Department of Physics and Applied Mathematics

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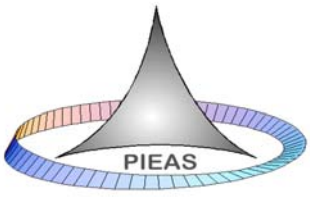
By

Said Rahman




Pakistan Institute of Engineering and Applied Sciences (PIEAS)
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August 2008

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**By**

**Said Rahman**

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of the requirements for the degree of

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# Declaration

I declare that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other university.

Signature: _____

Author's Name: Said Rahman

It is certified that the work in this thesis is carried out and completed under my supervision.

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*Dedicated*

*To*

*My sweat family members:*

*My parents, sisters, brother Gul Rahman and his family, my wife and Children(Farida Rahman, Uzma Rahman, Maryam Bibi,Inam ullah Khan, Atta ullah Khan and Subhanullah Khan) and especially to my younger brother Khair-ur-Rahman*

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1. Daniel J. Steck, **Said Rahman** and Matiullah (2008). Electrets as a Radon Progenies Dosimeter-Feasibility Study. J. Radiol. Prot (under review)
2. **Said Rahman**, Daniel J. Steck and Matiullah (2008). Development of a CR-39 based passive thoron progeny dosimeter - Preliminary studies Radiat. Meas. (under review)
3. **Said Rahman**, Matiullah and B.M.Ghauri (2008).Comparison of seasonal and yearly average indoor radon levels using CR-39 detectors. Radiat. Meas (under review)
4. **Said Rahman**, Munazza Faheem, Matiullah (2008).Natural Radioactivity Measurements in Pakistan - An Overview. J. Radiol. Prot. **28,** 1–10.
5. Munazza Faheem, **Said Rahman**, Shafi-ur-Rahman and Matiullah (2008).Radon – an environmental hazard. Science International, 20(1), 59-61.
6. Munazza Faheem, **Said Rahman**, Matiullah (2008).A Review of Radon Measurement Studies in Pakistan. J. Radiol. Prot. 28 (2008) 283–292.
7. **Said Rahman**, Matiullah and Badar Ghauri (2008). Effect of moisture on the radon exhalation rate from soil, sand and brick samples collected From NWFP and FATA, Pakistan. Radiat. Protect. Dosim., 130(2),172-177.
8. **S. Rahman**, Matiullah, S. A. Mujahid and S. Hussain (2008). Assessment of radiological hazards due to the presence of natural radionuclides in samples of building materials collected from the northwestern areas of Pakistan. J. Radiol. Prot. Radiol. Prot. 28, 205–212.
9. Matiullah, A. Ahad, Munazza Faheem and **Said Rahman** (2008). Measurement of radioactivity in vegetation of the Bahawalpur division and Islamabad federal capital territory – Pakistan. Radiat. Meas. Radiation Measurements 43 (2008) S532–S536.
10. Muhammad Rafique, Shahida Jabeen, M. Ikram Shahzad, **S. Rahman**, Shujaht Bukhari and Matiullah (2008).Measurement of Indoor Radon concentration and Dose Estimation in the city of Muzaffarabad after Earthquake (Oct. 2005), during summer, Azad Kashmir, Pakistan. J. Radiol. Prot(under review).
11. **S.Rahman**, Matiullah, Z. Rahman, N. Mati and B.M. Ghauri (2007). Measurement of indoor radon levels in North West Frontier Province and federally administered tribal areas- Pakistan during summer. Radiat. Meas. 42 (2), 304-310.
12. **S. Rahman**, N. Mati, Matiullah and B. Ghauri (2007). Radon Exhalation Rate From the Soil, Sand and Brick Samples Collected from NWFP and FATA, PAKISTAN. Radiat. Protect. Dosim. 124(4), 392-399.
13. Daniel J. Steck, **Said Rahman** and David Harrison (2007). Passive Radon Progeny Dosimeters: Feasibility Studies. 17th National Radon Conference of AARST, Jacksonville, Florida, USA, September, 2007

14. **S. Rahman**, Matiullah, S. A. Mujahid and S. Hussain (2007).Assessment of the radiological hazards due to naturally occurring radionuclides in soil samples collected from the North Western areas of Pakistan. Radiat. Protect. Dosim., 2008 128(2),191-197.

15. **S. Rahman**, N. Mati, Matiullah and B.M. Ghauri (2007).Seasonal indoor radon concentration in the North West Frontier Province and federally administered tribal areas—Pakistan. Radiat. Meas. 42, 1715 – 1722.

16. **S. Rahman**, M. Faheem, S. Rehman, and Matiullah (2006).Radon awareness survey in Pakistan. Radiat. Protect. Dosim., 121 (3), 333–336.

17. S. Rehman, Matiullah, S. Rehman and **S. Rahman** (2006).Studying $^{222}$Rn exhalation rate from Soil and Sand Samples using CR-39 detectors. Radiat. Meas., 41(6), 708-713.

18. S. A. Durrani and **Said Rahman** (2006).Radon as a possible indicator of impending earthquakes. Presented at: International Conference on 8 October 2005 Earthquake in Pakistan: It's Implications & Hazard Mitigation Islamabad, 18-19 January 2006.

19. **Said Rahman**, Shakeel-ur-Rehman, Munazza Faheem, Matiullah, Badar Ghauri and S. A Durrani (2006).A feasibility study of setting up radon measurement field stations for earthquake prediction in Pakistan. Paper presented at the 23rd International Conference on Nuclear Tracks in Solids, held in Beijing, China from 11-15 September, 2006.

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# Abstract

Radon has long been recognized as one of the indoor air problems. There is a strong relation between radon and lung cancer. It is the second leading cause of the lung cancer after cigarette smoking. The present research work concerning the **Measurement of seasonal and spatial variation of indoor radon and development of a passive dosimeter for thoron's progeny** is divided into two parts. The first part deals with the field and laboratory measurements which were performed using the passive radon dosimeters and in the second part laboratory experiments were carried out to develop a new passive thoron progeny dosimeter.

Chapter 1 gives a brief introduction to radon, its health effects, measurement techniques and the instruments used for the measurement of indoor radon concentration. Different dose conversion relations and excess lung cancer reports have also been discussed in this chapter. Chapter 2 describes different types of equipments and materials used in the research work. Information about the geology, climatic conditions and building characteristics of the houses surveyed have also been given in this chapter. It also includes procedure of the samples preparation for the measurement of radioactivity and radon exhalation rate in the laboratory using active and passive detectors. In chapter 3 reviews reported studies conducted in Pakistan concerning the measurement of natural radioactivity and indoor. Chapter 4 discusses the results and discussion of the present work concerning radon measurement performed throughout the years in four cycles which has covered all the seasons. Seasonal correction factor, weighted average indoor radon levels excess lung cancer risk and the dose delivered to the inhabitants using the local occupancy factor have also been included in this chapter. Chapter 5 deals with the results and discussions about the radon exhalation from the soil, sand and brick samples which were collected from the selected area. Effect of moisture contents on the radon exhalation rate using a closed can technique has also been presented in the chapter. The effect of back diffusion on the radon exhalation has also been studied and included in this chapter. Measurement of the natural radioactivity in the soil and other building materials,

like sand, brick, marble and cement samples which were collected form the selected area has been dealt with in chapter 6.

Research work performed at the University of St., John University USA has been included in chapter 7 and 8. These chapters include experiments performed in the exposure room using the electret ion chambers. Radon concentration in the exposure room was measured using both short term and long term electrets. It also includes the results of the performance factor for the alpha contamination chambers using the electrets as radon progeny dosimeter. Experiments were performed using both short term high sensitivity and long term (low sensitivity) electrets. Development of a new passive thoron progeny dosimeter using the principle of the surface deposition has been discussed in chapter 8. This chapter includes an introduction about the different types of active and passive equipments used for the measurement of thoron. It also discusses the calibrations of different types of active detectors for the measurements of surface deposited activities on the glass surfaces. Finally chapter 9 concludes the present research work and includes future recommendations.

# Chapter One

# An Overview of Environmental Radioactivity

## 1.1. Introduction

Every person, animal and object present on our planet earth are subjected to radiation and may indeed contain it. We cannot see it, smell it or feel it, but it is with us all the times. Natural radioactivity on earth has been in existence ever since the planet was formed and there are about 60 radionuclides present in nature. About 82% of the environmental radiation is from natural sources, the largest of which is radon. Some areas of the world, called high background radiation areas (HBRAs), have anomalously high levels of background radiations. Extreme HBRAs are found in Guarapari (Brazil), southwest France, Ramsar (Iran), parts of China and the Kerala coast of India (Dissanayake, 2005).

Radon exposure is known to be the second leading cause of lung cancer after cigarette smoking. In the past several decades, there have been more epidemiologic investigations exploring the association between radon (and its progeny) and lung cancer than any other environmental carcinogen. Studies concerning occupationally radon-exposed miners and direct observation from the individuals exposed to radon in their homes provide a firm scientific foundation which proves that radon is a major environmental carcinogen (IARC, 1988; ICRP, 1987; Nero, 1988; NRC, 1991; NRC, 1999; UNSCEAR, 2000).

## 1.2. Properties of Radon

Radon was discovered by the German chemist Friedrich E. Dorn. Radon has nine (19) short lived isotopes, but the most important is radon-222 ($^{222}$Rn), radon-220 (Thoron $^{220}$Rn) and radon-219 (Actinon, $^{219}$Rn). For millennia, advances in human progress have been tied to our ability to protect ourselves from the harmful effects of the

environment—ranging from human waste to the organic and inorganic by-products of everyday living and noxious gases. With the passage of time, humans have learnt more about the environment. With regard to the ill effects on human health of gases and fumes inside mines have been known since antiquity. Thus, Lucretius ( 95-55 BC), the Roman Epicurean poet-philosopher, in Book VI (Meteorology and Geology) has written that what malignant breath is exhaled by gold mines! How it acts upon men's features and complexions!. Vapors given off by the earth and blown out into the open, into the unconfined spaces of the air" (Lucretius, 55 BC). Of more recent origin, according to Steinhäusler (1988), are the medical observations of the redoubtable Swiss physician, Paracelsus (1493-1541) and Agricola in the sixteenth century "when it was noted that the mining population in parts of Germany (Schneeberg) and Bohemia (St Joachimsthalin Czechoslovakia) were suffering from a widespread fatal lung disease known as 'male metallorum' [metal sickness] or 'Schneeberger Krankheit' [Schneeberg Illness]. It was not until the nineteenth century that lung cancer was identified as the primary cause of death for about 75% of all miners in the Schneeberg region".

For humans, the greatest importance among radon isotopes is attributed to $^{222}Rn$ because it is the longest lived of the three naturally produced isotopes (Durrani and Illic 1999). It is well-known that airborne short-lived radon and thoron progeny inhalation has a large contribution towards the radiation exposure of the public (NRC, 1999; ICRP, 1994; UNSCEAR, 2000). Radon is an inert element in the gaseous form, with atomic number of 86. It is colorless, odorless, tasteless and radioactive. It is non reactive towards chemical agents. It is the heaviest member of the rare gas group (~100 times heavier than hydrogen and ~7.5 times heavier than air). When cooled below its freezing point, radon exhibits brilliant phosphorescence that becomes yellow at lower temperatures and orange-red at the temperature of the liquid air (CRC, 2001). Being a noble gas, it has greater ability to migrate freely through soil, air, etc. (Matiullah et al, 1993). There are no sinks for radon and it is estimated that only negligible quantity escape to the stratosphere (Gingrich, 1983). As a result, the ultimate and sole fate of radon is transformation or degradation through radioactive decay. Radon is readily absorbed on charcoal, silica gel and similar substances. This property serves to separate it from other gases by collecting it on activated charcoal.

$^{222}$Rn has been used as a tracer for the origin and trajectory of convective atmospheric transport of air masses to test general circulation models. $^{222}$Rn has also been used in more quantitative studies particularly to determine vertical matter diffusion coefficients. $^{222}$Rn is assumed to be generated by the land mass of a continent and using models for its mixing and transport in the atmosphere, outdoor air concentrations are calculated at a certain distance of the continent and compared with measurements performed at some other points in sea (Neman et al., 2005; Lee et al., 2001).

### 1.3. Sources of Indoor Radon

Radon comes from uranium that has been in the ground since the time the earth was formed. The rate of radon seepage is variable, partly because the amounts of uranium in the soil vary considerably (BEIR VI, 1999). Radon flows from the soil into the outdoor air and also into the air in homes from the movement of gases in the soil beneath homes. Outside air typically contains very low levels of radon, but it builds up to higher concentrations indoors when it is unable to disperse. Generally sources of radon in dwellings are, radon exhaled from the building materials and the soil/rocks below the building and inflow of radon containing air (Aldenkamp et al., 1992). According to significance the indoor radon sources may be classified in the following order as soil beneath the building, building materials, outdoor air, portable water supplies and natural gas (UNSCEAR, 2000).

Characterization of the indoor sources of radon requires consideration of the rate at which radon is generated in the source materials and its modes of transport through various materials into the indoor environment. The property of the materials which is considered most significant for the material to be an indoor radon sources, is the radium ($^{226}$Ra) contents in that material. A slight differences in $^{226}$Ra concentrations result in greatly varying $^{222}$Rn concentrations. However, all the radon produced in the grain doses not escape from the grain and its release depends on the porosity of the materials/ emanation coefficients and exhalation rate from the materials which are briefly discussed below.

## 1.4. Release Mechanism of Radon

The release mechanism of radon from the grain to the indoor environment is governed by emanation and exhalation. The release of radon form mineral grain to the pore space is called emanation. Emanation is described by emanation coefficient which is the ratio of the radon produced in the grain of the materials to the radon in the pore space of the material. Its value is different for different materials and it depends on the grain size of the materials. Smaller the grain size will cause more emanation and vice versa. Emanation is governed by the law of conservation of momentum. The value of the emanation coefficient is of the order of 0.2–0.3 (Durrani and Ilic, 1997) for common constituents of building material (e.g., sand**)**. The emanation increases with increase in the water contents in materials as moisture absorbs the recoil energy partly and the probability for radon atom remaining within the pore space is enhanced. The residual nucleus $^{222}$Rn recoils and is able to leave the rock grain provided it is close enough to the grain boundary and is free to migrate in the pore space of soil (Mujahid et al., 2005). The first possibility for escape is direct ejection of the radon atom by the recoil alpha emission. Conservation of momentum reveals that residual radon nucleus has energy of 86 keV which is sufficient to move the recoiling radon through 26 nm of $SiO_2$ (Fleisher, 1997; Durrani and Ilic, 1997).

Radon moves by diffusion and forced flow. Diffusion inevitably occurs even though its extent is limited. Hence diffusive migration sets a lower limit on the transport of radon. Forced flow depends on pressure gradients which may or may not be present in every situation. Diffusive flow in the materials is controlled by open, connected porosity. Higher porosity enable more extensive diffusive transport, but it is critical to consider only that fraction of the pore space that allows through motion. Near surface radon escapes into the atmosphere thereby lowering the natural concentration to near zero at the surface producing a near surface gradient whose profile is set by diffusion and mean life of radon concentration. If the radium concentration, porosity and emanation for a type of soil or the material are known then maximum radon concentration 'C' that can occur in the pore space can be calculated by the following equation

$$C = \frac{Aed(1-p)}{p} \qquad (1)$$

Where ‘A’ is radium content, ‘e’ is emanation coefficient, ‘d’ is diffusion coefficient and ‘p’ is the porosity of the material. Smaller the particles in which the radon atom is formed, greater is the chance of the atom escaping from it. Emanation is greater in finer grained particles. For clay it is between 40 - 70%. One parameter of importance is the ability of the gas to leave the grains of the soil after it is produced. The fraction of radon atoms, generated in the soil grains and reaching the pore volume of the soil is known as the emanation coefficient. This coefficient depends basically on the soil grain size-distribution, on the porosity and on the water content (Baixeras 2001). Emanation and transport mechanisms depend to a large extent on soil moisture content. Thus, radon flux at the soil surface is strongly affected by the weather conditions (Ferry et al., 2001). A reduction in the bricks exhalation from 50% to 90% is obtained when inner sides of the walls are painted. Since most of the dwellings in the cities are painted using different types of paints, very little contribution seems to come out from the building material which is in agreement with indoor results (Segoviat et al., 1994). Table 1.1 show the correlation between he radon concentration in the soil air and atmospheric pressure, soil and ambient temperature and atmospheric humidity

It is a well known fact that radon emanation is affected by moisture. The models which explain radon emanation can be considered to come in three types. One is to predict the maximum possibility of radon emanation assuming uniform distribution of radium in a solid grain independent of the moisture. The other two are to explain moisture effect on radon emanation, but their aims are different from each other. The first of them aims to demonstrate a theory explaining microscopic phenomena of radon emanation employing observed macroscopic phenomena of radon emanation under moist condition. The second aims to predict the leveling-off value of radon emanation under moist conditions employing an observed data of radon emanation under dry conditions.

Sasaki et al., have reported that emanation coefficient is affected by the moisture content. They have proposed close-packed spherical grain model and studied quantitatively if it can well predict the leveling-off value of radon emanation coefficient (Sasaki et al., 2004). The other mechanism which affect radon concentration is exhalation. The release of radon from pore space into the air is called exhalation. A

measure of exhalation is given by the exhalation rate, which is defined as the number of radon atoms leaving the material per unit surface area per unit time. Radon exhalation rate is highly affected by the parameters like atmospheric pressure, temperature and wind force. According to the published data, 60.4% of the indoor radon comes from the ground and surrounding soil of the buildings (Sun et al., 2004). The most important factor, controlling exhalation of radon from soil is geological structure of the top layer of the ground. Another important factor is rocks underlying the soil to the depth of about 10 m because radon cannot migrate from deeper levels due to its relatively short half life. The measurement technique of radon exhalations from the construction materials using nuclear track detectors (NTDs) was reported by Abu-Jarad in 1980 which is called the ‘‘can technique’’ (Rehman et al., 2003).

For radon transport through a porous medium, information on its generation, the structure of the medium, the physical processes causing the transport driving forces and the interaction of radon with the medium partitioning between air and water phase and adsorption at the solid interface are required (Cozmuta and van der Graaf, 2001) .

Table 1.1: Correlation coefficients between the radon concentration in the soil air and atmospheric pressure, soil and ambient temperature and atmospheric humidity.

| S.No | Parameter | Correlation coefficient |
|---|---|---|
| 1. | Soil temperature | 0.752 |
| 2. | Ambient temperature | 0.754 |
| 3. | Atmospheric pressure | −0.861 |
| 4. | Atmospheric humidity | −0.555 |

It is well documented that drops in atmospheric pressure may cause an increase in the radon transport into a house. This affect may, however, often be of relatively short duration and at most last only as long as the pressure is still dropping. Among the physical and geological factors characterizing the radon risk of a given type of the bedrock and subsoil are the radium concentration and permeability. Therefore, geological

classification is needed to be done on the basis of these parameters. If large variations in the exhalation rate occur during the growth time, the mean exhalation rate deduced from the gamma activity of the sample will outweigh the values of the exhalation rate occurring during the later part of the growth period (Stranden et al., 1985). The soil-gas radon concentration as well as the radon exhalation rate from the ground may vary often greatly over a small distance (Martin and Matěj, 2002).

### 1.5. Radiation Hazards

Radiation effects comprise of (1) deterministic effects that occur with certainty after doses high enough to cause major cell killing and (2) stochastic effects that are considered to occur more or less in proportion to the dose at all dose levels. The table 1.2 shows average dose received due to different radiation sources (Bølviken, 2001).

Table 1.2: Average annual effective dose per caput.

| 1. | Source | Dose ($mSv.yr^{-1}$) |
|---|---|---|
| 2. | Natural background | 2.4 |
| 3. | Diagnostic Medicine | 0.4 (0.02-1.2)[1] |
| 4. | Atmospheric weapon testing | 0.005 |
| 5. | Chernobyl accident | 0.001 |
| 6. | Nuclear fuel cycle | 0.0001 |
| 7. | Occupational Exposure | 0.001 (1.3)[2] |

[1]Global value (least developed countries-highly developed countries)

[2]Global value (worker average)

Out of 98% of the average radiation dose received by human beings is from natural sources, about 52% is due to the inhalation of radon, thoron and their progenies present in the dwellings (UNSCEAR, 1988). The International agency for Research on Cancer (IARC) has recognized radon as a class A carcinogen and as such it is considered to have no minimum acceptable dosage threshold (IARC, 1988).

In many epidemiological studies as well as in the case control studies of the radon risk, the excess number of cancers are related to the radon concentration (given in $Bq\ m^{-3}$), and not to the radon progeny exposure. A justification for such an approach has

resorted to the assumption that there is self compensation between the radiation doses from the unattached and attached fractions (Nikezic and Yu, 2005). As mentioned in the BEIR VI report that there is good evidence that a single alpha particle can cause major genomic changes in a cell, including mutation and transformation which may cause lung cancer as most cancers are of monoclonal origin (James et al., 2004). Form this it is concluded that no safe level of exposure can be determined. Quantitative risk estimates may be obtained from a recent large residential study, which are in general agreement with a linear extrapolation of risks observed in miners (Theakston, 2000).

The excess risk of lung cancer due to the radon is about 16% per 100 $Bq.m^{-3}$ throughout a wide range of exposure levels, then radon in homes currently accounts for about 9% of the deaths from lung cancer and hence 2% of all cancer deaths in Europe (Darby et al., 2005).

In order to measure the effect of radon on lung cancer, eighteen case–control studies of residential radon and lung cancer have been published, including seven studies in North America, nine in Europe and two in China. Some of these studies reported a positive or weakly positive association between lung cancer risk and residential radon concentration, while others have reported results consistent with no association (Krewski et al., 2002).

Two approaches can be taken to quantify the relationship between the exposure to ambient radon and radon progeny and the resulting lung cancer incidence: the 'epidemiological approach', in which epidemiological data on lung cancer incidence are directly related to the cumulative exposures and the 'dosimetric approach', in which the lung cancer incidence is predicted on the basis of cellular doses in bronchial epithelium (Hofmann,1998). Epidemiological and dosimetric approaches for determining the dose and risk to the lungs from exposure to radon and its decay products differ by a factor of about 3 (Meinhold, 2004). Data regarding higher dose exposures in miner populations, when extrapolated to low dose levels, suggests a linear no-threshold (LNT) relationship of lung cancer and radon. Ecologic studies are performed to study the effect of a carcinogen in an area (Heath et al., 2005).

Dose from exposure to radon daughters is primarily related to the intake of Potential Alpha Energy Concentration (PAEC) and the conversion coefficient is influenced by aerosol size. James et al. have observed that in the aerosol conditions which are normally encountered, radon concentration is a better index of dose than the concentration of PAEC, which require measurement of the unattached fraction '$f_p$' attached fraction '$f_a$' and equilibrium factor 'F' to improve the assessment of dose.

The BEIR VI committee has chosen to use the lung-cancer information from studies of miners, who were more heavily exposed to radon, to estimate the risks posed by radon exposure in homes. A linear model for extrapolation of risk from miners to residential populations is a reasonable approach. At present, the "time since exposure" provides a reasonable basis for the risk assessment (BEIR VI; 1999). The BEIR IV committee used data from 4 cohort studies of the underground miners and reported lung-cancer risk associated with radon-progeny using a linear relative risk model: $RR = 1 + \beta\omega$, where $\beta\omega$ estimates the excess relative risk (ERR) (NRC, 1988), $\omega$ is exposure and $\beta$ estimates the increment in ERR for unit change in exposure '$\omega$'.

Combined analysis of 11 cohorts of over 60,000 underground miners conducted by Lubin et al. and updated by the U.S. National Research Council which provides a comprehensive assessment of the lung cancer risks associated with radon. The BEIR VI committee modeled the excess relative risk (ERR) as a linear function of past exposure to radon. This model allows the effect of exposure to vary flexibly with the length of time that has passed since the exposure, with the exposure rate, and with the attained age. The mathematical form of the model for ERR (NRC , 1999) is:

$$ERR = \beta (w_{5-14} + \theta_{15-24} w_{15-24} + \theta_{25+} w_{25+})\varphi_{age}\gamma_z \qquad (2)$$

The parameter $\beta$ represents the slope of the exposure-risk relationship. Exposure in the last 5 years is excluded as it is not biologically relevant to the cancer risk—and exposures in 3 windows of past time, namely 5-14, 15-24, and 25 or more years previously. Those exposures are labeled $w_{5-14}$, $w_{15-24}$, and $w_{25+}$, respectively and each is allowed to have its own relative level of effect, $\theta_{5-14}$ (set equal to unity), $\theta_{15-24}$, and $\theta_{25+}$, respectively. The rate of exposure also affects risk through the parameter $\gamma_z$; thus, the effect of a particular level of exposure increases with decreasing exposure rate, as

indexed either by the duration of exposure or the average concentration at which exposure was received. The ERR also declines with increasing age as described by the parameter $\varphi_{age}$ (Lubin et al., 1995).

The BEIR VI suggested two alternative preferred models namely the "exposure-age-concentration model" and the "exposure-age-duration model". Both of the alternative models calculate the fractional increase in lung cancer risk due to a specified exposure.

For the relatively low exposure rates or long time durations, the risk per unit (WLM) exposure is maximal and increases linearly with the radon exposure (US EPA, 2003). In the present research work "exposure-age-concentration model" has been used in order to calculate the excess lung cancer from the measured indoor radon concentration. Using the ICRP-65 (ICRP, 1993) and UNSCEAR 2000 (UNSCEAR, 2000) dose conversion factors the effective dose to the inhabitants of the selected area was also calculated.

Many uncertainties affected the extrapolation of the risk from miners to the general population, the main being: (i) the average radon concentration in mines was about 100 times higher than in dwellings (ii) the composition of the inhaled air in dwellings is quite different from that in mines (iii) the characteristics of the exposed groups differ widely, miners being strong-built adult males exclusively (Bochicchio, 2005).

### 1.6. Equilibrium Factor

The short-lived decay products of radon gas are assumed to achieve a state of radioactive equilibrium with their parent in open air, with an effective half-life of about 30 min. If one considers only radioactive disintegration, the state of equilibrium generally varies as a function of the mean age of the radon atoms. Atmospheric processes such as turbulent mixing or wet and dry deposition however results in a state of disequilibrium between the activity concentration of radon gas in air and its decay products associated with the aerosols. The state of equilibrium can then be described by the equilibrium factor, F, i.e. the ratio of the equilibrium equivalent concentration to the radon activity concentration:

$$F = \frac{EEC}{C_{Rn}} \tag{3}$$

There is a wide range of values reported for F from individual outdoor measurements, ranging from 0.1 to 1(Winkler et al., 2001) Equilibrium factors between radon and its progeny and between thoron and its decay products depend on the ventilation rate inside the room (Misdaq et al., 2001; Galmarini, 2006). Knowledge of the amount of the short-lived radon progenies in air is necessary to obtain: (1) equilibrium factor (F) and (2) the unattached fraction ($f_p$) of radon progeny. The fraction of indoor radon progeny attached to airborne particles is highly dependent on particle concentration (Martell, 1983). Risk from radon as a source of radiation should be evaluated and controlled like the risks from any other radiation sources and that the "as low as reasonably achievable"(ALARA) principle should prevail (Suess, 1995; Godoy et al., 2002). Dose from the radon progenies can be calculated using the dose conversion factor (DCF) which varies for attached and unattached fraction of radon progenies.

$$C_p = C_{pae} + C_{pu} \tag{4}$$

Where $C_p$ is the potential alpha energy concentration, $C_{pae}$ is the aerosol attached potential alpha energy concentration and $C_{pu}$ is the potential energy concentration of the unattached fraction.

$$DCF = DCF_{ae} + DCF_u \tag{5}$$

Where DCF is the dose conversion factor for the radon progenies, $DCF_{ae}$ is the conversion factor for the aerosol attached fraction and $DCF_u$ is the conversion factor for the unattached fraction. The particle concentration varies between $10^3$ particles.cm$^{-3}$ and $10^6$ particles.cm$^{-3}$ depending upon the aerosols sources and human activities indoors and out doors. Unattached fraction can be approximated by the semi-empirical equation $f_p = 400/Z(cm^{-3})$, where Z is the aerosols concentration. Thus dose conversion factor values for the radon decay product aerosols and the unattached clusters vary between 4-10 mSv.WLM$^{-1}$ and 0.3-32 mSv.WLM$^{-1}$ , respectively (Porstendörfer, 1999).

The lungs dose due to the unattached radon decay products is much greater than the dose due to the radon progeny attached to the aerosol particles (Yu et al., 2005). Unattached fraction can be measured directly or can be calculated form the concentration measurement aerosols. The $f_p$ values vary from 0.005 and 0.2 and depend on the concentration number of the aerosols (Porstendörfer, 1996).

The dose conversion factor varies in indoor air as $9.1 + 64f_p$ . Thus unattached fraction has a greater influence in the DCF. Depending on the aerosols conditions, the dose varies over 4.2-11.5 mSv $WLM^{-1}$ in homes and in work places it varies from 4.2-7.1 mSv $WLM^{-1}$. In the case of normal aerosol conditions, the DCF varies 8-11.5 mSv $WLM^{-1}$ (Porstendörfer, 2001). Freshly generated $^{218}Po$ ions are mostly positively charged (88%) and react rapidly with trace gases and vapors in air and become small particles called clusters or "unattached" decay products with a size spectrum between 0.5 and 3 nm diameters. Neutralisation of the unattached $^{218}Po$ ions can be described by three processes: Recombination with small air ions, electron scavenging by OH radicals formed by radiolysis of water vapour and charge transfer by molecules of lower ionization potential (Pagelkopf and Porstendörfer, 2003; Porstendörfer, 1994).

### 1.7. Radon Concentration Measurement Devices

The environmental radon concentration is a function of time and climatic conditions. To monitor radon, both active and passive techniques have been developed. Active methods are usually used for short-term measurements of radon. Passive methods are more suitable for the assessment of radon exposure over long time scales and can be used for large-scale surveys at a moderate cost (Ahn and Lee, 2005).

Measurement of $^{222}Rn$ and $^{220}Rn$ concentrations can provide information on the upper limit for the potential α-energy exposure due to the presence of their daughters in air. The concentration of $^{222}Rn$ and $^{220}Rn$ is generally easier to measure than the concentration of any associated individual daughters (Amgarou, 2003). Radon and its daughters are alpha emitters and its progenies $^{212}Pb$, $^{214}Bi$ and $^{210}Pb$ and $^{210}Bi$ are β emitter and γ-rays accompany their β emission. Thus radon or its progenies can be measured by measuring one or other type of radiation emitted by them. Different techniques like nuclear emulsion, adsorption, solid scintillation, liquid scintillation,

gamma spectroscopy, beta monitoring, solid state alpha detectors, electrometer or electroscope, ionization chambers, surface barrier detectors, Thermoluminescent phosphors and electrets can be used in its measurements. To estimate population exposure, radon concentration instead of radon progeny is generally measured. Solid-state nuclear track detectors (SSNTDs) are low-cost, small-sized devices for large-scale studies in which radon concentration in dwellings can very easily be measured (UNSCEAR, 2000). Further the absorbed dose to the lungs is approximately proportional to the radon concentration rather than to the radon decay product concentration (James, 1987).

In active sampling generally radon and its decay products are brought either into the vicinity of a detector or into a collector device by forced pumping while in passive sampling radon and its decay products are collected through their natural diffusion (or permeation) into the sampler, containing a detector. The terms active and passive are also used to designate radiation detectors which operate with and without power supply, respectively. Totally passive monitoring systems work well for the measurement of only radon gas. Passive measurements are also most suitable for large-scale survey of radon concentrations in the indoor air. The measurements of radon decay products can be carried out by totally active monitoring systems, i.e. by using active sampling and real-time alpha detection and spectrometry. In this regard, some of the most commonly used methods are discussed briefly here.

### 1.7.1. Passive Techniques

*1.7.1.1. Charcoal Canister Technique*

Activated charcoal has capacity for adsorbing and retaining radon. Therefore, conventional charcoal canisters can be used to measure radon. It works on the adsorption of radon on charcoal, which was first observed by Rutherford (1906). Charcoal canisters are a convenient screening technique that gives a measure of the average radon over the time period that the canisters are on the site (generally about 1 to 3 days). One advantage of this device is the simplicity of construction. In the configuration described by Cohen and Nason (Cohen and Nason, 1986) a 1.5-centimeter deep bed of charcoal is placed in a commercial metal "ointments can" which has a 3-inch diameter and 1-inch height and a

4 inch diameter hole is drilled in the top of the can which is covered with a fine-mesh screen. This allows radon to enter by diffusion, with little convection. A desiccant is added to remove the water vapor. Before the detector is sent to the measurement site, it is baked out and the hole is covered with tape in order to block the unwanted radon before it is placed in the site where measurement is sought. At the site, the detector is exposed to the ambient atmosphere for time up to one week, after which the tape is replaced. The detector is then returned to the laboratory and is counted with gamma-ray detection system.

*1.7.1.2. Solid State Nuclear Track Detectors (SSNTDs)*

A heavy charged particle leads to intensive ionization when it passes through insulating materials. Along the path of the particle, a zone called the latent track is created, which is enriched with free chemical radicals and other chemical species. If a piece of material containing the latent track is exposed to some chemically aggressive solution (such as aqueous NaOH or KOH solution), the chemical reaction would be more intensive in the latent track. Such a solution is called the etchant. Through etching, the latent track becomes visible as a particle "track" which may be seen under an optical microscope (Nikezic and Yu, 2006).

Among the attractive features of SSNTD detectors is the availability in different shapes and dimensions, the possibility to be placed practically at any point, the insensitivity to β and γ yields, the high dynamic range and the true time integrating capability. As they do not require power supply or maintenance during the exposure and the costs of the detectors as well as of the processing are rather low, they are suitable for large scale surveys (Sima, 2001).

The most commonly used SSNTD is CR-39, which is based on the polymer of alil diglycol carbonate diethylene glycol bis allyl carbonate (PDAC) having formula $(C_{12}H_{18}O_7)_n$. There are two different modes of its usage in radon measurements: (a) as open (bare) detector and (b) as detector in a diffusion chamber. In the case of bare detector, humidity and dust affect the detection of alpha particles and the detector sensitivity is dependent on the equilibrium factor between radon and its short-lived progeny.

The diffusion chamber is a cup covered with a filter paper on the top and is frequently equipped with a CR-39 detector that is usually placed on the bottom of the cup. Progeny atoms move randomly in the chamber volume and can deposit onto available inner surfaces before decay. The deposition changes the irradiation geometry of the detector, i.e., detector sensitivity is dependent on the fraction of radon progenies decaying in the air prior to the deposition. The behavior of radon progenies inside the chamber (as well as the aerosol properties and air velocity inside the chamber) is unknown and it is difficult to estimate the fraction of radon progenies decaying prior to the deposition. The deposition fraction depends on different environmental conditions (Nikezic and Yu , 2000).

Another type of passive track detector is LR-115 film (Kodak-Pathé, France) (Odqlqlü et al., 2001). The cellulose nitrate LR- 115, having a thickness of about 12 μm, is a very useful material for the registration of alpha particles radon exhalation rates of building materials (Amrani et al., 1999). A major drawback of SSNTD is that they only integrate the received flux of particles. They do not provide time dependent response (Misdaq et al., 2001).

*1.7.1.3. Electrets*

Electret ion chambers are inexpensive, light-weight, passive charge-integrating devices for accurate measurement of different types of radiations. These detectors are more suitable for indoor radon measurements (Dua et al., 1999a,b). Electrets ion detectors which contain an electro-statically charged Teflon disk are widely used for long-term radon measurement. Ions generated by the decay of radon strike and reduce the surface voltage of the Teflon disk. By measuring the voltage reduction, the radon concentration can be calculated. The amount of voltage drop on the electret provides an accurate correlation to the number of ions collected and hence the concentration of the alpha-emitting isotope like radon (Kasper,1999). The longer they are left in place, the better sensitivity they are capable of providing. The EIC system is remarkably accurate and sensitive (Kitto, 2005). Electrets are also sensitive to gamma rays, therefore, correction for it is required when used for the measurement of radon.

*1.7.1.4. Thermoluminescent Detectors (TLDs)*

When an ionizing particle travels within a crystal it ejects some electrons from their normal position into the conduction band, leaving holes in the valance band. The electrons are then trapped into the defects of the crystal and stored there in a very stable position. If later on the crystal is heated the energy given to the electrons allow them to escape from their trap. Based upon this principle, several types of Thermoluminescent dosimeters have been developed. In this method if alpha particles hit TLD, subsequent heating of it will release an amount of light which is proportional to the total energy of the alpha particles. TLDs are sensitive to alpha, beta and gamma radiation, a procedure has to be adopted to determine the alpha contribution only. Two TLDs one of the TLDs is wrapped in a foil that will exclude all alpha particles, but the beta and gamma radiations are not excluded. After a certain time the TLDs are retrieved and analyzed by heating those to 300 $^{o}$C in the appropriate read out equipment. The contribution from alpha radiation can be determined by subtracting the energy of first TLD (exposed to only beta and gamma radiation) from second TLD (exposed to alpha, beta and gamma radiation) and hence the radon activity is measured (Tommasino, 1998; Vaupotič and Kobal, 2003).

