CHAPTER II

THEORY AND LITERATURE REVIEW

Chapter II describes about the theory and literature review of radon, thoron and their decay products, particle size of aerosols, its activity size distribution as well as determination techniques, alpha radiation detectors and dose assessment.

2.1 Radon, thoron and their decay products

Radon (^{222}Rn) is a decay product from the ^{238}U decay series (Figure 2-1). It is an inert gas having a half-life of 3.8 d, which is long enough to enter the human respiratory system. Another member of radon isotope family is thoron, ^{220}Rn, having a half life of 56 s and chemical properties thensame as that of radon. Thoron is a part of the ^{232}Th decay series (Figure 2-2). The decay products of radon and thoron are solid and act as airborne particles. Mostly of the decay products are ^{218}Po ($T_{1/2}$ = 3.05 m), ^{214}Pb (26.8 m) and ^{212}Pb (10.64 h). A long lived radioisotope, ^{210}Pb (22 y), is produced in the ^{222}Rn decay chain within one hour from ^{218}Po. Initially, decay products are free atoms in the air and "unattached" to other aerosol particles. But these decay products are very small that they easily attach to aerosol particles. The fraction that attach depends strongly on the size and concentration of carrier aerosol particles. The basic processes of radon decay product behavior in air as show in Figure 2-3a and 2-3b.

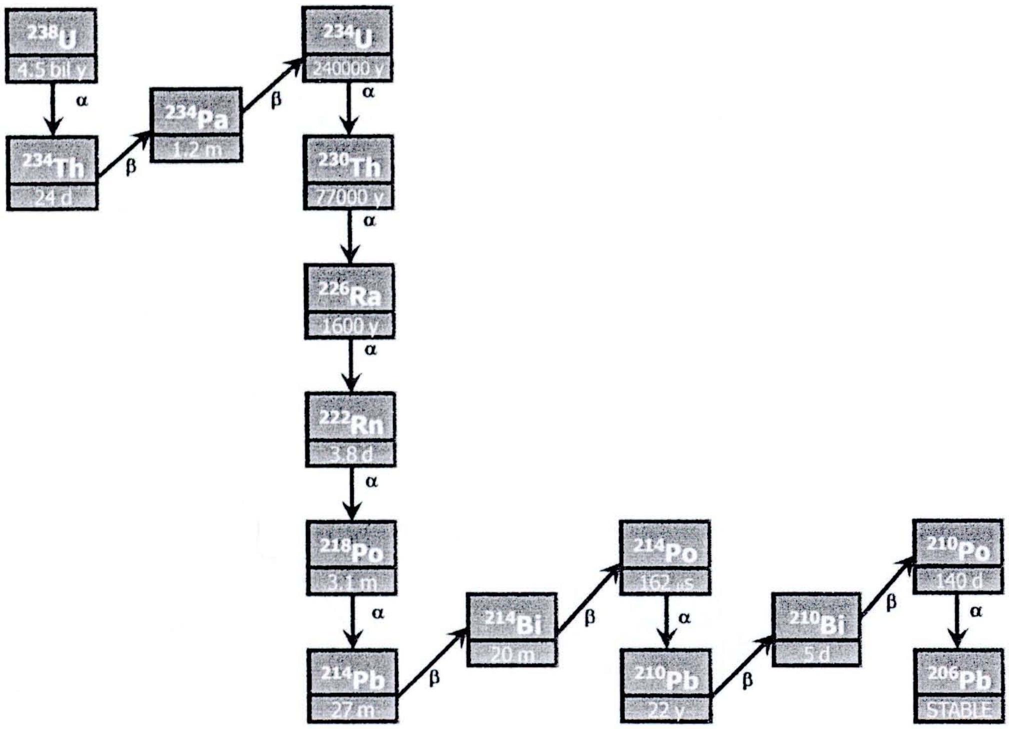


Figure 2-1 Natural decay series: Uranium-238.

