ATTACHED AND UNATTACHED FRACTION OF RADON DECAY PRODUCTS IN MINE ATMOSPHERE

By

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Dated: June 2010

This Work is Dedicated to

My Wife

Zewdie Araya

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Acknowledgments

Above all, I would like to thank the almighty; God, for letting me accomplish this stage.

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Addis Ababa University Gizachew Zihon

June, 2010

Abstract

In this work it is analyzed that radon daughters are produced as free ions, but they become attached to aerosol particles at a rate depending on the aerosol concentration. Most of the attached activities for Rn-222 progeny were associated with aerosol particles of the accumulation mode.

Various parameters influencing the concentration of the radon daughter products in the atmosphere of dwellings are reviewed. Risk factors for lung cancer from the inhalation of attached and unattached radon decay products are indicated. Methods for controlling excessive radon exposures in mine atmosphere, indoor, and outdoor are outlined.

The activity concentration of radon daughters and thoron daughters and also plot of the amounts of particles with time are discussed.

Introduction

Radon is naturally occurring, colorless, odorless, almost chemically inert and radioactive gas. It is a transformation product from the decay of ^{238}U, and ^{232}Th which are found in various concentrations in all soils and minerals. Its three isotopes(^{222}Rn, ^{220}Rn and ^{219}U), each originating from a different parent nuclide are the most abundant element in the atmosphere of dwellings.

Radon progeny are formed as a positive ions or atoms which are able to deposits on surfaces or attached to the particle of room air or unattached. Most of the literatures indicates that the activity size distribution of the airborne radon progeny in the indoor environment consists unattached fraction and attached fraction with various concentration in indoor, outdoor and in mine atmosphere.

Inhalation of the short-lived radon progeny which are unattached or attached makes the largest contribution to the natural radiation exposure. Highly diffusive unattached decay products are more hazardous than attached decay products.

In this work I have seen different current studies and literature values, it indicates that a number of authorities have considered doses and risks from radon. However, their focus was on ^{222}Rn rather than thoron and doses to the respiratory tract rather than doses to other organs and tissues. So, more work must be done on doses other organs and tissues and also on ^{220}Rn.

CHAPTER 1

Review Of Literature

Rutherford and Owens studding the “emanations from thorium”in 1899 wrote “the radiation from thorium was not constant but varied in a most capricious manner”. Rutherford made the key observations that “the emanation . . . acts like an ordinary gas” and that “. . . the intensity of the radiation has fallen to one half of its value after an interval of about one minute”.

Pierre and Marie Curie, studying the emanations from radium in 1899, conclude that “. . . it stayed radioactive for several days”. The Curies had detected radon-222, half-life 3.8 days, but they still had doubts as to whether the activity was really in the form of a gas [14].

Later work by Rutherford(1901) and also by Ernst Dorn(1900) confirmed that the radiation emitted by radium were a radioactive gas. Radon was called niton at first from the Latin word ’nitens’ meaning shining, but has been called radon since 1923 [10].

Actinon, another isotopes of radon, was discovered in 1904 by Friedrich Giessel and Andre-Lousi Debierne [15].

The abundance of naturally occuring uranium-235 is only about 0.7 percent therefore, the radon isotope Rn-219 is unimportant in the natural environment.[20]

Inaddition to the above three naturally occuring isotopes, another several isotopes of radon are known.

1.1 BASIC PROPERTIES OF RADON

Radon is naturally occuring, colourless, odourless and radioactive element. Radioactive element is one that gives off radiation and breaks down to form different elements. Radon is the heaviest noble gas. Its density is 9.72 grams per liter, making it about seven times as dense as air. You can not see, smell or test radon. Radon has the highest melting point (-71^0c), boiling point(-61.8^0c), critical temperature (104^0c) and critical perssure(62 atm.) compared to other nobel gas [6].

1.1.1 Physical properties of radon

Radon is the only one in gas state of uranium and thorium daughters, and as a gas it can migrate out of the soil and float upward in the atmosphere.

Radon dissolves in water and becomes a clear, colourless liquid below its boiling point. At even lower temperature liquid radon freezes. As a solid, its colour changes from yelow to orangish-red as the temperature is lowered even further. It is a dramatic sight since it also glows because of the intense radiation being produced [10].

Table 1.1: Physical properties of radon

Name	Radon
Symbol	222_{Rn}
Atomic number	86
Atomic mass	222gm/mol
Appearance	Colourlerss
Phase	gas
Electron cofiguration	$[X_e]4f^{14}5d^{10}6s^2 6p^6$
Electron per shell	2, 8, 18, 32, 18, 8
Boiling point	$211.3^0c(-61.7^0c)$
Melting point	$202^0c(-71^0c)$
Heat of fusion	3.247 KJ
Heat of vaporization	18.10 KJ/mol
Heat capacity at 25^0c	$20.786J/mol.^0k$
Thermal conductivity at 300^0c	$3.61mW/m.^0k$

1.1.2 Chemical properties of radon

Radon is an inert gas therefore it is a noble gas. It is the last member of the noble gas family. The term inert means incapable reacting with other substances .

Radon does not react with air .

Radon gas does not react with any acids or bases.

Radon does not react with water although it does dissolve slightly to the extent of about $230cm^3/kg$ at $293^0k(20^0c)$ [10].

1.2 SOURCES OF RADON

The major sources of radon is the soil, but ground water, natural gas and building materials also contribute.

Radon is an ubiquitous element found worldwide. Worldwide, an average of about two radon atoms are emitted from every square centimeter of soil every where on the earth every second on every day. It is for that reason that virtually every house on the planet always has had radon, and will always have radon occuring in the home [8].

The radioactive decay of radium-226 produces the inert radioactive gas, radon, which is then free to diffuse through porous soils and construction materials and eventually enter the environment within a building.

The fraction of radon atoms released into rock or soil pore space from a radium-bearing grain is called the emanation coefficient, the emanation factor or the emanation power.

Grain size and shape are two important factors that control the emanation of radon in soil [14].

1.2.1 Isotopes of radon

Radon is a transformation product from the decay of uranium-238, uranium-235 and thorium-232 which are found in various concentration in all soils and minerals. Radon occurs in several isotopic forms. Isotopes are two or more forms of an element. The three isotopes of radon occur in nature , each originating from a different parent nuclide are actinon(Rn-219), thoron(Rn-220) and radon(Rn-222) [6].

Table 1.2: Radon isotopes

Isotope	half-life	series
Rn-220	55.6 sec.	Th-232
Rn-219	3.96 sec.	U-235
Rn-222	3.82 days	U-238

1.2.2 Decay series of radon isotopes

Radon , Rn-222, is a noble gas produced by the decay of radium , Ra-226, which is a member of the uranium-238 decay series.

Thoron, Rn-220, is a noble gas produced by the decay of radium, Ra-224, which is a member of thorium-232 decay series.

Actinon, Rn-219, is a noble gas produced by the decay of radium, Ra-223, which is a member of uranium-235 decay series.

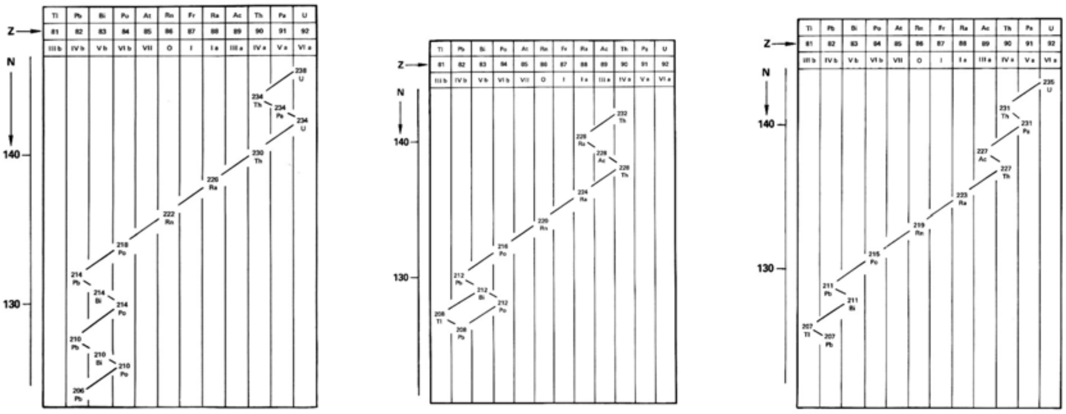
The radioactive transformation of radon and its radioactive products is a practical example of series decay.