### 1.7.2. Active Techniques

*1.7.2.1. Ionization Chamber*

An ionization chamber is essentially a capacitor, usually of cylindrical shape, in which an electric field is established between two electrodes. If the radon containing air is admitted to the field, the radiation from the decay of the radon daughters atoms will ionize the air and a current will flow between the electrodes. Over a period of approximately 3-4 hours, the radon in the chamber grows into a state of transient equilibrium with its short-lived daughters. Current can be measured any time. For low level of environmental samples typical measurement time ranges from 30 to 60 min. It is possible to measure the concentration of 5 Bq.m$^{-3}$ with an uncertainty of about 10-20 % (Friedmann, 1983).

*1.7.2.2. Scintillation Cell*

Scintillation produced by the alpha particles are detected by the use of scintillation cells developed by Lucus (Lucus 1957). The cell is coated on the inside with ZnS (Ag), except for a clear window of quartz, glass or plastic. The cells filled with air or other gases containing radon, are placed on top of and with the end window in direct contact with, a photomultiplier in a light-tight enclosure. Energy of alpha is converted into light pulses and the resulting electrical pulses from the photomultiplier are counted by a discriminator /scalar. The activity in the cell will grow over the first three hours before the state of transient equilibrium is established. The normal procedure is to wait 2-3 hours after the filling before the activity is counted. The efficiency of the cell is about 70-80 % . The volume of most scintillation cells is from one hundred to a few hundred $cm^3$. The lower limit of detection is about 0.5 $Bq.m^{-3}$.

Alpha-particle scintillation counting with liquid scintillator: In an alternative scintillation counting technique a liquid scintillator is used in place of the ZnS and the radon laden air is entered into the scintillator. In one application of this approach the radon-bearing air is passed through an organic solvent in which radon is highly soluble at low temperatures. The solvent with radon is then introduced into a vial containing a liquid scintillator. Liquid scintillation are also used for the measurement of radon exhalation LSC offers low detection limit of the exhalation coefficient as low as 0.1 $mBqm^{-2}\ s^{-1}$ (Bahtijari et al., 2007; Nishikawa et al., 1988). Liquid scintillation technique is popular for radon analysis due to the high solubility of radon in organic solvents (Prichard et al., 1991).

*1.7.2.3. Two Filter Method*

This technique is used to measure both radon and its daughters concentrations. Air is passed through first filter so that radon daughters are removed and allow the air to pass through a long decay chamber so that the daughters grow again and are collected on the second filter. The filters are counted separately; radon concentration is determined from the second filter and its daughter concentration from the first filter. Air is drawn at a typical rate of 10 $\ell.min^{-1}$ and usually for a period of five min. The front filter will remove all the daughters in the air sample and the second filter will collect those daughters being

produced by the decay of radon in the air while it passes through the cylinder. The alpha activity from the filter at the end of sampling is then a measure of the radon concentration in the sample air. For environmental monitoring purposes, large volume two-filter cylinder can have lower limit of detection of 0.7 $Bq.m^{-3}$.

*1.7.2.4. Active Pylon Detectors /Continuous Monitoring*

Radon concentration changes significantly and rapidly with time. Therefore grab sampling may not give an adequate value of the radon levels and thus require continuous monitoring of radon. It is the most useful method for studying the effect of atmospheric parameters like pressure, humidity, temperature and wind, ete. on radon concentration. Continuous measurements of radon concentration can be done by AB-5 Pylon monitor (Chalupnik and Wysocka, 2003). Electronic detectors can also be used for the measurement of radon/ thoron and their progenies. These devices give the results of individual daughters and the gas concentration. This is usually based on the gamma ray interaction with matter. Semiconductors like Si or Ge crystal are used for this purpose. This instrument has the property, if programmed, gives the time dependent concentration of radon and its daughters. However these instruments could not be used in field due to the requirement of the power. Some portable solid state devices are now available for this purpose. Method based on small accumulation chambers connected to a continuous Radon Gas Monitor RAD7, is equipped with a solid state alpha detector. The method allows the simultaneous measurements of radon and thoron using only the $^{218}Po$ peak for $^{222}Rn$ and $^{216}Po$ peak for $^{220}Rn$. RAD7 can produce an energy spectra in the range of 0-10 MeV with a resolution of 0.05 MeV which differentiates α particles emitted from the progeny of $^{220}Rn$ and $^{222}Rn$. Eight energy ranges, called windows A-H, are defined in the spectrum for data analysis. Window A collects α particles from $^{218}Po$ decay (6.00 MeV), which is used for the determination of $^{222}Rn$.

Window B collects α particles from $^{216}Po$ decay (6.78 MeV), which is used for the determination of $^{220}Rn$. Window C collects α particles from $^{214}Po$ decay (7.69 MeV) and may also be used for the determination of $^{222}Rn$. Filters are installed on the top of the sampler of RAD7 to screen out the progenies of $^{220}Rn$ and $^{222}Rn$, so that only the gas concentrations are measured. A desiccant drying tube containing anhydrous $CaSO_4$ is

installed to maintain a relative humidity of the incoming air below 10% during the measurements which is monitored by a humidity sensor. The sensitivity of the a particle detector is lowered significantly when the relative humidity is too high (Thomas et al., 2000).

*1.7.2.5. Surface Barrier Detector (SBD)*

Surface barrier detector is a semiconductor detector which is operated under reversed biased conditions. The alpha particles from radon decay enters the depletion region and creates electron hole pairs. Electron flow in one direction, holes in the other and total number of electrons collected can form an electronic pulse whose amplitude is proportional to the energy of the radiation. However, one disadvantage of the SBD is its sensitivity to light. The thin entrance windows are optically transparent and photons striking the detector surface can reach the active volume (Knoll, 2000).

*1.7.2.6. Monitoring of Radon and Thoron Daughters*

Dose delivered to the lungs is not due to radon, rather it is due to the short lived radon daughters, therefore it is necessary to measure the daughter's concentrations in different environments. The methods are based on the analysis of the activity from a filter (or detector) on which the daughters have been deposited. Three counts of this activity will determine both the individual daughters concatenations and the potential alpha energy concentration when certain relations are assumed between the daughter's concentrations. If the goal is to measure PAEC, one count exact method is used. For this purpose, there are two commonly used methods Kusnetz and the Rolle methods, differing only in the choice of sampling, waiting and counting times. The protocol is 5-40-2, 5-90-2. With Rolle method counting starts 1-6 minutes after sampling depending upon the length of the counting time. The alpha particles deposited on a filter are counted using scintillation counter.

**Two Count Methods**

The one count method is simple. By using two uncorrelated counts it is possible to improve one or both of these characteristics. The commonly used two counts methods are Hill Method, James and Strong (J-S) method, Shreve Method, 3R/WL method and Markov method.

**Three counts methods**

The three uncorrelated counts during and or after samplings are in principle used for individual progeny measurements. The **Tsivoglou method** and the modified **Tsivoglou method** are used.

**Tsivoglou method**: In the original Tsivoglou method the activity from a filter is measured at three time intervals (i.e. 5, 15, and 30 min after sampling). The amount of air sampled is about 50 ℓ. Because count rates are used instead of integrated counts, even at high concentrations the reproducibility may only be good with in 20-30 %. This method is modified by Thomas and in the Modified Tsivoglou method integration at the three intervals are used instead of count rates which reduces uncertainty of the Tsivoglou method considerably. The most commonly used scheme is sampling for 5 min and counting form 2-5 min, from 6-20 min and 21 to 30 min after the end of sampling. By distinguishing between the 6 MeV α-particles from $^{218}$Po and the 7.69 MeV from $^{214}$Po α-particles concentration of radon daughters can be calculated. However, in this case the delay between the sampling and counting should be as small as possible due to the short half life of $^{218}$Po (NEA/OECD, 1983).

## 1.8. Sampling Methods of Radon Measurements

Depending on the equipment used, the sampling techniques may be divided into the following categories.

### *1.8.1. Sampling Based on Radon Adsorption*

By adsorption, an extremely thin layer of radon gas adheres to the surfaces of the solids. Important adsorbent materials for radon are silica gels and zeolite minerals. Passive radon measurements can be achieved by adsorbing radon on activated charcoal, which is analysed by gamma ray spectrometry at the end of the exposure. Passive detectors such as TLDs can also be used in combination with activated charcoal. The activated charcoal detectors have a response that is highly dependent on the temperature and humidity.

### *1.8.2. Sampling Based on Radon Solubility or Absorption*

Radon is moderately soluble in water and its solubility depends on water temperature, the colder the water, greater is the solubility of radon. At normal environmental temperature,

radon concentrations are greatest, intermediate and least in the organic liquids, gas and the water phases, respectively.

### *1.8.3. Diffusion-based Samplers*

Diffusion-type samplers are based on the natural diffusion of radon gas into the vicinity of a detector or a trapping medium (typically activated charcoal). Transport of radon gas through a porous membrane occurs predominantly by diffusion through the free space represented by the pore structure. Porous membranes always ensure that aerosol and radon daughters will not enter into the sensitive volume of the detector. It is used for the discrimination of radon and thoron. Diffusion-based transport across porous membranes is also subject to the deposition of particulate material in the membrane pores, which leads to a decrease of the diffusion efficiency.

### *1.8.4. Permeation-based Samplers*

An efficient way to eliminate thoron and water vapour is to use permeation-based samplers. The cup-type container is closed by a nonporous membrane, in which the radon transport occurs by permeation. Permeation across a non-porous membrane is controlled by the solubility of the gas in the membrane material and by the diffusion of the dissolved molecules across the membrane under a concentration gradient. Using a suitable cup volume, thickness, area and the diffusion characteristics of the permeation membrane, it is possible to discriminate the thoron gas and to measure radon concentration. Polyethylene-based permeation samplers with activated charcoal or liquid scintillators have been successfully used for the measurement of radon gas in water (Dixon and Scivyer, 1999).

## 1.9. Etched Track Detectors

As this research work has been performed using SSNTDs, therefore it would be informative to briefly discuss track formation materials and basic principles of the formation of tracks in it. The study began in 1958 when Young observed etched tracks of fission fragments in LiF crystals. The number of these tracks showed a complete correspondence with the estimated number of fission fragments being recoiled into the crystal from the uranium foil. In 1959, Silk and Barnes observed hair latent tracks of fission fragments in mica using Transmission Electron Microscope (TEM). During early

1960s the team of Walker, Fleisher and Price pioneered the extensive development of this method. They extended the etching technique of Young to mica, glasses, plastics and mineral crystals (Fleischer et al., 1975; Durrani and Bull, 1987).

Due to the durability, the simplicity and the specific nature of the response of Solid State Nuclear Track Detectors (SSNTDs) led to their rapid application in a wide variety of applications in many braches of science and technology. These applications include studies in nuclear physics, radiography, cosmic rays, dosimetry, environmental science, geosciences, indoor radon measurement, earth sciences, mineral exploration, etc. (Fleischer et al., 1975).

The basic principle of track detectors is based on the fact that the passage of a heavily ionizing charged particle through a solid insulator creates microscopic trails of radial damage along its path. These latent tracks can be visualized by etching these trails. Particle tracks are formed in many insulating materials but not in conductors or semiconductors. The classification of track-storing and non-track-storing materials depends on electrical resistivity. Materials with values greater than ~ 2000 Ω-cm generally store tracks (Durrani and Bull, 1987). The condition for stable latent-track formation is sometimes expressed as a limiting value for the material resistivity. However, there is not a unique value of resistivity above which the track effect always appears. In this way, the material resistivity cannot serve as the unique criterion for track formation. Although the track effect is relatively well known and the technique is rather simple and straightforward, yet there is not a unique theory that explains track formation. However, the basic physical processes 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. A series of ionizations and excitations occurs and will create more and more free electrons and damaged molecules are created close to the particle track. 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.

## 1.10. CR-39 Polymeric Track Detectors

CR-39 (Columbia Resin-39) is the trade name of the thermoset plastic which is a polymeric form of diethylene glycol bis, allyl carbonate (PDAC). Its simple formula is $(C_{12}H_{18}O_7)_n$. Its excellent nuclear track recording properties were first reported by Cartwright et al in 1978. CR-39 can detect protons of energy up to 10 MeV and has a wide range (several tens of MeV) for α-particles detection (Durrani and Bull, 1987). CR-39 is highly isotropic, homogenous, relatively stable to the environmental conditions (unlike, say, LR 115). Much-work has been done to study the properties of CR-39 (Al-Najjar and Durrani, 1984; Green et al., 1982) confirming that it is a desirable solid state nuclear track detector.

The track recording efficiency of CR-39 also depends on the processing conditions and can therefore be modified, to some extent, by the processing conditions adopted. This includes etchant type, strength, temperature, and etching time. Extensive work has also been done to optimize the etching conditions using NaOH and KOH (Durrani and Bull, 1987).

## 1.11. Formation of the Latent Tracks

The range of a 6 MeV alpha particle in CR-39 is only about 40 μm, which means that on the average ~3700 ion pairs are created per micrometer, or 3–4 ion pairs per nanometer. This primary ionizing process triggers a series of new chemical processes that results 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. In conductive materials and in semiconductors, the process of recombination occurs and the latent tracks are not stable. A comprehensive survey on the materials that show the track effect is given by Fleischer et al (Fleischer et al., 1975).

As a result of the electronic and atomic collision-cascades, a cloud of interstitial atoms and vacancies are formed in the close vicinity of the ion trajectory. In inorganic solids the minimum energy of an atom to be removed from its original site and be displaced to another site (i.e. displacement energy) is of the order of 10–15 eV. On the

other hand the organic plastic detectors being made of long chain of molecules, the energy required to break the chain is considerably low i.e. 2–3 eV.

In order to explain track formation, several models/criteria have been proposed. These include, total energy loss model (dE/dx), primary ionization criterion, Restricted Energy Loss (REL), Secondary-Electron Energy Loss, Radius-Restricted Energy Loss (RREL) and lineal event-density (LED). Each criterion has its merits and demerits and is open to criticism. For further details the reader is referred to Durrani and Bull (Durrani and Bull, 1987). All the above models are used to explain the track formation in polymers while for crystals the following models are used.

*1.11.1. Thermal-Spike Model*

In this model it is assumed that energetic particle produce intense heating of the localized region in the lattice. The energy loss leads to electronic and atomic collisions. The atomic collision-cascade deposits its energy in the close vicinity of the ion trajectory. The thermal spike model simplifies the complex effects of the atomic collision-cascade by assuming a simple thermal distribution. According to the thermal spike model the deposited energy corresponds to an abrupt temperature rise in a small cylindrical volume around the ion trajectory at the time of passage $t = 0$. With the passage of the time i.e. for $t > 0$, thermal energy diffuses away from the ion trajectory. The thermal spike creates defects via thermal activation which are remaining as 'frozen defects' along the ion trajectory due to the rapid quenching of the temperature. In order for a material to register track the heat conductivity in the material should be low. Electron-phonon collisions are expected to be the predominant energy loss process in insulators and the excitation is communicated to the lattice more efficiently in such materials. This explains the inability of metals to show etchable tracks as the thermal spike becomes too broad and diffuses in the metal lattice, whereas in insulators a narrow intense spike is produced which leads to sufficient localized radiation damage capable of producing etchable tracks.

*1.11.2. Ion-Explosion Spike Model*

In ion explosion spike model a charged particle passing through the insulating material results in a high concentration of positive ions along its path due to the coulomb interaction. If the recombination time is long compared with the lattice vibration time

($\sim 10^{-13}$ s) mutual repulsion drives the ions into interstitial positions and leaving behind a vacancy-rich cylindrical core. For track formation, the electrostatic stress (i.e. the Coulomb repulsive forces within the ionized region) should be greater than the mechanical strength or lattice-bonding forces. The maximum permissible density of free electrons must be low. This condition restricts track formation to good insulators and excludes metals. The positive ion core contain a high concentration of holes. Tracks will not be formed in materials having high hole mobility. This model is currently the most widely accepted in the tracks field.

*1.11.3. Track Formation in Polymers*

In organic polymers, the passage of heavily charged particles results in scissions or a number of broken polymer. Chemically reactive sites are formed at the points of scission, which may be enlarged when an etchant such as NaOH enters the damaged region by dissolving the distorted and degraded portions. Both ions and excited molecules may acquire considerable vibrational energy and undergo bond rupture to form a complex array of stable molecules, free radicals and ionized molecules. The net effect on the plastic is the production of many broken molecular chains and production of a damaged region known as latent tracks.

The latent track is chemically transformed or removed by an etchant that leads to an observable etched track. The evolution of track shape during the etching process depends mainly on the ratio of track etch rate $V_T$ and bulk etch rate $V_B$.

## 1.12. Chemical Etching

The process of enlarging the size of the latent tracks produced by heavily ionizing particles is called etching and the solution used for this purpose is called etchant. The size of track depends upon the concentration of etching solution, etching time and temperature.

In order to etch the detectors, an elastic spring (holding many detectors) is attached to a wire and immersed into the etching solution within a beaker. The top of the beaker is covered with a glass lid to avoid evaporation. The beaker is then placed in a temperature controlled water bath. At the end of the etching, the detectors are removed and washed under running tap water, to remove the etching residue from the etch pits.

After drying, the detectors are counted under an optical microscope. The etched track diameters are typically a few μm in size and grow larger in size after prolonged etching. During the chemical etching material is placed in a suitable etchant, the solution preferentially attacks the damaged core of the track and penetrates along its length with track etch velocity $V_T$ while the surrounding undamaged material is attacked at a lower rate of bulk etch rate $V_B$, the bulk etch rate velocity. $V_B$ is generally constant for given etching conditions, whereas $V_T$ depends on the amount of damage present in the region of the core. Track development is governed by the ratio $V = V_T/V_B$ and track formation is not possible if $V \leq 1$. In other words, the condition $V > 1$ must be fulfilled for tracks to be formed.

The simplest case of track development refers to that when the incident particle enters a detector under normal incidence with respect to the detector surface. In this case the track formed is circular in shape and the parameters that are used to describe the geometry of etched tracks are shown in Figure 1.1. As may be seen in this Figure, *R* = full length of the latent track (unetched); L = length of track attacked by the etchant up to a given moment; $L_e$ = observed length of the etched track; h = thickness of the surface removed by etching; d = diameter of the etch-pit opening.

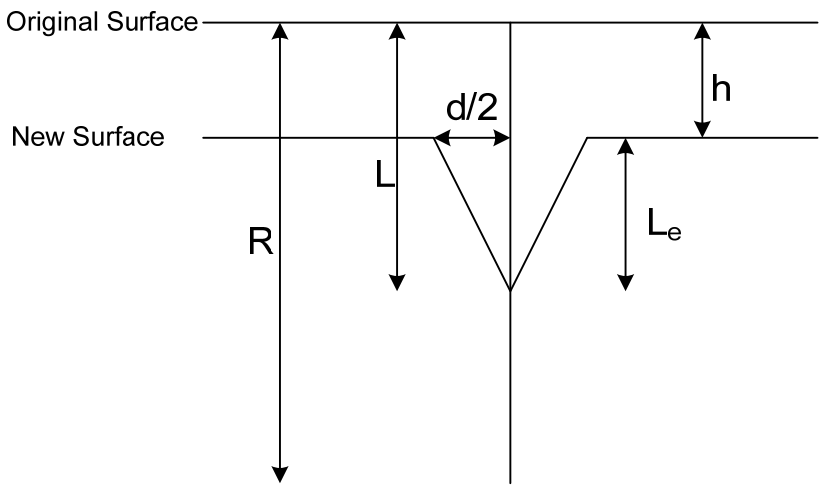



Figure 1.1: Some parameters used to describe the geometry of the etched tracks.

The linear rate of attack down the track is $V_T$ is assumed to be very small compared with the final dimensions of the etched track, so that during etching time $t$, the etch pit will extend to a distance $L$ from the point of origin, where $L = V_T\, t$. However, the surface is also being removed at a rate $V_B$, so that the length of the etch pit is

$$L_e = V_T t - V_B t \tag{6}$$

the formation of a cone with semi-cone angle $\delta$ given by

$$\sin\delta = \frac{V_T t}{L} = \frac{V_B t}{V_T t} = \frac{V_B}{V_T} \tag{7}$$

This angle $\delta = sin^{-1}\left(\frac{V_B}{V_T}\right)$ is also known as the critical angle of etching ($\theta_c$). In materials such as glasses where $V_T$ is not very much greater than $V_B$, etched tracks with large cone angles are produced. In plastics and minerals in which $V_T >> V_B$, long needle-like tracks of much smaller cone angle are usually produced.

The diameter of the track may be calculated by using the following relation (Durrani &Bull)

$$d = 2V_B t\sqrt{\frac{(V_T - V_B)}{(V_T + V_B)}} \tag{8}$$

The diameters of the surface openings of etched tracks increase with increasing $V_T$, reaching a maximum of $2V_B t$ when $V_T >> V_B$.

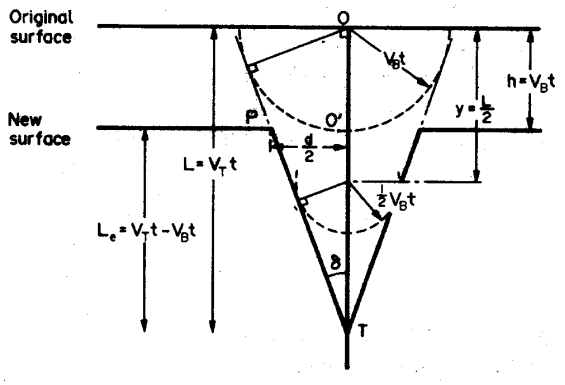



Figure 1.2: Construction for the calculation of etched-track parameters for a track of constant $V_T$, lying normally to the detector surface. The semi-cone-angle is denoted by δ.

In most realistic applications, the incident particles strike the detector with oblique incidence instead of normal incidence. But in case of radon and its progenies alphas or cosmic rays all incident angles are possible. It is, therefore, important to describe track growth for oblique incidence. This problem was considered in detail by Somogyi and Szalay (Somogyi and Szalay, 1973). The cross-section between a track in the conical phase and the post-etching surface is an ellipse and the corresponding track opening is elliptical. The ellipse is characterized by its major axis D and its minor axis d. These two parameters are important characteristics of a track opening for oblique incidence.

According to Somogyi and Szalay during the etching, the major axis of the track opening passes through three phases, while the minor axis develops through two phases.

After some lengthy calculations, it can be shown that major axis diameter of elliptical track is given by (Durrani and Bul1, 1987).

$$D = \frac{2V_B t\sqrt{V_T^2 - V_B^2}}{V_T \sin\theta + 1} \tag{9}$$

Where as the expression for minor axis d of the track opening, could be calculated using the following relation.

$$d = 2V_B t\sqrt{\frac{V\sin\theta - 1}{V\sin\theta + 1}} \tag{10}$$

In order to determine $V_T$, CR-39 is usually irradiated with $^{252}$Cf fission fragments at normal incidence. Then, for $\theta = 90°$, the relation for d can be simplified as

$$D = d = 2V_B t\sqrt{\frac{V-1}{V+1}} \tag{11}$$

Where $V = V_T/V_B$. As the track etch rate for fission fragments is very much higher than the bulk etch rate (so that $V >> 1$), the above equation reduces to:

$D = d \cong 2V_B t$

$$V_B \cong \frac{D}{2t} \tag{12}$$

Thus a measurement of the diameter of the normally incident fission-fragment tracks at a known etching time yields a value for the bulk etch rate. For further details , the reader is referred to Durrani and Bull, 1987.

### 1.13. Natural Radioactivity

Natural sources of radiation are cosmic rays and naturally occurring radioactive substances existing in the earth itself and inside the human body. Natural sources that account for exposure to the environmental radiation include radon (59%), terrestrial gamma rays (19%), cosmic rays (12%), and water and food (10%). Terrestrial gamma radiation dose rates vary mainly with geology, building materials, housing type and age of the building (Billon et al., 2005). The annual global per caput effective dose due to the natural radiation sources is 2.4 mSv (UNSCEAR, 2000). Few regions in the world, which are known for high background radiation areas (HBRAs), are due to the local geological controls and geochemical effects and cause enhanced levels of terrestrial radiation (UNSCEAR, 1993, 2000). Very HBRAs are found at Guarapari, coastal region of Espirito Santo and the Morro Do Forro in Minas Gerais in Brazil (Bennett, 1997; Paschoa, 2000). Yangjiang, in China (Wei and Sugahara, 2000); southwest coast of India (Sunta, 1993); Ramsar and Mahallat in Iran (Sohrabi, 1998) in the United States and Canada (NCRP, 1987). The interactions of cosmic-ray particles in the atmosphere produce a number of radionuclides, including $^{3}H$, $^{7}Be$, $^{14}C$ and $^{22}Na$. These nuclides are called cosmogenic nuclides.

Naturally occurring radionuclides of terrestrial origin (also called primordial radionuclides) are present in various degrees in all media in the environment, including the human body itself. Only those radionuclides with half-lives comparable to the age of the earth and their decay products, exist in significant quantities in different types of materials. Secondary radionuclides are radiogenic isotopes derived from the decay of primordial radionuclides. They have shorter half-lives than primordial radionuclides. Natural environmental radiation depends on geological and geographical conditions (Klement, 1982).

Irradiation of the human body from external sources is mainly due to the gamma radiations from radionuclides in the $^{238}U$ and $^{232}Th$ series and from $^{40}K$. These

radionuclides are also present in the body and irradiate the various organs with alpha and beta particles, as well as gamma rays. Some other terrestrial radionuclides, including those of the $^{235}U$ series, $^{87}Rb$, $^{138}La$, $^{147}Sm$ and $^{176}Lu$, exist in nature but at such low levels that their contributions to the dose to humans is negligible. Terrestrial radionuclides present at trace levels in all soils, however, the specific levels are related to the types of rock from which the soils originate. Higher radiation levels are associated with igneous rocks such as granite and lower levels with sedimentary rocks. The activity concentration of $^{40}K$ in soil is an order of magnitude higher than that of $^{238}U$ or $^{232}Th$.

Building materials contribute to the gamma radiation, mainly $^{40}K$, $^{226}Ra$, $^{232}Th$ and their progenies. Radioactivity levels in various building materials such as soil, sand, etc. have been reported by many workers from different geological regions in the world (Beretka and Mathew, 1985; Zikovsky and Kennedy, 1992; Tahir et al., 2005). Natural radioactivity in soil depends on soil type, mineral make up and density. Igneous rocks of granitic composition are strongly enriched in Th and U (on an average 15 $\mu g\ g^{-1}$ of Th and 5 $\mu g\ g^{-1}$ of U), compared to the rocks of basaltic or ultramafic composition (<1 $\mu g\ g^{-1}$ of U). There are exceptions, however, as some shales and phosphate rocks have relatively high content of those radionuclides (Tzortzis and Tsertos, 2004). These radionuclides are also part of food cycle and it is contained in variable amount in different types of consumable items. The level of uptake depends on the physical and chemical properties of the radionuclides and also on the environmental matrix of interest. In order to measure the concentration of these primordial radionuclides and the dose delivered by it, various types of instrument are used. These primordial nuclides are generally detected by the gammas emitted by these nuclides. The ambient gamma dose rate can be measured by using a NaI(Tl) Scintillometer (Amutha et al., 2005).

Instrumental neutron activation analysis (INAA) can be used for accurate elemental determination, as it is a powerful method for the direct analysis of solid food samples without dissolution thus eliminating the possibility of contamination. The technique also offers low detection limits for many inorganic elements (Waheed et al., 2004). For larger areas to be surveyed natural radionuclides aerial survey are also carried out. In such type of surveys gamma-ray spectrometer of energy range of 40 keV to 3000

keV with data control and storage and flight positioning instrumentation are used (Schwarz et al., 1992).

External exposure indoors depends mainly on construction materials (i.e. on concentrations of radionuclides present in these materials). Serious efforts should be made to understand relationships between exposure and construction materials, in order to find out the ways of assessment of this exposure and identify practical and user-friendly ways of evaluation from the point of view of radiation protection. For this reason the studies of exposure owing to the radionuclides in construction materials and their radiological evaluation are performed. Indoors dose rate depends on parameters like amount of construction material used and geometry of the premises. The most important parameter is concentration of radionuclides in the construction materials (Pilkyte et al., 2005).The availability of large intrinsic germanium detectors such as high purity germanium detector (HPGe) has opened new perspectives for fast, accurate and reliable environmental measurements. Both NaI(TI) and HPGe detectors are most commonly used with the striking contrast of results obtained with these two types of detectors. Resolution with HPGe detectors is better by a factor of 30 or more than that obtained with NaI(TI) conventional detectors. As a result of the improved resolution, many nuclear energy levels that could not even be seen with NaI(TI) detectors are identified easily with HPGe detectors (EG&G, ORTEC).

Due to the large decrease of counting efficiency with the distance from detector surface, which limit the usefulness of tall beakers, it was suggested to count large environmental samples in reentrant beakers, which covers the detectors from all directions, called Marinelli beakers or also inverted well beakers (IEBB, 1997). Densities of environmental samples vary appreciably, typically from 0.5 $g.cm^{-3}$ (dry organic material) to 1.5 $g.cm^{-3}$ (soil). This is the reason why it is so important to be able to prepare a calibrated Marinelli standard in each laboratory (Lavi and Alfassi , 2005). The use of extended sources in γ-ray spectrometry improves the sensitivity of detection thus enabling the measurement of low-activity environmental samples

# Chapter Two

## Experimental Procedures and Salient Features of the Selected Area for the Present Study

Having briefly discussed radon, its health hazards and natural radioactivity in the previous chapter, this chapter deals with the geology, building characteristics, climate, populations and building materials of the selected area. Different types of active and passive equipments used for the measurement of indoor radon and sampling procedures have also been discussed.


Figure 2.1: Map of the selected area. The shaded portion in the above map shows the selected area.

## 2.1. Geology and Physical Features of the Area Surveyed

The major portion of the selected area (shaded portion in Figure 2.1) lies in Peshawar basin which is intermountain basin situated at the southern margin of the Himalayas and northwest of the Indus Plain. It came into existence during the plio-Pliestocene time due to the uplifting of the Attock-Cherat Range. The lower Swat-Buner Schistose group and Swat granitic gneisses bound the Peshawar basin in northeast (Burbank and Tahirkhele 1985). These rocks are regarded to form the base of the stratigraphic sequence of the basin. The southern part of these rocks covers the Malakand Mountains and stretch eastward into the lower Swat-Buner area. The areas surveyed in this study comprised of low hills and alluvial plains in the Mardan, Swabi and Charsadda districts. The plains have mixed composition of eroded materials from the hills including clays, sand and pebbles (Riaz et al., 1998; Martin et al., 1962). The Bajuar agency consists of diorite rocks which indicates a continuation of metamorphic and igneous rocks consistent with the northern mountain chain. Soils in the Bajuar agency are considered to be generally fertile, varying from silt loam to loam containing a medium degree of organic matter (SIEE, 2005). Mohmand agency has diverse igneous lithologies which occur as alternating sheeted masses, intrusive, apparently concordant along the sequence of metasediments of Paleozoic age and metabasites. Sufaid Koh range forms part of the Cretaceous-tertiary Himalayan organic system. The rocks are of Triassic, Carboniferous and older–Paleozoic ages (Siraj et al., 2000).

The district Swabi may be divided into two parts, the northern hilly areas and the southern plain. The major parts of these hilly areas are in the northeast. There are also hills on the northwest called Naranji hills, the height of these hills are from 750 m to 1400 m. The plain areas of the district are intersected by a number of streams and many small riverine. The soil of the Swabi district has developed either from alluvium or loess plains. Texture of river alluvium ranges from sandy loam, sand and loam approaching clay. The soil of loess plains ranges from in texture from silt loam to silty clay loam or silty clay. The soil is irrigated for general cropping with canals supplemented by well-irrigation.

The district Swabi exhibits the following rock units Salkhala foundation, Manki formation, Sobra formatrion, Tanawal formation, Ambar formation, Misri banda Formation, Panjpir formation, Granites and Sills/Dykes. The Salkhala formation is the oldest unit of the area which comprises chorite quartzite-mica schist, graphitic schist, marble and quartzite. The formation has been assigned pre-Cambrian age. The Manki formation is characterized by phyllites, slate sand subordinate gray wakes and limestone and quartizite lenses. It is assigned a pre-Cambrian age. Sobra formation consist of limestone with subordinate quartzite and sandstone, its age is pre-Cambrian. Tanawal formation is quite thick and is comprised predominately of quartzite, quartzose sandstone and subordinate argillite, its age is Precambrian. Ambar formation consists of dolomite limestone with interrelations of quartzite and phyllites. It is assigned a Cambrian age. Misri banda Quartizite mainly of quartizite with subordinate argillite and lenses of conglomerates. The age of the formation is early to middle Ordovician. Panjpir formation consists dominantly of argillite, phyllites and subordinate lenses of limestone and quartzite. The formation has been assigned silunan age. Granite and Doleritic Sills/Dykes: In some parts of the district are some granitic rocks and doleritic sills/dykes at places which have been given Permian to carboniferous age.

Mardan district may broadly be divided into two parts. Northeastern hilly area and southwestern plain. The entire northern side of the district is bounded by hills. Rivers flows from north to the south. Most of the streams drain into the Kabul River. Charsadda is a part of the plain called Peshawar valley. This valley presents the appearance of having been remote centuries ago, the bed of a vast lake whose banks are formed by the surrounding mountains and whose waters were fed by the rivers that are now channeling through outfits of the former sub-igneous bed. Hills encircle it on every side except one, where the Kabul River flows out to join the Indus River.

Most of the plains are composed of light and porous sandy soil to a depth of 1 to 6 m below this lies the sandy mixture of clay often combined with beds of nodular limestone followed by gravel and sand. The plain consists of fine alluvial deposits the composition and depth of which varies in different localities and at different distances from the surfaces.

### *2.1.1. Geography*

The district Swabi (district census ,2000) lies between 33-55' and 34-25'N and 71-49' to 72 - 49' East longitudes. It is bounded by the district Buner in the north, in the east by Haripur district, on the south by district Attock, on the west by the Mardan and Nowshera Districts. The district Mardan (district census ,1999) lies from 34-05' N to 34-32' N and 71-48' to 72-25' E. It is bounded on the north by Buner district and Malakanad Protected area, on the east by the Swabi and Buner Districts, on the south by the Nowshera district and on the west by the Charsadda district and the Malakanad protected area. The total area of the district is 1632 $km^2$.

Charsadda (district Census Report No. 68) lies between 34-03 and 34-28N and 71-28 and 71-53 E longitudes. It is bounded by the Malakand district on the north, the Mardan district on the east, the Nowshera and Peshawar districts on the south and the Mohmand agency on the west. The Charsadda district lies in the central plain of the Peshawar valley. The Kabul River enters at a point near the south west of the district. It flows along the southern boundary of the district and crosses the district in the extreme south eastern corner. Mohmand agency lies 34° 30′ N, 71° 20′ E and was created in 1951. It covers an area of 2,296 $km^2$ and its population is estimated to be around 334,453. The Mohmand agency shares a border with the Bajuar agency to the north, the Dir district to its east, the district of Peshawar to its southeast and Afghanistan to the west. Bajuar agency, the smallest in size having an area of 1290 $km^2$ was created in 1973. Bajuar shares a border with Afghanistan's Kunar province to the north west; Pakistan's Dir district to its north east and the Mohmand agency to its west.

### *2.1.2. Climatic Conditions*

The Swabi, Mardan and Charsadda districts have extreme climates. The summer season is extremely hot. A steep rise of temperature is observed from May to June. Even July, August and September record quite high temperatures. During May and June, dust storms are quite frequent at night. The temperature reaches to its maximum in the month of June. Due to the intensive cultivation and irrigation the tract is humid and the heat is oppressive. A rapid fall in temperature is recorded from October onwards. The coldest month is January. Towards the end of the cold weather there are occasional

thunderstorms and hail storms. The maximum rainfall is received in July and August during which the weather becomes hot and humid. The relative humidity is quite high through out the year. Maximum humidity is recorded in December. No meteorological station is operating in the Swabi and Mardan districts and the data recorded in the Risalpur is the station which can represent the Swabi and Mardan district.

In the Charsadda, Mohmand and Bajuar, the average winter rainfall is higher than that of the summer rainfall. Charsadda district, Mohmand and Bajuar Agencies are close to Peshawar. Therefore, the data recorded in Peshawar can represents the Charsadda and Mohmand agency well. Tables 2.1 & 2.2 show maximum and minimum average temperature, precipitation and humidity recorded at Peshawar. However, the climate of the Bajuar agency is cold and the summer season is relatively less hot while the winter season is very cold.