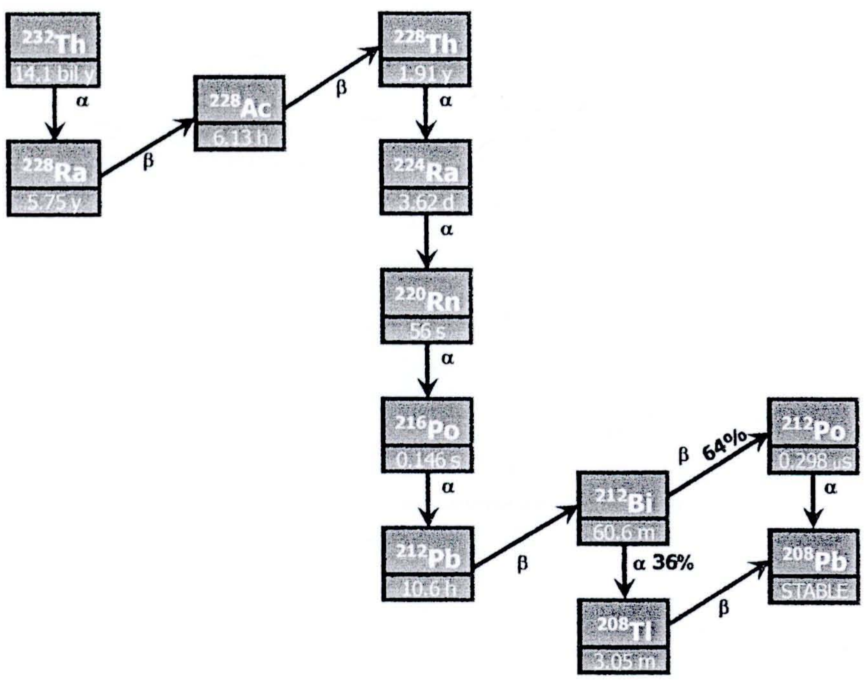
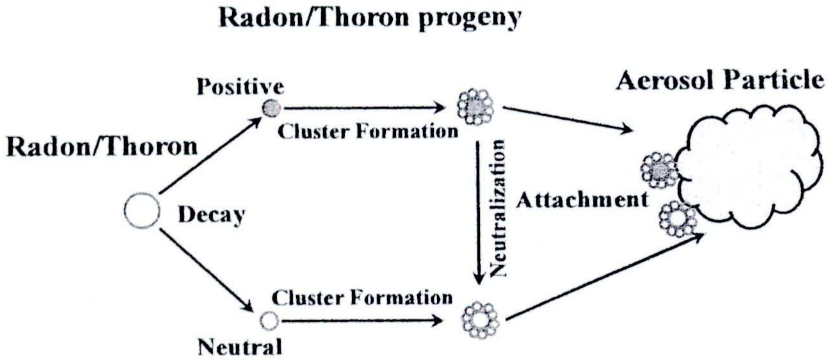
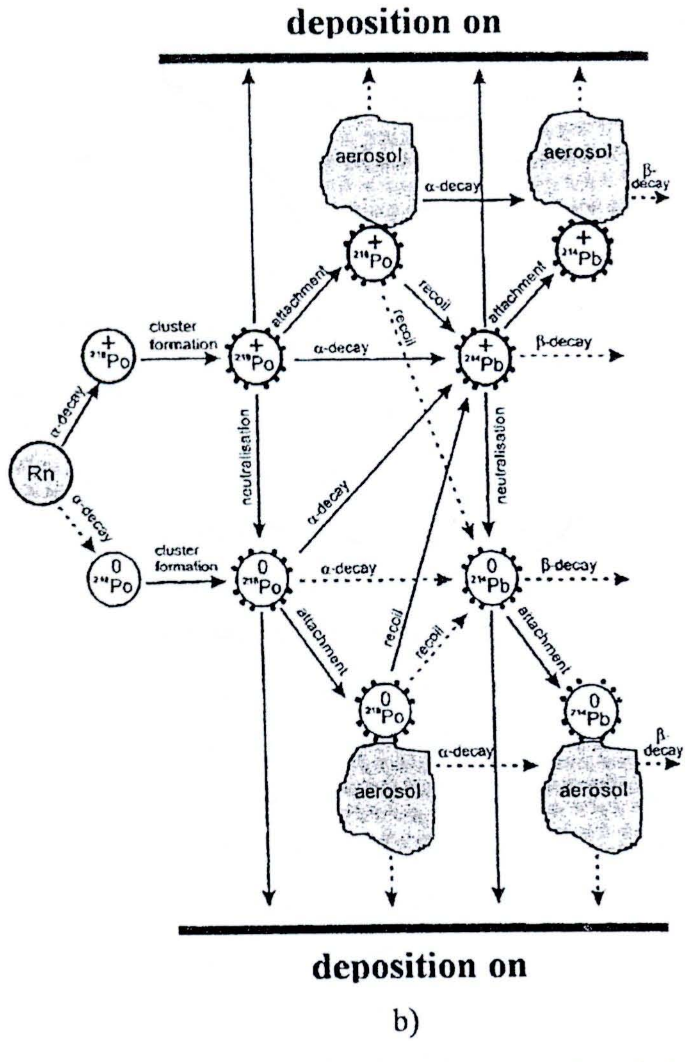


Figure 2-2 Natural decay series: Thorium-232.



a)



b)

Figure 2-3 a) Basic processes of radon decay product behavior in air defining "unattached" and "aerosol-attached" particle activities. b) Processes of ^{218}Po and ^{214}Pb in air [5].

2.2 Particle Size: A significant parameter of radioactive aerosol

Particle size is the most important attribute characterizing the properties and behavior of aerosols. Most aerosols have a wide range of sizes and their properties depend strongly on particle size. Particle size commonly refers to the dimension which is determined by its geometry. For spherical particles, it is their diameter. For irregularly shaped particle it is the volumetric equivalent diameter or light scattering equivalent diameter, electric mobility equivalent diameter and diffusion equivalent diameter. Airborne aerosol particles have irregular shapes, and their aerodynamic behavior is expressed in terms of the diameter of an idealized spherical particle known as aerodynamic diameter. The aerodynamic equivalent diameter (AED) (also called aerodynamic diameter) is the diameter of a sphere, with density = 1 g cm^{-3}, that has the same terminal settling velocity under gravity as the airborne particle considered. Particles are sampled and described on the basis of their aerodynamic diameter. Particles having the same aerodynamic diameter may have different dimensions and shapes.

In dosimetry and inhalation toxicology it is often more important to describe the size distribution of aerosols rather than individual particle size. Particle size distribution (PSD) is a description of how much of the aerosol is in each set (or continuum) of size intervals. One can count the number of particles in the size interval or one can weigh them (these are the two most common approaches). The PSD is most properly means the functional relation between the number of particles and some measure of the particle size. Size is usually taken to mean the diameter, so the PSD is often presented as a graph of the logarithm of the total number of particles smaller than particle diameter "d". The PSD can be monodisperse or polydisperse. Monodisperse means all the particles are of the same size and polydisperse refers that particles are of more than one size.

Most size distributions require two parameters: one that identifies the location or center of the distribution and another that characterizes the width or spread of the distribution. The most commonly used quantities for defining the location of distribution are the mean, mode, median and geometric mean. The distribution of mass and the distribution of count for the same sample of particles have different means, medians, geometric means, graphical representations and probability density functions. The median of the distribution of mass is called the mass median diameter (MMD), while the median of the distribution of count is called the count median diameter (CMD). These two parameters are frequently encountered in size distribution discourse. In discussing about the size distribution of radioactive aerosol, another entity that frequently comes across is the activity median aerodynamic diameter (AMAD).

AMAD is used when deposition depends mainly on sedimentation and intertial impaction, typically when the AMAD is greater than about 0.5 μm. Fifty percent of the activity in an aerosols is associated with particles of aerodynamic diameter greater than or smaller than the AMAD. A lognormal distribution of particle sizes is assumed. The AMAD refers to the entire distribution. The AMAD is the aerodynamic equivalent diameter (AED) for which one-half of the radioactivity in a distribution has an AED smaller than the AMAD and one-half of the radioactivity in a distribution has an AED larger than the AMAD. The AMAD, along with the associated the geometric standard deviation (σ_g), is the most useful diameter for characterizing the behavior of the aerosol in air, in sampling instruments, and the respiratory tract.