Table 1.3: Rn-222 and its progeny

Element	Symbol	Mass	Radiation	Half-life
Radon	222_{Rn}	222	alpha	3.82 days
Polonium	218_{Po}	218	alpha	3.11 min
Lead	214_{Pb}	214	beta	26.8 min
Bismuth	214_{Bi}	214	beta	19.9 min
Polonium	214_{Po}	214	alpha	164 micro sec
Lead	210_{Pb}	210	beta	22.3 year
Bismuth	210_{Bi}	210	beta	5.01 days
Polonium	210_{Po}	210	alpha	138.4 days
Lead	206_{Pb}	206	stable	infinite

Table 1.4: Rn-220 and its progeny

Element	symbol	half-life	radiation
Thoron	Rn-220	55.6 sec.	alpha
Polonium	Po-216	0.15 sec.	alpha
Lead	Pb-212	10.6 hours	beta
Bithmuth	Bi-212	60.6 min.	beta
Polonium	Po-212	ÃŮ304 n sec.	alpha
Lead	Pb-208	stable	
Thallium	Tl-208	3 min.	beta



***(a):** Uranium-238 decay series* ***(b):** Thorium-232 decay series* ***(c):** U-235 Decay Series*

Figure 1.1: Sources of the three radon Isotopes $\swarrow \equiv \alpha-$emitter; $\searrow \equiv \beta-$emitter

1.3 RADON IN MINE ATMOSPHERE

Radium, the immediate precursor of radon, available as part of the ore in soil and rocks is the major source of radon in mines.

Production and release into the mine atmosphere depends on

1) The grades,

2) Its emanation power,

3) Porosity and permeability of host rock to radon and

4) Moisture content of the ore.

Most of the radon produced within a mineral grain remains embedded in the grain, only 10 to 50 percent escapes to enter the pore space. If water is present in pore space, the radon atom can move easily remain in the pore space; if the pore space is dry, the radon atom may shoot across the pore and embed in another grain where it can not move [14].

Mining operations such as drilling and blasting bring fresh radon into the mine atmosphere. Radon exhaled from ore bodies migrates through rock and is exhaled from the earths surface or mine surfaces continuously [14].

The atmosphere of a mine can be characterized mainly by the following physical parameters:

1) Temperature,
2) Relative humidity and particle size distribution of aerosols,
3) Volume concentration of radon,
4) Age of ventilation air and volume concentration of the radon decay products.

In the air of the uranium mine, the concentration of Rn-222 and its daughter products depends on the richness of the ore and its composition, its physical and geological structure and techniques of mining and ventlation [2].

Human practice, type of extraction, transport or maintenance is also influencing the activity concentration.

The radioactivity in a mine atmosphere stems from emanation from the ore bodies, the mine walls and mine water. Radon gas, soluble in water, can be transported by underground water over a long distances and released when the pressure over the water is reduced. At a temperature of 20^0c, when an equilibrium state reached, radon will be present in water at 0.23 times the concentration it has the air in contact with [2].

Radon gas, on entering the mine atmosphere by various processes remains there till it is carried along in the ventlation current and discharged above ground.

Studies about the concentration of radon-222 and thoron-220 in mine atmosphere shows us that thoron-220 is much less than that of radon-222. The short half-life of thoron gas means that it is much less able to escape from the point where it is formed than radon-222 [8].

1.4 RADON IN INDOOR AIR

The most common way that radon enters a home is when lower indoor air pressure draws air from the soil, bed rock or drainage system into the house. If there is radon in the soil gas, it will also be drawn in. Just as gravity will make water flow from a high elevation to a lower elevation, pressure differences will make radon-laden soil gases move from an area of higher pressure to an area of lower pressure. If cracks, holes, and pores in the foundation are open to the soil, radon will be drawn indoors.“ In an average of home, about 90 percent of the radon originates in the soil ” [17].

The majority of the natural radioactive material found in the indoor environment is due to the premordial radionuclide, uranium-238 and its associated decay series members. The series member of primary concern is Rn-222, a gaseous radioactive pollutant that can accumulate in the air with in dwellings, particularly those with low outside air inflitration rates. The immediate precursor of radon-222 is radium - 226 which, because of its 1600 year half-life, serves as a virtually continuous sourse of radon-222 production with in residences [7].

Two of the isotopes of radon, thoron and actinon, which have very short half-lives, are not very important , but$^{222}\mathrm{Rn}$ has a long enough half-life to come to the surface from deep beneath and accumulate in our homes especialy in basements. So if radon diffuses to the surface indoors, it will spread in to some m^3, but if it came to the surface outdoor, it would be distributed in much bigger space. Therfore, the radon and its progeny concentration is much higher in closed spacces (indoor) than outdoors. So we have a high concentration of radon in the soil, a medium concentration of radon and its decay product daughters in the house (closed spaces biult on the ground) and low concentration of radon in the outside air [3].

Studies on this area shows that the concentation of radon gas decreases with the elevation above the ground level, that is ground floors have higher concentration as compaired to higher stories.

1.5 RADON IN OUTDOOR AIR

Radon arises in the soil all the time and diffuses upwards beccause there is a lower concentrations of it in the air than in the soil. Diffusion of radon through soil and through walls is slow, but if it comes in to the air, it will quickly spread uniformly in all avialable space.

Radon exhaled in to the free atmospher is rapidely dispersed and diluted by vertical convection and terbulence due to solar heating during day time [3].

Considerably high levels can occur if the radon is released in confind air space such as underground mines, homes, natural caves or tunnels. The radon level in the free atmosphere is about one-thousandth of that in the soil air.

At night and in the early mornning hours, atmospheric (tempreture)inversion conditions are often found, which tends to trap the radon closer to the ground. This means outdoor radon concentrations can vary diurnally.[4]

1.6 HEALTH HAZARDS DUE TO RADON

1.6.1 Discovery

As early as the 1500s an unusually high mortality from respiratory diseases (“black lung disease ”) was documented among under ground metals miners in the Erz Mountains of Eastern Europe. In the 1800s pulmonary malignancy was doccumented in miners from that area, and in the early 20th century shown to be primary carcinoma of the lung. [15]

In the 1920s high levels of radon were detected in mines in Czechoslovakia, where miners also had high lung cancer rates. It was proposed that the radon was the cause, but the hypothesis was not generally accepted untill the reports of epidemiological studies on other groups of radon-exposed miners in the 1950s and 1960s .[13]

Radon itself was initially assumed to be the cause of the lung cacers in miners. In the 1950s, Harly, in a doctoral thesis at Rensselear Polythecnical Institute, proposed that it was the decay products of radon that delivered the pretinent dose to the lung cells.

Only since the 1970s that radon and its decay daughter products has been recognized as a major source of radiation exposure to the general public. That is inhalation of short -lived radon progeny (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) makes the largest contribution to natural radiation exposure. [1]

The second most important isotope of the natural radioactive gas, radon, is thoron(Rn-220). Thoron and its decay daughter products is usually of smaller radiological significance than radon-222, at least in the UK(Wrixon et at 1988). Nevertheless, doses from thoron are not necessarilly negligible. The way in which thoron delivers doses is rather different from the more familiar case radon-222 [8].

1.6.2 Effects of radon on the body

Radon is inert, so it is unlikely to get into the body by inhalation or ingestion, therefore, the radiotoxicity of radon itself is low. Once radon accumulates in our homes, it undergose radioactive transformation. Resulting products are not gases any more. They are in solid state and become attached to dust particles due to their electrostatic charge. Radon and these particles are then inhaled. Because transformation products of radon are electrically charged, they readily deposit in the lung and since they have half-lives in the order of minutes, their transformation energy is almost certain to deposited in the lung tissue. Radon transformation products or progeny(called also daughter) emit alpha particles (helium nuclei) with energies ranging from 6 to 7.69 Mev. Because of the high charge and their mass, the energy is delivered in a huge jolt to the cellular structure of the surface of the bronchi and the lung, which damages and kills these cells. The body can replace damaged cells, but if a dameged cell replicates, then this cellular defect can lead to lung cancer.

