Alpha decay
Pb-211	36.1 min	Beta decay
Bi-211	2.14 min	Alpha decay
Tl-207	4.77 min	Beta decay

The half-life of Po-215 is very short and thus will represent only a small number of atoms inhaled. As such, it represents an insignificant dose compared to other isotopes in the chain. Therefore, to simplify calculations, inhaled Po-215 will be ignored.

7.1 UNATTACHED FRACTION

No specific information was found for the unattached fraction of Rn-219. This fraction appears to be related to the time the particles have to attach to dust particles and so is related to the half-life. The first decay product of Rn-219 is Po-215 which has a half-life of 1.7 microseconds. This implies there is little time for it to attach to dust particles before it decays and so the unattached fraction is considered to be 100%.

For Rn-222, the first decay product (Po-218) is assigned an unattached fraction of 18% due to its short half-life of 3.05 minutes. Its progeny (Pb-214) has a half-life of 26.8 minutes leading to an unattached fraction of 2.1%. The progeny of Rn-220 are assigned an unattached fraction of 2% due to a longer half-life (10.64 hrs for Pb-212). It appears there is little change in the unattached fraction once the half-life of the progeny reaches a particular value. Since the second decay product of Rn-219 is Pb-211 with a half-life longer than Pb-214, an unattached fraction of 2% will be assigned to the second and subsequent decay products of Rn-219.

7.2 EQUILIBRIUM

The equilibrium of the Rn-219 progeny has little effect on the conversion factor. The initial progeny (Po-215) has a very short half-life and therefore represents very few atoms in one working level. The next progeny (Pb-211) drives the composition of progeny in a working level. This decays to Bi-211 which has a 2.13 minute half-life then to Po-211 which has a 0.516 sec half-life. Given the short half-lives of the progeny produced after Pb-211, it is reasonable to assume they are in 100% equilibrium with Pb-211.

7.3 RADON-219 RESULTS

As a result of these parameters, the Rn-219 conversion factors are listed in the table below.

Table 7-1. Dose Conversion Factors for Radon 219.

	Conversion Factor (Rem/WLM)
ET1 compartment	1066
ET2 compartment	2.92
Lungs	14.66

8.0 DOSE TO ORGANS OUTSIDE THE RESPIRATORY TRACT

The previous sections of this document describe the conversion factors for the respiratory tract for Rn-220, Rn-222 and Rn-219. Since the ICRP lung model is not element specific, no special treatment was necessary for decay products other than normal buildup and decay of radioactive isotopes. However, to determine dose to organs outside the respiratory tract, element specific biokinetic models must be used.

Each of these three isotopes of radon first decays to an isotope of polonium followed by lead then bismuth. For most isotopes, the ICRP recommends assuming decay products behave the same as the parent isotope (shared kinetics). However for some decay chains, the decay products are essentially assumed to behave consistent with their own characteristic model. This is the case for the decay chains described in this document. Biokinetic models for these elements are not identical which requires some consideration as to where decays in one model enter the next model. ICRP publication 67 (ICRP 1993) describes the method for handling this situation with publication 71 (ICRP 1995) Tables C-3 and C-4, providing transfer rates based on that description.

8.1 MODEL PARAMETERS

The absorption rate, particle size, unattached fractions and equilibrium factors used for the respiratory tract conversion factors are again used here for each isotope of radon. Only the default equilibrium factor of 0.8 for Rn-220 is used here since only modest differences occur in the calculated values using different factors. Specific effective energy (SEE) values were extracted from the computer program DCAL (DCAL 2006). However, it is necessary to discuss the SEE values associated with the “other” compartment. The “other” compartment in DCAL represents the other soft tissue compartment in the ICRP biokinetic models. This compartment is made up of all soft tissue not specifically described in the model. The mass and assigned fractions (AF) associated with this compartment vary depending on which organs are modeled and so they can vary depending on whether the decays occur as part of the ingrown or inhaled material. For that reason, the decays of an isotope in the soft tissue compartment are kept separate based on the original source of the inhaled material and multiplied by the applicable SEE.

Dose from the radon gas itself was also considered. For Rn-222, appendix C of ICRP publication 32 (ICRP 1981) was used to determine the dose to non-respiratory tract tissue from continuous inhalation of the gas. This dose was added to the dose calculated from the inhalation of the decay products. The half-life of Rn-222 is 3.8 days while the half-lives of Rn-220 and Rn-219 are much shorter (55.6 seconds and 3.96 seconds respectively). These short half-lives represent a much faster removal mechanism than Rn-222 and presumably a much smaller saturation concentration in the body tissues. Because of this, dose from the inhaled gas for these two isotopes was ignored.