Aerosols are defined as a suspension of solid or liquid in a gas. The term aerosol includes both the particles and the suspending gas, which is usually air. Thus an aerosol is a two-phase system, consisting of the particles and the gas they are suspended in. A complete description of the atmospheric aerosol would include an accounting of the chemical composition, morphology, and size of each particle as well as the relative abundance of each particle type as a function of particle size [18]. Most of the airborne radionuclides attach on the surface of aerosol particles and form radioactive aerosol. The majority of these aerosols present in natural and work environments are polydisperse.

The distribution of aerosol particles with respect to size is a very important physical parameter governing particle behavior. Aerodynamic size, rather than geometric size, determines the trajectory of the particle in a gas stream because it accounts for all three major aerodynamic factors: size, shape and mass density. The aerodynamic size distribution of aerosol particle captured by the sampler can be represented by the lognormal distribution. Thus the lognormal distribution (i.e., the situation in which the logarithms of particle diameter (d_p) are distributed normally) are in use for describing size distributions of aerosols. The geometric mean is the median of the distribution and the metric of variability around this central tendency is the geometric standard deviation (σ_g). The σ_g , is a dimensionless term, is the ratio of particle size at the 84^{th} (or 16^{th}) percentile to the 50^{th} percentile [19]. Thus, the only two parameters needed to describe a lognormal distribution of particle sizes for the radioactive aerosol are the median diameter and the geometric standard deviation (σ_g). However, the actual size distribution may be obtained in various ways. The discussion in this dissertation will be focus on AMAD because it is the most commonly used measurement of radioactive aerosol distribution. However, alternative descriptions are also used for particles with actual physical sizes below 0.5 μm because in such a case, aerodynamic properties become less important. Due to their instability as an aerosol depends mainly on their interaction with air molecules. Like particles in Brownian motion, they are caused to "diffuse". For these small particles and especially for ultrafine particles, this interaction is independent of the particle density and varies only with geometric particle diameter. Very small particles are not expressed in aerodynamic equivalency, but instead to a thermodynamic-equivalent size. The thermodynamic particle diameter is the diameter of a spherical particle that has the same diffusion coefficient in air as the particle of interest. The activity median thermodynamic diameter (AMTD) is the diameter associated with 50 percent of the activity for particles classified thermodynamically.

2.2.1 Activity size distribution of radioactive aerosol

Usually the activity size distribution of radon decay products can be determined by two approaches. By calculation, if the number size distribution *Z(d)* of the atmospheric aerosol is known by measurement, then the activity size distribution *C(d)* can be obtained by the correlation expression between *C(d)* and *Z(d)* as follows:

$$C(d) = \frac{c}{x}\beta(d)\,Z(d) \tag{2-1}$$

where c is the activity concentration, x is the attachment rate and $\beta(d)$ is the attachment probability [20]. While the other one is the direct measurement of the activity size distribution of the decay products. The activity size distribution of radioactive aerosol can be obtained directly using impactors or impingers, multi-channel graded wire screen diffusion batteries.

At present, cascade impactors are the instruments of choice for measuring the particle size distribution of aerosol. The cascade impactors are widely used for measuring the size distribution of aerosol particles in the area of environmental pollution [3], health physics and in atmospheric electricity. The inertial impactors are devices widely used for sampling and size-selective collection of aerosol particles. There are two classes of inertial impactors: single stage impactors and multiple stage impactors that are popularly known as cascade impactors. The cascade impactor is an instrument used for the classification of aerosols in terms of AED and for possible subsequent chemical analysis.

2.2.2 Activity size distribution determination techniques

Airborne particle size varies from molecular clusters measuring approximately 1 nanometer to cloud droplets and dust particles measuring around 100 micrometers, five to six orders of magnitude larger. Size is an important particle property, because it largely determines particle behavior in gas suspension. Particles at different ends of the size range behave in completely different ways and are even governed by different physical laws. As there is no single measurement technique capable of handling this range of sizes, the most appropriate method needs to be selected on a case-by-case basis. There are various methods for aerosol size measurement. These are mobility analyzers, diffusion batteries, optical particle counters, optical microscopes, time of flight methods, inertial methods, impactors, scanning electron microscope, transmission electron microscope etc. The main features of these methods are discussed in Appendix A.

Particle shape is another important parameter. Particle diameter is an unambiguous measure of particle size only for spherical particles, in contrast, is difficult to define for non-spherical particles, such as agglomerates, fibrous, and crystals. As a result, particle size is usually defined by the chosen measurement method, and particle size given in equivalent diameter, most commonly aerodynamic equivalent diameter, electrical mobility equivalent diameter, light scattering equivalent diameter, optical equivalent diameter and diffusion equivalent diameter.

Aerodynamic diameter is useful for characterizing particle settling and inertial behavior, and can be used to describe the behavior of particles in the human respiratory tract, filters, cyclones, and impactors. The most common instrument used here is impactor. Mobility equivalent diameter provides information on how particles respond to external forces, and is important when diffusion or electrical forces govern the behavior of particles. Mobility equivalent diameter is usually measured using electrical mobility analyzers, such as differential mobility analyzers (DMA) [21] and scanning mobility analyzers (SMPS) [22]. Optical diameter, for its part, depends on the interaction of light with particles. In practice, data is reported in terms of an equivalent diameter for particles with the same refractive index as that of the calibration aerosol of the instrument employed. Diffusion equivalent diameter is usually measured using diffusion battery. Diffusion battery devices separate radon decay products into size fractions using differential mobility to capture the higher-mobility particles. Often these devices draw the air sample through one or more fine mesh screens that precede a "collect-all" filter.

Of all the techniques, inertial impactors are devices widely used for the sampling and size-selective collection of aerosol particles. Their principle of operation is simple: an aerosol stream passes through a nozzle and impinges upon a collection plate. Particles in the aerosol stream having large enough inertia will impact upon the collection plate while the other particles will follow the airflow out of the impaction region. There are two classes of inertial impactors: single stage impactors and multiple stage impactors (also called cascade impactors). The cascade impactors are commonly used to determine the aerosol size distribution. They have sharp cut-point characteristics, low internal particle holdup, and are easy to operate. Particles can be collected on substrates for microscopic analysis or additional measurements of mass or composition. They are designed for applications where wide size-range coverage and fast response are required. The theoretical principle and construction details of a cascade impactor are presented in Appendix B.