First notes about the lung cancer are more than 300 years old. Nowadays peopel still die of consequences of being exposed to radon and its progeny. The United States Environmental Protection Agency(EPA) estimated that 20, 000 deaths occur annually from radon-induced lung cancer [5].

An average human gets more than half of his dose in the life time from radon. If concentration of radon were decreased, the dose to humans would be lower.

A number of authorities have considered doses and risks from radon. However, their focus was on Rn-222 rather than thoron and on doses to the respiratory tract rather than doses to other organs and tissues [8].

CHAPTER 2
Attached and Unattached Fraction of Radon

Radon and thoron decay daughter products appear in two size modes, they are;
1) unattached to aerosol particles and
2) attached to aerosol particles. [18]

Short-lived radon daughters and thoron daughters are initially born in an atomic state but subject to attachment to aerosol particles and/or adjacent wall surfaces; nevertheless, a considerable fraction remains unattached, [4]

Radon decay products are normall electrically charged. This causes the products to quickly attach to particles normally in the air. This greatly affects the aerodynamic characteristics of theses particles which intern affects the deposition of the particles in the lung. [18]

The decay daughter products of radon are not gases and occur as unattached ions or atoms, condensation nuclei or attached to particles. The attached and unattached fraction of radon are found in various concentration in the atmosphere of uranium mines, indoors and outdoors.

2.1 ATTACHED FRACTION OF RADON

The decay products of radon(Rn-222) and thoron(Rn-220) are in solid state and become attached to aerosols and dust particles in the air due to their electrostatic charge. They freqently collide with and attach themselves to large dust particles within the air inside a dwelling.

The effective size of such attached decay products rangs from 0.05 micrometer to a few micrometers in diameter. [7]

Depending on the concentration of dusts in the room air, upto 80 percent of the decay products will attach to dust particles. So, the attached fraction of radon decay products are defined as the ions or atoms of radon decay products that are attached to aerosol particles in the 50-500 nm rang, dust particles and also solid surfaces. [3]

The decay products of Rn-220 have longer half-lives and thus a longer period of time for the attachment to occur, when we compair with the Rn-222 progeny. [11]

Radon progeny are formed as positive ions or atoms, which are able to deposite on surfaces or attach to the particles of room air such as aerosol.
This mechanism is explained below.

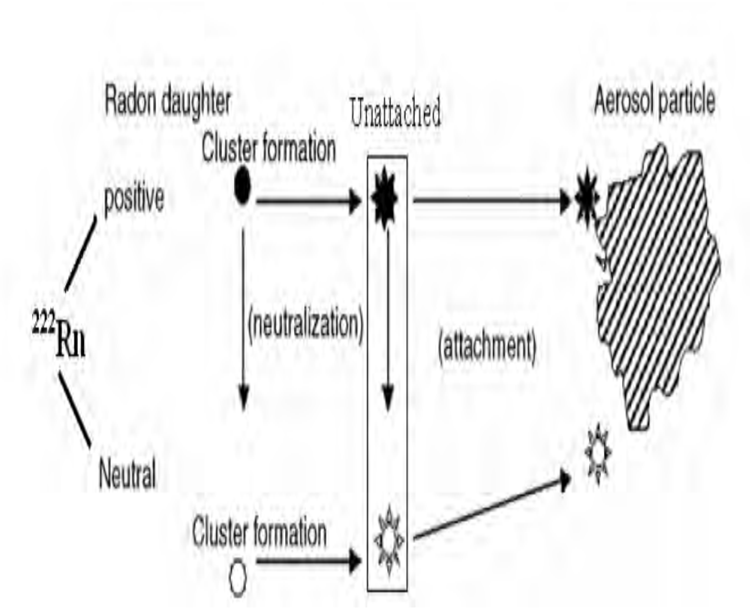


Figure 2.1: Formation of radioactive aerosols. [1]

The activity size distribution of radon progeny has been determined by tagging the natural aerosol particles with radon progeny.
Most of the litratures indicate that the activity size distribution of the airborne radon progeny in the indoor environment consists of ultrafine clusters with median diameters below 4nm(unattached activity) and radon progeny associated with ambient aerosol in size range between 0.1 micrometer and 0.4 micrometer (attached activity). [1]
Raising aerosol concentration increases equilibrium factor, because the attachement process becomes much faster than the loss of atoms by plateout. Relative humidity also modifies the condition of attachement of free fraction to aerosols by changing the total number of condensation nuclei; a high level of humidity(often close to 100 percent in under ground mines) reduces the proportion of free fraction. [2]

2.2 UNATTACHED FRACTION OF RADON

Unattached fraction of radon decay products are the short-lived radon progeny especially those of ultrafine progeny smaller than 2nm in diameter. unattached fraction of radon decay products are in small clusters or attached to very small particles(1-10 nanometer in diameter). The fraction of unattached (free) ions, though with important contribution to the dose in the lung, was determined by several methods and concidered small(about 15 percent), as compared to the fraction of the attached onces. [2]

Depending on the concentration of dust in the room air, upto 20 perecent of the decay products will not attach to dust particles and will remain in free ion state. since unattached decay products are often positively charged, they tend to attach other polar molecules in the air, such as water vapour and traces gases, and are believed to exist, at least temporarily, as very small and highly diffusive ion clusters. [7]

Increasing of unattached radon decay products can be caused by the reduction of suspended particles to which the radon decay products can attach caused by very clean air or the presence of air filters. [16]

The unattached fraction of Rn-220 decay products can be different due to greatly different half-lifves of the products. The Rn-220 products have longer half-lives and thus a longer period of time for the attachment to occur than Rn-222 decay products.

Yamasaki et. al. performed a theoretical calculation that showed the unattached fraction for Rn-220 decay products to be approximately 1.6 percent for indoor air. [11]

Porstendorfer demonstration showed 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. 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. [11]

It may be conclude that the eqiulibrium factor (F) and also the unattached fraction (f_p) is only slightely influenced by the following parameters; Outdoor concentration of radon daughters, (for ventilation rate less than 1/h), recoil process, radon emanation rate, ventilation rate and deposition rate of aerosols.

At night and in the early morning hours, atmospheric (temperature) inversion conditions are often found, which tend to trap the unattached radon daughters and aerosol particles to the ground. This shows us that unattached radon daughter and total radon daughter concentration can vary diurnally. The unattached radon daughters concentration varies inversely with the concentration of aerosol. [4]

2.3 PARTICLE SIZE

The radon ($^{222}\mathrm{Rn}$) and thoron ($^{220}\mathrm{Rn}$) decay products condense on all surfaces including the surface of airborn particles and droplets in the atmosphere. Therefore, their behaviour in the atmosphere, especialy concerning deposition on surfaces and in the lung during inhalation are determined to a large extent by the activity size distribution of the aerosol. The relative size distribution of the attached decay products depends on the attachement coefficient and on the relative size distribution of the natural aerosol. [9]

Aerosol measurments in the mines, indoors and inside human respiratory tract have shown a range between 0.05 micrometer and 0.5 micrometer, but rarely bigger hygroscopic aerosols can be also found. From the radiation protection point of view, great importance is related to the fraction of free ions and those attached to particles, because the free ions, being smaller in size are mainely deposited on the bronchail epithelium.

The variation of the aerosol concentration in different types of biuldings and different times is fairly large in contrast to the activity size distribution of the radon daughters. The aerosol concentration indoors depends mainly on the particle concentration in the free atmospher, the ventilation rate of the room and the number of particle source indoors(eg. cigarette smoke).[9]

The particle concentration of 2×10^3 - 2×10^4 particles/cm^3 indoors were much less than outdoors for low ventilation rates ($V < 0.3/h$). For ventilation rate ($\nu > 1/h$) the nuclei concentration is about the same as outside and the concentration range is about $10^4 - 10^5$ particles/cm^3 [9].

The particle size distribution affects the regional deposition of the aerosol in the lungs. This size is greately affected by the unattached fraction. The fraction that is attached to other particulates can exhibit the aerodynamic characterstics of the larger particle to which it is attached. [11]

Studies on this area is given below.

Nikezic et al. indicated a particle size distribution for the attached fraction of 0.2μ with geometric standard devation (GSD) of 2.35 while the unattached fraction was 0.0015μ with a GSD of 1.1 [11].