Table 2.1: Long-term average climatic conditions of Mardan, Swabi as recorded in the meteorological station Risalpur.

| Month | Maximum Temperature | Minimum Temperature | Precipitation (mm) | Relative humidity (%) |
|---|---|---|---|---|
| January | 18.3 | 4 | 26 | 58.6 |
| February | 19.5 | 6.3 | 42.7 | 57.5 |
| March | 23.7 | 11.2 | 78.4 | 58.4 |
| April | 30 | 16.4 | 48.9 | 51.7 |
| May | 35.9 | 21.3 | 27 | 37.3 |
| June | 40.4 | 25.7 | 27.7 | 36.2 |
| July | 37.7 | 26.6 | 42.3 | 55 |
| August | 35.7 | 25.7 | 67.7 | 64.6 |
| September | 35 | 22.7 | 17.9 | 58.7 |
| October | 31.2 | 16.1 | 9.7 | 54.9 |
| November | 25.6 | 9.6 | 12.3 | 60.1 |
| December | 20.1 | 4.9 | 23.3 | 63.7 |
| Mean | 29.4 | 15.9 | 35.3 | 60.1 |

Table 2.2: Long-term average climatic conditions of Mardan, Swabi as recorded in the meteorological station Peshawar.

| Month | Maximum Temperature | Minimum Temperature | Precipitation (mm) | Relative humidity (%) |
|---|---|---|---|---|
| January | 17.9 | 2 | 35.4 | 69.3 |
| February | 19.2 | 5.1 | 53.2 | 67.5 |
| March | 23.8 | 9.9 | 80.2 | 67.1 |
| April | 30.3 | 15.1 | 46.6 | 56.4 |
| May | 36.6 | 20 | 26.2 | 39.4 |
| June | 41.5 | 24.9 | 18.3 | 360 |
| July | 38.5 | 26.3 | 113.4 | 55.4 |
| August | 36.2 | 25.4 | 125.8 | 66.4 |
| September | 35.6 | 22.1 | 39.9 | 60.1 |
| October | 31.7 | 14.5 | 13.8 | 60.3 |
| November | 25.3 | 7.3 | 15.7 | 67.9 |
| December | 19.3 | 2.7 | 28.9 | 73.3 |
| Mean | 29.6 | 14.64 | 597.6 | 60.1 |

## 2.2. Building Characteristics

In the district Swabi 68% houses were constructed at least 10 years ago according to the 1998 census. About 69% housing units were constructed from the baked bricks and cemented blocks. Shaped stones were used in the construction of the outer walls in the urban and rural area in the district. About 65% roofs of the housing units were built of wood and bamboo whereas 23% were built from reinforced cement concrete or bricks (RCC/RBC). According to the latest census, urban proportion of the district Mardan is 20%. Housing units with 2 to 4 rooms is ~ 66%. About 67% housing units were constructed at least 10 years ago according to 1998 census. The district has 50% of the walls in the standard category of baked bricks/blocks and stone with cement bonding and 48% of the houses are made of unbaked bricks with mud bonding. The wooden category is 1%. The predominant construction materials of roofs of the housing units (~75) are built from baked bricks supported by the girder or wooden log/bamboo. While 16% of

the housing units have been bonded with RCC/RBC for roofs. About 7% houses have roofs which have been constructed from the cement/iron sheets. About 71 % of the housing units were constructed at least 10 years ago, according to the 1998 census record. Unbaked bricks/ earth bounded were the main construction material used in the construction of the outer walls of the buildings representing 69% followed by baked bricks, blocks and shaped stones, 28%. In the rural areas, main material used in the construction of walls are unbaked bricks, stones etc., whilst in the urban areas it was baked bricks, shaped stones etc, where this percentage is recorded as 50%. For the construction of roofs, about 85% of the housing units used wood and bamboo as construction materials in the roofs of their buildings. About 8% used reinforced cement concrete or bricks (RCC/RBC), 4% used cement/iron sheet while remaining ~3% have used other construction materials. Marked difference was observed in construction materials in urban and rural housing units though the wood/bamboo is still the main materials used in both the areas. There are ~ 79% housing units in urban areas and 87 % in rural areas that have used such materials.

### 2.3. Selection of the Houses for Indoor Radon Measurements

In the present study, houses surveyed in the Mardan, Swabi and Charsadda districts were built from baked bricks and cement. Each room contained one or two windows. These included both single and double storey houses. Each house contained at least two rooms. Dosimeters were installed in a bedroom and drawing room of each of the selected house. In the case of double storey houses, dosimeters were installed in bedroom and drawing room located at the ground floor. All the houses surveyed were detached and semi-detached houses. The roofs were made of cement and concrete. Houses surveyed in the Mohmand agency were large detached houses and made of mud and stones. All the houses surveyed were single storey containing relatively larger number of rooms (i.e. up to 10 rooms). There were usually one or no windows in the rooms. The houses surveyed in the Bajuar agency were single storey and were made of mud with poor ventilation system. Each house had at least four rooms. Most of the houses surveyed in the Mohmand agency had no electricity supply.

In each district/agency, fourty representative houses were selected for indoor radon levels measurements. Dosimeters were installed at head height in bedroom and drawing room of each house at the ground floor. These dosimeters were exposed to radon for three months in each of the four seasons of the year. After exposure to radon, dosimeters were collected, etched and counted an optical microscope.

### 2.4. Occupancy Factor

Occupancy factor plays a major role in the dose calculation due to the indoor radon. Therefore, information about the indoor occupancy were collected and average occupancy factor for each district/ agency as well as overall average occupancy factor for the selected area was calculated, which was slightly lower than that reported by other workers (Killip, 2004). Information about the indoor occupancy was collected during the installation of the dosimeters. Information was obtained through direct interviews with the occupants of the houses where the dosimeters were installed. Occupancy factors for the Swabi, Mardan, Charsadda, Mohmand and Bajuar were found to be 0.49, 0.41, 0.48, 0.51 and 0.50, respectively with an average value of 0.48. Besides indoor occupancy, information about the usage of the bedrooms and drawing rooms were also obtained from the occupants. This data revealed that occupants spent ~ 60% of their indoor time in the bedroom and ~ 40% time in drawing room.

### 2.5. Weighted Average Indoor Radon

Weighted average indoor radon concentration was calculated using the occupancy values of the bedrooms and drawing rooms. Weighted average annual arithmetic mean for each house was calculated using the following formula.

Weighted average radon concentration = (0.4 × drawing room+ 0.6 × bedroom) indoor radon concentration (however in the houses where only one detector was retrieved from the home was considered as a representative of that home and was included in the analysis of the data). An average radon level in the bedrooms and drawing rooms levels in each house was calculated. Using the mean annual radon levels in each house, annual effective dose was calculated using the ICRP-65 and UNSCEAR conversion factors (Jing, 2005; UNSCEAR, 2000).

## 2.6. Seasonal Correction Factor

The seasonal correction factor was calculated by dividing the arithmetic mean of each season (i.e. summer, autumn, winter, spring) by the annual arithmetic mean. The seasonally averaged data as well as yearly averaged data was calculated by adding the summer, autumn, winter, spring data and dividing it by 4, annually averaged data was also calculated. In Pakistan, summer season span over June, July and August, autumn season is from September to November, winter season begins in December and ends in February and spring season begins in March and ends in May (Shamshad, 1988). CR-39 based radon dosimeters were used in this study, which was carried out from June 1, 2005 to May 31, 2006.

## 2.7. Comparison of Yearly Average and Seasonally Measured Average Measurements

In order to measure effect of the long-term exposure of CR-39 detector with respect to the seasonal measurements, two detectors were installed in each drawing room (living room). One detector was replaced four times (i.e. in each season) during the year for seasonal measurement and the other one was exposed to the indoor radon for the whole year. The results were compared with each other. Using the annual weighted average values of indoor radon concentration and the BEIR-VI formula, excess relative lung cancer risk was calculated.

## 2.8. CR-39 Detector and its Chemical Etching

CR-39 based National Radiological Protection Board (NRPB), now called the Radiation Protection Division of the Health Protection agency, UK dosimeters were used in this study. CR-39 detectors were etched in 25% NaOH at 80 $^{o}$C. After measuring track densities manually with an optical microscope, they were then related to the radon concentration level using calibration factor of 2.7 tracks.cm$^{-2}$.h$^{-1}$/kBq.m$^{-3}$ (Miles, 2005).

## 2.9. Radon Exhalation Rate

In order to study the potential of different building materials as an indoor radon source, radon exhalation was measured in the samples of soil, sand and bricks which were collected from the selected area. Samples were collected in such a way that it were representative of the district/agency and were spatially disturbed over the district/ agency.

*2.9.1. Setup for CR-39 Detector*

In order to study radon exhalation rate from the most commonly used building materials, samples were collected from the Swabi, Mardan and Charsadda districts of NWFP as well as from the Mohmand and Bajuar agencies of FATA, Pakistan. These included soil, sand and bricks sample. From each districts/agency, 10 soil representative samples were collected. In the case of sand, a total number of ten samples (i.e. 2 samples per district/agency) were collected from streams wherefrom people collect & transport sand and use it in the construction of their houses. Due to the inconvenience, bricks are not commonly used in agencies. Therefore, brick samples were collected only from the Swabi, Mardan and Charsadda districts (4 samples per district).

All the samples were crushed and dried in an oven at 110 $^{o}$C. These samples (each weighing 200 g) were then put into the plastic containers of volume $5.4\times10^{3}$ cm$^{3}$. The grain sizes of soil/brick and sand were 0.002 mm - 0.06 mm and 0.06 mm to 2 mm, respectively. The texture of the soil/brick samples was uniform and fine whereas the texture of the sand samples was coarse. No compaction was used during the placement of the samples in the containers (Just slight shaking was performed to level the surface of the samples). In order to sieve the crushed samples, 200 and 250 meshes were used.

After installing the CR-39 based NRPB radon dosimeters at a height of 25 cm from the surface of the samples, the containers were then hermetically sealed. Dosimeters were exposed to radon for 40 and some for 80 days. This resulted in exposure of the dosimeters to variable levels of radon concentration (i.e. starting from zero concentration level to equilibrium concentration level). In order to calculate the effective time of the radon exposure, following relation was used (Durrani and Iliç, 1997)

$$T_{effective} = t - \tau\left(1 - e^{-\lambda t}\right) \qquad (1)$$

Where $\tau$ is the mean life of radon (5.5 days), t is the total exposure time (days) and λ is the $^{222}$Rn decay constant.

After the exposure, CR-39 detectors were etched in 25% NaOH at 80 $^{o}$C for 16 h and counted under an optical microscope. The track densities were related to the radon concentration level.

To study the effect of humidity, a series of experiments were performed by adding different moisture contents in these samples and then the containers were hermetically sealed. Dosimeters were exposed to radon for 60-80 days in phase one, two and three (using dried (0%), 15% and 30% moisture contents by weight) of the experiment and for 65 days in the fourth and final phase using 45% moisture content by weight.

*2.9.2. Calculation of the Exhalation Rate*

Measured radon concentration values were used to calculate the exhalation rate using the following equations (Rehman et al., 2006)

$$F_0 = \frac{C(t)[\omega A + \lambda V]}{A\left[1 - e^{-\left(\frac{\omega A}{V} + \lambda\right)t}\right]} \tag{2}$$

$$F = F_0 - \omega C \tag{3}$$

Where

A = Surface area of the sample (cm$^2$), V = volume of the void space in a closed chamber,

t = $^{222}$Rn accumulation time in a closed chamber.

$\omega = \varepsilon\lambda Z_0$, known as back diffusion constant for given material.

$Z_0$ = Thickness of the sample in the sealed chamber.

$C(t)$ = $^{222}$Rn concentration just on the surface of the sample which has to be exhaled from the surface of the sample to the void space of the chamber.

$$F_0 = R\rho_b \lambda E Z_0 \quad (4)$$

$\lambda$ = $^{222}$Rn decay constant (h$^{-1}$)

$\rho_b$ = Bulk density of the sample (kg.m$^{-3}$)

$E$ = ($E_{air}$ + $E_{water}$ + $E_{solid}$) Sum of fractional emanation coefficient of $^{222}$Rn in air, water and adsorbed phase.

R = Concentration of $^{226}$Ra (Bq.kg$^{-1}$)

All the quantities on the right hand side in Eq. (2) are known except $C(t)$ which was experimentally determined for CR-39 based NRPB radon dosimeter. Putting the value of $C(t)$ in Eq. (2), exhalation rate, $F_o$ was determined.

In a closed chamber which contains a sample, $^{222}$Rn concentration increases with the passage of time from zero to its maximum value. After reaching its maximum value, back diffusion of radon also take place which reduces the $^{222}$Rn concentration by a factor $\omega$ in the chamber. Therefore, exhalation rate F, corrected for back diffusion, was determined using Eq (3). Exhalation rate was also calculated using the following equation (Abu-Jarad et al., 1980)

$$E_x = \frac{\mathrm{CtV\lambda}}{\mathrm{S[t\text{-}1/\lambda(1-e^{-\lambda t})]}} \quad (5)$$

Where $E_x$ *is radon* exhalation rate (mBq.m$^{-2}$-h $^{-1}$), C is mean radon concentration as measured by CR-39 detector (Bq.m $^{-3}$), V is volume of the cane (m$^3$), t is the exposure time, λ is the radon decay constant and S is the surface area from which radon is exhaled into the closed can.

### 2.10. Gamma Spectroscopy

Natural radioactivity was also measured in the soil, sand, brick, marble and cement samples collected from the selected area. For the gamma spectroscopy, a total of fifty soil samples (i.e., 10 samples from each district/agency) were collected from three districts and two tribal agencies from undisturbed sites to ensure that there was no influence of man-made structures and anthropogenic activities. Similarly, thirty-eight

samples of the building materials were also collected from the Swabi, Mardan and Charsadda districts as well as from the Mohmand and Bajuar agencies of the federally administered tribal areas (FATA) Pakistan. These included 10 samples of brick from the above-mentioned three districts and 2 samples of sand from each district/agency, 12 marble samples from all the districts/agencies and five branded cement samples from the selected area.

*2.10.1. Processing and Preparation of Samples*

Samples (each weighting 1.5 kg) were crushed, sieved and dried at 110˚C for 24 hours. The samples were placed in Marinelli beakers and were hermitically sealed. These sealed beakers were then placed in undisturbed position for a period of two months in order to attain equilibrium between long-lived parents ($^{226}$Ra, $^{232}$Th, $^{40}$K) and their shorter-lived daughters. It may be noted here that if the containers are not hermitically sealed then this will result in some portion of the radon to exhale from the container and thus will underestimate the results. However, escape of radon during crushing will have no effect on the results because after crushing the container were kept for sufficiently long time to attain nearly secular equilibrium after sealing.

*2.10.2. Gamma Spectrometry*

The gamma spectrometer used for obtaining the spectra was a P-type HPGe detector. The resolution and relative efficiency of the detector for 1332 keV ($^{60}$Co) was 2.5 keV and 90%, respectively. Figure 2.2 shows the efficiency calibration curve of the HPGe detector using mixed radionuclides calibration source.

The detector and preamplifier were placed inside a low-background well-type lead shielding and cooled by liquid nitrogen from vertical dipstick cryostat. Energy and efficiency calibration of the detector were performed using standard point sources and mined nuclides gamma reference source (from AEA technology QSA GmH, Germany). Background signals were periodically recorded for the similar time periods and were subtracted from each result obtained.

Spectra were collected for about 12 hours in order to get sufficient counts at the desired peaks. $^{226}$Ra concentration was determined by means of its progeny photo peaks of gamma-ray lines: $^{214}$Pb (295.21 keV, 352 keV) and $^{214}$Bi (609 keV, 1120.29 keV),

$^{232}$Th was determined through its progeny photo peaks of gamma-ray lines: $^{228}$Ac (338.32 keV, 911.21 keV, 968.97 keV) whereas $^{40}$K activity was measured directly through its gamma-ray energy peak of 1460.83 keV. The software Personnel Computer Analyzer (PCA-II) was used for the collection and analysis of the spectra.

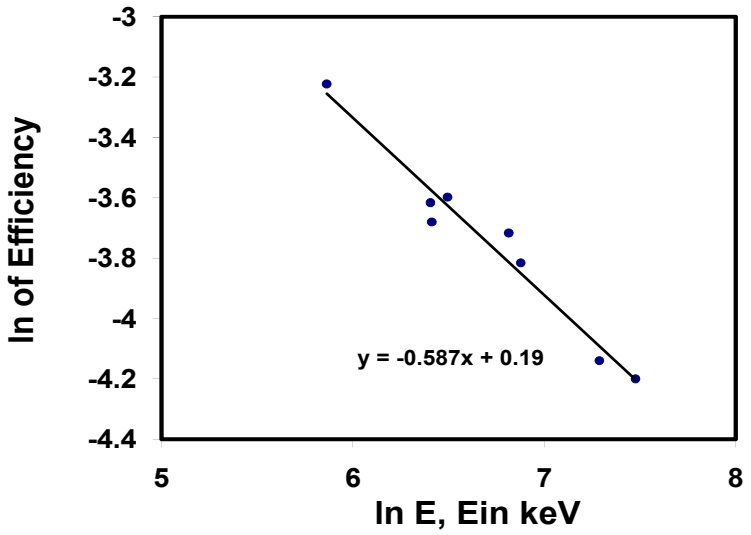



Figure 2.2: Efficiency calibration curve of the HPGe detector using mixed radionuclides calibration source prepared in Marinelli geometry

## 2.11. Electret Ion Chambers

In order to measure the indoor radon, equilibrium factor and unattached fraction of radon, electret ion chambers (EIC) and electret radon progeny integrating sampling unit (E-RPISU) was used, which are briefly described below.

Commercially available electret ion chambers, so called electret-passive environmental radon monitors (E-PERM), were used for the radon measurement. E-PERM system consists of three components (1) electrostatically charged Teflon called electrets (2) an ion chamber made of conductive plastics to which an electret can be loaded (3) a Voltage reader to read the surface potential of the electrets. In the present study, two types of electrets which were made of Teflon were used. Experiments were performed using both short term (high sensitivity) and long term (low sensitivity)

electrets. The electrets produces electric field and thus are capable of attracting opposite sign charge generated by the decay of radon/thoron and its daughter products within the chamber.

For the measurement of radon/thoron and its progenies different types of chambers were used. Nuclear radiation emitted by radon/thoron or other radioactive materials during decay generates ions in the volume of the conductive plastic and are collected on the charged electrets. There are different configuration of the chambers. The chamber that have a dome and on/off facility, called standard "S" chamber. In the present study the standard chamber having short term electrets (SST) combination was used. In order to read the potential of the electret the electronic instrument called surface potential electric voltage reader (SPER) was used. To measure the potential drop of the electret, before placing the electret in the chamber its initial value was recorded (I), after exposure the final voltage (F) of the electret was recorded, the exposure time in days "D" was also recorded. The calibration factor 'CF' for E-PERM was calculated using the standard procedures.

### 2.12. Measurement of Radon Progenies with Alpha Contamination Chambers

Electret ion chambers (EIC) with its aluminized Mylar window facing down is used to measure alpha radiation from the contaminated surfaces. Area monitored is 48.7 $cm^2$ and the response of electret ion chamber is used for all the alpha radiations emitted from different isotopes. The results are expressed in alpha counts per 100 $cm^2$ in $4\pi$ geometry.

In the present work EICs were used in the inverted form for the measurement of radon and thoron progenies deposited on the surfaces. In these experiments electret ion chamber with Mylar side was directed upward. Ionization produced by radon progenies were measured instead of alpha contamination on the surfaces. In order to measure the performance factor (PF) of this alpha contamination chamber, radon concentration was measured simultaneously using the standard chambers with short-term electrets. Experiments were performed using both short term (high sensitivity) and long term (low sensitivity) electrets.

As these chambers are also sensitive to gamma radiation, therefore, to correct the readings for the gamma background an additional electret with plastic cover which blocked the detection of alpha radiation was also used.

## 2.13. Active Solid State Alpha Detector for Measuring the Surface Deposited Activity

To measure the efficiency of different plastics/ filter materials and also to measure the surface deposited α activity active solid state surface barrier detector was used.

Computerized APTEC alpha-spectroscopic multi-channel analyzer was calibrated for the measurement of the radon and thoron progenies. The system worked by connecting semiconductor diode detector through a pre-amplifier and an amplifier and finally into a special MCA card built into the computer.

To calibrate the APTEC (Surface barrier detector) three standard sources, namely $^{230}$Th, $^{241}$Am 25mm diameter each and $^{230}$Th of square shaped source were used. The efficiency of the detector was measured by using $^{241}$Am and $^{230}$Th which came out to be 0.26. Using the flat $^{230}$Th source and having distance of 4 mm between the detector and the source, the efficiency of the detector was measured as 0.19. $^{214}$Po source was placed under the APTEC silicon (Si) crystal alpha detector (Surface barrier detector) below the filtering (attenuating) materials (plastics) and the counts were collected for sufficient time in order to obtain peaks for the $^{214}$Po and $^{212}$ Po.

In order to develop passive dosimeters, different types of plastic sheets were used and their efficiencies for radon and thoron progenies were calculated.

## 2.14. Ultrafine Particle Counter (UPC) P-track

Dose due to the radon/thoron progenies depends on radon/thoron concentration and the attachment of the progenies to the aerosols particles. Unattached fractions of radon and thoron progenies concentration depend on the particle size and number in the indoor environment. Ultrafine particles (particle 0.1 micrometers or smaller in diameter) contribute little to the total mass but exist in very high number concentrations, especially in the urban areas. Particles of this size can almost unrestrictedly enter into the lungs and result in a greater inflammatory potential

In the present study, ultrafine particles were measured on an hourly basis using the Condensation Particle Counting (CPC) P-track system. It uses the condensation particle counting technique. In order to measure the affect of different aerosol generating activities, the following cleaning and burning activities were performed in the indoor environment. HEPA filter, HEPA filter with ionizer, Candle burning, Cigarette smoking, Propane cooker, The Joe smoker system, etc.

Table 2.3: Different types of Materials used for the fabrication of surface deposition dosimeter.

| S.No | Material | Gauge |
|---|---|---|
| 1. | Mylar | 8 |
| 2. | MM | 16 |
| 3. | 3M2708+M | 58 |
| 4. | CI75 | 75 |
| 5. | CI92 | 92 |
| 6. | CI75+2708 | 125 |
| 7. | 3M125 | 145 |
| 8. | FFMM | 200±50 |
| 9. | FFM | 200±51 |
| 10. | FFM-07 | 200±50 |
| 11. | 3M114 | 200 |
| 12. | 3M146-07 | 285 |
| 13. | 3MM | 250 |

### 2.15. Active Alpha Detectors to Measure Surface Deposited Activity

In order to measure surface deposited activity during the different indoor aerosols conditions, two different types of active solid state detectors were used which were APTEC and Science Applications International Corporation **(**SAIC) ® Alpha Analyzers of model AP-2 systems.

These handheld AP-2 systems having programmable windows which allowed $^{218}$Po, $^{214}$Po and $^{212}$Po counting for up to one hour with out any interruption. Before its usage these detectors were calibrated using standard sources of $^{232}$Th, $^{241}$Am and $^{238}$U. Using the

calibration information $^{218}$Po, $^{214}$Pb, and $^{214}$Bi-$^{214}$Po activities in case of radon and $^{212}$Pb and $^{212}$Bi - $^{212}$Po in the case of thoron progenies activities on the surfaces of the glass sheets were calculated.

A spreadsheet was setup to accept the raw data as an input from the specified detectors, perform the necessary correction and then output the initial activities (equilibrium values) of $^{218}$Po, $^{214}$Pb, and $^{214}$Bi-$^{214}$Po. After experimental consideration, the protocol developed by Dumm (Dumm, 2005) was used. This protocol contains a practical set of counting intervals that minimized uncertainty. For instance, the long interval needed to be short enough to be convenient for making several measurements in a day and the SAIC AP-2 detectors could only count for an hour without being restarted. Thoron as the element of interest was determined from its progeny $^{212}$Pb which has a half life of 10.6 h for which a protocol was developed to collect the count for one hour.

**Air Borne Progeny Measurements**

### 2.16. Measurement of Unattached Fraction using Ludlum scintillation cell

To correlate the airborne radon/thoron attached to the aerosols or unattached progenies activity to the surface deposited activity, both airborne activity and the surface deposited activity measurement were performed simultaneously. Airborne progenies were measured using the active scintillation cell system. Two different protocols were used to measure for radon and thoron progenies due to the difference in their half lives. For the measurement of radon progenies, Tsivoglou method was used which is based on the one minute counting interval for 50 min for the concentration of $^{218}$Po, $^{214}$Pb and $^{214}$Bi – $^{214}$Po after sampling of 5 min. For thoron progeny measurement the counting protocol developed by Khan, Busigin and Philips (KBP) was used (Khan and Philips, 1982; Khan et al., 1982). The time at which the surface deposition of thoron was measured a sample form the indoor air was also taken. 50% cutoff of the screen was measured using the relation provided by Knutson et al. Cooking or any other activity involving burning increases the ultrafine particles concentration.

### 2.17. Electrostatic Collection of Alpha-emitters (RAD7 Active Detector)

In order to measure $^{222}$Rn and $^{220}$Rn in the exposure room, active detector RAD7 was used which works on the principle of electrostatic collection of the α-emitters with

spectral analysis. The RAD7 system contains a solid-state ion-implanted planar silicon detector and a built-in pump with a flow rate of 1 $\ell.min^{-1}$. The detector operates in external relative humidity ranging from 0% to 95% and internal humidities of 0% – 10% with a sensitivity of 4 Bq $m^{-3}$ and an upper linear detection limit of 800 kBq $m^{-3}$. The detector was calibrated with an accuracy of ± 5%. The spectra are in 200 channels and the RAD7 groups these channels into eight windows of energy ranges. A, B, C, and D are the major windows and E, F, G, and H are the diagnostic windows. Window A covers the energy range from 5.40 to 6.40 MeV, showing the total counts from 6.00 MeV α particle from the 3-min $^{218}$Po decay (daughter of $^{222}$Rn). Window B covers the region 6.40 MeV – 7.40 MeV, showing the total counts of 6.78 MeV α-particles from the $^{216}$Po ($^{220}$Rn daughter). Window C represents total counts of the 7.69 MeV α particles from $^{214}$Po (the fourth nuclide in the $^{222}$Rn decay chain), while the window D represents the total counts of the 8.78 MeV α particles from the decay of $^{212}$Po (the fourth nuclide in the $^{220}$Rn decay chain). In other words, windows A and B represent "new" $^{222}$Rn and $^{220}$Rn, while windows C and D represent "old" $^{222}$Rn and $^{220}$Rn, respectively. The RAD7 separates $^{222}$Rn and $^{220}$Rn signals by their progeny's unique α - particle energies with little cross-interference (Durridge, 2000). In the present work RAD7 data of radon and thoron was collected on hourly basis while collecting the surface deposited or airborne activity. Relative humidity(RH) in the instrument was maintained below 10% throughout the measurement. In the case it is raised above 10%, then desiccant should be replaced as it would be depleted. The RAD7 underestimate (reads low) if the internal RH rises above 10%. For thoron the sample tubing was kept short in order to reduce its decay in the tube due to its shorter half life.

# Chapter Three

# Natural Radioactivity Measurements in Pakistan - An Overview

## 3.1. Introduction

Over the last few decades, there has been an increased concern about the public exposure associated with the enhanced natural radiation environment. The study of the distribution of primordial radionuclides allows the understanding of the radiological implication of these elements due to the γ-ray exposure of the body and irradiation of lungs tissues from inhalation of radon and its daughters (Alam et al., 1999; Singh et al., 2005).

The presence of natural radioactivity in building materials results in the internal and external exposure to the occupants. In particular, it is important to assess the radiation hazards arising due to the use of soil, sand and other building materials in the construction of dwellings. Assessment of the gamma radiation dose from natural sources is of particular importance because it is the largest contributor to the external dose of the world population (UNSCEAR, 1988). The most commonly encountered primordial radionuclides are $^{238}U$, $^{232}Th$, their decay products and $^{40}K$. The level of the natural radioactivity in soil, in the surrounding environment and the associated external exposure due to the gamma radiation depends primarily on the geological and geographical conditions of the region (UNSCEAR, 2000) .

A normal male containing 140 g of K has about 4400 Bq due to $^{40}K$. Since K is found in the intracellular fluids, about 98% of the K in the body is within cells. Thus at least 98 % of these disintegrations take place within the body cells and are potentially capable of altering the cell's DNA. The body content of K is under strict homeostatic control and is maintained at a relatively constant level of about 140g/70 kg. This natural $^{40}K$ delivers a dose 0.2 mSv/yr to the gonads and other soft tissues and 0.15 mSv/yr to bone. In soil and other rocks, its concentration has a vast variation. Average

concentrations of $^{40}K$ in continental crust and soil are 850 and 400 $Bq.kg^{-1}$, respectively where as in rocks it ranges from 70 - 1500 $Bq.kg^{-1}$ (Rowland: http://www.rerowland.com/K40.html; Eisenbud and Gesell, 1997).

Due to the increasing social concern, a large number of research groups are engaged in the measurement of natural radioactivity on national levels worldwide (Tzortzis and Tsertos, 2004; Ahmed et al., 1997; Merdanoglu and Altınsoy, 1997; Tzortzis et al., 2003; Veiga et al., 2006; Xinwei, 2005). In this regard, considerable work concerning the measurements of natural radioactivity and indoor radon have also been carried out in Pakistan. In this regard, a brief review of the published data so far, is presented in this chapter

## 3.2. Summary of the Studies Conducted in Pakistan

Measurement of natural radioactivity in Pakistan gained momentum in early 90's and a number of articles were reported in the international research journals. In this regard, Tufail et al., 1994a&b; Tufail et al.,1992a&b; Tufail et al., 1993) have reported gamma activity in the samples of bricks which were collected from the Rawalpindi and Islamabad areas, ceramic products of Lahore and in cement samples collected from several factories of Pakistan. They have also measured activities in the dwellings of some selected areas of Pakistan. Ali et *al*. (1997) have reported gamma-ray activity and dose rate from brick samples collected from some areas of the North West Frontier Province (NWFP), Pakistan. Qazi and Jafri (1996) have reported measurement of radio-ecological survey on Miocene-Pliocene rocks of Qabool Khel area. Khan *et al*. (1998) have measured natural radioactivity due to $^{40}K$, $^{226}Ra$ and $^{232}Th$ in the samples of phosphate rock, which were collected from various localities of the Hazara division of Pakistan as well as from the locally prepared products and imported fertilizer. Jamil *et al*. (1998) have reported measurements of radionuclides in coal samples collected from the Punjab and Balochistan provinces. Butt *et al.* (1998) have carried out environmental gamma radiation mapping of Pakistan. Zaidi *et al.* (1999) have reported radium equivalent activity in sand samples and building materials collected from the Rawalpindi/Islamabad. They have also measured uranium and thorium contents in the collected samples using

instrumental neutron activation analysis(INAA). Tufail *et al. (*2000) have reported natural radioactivity in marble samples.

Iqbal *et al.* (2000) have reported $^{226}Ra$, $^{232}Th$ and $^{40}K$ activities in marble samples using NaI (Tl) gamma-ray spectrometer with a matrix-inversion-based spectral stripping technique. Khan and Khan(2001) have monitored natural gamma-emitting radionuclides in Portland cement manufactured in the North West Frontier Province (NWFP) of Pakistan. Aslam *et al.* (2002) have determined natural radioactivity in various types of marbles available in the Rawalpindi/Islamabad using HPGe gamma-ray spectrometer. Khan *et al. (*2002) have measured activity concentrations of natural gamma-emitting radionuclides in baked brick samples, collected from six highly populated areas of the North-West Frontier Province (NWFP) of Pakistan. Ali *et al.* (2002) have measured natural radioactivity in the building materials samples collected from the quarries and outcrops of the rock units forming the Shewa-Shahbaz Garhi igneous complex, North-West Pakistan.

Khan *et al. (*2003) have reported the natural radioactivity in the aquatic media (i.e., river, stream and drinking water) from the samples of northwestern areas of Pakistan. Jabbar *et al.* (2003a) have measured natural and fallout radionuclide concentrations in the environment of Islamabad which according to them was within the permissible limits. Akhter *et al.* (2003a) have reported the nutritional status of dietary potassium and the radiological impact of its isotope $^{40}K$ for the Pakistani population. They have determined potassium concentration in dietary samples by atomic absorption spectrometry. Akhter *et al.* (2003b) have also determined radiation doses due to the ingestion of thorium activity by the general public. Matiullah *et al. (*2004) have reported gamma activity from primordial radionuclides measured in the soil of the Bahawalpur division using gamma spectrometry technique.

Akhtar *et al. (*2004a&b) have measured natural radioactivity in virgin and fertilized saline soils as well as in the barren soil of Lahore. Chaudhry *et al.* (2002) have reported specific activity of natural radionuclides in the agricultural soil of eastern salt range of Pakistan. Akram *et al.* (2004) have used fission-track technique for the estimation of uranium concentration in drinking water collected from the natural springs

of the Muzaffarabad and hilly areas of Reshian, Azad Kashmir. Akhtar *et al.* (2004) have measured amount of radioactivity in the fertile soil, in NIAB (Nuclear Institute for Agriculture and Biology) at Faisalabad, Pakistan. Zaidi *et al.* (2004) have measured natural radioactivity in the samples of sand, stone and building materials collected from Karachi using γ-ray spectrometry and instrumental neutron activation analysis (INAA).

Khan *et al*. (2005) have reported activity concentrations of naturally occurring radionuclides i.e., $^{226}$Ra, $^{232}$Th and $^{40}$K in sand samples of the North Western areas of Pakistan using gamma-spectrometry. Tahir *et al. (*2005) have reported activity concentration in the soil samples collected from different districts of the Punjab province. Younis *et al.* (2005) have studied natural and fall-out radionuclides in samples of soil, vegetation and water collected from some regions of the North West Frontier Province (NWFP) of Pakistan. Akram *et al. (*2006) have reported measurement of gamma emitting radionuclides in shallow marine sediments off the Sindh coast using a gamma spectrometry technique. Tufail *et al.* (2006a) have measured gamma ray activity mass concentrations in phosphate rock and fertilizer samples collected from different fertilizer manufacturing factories and suppliers in Pakistan.

Natural radioactivity has been measured by Tufail *et al.* (2006b) in barren and cultivated soil of the Faisalabad area in the Punjab province of Pakistan. Akram *et al*. (2006) have reported concentration of natural and artificial radionuclides in the bottom sediments of the Karachi Harbour/Manora channel area. Rehman *et al.* (2006) have measured the radium and uranium contents in different ore samples. Akram *et al.* have measured natural radionuclide contents of $^{226}$Ra, $^{228}$Ra and $^{40}$K in the inter-tidal sediments collected from selected locations off the 745 km long Balochistan Coast. Akhtar *et al.* (2007) have measured natural radioactivity in soil samples collected from the agricultural farms consisting of saline and normal soil which had been under fertilizer treatment for the past many years to investigate the effect of fertilizers in soil and wheat grown in those sites. Fatima *et al.* (2007a&b) have measured activity concentrations of the natural radionuclides in soil samples of the southern Punjab, Pakistan by gamma-ray spectrometry. In another study, they have reported natural radioactivity in different brands of drinking water in the cities of Islamabad and Rawalpindi using gamma

spectrometry technique. Akhter *et al.* (2007) have measured daily dietary intakes of three naturally occurring long-lived radionuclides for the adult population of Pakistan using neutron activation analysis, inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectrometry (AAS), respectively. Tufail *et al.* (2007) have measured activity concentrations of primordial radionuclides in bricks, which were fabricated from saline soil of the Lahore and Faisalabad in the Punjab province of Pakistan. Faheem *et al. (*2008). have reported measurement of $^{226}$Ra, $^{232}$Th and $^{40}$K concentrations in samples of soil and building material collected from the Gujranwala, Gujrat, Hafizabad, Sialkot, Mandibahauddin and Narowal districts of the Punjab province.

### 3.3. Reported Indoor Radon Studies for Pakistan

A number of studies concerning indoor radon have been conducted in Pakistan. A brief review of these studies is given below. Najeeb *et al*(2005) have used CN-85 SSNTD tubes to measure radon/thoron concentration in the Lahore and Kasur cities. Indoor radon concentrations were also measured by Akram *et al.* (2005) in some dwellings of the Skardu city, northern Pakistan. A series of studies have also been reported by Iqbal et al. (2007a,b,c) in dwellings of the Jhelum valley, Azad Jammu and Kashmir and in the Muzaffarabad city Rawalakot areas of the Azad Jammu and Kashmir.