In general, there are advantages and disadvantages for every particle sizing technique and for every particular instrument. It stands to reason that certain techniques are better suited for certain tasks, and that no instrument will be able to solve all problems. There are several publications using different methods for particle size characteristics by various researchers. There has been significant progress in techniques for the determination of the activity size distribution in the recent days. Despite the progress, many inconsistencies/differences still exist with respect to the activity distribution, especially in the range of smaller particle size.

Porstendörfer et al. [20] studied the activity size distribution of short–lived radon decay products in ambient air continuously for several hours. They used two different measurement techniques: direct measurements with a low pressure on-line alpha cascade impactor (OLACI) and an indirect determination based on measurement with a differential mobility analyzer (5~200nm) or a laser aerosol spectrometer (100~5000nm). The results of both measurement techniques show that the greatest activity fraction of the radon decay products is adsorbed on aerosol particles in the accumulation size range.

The size distribution studies of radon/thoron decay products have also been performed in the open air by Becker et al. [23]. A high volume cascade impactor was used and the gamma activity on were measured by a well type Ge detector. The impactor data were evaluated by means of an improved computer program taking into account the effect of inter stage losses on the measured precipitation values of the impactor.

Yamada et al. [24] measured the aerosol size information using a commercial cascade impactor i.e. electrical low pressure impactor (ELPI). The impactor covered a wide diameter range from 0.03 to10 μm, gave number weighted size distribution in real time by an electrical detection method. ELPI allowed size distribution data on aerosol number and activity to be independently determined for the same impactor sample.

Rahman, et al. [25] evaluated the size characteristic of low pressure cascade impactor using imaging plate technique for radon decay products. The radon aerosol-particle size distribution was obtained by drawing air sample through a 13 stage low pressure Anderson cascade impactor. The impactor, which covers a wide diameter from 0.05 to 12 μm. The air sample was collected on 47 mm diameter of stainless steel plates with a coating of silicon grease of 7.5 $mg.cm^{-2}$ taken as collection media.

The activity size distributions of both unattached and attached fractions of short lived radon decay products (^{218}Po, ^{214}Pb and ^{214}Bi) were measured in indoor air by Mohammed [26]. The measurements were performed with a wire screen diffusion battery and a low pressure cascade impactor (Berner type). In addition, the collected activity on each impactor stage was measured with a germanium detector. Most of the attached activities were associated with the aerosol particles of accumulation mode.

Knutson and Tu [27] improved particle size data for reconstructing the radiation dose by combining data from an impactor with data from a diffusion-based sampler. It was possible to cover the particle size range from 0.5 to 5000 nm. In case of attached radon progeny, a micro-orifice uniform deposit impactor (MOUID) was used. After sampling, each sampling substrate was simultaneous counted the alpha particles by ZnS(Ag) alpha scintillation counters and the weighted least squares method was used to calculate the activity of ^{218}Po, ^{214}Pb and ^{214}Bi on each substrate. The expectation-maximization algorithm was used to calculate particle size distributions from the activities measured each substrate of the MOUDI.

A new technique for measuring the activity size distribution of radon progeny were developed by Tokonami, et al [28]. This activity size distribution instrument incorporates both impactor and wire screen method. The wire screen prevents the invasion of unattached fractions into the cascade impactor. After that, attached fractions are introduced into the four-stage low pressure cascade impactor, which covers a diameter range from 0.07 to 2.1 μm. The silicon photodiodes, while the ceramic windows were removed, were installed in each stage of the impactor for measuring alpha particles of radon progeny. This instrument can determine the size distribution of radon progeny and the aerosol in a normal environment within 90 minutes.

All these studies support the fact that cascade impactors are convenient as particulate size distribution measuring instrument for indoor as well as for outdoor sources. The reviewing of the earlier research works provided a helpful suggestion to ensue the present study using the impactors described in Appendix A.

2.3 Alpha radiation detectors

A number of different techniques are used for radon measurements at home or at workplaces. These range from collection of radon decay products on an air filter and counting, exposing a charcoal canister for several days and performing gamma spectroscopy for absorbed decay products, exposure of an electret ion chamber and readout, and long-term exposure of CR-39 plastic with subsequent chemical etching and alpha track counting. All these approaches have different advantages and disadvantages which need to be evaluated prior to use. The most commonly used radon measurement devices are Charcoal Canisters, Solid state nuclear track detector or SSNTD, scintillation counter, liquid scintillation counters (LSC), Proportional counter and multi channel analyzer (MCA) etc. The main features of all these devices are described in Appendix C.

All commercial instruments, to measure the activity of the alpha particles from the aerosols on impactor substrates, are expensive, too large and cumbersome to conduct experiments in the normal environment. Generally, is analyzed either with a solid state detector or with a traditional ZnS (Ag) scintillation detector. These detectors are sensitive to light leaks through the Aluminized Mylar window in case of alpha scintillators. Zinc sulfide scintillation counters are prone to window punctures. Scintillation counters can be affected by magnetic fields, adversely affecting the instrument response. The photomultiplier tubes that they contain are fragile, require a well-regulated power supply, represent a shock hazard, and operationally degrade over time. In addition, these instruments are also mechanically affected by humidity and temperature [9].

So in this study the solid state nuclear track detectors (SSNTDS), namely CR-39 has been widely used for radon and thoron measurements, was proposed with the potential to overcome above limitations of ZnS (Ag) scintillation detector [10].

2.3.1 Nuclear track detector as radiation detector

Operation of the solid-state nuclear track detector is based on the fact that a heavy charged particle will cause extensive ionization of the material when it passes through a medium. For example, an alpha particle with energy of 6 MeV creates about 150,000 of ion pairs in cellulose nitrate. Since the range of a 6 MeV alpha particle in this material is only about 40 mm that means on average 3700 ion pairs are created per μm, or 3–4 ion pairs per nm. An alpha particle ionizes almost all molecules close to its path. This primary ionizing process triggers a series of new chemical processes that result in the creation of free chemical radicals and other chemical species. Along the path of the alpha particle, a zone enriched with free chemical radicals and other chemical species is then created. This damaged zone is called a latent track.