8.2 ORGAN DOSE CONVERSION FACTOR RESULTS

Table 8-1 provides the calculated dose conversion factors for each radon isotope. It should be noted that these values are in units of mrem rather than rem used with the respiratory tract factors. Only the highest organ doses are provided. The remaining organs were similar enough to allow a single value to be presented as “all other organs”. This value represents a value that is equal to or higher than all the remaining organ factors.

Table 8-1. Dose Conversion Factors for Organs outside the Respiratory Tract

Organ	**Rn-219 (mrem/WLM)**	**Rn-220 (mrem/WLM)**	**Rn-222 (mrem/WLM)**
Urinary Bladder	1.5	10	9.6
Bone surfaces	21	210	18
Stomach	8.2	10	16
Small intestine	4.2	11	12
Upper large intestine	2.4	15	10
Lower large intestine	1.5	16	- [a]
Colon	2.0	15	9.8
Kidney	15	240	60
Liver	4.3	58	11
Red bone marrow	3.1	27	9.9
LN(ET)	2.0	13	17
LN(TH)	1.5	9.6	9.9
All other organs	1.4	9.1	9.3

a. Value was at or below the value for all other organs so the all other organs value should be used.

REFERENCES

Birchall A., James A. C., *Uncertainty Analysis of the Effective Dose per Unit Exposure from Radon Progeny and Implications for ICRP Risk-Weighting Factors*. Radiation Protection Dosimetry vol. 53, pp 133-140 (1994)

DCAL 2006, K. F. Eckerman, R. W. Leggett, M. Cristy, C. B. Nelson, J. C. Ryman, A. L. Sjoreen, and R. C. Ward, User Guide to the DCAL System, ORNL/TM-2001/190, UT-Battelle, Oak Ridge National Laboratory, Oak Ridge, Tennessess, August 2006, SRDB Ref ID 43944

Domanski, T., “Correlation between the equilibrium factor F and the relative concentration of radon daughters in mine air”, *Health Physics*, Vol. 137, 177 (1979)

GE 1989, General Electric Company, Nuclear Energy Operations, *Nuclides and Isotopes Fourteenth Edition, Chart of the Nuclides*, (1989)

ICRP Publication 32, *Limits for Inhalation of Radon Daughters by Workers.* ICRP Vol. 6 No. 1 (1981)

ICRP Publication 66, *Human Respiratory Tract Model for Radiological Protection.* ICRP Vol. 24 No. 1-3 (1994)

ICRP Publication 67, *Age-dependent doses to Members of the Public from Intakes of Radionuclides: Part 2 Ingestion Dose Coefficients.* ICRP Vol. 23 No. 3/4 (1993)

ICRP Publication 71, *Age-dependent doses to Members of the Public from Intakes of Radionuclides: Part 4 Inhalation Dose Coefficients.* ICRP Vol. 25 No. 3 - 4 (1995)

Marsh J. W., Birchall A., *Determination of Lung-To-Blood Absorption Rates For Lead and Bismuth which are Appropriate for Radon Progeny*. Radiation Protection Dosimetry vol. 84, No. 4, pp 331-337 (1999)

NCRP (National Council on Radiation Protection and Measurements) Report No. 78, *Recommendations of the National Council on Radiation Protection and Measurements, Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States*, Bethesda, Maryland, (1984)

Nikezic D. Haque A. K. M. M., Yu K. N. *Effects of Different Deposition Models on the Calculated dose Conversion Factors for ^{222}Rn Progeny*. Journal of Environmental Radioactivity vol 61, issue 3, pp. 305-318 (2002)

Pillai, P. M. B., Paul, A. C. Studies of the Equilibrium of ^{220}Rn (Thoron) and its Daughters in the Atmoshphere of a Monazite Plant and its Environs. Radiation Protection Dosimetry vol. 82, No. 3, pp 229-232 (1999)

Porstendorfer J., *Physical Parameters and Dose Factors of the Radon and Thoron Decay Products*. Radiation Protection Dosimetry vol. 94, No. 4, pp 365-373 (2001)

Samet, J. M., Albert, R. E., Brain, J. D., Guilmette, R. A., Hoopke, P. K., James, A. C., and Jaufman, D. G. *Comparative Dosimetry of Radon in Mines and Homes*. National Academy Press (1991)

Yamasaki, T., Guo, Q., Jida, T. Distributions of Thoron Progeny Concentrations in Dwellings Radiation Protection Dosimetry vol. 59, No. 2, pp 135-140 (1995)