Tufail et al. (1988,1992) have measured indoor radon in the bed rooms, kitchens and drawing rooms of the houses of Lahore, Islamabad and Rawalpindi cities. Tufail *et al.* (1993) have reported measurement of radon concentration, gamma ray activities in dwellings of the Dera Ismail Khan and have estimated the internal and external doses for the dwellers of the area.

Matiullah et *al.* (2003) have measured indoor radon concentration levels in seven major cities, namely, Fort Abbas, Minchin Abad, Hasilpur, Bahawalpur, Liaqatpur, Rahimyar Khan and Sadiq Abad of the Bahawalpur Division. Khan *et al.* (2005) have measured radon concentration in the new and old buildings of the Fatima Jinnah Women University (FJWU) campus, Rawalpindi, Pakistan. In all the above mentioned studies solid state nuclear track detectors have been used for the measurement of indoor radon concentration. For further details, the readers is referred to the review paper by Faheem et al. (2008).

### 3.4. Summary of the Results

In the preceding section, the natural radioactivity measurements studies reported by different groups in Pakistan. In this section their reported results would be discussed. Tufail *et al* have reported average activity values of 43.3 ± 6.0, 52.2 ± 6.0 and 631.3 ± 82.7 $Bq.kg^{-1}$ for $^{226}Ra$, $^{232}Th$ and $^{40}K$, respectively. They have also estimated radium equivalent concentration value of 168.6 ± 17.8 $Bq.kg^{-1}$ in the bricks samples collected from the Rawalpindi and Islamabad region. Tufail *et al.* have reported activity due to $^{40}K$ which ranged from 144.10 ± 24.37 $Bq.kg^{-1}$ to 834.00 ± 31.69 $Bq.kg^{-1}$ with an average value of 403.46 ± 5.64 $Bq.kg^{-1}$. For $^{226}Ra$, they have reported specific activity values which ranged from 63.06 ± 3.48 $Bq.kg^{-1}$ to 123.90 ± 5.42 $Bq.kg^{-1}$ with an average value of 83.43 ± 0.90 $Bq.kg^{-1}$. In the case of $^{232}Th$, the specific activity values varied from 10.02 ± 4.88 $Bq.kg^{-1}$ to 124.50 ± 4.44 $Bq.kg^{-1}$ with an average value of 85.84 ± 0.88 $Bq.kg^{-1}$. They have also reported specific activity of natural radionuclides in the cement samples. According to them, specific activity for $^{40}K$ varied from 41.4 ± 34.4 $Bq.kg^{-1}$ and 308.7 ± 32.5 $Bq.kg^{-1}$. For $^{226}Ra$, the specific activity varied from 17.5 ± 3.3 $Bq.kg^{-1}$ and 60.3 ± 3.6 $Bq.kg^{-1}$. The range of activities for $^{232}Th$ was between 15.6 ± 2.2 $Bq.kg^{-1}$ and 50.8 ± 3.9 $Bq.kg^{-1}$. In another article they have reported $^{226}Ra$, $^{232}Th$ and $^{40}K$ activity values in the dwellings of Dera Ismail Khan which were 26.9, 26.0 and 759.1 Bq $kg^{-1}$, respectively. Qazi and Jafri have reported surface radioactivity, ranging from 150 ± 25 to 350 ± 25 $counts.s^{-1}$. They have also reported trace amounts of uranium contents in the plants and animals samples of the area surveyed.

Khan *et al.* have reported very high $^{226}Ra$ content in phosphate rock and in local/ imported fertilizers which varied from 307.7 $Bq.kg^{-1}$ to 617.5 $Bq.kg^{-1}$. Jamil *et al.* have reported maximum activity concentrations for $^{226}Ra$, $^{232}Th$ and $^{40}K$ as 31.4 ± 3, 32.7 ± 3.2 and 21.4 ± 5 $Bq.kg^{-1}$, respectively in the coal samples which were collected from the Punjab and Balochistan provinces. Butt *et al.* have reported total gamma activity for alluvium (shales and clays), sandstone, lime stone, shales as 810.75, 440.13, 113.97 and 947.79 $Bq.kg^{-1}$, respectively. For Ultrabasic rocks, basic rocks, granite and metamorphic, intermediate to acidic rocks and metamorphic schist and gneiss, they have reported total gamma activity as 10.30 $Bq.kg^{-1}$, 240.26 $Bq.kg^{-1}$, 1295.70 $Bq.kg^{-1}$, 511.06 $Bq.kg^{-1}$ and 966.29 $Bq.kg^{-1}$, respectively. Zaidi *et al.* have reported mean radium equivalent activities

for sand, cement and bricks as 62 $Bq.kg^{-1}$, 44 $Bq.kg^{-1}$ and 101 $Bq.kg^{-1}$, respectively. They have also reported $^{232}Th$ concentration in the samples of bricks, sand and cement which ranged from 6.7 - 7.5(27-31 $Bq.kg^{-1}$), 3.6 - 5.2 (15-21 $Bq.kg^{-1}$) and 1.7 – 3.7(7-15 $Bq.kg^{-1}$ ) $\mu g.g^{-1}$, respectively. For $^{238}U$, concentration values varied from 2.3 – 2.7 $\mu g.g^{-1}$ (29-34 $Bq.kg^{-1}$), 0.51 – 1.2 $\mu g.g^{-1}$ (6-15 $Bq.kg^{-1}$) and 1.2 – 1.7 $\mu g.g^{-1}$ (15-21 $Bq.kg^{-1}$) in the samples of bricks, sand and cement, respectively using INAA. In the marble samples, Tufail *et al.* have reported average specific activity values of 27, 26 and 58 $Bq.kg^{-1}$ for $^{226}Ra$, $^{232}Th$ and $^{40}K$, respectively. Iqbal *et al.* have reported activity concentrations values for the marble samples which ranged from 4 – 63 $Bq.kg^{-1}$, 9 – 40 $Bq.kg^{-1}$ and 7 – 105 $Bq.kg^{-1}$ for $^{226}Ra$, $^{232}Th$ and $^{40}K$, respectively.

Khan and Khan have reported range of combined specific activity due to the $^{40}K$, $^{226}Ra$ and $^{232}Th$ as 187.8 ± 63.5 $Bq.kg^{-1}$ – 573.2 ± 73.1 $Bq.kg^{-1}$ for Portland cement; 54.5 ± 16.1 $Bq.kg^{-1}$ –183.9 ± 31.4 $Bq.kg^{-1}$ for limestone; 87.1 ± 30.7 $Bq.kg^{-1}$ – 297.1 ± 64.4 $Bq.kg^{-1}$ for gypsum; 696.4 ± 79.1 $Bq.kg^{-1}$ –1043.9 ± 85.0 $Bq.kg^{-1}$ for slate; and 490.9 ± 54.5 $Bq.kg^{-1}$ – 570.2 ± 59.8 $Bq.kg^{-1}$ for latrite. Aslam *et al.* have reported activity concentration of $^{40}K$, $^{226}Ra$ and $^{232}Th$ from 6.15 $Bq.kg^{-1}$ to 159.65 $Bq.kg^{-1}$, 1.45 $Bq.kg^{-1}$ to 29.34 $Bq.kg^{-1}$ and 1.16 $Bq.kg^{-1}$ to 6.28 $Bq.kg^{-1}$, respectively. Khan *et al.* have reported average values of the activity concentrations due to $^{40}K$, $^{226}Ra$ and $^{232}Th$ as 680.3 ± 22.2 $Bq.kg^{-1}$ - 784.4 ± 30.7 $Bq.kg^{-1}$, 36.9 ± 3.5 $Bq.kg^{-1}$ - 51.9 ± 3.3 $Bq.kg^{-1}$ and 52.5 ± 3.6 $Bq.kg^{-1}$ - 67.6 ± 3.1 $Bq.kg^{-1}$, respectively. Ali *et al.* have reported fairly high mean concentrations of 51 ± 16 $Bq.kg^{-1}$ of $^{238}U$, 70 ± 20 $Bq.kg^{-1}$ of $^{232}Th$ and 1272 ± 367 $Bq.kg^{-1}$of $^{40}K$ in the samples which were collected from the quarries and outcrops of the rock units forming the Shewa-Shahbaz Garhi igneous complex, North-West Pakistan.

Khan *et al.,* have reported annual ingestion of radionuclides in the aquatic samples, using local consumption rates (average over the whole population) of 0.9 $l\,d^{-1}$, as 49.2, 6.2 and 1.1 Bq. $y^{-1}$ for $^{40}K$, $^{226}Ra$ and $^{232}Th$, respectively. Akhter *et al.* have reported average dietary potassium concentration as 4.54 ± 0.89 mg/g (134 ± 26 $Bq.kg^{-1}$) which led to potassium dietary intake of 2.69 ± 0.54 g/day. For this intake, daily $^{40}K$ activity of 79.94 Bq was reported. They have also reported thorium concentration, determined using instrumental neutron activation analysis. Their reported values which

varied from 1.6 ng $g^{-1}$ (0.0027 Bq.$kg^{-1}$) to12 ng $g^{-1}$ (0.054 Bq.$kg^{-1}$) and the median daily thorium intake was 2.7 µg.$d^{-1}$. Matiullah *et al.* have reported the measured mean activity of $^{226}$Ra, $^{232}$Th and $^{40}$K as 32.9 ± 0.9 Bq.$kg^{-1}$, 53.6 ± 1.4 Bq.$kg^{-1}$, and 647.4 ± 14.1 Bq.$kg^{-1}$, respectively. The mean radium equivalent activity $Ra_{eq}$, for the selected area was reported as 158.5 ± 4.1 Bq.$kg^{-1}$

Akhtar *et al.* have reported activity concentrations for the naturally occurring radionuclides, namely $^{40}$K, $^{238}$U, and $^{232}$Th in the virgin and fertilized saline soil samples. $^{40}$K, for virgin and cultivated saline soil was 500 − 610.2 Bq.$kg^{-1}$ and 560.2 Bq.$kg^{-1}$ − 635.6 Bq.$kg^{-1}$, respectively; $^{238}$U, 26.3 Bq.$kg^{-1}$ − 31.6 Bq.$kg^{-1}$ and 30.3 − 38.7 Bq.$kg^{-1}$, and $^{232}$Th, 50.6 − 55.3 Bq.$kg^{-1}$ and 50.6 Bq.$kg^{-1}$ − 64.0 Bq.$kg^{-1}$, respectively. They have also reported the activity of natural radionuclides to be $^{40}$K, 524.84 Bq.$kg^{-1}$ − 601.62 Bq.$kg^{-1}$, $^{226}$Ra, 24.73 Bq.$kg^{-1}$ − 28.17 Bq.$kg^{-1}$ and $^{232}$Th, 45.46 Bq.$kg^{-1}$ − 52.61 Bq.$kg^{-1}$ in the barren soil of Lahore.

Chaudhry *et al.* have reported average specific activities of $^{40}$K, $^{226}$Ra and $^{232}$Th in the soil samples as 666 Bq.$kg^{-1}$, 51 Bq.$kg^{-1}$ and 59 Bq.$kg^{-1}$, respectively. Akram *et al.* have reported uranium concentration in water samples, collected from the Muzaffarabad and Reshian area, which ranged from 0.03 ± 0.01 µg.$\ell^{-1}$ (0.0004 ± 0.0001 Bq.$kg^{-1}$) to 6.67 ± 0.14 µg.$\ell^{-1}$ with an average value of 1.36 ± 0.05 µg.$\ell^{-1}$ (0.0170 ± 0.0006 Bq.$kg^{-1}$). Akhtar *et al.* have also reported activity concentration of the concerned radionuclides for the NIAB soil as: $^{40}$K, 614.4 - 670.7 Bq.$kg^{-1}$; $^{226}$Ra, 28.6 - 32.6 Bq.$kg^{-1}$; and $^{232}$Th, 51.6 Bq.$kg^{-1}$ - 60.3 Bq.$kg^{-1}$. Zaidi *et al.* have reported that specific activities in samples of sand, stone and building materials, collected from Karachi, had radium equivalent activity less than 370 Bq.$kg^{-1}$. Khan *et al.* have reported activity concentrations of $^{226}$Ra, $^{232}$Th and $^{40}$K in sand samples, collected, from NWFP as 36.9-51.9 Bq.$kg^{-1}$, 52.5-67.6 Bq.$kg^{-1}$ and 680-784 Bq·$kg^{-1}$, respectively. Tahir *et al.* have reported mean activity concentrations of $^{232}$Th, $^{226}$Ra and $^{40}$K as 41 ± 8 Bq.$kg^{-1}$, 35 ± 7 Bq.$kg^{-1}$ and 615 ± 143 Bq.$kg^{-1}$ in soil samples which were collected from different districts of the Punjab. They have measured mean values of radium equivalent index ($Ra_{eq}$) as 141 ± 27 Bq.$kg^{-1}$.

Younis *et al.* have reported average specific activities of $^{40}K$, $^{226}Ra$ and $^{232}Th$ in the soil samples as 307 ± 101 $Bq.kg^{-1}$, 10.2 ± 3 $Bq.kg^{-1}$ and 2 ± 6 $Bq.kg^{-1}$, respectively. They observed that vegetation samples had smaller values of specific activities and even the analysis of water samples showed values less than lower limit of detection (LLD) for the above-mentioned radionuclides. Akram *et al.* have reported activity concentration in various sediment samples off the Sindh coast, Arabian sea which varied from 15.93 ± 5.22 $Bq.kg^{-1}$ to 30.53 ± 4.70 $Bq.kg^{-1}$ for $^{226}Ra$, 11.72 ± 1.22 to 33.94 ± 1.86 $Bq.kg^{-1}$ for $^{228}Ra$ and 295.22 ± 32.83 $Bq.kg^{-1}$ to 748.47 ± 28.75 $Bq.kg^{-1}$ for $^{40}K$, respectively.

Tufail *et al.* have reported activity mass concentrations of $^{238}U$ ($^{226}Ra$) in samples of phosphate rocks which were collected from the Jordan and Pakistan as 428 ± 11 and 799 ± 10 $Bq.kg^{-1}$, respectively. In triple-superphosphate fertilizer, they reported activity mass concentrations of $^{238}U$ as 701 ± 21 $Bq.kg^{-1}$. They have also reported activity concentration of natural radionuclides in barren and cultivated soils. For $^{40}K$, the values were 499 $Bq.kg^{-1}$ – 604 $Bq.kg^{-1}$ and 563 $Bq.kg^{-1}$ – 629 $Bq.kg^{-1}$, respectively; for $^{226}Ra$, 24–29 and 27–33 $Bq.kg^{-1}$, and for $^{232}Th$, 49–54 $Bq.kg^{-1}$ and 46–62 $Bq.kg^{-1}$. Akram *et al.* have measured activity concentration in samples which were collected from the bottom sediments of Karachi Harbour/Manora channel area. They have reported $^{226}Ra$, $^{228}Ra$, and $^{40}K$ activities in sea sediment samples from their studied area which varied from 18.5 ± 4.3 $Bq.kg^{-1}$ to 29.1 ± 3.8 $Bq.kg^{-1}$ for $^{226}Ra$, 11.7 ± 1.2 $Bq.kg^{-1}$ to 27.7 ± 4.2 $Bq.kg^{-1}$ for $^{228}Ra$ and 332.2 ± 9.3 $Bq.kg^{-1}$ to 729.2 ± 36.7 $Bq.kg^{-1}$ for $^{40}K$. For Layari river, the activity values varied from 14.9 ± 2.6 to 29.7 ± 2.9 $Bq.kg^{-1}$, 8.6 ± 0.9 $Bq.kg^{-1}$ to 31.6 ± 1.3 $Bq.kg^{-1}$ and 197.3 ± 11.6 to 643.7 ± 25.9 $Bq.kg^{-1}$, respectively for $^{226}Ra$, $^{228}Ra$ and $^{40}K$. Rehman *et al*. have calculated $^{238}U$ contents that ranged from 13 to 37 ppm in the ore samples. Akram *et al.,* have measured natural radioactivity in various sediment samples which ranged from 14.4 ± 2.5 $Bq.kg^{-1}$ to 36.6 ± 3.8 $Bq.kg^{-1}$ for $^{226}Ra$, 9.8 ± 1.2 $Bq.kg^{-1}$ to 35.2 ± 2.0 $Bq.kg^{-1}$ for $^{228}Ra$ and 144.6 ± 9.4 $Bq.kg^{-1}$ to 610.5 ± 23.9 $Bq.kg^{-1}$ for $^{40}K$. Radioactivity values measured by Akhtar *et al.* in soil samples of the agricultural farms which were from 550–644 $Bq.kg^{-1}$, 20–35 $Bq.kg^{-1}$ and 42–58 $Bq.kg^{-1}$ for $^{40}K$, $^{226}Ra$ and $^{232}Th$, respectively.

Fatima *et al.* have reported mean radium equivalent activity ($Ra_{eq}$) as 96.7 ± 5.2 $Bq.kg^{-1}$ in the soil samples of the southern Punjab. In another study, they have reported mean concentrations of $^{226}Ra$, $^{232}Th$ and $^{40}K$ in bottled drinking water as 11.3 ± 2.3 $Bq.kg^{-1}$, 5.2 ± 0.4 $Bq.kg^{-1}$ and 140.9 ± 30.6 $mBq.\ell^{-1}$, respectively. Akhter *et al.,* have reported daily intakes of $^{232}Th$, $^{238}U$ and $^{40}K$ which ranged from 4 mBq to 29 mBq, 17 mBq to 82 mBq and 51 Bq to 128 Bq, respectively. Geometric means of these intakes due to these radionuclides were10 mBq $d^{-1}$, 33 mBq $d^{-1}$ and 78.5 $Bq.d^{-1}$, respectively. Tufail *et al.* have reported activity mass concentrations of $^{40}K$, $^{226}Ra$ and $^{232}Th$ measured in the brick samples as 567.7 ± 38.3 (493–631 $Bq.kg^{-1}$), 28.4 ± 3.8 (23–35 $Bq.kg^{-1}$), and 56.0 ± 4.6 (46–65) $Bq.kg^{-1}$, respectively.

Faheem *et al.* have reported average $^{226}Ra$, $^{232}Th$ and $^{40}K$ concentrations in samples of soil and building material which were collected from six districts of the Punjab province ranging from 20 ± 9 $Bq.kg^{-1}$ to 43 ± 17 $Bq.kg^{-1}$, 29 ± 8 $Bq.kg^{-1}$ to 53 ± 9 $Bq.kg^{-1}$ and 98 ± 38 $Bq.kg^{-1}$ to 621 ± 189 $Bq.kg^{-1}$, respectively. Whereas average radium equivalent activities were found to range from 69 ± 25 $Bq.kg^{-1}$ to 165 ± 32 $Bq.kg^{-1}$.

In the work reported so far for Pakistan, emphasis has been made on the health hazards associated with the natural radioactivity present in soil and other building materials. Besides measurement of natural radioactivity in soil and building materials, limited data is also available for Pakistan concerning the use of natural radioactivity in exploration of uranium and other related minerals deposits in different types of rocks and soil. Few articles regarding measurements of natural radioactivity in air have also been reported. Most of the studies related to the natural radioactivity have been conducted using high purity germanium detector (HPGe). In several reported studies, relatively low resolution NaI (Tl) detector has also been used using spectrum stripping technique. Fission track dating technique has also been used to measure naturally occurring uranium in rocks and water samples. Some reported research papers are based on the use of INAA technique for the measurement of gamma ray activity of radionuclides present in different food and vegetable samples.

The lowest reported values for $^{226}Ra$, $^{232}Th$ and $^{40}K$ were as 1.45 $Bq.kg^{-1}$, 1.16 and 7 $Bq.kg^{-1}$, whilst the highest were 799 $Bq.kg^{-1}$, 124 $Bq.kg^{-1}$ and 1272 $Bq.kg^{-1}$, respectively. Relatively low activity concentrations of natural radionuclides have been reported for marble samples whereas higher values have been reported for phosphate rocks samples. Reported range of uranium concentration in water samples is from 0.03 ± 0.01 $\mu g.\ell^{-1}$ (0.0004 ± 0.0001 $Bq.kg^{-1}$) to 6.67 ± 0.14 $\mu g.\ell^{-1}$ with an average value of 1.36 ± 0.05 $\mu g.\ell^{-1}$ (0.0170 ± 0.0006 $Bq.kg^{-1}$). The reported values for natural radioactivity show a wide variation in the activity concentration of the concerned radionuclides in different types of rocks, soil, sand and bricks. Uptake of radionuclides due to the use of different types of diets and bottled mineral water used in Pakistan has also been reported and its radiological effects have been assessed. Radioactivity measurements have also been reported for the land used for cultivation of different types of crops. According to the reported data, natural radioactivity present in the building materials is relatively low. However, the area for which the data is reported represents a very small portion of the cultivated land of Pakistan and therefore further research work in this regard will be of much interest. In view of the above discussion, a comprehensive study was planned for the present research work and was conducted in some selected parts of the NWFP, Pakistan. Spatial and seasonal variations of indoor radon, radon exhalation rate and natural radioactivity from soil and other different building materials were studied which are presented in this thesis.

### 3.5. Conclusions

To conclude, reported data concerning measurement of natural radioactivity in the soil, sand, brick, marble and other building materials for Pakistan and a brief review of indoor radon data have been presented in this chapter. Reported radioactivity values show a wide variation of activity contents in different types of soil and other building materials. Most of the reported studies are based on using high purity germanium detectors(HPGe) whereas in some studies, NaI (Tl) detector using spectrum stripping technique and INAA have also been used. High contents of natural radioactivity have been reported for phosphate rocks. Therefore, great care is needed to be taken using these rocks for different purposes. Fission tack dating technique has also been used for the measurement of uranium contents in different types of rocks. All the reported values of the natural

radioactivity and indoor radon concentration are within the permissible limits and do not pose any serious threat to the general public.

After reviewing the studies conducted in Pakistan concerning measurement of Natural radioactivity and indoor radon, the next chapter deals with the analysis of the work done in this research work regarding the measurement of Indoor radon and its spatial and temporal variations in some selected parts of the NWFP, Pakistan.

# Chapter Four

# Measurement of Seasonal and Spatial Distribution of Indoor Radon Levels

## 4.1. Introduction

Indoor radon levels are known to vary from house to house which in turn depends on radon source, building characteristics, natural daily cycle, other longer temporal and spatial cycles, related to occupancy, geological and meteorological factors, dwelling characteristics and habits of the occupants (Arvela, 1995; Majborn, 1992; Groves-Kirkby et al., 2006). In countries with relatively higher contributions from building materials, the winter to summer ratios should be lower (Arvela, 1995).

According to the measurements, in the very same room the yearly average of radon concentration may also change by 25–50% from year to year (Papp et al., 2001). Radon concentration varies throughout the year with the greatest concentrations occurring during the winter months in homes but outdoor concentrations are greatest during the summer months (Grainger et al., 2005; Bochicchio, 2004). For radon concentration temporal variations, a 12-month total period of measurement is generally considered the best estimate of the average value. In order to determine annual average from the indoor radon levels, measured for a less than a year, seasonal correction factor has to be applied (Grainger et al., 2000; Baysson et al., 2003; Karpińska et al., 2005; Bochicchio, 2005).

Longer measurements give more accurate estimates of the annual average concentrations than short measurements; the magnitude of the improvement caused by using longer measurements is not well established as the long-term exposure may reduce the efficiency of the detector for the registration of tracks.

In view of the above introduction a systematic studies were conducted aiming at the following objectives (1) To measure indoor radon levels, its seasonal and spatial variations in some selected areas of the North West Frontier Province (NWFP) and Federally Administered Tribal Areas (FATA), Pakistan. (2) To set a baseline data for these areas which would be of great help for radiological database of Pakistan. (3) To calculate the seasonal correction factor. As the area understudy has four distinct seasons, variation in the indoor radon levels was expected. (4) A study was also conducted to compare yearly average of the seasonal measurements with that of the yearly exposed CR-39 detectors in order to study the affect of the long-term exposure on CR-39 detectors.

## 4.2. Materials and Methods

In order to measure the above-mentioned quantities a series of field experiments were designed in the selected area of NWFP and FATA. Details of the installation of the dosimters and selection of the houses is given in chapter 2.

For the analysis of the seasonally averaged, yearly averaged and the yearly exposed CR-39, only those homes were accepted wherefrom both seasonal and yearly exposed radon dosimeters were recovered. It may be noted here that from 28, 30, 25 houses of Charsadda, Swabi and Mardan and 27, 29 houses in Mohmand and Bajuar agency, all the seasonally dosimeters exposed in all the seasons and yearly exposed radon dosimeters were recovered, respectively.

CR-39 detectors were then etched in 25% NaOH at 80 $^{o}$C and track densities were then related to the radon concentration levels using calibration factor of 2.7 tracks.cm$^{-2}$.h$^{-1}$/kBq.m$^{-3}$. Using the mean annual radon levels in each house, annual effective dose was calculated using the ICRP-65 and UNSCEAR conversion factors (Jing, 2005; UNSCEAR, 2000). Using the annual weighted average values of indoor radon concentration and the BEIR VI formula, excess relative risk of lung cancer were calculated.

## 4.3. Results

As mentioned above, $^{222}$Rn concentration levels were determined using the calibration factor of 2.7 tracks cm$^{-2}$ h$^{-1}$/kBq m$^{-3}$. Having determined the $^{222}$Rn concentrations, statistical analysis of the data was performed. Geometric mean, arithmetic mean and

Table 4.1: Indoor radon levels in Bq $m^{-3}$ in bed rooms and drawing rooms of all the houses which were surveyed in NWFP and FATA areas of Pakistan during the Summer season.

| H. No | Mohmand | | Bajuar | | Swabi | | Mardan | | Charsadda | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room |
| 1 | 53±5 | L | 170±4 | 86±4 | 52±4 | 46±5 | 21±8 | 29±5 | 95±5 | 34±4 |
| 2 | 50±5 | 43±5 | 80±4 | 45±5 | 65±4 | 55±5 | 78±5 | 32±5 | 68±5 | 32±6 |
| 3 | 58±4 | 38±5 | 72±4 | 85±4 | 56±4 | 48±5 | 57±4 | 31±5 | L | 43±4 |
| 4 | 50±5 | 72±3 | 127±4 | 44±5 | 51±4 | 50±5 | 267±4 | 74±4 | 80±5 | 52±5 |
| 5 | 45±5 | L | 43±5 | 76±4 | L | 55±5 | 68±4 | 39±5 | 323±5 | 72±5 |
| 6 | 246±4 | 107±4 | 58±5 | 35±5 | 35±6 | 31±5 | 45±5 | 38±5 | 56±5 | 55±5 |
| 7 | 39±5 | 54±6 | 57±4 | 56±4 | 38±5 | 47±5 | 66±5 | 36±5 | 96±5 | 85±5 |
| 8 | 34±5 | L | 147±4 | 111±5 | 28±5 | 55±5 | 186±5 | 103±5 | 154±5 | 55±5 |
| 9 | 48±5 | 23±5 | 116±4 | 112±5 | 102±4 | 99±5 | 55±5 | 39±5 | 91±4 | 45±5 |
| 10 | 25±6 | 47±7 | L | L | 36±5 | 48±5 | 40±5 | L | 54±5 | 281±5 |
| 11 | 60±5 | L | 90±4 | 90±4 | 88±4 | 45±5 | 51±5 | 45±7 | 96±5 | 56±5 |
| 12 | 52±5 | 62±4 | 50±5 | 48±5 | 53±4 | 54±4 | 42±5 | 48±4 | L | L |
| 13 | 105±4 | 59±5 | 43±5 | 44±5 | 36±5 | 44±5 | 31±5 | 51±4 | 74±5 | 47±4 |
| 14 | 67±4 | 79±4 | 46±4 | 52±4 | 36±5 | 50±4 | 58±5 | 45±5 | 52±5 | 48±5 |
| 15 | 60±4 | 39±5 | 131±4 | 36±5 | L | 63±4 | 28±6 | 28±5 | 57±5 | L |
| 16 | 41±5 | 55±4 | 49±5 | L | 171±3 | 99±5 | 49±6 | 65±5 | 59±5 | 65±5 |
| 17 | 189±5 | 124±5 | 71±4 | 87±4 | 24±5 | 44±5 | 46±5 | 34±5 | 45±6 | 95±5 |
| 18 | 36±6 | 78±4 | 42±5 | 43±5 | 24±6 | 77±4 | 80±5 | 31±5 | 92±4 | 147±5 |
| 19 | 122±4 | 77±4 | 91±4 | 58±5 | L | 55±4 | 23±7 | L | 51±5 | 69±5 |
| 20 | L | 76±4 | 96±4 | 84±4 | 54±4 | 31±5 | 60±5 | 57±5 | 63±5 | 69±5 |
| 21 | 61±5 | 37±5 | 89±4 | 48±5 | 88±4 | 42±5 | 59±5 | 18±6 | 95±4 | 81±5 |
| 22 | 73±4 | 42±5 | 57±4 | 55±4 | 34±5 | 72±4 | 49±5 | 76±4 | 76±5 | 47±5 |
| 23 | 106±4 | 115±4 | 97±4 | 72±4 | 33±5 | 50±5 | 26±6 | L | 115±5 | 45±5 |
| 24 | 37±5 | 50±4 | 63±4 | 90±4 | 24±6 | 49±5 | 50±5 | 81±4 | 97±5 | 47±5 |
| 25 | 58±55 | 54±7 | L | 79±4 | 32±5 | 34±5 | 29±5 | 25±5 | L | 28±5 |
| 26 | L | 82±5 | L | 62±4 | 25±6 | 45±5 | 32±5 | 30±5 | 32±5 | 35±5 |
| 27 | 42±5 | L | 97±4 | 48±5 | 74±5 | 44±5 | 46±5 | 33±5 | 96±5 | 69±6 |
| 28 | L | 45±5 | 176±4 | 38±5 | 36±5 | 51±5 | 57±7 | 58±5 | 53±5 | 38±6 |
| 29 | 33±5 | 63±4 | 137±4 | 123±4 | L | 47±5 | L | 62±4 | 110±5 | L |
| 30 | 29±6 | 51±4 | 35±5 | 31±6 | 41±5 | 40±5 | L | L | L | L |
| 31 | L | 65±55 | 43±5 | 46±6 | 33±5 | L | 41±7 | 46±5 | 75±5 | 48±5 |
| 32 | L | L | 70±4 | 125±4 | 50±4 | 48±5 | L | 56±3 | 91±5 | 63±5 |
| 33 | 71±4 | 78±5 | 61±5 | 87±4 | 25±6 | L | L | 48±6 | 64±5 | 113±4 |
| 34 | 50±5 | 54±5 | 51±5 | 29±5 | L | 72±5 | 115±4 | 66±4 | 61±5 | 50±5 |
| 35 | 40±5 | 68±5 | 100±4 | 106±4 | L | 106±5 | 53±4 | 33±5 | 92±5 | 64±5 |
| 36 | 71±4 | L | 37±5 | 75±4 | 89±4 | 42±5 | 35±5 | 30±5 | 85±5 | 78±4 |
| 37 | 63±5 | 45±5 | 32±5 | 41±5 | 112±4 | 120±5 | 42±5 | 29±5 | 89±5 | 59±4 |
| 38 | L | 36±4 | 50±5 | 45±5 | 42±5 | 62±4 | 33±5 | 50±5 | L | L |
| 39 | 78±4 | 58±4 | L | 43±5 | 13±6 | 44±5 | 38±6 | 30±5 | 65±5 | 39±5 |
| 40 | 33±5 | 54±4 | 54±4 | 40±5 | 71±4 | 71±5 | 29±5 | 53±5 | 83±5 | 65±5 |

standard deviation were calculated for each season. Radon concentration levels observed in each house during the summer season are shown in table 4.1.

As may be seen in table 4.1, in summer season indoor radon concentration levels varied from 25 ± 6 to 246 ± 4 Bq $m^{-3}$ and 23 ± 5 to 124 ± 5 Bq $m^{-3}$ in the bed rooms and drawing rooms of the Mohmand agency, respectively. In the Bajuar agency, radon concentration level varied from 32 ± 5 to 176 ± 4 Bq $m^{-3}$ and 29 ± 5 to 125 ± 4 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Swabi district, variation in the radon concentration level ranged from 13.4 ± 6 to 171 ± 3 Bq $m^{-3}$ and 31 ± 5 to 120 ± 5 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Mardan district, radon concentration level varied from 21 ± 8 to 267 ± 4 Bq $m^{-3}$ and 18 ± 6 to 103 ± 5 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Charsadda district, this variation ranged from 32 ± 5 Bq $m^{-3}$ to 323 ± 5 and 28 ± 6 to 281 ± 6 Bq $m^{-3}$, respectively. According to the weighted average indoor radon in the Mohmand agency varied from 34 ± 6 to 191 ± 4 Bq $m^{-3}$ while in the Bajuar agency, it varied from 33 ± 5 to 137 ± 5 Bq $m^{-3}$. As may be seen in table 4. 2, variation of indoor radon in Mardan and Swabi districts is from 24 ± 7 Bq $m^{-3}$ to 189 ± 4 Bq $m^{-3}$ and 24 ± 6 to 142 ± 4 Bq $m^{-3}$, respectively. Maximum variation of radon occurred in Charsadda, which ranged from 33 ± 6 to 222 ± 5 Bq $m^{-3}$. All the houses selected in the Mohmand and Bajuar agencies were detached houses whereas more than 50% houses in the Charsadda, Mardan and Swabi districts were detached houses. The remaining houses were semi-detached. No significant difference was observed in the radon levels measured in detached and semi-detached houses.

As may be seen in table 4.3, in autumn season indoor radon concentration level varied from 36 ± 6 to 131 ± 4 Bq $m^{-3}$ and 39 ± 6 to 147 ± 5 Bq $m^{-3}$ in the bed rooms and drawing rooms of the Mohmand agency, respectively. In the Bajuar agency, radon concentration level varied from 45 ± 4 to 191 ± 4 Bq $m^{-3}$ and 47 ± 6 to 221 ± 4 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Swabi district, variation in the radon concentration level ranged from 52 ± 5 to 155 ± 4 and 43 ± 6 to 188 ± 4 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Mardan district, radon concentration level varied from 50 ± 5 to 126 ± 6 Bq $m^{-3}$ and 57 ± 6 to 126 ± 5 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Charsadda district, this variation ranged from 50 ± 5 Bq $m^{-3}$ to 318 ± 5 and 42 ± 5 to 132 ± 5 Bq $m^{-3}$, respectively.

Weighted average indoor radon in the Mohmand agency varied from 46 ± 6 to 124 ± 4 Bq $m^{-3}$ while in the Bajuar agency it varied from 47 ± 4 to 173 ± 4 Bq $m^{-3}$. As may be seen in table 4.4, variation in the indoor radon in the Mardan and the Swabi districts is from 60 ± 5 to 105 ± 4 Bq$m^{-3}$ and 53 ± 6 to 122 ± 4 Bq $m^{-3}$, respectively. Maximum variation in the indoor radon occurred in the Charsadda district, which ranged from 58 ± 4 to 234 ± 5 Bq $m^{-3}$.

As may be seen in table 4.5, in winter season indoor radon concentration levels varied from 51 ± 6 to 238 ± 5 Bq $m^{-3}$ and 50 ± 7 to 117 ± 4 Bq $m^{-3}$ in the bed rooms and drawing rooms of the Mohmand agency, respectively. In the Bajuar agency, radon concentration level varied from 41 ± 7 to 176 ± 5 Bq $m^{-3}$ and 40 ± 6 to 213 ± 4 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Swabi district, variation in the radon concentration level ranged from 33 ± 7 to 203 ± 4 and 33 ± 7 to 138 ± 4 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Mardan district, radon concentration level varied from 37 ± 5 to 248 ± 4 Bq $m^{-3}$ and 44 ± 6 to 146 ± 6 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In the Charsadda district, this variation ranged from 55 ± 7 Bq $m^{-3}$ to 319 ± 5 and 48 ± 7 to 146 ± 6 Bq $m^{-3}$, respectively.

As may be seen in table 4.6, in the Mohmand agency weighted average indoor radon in the winter season varied from 25 ± 6 to 189 ± 5 Bq $m^{-3}$ while in the Bajuar agency, it varied from 44 ± 6 to 187 ± 5 Bq $m^{-3}$. Table 4.6 the variation of indoor radon in Mardan and Swabi Districts are from 48 ± 5 to 177 ± 4 Bqm$^{-3}$ and 40 ± 7 to 148 ± 4 Bq $m^{-3}$ respectively. Maximum variation of radon occurred in Charsadda, which ranged from 53 ± 7 to 226 ± 6 Bq $m^{-3}$.

As may be seen in table 4.7, in Spring season indoor radon concentration levels varied from 30 ± 6 to 131 ± 5 Bq $m^{-3}$ and 22 ± 7 to 129 ± 5 Bq $m^{-3}$ in the bed rooms and drawing rooms of Mohmand agency, respectively. In the Bajuar agency, radon concentration level varied from 29 ± 6 to 349 ± 5 Bq $m^{-3}$ and 27 ± 7 to 229 ± 5 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively. In Swabi district, variation in the radon concentration level ranged from 32 ± 6 to 156 ± 5 and 26 ± 6 to 79 ± 5 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively.