If a piece of material containing latent tracks is exposed to some chemically aggressive solution, chemical reactions would be more intensive along the latent tracks. Aqueous solutions of NaOH or KOH are the most frequently used chemical solutions. The overall effect is that the chemical solution etches the surface of the detector material, but with a faster rate in the damaged region. In this way, a ''track'' of the particle is formed, which may be seen under an optical microscope. This procedure is called ''detector etching'' or track visualization, and the effect itself is called the ''track effect''.

The track effect is relatively well known, and the technique is rather simple and straightforward, there is not a unique theory that explains track formation. The basic physical processes after the initial charged particle loses its energy are the ionization and excitation of molecules of the material. This first ''physical'' phase in which the initial particle delivers its energy to the atoms surrounding its path is very short in time; stopping of the particle occurs within a time of the order of picoseconds. The free electrons created in these primary interactions will slow down through a series of ionizations and excitations, and will create more and more free electrons. Some of these may go further away from the initial particle path creating the so-called delta (δ) rays. A large number of free electrons and damaged molecules are created close to the particle track.

In the second physiochemical phase, new chemical species are created by interactions of the damaged molecules. During etching, the interactions of these new chemical species with the etching solution are stronger than that with the undamaged detector material. However, it is not known which chemical species are formed after the particle passage through the material, and the nature of damage is also not entirely known.

2.3.2 Stopping power, restricted energy loss

The primary process of charged-particle interaction with the detector material is ionization and excitation of the molecules in the detector. The initial charged particle loses its energy through the many interaction processes. Theoretically, it interacts through Coulomb force with charged particles (electrons and nuclei) in the material. Of course, distal interactions may be neglected and we focus on the particle interactions with atoms and molecules that are close to its path. The majority of the interactions occur with electrons and only a small number of interactions are with nuclei. Since the initial heavy charged particle (only such particles can produce tracks) is much heavier than electrons, the direction of the particle effectively does not change and the path is almost completely a straight line. This may not be true if the particle interacts with a nucleus, where a significant deviation from the initial direction may occur. However, such interactions are relatively rare. Some deviations from the straight line can happen close to the end of the particle range, when the energy of a particle becomes very low.

The particle loses its energy in many small interaction processes, so the energy loss each time is usually very small when compared to its energy. For example, ionization of one molecule in air on average needs about 32 eV, which is 10^{-5} to 10^{-6} of the particle energy (assuming that the particle energy is in the MeV region). As a result of these many small interaction processes, the particle will continuously slow down in the detector material. The physical quantity that describes the slowing down of charged particles in mater is the stopping power -dE/dx (or the stopping force), where dE is the energy lost in the distance dx. Stopping power is given in J/m or in keV/mm. The energy lost by a particle in the distance dx is the energy transferred to the material so this quantity is also called the linear energy transfer (LET).

The first expression for the stopping power was given by Bohr [29]. That was a classical consideration of the particle interaction with a free electron, where the energy lost in the collision with one electron was integrated in some assumed limits of interaction and the expression for the stopping power was derived. This was modified by taking into account the quantum effects by Bethe [30], and the relativistic effects by Bloch [31], and finally the well-known Bethe–Bloch expression for the stopping power was given as:

$$-\frac{dE}{dx} = \frac{Z^2 e^4}{4\pi\varepsilon_0^2 m_0 v^2} N \left[ln \frac{2 m_0 v^2 W_{max}}{\bar{I}^2 \left(1-\beta^2\right)} - 2\beta^2 - \delta - U \right] \qquad (2\text{-}2)$$

where Z was the charge of the incident particle, v its velocity, $\beta = v/c$, m_0 the rest mass of the electron, N the number of electrons per unit volume, $\bar{I}$ the average excitation potential of electrons in the stopping material, W_{max} the maximal value of transferred energy of electron, δ the correction for polarization of the material and U takes into account non-participation of inner electrons in the collision. The stopping power given in the above equation takes into account only collisions with electrons. Events with nuclei are not considered.

Equation 2-2 has been from perturbation theory and the first Born approximation. The drawback of this equation is that in the low-energy region, this approximation may not be valid, i.e., the function inside the logarithm may become less than 1, thus the whole expression becomes negative in the low-energy region. In addition, this formula does not take into account some effects that appear when the energy of particles falls below some limits. Slowly moving charged particles can experience the charge exchange process, viz. capture of an electron in a collision with an atom of the stopping medium, and lose it in subsequent collisions. The charge of ions is not equal to Z and the effective charge Z_{eff} should be introduced to describe the process. However, such a simple change of the formula is not sufficient to describe the complicated process of charge exchange.

When the particle loses energy in the material, part of the energy is taken by energetic electrons which can then go far away from the initial particle path and are called δ rays. This energy is spent far away from the particle path and does not take part in the formation of the particle track. For this reason, a new quantity called the restricted energy loss (REL) was introduced $(-dE/dx)_{Eb}$. Only energy transfers smaller than Eb are considered for calculations of dE. Here, for collisions with energy transfer larger than E_b, δ electrons are assumed to be formed, which do not take place in track formation. As we will see later, there is not a unique value for E_b.

The concept of REL is also used in other fields of physics. However, this quantity is not unique, and may be different for various materials. For this reason, a microdosimetric quantity called linear energy, which does not have such shortcomings, is used.

Nowadays, some computer softwares are available for the calculation of stopping power and range of charged particles in different media. The most well-known one is the SRIM (Stopping and Range of Ions in Matter) program developed by Ziegler et al. [32].

2.4 Dose assessment

There are two approaches for the dose assessment due to radon and thoron progeny inhalation: (i) dosimetric approach that developed by the International

Commission on Radiological Protection (ICRP) [33] to calculate dose and (ii) epidemiological approach that derived directly from studies on cohorts of miners.