Porstendorfer indicated particle sizes for various environments. The unattached median particle sizes range from 0.00013μ to 0.0013μ with GSDs ranging from 1.1 to 1.3. For the attached fraction, the major contribution (about 86 percent) exhibited median particle size of 0.33μ for outdoor air and 0.217μ for indoor air. [11]

Birchall and James indicated that available data of attached aerosol size in underground uranium mines indicates a particle size between 0.15μ and 0.5μ with Samet et, al. [11]

Based on the above reffernces, this calculation will use a median particle size of 0.25µ for the attached fraction. A size of 0.0015µ will be used for the unattached fraction. [11]

2.4 BEHAVIOUR OF RADON PROGENY

The decay products are produced by decay of the gases radon-222 and radon-220(thoron). After their formation a large fraction of ^{218}Po (80-82 percent) and ^{212}Pb (85-88 percent) is positively charged. These ions become neutral by recombination with negative air ions and charge trnsfer processes in connection with No, NO_2, H_2o vapours and other air impurities. Due to these neutralization processes, a large fraction of the daughter atoms in the atmosphere are neutral when they attach to aerosols. Furthermore the unattached radon daughters may not be a single chemical species, but instead, depending on the conditions, may be hydrated or react chemically with oxygen or various trace gases of the atmosphere.

The most important parameter for characterisation of the unattached radon and thoron decay products is their diffusivity. Recent investigations shows that the diffusion coefficient of the posetively charged decay products have values between 0.024-0.039 cm^2/s. Diffusion coefficients between 0.068 and0.085 cm^2/s were measured for neutral radon and thoron daughters. [9]

2.4.1 Behaviour of radon-222 progeny

When an atom of ^{218}Po is formed through the decay of radon atom, it is a free ion. Molecules of water vapour or trace gases coalesce almost immediately around the ion, forming a molecular cluster of 2-20nm in diameter. The ion and the cluster are referred to as the“unattached decay products”. Unattached ^{218}Po is highly mobile, and after 10-100 seconds, it attaches itself to aerosol particles in the 50-500 nm range, dust particles, or solid surfaces.

In aerosol form the particles tend to remain suspended, although they are subject to electrostatic, inertial and diffusive forces by which they can be removed.

Some of the unattached ^{218}Po may plateout onto surfaces(particularly indoors), or be transported with the air circulation, or decay into unattached ^{214}Pb. Attached ^{218}Po is relatively immobile and its plateout is negligible. The attached and unattached fractions behave differently in the environment and in the respiratory passage. When an attached ^{218}Po atom decays, the ^{214}Pb then created may remain on the aerosol or become unattached as a result of the recoil energy. Subsequently, the behaviour of ^{214}Pb is similar to that of ^{218}Po . On decay of ^{214}Pb, the ^{214}Bi remains typically attached due to the low recoil energy of the beta decay. [3]

2.4.2 Behaviour of thoron progeny

When the decay chain of Rn-220 is in 100 percent 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 average alpha energy released through the decay of Po-216 and Po-212 is 7.8 Mev and Bi-212 emits an alpha only 36 percent of the time but the other 64 percent of the time it emits beta particles. 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 working level measurment or the lung dose. Pb-212 is the primary contributer to working level measurement due to Pb-212 has half-life approximately 10 times larger than Bi-212. On the other hand, Pb-212 atom inhaled have more time to be removed from the lungs perior to emitting all energy than will ultimately be emitted by the remainder of the decay chain. This causes Pb-212 to produce less lung dose per unit activity inhaled than that of Bi-212.

The degree of the decay chain equilibrium depends entirely on the circumstances surrounding the production and movement of the Rn-220 gas in the breathing zone. [11]

2.5 CONCENTRATION OF RADON PROGENY IN A HOUSE

In the air of a house, a large fraction of radon and thoron decay products are attached to the aerosol particles. The smaller fraction is free or unattached.

The concentration of radon and thoron decay products and therefore the actual ratio(F) and unattached fraction (f_p) in a house are influenced by the basic processes of attachement, recoil and deposition(plateout), and by room specific parameters of radon emanation and ventilation.[9]

The illustration of this is given below:

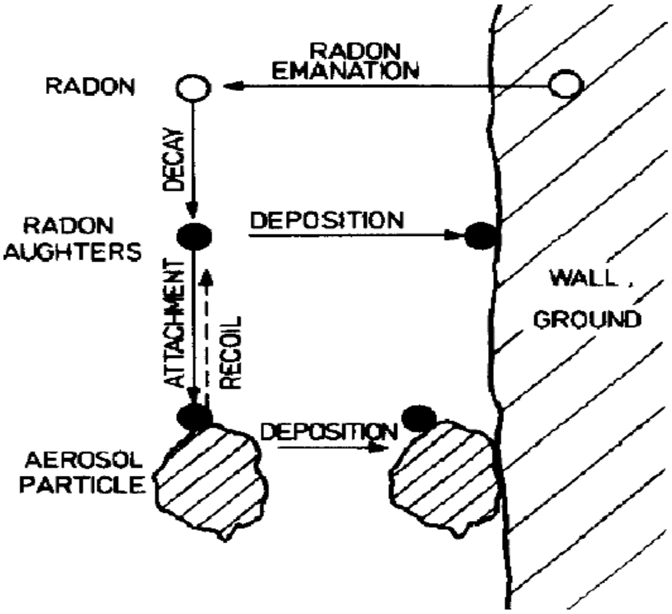


Figure 2.2: The basic processes influencing the activity balance of radon and thoron daughters.[9]

In general, radon daughter concentrations are higher in house than in the free atmosphere. This is due to additional radon sources such as building materials and tap water and low rates of air exchange with the free atmosphere. Sealing of windows to save energy, the use of waste products with an excessive radium content as a construction material raises the airborne concentration of radon gases(Rn-222 and Rn-220) and their decay daughter products.

According to United Nations Scientific Committee on the Effect of Atomic Radiation (UNSCEAR), radon daughters may be combined as the so called equilibrium equivalent concentration C_{eq} which is related to the potential alpha energy concentration. Equilibrium equivalent concentration of radon daughter products equals the concentration of radon (C_o) if they are in radioactive equilibrium.

Thus the actual ratio $(F) = \frac{C_{eq}}{C_o}$ for radon and thoron.

In an atmosphere a large fraction of the radon and thoron decay products are attached to the atmospheric aerosol.

The smaller fraction is free (unattached). The unattached fraction (f_p) of the daughters is

$$f_p = \frac{C^f_{eq}}{C_{eq}} \tag{2.1}$$

Where C^f_{eq} is equilibrium equivalent concentration of unattached fraction C_{eq} is equilibrium equivalent concentration of radon daughters. [9]

2.6 HEALTH EFFECT OF ATTACHED AND UNATTACHED FRACTION

Inhalation of the short-lived radon-222 progeny (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) and thoron (Rn-220) progeny(^{216}Po, ^{212}Pb and ^{212}Bi) makes the largest contribution to natural radiation exposure. The unattached and attached radon progeny are deposited in different regions of the human respiratory tract due to the differnt particle sizes. [1]

The health hazard associated with the radon decay series stems from the inhalation by humans of both the attached and unatached decay products, and their eventual decay and irradiation of susceptible lung cell populations. Epidemiological studies on uranium mines have demonstrated a causal relationship between the inhalation of high concentrations of radon decay products and an increased risk of lung cancer. 12]

The radiological consequence of the attachment state of the decay product being inhaled stems from the knowledge that highly diffusive unattached decay product atoms preferntially deposit in the upper segments of the tracheo-bronchial tree of the lungs. This is the site with in the lungs where most of the cancers among the uranium mines have occured. As a result, the unattached decay products are beleived to have the potentiality of causing a higher localized lung dose and have a higher associated risk.

Incontrast the large attached decay products are deposited rather uniformly throughout the respiratory system, and are considered a much lesser risk of health damage (cancer) on the exposed individual. [7]

Most of the unattached radon progency is deposited in the respiratory tract during breathing, whereas 80 percent of the attached radon progeny are exhaled with out deposition.