Table 4.2: Weighted average indoor radon during the Summer season.

| Detector No | Mohmand | Charsadda | Bajuar | Swabi | Mardan |
|---|---|---|---|---|---|
| 1. | 53±5 | 70±4 | 137±4 | 50±5 | 24±7 |
| 2. | 47±5 | 53±5 | 66±5 | 61±4 | 60±5 |
| 3. | 50±4 | 43±4(D) | 77±4 | 53±4 | 47±5 |
| 4. | 60±4 | 69±5 | 94±4 | 51±4 | 189±4 |
| 5. | 45±5 | 222±5 | 56±5 | 55±5(D) | 56±4 |
| 6. | 191±4 | 56±5 | 49±5 | 33±5 | 42±5 |
| 7. | 45±5 | 91±5 | 56±4 | 41±5 | 54±4 |
| 8. | 34±6(B‡) | 115±5 | 133±4 | 39±5 | 153±4 |
| 9. | 38±5 | 72±5 | 114±4 | 100±4 | 49±5 |
| 10. | 34±6 | 145±5 | L | 41±5 | 40±5(B) |
| 11. | 60±5(B) | 80±5 | 90±4 | 71±4 | 48±5 |
| 12. | 56±5 | L | 49±5 | 53±4 | 45±4 |
| 13. | 84±4 | 63±4 | 43±5 | 39±5 | 39±5 |
| 14. | 72±4 | 50±5 | 48±4 | 41±5 | 53±5 |
| 15. | 52±4 | 57±5(B) | 93±4 | 63±4(D) | 28±5 |
| 16. | 47±5 | 61±5 | 49±5(B) | 142±4 | 55±6 |
| 17. | 163±5 | 65±5 | 77±4 | 32±5 | 41±5 |
| 18. | 53±5 | 114±5 | 43±5 | 45±5 | 60±5 |
| 19. | 104±4 | 58±5 | 77±4 | 55±4(D) | 23±7(B) |
| 20. | 767±4(B) | 65±5 | 91±4 | 45±4 | 59±5 |
| 21. | 52±5 | 90±4 | 73±4 | 69±4 | 43±5 |
| 22. | 61±4 | 64±5 | 56±4 | 49±4 | 60±5 |
| 23. | 110±4 | 87±5 | 87±4 | 39±5 | 26±6(B) |
| 24. | 43±4 | 77±5 | 74±4 | 34±5 | 63±5 |
| 25. | 56±6 | 28±6(D) | 79±4 | 33±5 | 28±5 |
| 26. | 82±5(D) | 33±5 | 62±4 | 33±5 | 31±5 |
| 27. | 42±5(B) | 85±5 | 78±4 | 62±5 | 41±5 |
| 28. | 45±5(D) | 47±5 | 121±4 | 42±5 | 57±6 |
| 29. | 45±5 | 110±5(B) | 132±4 | 47±5(D) | 62±4(D) |
| 30. | 39±5 | L | 33±5 | 40±5 | L |
| 31. | 65±4(D) | 64±5 | 44±5 | 33±5(B) | 43±6 |
| 32. | L | 80±5 | 92±4 | 49±5 | 56±3(D) |
| 33. | 74±4 | 84±5 | 71±5 | 25±6 | 48±6(D) |
| 34. | 51±5 | 57±5 | 42±5 | 72±5(D) | 95±4 |
| 35. | 52±4 | 81±5 | 103±4 | 106±5(D) | 45±5 |
| 36. | 71±4(B) | 82±5 | 52±5 | 70±5 | 33±5 |
| 37. | 55±5 | 77±4 | 35±5 | 115±4 | 37±5 |
| 38. | 36±4(D) | L | 48±5 | 50±4 | 40±5 |
| 39. | 70±4 | 55±5 | 43±5(D) | 26±6 | 35±5 |
| 40. | 41±5 | 75±5 | 48±5 | 71±4 | 39±5 |

‡ B= Bedroom data only and D= Drawing room Data only and L= detector is lost.

Table 4. 3: Indoor radon levels in Bq $m^{-3}$ in bedrooms and drawing rooms of all the houses which were surveyed in NWFP and FATA areas of Pakistan during the Autumn season.

| H No | Mohmand | | Bajuar | | Swabi | | Mardan | | Charsadda | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room |
| 1 | 62±5 | 63±5 | 86±4 | 82±4 | 68±6 | 56±6 | 60±5 | 76±7 | 63±5 | 61±5 |
| 2 | 50±6 | 56±5 | 102±4 | 58±5 | 80±5 | 59±5 | 61±5 | 73±6 | 73±5 | 81±5 |
| 3 | 74±4 | 69±5 | 71±5 | 61±6 | 89±5 | 108±4 | 90±4 | L | 77±5 | 59±5 |
| 4 | 60±6 | 77±5 | 99±4 | 89±4 | 100±5 | 73±5 | 126±6 | 58±6 | 86±5 | 68±5 |
| 5 | 56±6 | 68±5 | 96±4 | 68±4 | 104±5 | 68±5 | 54±5 | 71±5 | 79±5 | 73±5 |
| 6 | 77±5 | 70±5 | 83±5 | 90±4 | 66±4 | 105±4 | 75±4 | 126±5 | 58±5 | 89±5 |
| 7 | 54±6 | 52±5 | 111±4 | 91±4 | 86±5 | 63±5 | 63±5 | 68±5 | 83±6 | 132±5 |
| 8 | L | L | 97±5 | 165±4 | 66±5 | 62±5 | 67±5 | 84±4 | 82±5 | 45±5 |
| 9 | 57±5 | 48±6 | 74±4 | 142±4 | 155±4 | 72±5 | 85±5 | 66±5 | 63±5 | L |
| 10 | 68±4 | 60±5 | 141±4 | 221±4 | L | L | 121±4 | 80±4 | 90±6 | 76±5 |
| 11 | 63±5 | L | L | 63±5 | 73±5 | 65±5 | 56±6 | 71±5 | 78±6 | 64±5 |
| 12 | 79±5 | 77±5 | 67±5 | 71±6 | 81±4 | 80±5 | 74±5 | 69±6 | L | L |
| 13 | 68±4 | 52±5 | L | L | 99±4 | 58±5 | 68±5 | 64±5 | 178±6 | 54±6 |
| 14 | 64±5 | 51±6 | 51±5 | 60±4 | 73±5 | 70±5 | 69±5 | 64±5 | 68±5 | 93±4 |
| 15 | 64±5 | 59±5 | 94±4 | 78±4 | 56±6 | 62±5 | 62±6 | 82±6 | 76±6 | 64±5 |
| 16 | 69±5 | 89±5 | 67±6 | 47±6 | 85±5 | 85±5 | 75±5 | 61±5 | 85±5 | 64±6 |
| 17 | L | 53±5 | 171±4 | 76±3 | 74±5 | 188±4 | 76±5 | L | 78±5 | L |
| 18 | 36±6 | 62±5 | 137±5 | 95±4 | 82±5 | 89±5 | 73±4 | 77±5 | 81±5 | 104±5 |
| 19 | 85±5 | 91±4 | 78±4 | 167±4 | 100±5 | 85±5 | 74±6 | 75±5 | 50±5 | L |
| 20 | L | 63±5 | L | L | 72±5 | 81±4 | 103±5 | 96±5 | 72±5 | 88±4 |
| 21 | 96±5 | 147±4 | 45±4 | 50±5 | 109±4 | L | 65±4 | 81±5 | 115±6 | 100±5 |
| 22 | 86±5 | 84±5 | 85±4 | 66±4 | 75±5 | 72±5 | 83±5 | 62±6 | 59±5 | 83±5 |
| 23 | 131±4 | 71±5 | 60±4 | 92±4 | 79±5 | 66±5 | 65±5 | 84±4 | 318±5 | 107±5 |
| 24 | 78±5 | 70±5 | 60±4 | 76±3 | 75±6 | 55±5 | 73±5 | 72±5 | 68±4 | 42±5 |
| 25 | 47±6 | 61±5 | 191±4 | 78±4 | 64±5 | 67±4 | 67±5 | L | 68±5 | 72±5 |
| 26 | 120±4 | 131±4 | 174±4 | 106±4 | 66±6 | 64±4 | 71±4 | 71±5 | 71±5 | 44±5 |
| 27 | 121±4 | 71±5 | 61±5 | 73±5 | 52±5 | 56±5 | 75±5 | 68±6 | 78±5 | 80±5 |
| 28 | 88±4 | 75±5 | 84±4 | 67±6 | L | 112±5 | 68±5 | 67±6 | 81±5 | 77±5 |
| 29 | 71±5 | 95±5 | 91±5 | 75±5 | 105±5 | 55±5 | 79±6 | 80±5 | 99±5 | 85±5 |
| 30 | 86±5 | 93±5 | 74±5 | 79±5 | 80±5 | 90±4 | 100±5 | 74±5 | 63±6 | 57±5 |
| 31 | 80±5 | 61±5 | 51±5 | 55±5 | 86±5 | 80±5 | 74±5 | 62±5 | 89±5 | 68±5 |
| 32 | L | L | 119±4 | 103±4 | 62±5 | 45±5 | 59±6 | 69±5 | 72±5 | 75±5 |
| 33 | 104±5 | L | 97±5 | 60±4 | 76±4 | 53±6 | 73±5 | 65±5 | 67±5 | 71±4 |
| 34 | 124±5 | 74±5 | 47±4 | 63±5 | 63±6 | 64±5 | 68±6 | 72±5 | 71±5 | 77±5 |
| 35 | 72±6 | 83±4 | 51±5 | 73±4 | L | 140±5 | 73±5 | 78±5 | L | 102±5 |
| 36 | 64±5 | 84±5 | 57±5 | 69±4 | 82±5 | 43±6 | 78±5 | 76±5 | 135±5 | 71±6 |
| 37 | 55±6 | 62±5 | 80±4 | 92±4 | 151±4 | 59±6 | 70±6 | 60±5 | 85±5 | 113±5 |
| 38 | 96±4 | 39±6 | 78±5 | 53±5 | 94±5 | 62±5 | 76±5 | 57±6 | L | 74±5 |
| 39 | 75±4 | 64±6 | 90±4 | 97±4 | 82±5 | 96±4 | 50±5 | 74±5 | 64±5 | 49±5 |
| 40 | 86±5 | 87±5 | 82±4 | 97±5 | 55±6 | 50±5 | 68±6 | 66±6 | 82±6 | 76±5 |

Table 4.4: Weighted average indoor radon during the Autumn season.

| H. No. | Mohmand | Charsadda | Bajuar | Swabi | Mardan |
|---|---|---|---|---|---|
| 1. | 62±5 | 62±5 | 84±4 | 95±5 | 66±6 |
| 2. | 52±6 | 76±5 | 84±4 | 53±5 | 66±5 |
| 3. | 72±4 | 70±5 | 67±5 | 34±6 | 90±4(B) |
| 4. | 67±6 | 79±5 | 95±4 | 59±6 | 99±6 |
| 5. | 61±6 | 77±5 | 85±4 | 40±6 | 61±5 |
| 6. | 74±5 | 70±5 | 86±5 | 53±5 | 95±4 |
| 7. | 53±6 | 103±6 | 103±4 | 36±6(B) | 65±5 |
| 8. | L | 67±5 | 124±5 | 40±5 | 74±5 |
| 9. | 53±5 | 63±5(B) | 101±4 | 97±5 | 77±5 |
| 10. | 65±4 | 84±6 | 173±4 | 124±6 | 105±4 |
| 11. | 63±5(B) | 72±6 | 63±5(D) | 47±6 | 62±6 |
| 12. | 78±5 | L | 69±5 | 83±5 | 72±5 |
| 13. | 62±4 | 128±6 | L | 37±6 | 66±5 |
| 14. | 59±5 | 78±5(B) | 55±5 | 40±4 | 67±5 |
| 15. | 62±5 | 71±6 | 88±4 | 48±6 | 70±6 |
| 16. | 77±5 | 77±5 | 59±6 | 46±6 | 69±5 |
| 17. | 53±5 | 78±5 | 133±4 | 41±6 | 76±5(B) |
| 18. | 46±6 | 90±5 | 120±5 | 111±5 | 75±4 |
| 19. | 87±5 | 50±5(B) | 114±4 | 40±6 | 74±6 |
| 20. | 63±5 | 78±5 | L | 35±6(D) | 100±5 |
| 21. | 116±4 | 109±6 | 47±4 | 44±7 | 71±4 |
| 22. | 85±5 | 83±5 | 77±4 | 51±5 | 75±5 |
| 23. | 107±4 | 234±5 | 73±4 | 26±6(D) | 73±5 |
| 24. | 75±5 | 58±4 | 66±4 | 47±6 | 73±5 |
| 25. | 53±5 | 70±5 | 146±4 | 47±5 | 67±5(B) |
| 26. | 124±4 | 60±5 | 147±4 | 52±5 | 71±4 |
| 27. | 101±4 | 79±5 | 66±5 | L | 72±5 |
| 28. | 83±4 | 79±5 | 77±4 | 46±6 | 68±5 |
| 29. | 81±5 | 93±5 | 85±5 | 33±5(B) | 79±6 |
| 30. | 89±5 | 61±6 | 76±5 | 55±6 | 90±5 |
| 31. | 72±5 | 81±5 | 53±5 | 48±5 | 69±5 |
| 32. | L | 73±5 | 113±4 | 71±5 | 63±6 |
| 33. | 104±5(B) | 69±5 | 82±5 | 51±6 | 70±5 |
| 34. | 104±5 | 73±5 | 53±4 | 51±6 | 70±6 |
| 35. | 76±5 | 102±5(D) | 60±5 | 44±6 | 75±5 |
| 36. | 72±5 | 109±5 | 62±5 | 38±6 | 77±5 |
| 37. | 58±6 | 113±5 | 85±4 | 85±4 | 66±6 |
| 38. | 73±5 | 74±5(D) | 68±5 | 39±6(B) | 68±5 |
| 39. | 71±5 | 58±5 | 93±4 | 74±5(D) | 60±5 |
| 40. | 86±5 | 80±6 | 88±4 | 59±6 | 67±6 |

Table 4.5: Indoor radon levels in Bq $m^{-3}$ in bed rooms and drawing rooms of all the houses which were surveyed in NWFP and FATA areas of Pakistan in the Winter season.

| H No | Mohmand | | Bajuar | | Swabi | | Mardan | | Charsadda | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room |
| 1 | 136±5 | 91±5 | 117±5 | 129±5 | 147±4 | 72±5 | 49±6 | 55±5 | 96±5 | 71±7 |
| 2 | 74±5 | 54±6 | 41±7 | 56±5 | 66±5 | 44±6 | 67±5 | 75±5 | 75±6 | 69±7 |
| 3 | 141±5 | 78±5 | L | 73±5 | 58±6 | 67±5 | 67±5 | 59±5 | 76±7 | 67±6 |
| 4 | L | 99±5 | 112±5 | 158±5 | 60±5 | 54±6 | 169±4 | L | 58±7 | 56±6 |
| 5 | 141±5 | 57±5 | 123±5 | 62±5 | 51±7 | 86±5 | 83±5 | 80±4 | 78±7 | 85±5 |
| 6 | 60±6 | 109±5 | L | 77±5 | 74±5 | 98±5 | 122±4 | 146±6 | 66±6 | 65±6 |
| 7 | 60±5 | 58±6 | 98±5 | 73±5 | 49±7 | 71±5 | 51±6 | 62±6 | 77±6 | 90±6 |
| 8 | L | 80±5 | L | 126±5 | 143±5 | 91±5 | 198±4 | 65±5 | 62±6 | 62±6 |
| 9 | 69±6 | 84±5 | 45±5 | 140±5 | 103±5 | 69±5 | 65±5 | 55±5 | 58±6 | 52±7 |
| 10 | L | 62±6 | 120±5 | 83±5 | 100±5 | 88±5 | 161±5 | 76±5 | 71±7 | 110±5 |
| 11 | 72±6 | L | 169±5 | 213±4 | 76±5 | 79±5 | 43±6 | 108±5 | 72±6 | 48±7 |
| 12 | 91±5 | 63±6 | 91±5 | 58±6 | 55±6 | 40±6 | L | 68±4 | L | L |
| 13 | 114±5 | 56±6 | 43±6 | 46±6 | 95±5 | 76±5 | 83±5 | 63±5 | 55±7 | 51±6 |
| 14 | 53±6 | 70±6 | 107±4 | 94±5 | 51±6 | 58±6 | 59±5 | 45±6 | 71±6 | L |
| 15 | 68±6 | 60±6 | 69±5 | 101±4 | 45±6 | 50±6 | 64±5 | 77±4 | 73±6 | 63±6 |
| 16 | 69±5 | 58±6 | 176±5 | 53±6 | L | 61±7 | 67±5 | L | 65±7 | 91±5 |
| 17 | 107±5 | 62±6 | 42±7 | 69±5 | 63±5 | 66±5 | 66±5 | 55±6 | 69±6 | 75±5 |
| 18 | 98±5 | 70±5 | 139±5 | 89±5 | 112±5 | 70±5 | 55±5 | 63±6 | 101±5 | 81±5 |
| 19 | 58±5 | 105±6 | 53±6 | 40±6 | 147±4 | L | L | L | 77±6 | 70±6 |
| 20 | 65±6 | 99±5 | 49±6 | 101±5 | 60±6 | 72±6 | 104±5 | 94±5 | 88±5 | 76±6 |
| 21 | 102±5 | 54±6 | L | L | L | 68±6 | 101±5 | 71±5 | 70±7 | 146±6 |
| 22 | 72±5 | L | 73±4 | 80±5 | 203±4 | 65±5 | 56±5 | 122±5 | L | 66±6 |
| 23 | 93±4 | 60±6 | 103±5 | 70±5 | L | 45±6 | 111±5 | L | 319±5 | 87±7 |
| 24 | 52±6 | 64±6 | 49±5 | 44±5 | 92±5 | 95±5 | L | 57±6 | 70±6 | 85±5 |
| 25 | 52±6 | 52±6 | 154±5 | 76±5 | 104±5 | 69±5 | 114±5 | 123±5 | 91±5 | 73±6 |
| 26 | L | 83±5 | 126±5 | 82±5 | 33±7 | 51±6 | 61±6 | 52±6 | 89±5 | L |
| 27 | 83±6 | 64±5 | L | 76±5 | 35±7 | 47±6 | 65±6 | 59±6 | 74±5 | L |
| 28 | 52±6 | 58±6 | 94±5 | 119±4 | L | 70±5 | 68±6 | 57±5 | L | 64±6 |
| 29 | 51±6 | 56±6 | 150±5 | 98±5 | 66±6 | L | 66±5 | 63±6 | 77±7 | 103±5 |
| 30 | 69±5 | 77±5 | 56±5 | 53±5 | 73±5 | 71±5 | 248±4 | 70±5 | 85±6 | 82±6 |
| 31 | 82±5 | 107±5 | 115±5 | 137±5 | 49±6 | 61±5 | 59±6 | 69±5 | 134±5 | 67±6 |
| 32 | L | L | L | L | 78±5 | 33±7 | 55±6 | 50±6 | 81±6 | 111±4 |
| 33 | 58±6 | 53±6 | 103±4 | 104±5 | 118±4 | 64±6 | 58±6 | 44±6 | 102±6 | 108±5 |
| 34 | 82±5 | 117±4 | 144±5 | 53±6 | 82±6 | 72±6 | 63±5 | 67±6 | 89±5 | 87±5 |
| 35 | 76±6 | 78±5 | 61±6 | 125±4 | 39±7 | 138±4 | 37±5 | 65±5 | 80±5 | 66±6 |
| 36 | 70±6 | 81±6 | 49±6 | L | 65±5 | L | 57±6 | 47±6 | 93±5 | 78±6 |
| 37 | 55±6 | 66±6 | | 89±5 | 119±4 | 77±5 | 58±5 | 51±7 | 103±5 | 96±5 |
| 38 | 54±6 | 50±7 | 151±5 | 112±4 | 49±6 | 70±5 | 62±5 | 46±6 | 81±5 | 51±6 |
| 39 | 69±5 | 62±5 | 101±4 | 71±5 | 77±5 | 71±6 | 72±5 | 54±6 | 86±6 | 75±6 |
| 40 | 238±5 | 116±5 | 173±5 | 102±5 | 113±4 | 47±7 | 139±5 | 69±5 | 79±6 | 72±7 |

Table 4.6: Weighted average indoor radon during the Winter season.

| House No. | Mohmand Winter | Charsadda Winter | Bajuar Winter | Swabi Winter | Mardan Winter |
|---|---|---|---|---|---|
| 1. | 118±5 | 86±6 | 122±5 | 117±4 | 51±6 |
| 2. | 66±5 | 73±6 | 47±6 | 57±5 | 70±5 |
| 3. | 116±5 | 72±7 | 73±5(D) | 62±6 | 64±5 |
| 4. | 99±5(D) | 57±7 | 130±5 | 58±5 | 169±4(B) |
| 5. | 107±3 | 81±6 | 99±5 | 65±6 | 82±5 |
| 6. | 80±6 | 66±6 | 71±5 | 84±5 | 132±5 |
| 7. | 59±5 | 82±6 | 88±5 | 58±6 | 55±6 |
| 8. | 80±5(D) | 62±6 | 126±5(D) | 122±5 | 145±4 |
| 9. | 75±6 | 56±6 | 83±5 | 89±5 | 61±5 |
| 10. | 25±6 | 87±6 | 105±5 | 95±5 | 127±5 |
| 11. | 72±6(B) | 62±6 | 187±5 | 77±5 | 69±6 |
| 12. | 80±5 | L | 78±5 | 49±6 | 68±4(D) |
| 13. | 91±5 | 53±7 | 44±6 | 87±5 | 75±5 |
| 14. | 60±6 | 71±6(B) | 102±4 | 54±6 | 53±5 |
| 15. | 65±6 | 69±6 | 82±5 | 47±6 | 69±5 |
| 16. | 65±5 | 75±6 | 127±5 | 61±7(D) | 67±5 |
| 17. | 89±5 | 71±7 | 53±6 | 64±5 | 66±5 |
| 18. | 87±5 | 93±5 | 119±5 | 95±5 | 58±5 |
| 19. | 77±5 | 74±6 | 48±6 | 147±4(B) | L |
| 20. | 79±6 | 83±5 | 70±6 | 65±6 | 100±5 |
| 21. | 83±5 | 100±7 | L | 68±6(D) | 89±5 |
| 22. | 72±5(B) | 66±6(D) | 76±4 | 148±4 | 82±5 |
| 23. | 80±5 | 226±6 | 90±5 | 45±6(D) | 111±5 |
| 24. | 57±6 | 76±6 | 47±5 | 93±5 | 57±6 |
| 25. | 52±6 | 84±5 | 123±5 | 90±5 | 114±5 |
| 26. | 83±5(D) | 89±5(B) | 108±5 | 40±7 | 57±6(D) |
| 27. | 75±6 | 74±5(B) | 76±5(D) | 40±7 | 63±6 |
| 28. | 54±6 | 64±6(D) | 104±5 | 70±5(D) | 64±6 |
| 29. | 53±6 | 87±6 | 129±5 | 66±6 | 65±5 |
| 30. | 72±5 | 84±6 | 55±5 | 72±5 | 177±4 |
| 31. | 92±5 | 107±5 | 124±5 | 54±6 | 63±6 |
| 32. | L | 93±5 | L | 60±5 | 53±6 |
| 33. | 56±6 | 104±6 | 103±4 | 96±5 | 52±6 |
| 34. | 96±5 | 88±5 | 108±5 | 78±6 | 65±5 |
| 35. | 77±6 | 74±5 | 87±5 | 79±6 | 48±5 |
| 36. | 74±6 | 87±5 | 49±5(B) | 65±5(B) | 53±6 |
| 37. | 59±6 | 100±5 | 89±5 | 102±4 | 55±6 |
| 38. | 52±6 | 69±5 | 135±5 | 57±6 | 56±5 |
| 39. | 66±5 | 82±6 | 89±5(D) | 75±5 | 65±5 |
| 40. | 189±5 | 76±6 | 145±5 | 87±5 | 111±5 |

In the Mardan district, radon concentration level varied from 24 ± 6 to 135 ± 5 Bq $m^{-3}$ and 25 ± 7 to 180 ± 5 Bq $m^{-3}$ in bedrooms and drawing rooms, respectively.

In Charsadda district this variation ranged from 45 ± 7 Bq $m^{-3}$ to 236 ± 4 Bq $m^{-3}$ and 36 ± 7 to 182 ± 5 Bq $m^{-3}$, respectively. According to the weighted average indoor radon in spring season ( table 4.8) in Mohmand agency varied from 33 ± 6 to 105 ± 5 Bq $m^{-3}$ while in Bajuar agency it varied from 39 ± 6 to 236 ± 5 Bq $m^{-3}$. As may be seen from table 4.8 the variation of indoor radon in the Mardan and Swabi districts were from 24 ± 6 to 109 ± 5 Bq$m^{-3}$ and 34 ± 6 to 124 ± 6 Bq $m^{-3}$, respectively. Maximum variation of radon occurred in Charsadda, which ranged from 44 ± 6 to 214 ± 4 Bq $m^{-3}$.

### 4.4. Yearly Minimum-Maximum Indoor Radon Concentration

Minimum and maximum indoor radon concentration levels observed in each district/agency for each season are shown in figure 4.1, as may be seen in this figure radon concentration levels in district Mardan vary from 21 ± 8 to 267 ± 4 Bq $m^{-3}$ in bedrooms and from 18 ± 6 to 180 ± 5 Bq $m^{-3}$ in drawing rooms respectively. In the district Swabi, the variation in the indoor radon concentration level ranged from 13 ± 6 to 203 ± 4 Bq $m^{-3}$ in bedrooms and from 26 ± 6 to 188 ± 4 Bq $m^{-3}$ in drawing rooms. In the district Charsadda indoor radon variations ranged from 32 ± 5 Bq.$m^{-3}$ to 323 ± 5 Bq $m^{-3}$ in bedrooms and from 28 ± 6 to 318 ± 5 Bq $m^{-3}$ in drawing rooms, respectively.

In the Mohmand agency, indoor radon concentration levels varied from 25 ± 6 to 246 ± 4 Bq $m^{-3}$ and from 22 ± 7 to 129 ± 5 Bq $m^{-3}$ in the bedrooms and drawing rooms, respectively. In the Bajuar agency, radon concentration level was found to vary from 29 ± 6 to 349 ± 5 Bq $m^{-3}$ and 27 ± 7 to 229 ± 5 Bq $m^{-3}$ in bedrooms and drawing room, respectively. Seasonal arithmetic and geometric mean and their respective standard deviations are shown in Figure 4.2.

District wise yearly average indoor radon levels are shown in Figure 4.3 whereas Figure 4.4 shows minimum and maximum values of the yearly average for each district. As may be seen in Figure 4.3, minimum yearly average for bedrooms is 69 ± 31 Bq $m^{-3}$ and for drawing rooms the mean values is 63 ± 20 Bq $m^{-3}$. Minimum yearly average value of 38 ± 7 Bq $m^{-3}$ was found in a bedroom of the Swabi district (see, Figure 4.4).

Table 4.7: Indoor radon levels in Bq $m^{-3}$ in bed rooms and drawing rooms of all houses surveyed in NWFP and FATA areas of Pakistan in Spring season.

| H. | Mohmand | | Bajuar | | Swabi | | Mardan | | Charsadda | |
|---|---|---|---|---|---|---|---|---|---|---|
| No | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room |
| 1 | 74±5 | 40±6 | 83±5 | 61±5 | 118±5 | 61±5 | 51±5 | 46±5 | 52±6 | 54±6 |
| 2 | 33±6 | 94±5 | 119±5 | 53±5 | 57±5 | 46±6 | 44±6 | 51±5 | L | 48±6 |
| 3 | 100±5 | 42±6 | 72±5 | 79±5 | 34±6 | 34±7 | 52±5 | 61±5 | 50±6 | 45±6 |
| 4 | 32±6 | 129±5 | 34±6 | 86±5 | 60±6 | 58±5 | L | L | 50±6 | 53±6 |
| 5 | 91±5 | 52±5 | 46±6 | 47±6 | 42±6 | 37±6 | 32±6 | 51±5 | 52±6 | 65±6 |
| 6 | 48±6 | 22±7 | 90±5 | 96±5 | 52±5 | 55±6 | 51±5 | 61±5 | 51±6 | 49±6 |
| 7 | 120±5 | L | 46±6 | 35±7 | 36±6 | L | 64±5 | 32±6 | 53±6 | 54±6 |
| 8 | 52±5 | 43±5 | 86±4 | 122±5 | 42±5 | 38±6 | L | L | L | 36±7 |
| 9 | 71±5 | 29±6 | 49±5 | 103±5 | 109±5 | 78±5 | 59±5 | 55±6 | 46±6 | 57±6 |
| 10 | 40±6 | 33±6 | 138±4 | 86±5 | 154±6 | 79±5 | 97±5 | 114±4 | 80±5 | 80±5 |
| 11 | 63±5 | L | 73±5 | 79±6 | 51±6 | 42±6 | 56±5 | 50±6 | L | 55±6 |
| 12 | 57±5 | 39±6 | 50±5 | L | 101±5 | 57±6 | L | 96±5 | L | L |
| 13 | 68±5 | 63±5 | 57±5 | 54±6 | 33±6 | 44±5 | 25±7 | 24±6 | 66±5 | 58±6 |
| 14 | L | 99±5 | L | 92±5 | 41±6 | 38±6 | 64±5 | 51±6 | 59±5 | 59±6 |
| 15 | 117±5 | 86±5 | 50±6 | 45±6 | 52±6 | 42±6 | 58±5 | 135±5 | 50±6 | 59±6 |
| 16 | 78±5 | 99±5 | 101±5 | 49±5 | 41±6 | 53±5 | 58±5 | 48±5 | 52±6 | 60±6 |
| 17 | L | L | 65±5 | 48±6 | 41±6 | 42±6 | 33±6 | 35±6 | 71±5 | 41±6 |
| 18 | 52±5 | 36±6 | 96±5 | L | 156±5 | 44±6 | 180±5 | 24±7 | 65±6 | 61±6 |
| 19 | 86±5 | 100±5 | 69±6 | 68±5 | 36±6 | 46±6 | 73±5 | L | 61±6 | 68±6 |
| 20 | 65±5 | 72±5 | 148±5 | 135±5 | L | 35±6 | 56±5 | 55±5 | L | 55±6 |
| 21 | 74±5 | 77±5 | 54±5 | 61±5 | 38±9 | 54±5 | 56±5 | 57±5 | 236±4 | 182±5 |
| 22 | 62±6 | 105±5 | 29±6 | 55±5 | 51±5 | 50±6 | L | L | 59±6 | 53±6 |
| 23 | 131±5 | L | 349±5 | 67±5 | L | 26±6 | 26±6 | 85±5 | 74±5 | 59±6 |
| 24 | 74±5 | 39±5 | 97±5 | 56±5 | 42±6 | 54±5 | 48±5 | 42±6 | 50±6 | 60±5 |
| 25 | 59±5 | 44±5 | L | 56±5 | 55±5 | 35±6 | L | 122±5 | 55±6 | 82±5 |
| 26 | 59±5 | 54±5 | 75±5 | 69±4 | 46±5 | 60±5 | L | 34±6 | 50±6 | 57±6 |
| 27 | 123±5 | 41±5 | 87±5 | 54±6 | L | L | 60±5 | 60±5 | 52±6 | 49±6 |
| 28 | 30±6 | 44±5 | 68±6 | 51±5 | 49±6 | 42±6 | 29±6 | 37±6 | 70±5 | 48±6 |
| 29 | 45±6 | L | 49±6 | 229±5 | 33±5 | L | 48±5 | 50±6 | 50±6 | 58±6 |
| 30 | 39±6 | 92±4 | 38±6 | 65±5 | 48±6 | 66±5 | 41±5 | 100±5 | 56±5 | 61±6 |
| 31 | 35±6 | 30±6 | L | L | 53±5 | 40±5 | 46±6 | 58±5 | 46±6 | 42±6 |
| 32 | L | 61±5 | 96±4 | 40±6 | 98±4 | 31±6 | 81±5 | 44±6 | 51±6 | 48±6 |
| 33 | 68±5 | L | 65±6 | 47±6 | 44±6 | 62±5 | L | 32±6 | 45±7 | 53±6 |
| 34 | 61±5 | 100±5 | L | 50±6 | 40±6 | 68±5 | 48±5 | 82±5 | 164±5 | 55±6 |
| 35 | 74±5 | 102±5 | 51±5 | 59±5 | 36±6 | 55±7 | 44±6 | 41±6 | 52±6 | 81±5 |
| 36 | 60±5 | 47±6 | 46±5 | 59±5 | 32±6 | 47±6 | 46±6 | 30±6 | 52±6 | 57±6 |
| 37 | 59±6 | 32±6 | 55±5 | 27±7 | 102±4 | 59±5 | 129±5 | 95±5 | 74±5 | 85±5 |
| 38 | 64±5 | 38±6 | 52±6 | 46±6 | 39±6 | L | 35±6 | L | 46±6 | 49±6 |
| 39 | L | 79±5 | 48±5 | 49±5 | L | 74±5 | 26±7 | 54±5 | 54±6 | 63±5 |
| 40 | 96±5 | 42±6 | 68±6 | 70±5 | 46±6 | 79±5 | 55±5 | 54±6 | 113±4 | 51±6 |

Table 4.8: Weighted average indoor radon in the Spring season.

| H.No | Mohmand | Charsadda | Bajuar | Swabi | Mardan |
|---|---|---|---|---|---|
| 1. | 60±5 | 53±6 | 74±5 | 63±6 | 48±5 |
| 2. | 57±6 | 48±6(D) | 93±5 | 72±5 | 48±5 |
| 3. | 77±5 | 48±6 | 75±5 | 97±5 | 57±5 |
| 4. | 71±6 | 51±6 | 55±6 | 89±5 | L |
| 5. | 75±5 | 57±6 | 46±6 | 90±5 | 43±5 |
| 6. | 38±6 | 50±6 | 92±5 | 82±4 | 57±5 |
| 7. | 120±5(D) | 53±6 | 42±6 | 77±5 | 45±6 |
| 8. | 48±5 | 36±7(D) | 100±4 | 64±5 | L |
| 9. | 54±5 | 50±6 | 71±5 | 122±4 | 57±6 |
| 10. | 37±6 | 80±5 | 117±4 | L | 107±4 |
| 11. | 38±5 | 55±6(D) | 75±5 | 70±5 | 52±6 |
| 12. | 50±5 | L | 50±5(B) | 81±4 | 96±5(B) |
| 13. | 66±5 | 63±5 | 56±5 | 83±4 | 24±6 |
| 14. | 99±5(D) | 59±5 | 92±5(D) | 72±5 | 56±6 |
| 15. | 105±5 | 54±6 | 48±6 | 58±6 | 104±5 |
| 16. | 86±5 | 55±6 | 80±5 | 85±5 | 48±5 |
| 17. | L | 59±5 | 58±5 | 120±5 | 35±6 |
| 18. | 46±5 | 63±6 | 96±5(B) | 85±5 | 86±6 |
| 19. | 92±5 | 64±6 | 69±6 | 94±5 | 73±5(D) |
| 20. | 68±5 | 55±6 | 143±5 | 76±5 | 55±5 |
| 21. | 75±5 | 214±4 | 57±5 | 109±4(B) | 57±5 |
| 22. | 79±6 | 57±6 | 39±6 | 74±5 | L |
| 23. | 131±5(B) | 68±5 | 236±5 | 74±5 | 61±5 |
| 24. | 60±5 | 54±6 | 81±5 | 67±6 | 44±5 |
| 25. | 53±5 | 66±6 | 56±5(D) | 65±5 | 122±5(B) |
| 26. | 57±5 | 53±6 | 73±5 | 65±5 | 34±6 |
| 27. | 90±5 | 51±6 | 74±5 | 54±5 | 60±5 |
| 28. | 36±6 | 61±5 | 61±6 | 112±5(D) | 34±6 |
| 29. | 45±6(B) | 53±6 | 121±6 | 85±5 | 49±6 |
| 30. | 60±5 | 58±5 | 49±6 | 84±5 | 76±5 |
| 31. | 33±6 | 44±6 | L | 84±5 | 53±5 |
| 32. | L | 50±6 | 74±5 | 55±5 | 59±6 |
| 33. | 56±5 | 48± | 58±6 | 67±5 | 32±6(B) |
| 34. | 77±5 | 120±5 | 50±6(D) | 63±6 | 68±5 |
| 35. | 85±5 | 64±6 | 54±5 | 140±5(D) | 42±6 |
| 36. | 55±5 | 54±6 | 51±5 | 66±5 | 36±6 |
| 37. | 60±6 | 78±5 | 44±6 | 114±5 | 109±5 |
| 38. | 51±5 | 47±6 | 50±6 | 81±5 | 35±6(D) |
| 39. | 79±5(D) | 58±6 | 48±5 | 88±5 | 43±6 |
| 40. | 74±5 | 88±5 | 69±6 | 53±6 | 54±6 |

In drawing rooms, a minimum value of 39 ± 5 Bq $m^{-3}$ was observed in the district Swabi as well as in the Mohmand agency. Maximum value of 207±5 Bq $m^{-3}$ was found in a bedroom of the Charsadda district. According to the weighted yearly average, a minimum value of 47 ± 5 Bq $m^{-3}$ was found in the Mohmand agency and a maximum value of 154 ± 5 Bq $m^{-3}$ was observed in the district Charsadda. Minimum and maximum weighted yearly average indoor radon came out to be 66 ± 27 and 83 ± 39 Bq $m^{-3}$ respectively. Overall arithmetic mean of the area surveyed in the present study was found to be 72 ± 32 Bq $m^{-3}$.