In this study, the dosimetric approach will be used to calculate the dose conversion factors of radon and thoron decay products. The dose calculations were conducted using a computer program LUDEP (Lung Dose Evaluation Program) [34].

2.4.1 The new ICRP lung model and LUDEP

LUDEP and the new ICRP respiratory tract model were developed for dose assessment over the past ten years. To implement new models, there were extensive period of consultation with interested parties and several papers have been reported describing its progress from time to time. ICRP adopted version 1.0 as its first model to implement structurally. However, version 1.1 was the first to be fully compatible with ICRP Publication 66 [33].

2.4.2 Description of LUDEP

LUDEP is a suite program using Turbo and Power Basic and have been compiled for the IBM1 - compatible personal computer. It enables the user to calculate doses and dose rates to the respiratory tract regions and other body organs for a wide range of user-defined conditions. The software has been designed to be as flexible as possible, permitting the user to change most of the parameters used in the dose calculation and display the results obtained at each stage of the calculation. Although flexibility can be useful, it requires the user to make more decisions and in some situations this can increase the probability of errors. In the majority of situations, the user will not wish to deviate from ICRP-recommended parameter values, and so LUDEP has been designed to select these default values automatically when loaded.

The program has been designed in a modular form, with each module called automatically by a central program, over which the user has direct control. The upper part of the screen contains the menu for selecting the modules which enable the various parameters to be specified and the dose calculations to be performed; the lower part of the screen displays the values of several of the more important parameters already chosen by the user. The necessary parameters are entered using the options contained in the 'Input Parameters' menu, described below.

The first option, INTAKE REGIME, allows details of the intake or exposure to the radionuclide to be entered.

The next, TIME, enables the user to specify the time at which the dose rate or cumulative dose is to be calculated.

DEPOSITION permits the fractional deposition in each region of the respiratory tract to be specified directly, or calculated from specific particle size parameters and/or physiological parameters.

In PARTICLE TRANSPORT, the rates at which deposited particles move from one region of the respiratory tract to another, and the rates at which particles are cleared from the respiratory tract, can be altered.

In ABSORPTION, the rates of particle dissolution and subsequent uptake to blood are specified.

RADIONUCLIDES enable the radionuclide of interest to be selected from one of two databases. The first incorporates decay data from ICRP Publication 38, and is recommended to the user. The second is included for comparison purposes.

BIOKINETIC MODEL allows the user either to enter a biokinetic model directly or to select one of the models specified in Publication 30 [35].

The calculations menu contains options for calculating dose to the body organs.

The option, DOSE CALCULATION, accesses the modules in which the doses or dose rates to the regions of the respiratory tract and to the body organs are calculated, using an internal database of specific absorbed fractions for photons. The user is given the choice of using either the ICRP Publication 26 tissue weighting factors, or those given in ICRP Publication 60 [36].

The final menu option, LUDEP UTILITIES, contains some useful facilities, including those for saving all the parameters into a disk file and entering the DOS environment with LUDEP stored in memory.

2.4.3 Mathematical approaches used in LUDEP

In ICRP Publication 66 [33] the deposition of a mono-disperse aerosol in the different regions of the respiratory tract is modeled by treating the regions as a series of filters. Deposition occurs in all regions of the HRT (Human Respiratory Tract), but with different efficiencies. The deposition pattern depends on the aerosol diameter as well as airflow characteristics. The behavior of small-size particles which are deposited by diffusion is described in terms of the thermodynamic diameter d_{th} and the diffusion coefficient D. Deposition of larger particles is described by the aerodynamic diameter d_{ae}.

The aerodynamic diameter is defined in terms of the equivalent particle volume diameter d_e i.e., the diameter of a spherical particle with the same volume as the considered particle. Each region of HRT has deposition efficiency, η, which denotes the fraction of the number of particles that enter a single region of the respiratory tract that is deposited in that region. The deposition efficiency, η depends on both the thermodynamic and the aerodynamic diameters of the particles. Algebraic expressions for η are given in ICRP Publication 66 as,

$$\eta = \sqrt{\eta_{th}^2 + \eta_{ae}^2} \qquad (2\text{-}3)$$

where, η_{th} is the thermodynamic deposition efficiency and η_{ae}, is the efficiency of the aerodynamic deposition process which includes both "impaction", η_i and "sedimentation", η_s components and can be related by the following expression:

$$\eta_{ae} = 1-(1-\eta_i)(1-\eta_s) \qquad (2\text{-}4)$$

LUDEP implements above equations directly for monodisperse aerosols and treats polydisperse aerosols as a convolution of 100 monodisperse aerosol of appropriate particle size.

The LUDEP dose calculation module combines the respiratory tract model with the ICRP gastrointestinal (GI) tract model [34] and the biokinetic models to form one large non-recycling compartment model. The deposition fractions are combined with the intake to determine the initial number of atoms in each compartment. The remaining activity and integrated disintegrations in each compartment are then calculated using a very fast algorithm.

Dosimetry for body organs is treated in the conventional manner [34]. First, the dose to each of the target organs from one disintegration in each source organ is calculated by combining decay information for chosen radionuclide with the appropriate absorbed fractions [34] to form a matrix of specific effective energy SEE values. The dosimetric formulation of ICRP Publication 30 [35], in which the committed equivalent dose, H_T in a target organ T is determined by the energy absorbed per unit mass from the radiation emitted from a source organ, can be expressed as:

$$H_{(t,t_0)} = c\sum_S \sum_t q_{S,t}(t)\, SEE\,(T \leftarrow S;t) \qquad (2\text{-}5)$$

where, $q_{s,j}(t)$ is the activity of radionuclide j present in source organ S at age t ; $SEE(T \leftarrow S;t)$ is the total energy absorbed per unit mass in the target T ; the contribution of each radiation emitted by the radionuclide are weighted by their radiation weighting factor, per nuclear transformation of radionuclide in source region S ; and c is any numerical constant required by the units of q and SEE .

The SEE matrix is then multiplied by the array containing the number of disintegrations in each source organ to give the dose to each target organ. Dosimetry of the respiratory tract is treated by using algebraic approximations [34] for the energy-dependent absorbed fractions from the various sub-regions of the respiratory tract to the sensitive cells.