The unattached activity amounts upto about 10 percent of the total activity, but it considered to yield about 50 percent of the total radiation dose. Therefore, measuments of the unattached fraction are essential for the estimation of dose.[4]

Because the dose to the lung tissues can not be measured, a dosometric model is necessary to estimate the radiation dose exposure. In all dosimetric models the calculated dose principally depends on activity concentration and the activity size distribution of the inhaled radioactive aerosol.[2]

Over half of the total effective dose from natural background, radiation to every member of the human population comes from inhalation of the naturally present radon, thoron, and their daughter products. In the 1950s, it was recognized that it was the inhalation of short -lived radon daughter products that was the responsible agent.[3]

2.7 THE REMOVAL OF RADON AND ITS DAUGHTERS

The level of airborne activity of short-lived radon daughter products in indoor air may be controlled by various means, like filtration and ventilation. Ventilation with radon free air is a very effective way, because non filterd air in the houses has always higher concentrations of radon than the air outdoors. Ventilation removes radon and its progeny. Removing radon from indoor air by ventilation is much more efficient than filtering. But ventilation unfortunately makes the heating more expensive, especially in winter. Internal filtration, on the other hand, where the air is circulated through a filtration system, will not affect the radon level, but may reduce the level of the daughter activitys. When air is filtered, dust particles and also radons progeny stay on the filter. We can only remove radons progeny by filtering. Filtration may, however, also change the arosol composition of the air, and increases the fraction of daughter products in the unattached state.

The most effective means of reducing the indoor concentration of radon and its airborne, short-lived progeny is ventilation. If the air is replaced example once per hour with radon-free air, radon concentration in the room can at most reach 0.75 percent of the unventilated value and the daughter products even less than that. [6]

Attempts to remedy the problem of radon decay product exposure fall into two categories:

1) Control thecniques applied to mine atmospheres and

2) theoretical and limited experimental studies applied to the radon and radon decay products inbuildings.

Control strategies also fall into two basic categories:

1) the prevention of gas buildup inside a structure (mine or building), either by providing a barrier to prevent the radon from entering or by selecting foundation and constraction materials that are relatively low in their naturally radionuclide content, and

2) the removal of radon decay products from the interior air. As stated above, airborne decay products can exist as either free species or attached to aerosol particles, and different control strategics have been devised for each case.

The traditional method for the control of radon decay products in uranium mines has been mechanical ventilation, and maximum permissible concentrations for such products have been expressed interms of Working Level(WL). Significant decreases in radon decay product concentrations have been accomplished by recirculating large volumes of air within a mine shaft, without introducing makeup air. Decreases in working levels by a factor of 10 to 20 using reciculation rates of 20 and 60 per hour have been reported. The large recirculation rates separately caused radon decay product removal by both increased deposition on mine surfaces of decay products attached to aerosol particles and increased diffusion of unattached decay products to mine surfaces.

Both filtration and electrostatic precipitation have also been used for radon decay product removal in mines. [7]

It is practically showed that surfaces deposition is also the most important parameter in the reduction of radon and thoron and their decay products in the room air.

If C_j is the airborne concentration of the j^{th} nuclide and

S is the surface area available for deposition,

then the rate of removal is $C_j V_g S$

where V_g is the deposition velocity of the radionuclides.

Since the total airborne radioactivity in a room with volume V is $C_j V$,

its fractional rate or removal is $\frac{V_g S}{V}$, assuming always well mixed room air.

An estimation of the deposition velocity for the free (V_g^f) and attached (V_g^a) decay products can be obtained using the experiemental results on aerosol deposition in a turbulent atmosphere. [9]

CHAPTER 3

Instruments and Methods

3.1 INSTRUMENT

The hourly concentrations of the radon daughters were obtained separately and simultaneously with a radon daughter moniter, which has air filitration and gross alpha counting systems. The instrument can automatically operated (and maintenance free) over a period of two months.

The concentration of individual radon daughts can be measured by means of a filter method. In this method, radon daughters in the air are sampled on a paper filter, and their gross alpha activity is counted three times successively with certain time delays.

Radon daughter moniter consists of a scintillation counter, timer-scaler, air pump, filter tape winder, and a RAM cassette. Inorder to make the system operator free, an automatic motorized tape winder is used to move a filter tape reqularly.

The filter tape is a membrane filter (0.8 micrometer in pore size) 60 mm in width and 10mm in length. Sampled air is drawn through an active spot (50mm in diameter) which faces the tape surface. The scilntillation detector [zns(Ag)] for the alpha counting mounted near the tape surface at a distance of 7mm. Output signals from the detector are transfered to the timer-scaler, and the data are stored temporarily in a compact RAM cassette. The system is controlled by an incorporated microprocessers where the storage and read out of data are also covered.[4]

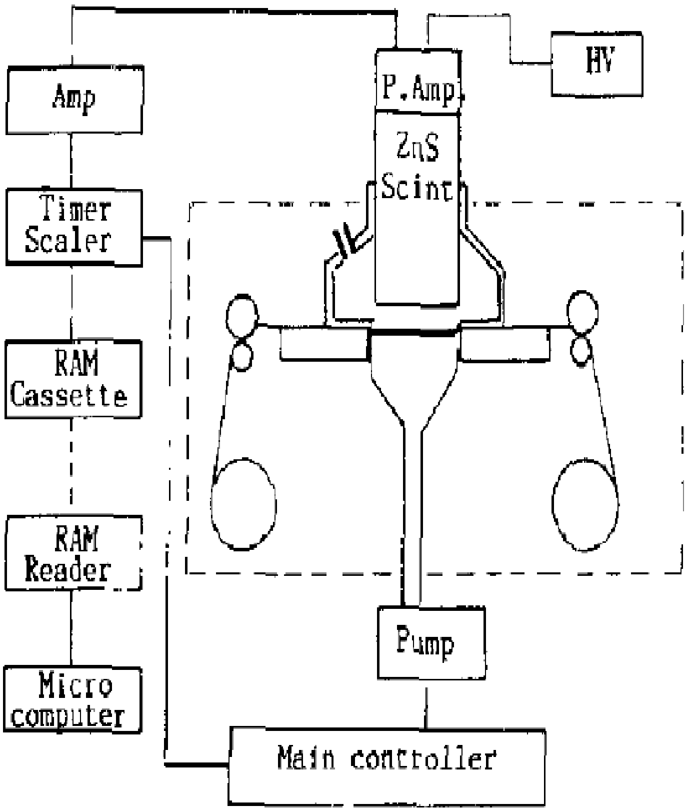


Figure 3.1: A schematic of the radon daughter monitor

3.1.1 Instrument for measuring unattached fraction

A wire screen diffusion battery is an instrument used to determine the size distribution of unattached radon progeny. The diffussion battery consisted of five stainless steel screens with 24, 35, 50, 200, and 635 mesh numbers. The screens were calibrated with monodisperse silver aerosol particles. The measured 50 percent cut-off diametres of the screens are 0.9, 1.3, 1.9, 4.0, and 7.9 nm.

The theory of this instrument is based on that the motion of very fine particles, in the diameter size range of about 2 nm, is strongly affected by randum collisions with gas molecules (diffusion). A particle undergoing diffusion travels a random, irregular path. Its position at any given time depends on its most recent collision with a molecule. Therefore, some of these particles collide with the screen wires. Surface-attractive force between particle and wire cause the particle to stick to the screen. Because of diffusion, a larger fraction of small particles will collide with the screen than of large particles. [1]

3.1.2 Instrument for measuring attached fraction

A low pressure Berner Cascade impactor is an instrument used to determine the activity size distribution of attached short-lived radon progeny. [11] It consisted of eight size fractionating stages and a back-up filter holder, and operated at a flow rate of 1.7 m^3/h. Aluminum foils were used as a collection media and a glass fiber filter as the back up filter. [12] The collected activity on each impactor stage was measured with a well-type 3x3“NaI(Tl) detector. The measured 50 percent cut-off diameters were 82, 157, 270, 650, 1100, 2350, 4250 and 5960.

The effect of the low pressure cascade impactor reduces the drag force on the particles. This reduction in drag allows smaller particle sizes to be collected in low pressure impactors compared with impactors which are operated at the normal pressure (Sierra impactor). [1]

3.2 METHODS

3.2.1 Determination of unattached fraction

To determine the unattached activities of radon progeny, the aerosol attached and total radon progeny concentrations were measured.