### 4.5. Seasonal Correction Factor

The seasonal correction factor was calculated by dividing the arithmetic mean, calculated for each cycle (i.e. summer, autumn, winter and spring seasons), by the annual arithmetic mean. The results obtained are shown in Figure 4.5. For bedrooms, the seasonal correction factor was found to be 1.15 ± 0.47, 0.87 ± 0.55, 0.92 ± 0.37 and 1.14 ±. 056 for spring, winter, autumn and summer seasons, respectively. For drawing rooms, the seasonal correction factor was found to be 1.14 ± 0.39, 0.91 ± 0.35, 0.89 ± 0.34 and 1.17 ± 0.39 for spring, winter, autumn and summer seasons, respectively. Overall seasonal weighted correction factor came out to be 1.15 ± 0.43, 0.89 ± 0.47, 0.91 ± 0.35, 1.15 ± 0.49 for spring, winter, autumn and summer seasons, respectively. The results show that there is a slight difference in the seasonal correction factor of the bedrooms and drawing rooms. Individual data values observed in different seasons show wide variations as compared to the average seasonal correction factor.

### 4.6. Seasonally Averaged and Yearly Averaged Indoor Radon

In order to know the affect on efficiency of these detectors, comparison of the seasonally measured average indoor radon concentration and the yearly exposed CR-39 detector was made. Whilst taking seasonal measurements, one detector was placed in the drawing rooms for one year. In this section, the data of only those detectors have been taken into account for which both the detectors in drawing rooms in all the four seasons and the yearly exposed detectors were recovered. Minimum, maximum and average indoor radon concentration levels observed in each district/agency for each season as well for the

yearly exposed CR-39 detectors are shown in table 4.9 whereas the individual values are shown in Figures 4.6 – 4.10.

Table 4.9: Minimum, maximum and average radon concentration levels in Bq $m^{-3}$ during the four seasons and yearly averaged exposed detectors in the NWFP and FATA.

| Location | | Summer | Autumn | Winter | Spring | Seasonal Average | Yearly Average |
|---|---|---|---|---|---|---|---|
| Swabi | Min | 26±6 | 33±5 | 45±5 | 31±5 | 39±5 | 23±5 |
| | Max | 79±5 | 138±4 | 188±4 | 120±5 | 110±5 | 92±6 |
| | Average | 50±14 | 68±20 | 79±30 | 58±22 | 64±13 | 50±15 |
| Mardan | Min | 18±6 | 60±5 | 45±6 | 25±7 | 46±7 | 27±5 |
| | Max | 81±4 | 126±5 | 146±6 | 180±5 | 90±5 | 92±6 |
| | Average | 43±15 | 74±13 | 68±22 | 58±32 | 61±11 | 49±15 |
| Charsadda | Min | 36±7 | 48±6 | 42±5 | 32±5 | 50±5 | 37±6 |
| | Max | 182±5 | 146±6 | 132±5 | 280±5 | 137±5 | 100±6 |
| | Average | 61±26 | 80±21 | 77±21 | 69±48 | 72±21 | 58±16 |
| Mohmand | Min | 22±7 | 50±7 | 39±6 | 23±6 | 39±6 | 32±5 |
| | Max | 129±5 | 117±4 | 147±4 | 107±4 | 94±5 | 156±4 |
| | Average | 64±30 | 76±21 | 73±23 | 57±18 | 68±15 | 61±31 |
| Bajuar | Min | 31±6 | 53±5 | 40±5 | 27±5 | 53±5 | 20±5 |
| | Max | 123±4 | 167±5 | 213±4 | 229±4 | 131±5 | 112±5 |
| | Average | 67±27 | 85±29 | 94±37 | 69±37 | 79±21 | 71±26 |

As may be seen in table 4.9, radon concentration levels vary from 39 ± 5 to 110 ± 5 Bq $m^{-3}$, with an average of 64 ± 13 Bq $m^{-3}$ and from 23 ± 5 to 92 ± 6 Bq $m^{-3}$ having an average of 50 ± 5 Bq $m^{-3}$ in the drawing rooms of the district Swabi using seasonally and yearly exposed CR-39 detectors, respectively.

In the district Mardan, radon concentration varied from 46 ± 7 to 90 ± 5 in the case of seasonally measured yearly values with an average 61 ± 11 Bq $m^{-3}$ and from 27 ± 5 to 92 ± 6 Bq $m^{-3}$ in the case where CR-39 were exposed for the year with an average of 49 ± 15 Bq $m^{-3}$. In the district Charsadda, variation in the indoor radon level range from 50 ± 5 to 137 ± 5 with an average of 72 ± 21 in the seasonally exposed CR-39 and from

37 ± 6 to 100 ± 6 Bq $m^{-3}$ having an average of 58 ± 16 Bq $m^{-3}$ in the yearly exposed CR-39 detectors, respectively.

In the Mohmand agency, variation in the indoor radon was found to range from 39 ± 6 - 94 ± 5 Bq $m^{-3}$ with an average of 68 ± 15, and in the range of 32 ± 5 to 156 ± 4 with an average of 61 ± 31 Bq $m^{-3}$ in the case of seasonally exposed and yearly exposed detectors, respectively. In the Bajuar agency, variations in the indoor radon ranged from 53 ± 5 Bq.$m^{-3}$ to 131 ± 5 Bq $m^{-3}$ in the case of seasonally exposed CR-39 detector with an average of 79 ± 21 Bq $m^{-3}$ whilst it varied from 20 ± 5 to 112 ± 5 Bq $m^{-3}$ having an average of 71 ± 26 Bq $m^{-3}$ for the yearly exposed detectors.

### 4.7. Comparison of Indoor Radon Levels in Bedrooms and Drawing Rooms

It would be informative to compare the indoor radon concentration levels observed in bedroom and drawing room of the same house. As mentioned earlier, all the dosimeters were installed on ground floor, and the houses surveyed were mainly detached type. Ratio of the radon level in the bedroom to that of radon level in the drawing room was determined. Results obtained are shown in table 4.10 In the Mohmand agency and Swabi district, no significant difference was observed in the radon levels in the bedrooms and drawing rooms in the summer season. In the Mardan districts, Bajuar agency and Charsadda districts, this ratio was found to be 1.4, 1.4 and 1.5, respectively. Radon levels were found to be relatively higher in bedrooms as compared to that in drawing rooms. This may be due to the ventilation system, because drawing rooms have usually better ventilation than that of bedrooms in houses of the areas studied. In summer season, largest fluctuation in the bedroom/drawing room ratio was found in the Charsadda district. The bedroom to drawing room ratio varied from 0.2 to 4.5.

In Autumn season, radon average levels in bedrooms and drawing rooms of the Mardan district and Mohmand agency were almost similar. The ratio varied from 0.6 - 2.2 and 0.4-1.7, respectively. In the Swabi it varied from 0.4 - 2.6 with an average of 1.2 whilst in the Charsadda district it varied from 0.6 - 3.3 with an average of 1.2. In the Bajuar agency, it varied from 0.5 - 2.5 with an average of 1.1. In the winter season only in the Mohmand agency this ratio was equal whilst in all the areas average radon in bedroom was 20% higher as compared to that in the drawing rooms.

Minimum ratio of 0.3 was observed in the Bajuar and Swabi and Maximum value of 3.7 was noted in the Charsadda district. In spring season, the average radon concentration in bedrooms was higher than that of the drawing rooms.

Table 4.10: Average ratio of the indoor radon levels in bedroom to drawing room in the selected area.

| Location | Quantity | Summer | Autumn | Winter | Spring | Average |
|---|---|---|---|---|---|---|
| Mardan | Minimum | 0.5 | 0.6 | 0.4 | 0.1 | 0.8 |
| | Maximum | 3.6 | 2.2 | 3.5 | 3.3 | 2.9 |
| | Average | 1.4 | 1.0 | 1.2 | 1.2 | 1.2 |
| Mohmand | Minimum | 0.4 | 0.4 | 0.4 | 0.3 | 0.6 |
| | Maximum | 2.2 | 1.7 | 1.8 | 4.0 | 2.3 |
| | Average | 1.1 | 1.0 | 1.0 | 1.1 | 1.0 |
| Swabi | Minimum | 0.3 | 0.4 | 0.3 | 0.6 | 0.5 |
| | Maximum | 2.1 | 2.6 | 3.1 | 3.6 | 2.0 |
| | Average | 1.0 | 1.2 | 1.2 | 1.2 | 1.2 |
| Bajuar | Minimum | 0.5 | 0.5 | 0.3 | 0.2 | 0.6 |
| | Maximum | 4.6 | 2.5 | 3.3 | 5.2 | 2.3 |
| | Average | 1.4 | 1.1 | 1.2 | 1.3 | 1.3 |
| Charsadda | Minimum | 0.2 | 0.6 | 0.5 | 0.6 | 0.8 |
| | Maximum | 4.5 | 3.3 | 3.7 | 3.0 | 2.6 |
| | Average | 1.5 | 1.2 | 1.2 | 1.1 | 1.2 |

A minimum ratio of 0.1 was observed in the district Mardan whilst maximum ratio of 5.2 was observed in the Bajuar agency. In general, this ratio shows that radon concentration in bedrooms is higher than that in the drawing rooms, respectively.

### 4.8. Dose Estimation

In order to estimate the annual mean effective dose H (mSv) expected to be received by the general public due to the radon and its progeny, ICRP 65 and UNSCEAR 2000 recommended conversion factors and the annual weighted average indoor radon levels were used. Initially, ICRP recommended occupancy factor of 0.8 was used to calculate the dose. The ICRP factor is higher than that of the average occupancy factor of the selected area (i.e., 0.48). Therefore, using the actual occupancy factor, the dose received

by the public will be ~ 40% lower than that if ICRP recommended conversion factor is used. The results obtained using actual occupancy factor are shown in table 4.11, which shows the mean values of the effective dose received due to the weighted average indoor radon levels. Using ICRP-65 conversion factor, minimum and maximum values of 0.34 ± 0.05 and 1.41 ± 0.05 mSv were obtained in Bajuar agency. UNSCEAR recommended factor yielded minimum and maximum values of 1.20 ± 0.17 and 4.97 ± 0.17 mSv, respectively. In the Swabi ICRP recommended factor yielded minimum and maximum values of 0.50 ± 0.06 and 1.10 ± 0.05 and where as UNSCEAR 2000 factor gave minimum and maximum values of 1.78 ± 0.21 and 3.89 ± 0.17 mSv, respectively.

In the Mohmand agency annual effective dose varied form 0.52 ± 0.06 to 1.33 ± 0.06 mSv and 1.82 ± 0.21 to 4.69 ± 0.19 mSv for ICRP and UNSCEAR conversion factors, respectively. In the district Mardan, annual effective dose showed variation from 0.33 ± 0.04 to 0.97 ± 0.04 using ICRP conversion factor whilst using UNSCEAR factor it varied from 1.47 ± 0.16 to 4.28 ± 0.16 mSv, respectively. In the Charsadda district variation in the dose was form 0.56 ± 0.06 to 1.59 ± 0.05 mSv and from 1.98 ± 0.20 to 5.59 ± 0.19 mSv in the cases of ICRP and UNSCEAR conversion factors, respectively.

Mean annual effective doses (see, table 4.12) were 0.70 ± 0.28, 0.46 ± 0.20, 0.79 ± 0.38, and 0.78 ± 0.32 and 0.85 ± 0.40 mSv for the Swabi, Mardan and Charsadda districts and Mohmand and Bajuar agency, respectively. The UNSCEAR 2000 conversion factor resulted in mean annual effective doses of 2.48 ± 1, 2.03 ± .89, 2.79 ± 1.33, 2.76 ± 1.12, 3.10 ±1.46 mSv in the Swabi, Mardan, Charsadda districts and Mohmand and Bajuar agencies, respectively.

### 4.9. Excess Lung Cancer Risk

In order to calculate the excess lung cancer risk, BEIR VI conversion factors were used (NRC, 1988; Lubin et al., 1994). U.S. National Research Council, BEIR VI committee modeled the excess relative risk (ERR) as a linear function of the past exposure to radon. This model allows the effect of exposure to vary flexibly with the length of time that has passed since the exposure, with the exposure rate, and with the attained age. The mathematical form of the model for ERR (NRC, 1999) is:

$$ERR = \beta (w_{5\text{-}14} + \theta_{15\text{-}24}\, w_{15\text{-}24} + \theta_{25+}\, w_{25+})\varphi_{age}\gamma_z \qquad (2)$$

The parameter β represents the slope of the exposure-risk relationship. Exposure in the last 5 years is excluded as it is not biologically relevant to the cancer risk—and exposures in 3 windows of past time, namely 5-14, 15-24, and 25 or more years previously is taken into account. Those exposures are labeled $w_{5\text{-}14}$, $w_{15\text{-}24}$, and $w_{25+}$, respectively and each is allowed to have its own relative level of effect, $\theta_{5\text{-}14}$ (set equal to unity), $\theta_{15\text{-}24}$, and $\theta_{25+}$, respectively. The rate of exposure also affects risk through the parameter $\gamma_z$; thus, the effect of a particular level of exposure increases with decreasing exposure rate, as indexed either by the duration of exposure or the average concentration at which exposure was received (Lubin et al., 1995).

Two alternative preferred models namely the "exposure-age-concentration model" and the "exposure-age-duration model" have been proposed by BEIR VI. In the present work excess lung cancer risk is calculated using the weighted average radon concentration and the "exposure-age-concentration model". Occupancy factor is the main parameter which affects the risk.

Therefore, local occupancy factor was used to calculate the risk. In order to make the comparison US EPA occupancy factor was also used. For calculation of excess lung cancer risk two age groups (i.e., 55 and 35 yr) were selected. An assumption was made that radon concentration over the years is same as measured in this study. The results are shown in table 4.13. Excess relative risk (ERR) variation in the Swabi district was form 0.31 ± 0.04 to 0.69 ± 0.03 for 35 yr age and for 55 yr inhabitants its values were 0.25 ± 0.03 to 0.55 ± 0.03, respectively. If US EPA conversion factor is used then these values comes out to be 0.36 ± 0.03 to 0.78 ± 0.03 and 0.29 ± 0.03 to 0.63 ± 0.03 for 35 and 55 yr age, respectively.

In the Mardan district, ERR varied from 0.26 ± 0.03 to 0.76 ± 0.03 for 35 yr of age and from 0.21 ± 0.03 to 0.61 ± 0.03 for 55 yr of age inhabitants, respectively. The US EPA conversion values yielded excess lung cancer from 0.36 ± 0.03 to 1.04 ± 0.03 and 0.29 ± 0.03 to 0.83 ± 0.03 for 35 and 55 yr age, respectively.

Table 4.11: Annual effective dose calculated using ICRP-65 and UNSCEAR-2000 conversion factor.

| Bajuar | | Swabi | | Mohmand | | Mardan | | Charsadda | |
|---|---|---|---|---|---|---|---|---|---|
| ICRP-65 | UNSCEAR | ICRP-65 | UNSCEAR | ICRP-65 | UNSCEAR | ICRP-65 | UNSCEAR | ICRP-65 | UNSCEAR |
| 1.11±0.05 | 3.91±0.17 | 0.86±0.05 | 3.03±0.19 | 0.82±0.06 | 2.90±0.20 | 0.33±0.04 | 1.47±0.16 | 0.70±0.05 | 2.47±0.19 |
| 0.77±0.05 | 2.72±0.19 | 0.65±0.05 | 2.28±0.19 | 0.61±0.06 | 2.17±0.21 | 0.43±0.04 | 1.88±0.16 | 0.68±0.06 | 2.41±0.20 |
| 0.77±0.05 | 2.73±0.18 | 0.65±0.06 | 2.28±0.20 | 0.87±0.05 | 3.06±0.19 | 0.42±0.03 | 1.86±0.15 | 0.64±0.06 | 2.26±0.21 |
| 0.99±0.05 | 3.51±0.18 | 0.68±0.05 | 2.39±0.19 | 0.73±0.06 | 2.57±0.20 | 0.97±0.04 | 4.28±0.16 | 0.66±0.06 | 2.33±0.20 |
| 0.76±0.05 | 2.68±0.18 | 0.68±0.06 | 2.39±0.21 | 0.81±0.06 | 2.86±0.20 | 0.42±0.04 | 1.87±0.16 | 1.13±0.06 | 3.97±0.20 |
| 0.81±0.05 | 2.85±0.18 | 0.67±0.05 | 2.35±0.18 | 1.05±0.06 | 3.71±0.20 | 0.57±0.04 | 2.51±0.16 | 0.62±0.06 | 2.20±0.20 |
| 0.77±0.05 | 2.71±0.18 | 0.59±0.06 | 2.07±0.20 | 0.69±0.06 | 2.44±0.21 | 0.38±0.04 | 1.69±0.17 | 0.85±0.06 | 3.00±0.20 |
| 1.26±0.05 | 4.44±0.17 | 0.70±0.06 | 2.48±0.19 | 0.56±0.06 | 1.96±0.20 | 0.87±0.04 | 3.82±0.16 | 0.82±0.06 | 2.89±0.20 |
| 0.98±0.05 | 3.46±0.17 | 1.08±0.05 | 3.81±0.17 | 0.61±0.06 | 2.14±0.21 | 0.43±0.04 | 1.88±0.16 | 0.61±0.06 | 2.15±0.21 |
| 1.40±0.05 | 4.94±0.17 | 0.92±0.05 | 3.24±0.19 | 0.52±0.06 | 1.82±0.21 | 0.69±0.04 | 3.05±0.17 | 1.02±0.06 | 3.60±0.20 |
| 1.18±0.05 | 4.16±0.18 | 0.70±0.05 | 2.48±0.19 | 0.71±0.06 | 2.51±0.20 | 0.40±0.04 | 1.79±0.16 | 0.74±0.06 | 2.60±0.21 |
| 0.66±0.05 | 2.33±0.19 | 0.70±0.05 | 2.49±0.19 | 0.73±0.06 | 2.57±0.20 | 0.47±0.04 | 2.07±0.16 | L | L |
| 0.51±0.05 | 1.79±0.20 | 0.65±0.05 | 2.30±0.18 | 0.84±0.05 | 2.96±0.18 | 0.36±0.04 | 1.58±0.15 | 0.79±0.06 | 2.80±0.20 |
| 0.75±0.05 | 2.65±0.17 | 0.55±0.06 | 1.93±0.20 | 0.74±0.06 | 2.59±0.20 | 0.40±0.04 | 1.77±0.16 | 0.66±0.05 | 2.33±0.19 |
| 0.82±0.05 | 2.91±0.18 | 0.55±0.06 | 1.96±0.21 | 0.78±0.06 | 2.75±0.20 | 0.47±0.04 | 2.09±0.16 | 0.65±0.06 | 2.30±0.21 |
| 0.84±0.05 | 2.96±0.20 | 0.95±0.05 | 3.34±0.19 | 0.76±0.06 | 2.67±0.19 | 0.42±0.03 | 1.86±0.15 | 0.69±0.06 | 2.44±0.20 |
| 0.85±0.05 | 3.01±0.18 | 0.68±0.05 | 2.40±0.19 | 1.33±0.06 | 4.69±0.19 | 0.35±0.04 | 1.53±0.15 | 0.70±0.06 | 2.46±0.20 |
| 0.98±0.05 | 3.47±0.19 | 0.89±0.05 | 3.14±0.19 | 0.64±0.06 | 2.25±0.20 | 0.49±0.04 | 2.16±0.16 | 0.93±0.05 | 3.28±0.19 |
| 0.82±0.05 | 2.88±0.19 | 0.86±0.05 | 3.04±0.19 | 0.99±0.05 | 3.50±0.19 | 0.41±0.03 | 1.81±0.15 | 0.65±0.06 | 2.31±0.20 |
| 1.08±0.05 | 3.80±0.19 | 0.63±0.05 | 2.21±0.19 | 0.77±0.06 | 2.72±0.20 | 0.55±0.04 | 2.42±0.16 | 0.76±0.05 | 2.67±0.18 |
| 0.62±0.05 | 2.20±0.17 | 0.73±0.06 | 2.57±0.21 | 0.90±0.06 | 3.17±0.20 | 0.45±0.04 | 2.00±0.16 | 1.32±0.05 | 4.67±0.19 |
| 0.66±0.05 | 2.33±0.17 | 0.85±0.05 | 3.00±0.18 | 0.82±0.05 | 2.91±0.19 | 0.51±0.04 | 2.23±0.15 | 0.66±0.05 | 2.32±0.19 |
| 1.29±0.05 | 4.55±0.17 | 0.55±0.05 | 1.95±0.19 | 1.12±0.05 | 3.97±0.18 | 0.45±0.03 | 2.01±0.14 | 1.59±0.05 | 5.59±0.19 |
| 0.71±0.05 | 2.51±0.16 | 0.64±0.06 | 2.25±0.20 | 0.65±0.06 | 2.28±0.20 | 0.41±0.04 | 1.82±0.16 | 0.68±0.05 | 2.41±0.18 |
| 1.41±0.05 | 4.97±0.17 | 0.62±0.06 | 2.20±0.19 | 0.59±0.06 | 2.08±0.22 | 0.56±0.04 | 2.45±0.17 | 0.70±0.06 | 2.48±0.20 |
| 0.34±0.05 | 1.20±0.17 | 0.50±0.06 | 1.78±0.21 | 0.98±0.05 | 3.45±0.18 | 0.35±0.03 | 1.54±0.16 | 0.56±0.06 | 1.98±0.20 |
| 0.79±0.05 | 2.78±0.18 | 0.55±0.06 | 1.94±0.20 | 0.87±0.05 | 3.07±0.19 | 0.41±0.03 | 1.81±0.15 | 0.74±0.05 | 2.60±0.19 |
| 0.97±0.05 | 3.41±0.18 | 0.56±0.06 | 1.98±0.20 | 0.62±0.06 | 2.19±0.20 | 0.39±0.04 | 1.72±0.16 | 0.65±0.05 | 2.31±0.19 |
| 1.24±0.05 | 4.37±0.18 | 0.65±0.06 | 2.29±0.19 | 0.65±0.06 | 2.28±0.21 | 0.45±0.04 | 1.98±0.17 | 0.86±0.06 | 3.02±0.20 |
| 0.57±0.05 | 2.00±0.20 | 0.67±0.05 | 2.35±0.19 | 0.71±0.06 | 2.52±0.20 | 0.80±0.04 | 3.52±0.16 | 0.70±0.06 | 2.45±0.21 |
| 0.78±0.05 | 2.76±0.18 | 0.61±0.06 | 2.14±0.20 | 0.73±0.06 | 2.56±0.21 | 0.40±0.04 | 1.76±0.16 | 0.76±0.05 | 2.70±0.19 |
| 0.99±0.05 | 3.48±0.19 | 0.62±0.05 | 2.20±0.18 | L | L | 0.40±0.03 | 1.76±0.15 | 0.76±0.05 | 2.69±0.19 |
| 0.84±0.05 | 2.95±0.18 | 0.67±0.06 | 2.37±0.20 | 0.75±0.06 | 2.63±0.20 | 0.37±0.04 | 1.65±0.16 | 0.79±0.06 | 2.77±0.19 |
| 0.72±0.05 | 2.55±0.19 | 0.68±0.06 | 2.41±0.21 | 0.90±0.06 | 3.19±0.19 | 0.52±0.03 | 2.30±0.15 | 0.87±0.05 | 3.08±0.18 |
| 0.81±0.05 | 2.84±0.18 | 0.70±0.06 | 2.48±0.22 | 0.80±0.06 | 2.81±0.20 | 0.37±0.04 | 1.62±0.16 | 0.78±0.05 | 2.77±0.19 |
| 0.59±0.05 | 2.08±0.18 | 0.61±0.06 | 2.16±0.20 | 0.75±0.06 | 2.65±0.21 | 0.35±0.04 | 1.54±0.16 | 0.86±0.05 | 3.03±0.19 |
| 0.62±0.05 | 2.18±0.18 | 1.10±0.05 | 3.89±0.17 | 0.64±0.06 | 2.26±0.21 | 0.47±0.04 | 2.05±0.17 | 0.91±0.05 | 3.20±0.18 |
| 0.80±0.05 | 2.82±0.19 | 0.63±0.05 | 2.22±0.19 | 0.64±0.06 | 2.28±0.21 | 0.37±0.04 | 1.64±0.16 | 0.63±0.06 | 2.23±0.20 |
| 0.78±0.05 | 2.77±0.17 | 0.67±0.06 | 2.36±0.20 | 0.78±0.06 | 2.75±0.18 | 0.35±0.03 | 1.56±0.14 | 0.65±0.06 | 2.29±0.19 |
| 0.93±0.05 | 3.28±0.18 | 0.71±0.06 | 2.52±0.19 | 1.08±0.06 | 3.80±0.20 | 0.47±0.04 | 2.09±0.16 | 0.82±0.06 | 2.90±0.20 |

Table 4.12: Mean effective dose in mSv expected to be received by the inhabitants of the area using ICRP-65 and UNSCEAR, 2000 conversion factors.

| S.No | Conversion Factor | Bed Room AM±SD | Drawing Room AM±SD | Bed Room GMG±GSD | Drawing Room GM±GSD | Overall Weighting AM±SD | Overall Weighted AM±SD |
|---|---|---|---|---|---|---|---|
| Charsadda | ICRP-65 | 0.83±. 44 | 0.72±.28 | 0.78±0.01 | 0.68±.01 | 0.79±.38 | 0.74±.01 |
| | UNSCEAR | 2.95±1.56 | 2.55±.98 | 2.74±.05 | 2.41±.05 | 2.79±1.33 | 2.61±.05 |
| Mardan | ICRP-65 | 0.48±.24 | 0.43±.15 | 0.44±.01 | 0.41±.01 | 0.46±.20 | 0.42±.01 |
| | UNSCEAR | 2.13±1.05 | 1.88±.65 | 1.94±.04 | 1.79±.04 | 2.03±.89 | 1.85±.04 |
| Swabi | ICRP-65 | 0.73±.33 | 0.66±.21 | 0.67±.02 | 0.63±.01 | 0.70±.28 | 0.65±.02 |
| | UNSCEAR | 2.57±1.17 | 2.34±.76 | 2.36±.06 | 2.24±.05 | 2.48±1 | 2.29±.05 |
| Mohmand | ICRP-65 | 0.81±.36 | 0.74±.26 | 0.75±.02 | 0.70±.01 | 0.78±.32 | 0.72±.02 |
| | UNSCEAR | 2.85±1.27 | 2.62±.90 | 2.64±.06 | 2.47±.05 | 2.76±1.12 | 2.54±.05 |
| Bajuar | ICRP-65 | 0.92±.44 | 0.80±.35 | 0.80±.02 | 0.74±.01 | 0.85±.40 | 0.77±.02 |
| | UNSCEAR | 3.23±1.60 | 2.90±1.26 | 2.92±.06 | 2.69±.05 | 3.10±1.46 | 2.79±.06 |
| Over all | ICRP-65 | 0.78±.38 | 0.70±.26 | 0.71±.01 | 0.66±.01 | 0.74±.33 | 0.69±.01 |
| | UNSCEAR | 2.75±1.34 | 2.46±.90 | 2.50±.05 | 2.32±.05 | 2.61±1.16 | 2.43±.05 |

In the Charsadda district the ERR values varied from 0.35 ± 0.03 to 0.99 ± 0.03 and 0.28 ± 0.03 to 0.79 ± 0.03 for 35 and 55 yr of age, respectively. However, for the EPA occupancy factor, these values varied form 0.41 ± 0.03 to 1.16 ± 0.03 and 0.33 ± 0.03 to 0.92 ± 0.03 for 35 and 55 yr of ages, respectively.

In the Mohmand agency, this variation was from 0.32 ± 0.04 to 0.83 ± 0.03 and from 0.26 ± 0.03 to 0.66 ± 0.03 for 35 and 55 yr ages respectively. For US EPA factor these values were 0.35 ± 0.04 - 0.91 ± 0.03 and 0.28 ± 0.03 to 0.73 ± 0.03 for 35 and 55 yr ages respectively. In the Bajuar agency, the excess lung cancer risk varied from 0.21 ± 0.03 to 0.89 ± 0.03 and 0. 17 ± 0.02 to 0.71 ± 0.03 for the area using the local occupancy factor whilst it varied from 0.24 ± 0.03 to 1.0 ± 0.03 and from 0.19 ± 0.03 to 0.80 ± 0.03 for the 35 and 55 yr age groups using US EPA occupancy factor, respectively. In general, using the US EPA occupancy factor the BEIR VI gave 14% (Swabi), 10% (Mohmand), 37% (Mardan) 17% (Charsadda) and 12% (Bajuar) higher excess lung cancer risk as compared to the use of local occupancy factor for each district /agency with an average of 18%.

## 4.10. Discussion

Indoor radon concentration annual arithmetic mean of the present study (72 ± 32 Bq $m^{-3}$) lies within the published values of the for different countries (see, UNSCEAR, 2000 and references quoted there in). Comparing the present data with the neighboring country India, the present values are higher than the values reported for Ammachal Pradesh (45 Bq $m^{-3}$), Asam (42 Bq $m^{-3}$), Mizoram (38 Bq $m^{-3}$) whilst it is lower than that reported for Megahalaya (68 Bq.$m^{-3}$) (Dwivedia et al., 2005). For Pakistan, higher value of the arithmetic mean of 111.34 Bq $m^{-3}$ has been reported for Skardu City, which is much higher than the mean value of the present study (Akram et al.,2005). Lower value of 31 Bq $m^{-3}$ is reported for the Bahawalpur Division (Matiullah et al., 2003). Variation in the indoor radon concentration level in the houses surveyed may mainly be due to the local geological formations on which the houses have been built as well as ventilation system of the surveyed houses. Keeping socio-economic conditions of the area surveyed, nothing can be done about the first factor. Therefore, to minimize the indoor radon level, better ventilation systems are needed to be incorporated in these houses. This study revealed that Charsadda district and Bajuar agency has relatively higher indoor radon levels.

Different countries/agencies have recommended different maximum permissible limits for the indoor radon concentration levels in domestic properties. If we compare our results with ICRP recommended maximum constraint limit of 600 Bq $m^{-3}$ (ICRP-65), EPA action level of 4 pCi.$\ell^{-1}$(148 Bq $m^{-3}$) or NRPB, UK limit of 200 Bq $m^{-3}$ (NRPB, 1990) it is clear that all yearly arithmetic mean values of all the districts/agencies are below the recommended limits of ICRP, NRPB, UK or US EPA limits.

Only in seven bedrooms of the houses, yearly average indoor radon greater than that of the US EPA limits whilst all the values of the indoor radon concentration in drawing rooms are within the limits. According to the weighted average indoor radon concentration data, only in one house exceeded the EPA limit, no value is higher than NRPB and ICRP limits.

Individual readings in different houses exceeded the US EPA or NRPB limits i.e. 3, 2, 4 and 2 drawing rooms in spring, winter, autumn and summer respectively exceeded the EPA limit whilst one drawing room in each season exceeded the NRPB limit.