To calculate regional doses in the ICRP dosimetric system, it is necessary to sum doses those for extrathoracic airways and those for the thoracic regions. Since the regions of respiratory tract vary greatly in radiation sensitivity, therefore the regional doses must be adjusted for their relative sensitivity to sum up finally. The regional doses, weighted with factors assigned for the partitions of radiation detriment, are summed to give a value of committed equivalent dose for extrathoracic region and another for the thoracic regions, as follows:

$$H_{ET} = H_{ET_1}A_{ET_1} + H_{ET_2}A_{ET_2} + H_{LN_{ET}}A_{LN_{ET}} \qquad (2\text{-}6)$$

$$H_{TH} = H_{BB}A_{BB_1} + H_{bb}A_{bb} + H_{AI}A_{AI} + H_{LN_{TH}}A_{LN_{TH}} \qquad (2\text{-}7)$$

where, H represents the committed equivalent dose,

A represents the assigned fractions of tissue weighting factors, w_T,

ET_1 represent the anterior nose, ET_2 is the posterior nasal passages, larynx and mouth,

LN_{ET} represents the lymphatics of the extrathoracic region,

BB *is* the bronchial, bb is the bronchiolar, AI is the alveolar-interstitial and

LN_{TH} is the lymphatics of the thoracic region.

The appropriate ICRP tissue weighted factor, T_w can then be applied to these two values in calculating effective dose as described in ICRP 60 [36].

2.4.4 Best estimated parameters for calculating dose using LUDEP

The ICRP 66 lung dose model offers the ability to input data characteristic of specific material. The ICRP 66 model employs ten input parameters for determination of regional deposition fraction [37]. Thus the program package LUDEP has also been designed to be as flexible as possible, permitting the user to change all these ten parameters. These input parameters were varied according to their characteristic distributions, in an effort to perform uncertainty analysis of regional deposition fraction.

The sensitivity of the weighted equivalent dose to lung per unit exposure of radon decay products to HRTM was verified and cited in literatures. The parameters considered to be the most influential are: (i) aerosol parameter, (ii) breathing rate, fraction breathed through nose and the age and gender of subject itself, (iii) target cell parameters, and (iv) the parameters that define the absorption rates of radon & thoron decay products from lung to blood.

While considering all these sensitive parameters, best estimated input parameter values were taken for LUDEP to calculate dose for the present study and these values are presented in Table 2-1.

These parameter values were the best representation for the radon and thoron decay products measured indoor and workplace and were recommended by Ishikawa et al. [38, 39], Porstendörfer et al. [40, 41], Marsh et al. [42], Nuccetelli, and Bochicchio [43] and by Kranrod et al. [44]. The best estimated parameter values used for the lung model are the HRTM default values for a male adult at indoor environment.

Table 2-1 The best estimated parameter values for the this study

Input category	Parameter	Input value
Time	Time for dose calculation (years)	50
Deposition	Nose/mouth breathing	Nose breathing
	Breathing rate (m^3 h^{-1})	0.78
	Particle density (g cm^{-3})	1
	Particle shape factor	1
Absorption	Half-time for absorption into blood (h)	10
	Fraction cleared by rapid dissolution (d^{-1})	1
	Rapid dissolution rate (d^{-1})	1.65
Radionuclides	—	RnP:^{218}Po,^{214}Pb,^{214}Bi TnP: ^{212}Pb,^{212}Bi
Bio-kinetic model	—	ICRP 30
Dose calculation	Radiation weighting factor (alpha particles)	20
	Tissue weighting factor	ICRP 60
	Assigned partition for tissue weighting factor among thoracic region (BB:bb:AI)	0.333:0.333:0.333
	Equilibrium factor	RnP:0.4, TnP:0.02

2.4.5 Dependence of dose on radon/thoron decay products particle size

The particle size distribution of radon/thoron aerosols characterized by AMAD is an important attribute for dose assessment. When radon thoron and their decay products are inhaled, only a minor portion of radon and thoron decays in the lungs, whereas radon and thoron decay products appear in the form of clusters and aerosols deposited on the walls of airways in the mouth, nose and lungs, where they further decay and damage the nearby tissue. For this reason, the main concern for radon and thoron dose assessment are not radon and thoron themselves rather their decay products ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi. Therefore, it is important to comprehend the dependency of dose on radon and thoron decay products particle characteristics. This dependency was evaluated in the study by calculating "Dose Conversion Factor" (DCF) for radon and thoron decay products with different activity median diameter (AMAD). The dose conversion factor for radon thoron and their decay product can be calculated using the following equation [38].

$$DCF_{RnP} = \frac{BH \times \left(\sum_i C^u(i) D^u(i) + \sum_i C^A(i) D^A(i) \right) \times 3700}{F} \quad (2\text{-}8)$$

$$DCF_{TnP} = \frac{BH \times \left(\sum_i C^u(i) D^u(i) + \sum_i C^A(i) D^A(i) \right) \times 276}{F} \quad (2\text{-}9)$$

where, B, breathing rate (0.78 m^3 h^{-1})

$D(i)$, Effective dose per unit intake of ^{218}Po, ^{214}Pb and ^{214}Bi in the case of Radon decay products and ^{212}Pb and ^{212}Bi in the case of thoron decay products (Sv Bq^{-1})

H, Exposure hours per month (170 h)

$C(i)$, Activity concentration ratios of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi to ^{222}Rn and ^{220}Rn, respectively. (Bq m^{-3})

U, Unattached fraction; A, Attached fraction and F, Equilibrium factor.