Each measurement consisted of two parallel samples: one with a single screen and the other as a referrence sample without screen. This procedure was repeated with different screens. The screen was used only for collecting the unattached activities. The activities penetrating the screen (mostly attached to aerosol particles) and that of the reference sample were collected on membrane filters (Sartorius membrane filter type SM 1.2 mm pore size, 25 mm diameter and an efficiency reaching about 100 percent) and the alpha activities were detecting during and after air sampling by a surface barrier detector.

Inorder to determine the activity concentrations of radon progeny (^{218}Po,^{214} Pb and ^{214}Po), the measurments were performed in two steps.

Firstly, the alph particle spectrum was collected during a sampling period of 30 minutes.

Secondly, after waiting for a time period of 30 minutes without sampling, the alpha particle spectrum was measured again (during decay) for a time period of 30 min. From the measured alpha counts of ^{218}Po and ^{214}Po during the sampling period and the ^{214}Po counts during the decay period,the activity concentrations of (^{218}Po, ^{214}Pb and ^{214}Po) could be calculated according to a method decribed by Wicke.[14] The attached activities were derived from the sample obtained with the screen. The collected unattached activity on the screen is the difference between the measurments of the reference sample (without screen) and the screen sample.[1]

3.2.2 Determination of attached fraction

For determination of the size distribution of the attached radon progeny (^{214}Pb) with the low pressure Berner impactor, several runs were conducted at different times. After air sampling, the foils were pressed into pellets and the relative gross gamma-ray emitting activities on each impactor stage were measured with a well type 3x3" NaI(Tl) detector connected to a multichannel analyzer. [1]

3.3 MATHEMATICAL MODEL FOR RADON AND ITS PROGENY

In many cases, the daughter product of a nuclear decay is itself radioactive and part of a decay chain. The radioactive transformation of radon-222 and thoron-220 and their radioactive products is a practical example of series decay.

The number of nuclei which decay per unit time is proportional to their abundance. This described by the equation below;

$$\frac{dN_1}{dt} = -\lambda_1 N_1 \tag{3.1}$$

where N_1 is number of atoms at that time.

λ_1 is decay constant

t is time in which the number of nuclei is decreased by a factor(e=2.7)

The second nuclides in a series are produced by the decay of the first nuclides, but they themselves also decay.

This described by the equation below;

$$\frac{dN_i}{dt} = \lambda_{i-1} N_{i-1} - \lambda_i N_i \tag{3.2}$$

We have N_o nuclei of element one at the begining and no others.

The solution for the first and the n^{th} element is

$$N_1(t) = N_o e^{-\lambda_1} t \tag{3.3}$$

$$N_i(t) = N_1(o) \Pi_{l=1}^{i-1} \lambda_l \Sigma_{j=1}^{i} \frac{e^{-\lambda_j t}}{\Pi_{k=1}^{i} (\lambda_k - \lambda_j)} \tag{3.4}$$

Where K runs over all integers from one to i except j.

When after some time an equlibrium is reached, the time derivatives are zero, that is

$$\frac{dN_i}{dt} = 0 = \lambda_{i-1} N_{i-1} - \lambda_i N_i, \tag{3.5}$$

which implies that the activities of the daughter and its precursor are the same and do not change with time. This is called secular equlibrium.[6]

3.3.1 Activity concentration

Activity concentration of airborne radon decay products and thoron decay products were determined by similar mathematical computations used by Raabe and Wrenn(Raabe and E.Wrenn,1969) and Papp and Darocy(Papp and Daroczy,1997).

The differential equations which describe the number of atoms of the decay daughters on the given sample of air is

$$\frac{dN_i}{dt} = Kn_i - \lambda_i N_i \tag{3.6}$$

Where N_i is number of atoms in the filter, (i=1,2,...,7)

n_i is number of atoms in a unit volume of the sampled air, (i=1,2,...,7)

K is air sampling flow rate which is constant

λ_i=decay constant, (i=1,2,...,7)

t=time elapsed.

Let the number 1 to 7 represents the decay products of radon(Po-218,Pb-214,Bi-214) and the decay products of thoron(Pb-212, Bi-212, Tl-208) and the last one is stable decay products.

The amount of the atoms inside the measuring chamber can be described by the following defferential equations for each progeny using equation number one.[20]

$$dN_1 = Kn_1 dt - \lambda_1 N_1 dt, N_1(0) = 0 \tag{3.7}$$

$$dN_2 = Kn_2 dt - \lambda_2 N_2 dt + \lambda_1 N_1 dt, N_2(0) = 0 \tag{3.8}$$

$$dN_3 = Kn_3 dt - \lambda_3 N_3 dt + \lambda_2 N_2 dt, N_3(0) = 0 \tag{3.9}$$

$$dN_4 = Kn_4 dt - \lambda_4 N_4 dt, N_4(0) = 0 \tag{3.10}$$

$$dN_5 = Kn_5 dt - \lambda_5 N_5 dt + \lambda_4 N_4 dt, N_5(0) = 0 \tag{3.11}$$

$$dN_6 = Kn_6 dt - \lambda_6 N_6 dt + \lambda_5 N_5 dt, N_6(0) = 0 \tag{3.12}$$

$$dN_7 = Kn_7 dt - \lambda_7 N_7 dt, N_7(0) = 0 \tag{3.13}$$

Where k and n_i are constants during the sampling period.

The solution for the above differential equations are given below: [20]

$$N_1 = Kn_1[\frac{1 - e^{-\lambda_1 t}}{\lambda_1}] \tag{3.14}$$

$$N_2 = Kn_1[\frac{1 - e^{-\lambda_2 t}}{\lambda_2} - \frac{e^{-\lambda_2 t} - e^{\lambda_1 t}}{\lambda_1 - \lambda_2}] + Kn_2[\frac{1 - e^{-\lambda_2 t}}{\lambda_2}] \tag{3.15}$$

$$N_3 = Kn_1\left[\frac{1 - e^{-\lambda_3 t}}{\lambda_3} - \frac{e^{-\lambda_2 t} - e^{-\lambda_3 t}}{\lambda_3 - \lambda_2} - \frac{\lambda_2(e^{-\lambda_2 t} - e^{-\lambda_3 t})}{(\lambda_3 - \lambda_2)(\lambda_1 - \lambda_2)} + \frac{\lambda_2(e^{-\lambda_3 t} - e^{-\lambda_1 t}}{(\lambda_1 - \lambda_3)(\lambda_1 - \lambda_2)}\right]$$
$$+Kn_2\left[\frac{1 - e^{-\lambda_3 t}}{\lambda_3} - \frac{(e^{-\lambda_2 t} - e^{-\lambda_3 t})}{\lambda_3 - \lambda_2}\right] + Kn_3\left[\frac{1 - e^{-\lambda_3 t}}{\lambda_3}\right] \tag{3.16}$$

$$N_4 = Kn_4\left[\frac{1 - e^{-\lambda_4 t}}{\lambda_4}\right] \tag{3.17}$$

$$N_5 = Kn_4\left[\frac{1 - e^{-\lambda_5 t}}{\lambda_5} - \frac{e^{-\lambda_5 t} - e^{-\lambda_4 t}}{\lambda_4 - \lambda_5}\right] + Kn_5\left[\frac{1 - e^{-\lambda_5 t}}{\lambda_5}\right] \tag{3.18}$$

$$N_6 = Kn_4\left[\frac{1 - e^{-\lambda_6 t}}{\lambda_6} - \frac{e^{-\lambda_5 t} - e^{-\lambda_6 t}}{\lambda_6 - \lambda_5} - \frac{\lambda_{5(e^{-\lambda_5 t} - e^{-\lambda_6 t})}}{(\lambda_6 - \lambda_5)(\lambda_5 5 - \lambda_6)} + \frac{\lambda_{5(e^{-\lambda_6 t} - e^{-\lambda_4 t})}}{(\lambda_4 - \lambda_6)(\lambda_4 - \lambda_5)}\right] +$$
$$Kn_5\left[\frac{1 - e^{-\lambda_6 t}}{\lambda_6} - \frac{e^{-\lambda_5 t} - e^{-\lambda_6 t}}{\lambda_6 - \lambda_5}\right] + Kn_6\left[\frac{1 - e^{-\lambda_6 t}}{\lambda_6}\right] \tag{3.19}$$

$$N_7 = Kn_7\left[\frac{1 - e^{-\lambda_7 t}}{\lambda_7}\right] \tag{3.20}$$

The number of atom in the filter at the end of the sampling is N_{Ti} (i=1,2,...,7) can be expressed by replacing t by T on the above equation, because end of sampling time is equal to the air sampling time (T).