Table 4.13: Excess relative risk of lung cancer due to the indoor radon in the selected areas.

| Bajuar | | Swabi | | Mohmand | | Mardan | | Charsadda | |
|---|---|---|---|---|---|---|---|---|---|
| Age 35 | Age 55 | Age 35 | Age 55 | Age 35 | Age 55 | Age 35 | Age 55 | Age 35 | Age 55 |
| 0.70± .03 | 0.56±0.02 | 0.53±0.03 | 0.43±0.03 | 0.51±0.04 | 0.41±0.03 | 0.26±0.03 | 0.21±0.02 | 0.44±0.03 | 0.35±0.03 |
| 0.49±0.03 | 0.39±0.03 | 0.40±0.03 | 0.32±0.03 | 0.38±0.04 | 0.30±0.03 | 0.34±0.03 | 0.27±0.02 | 0.43±0.04 | 0.34±0.03 |
| 0.49±0.03 | 0.39±0.03 | 0.40±0.03 | 0.32±0.03 | 0.54±0.03 | 0.43±0.03 | 0.33±0.03 | 0.26±0.02 | 0.40±0.04 | 0.32±0.03 |
| 0.63±0.03 | 0.50±0.03 | 0.42±0.03 | 0.34±0.03 | 0.45±0.04 | 0.36±0.03 | 0.76±0.03 | 0.61±0.02 | 0.41±0.04 | 0.33±0.03 |
| 0.48±0.03 | 0.38±0.03 | 0.42±0.04 | 0.34±0.03 | 0.50±0.04 | 0.40±0.03 | 0.33±0.03 | 0.27±0.02 | 0.71±0.04 | 0.56±0.03 |
| 0.51±0.03 | 0.41±0.03 | 0.41±0.03 | 0.33±0.03 | 0.65±0.04 | 0.52±0.03 | 0.45±0.03 | 0.36±0.02 | 0.39±0.04 | 0.31±0.03 |
| 0.49±0.03 | 0.39±0.03 | 0.37±0.04 | 0.29±0.03 | 0.43±0.04 | 0.34±0.03 | 0.30±0.03 | 0.24±0.02 | 0.53±0.04 | 0.42±0.03 |
| 0.80±0.03 | 0.64±0.03 | 0.44±0.03 | 0.35±0.03 | 0.35±0.03 | 0.28±0.03 | 0.68±0.03 | 0.54±0.02 | 0.51±0.04 | 0.41±0.03 |
| 0.62±0.03 | 0.50±0.02 | 0.67±0.03 | 0.54±0.02 | 0.38±0.04 | 0.30±0.03 | 0.34±0.03 | 0.27±0.02 | 0.38±0.04 | 0.30±0.03 |
| 0.89±0.03 | 0.71±0.02 | 0.57±0.03 | 0.46±0.03 | 0.32±0.04 | 0.26±0.03 | 0.55±0.03 | 0.44±0.02 | 0.64±0.03 | 0.51±0.03 |
| 0.75±0.03 | 0.60±0.03 | 0.44±0.03 | 0.35±0.03 | 0.44±0.03 | 0.35±0.03 | 0.32±0.03 | 0.25±0.02 | 0.46±0.04 | 0.37±0.03 |
| 0.42±0.03 | 0.33±0.03 | 0.44±0.03 | 0.35±0.03 | 0.45±0.03 | 0.36±0.03 | 0.37±0.03 | 0.30±0.02 | L | L |
| 0.32±0.04 | 0.26±0.03 | 0.41±0.03 | 0.32±0.03 | 0.52±0.03 | 0.42±0.03 | 0.28±0.03 | 0.23±0.02 | 0.50±0.04 | 0.40±0.03 |
| 0.47±0.03 | 0.38±0.02 | 0.34±0.04 | 0.27±0.03 | 0.46±0.04 | 0.37±0.03 | 0.32±0.03 | 0.25±0.02 | 0.41±0.03 | 0.33±0.03 |
| 0.52±0.03 | 0.42±0.03 | 0.34±0.04 | 0.28±0.03 | 0.49±0.03 | 0.39±0.03 | 0.37±0.03 | 0.30±0.02 | 0.41±0.04 | 0.33±0.03 |
| 0.53±0.04 | 0.42±0.03 | 0.59±0.03 | 0.47±0.03 | 0.47±0.03 | 0.38±0.03 | 0.33±0.03 | 0.27±0.02 | 0.43±0.04 | 0.35±0.03 |
| 0.54±0.03 | 0.43±0.03 | 0.42±0.03 | 0.34±0.03 | 0.83±0.03 | 0.66±0.03 | 0.27±0.03 | 0.22±0.02 | 0.44±0.03 | 0.35±0.03 |
| 0.62±0.03 | 0.50±0.03 | 0.55±0.03 | 0.44±0.03 | 0.40±0.04 | 0.32±0.03 | 0.39±0.03 | 0.31±0.02 | 0.58±0.03 | 0.46±0.03 |
| 0.52±0.03 | 0.41±0.03 | 0.54±0.03 | 0.43±0.03 | 0.62±0.03 | 0.49±0.03 | 0.32±0.03 | 0.26±0.02 | 0.41±0.04 | 0.33±0.03 |
| 0.68±0.03 | 0.54±0.03 | 0.39±0.03 | 0.31±0.03 | 0.48±0.04 | 0.38±0.03 | 0.43±0.03 | 0.35±0.02 | 0.47±0.03 | 0.38±0.03 |
| 0.40±0.03 | 0.32±0.02 | 0.45±0.04 | 0.36±0.03 | 0.56±0.03 | 0.45±0.03 | 0.36±0.03 | 0.29±0.02 | 0.83±0.03 | 0.66±0.03 |
| 0.42±0.03 | 0.33±0.02 | 0.53±0.03 | 0.42±0.03 | 0.51±0.03 | 0.41±0.03 | 0.40±0.03 | 0.32±0.02 | 0.41±0.03 | 0.33±0.03 |
| 0.82±0.03 | 0.65±0.02 | 0.34±0.03 | 0.27±0.03 | 0.70±0.03 | 0.56±0.03 | 0.36±0.03 | 0.29±0.02 | 0.99±0.03 | 0.79±0.03 |
| 0.45±0.03 | 0.36±0.02 | 0.40±0.04 | 0.32±0.03 | 0.40±0.03 | 0.32±0.03 | 0.32±0.03 | 0.26±0.02 | 0.43±0.03 | 0.34±0.03 |
| 0.89±0.03 | 0.71±0.02 | 0.39±0.03 | 0.31±0.03 | 0.37±0.04 | 0.29±0.03 | 0.44±0.03 | 0.35±0.02 | 0.44±0.03 | 0.35±0.03 |
| 0.21±0.03 | 0.17±0.02 | 0.31±0.04 | 0.25±0.03 | 0.61±0.03 | 0.49±0.03 | 0.28±0.03 | 0.22±0.02 | 0.35±0.03 | 0.28±0.03 |
| 0.50±0.03 | 0.40±0.03 | 0.34±0.04 | 0.27±0.03 | 0.54±0.03 | 0.43±0.03 | 0.32±0.03 | 0.26±0.02 | 0.46±0.03 | 0.37±0.03 |
| 0.61±0.03 | 0.49±0.03 | 0.35±0.04 | 0.28±0.03 | 0.39±0.04 | 0.31±0.03 | 0.31±0.03 | 0.24±0.02 | 0.41±0.03 | 0.33±0.03 |
| 0.78±0.03 | 0.63±0.03 | 0.40±0.03 | 0.32±0.03 | 0.40±0.04 | 0.32±0.03 | 0.35±0.03 | 0.28±0.02 | 0.54±0.04 | 0.43±0.03 |
| 0.36±0.04 | 0.29±0.03 | 0.41±0.03 | 0.33±0.03 | 0.44±0.03 | 0.35±0.03 | 0.63±0.03 | 0.50±0.02 | 0.44±0.04 | 0.35±0.03 |
| 0.49±0.03 | 0.39±0.03 | 0.38±0.04 | 0.30±0.03 | 0.45±0.04 | 0.36±0.03 | 0.31±0.03 | 0.25±0.02 | 0.48±0.03 | 0.38±0.03 |
| 0.62±0.03 | 0.50±0.02 | 0.39±0.03 | 0.31±0.03 | L | L | 0.32±0.03 | 0.25±0.02 | 0.48±0.03 | 0.38±0.03 |
| 0.53±0.03 | 0.42±0.03 | 0.42±0.03 | 0.33±0.03 | 0.46±0.04 | 0.37±0.03 | 0.30±0.03 | 0.24±0.02 | 0.49±0.03 | 0.39±0.03 |
| 0.46±0.03 | 0.36±0.03 | 0.43±0.04 | 0.34±0.03 | 0.56±0.03 | 0.45±0.03 | 0.41±0.03 | 0.33±0.02 | 0.55±0.03 | 0.44±0.03 |
| 0.51±0.03 | 0.41±0.03 | 0.44±0.04 | 0.35±0.03 | 0.50±0.03 | 0.40±0.03 | 0.29±0.03 | 0.23±0.02 | 0.49±0.03 | 0.39±0.03 |
| 0.37±0.03 | 0.30±0.03 | 0.38±0.04 | 0.30±0.03 | 0.47±0.04 | 0.37±0.03 | 0.27±0.03 | 0.22±0.02 | 0.54±0.03 | 0.43±0.03 |
| 0.39±0.03 | 0.31±0.03 | 0.69±0.03 | 0.55±0.02 | 0.40±0.04 | 0.32±0.03 | 0.37±0.03 | 0.29±0.02 | 0.57±0.03 | 0.45±0.03 |
| 0.51±0.03 | 0.40±0.03 | 0.39±0.03 | 0.31±0.03 | 0.40±0.04 | 0.32±0.03 | 0.29±0.03 | 0.23±0.02 | 0.40±0.04 | 0.32±0.03 |
| 0.50±0.03 | 0.40±0.02 | 0.42±0.03 | 0.33±0.03 | 0.48±0.03 | 0.39±0.03 | 0.28±0.03 | 0.22±0.02 | 0.41±0.03 | 0.32±0.03 |
| 0.59±0.03 | 0.47±0.03 | 0.44±0.03 | 0.35±0.03 | 0.67±0.03 | 0.54±0.03 | 0.37±0.03 | 0.30±0.02 | 0.52±0.03 | 0.41±0.03 |

Indoor radon in 4, 16, 4 and 9 bedrooms in different houses exceeded EPA limit in the spring, winter, autumn and summer season respectively. One drawing room data in each season exceeded the NRPB limit. Weighted average results in lesser fluctuation in the indoor radon concentration and no value exceeded the ICRP or NRPB limit and only few values are higher than US EPA limits. There is no available data indicating the seasonal variation of radon levels in this locality, therefore, the values obtained may provide a basis for the future studies. Other workers or groups have noted that the indoor radon levels are inversely related to the outside temperature, which was also found to be true in the present study. In a study carried out in UK, Pinel et al.1995, has reported seasonal correction factor which has similar trend as reported in this work.

Analysis of the annual averages of the data show that weighted average indoor radon has relatively lesser fluctuations as compared to the individual values. Radon levels showed wide variations measured in different seasons of the year. Highest and lowest indoor radon levels were observed in winter and summer seasons, respectively. From the observed indoor radon levels, seasonal correction factor was calculated and compared with the correction factors reported for other countries of the world. For example, Grainger et al., 2000, have reported seasonal correction factors of 1.17 and 0.85 for summer and winter in the Isle of Man, UK. Their results are in agreement with the seasonal factor derived in the present study. For France, Baysson et al., 2003 have reported seasonal correction factors of 0.93, 0.99, 1.075 and 0.99 for winter, spring, summer and autumn, respectively. The data of Baysson et al., 2003 show different trend compared with the present results. The results of Pinel et al. 1995 and UKCCS, 2000 agree well in winter with the values of the current study. The data reported by Matiullah et al., 2003 and Mishra et al., 2004 also show similar trend as that of the present data.

Highest seasonal correction factors of 1.33 ± 0.3 and 1.32 ± 0.47 were found for drawing rooms and bedrooms in the Mardan and Swabi districts in the summer season, respectively which is ~18% higher than the overall seasonal correction factor. Seasonal correction factor is higher in spring and summer seasons and lower in winter and autumn seasons. Although there are different average values of the indoor radon and seasonal correction factor for bedroom and drawing rooms yet this difference is not statistically

significant. Weighted average values of the present study revealed that Bajuar agency has relatively higher indoor radon levels as compared to the other districts/agency.

Comparison of the results of the yearly and seasonally exposed detector indicate that in the district Swabi, out of 30 values, in twenty-five drawing rooms the yearly averaged value was lower than the seasonally obtained average values. The individual values in each drawing room show fluctuations. Nevertheless, yearly exposed detectors gave value which were 23% lower than the seasonally measured values. In the district Mardan, 19 out of 25 in drawing rooms seasonally measured average radon was higher as compared to the yearly averaged indoor radon levels. The seasonally averaged value is ~19% higher than the yearly measured indoor radon levels in Mardan.

In the district Charsadda, out of 29 drawing rooms only two yearly exposed CR-39 detectors yielded indoor radon levels higher than the seasonally measured values. In general, the yearly average values were ~25% lower than the seasonally measured average values. In the Mohmand agency in 18 out of 27 drawing rooms, seasonally measured values were higher than the yearly measured values. In this agency, yearly values were on the average ~10% lower than the seasonally measured values. In the Bajuar agency, a similar trend was observed.

The reason of relatively lower yearly indoor radon levels may partially be due to the fact that a layer of dust may be settled on the surface of the CR-39 there by reducing the track registration efficiency of CR-39 because some of the alpha particles may loose its energy in the dead layer of the dust above the CR-39 detectors which in turn results in lower indoor radon levels. It has been shown (Homer and Miles,1986) that heat and humidity in the presence of oxygen in the air can affect the sensitivity of the etched-track detector during their use to measure radon. The magnitude of the effect depends on the detector materials, the etching conditions and counting techniques. In one study (Wrixon et al., 1988), it has been reported that when tracks in CR-39 were counted using a semi-automatic system, the sensitivity of the etched track detector was reduced by 18% during the exposure of 6 months, resulting in an average sensitivity, which was lower 9% lower than that of the initially measured sensitivity. Corrections of such an effect must be taken into account in calculating the of radon concentrations.

As mentioned earlier, different countries/agencies have recommended different maximum permissible limits for indoor radon concentration level. For example, ICRP recommends a maximum constraint limit of 600 Bq $m^{-3}$ (ICRP-65), EPA action level is 4 $pCi.\ell^{-1}$ (148 Bq $m^{-3}$) and Health Protection agency, UK follow a limit of 200 Bq $m^{-3}$ (NRPB, 1987 and 1990) for indoor radon level (domestic properties). It is worth mentioning here that Pakistan Nuclear Regulatory Authority (PNRA) is responsible for defining radiation exposure limits for occupational radiation workers and general population. Generally, ICRP recommended limits are adopted by the PNRA in Pakistan. However, so far, no limits have been defined for indoor radon concentration levels by the PNRA. Like other countries of the world, PNRA has also to define indoor radon exposure limits at some stage. In this regard, environmental conditions and economic conditions, etc. of Pakistan have to be taken into consideration. It is suggested that the value recommended by the ICRP may be adopted in this regard. However, for this purpose, extensive indoor radon monitoring is necessary to map the country to generate baseline data.

### 4.11. Conclusions

To conclude, indoor radon levels have been measured in some districts of the NWFP which included Swabi, Mardan and Charsadda as well the Mohmand and Bajuar Agencies of FATA. From the measured indoor radon levels, annual effective doses were calculated. All of the houses surveyed had indoor radon levels with in permissible level when ICRP recommended limit of 600 Bq $m^{-3}$ was used. Few houses had higher radon levels if NRPB (Health Protection agency) UK and US (environmental protection agency) EPA limits of 200 and 148 Bq $m^{-3}$ were used. There is a higher fluctuation during the summer (by a factor of 5 in one case) in the indoor radon levels on the same floor in different rooms of the same house. However it may be mentioned here that Pakistan has variable geologies and climatic conditions. It is, therefore, suggested that an extensive study of the indoor radon levels through out the country may be initiated. Seasonal correction factor has been calculated and compared with the correction factors reported for other countries of the world. Maximum indoor radon concentration levels have been observed in the winter whereas minimum concentration levels were found in the summer season. The indoor radon levels have been found to depend on the season of

the year and therefore seasonal correction factor has to be applied in calculating the annual mean radon concentration from the measured data. The dose has to be calculated using local occupancy factor. Seasonally measured average values are higher as compared to the yearly exposed CR-39 detectors. Long term exposure of CR-39 reduces its results in reduced track registration efficiency duce to the formation of a layer of non radioactive dust over the surface of the detectors. Seasonally measured values are ~13% higher than the yearly measured values.

After the detailed analysis of indoor radon and its spatial and temporal variations in the next chapter experiments about the radon exhalation rate has been discussed.

Table 4.14: Yearly average indoor radon in the bedrooms and drawing rooms of the selected area.

| H. No | Mohmand | | Bajuar | | Mardan | | Swabi | | Charsadda | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room | Bed Room | Drawing Room |
| 1. | 81±5 | 65±5 | 114±4 | 90±4 | 44±5 | 53±6 | 96±5 | 59±5 | 76±5 | 55±6 |
| 2. | 52±5 | 62±5 | 86±5 | 53±5 | 64±5 | 56±6 | 67±5 | 51±5 | 72±5 | 57±6 |
| 3. | 93±4 | 57±5 | 72±5 | 75±5 | 69±5 | 47±5 | 59±5 | 64±5 | 68±6 | 54±5 |
| 4. | 47±6 | 94±5 | 93±5 | 94±5 | 187±5 | 66±5 | 68±5 | 59±5 | 68±6 | 57±5 |
| 5. | 83±5 | 59±5 | 77±5 | 63±5 | 64±4 | 55±5 | 66±6 | 61±5 | 133±6 | 74±5 |
| 6. | 108±5 | 77±5 | 77±5 | 75±5 | 76±5 | 90±5 | 57±5 | 72±5 | 58±5 | 64±5 |
| 7. | 68±5 | 55±6 | 78±5 | 64±5 | 53±4 | 57±5 | 52±5 | 60±5 | 77±6 | 90±5 |
| 8. | 43±5 | 62±5 | 110±4 | 131±5 | 150±5 | 84±5 | 70±5 | 62±5 | 99±5 | 50±6 |
| 9. | 61±5 | 46±6 | 71±4 | 124±5 | 65±5 | 55±5 | 117±4 | 79±5 | 64±5 | 51±6 |
| 10. | 44±5 | 50±6 | 133±4 | 130±5 | 109±6 | 84±6 | 97±±5 | 72±5 | 74±6 | 137±5 |
| 11. | 65±5 | L | 111±5 | 111±5 | 50±5 | 70±5 | 72±5 | 58±5 | 82±6 | 56±6 |
| 12. | 70±5 | 60±5 | 64±5 | 59±6 | 71±5 | 62±4 | 72±5 | 58±5 | L | L |
| 13. | 89±4 | 58±5 | 48±5 | 48±6 | 52±5 | 51±5 | 66±5 | 55±5 | 93±6 | 52±6 |
| 14. | 61±5 | 75±5 | 68±4 | 75±5 | 59±5 | 55±5 | 50±5 | 54±5 | 62±5 | 67±5 |
| 15. | 77±5 | 61±5 | 86±5 | 65±5 | 72±5 | 61±5 | 51±6 | 54±5 | 64±6 | 62±6 |
| 16. | 64±5 | 75±5 | 98±5 | 50±6 | 60±5 | 61±5 | 99±5 | 75±6 | 65±6 | 70±5 |
| 17. | 148±5 | 80±5 | 87±5 | 70±5 | 56±5 | 41±6 | 51±5 | 85±5 | 66±5 | 70±5 |
| 18. | 56±5 | 61±5 | 104±5 | 76±5 | 58±6 | 88±5 | 93±5 | 70±5 | 85±5 | 98±5 |
| 19. | 88±5 | 93±5 | 73±5 | 83±5 | 48±5 | 74±5 | 94±5 | 62±5 | 60±6 | 69±5 |
| 20. | 65±6 | 77±5 | 98±5 | 107±5 | 81±5 | 76±5 | 62±5 | 55±5 | 74±5 | 72±6 |
| 21. | 83±5 | 79±5 | 63±4 | 53±5 | 70±5 | 57±5 | 78±6 | 55±5 | 129±5 | 127±5 |
| 22. | 73±5 | 77±5 | 61±5 | 64±4 | 63±5 | 87±5 | 91±5 | 65±5 | 65±5 | 62±5 |
| 23. | 115±4 | 82±5 | 152±5 | 75±5 | 72±5 | 55±5 | 56±5 | 47±5 | 207±5 | 75±6 |
| 24. | 60±5 | 56±5 | 67±5 | 67±4 | 55±5 | 65±5 | 58±6 | 63±5 | 71±5 | 59±5 |
| 25. | 54±5 | 53±6 | 173±5 | 72±4 | 83±5 | 74±5 | 64±5 | 51±5 | 71±5 | 64±6 |
| 26. | 90±5 | 88±5 | L | 80±4 | 50±5 | 51±5 | 43±6 | 55±5 | 61±5 | 45±6 |
| 27. | 92±5 | 59±5 | 82±5 | 63±5 | 61±6 | 55±5 | 54±6 | 49±5 | 75±5 | 66±5 |
| 28. | 57±5 | 56±5 | 106±5 | 69±5 | 58±6 | 53±6 | 43±6 | 69±5 | 68±5 | 57±6 |
| 29. | 50±6 | 71±5 | 107±5 | 131±5 | 65±5 | 63±5 | 68±5 | 51±5 | 84±6 | 82±5 |
| 30. | 56±5 | 78±5 | 51±5 | 57±5 | 149±6 | 62±5 | 60±5 | 67±5 | 68±6 | 67±6 |
| 31. | 66±5 | 66±5 | 70±5 | 79±5 | 58±6 | 56±5 | 55±5 | 60±6 | 86±5 | 56±5 |
| 32. | L | L | 95±4 | 89±5 | 53±6 | 64±5 | 72±5 | 39±5 | 74±5 | 74±5 |
| 33. | 75±5 | 56±6 | 81±5 | 74±5 | 54±5 | 52±6 | 66±5 | 60±6 | 70±6 | 86±5 |
| 34. | 79±5 | 86±5 | 81±5 | 49±5 | 82±5 | 63±5 | 62±6 | 69±5 | 96±5 | 67±5 |
| 35. | 65±5 | 83±5 | 66±5 | 91±4 | 51±6 | 55±5 | 38±7 | 110±5 | 75±5 | 78±5 |
| 36. | 66±5 | 71±6 | 47±5 | 68±4 | 50±5 | 50±6 | 67±5 | 44±6 | 91±5 | 71±6 |
| 37. | 58±6 | 58±5 | 56±5 | 62±5 | 66±5 | 67±6 | 121±4 | 79±5 | 88±5 | 88±5 |
| 38. | 71±5 | 39±6 | 83±5 | 64±5 | 57±5 | 47±6 | 56±5 | 65±5 | 64±6 | 58±6 |
| 39. | 74±4 | 66±5 | 80±4 | 65±5 | 53±6 | 46±6 | 57±5 | 71±5 | 67±5 | 56±5 |
| 40. | 113±5 | 75±5 | 94±5 | 77±5 | 73±5 | 61±5 | 71±5 | 62±5 | 89±5 | 66±6 |

Table 4.15: Weighted average indoor radon levels in the NWFP and FATA, Pakistan.

| H. No | Mohmand | Swabi | Mardan | Charsadda | Bajuar |
|---|---|---|---|---|---|
| 1. | 75±5 | 81±5 | 48±5 | 68±5 | 104±4 |
| 2. | 56±5 | 61±5 | 61±5 | 66±5 | 73±5 |
| 3. | 79±5 | 61±5 | 60±5 | 62±6 | 73±5 |
| 4. | 66±5 | 64±5 | 139±5 | 64±6 | 94±5 |
| 5. | 74±5 | 64±6 | 61±5 | 109±5 | 71±5 |
| 6. | 95±5 | 63±5 | 81±5 | 60±5 | 76±5 |
| 7. | 63±5 | 55±5 | 55±5 | 82±6 | 72±5 |
| 8. | 50±5 | 66±5 | 124±5 | 79±6 | 118±4 |
| 9. | 55±5 | 102±5 | 61±5 | 59±6 | 92±4 |
| 10. | 47±5 | 87±5 | 99±5 | 99±5 | 132±4 |
| 11. | 65±5 | 66±5 | 58±5 | 72±6 | 111±5 |
| 12. | 66±5 | 67±5 | 67±5 | L | 62±5 |
| 13. | 76±5 | 62±5 | 51±5 | 77±6 | 48±5 |
| 14. | 67±5 | 52±5 | 57±5 | 64±5 | 71±4 |
| 15. | 71±5 | 52±6 | 68±5 | 63±6 | 78±5 |
| 16. | 69±5 | 89±5 | 60±5 | 67±6 | 79±5 |
| 17. | 121±5 | 64±5 | 50±5 | 68±5 | 80±5 |
| 18. | 58±5 | 84±5 | 70±6 | 90±5 | 92±5 |
| 19. | 90±5 | 81±5 | 59±5 | 63±6 | 77±5 |
| 20. | 70±5 | 59±5 | 79±5 | 73±5 | 101±5 |
| 21. | 81±5 | 69±6 | 65±5 | 128±5 | 59±4 |
| 22. | 75±5 | 80±5 | 72±5 | 64±5 | 62±5 |
| 23. | 102±5 | 52±5 | 65±5 | 154±5 | 121±5 |
| 24. | 59±5 | 60±5 | 59±5 | 66±5 | 67±4 |
| 25. | 53±6 | 59±5 | 79±5 | 68±5 | 132±4 |
| 26. | 89±5 | 48±6 | 50±5 | 54±5 | 32±4 |
| 27. | 79±5 | 52±5 | 59±6 | 71±5 | 74±5 |
| 28. | 56±5 | 53±5 | 56±6 | 63±5 | 91±5 |
| 29. | 59±5 | 61±5 | 64±5 | 83±6 | 117±5 |
| 30. | 65±5 | 63±5 | 114±6 | 67±6 | 53±5 |
| 31. | 66±5 | 57±5 | 57±6 | 74±5 | 73±5 |
| 32. | L | 59±5 | 57±5 | 74±5 | 93±4 |
| 33. | 68±6 | 63±5 | 54±5 | 76±5 | 79±5 |
| 34. | 82±5 | 65±6 | 74±5 | 85±5 | 68±5 |
| 35. | 72±5 | 66±6 | 53±5 | 76±5 | 76±5 |
| 36. | 68±5 | 58±5 | 50±5 | 83±5 | 55±5 |
| 37. | 58±6 | 104±4 | 67±5 | 88±5 | 58±5 |
| 38. | 59±5 | 60±5 | 53±5 | 61±6 | 75±5 |
| 39. | 71±5 | 63±5 | 50±6 | 63±5 | 74±5 |
| 40. | 98±5 | 67±5 | 68±5 | 80±5 | 87±5 |

Figure 4.1: Minimum and maximum radon concentration levels in each season in the listed areas of the NWFP and FATA.

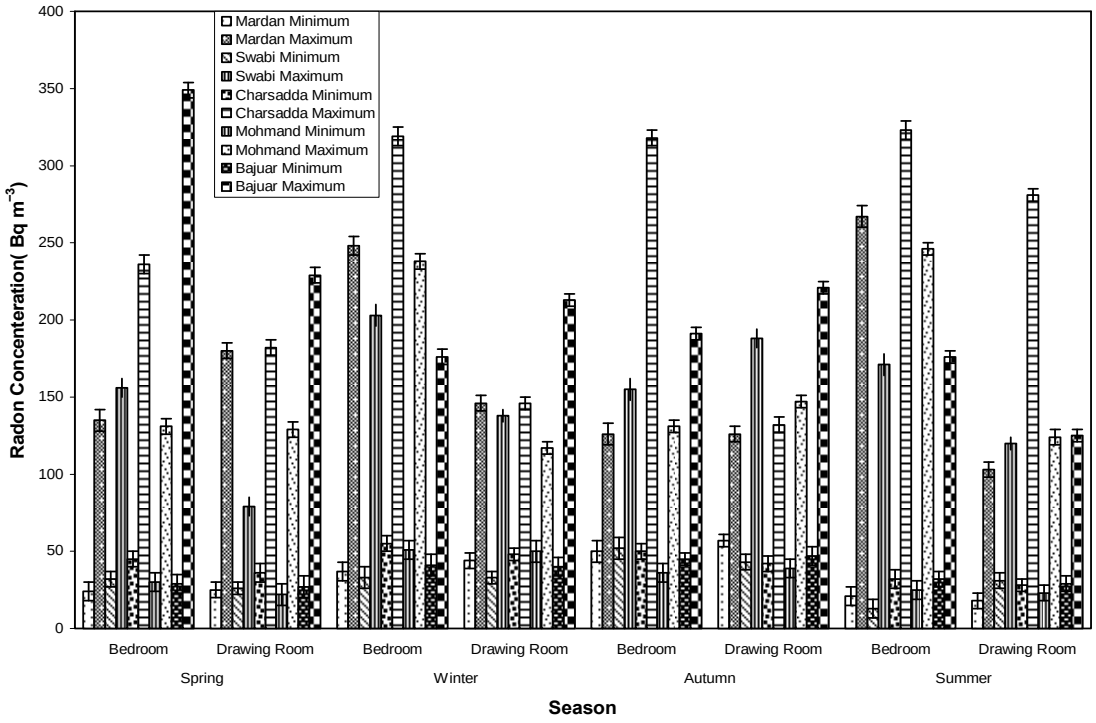



Figure 4.2: Mean seasonal indoor radon concentration in the listed areas of the NWFP and FATA, Pakistan.

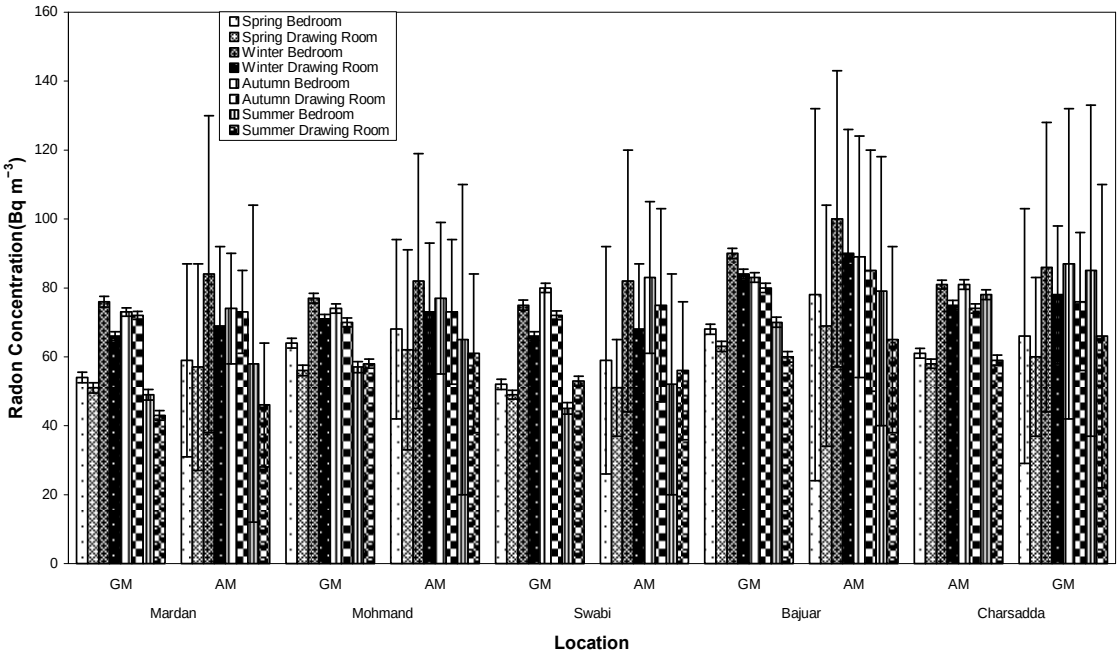


Figure 4.3: Yearly average radon concentration levels in NWFP and FATA.

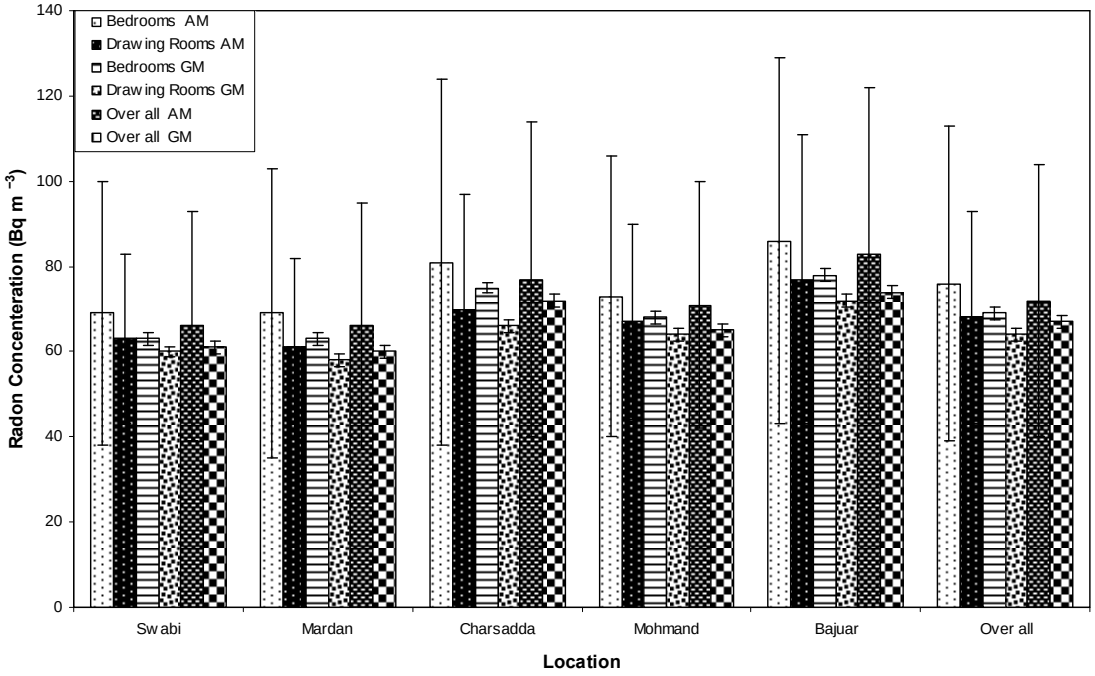



Figure 4.4: Yearly average minimum and maximum indoor radon concentration levels in Bq $m^{-3}$ in bedrooms and drawing rooms of the area selected.

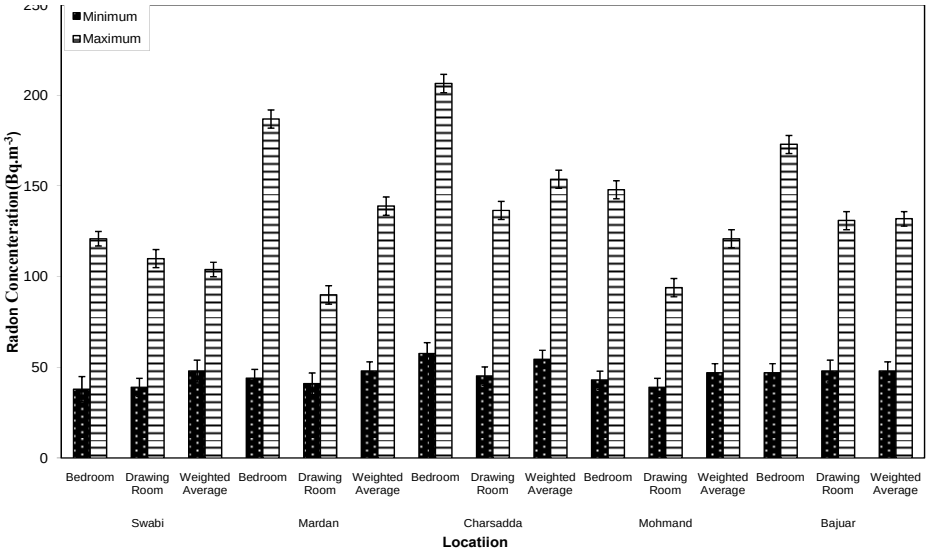


Figure 4.5: Seasonal correction factor for the listed areas of NWFP and FATA.

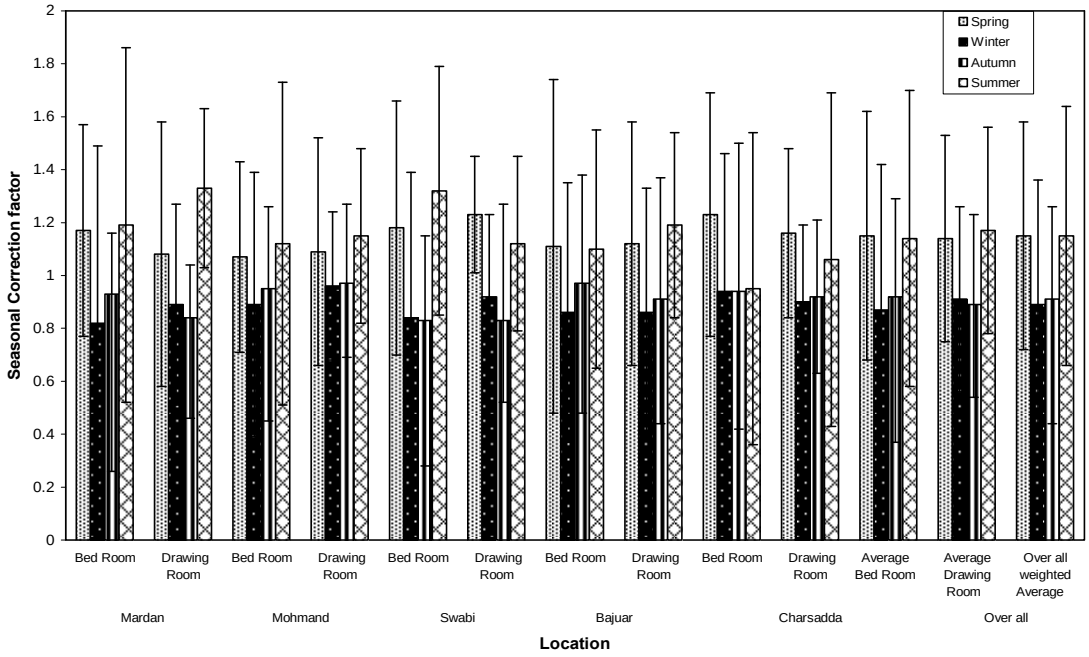



Figure 4.6: Yearly and seasonally averaged yearly radon levels in Swabi district.

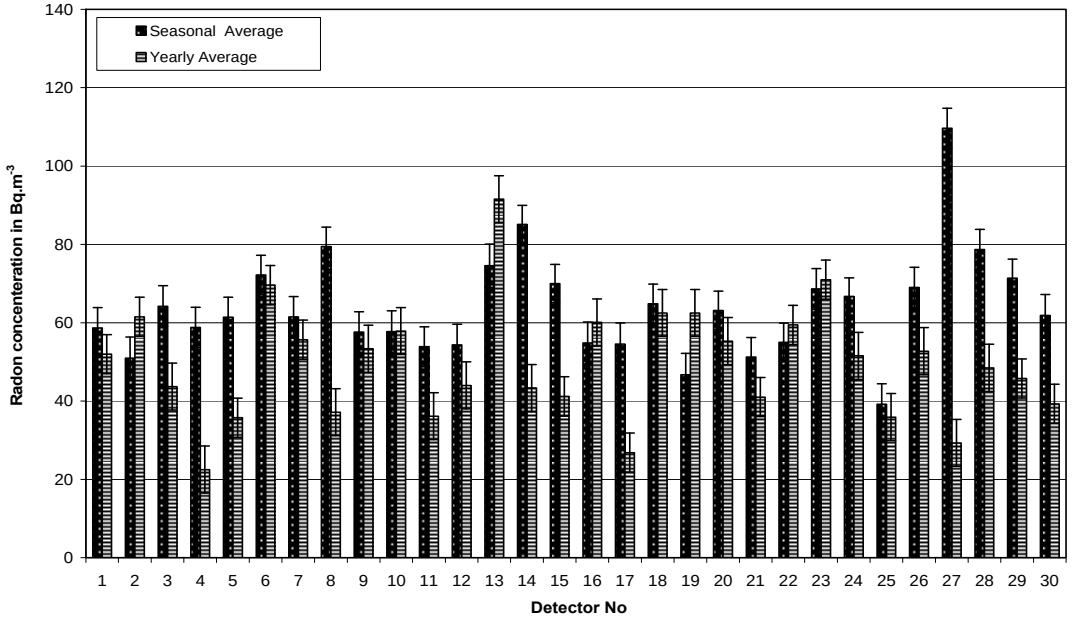


Figure 4.7: Yearly and seasonally averaged yearly radon levels in Mardan district.