The dose conversion factor for each radon decay products can be calculated as function of activity median diameter (AMD) according to the following equations:

$$DCF^M\left(^{218}Po\right) = B \times \left[\frac{PD^M\left(^{218}Po\right)}{A_p} \right] \quad (2\text{-}10)$$

$$DCF^M\left(^{214}Pb\right) = B \times \left[\frac{PD^M\left(^{214}Pb\right)}{B_p} \right] \quad (2\text{-}11)$$

$$DCF^M\left(^{214}Bi\right) = B \times \left[\frac{PD^M\left(^{214}Bi\right)}{C_p} \right] \quad (2\text{-}12)$$

$$DCF^M\left(^{212}Pb\right) = B \times \left[\frac{PD^M\left(^{212}Pb\right)}{D_p} \right] \quad (2\text{-}13)$$

$$DCF^M\left(^{212}Bi\right) = B \times \left[\frac{PD^M\left(^{212}Bi\right)}{E_p} \right] \quad (2\text{-}14)$$

Where, DCF^M , is the dose conversion factor each decay products at particle diameter M, mSv (Bq m^{-3} h$)^{-1}$,

D^M , is the effective dose per unit intake for each decay products at particle diameter M, mSv (Bq^{-1})

B, is the breathing rate 0.78 m3 h^{-1},

P, is the value of PAEC that equals 1 Bq i.e. 1.3×10^{5} MeV

A_p, B_p, C_p, D_p and E_p are values of PAEC for unit radioactivity of ^{218}Po, ^{214}Pb, ^{214}Bi, ^{212}Pb and ^{212}Bi, i.e. 3673.6 MeV(Bq^{-1}), 17832.7 MeV(Bq^{-1}), 13241.5 MeV(Bq^{-1}), 431042.4 MeV(Bq^{-1}) and 40916.6 MeV(Bq^{-1}), respectively.

The effective dose per unit exposure for each radon and thoron decay product were estimated by LUDEP, assuming the equilibrium factor 0.4 for aerosol attached particles and 0.1 for unattached particles and the best input parameter shown in Table 2-1 were also used. The dependence of dose per unit exposure DCF on AMAD of radon and thoron decay products were thus evaluated and are illustrated in Figure 2-4 and 2-5, respectively.

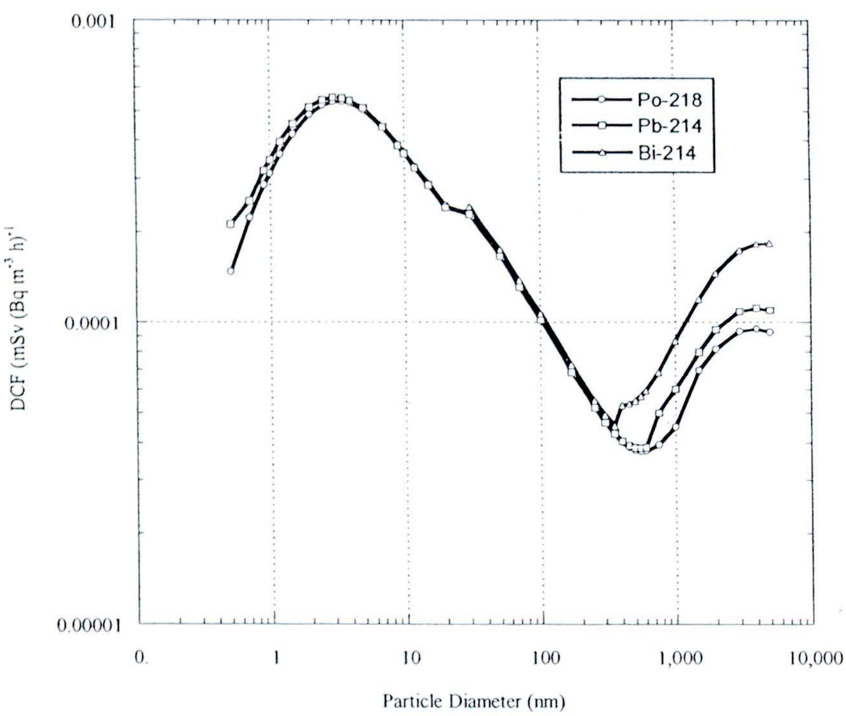


Figure 2-4 Variation of dose conversion factor from radon progeny (DCF_{RnP}) as a function of AMAD.

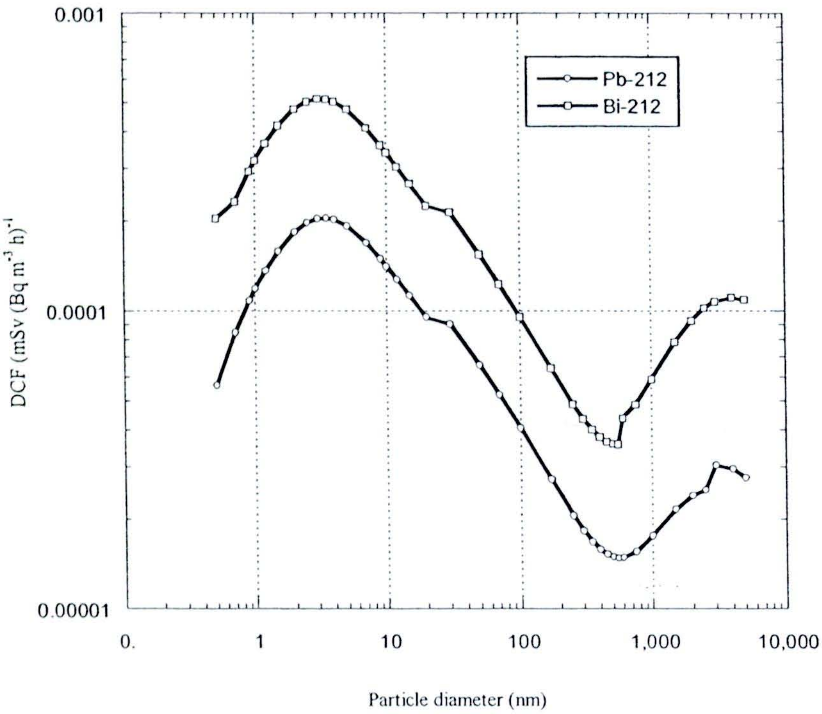


Figure 2-5 Variation of dose conversion factor from thoron progeny (DCF_{TnP}) as a function of AMAD.

The DCF for all decay products of radon and thoron exhibit almost identical dependency on median diameters of radon/thoron aerosols particles. A reduction of DCF was observed below the range of 100 nm. The highest DCF was noticed around 3.5 nm and the lowest value appeared at 550 nm.