So, N_{Ti} (i=1,2,...,7) can be expressed as:

$$N_{T1} = Kn_1[\frac{1 - e^{-\lambda_1 T}}{\lambda_1}] \tag{3.21}$$

$$N_{T2} = Kn_1[\frac{1 - e^{-\lambda_2 T}}{\lambda_2} - \frac{e^{-\lambda_2 T} - e^{-\lambda_1 T}}{\lambda_1 - \lambda_2}] + Kn_2[\frac{1 - e^{-\lambda_2 T}}{\lambda_2}] \tag{3.22}$$

$$N_{T3} = kn_1\left[\frac{1 - e^{-\lambda_3 T}}{\lambda_3} - \frac{e^{-\lambda_2 T} - e^{-\lambda_3 T}}{(\lambda_3 - \lambda_2)} - \frac{\lambda_2(e^{-\lambda_2 T} - e^{-\lambda_3 T})}{(\lambda_3 - \lambda_2)(\lambda_1 - \lambda_2)} +\right.$$
$$\left.\frac{\lambda_2(e^{-\lambda_3 T} - e^{-\lambda_1 T}}{(\lambda_1 - \lambda_3)(\lambda_1 - \lambda_2)}\right] + Kn_2\left[\frac{1 - e^{-\lambda_3 T}}{\lambda_3} - \frac{(e^{-\lambda_2 T} - e^{-\lambda_3 T})}{\lambda_3 - \lambda_2}\right] +$$
$$Kn_3[\frac{1 - e^{-\lambda_3 T}}{\lambda_3}] \tag{3.23}$$

$$N_{T4} = Kn_4[\frac{1 - e^{-\lambda_4 T}}{\lambda_4}] \tag{3.24}$$

$$N_{T5} = Kn_5[\frac{1 - e^{-\lambda_5 T}}{\lambda_5} - \frac{e^{-\lambda_5 T} - e^{-\lambda_4 T}}{\lambda_4 - \lambda_5}] + Kn_5[\frac{1 - e^{-\lambda_5 T}}{\lambda_5}] \tag{3.25}$$

$$
\begin{aligned}
N_{T6} = Kn_4\Bigg[\frac{1-e^{-\lambda_6 T}}{\lambda_6} - \frac{e^{-\lambda_5 T}-e^{-\lambda_6 T}}{\lambda_6-\lambda_5} - \frac{\lambda_{5(e^{-\lambda_5 T}-e^{-\lambda_6 T})}}{(\lambda_6-\lambda_{5)(\lambda_5-\lambda_6)}} + \\
\frac{\lambda_5(e^{-\lambda_6 T-e^{-\lambda_4 T}})}{(\lambda_4-\lambda_6)(\lambda_4-\lambda_5)}\Bigg] + Kn_5[\frac{1-e^{-\lambda_6 T}}{\lambda_6} - \frac{e^{-\lambda_5 T}-e^{-\lambda_6 T}}{\lambda_6-\lambda_5}] + \\
Kn_6[\frac{1-e^{-\lambda_6 T}}{\lambda_6}]
\end{aligned}
\tag{3.26}
$$

$$
N_{T7} = Kn_7[\frac{1-e^{-\lambda_7 T}}{\lambda_7}] \tag{3.27}
$$

From the above equation we can expressed the numbers of atoms in a unit volume of the sampled air n_i (i=1,2,...,7) as follows:

$$
n_1 = \frac{\lambda_1 N_{T1}}{K(1-e^{-\lambda_1 T}} \tag{3.28}
$$

$$
n_2 = \frac{\lambda_2 N_{T2}}{K(1-e^{-\lambda_2 T})} - n_1[1 - \frac{\lambda_{2(e^{-\lambda_2 T}-e^{-\lambda_1 T})}}{(\lambda_1-\lambda_{2)(1-e^{-\lambda_2 T})}}] \tag{3.29}
$$

$$
\begin{aligned}
n_3 = \frac{\lambda_3 N_{T3}}{K(1-e^{-\lambda_3 T})} - n_2[1 - \frac{\lambda_3(e^{-\lambda_2 T}-e^{-\lambda_3 T})}{(\lambda_{3-\lambda_2)(1-e^{-\lambda_3 T})}}] - n_1[1 - \frac{\lambda_3(e^{-\lambda_2 T}-e^{-\lambda_3 T}}{(\lambda_3-\lambda_2)(1-e^{-\lambda_3 T})} - \\
\frac{\lambda_2\lambda_3(e^{-\lambda_2 T}-e^{-\lambda_3 T})}{(\lambda_3-\lambda_2)(\lambda_1-\lambda_2)(1-e^{-\lambda_3 T})} + \frac{\lambda_2\lambda_3(e^{-\lambda_3 T}-e^{-\lambda_1 T})}{(\lambda_1-\lambda_3)(\lambda_1-\lambda_2)(1-e^{-\lambda_3 T})}]
\end{aligned}
\tag{3.30}
$$

$$
n_4 = \frac{\lambda_4 N_{T4}}{K(1-e^{\lambda_4 T})} \tag{3.31}
$$

$$
n_5 = \frac{\lambda_5 N_{T5}}{K(1-e^{-\lambda_5 T})} - n_4[1 - \frac{\lambda_5(e^{-\lambda_5 T}-e^{-\lambda_4 T})}{(\lambda_4-\lambda_5)(1-e^{-\lambda_5 T})}] \tag{3.32}
$$

$$
\begin{aligned}
n_6 = \frac{\lambda_6 N_{T6}}{K(1-e^{-\lambda_6 T})} - 0.36n_5[1 - \frac{\lambda_6(e^{-\lambda_5 T}-e^{-\lambda_6 T})}{(\lambda_6-\lambda_5)(1-e^{-\lambda_6 T})}] - \\
0.36n_4[1 - \frac{\lambda_6(e^{-\lambda_5 T}-e^{-\lambda_6 T}}{(\lambda_6-\lambda_5)(1-e^{-\lambda_6 T})} - \frac{\lambda_5\lambda_6(e^{-\lambda_5 T}-e^{-\lambda_6 T})}{(\lambda_6-\lambda_5)(\lambda_4-\lambda_5)(1-e^{-\lambda_6 T})} + \\
\frac{\lambda_5\lambda_6(e^{-\lambda_6 T}-e^{-\lambda_4 T})}{(\lambda_4-\lambda_6)(\lambda_4-\lambda_5)(1-e^{-\lambda_6 T})}]
\end{aligned}
\tag{3.33}
$$

$$
n_7 = \frac{\lambda_7 N_{T7}}{K(1-e^{-\lambda_7 T})} \tag{3.34}
$$

The solution of the equation for the decay after the end of sampling are: [20]

$$
N_1 = N_{T1}e^{-\lambda_1 t} \tag{3.35}
$$

$$
N_2 = N_{T1}[\lambda_1\frac{e^{-\lambda_2 t}-e^{-\lambda_1 t}}{\lambda_1-\lambda_2}] + N_{T2}e^{-\lambda_2 t} \tag{3.36}
$$

$$
\begin{aligned}
N_3 = N_{T1}[\frac{\lambda_1\lambda_2(e^{-\lambda_2 t}-e^{-\lambda_3 t})}{(\lambda_3-\lambda_2)(\lambda_1-\lambda_2)} - \frac{\lambda_1\lambda_2(e^{-\lambda_3 t}-e^{-\lambda_1 t})}{(\lambda_1-\lambda_3)(\lambda_1-\lambda_2)}] + \\
N_{T2}[\frac{\lambda_2(e^{-\lambda_2 t}-e^{-\lambda_3 t})}{\lambda_3-\lambda_2}] + N_{T3}e^{-\lambda_3 t}
\end{aligned}
\tag{3.37}
$$

$$N_4 = N_{T4} e^{-\lambda_4 t} \tag{3.38}$$

$$N_5 = N_{T4} [\frac{\lambda_4 (e^{-\lambda_5 t} - e^{-\lambda_4 t})}{\lambda_4 - \lambda_5}] + N_{T5} e^{-\lambda_5 t} \tag{3.39}$$

$$N_6 = 0.36 N_{T4} [\frac{\lambda_4 \lambda_5 (e^{-\lambda_5 t} - e^{-\lambda_6 t})}{(\lambda_6 - \lambda_5)(\lambda_4 - \lambda_5)} - \frac{\lambda_4 \lambda_5 (e^{-\lambda_6 t} - e^{-\lambda_4 t})}{(\lambda_4 - \lambda_6)(\lambda_4 - \lambda_5)}] +$$

$$0.36 N_{T5} [\frac{\lambda_5 (e^{-\lambda_5 t} - e^{-\lambda_6 t})}{\lambda_6 - \lambda_5}] + N_{T6} e^{-\lambda_6 t} \tag{3.40}$$

$$N_7 = N_{T7} e^{-\lambda_7 t} \tag{3.41}$$

3.4 PLOT OF ACTIVITY CONCENTRATION WITH TIME

3.4.1 Plot of Rn-222 and its progeny

Considering a chain of decays of 222_{Rn}, that is $222_{Rn} \rightarrow 218_{Po} \rightarrow 206_{Pb}$, for the case where the decay probabilities are considered to be equal.

In this decay the parent is relatively long lived that is the wavelength of Rn-222 is much less than the wavelength of Po-218, then $N_2(t)$ (number of atoms Po-218) is initially grows rapidly and eventually, after time t, it approaches an equilibrium ratio with number of atoms of Rn-222, and both the decay products then decay at the same rate. [19]

Note:For Rn-222 decay the number of particles decreases as time increases according to the equation given below.

$$N_1(t) = N_{T1}e^{-\lambda_1 t} \tag{3.42}$$

Where$N_1(t)$ is number of atoms of Rn-222 at any time .

λ_1 is decay constants of Rn-222.

N_{T1} is number of atoms of Rn-222 at time t =0 .

For the decay products of Po-218,the number of particles initially grows rapidly,and eventually,after the time t they decay at the same rate according to the equation,that is

$$N_2(t) = N_{T1}[\frac{\lambda_1(e^{-\lambda_2 t} - e^{-\lambda_1 t})}{\lambda_1 - \lambda_2}] + N_{T2}e^{-\lambda_2 t} \tag{3.43}$$

Where λ_1 is decay constants of Rn-222.

λ_2 is decay constants of Po-218.

$N_2(t)$ is number of particles of Po-218 at any time t.

N_{T2} is number of atoms at the end of sampling.

Then based on the given information the plot is

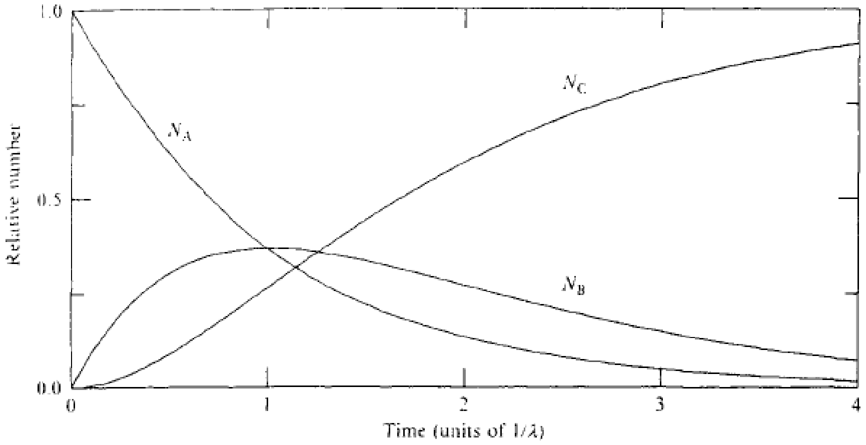


Figure 3.2: Variation with time of the amount of the isotope Rn-222, Po-218 and Pb-206 in the decay chain where decay probabilities are considered to be equal.[19]

Where N_A is the number of atoms of Rn-222 at any time.

N_B is the number of atoms of Po-218 at any time.

N_C is the number of atoms of Pb-206

3.4.2 Plot of Rn-220 and its progeny

Considering a chain of decays of radon-220, that is Rn-220 → Po-216 → Pb-208 .

In this decay the first rapid decay of Rn-220 to Po-216 followed by the slower decay of Po-216 to Pb-208.

Note:For Rn-220 decay the number of particles decreases as time increases, according to the equation:

$$N_1(t) = N_{T1}e^{-\lambda_1 t} \tag{3.44}$$

Where $N_1(t)$ is number of atoms of Rn-220 at any time t.

λ_1 is decay constants of Rn-220.

N_{T1} is number of atoms at the end of sampling.

For the decay products of Po-216,the number of particles increases from zero to some values for a given time and also decreases for the next time and remain constants at the end of time.

The variation with time of the amount of the isotope Po-216 is shown by the following formula.

$$N_2(t) = N_{T1}[\frac{\lambda_1(e^{-\lambda_2 t} - e^{-\lambda_1 t})}{\lambda_1 - \lambda_2}] + N_{T2}e^{-\lambda_2 t} \tag{3.45}$$

Where $N_2(t)$ is number of atoms of Po-216 at any time t.

λ_1 is decay constants of Rn-220.

λ_2 is decay constants of Po-216.

Then based on the above information the plot is

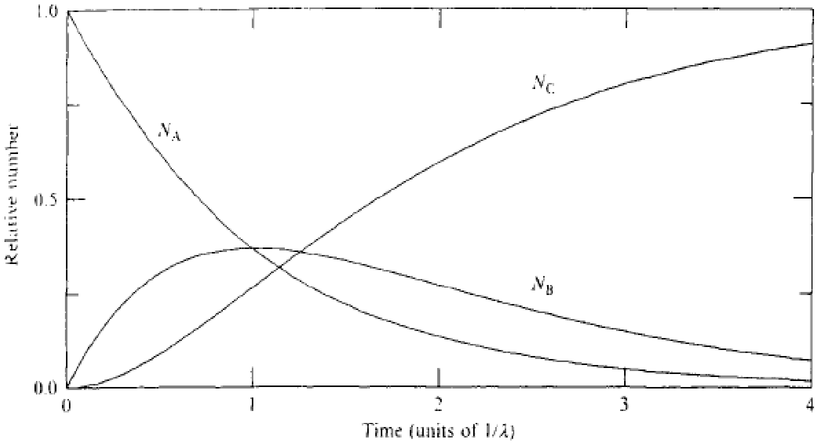


Figure 3.3: Variation with time of the amount of the isotope Rn-220,Po-216 and Pb-208 in the decay chain where decay probabilities are considered to be equal.[19]

Where N_A is number of atoms of Rn-220 at any time.

N_B is the number of atoms of Po-216 at any time.

N_C is the number of atoms of Pb-208 at any time

CHAPTER 4

Conclusion

In this work ,the attached and unattached fraction of radon and its progeny in mine atmospher ,indoor and outdoor was discussed . Depending on the concentration of dust in the room air, upto 20 percent of the decay products will not attach to dust particles and will remain in a free ion state . Since unattached decay products are often positively charged , they tend to attract other small polar molecules in the air. In addition to this the mathimatical model for radon and its progeny and instrument and methods are studied by comparing and anaysing the works in other part of the world.

From this work we can conclude that there is high concentration of attached and unattached fraction of radon in radium mines, medium concentration of attached and unattached fraction of radon in closed spaces biult in the ground and low concentration of them in the outside air.

In this area nothing is done in Ethiopia and suggestions to study various aspects of radon and thoron concentration are

- It needs due attention of the concerned body to find radon concentration in various part of the country (emphasis on mining areas)
- Measuring radon and its progeny so as to establish “Radon map of Ethiopia ”
- Health effect of radon and its progeny in Ethiopia

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DECLARATION

I the under signed declare that the project is my original work, has not been presented for a degree in any other university and that all sources of material used for the project have been duly acknowledged.

Name: ______________________

Signature: ______________________

This project has been submitted for examination with my approval as university advisor.

Name: ______________________

Signature: ______________________