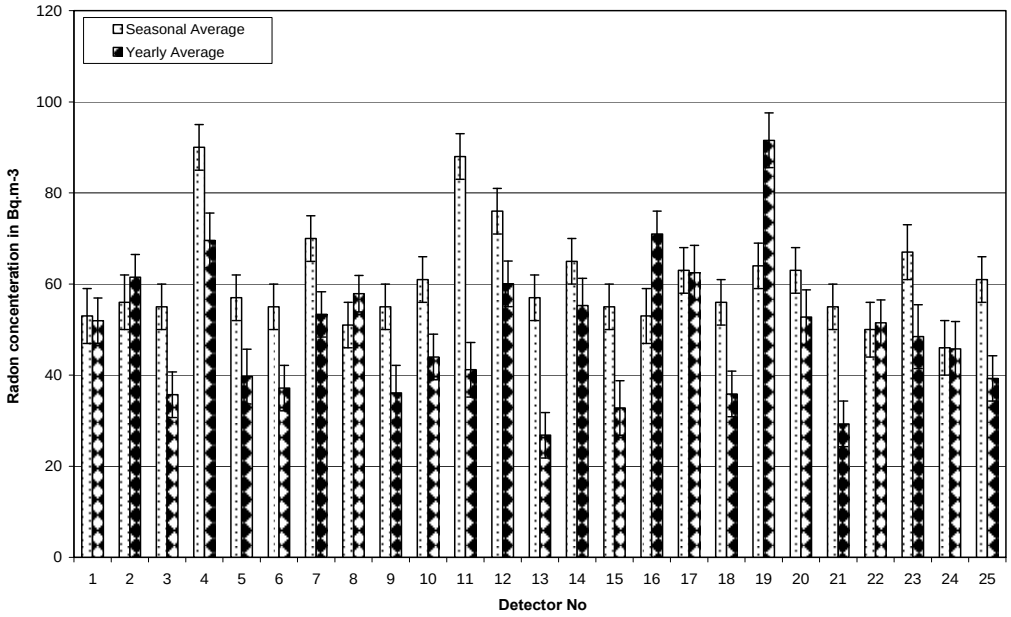



Figure 4.8: Yearly and seasonally yearly averaged radon levels in Charsadda district.

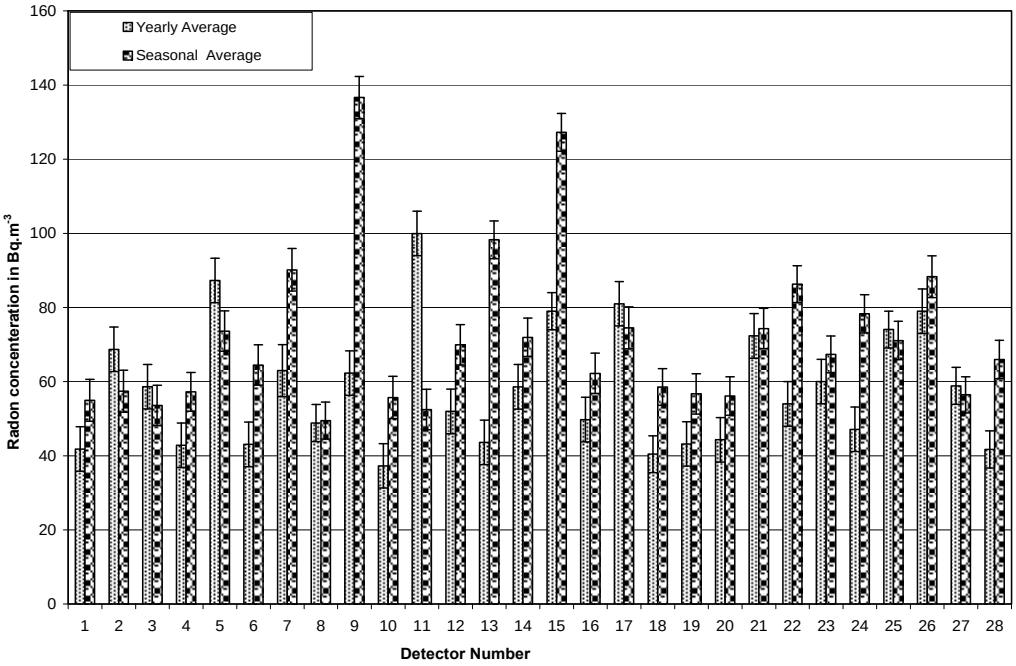


Figure 4.9: Yearly and seasonally averaged yearly radon levels in Mohmand agency.

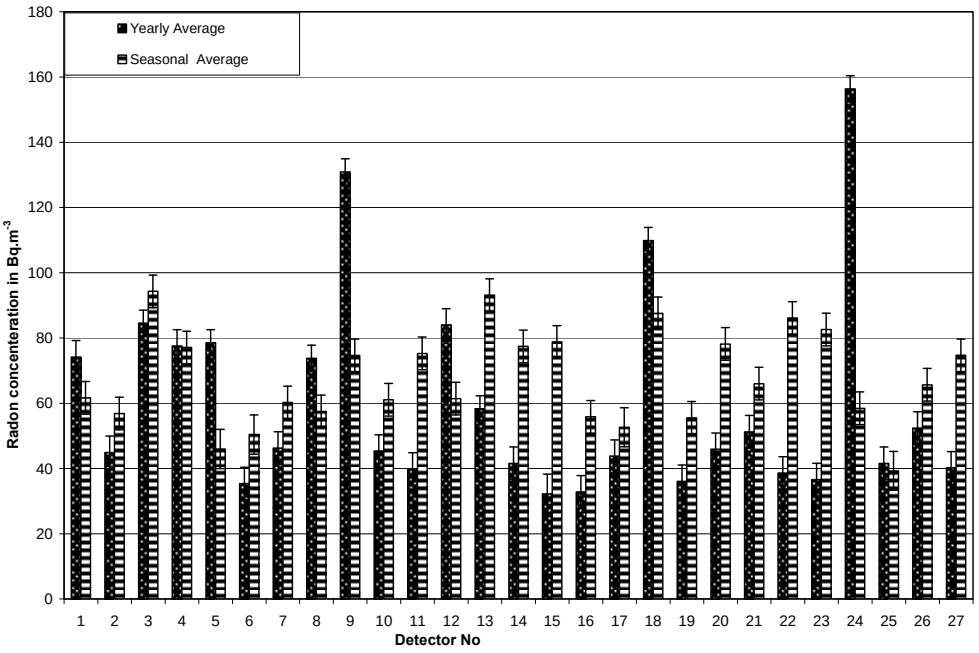
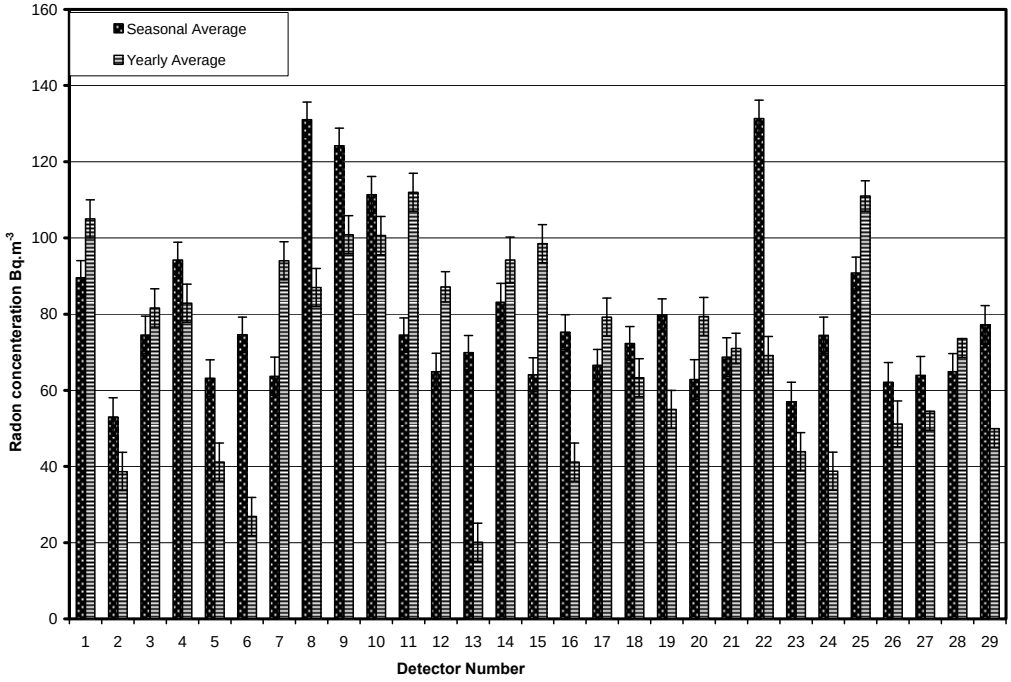



Figure 4.10: Yearly and seasonally averaged yearly radon levels in Bajuar agency.



# Chapter Five

# Experimental Studies on Radon Exhalation Rate from the Soil, Sand and Brick Samples

## 5.1. Introduction

In order to characterize building materials as an indoor radon source, knowledge of the radon exhalation rate from these materials is very important (BEIR-VI, 1999; Sharma and Virk, 2001). Radon produced in soil and other building materials is transported to the indoor air through diffusion and convective flow (Jang et al., 2005). During this process, a small fraction of the generated radon is able to escape to the atmosphere. A measure of exhalation is given by the exhalation rate, which is the number of radon atoms leaving the material per unit surface area per unit time. The parameters like atmospheric pressure, temperature and wind force greatly influence the radon exhalation rate. Rainfall or snow cover may lead to the temporal sealing of the soil surface, whereby $^{222}Rn$ is accumulated beneath the sealing and the exhalation rate is reduced. According to the published data, 60.4% of the indoor radon comes from the ground and surrounding soil of the buildings (Sun et al., 2004).

Building materials as indoor radon source has received a greater attention in some countries of the world (e.g., The Netherlands, China and Italy), where rocks enriched in radon isotopes precursors are used as building materials either as stony materials or in loose form to prepare cements (Tuccimei et al., 2006). In the Netherlands, radon from building materials constitutes 70% of the average radon concentration (Cozmuta et al., 2003). Low humidity conditions are known to dramatically reduce the radon exhalation rate from concrete (Roelofs and Scholten,1994). In a latitudinal study carried out in Hong Kong, the radon exhalation rate was found to decrease with the age due to the gradual dehydration of the concrete (Yu et al., 1996).

Within building materials, the dominant transport mechanism of radon is molecular diffusion, which is driven by a gradient of concentration. The radon flux exhaled from this kind of materials varies from one medium to another, depending on the different physical parameters. The two main parameters of building materials are porosity and water content (Fournier et al., 2005; UNSCEAR, 2000). Cementitious materials such as concrete, brick, and ceramic tiles have the highest $^{222}Rn$ exhalation rates as compared to the fabricated materials (e.g. card boards) (Roelofs and Scholten, 1994; Jang et al., 2005). Radon exhalation from the soil surface in the US, determined using passive diffusion measurement technique has been reported to be in the range of 5.0 to 6.7 mBq $m^{-2}$ $s^{-1}$ with an average value of 5.8 ± 0.6 mBq $m^{-2}$ $s^{-1}$ (Brounstein and Johnson, 2005).

It is highly desirable to study the radon exhalation form soil and other building materials used in the area chosen for the present study. Consequently radon exhalation rate from different samples of building materials, collected from NWFP and FATA, Pakistan, was selected using CR-39 based NRPB radon dosemeters. The effect of moisture contents on the radon exhalation rate from these materials was also studied.

Table 5.1: Radon exhalation rate ($mBq.m^{-2}.h^{-1}$) from different soil samples having 0%, 15%, 30% and 45% moisture content (MC), collected from the district Swabi.

| Location | (MC 0 %) I | (MC 0 %) II | (MC 15%) I | (MC 15 %) II | (MC 30 %) I | (MC 30%) II | (MC 45%) I | (MC 45%) II |
|---|---|---|---|---|---|---|---|---|
| Swabi | 270±11 | 288±13 | 381±9 | 412±15 | 322±9 | 348±15 | 296±9 | 317±15 |
| Bachai | 285±11 | 304±12 | 363±9 | 392±15 | 371±9 | 401±14 | 294±12 | 315±12 |
| Zaida | 300±8 | 321±9 | 361±9 | 390±15 | 470±13 | 508±9 | 280±9 | 300±9 |
| Gadoon Sw | 246±9 | 263±10 | 216±8 | 234±9 | 259±8 | 259±15 | 406±15 | 265±12 |
| Swabi City | 155±11 | 166±12 | 313±9 | 338±15 | 290±15 | 313±11 | 277±11 | 297±15 |
| Mangal Chai | 203±10 | 217±10 | 364±15 | 392±15 | 372±15 | 401±11 | 476±9 | 515±9 |
| R.Q Khan | 141±10 | 151±11 | 364±15 | 393±11 | 579±15 | 625±11 | 253±11 | 271±12 |
| Dagi | 157±11 | 167±12 | 340±9 | 367±9 | 337±15 | 364±15 | 236±15 | 253±11 |
| Yar Hussain | 237±10 | 254±10 | 308±9 | 332±15 | 631±9 | 681±15 | 285±12 | 305±13 |
| Lahore | 288±9 | 308±8 | 327±15 | 353±11 | 335±15 | 362±12 | 324±9 | 347±15 |
| AM±S.D | 228±60 | 244±64 | 334±48 | 360±52 | 397±124 | 426±136 | 313±74 | 318±73 |
| GM±GSD | 220±1.16 | 241±1.17 | 330±1.09 | 356±1.09 | 381±1.16 | 408±1.17 | 306±1.11 | 312±1.11 |

For this study, samples were collected from the Swabi, Mardan and Charsadda districts of NWFP as well as from the Mohmand and Bajuar Agencies of FATA, Pakistan. From each district/agency, 10 soil representative samples were collected. In the case of sand, a total number of ten samples (i.e. 2 samples per district/agency) were collected from different streams of the selected area wherefrom people collect sand and transport it for the use in construction of their houses.

Table 5.2: Radon exhalation rate ($mBq.m^{-2}.h^{-1}$) from different soil samples having 0%, 15%, 30% and 45% moisture content (MC), collected from the district Mardan.

| Location | (MC 0 %) I | (MC 0 %) II | (MC 15%) I | (MC 15 %) II | (MC 30 %) I | (MC 30%) II | (MC 45%) I | (MC 45%) II |
|---|---|---|---|---|---|---|---|---|
| Rustum | 227±14 | 261±12 | 279±15 | 302±11 | 398±10 | 430±11 | 264±11 | 283±11 |
| Fazal Abad | 266±13 | 306±12 | 304±15 | 328±15 | 428±9 | 462±10 | 350±15 | 375±11 |
| Taja | 248±14 | 286±12 | 405±9 | 545±15 | 424±8 | 457±9 | 419±9 | 449±9 |
| Taja(NW) | 274±10 | 293±8 | 311±9 | 359±15 | 490±10 | 529±11 | 303±9 | 324±15 |
| Tahat Bhai | 294±11 | 314±8 | 333±15 | 324±11 | 371±10 | 401±11 | 303±9 | 324±15 |
| Pat Baba | 305±13 | 326±12 | 300±9 | 359±15 | 379±9 | 409±10 | 350±15 | 375±11 |
| Chargul | 206±10 | 220±8 | 333±9 | 337±15 | 302±9 | 326±10 | 303±9 | 325±9 |
| Nawan Killi | 309±9 | 331±12 | 312±9 | 359±15 | 294±10 | 317±11 | 264±11 | 283±11 |
| Toro | 199±10 | 212±9 | 333±9 | 383±15 | 391±11 | 422±12 | 303±9 | 325±9 |
| Rustum | 270±10 | 288±8 | 355±9 | 336±15 | 324±10 | 350±11 | 342±9 | 366±15 |
| Average | 260±39 | 284±41 | 327±35 | 363±68 | 380±61 | 410±66 | 320±47 | 343±50 |
| GM | 257±1.08 | 281±1.08 | 325±1.05 | 359±1.09 | 376±1.09 | 406±1.09 | 317±1.07 | 340±1.07 |

## 5.2. Calculation of the exhalation rate

In order to calculate effective time of the radon exposure, following relation was used (Durrani and Iliç, 1997) :

$$T_{effective} = t - \tau\left(1 - e^{-\lambda t}\right) \qquad (1)$$

Where $\tau$ is the mean life of radon (5.5 days), t is the total exposure time (days) and λ is the $^{222}Rn$ decay constant

Measured radon concentration values were used to calculate the exhalation rate using the following equations (Rehman et al., 2006) .

$$F_0 = \frac{C(t)[\omega A + \lambda V]}{A\left[1 - e^{-\left(\frac{\omega A}{V} + \lambda\right)t}\right]} \quad (2)$$

$$F = F_0 - \omega C \quad (3)$$

Where

A = Surface area of the sample ($cm^2$), V = volume of the void space in a closed chamber, t = $^{222}$Rn accumulation time in a closed chamber.

$\omega = \varepsilon\lambda Z_0$, known as back diffusion constant for given material.

$Z_0$ = Thickness of the sample in the sealed chamber.

$C(t)$ = $^{222}$Rn concentration just on the surface of the sample which has to be exhaled from the surface of the sample to the void space of the chamber.

$$F_0 = R\rho_b\lambda EZ_0 \quad (4)$$

$\lambda$ = $^{222}$Rn decay constant ($h^{-1}$).

$\rho_b$ = Bulk density of the sample ($kg.m^{-3}$).

$E$ = Sum of fractional emanation coefficient of $^{222}$Rn in air, water and adsorbed phase. ($E_{air} + E_{water} + E_{solid}$).

R = Concentration of $^{226}$Ra ($Bq.kg^{-1}$)

All the quantities on the right hand side in Eq. (2) are known except $C(t)$ which was experimentally determined for CR-39 based NRPB radon dosimeter. Putting the value of $C(t)$ in Eq. (2), exhalation rate, $F_o$ was determined.

In a closed chamber, which contains a sample, $^{222}$Rn concentration increases with the passage of time from zero to its maximum value. After reaching its maximum value, back diffusion of radon also take place, which reduces the $^{222}$Rn concentration by a

factor $\omega$ in the chamber. Therefore exhalation rate F, corrected for back diffusion, was determined using Eq (3). Exhalation rate was also calculated using the following equation (Abu-Jarad et al., 1980)

$$Ex = \frac{\mathrm{CtV\lambda}}{\mathrm{S[t\text{-}1/\lambda(1-e^{-\lambda t})]}} \tag{5}$$

Where $E_x$ *is radon* exhalation rate ($mBq.m^{-2}.h^{-1}$), C is mean radon concentration as measured by CR-39 detector ($Bq.m^{-3}$), V is volume of the can ($m^3$), t is the exposure time, λ is the radon decay constant and S is the surface area from which radon is exhaled into the closed can. For further details, the reader is referred to ref. 25. The results these obtained using these two different relations are shown in table as (I and II for relation 3 and 5), respectively.

### 5.3. Results

As mentioned earlier, CR-39 detectors exposed in closed chambers to radon were etched in 25% NaOH at 80 $^oC$ for 16 h and counted under an optical microscope.

Table 5.3: Radon exhalation rate($mBq.m^{-2}.h^{-1}$) from different soil samples having 0%, 15%, 30% and 45% moisture content (MC), collected from the district Charsadda.

| Location | (MC 0 %) I | (MC 0 %) II | (MC 15%) I | (MC 15 %) II | (MC 30 %) I | (MC 30%) II | (MC 45%) I | (MC 45%) II |
|---|---|---|---|---|---|---|---|---|
| Charsadda bazaar | 371±9 | 428±10 | 403±9 | 435±10 | 344±9 | 372±10 | 233±12 | 250±13 |
| Umerzai | 219±9 | 241±12 | 411±9 | 443±9 | 382±10 | 413±11 | 243±10 | 260±11 |
| Halimzai | 113±11 | 130±10 | 268±10 | 289±10 | 342±10 | 369±11 | 275±10 | 295±11 |
| Kharaqy | 233±11 | 268±14 | 265±8 | 445±10 | 336±10 | 362±12 | 336±10 | 359±11 |
| Tangai | 296±9 | 341±13 | 412±9 | 626±9 | 377±11 | 407±11 | 290±11 | 311±11 |
| Sherpao | 375±8 | 432±12 | 580±9 | 385±9 | 434±9 | 469±10 | 329±10 | 353±11 |
| Shara | 332±9 | 382±11 | 357±9 | 425±9 | 369±10 | 399±11 | 252±10 | 270±10 |
| Pahlawan Qila | 415±9 | 478±10 | 341±9 | 368±10 | 600±9 | 648±10 | 386±9 | 414±10 |
| Mata | 363±8 | 418±10 | 356±9 | 384±10 | 249±11 | 269±12 | 298±9 | 319±9 |
| Garangi | 324±11 | 373±9 | 319±10 | 311±10 | 338±10 | 365±10 | 294±12 | 318±12 |
| Average | 304±93 | 349±107 | 371±91 | 411±93 | 377±91 | 407±99 | 294±47 | 315±50 |
| GM | 287±1.22 | 329±1.22 | 362±1.12 | 402±1.12 | 368±1.12 | 398±1.12 | 143±1.08 | 290±1.08 |

From the measured track densities, $^{222}Rn$ concentration levels were calculated in closed plastic containers using the calibration factor of 2.7 $tracks.cm^{-2}.h^{-1}/kBq.m^{-3}$.Having determined the $^{222}Rn$ concentrations, exhalation rate from each sample was then

calculated using equation (3) and (5). Radon exhalation obtained at 0%, 15%, 30% and 45% moisture contents from these soil samples are shown in tables 5.1-5.5. As may be seen in these tables, variation in the radon exhalation rate ranged from 141 ± 10 (Rashaka Qaisar Khan) to 300 ± 8 $mBq.m^{-2}.h^{-1}$ (Lahore, district Swabi) with an average of 228 ± 60 $mBq.m^{-2}.h^{-1}$ in the soil samples collected from different locations of the district Swabi. In the district Mardan, variation in the radon exhalation rate was from 199 ± 10 (Toro) to 309 ± 9 $mBq.m^{-2}.h^{-1}$ (Nawan Killi, Rustum) with an average value of 260 ± 39 $mBq.m^{-2}.h^{-1}$. In district Charsadda, variation in the radon exhalation rate from soil samples was found to be from 113 ± 11 (Halimzai) to 415 ± 9 $mBq.m^{-2}.h^{-1}$ (Palwan Qila area) with an average value of 303 ± 93 $mBq.m^{-2}.h^{-1}$.

The exhalation rate from soil samples collected from the Mohmand agency varied from 146 ± 11 (Safi) to 316 ± 9 $mBq.m^{-2}.h^{-1}$ (Alingar) with an average value of 251 ± 44 $mBq.m^{-2}.h^{-1}$. In the Bajuar agency, the radon exhalation rate varied from 174 ± 9 $mBq.m^{-2}.h^{-1}$ (Loisum) to 311 ± 8 $mBq.m^{-2}.h^{-1}$ (Tangai area) with an average value of 252 ± 47 $mBq.m^{-2}.h^{-1}$.

Table 5.4: Radon exhalation rate($mBq.m^{-2}.h^{-1}$) from different soil samples having 0%, 15%, 30% and 45% moisture content (MC), collected from the Mohmand agency.

| Location | (MC 0 %) I | (MC 0 %) II | (MC 15%) I | (MC 15 %) II | (MC 30 %) I | (MC 30%) II | (MC 45%) I | (MC 45%) II |
|---|---|---|---|---|---|---|---|---|
| ZarGara | 267±11 | 308±13 | 420±9 | 454±10 | 384±9 | 414±10 | 315±9 | 337±10 |
| Jabar Mula | 258±11 | 298±13 | 268±10 | 289±11 | 385±10 | 415±11 | 257±11 | 275±12 |
| Qala Kawar | 247±12 | 284±14 | 237±11 | 255±12 | 269±15 | 291±16 | 285±12 | 305±13 |
| Mohammad Gat | 255±12 | 294±14 | 401±9 | 433±10 | 399±15 | 431±16 | 328±9 | 352±10 |
| Usman Jan Qala | 250±13 | 288±15 | 330±10 | 357±10 | 389±12 | 420±11 | 345±12 | 369±13 |
| Alingar | 251±16 | 290±18 | 313±10 | 337±11 | 386±12 | 416±13 | 315±10 | 337±11 |
| Qala Mohmand | 290±11 | 310±11 | 340±10 | 367±10 | 316±12 | 341±13 | 313±10 | 335±11 |
| Alingar Karkano | 316±9 | 338±9 | 429±9 | 463±10 | 618±10 | 667±11 | 353±10 | 378±11 |
| Nawagi Dag | 228±9 | 243±10 | 342±9 | 370±9 | 341±11 | 368±12 | 367±10 | 394±11 |
| Safi (Shewa) | 146±11 | 157±11 | 299±9 | 323±9 | 295±10 | 319±11 | 225±10 | 242±11 |
| Average | 251±44 | 281±50 | 338±64 | 365±69 | 378±96 | 408±103 | 310±44 | 332±47 |
| GM | 247±1.11 | 276±1.12 | 332±1.10 | 359±1.10 | 369±1.12 | 398±1.12 | 307±1.08 | 329±1.08 |

Table 5.6 shows radon exhalation rate from different brands of the dried brick samples which were collected from the districts of Swabi, Mardan and Charsadda. The exhalation rate from dried brick samples was found to vary from 245 ± 12 to 364 ± 11 $mBq.m^{-2}.h^{-1}$

with an average value of 294 ± 29 $mBq.m^{-2}.h^{-1}$. Table 5.7 shows radon exhalation rate from sand samples which were collected from the listed areas. As may be seen in table 5.6, variation in radon exhalation rate in the dried samples ranges from 205 ± 16 $mBq.m^{-2}.h^{-1}$ (Mohmand agency) to 291 ± 13 $mBq.m^{-2}.h^{-1}$ (Tangai, district Charsadda) with an average value of 248 ± 25 $mBq.m^{-2}.h^{-1}$.

Using different levels of moisture contents radon exhalation showed a wide variation. As may be seen in tables 5.1-5.5 for soil, an average radon exhalation rate of 334 ± 48 $mBq.m^{-2}.h^{-1}$ was found in the samples which were collected from the district Swabi at 15% moisture contents, level whilst at 30 % and 45% moisture content, average values came out to be 397 ± 124 and 313 ± 74 $mBq.m^{-2}.h^{-1}$, respectively. For the district Mardan, average exhalation rate was 327 ± 35, 380 ± 61 and 320 ± 47 $mBq.m^{-2}.h^{-1}$ for 15%, 30% and 45% moisture content level, respectively.

Table 5.5. Radon exhalation rate($mBq.m^{-2}.h^{-1}$) from different soil samples having 0%, 15%, 30% and 45% moisture content (MC), collected from the Bajuar agency.

| Location | (MC 0 %) I | (MC 0 %) II | (MC 15%) I | (MC 15 %) II | (MC 30 %) I | (MC 30%) II | (MC 45%) I | (MC 45%) II |
|---|---|---|---|---|---|---|---|---|
| Mashkanro | 251±9 | 269±9 | 348±9 | 440±15 | 283±11 | 306±12 | 296±15 | 317±15 |
| Loisum | 174±9 | 186±9 | 333±9 | 360±9 | 362±9 | 390±15 | 299±15 | 321±15 |
| Loi Juhar | 243±9 | 260±10 | 385±9 | 484±15 | 477±9 | 515±15 | 426±15 | 456±11 |
| Mamond | 295±9 | 315±9 | 448±11 | 517±15 | 354±9 | 382±15 | 359±8 | 385±9 |
| Zorbandar | 269±8 | 288±9 | 479±9 | 369±12 | 372±15 | 402±15 | 342±9 | 366±15 |
| Tangai | 311±8 | 332±9 | 342±9 | 407±15 | 401±15 | 460±15 | 287±15 | 308±11 |
| Khar | 199±9 | 212±9 | 377±9 | 394±9 | 461±9 | 497±15 | 286±11 | 306±12 |
| Asghar | 206±8 | 220±9 | 365±9 | 433±15 | 393±12 | 425±13 | 403±9 | 432±9 |
| Rashakai | 305±9 | 326±9 | 401±15 | 480±15 | 420±9 | 453±9 | 303±15 | 324±15 |
| Tangkhata | 270±9 | 288±9 | 445±9 | 376±11 | 426±15 | 588±11 | 395±15 | 423±11 |
| Average | 252±47 | 270±50 | 392±50 | 426±54 | 395±56 | 442±80 | 340±53 | 364±57 |
| GM | 248±1.11 | 265±1.11 | 390±1.07 | 423±1.07 | 391±1.08 | 435±1.15 | 336±1.08 | 360±1.08 |

In the district Charsadda the average value for 15%, 30% and 45% moisture content was 371 ± 91, 377 ± 91 and 294 ± 47 $mBq.m^{-2}.h^{-1}$, respectively. In the Mohmand agency, the radon exhalation values were 338 ± 64, 378 ± 96 and 310 ± 44 $mBq.m^{-2}.h^{-1}$ for 15%, 30% and 45% moisture content levels, respectively whereas in the Bajuar agency, radon

exhalation rate was 392 ± 50 mBq.m$^{-2}$.h$^{-1}$, 395 ± 56 and 340 ± 53 mBq.m$^{-2}$.h$^{-1}$ for 15%, 30% and 45% moisture content levels, respectively. For bricks samples (see table 5.6), variation in the average exhalation rate ranged from 344 ± 60 to 362 ± 36 mBq.m$^{-2}$.h$^{-1}$ for 15%, 30% moisture content levels. For 45% moisture content, its value was 310 ± 45 mBq.m$^{-2}$.h$^{-1}$.

Table 5.6: Radon exhalation rate (mBq.m$^{-2}$.h$^{-1}$) from different brick samples having 0%, 15%, 30% and 45% moisture content (MC), collected from the different areas of NWFP and FATA.

| Location | (MC 0 %) I | (MC 0 %) II | (MC 15%) I | (MC 15 %) II | (MC 30 %) I | (MC 30%) II | (MC 45%) I | (MC 45%) II |
|---|---|---|---|---|---|---|---|---|
| Star | 364±11 | 389±12 | 411±8 | 451±9 | 379±15 | 415±11 | 285±9 | 315±9 |
| Mumtaz | 245±12 | 262±13 | 261±8 | 287±9 | 383±9 | 420±15 | 321±15 | 349±11 |
| NR | 309±11 | 331±11 | 421±8 | 462±9 | 276±12 | 302±13 | 295±9 | 321±15 |
| PK | 277±11 | 296±12 | 369±8 | 405±9 | 391±8 | 428±9 | 249±15 | 270±15 |
| SS | 296±12 | 316±13 | 308±8 | 337±9 | 341±8 | 374±9 | 333±8 | 363±15 |
| PS | 295±11 | 315±12 | 330±9 | 361±15 | 360±9 | 394±15 | 354±8 | 384±11 |
| NS | 276±11 | 295±12 | 287±9 | 315±9 | 357±9 | 392±9 | 292±15 | 317±11 |
| KK | 312±10 | 334±11 | 376±8 | 411±9 | 412±8 | 451±9 | 295±9 | 321±15 |
| GD | 269±12 | 288±13 | 271±9 | 298±15 | 371±9 | 407±15 | 249±15 | 270±15 |
| PR | 298±12 | 319±13 | 375±8 | 411±9 | 398±8 | 436±9 | 413±8 | 449±9 |
| TB | 284±11 | 304±12 | 292±8 | 319±9 | 353±9 | 387±9 | 302±8 | 328±9 |
| SD | 298±11 | 319±12 | 426±7 | 466±9 | 326±8 | 357±9 | 331±8 | 360±9 |
| Average | 294±29 | 314±31 | 344±60 | 377±65 | 362±36 | 397±40 | 310±45 | 337±49 |
| GM | 293±1.06 | 313±1.06 | 339±1.15 | 372±1.15 | 360±1.06 | 395±1.06 | 307±1.08 | 334±1.08 |

For sand samples (see table 5.7), average radon exhalation rate was in the range of 365 ± 22, 393 ± 31 and 294 ± 53 mBq.m$^{-2}$.h$^{-1}$ for 15%, 30% and 45% moisture contents, respectively. In order to know that whether change in exhalation rate is significant with respect to the change in moisture contents, results obtained concerning the change in the radon exhalation rate as a function of moisture content was tested applying Student T-Test (values below 0.05 are significant). The results of the paired T-test are given in table 5.8. According to this table, taking dried samples as a baseline data, the change in the exhalation rate is significant for the moisture content of 15%, 30% and 45% at 95% confidence level. Between 15% and 30% moisture content, the change in exhalation rate is significant for soil and sand samples. Similar trend was

observed for soil samples between 15% and 45% as may be seen in table 5.8. For 30%-45% moisture content, exhalation rate is significant in soil, sand and brick samples at 95% confidence level.

## 5.4. Discussion

For inter-comparison, exhalation rate was calculated using two different relations. The results obtained are shown in tables 5.1-5.7. As may be seen in these tables, the relation given by Rehman et al. yields relatively lower exhalation rate (~ 6-13 % less) as compared to that given by Abu-Jarad et al. (1980). This may be due to the inclusion of the back diffusion factor by Rehman et al. In the case of dried soil, higher average radon exhalation rate of 304 ± 93 $mBq.m^{-2}.h^{-1}$ was found in the samples collected from the district Charsadda whereas lower value of average radon exhalation rate of 228 ± 60 $mBq.m^{-2}.h^{-1}$ was observed in the district Swabi. In the case of dried sand samples, maximum radon exhalation rate of 291 ± 13 $mBq.m^{-2}.h^{-1}$ was found in the samples collected from the district Charsadda.

As may be seen in table 5.5, higher average radon exhalation rate was observed at 15% moisture content from the sample collected from the Bajuar agency with an average of 392 ± 50 $mBq.m^{-2}.h^{-1}$. Minimum value of 327 ± 35 $mBq.m^{-2}.h^{-1}$ was found in the Mardan district. At 30% moisture content, average minimum was 377 ± 91 $mBq.m^{-2}.h^{-1}$ for the Charsadda whilst a maximum value of 397 ± 124 $mBq.m^{-2}.h^{-1}$ was observed from the soil samples collected from the district Swabi.

For 45% moisture content the lower average value of 294 ± 47 $mBq.m^{-2}.h^{-1}$ was observed in samples collected from the district Charsadda whilst higher value of 340 ± 53 $mBq.m^{-2}.h^{-1}$ was observed in samples, which were collected form the Bajuar agency respectively. Extensive data is available about the radon exhalation rate in the open literature.

Table 5.9 shows present data along with some already published data of the listed workers (Al-Jarallah et al., 2005; Oufni, 2003; Levin et al., 2002; Kumar et al., 2003; Hafez et al., 2001; Sroor et al., 2001; Amrani and Cherouati , 2001; Singh et al., 2005; Maged and Ashraf, 2005; El-Bahi, 2004; Yahong et al., 2002).

Table 5. 7: Radon exhalation rate ($mBq.m^{-2}.h^{-1}$) from different sand samples having 0%, 15%, 30% and 45% moisture content (MC), collected from the selected area.

| Location | (MC 0 %) I | (MC 0 %) II | (MC 15%) I | (MC 15 %) II | (MC 30 %) I | (MC 30%) II | (MC 45%) I | (MC 45%) II |
|---|---|---|---|---|---|---|---|---|
| Gandab Khwar | 291±13 | 331±11 | 384±15 | 421±13 | 358±9 | 393±15 | 230±11 | 250±11 |
| Sheikh Baba | 276±12 | 314±12 | 367±12 | 402±12 | 415±8 | 449±9 | 329±9 | 358±15 |
| Maniri | 244±13 | 277±12 | 392±11 | 429±13 | 419±9 | 459±9 | 255±15 | 277±11 |
| Lahore | 260±14 | 295±12 | 373±15 | 409±12 | 439±8 | 481±9 | 295±12 | 321±13 |
| Rustum Khwar | 265±12 | 301±11 | 342±15 | 375±11 | 381±9 | 417±15 | 274±12 | 298±13 |
| Toro Nalai | 242±15 | 275±13 | 333±12 | 364±11 | 374±9 | 381±9 | 268±11 | 291±12 |
| Zorbandar | 232±18 | 263±1 | 397±11 | 435±13 | 435±15 | 476±11 | 421±11 | 458±12 |
| Sheih Khwar | 233±15 | 265±13 | 368±15 | 404±12 | 398±8 | 436±9 | 311±15 | 338±11 |
| Yaqurban | 235±14 | 267±13 | 339±11 | 371±11 | 374±8 | 415±9 | 301±15 | 328±11 |
| Tangai | 205±16 | 232±14 | 360±9 | 394±12 | 347±9 | 382±15 | 260±15 | 282±11 |
| Average | 248±25 | 282±29 | 365±22 | 400±27 | 393±31 | 428±37 | 294±53 | 320±58 |
| GM | 247±1.05 | 281±1.05 | 365±1.03 | 400±1.03 | 392±1.04 | 427±1.05 | 290±1.09 | 316±1.09 |

Our results are seen to be within the reported values. A large variation in the exhalation rate of the reported values of is seen in table 5.9. For instance, Shweikani and Hushari (2005) have reported the exhalation rate ranging from 72000 - 32400000 $mBq.m^{-2}.h^{-1}$ (20 ± 5 - 9000 ± 1000 $mBq.m^{-2}.s^{-1}$) whereas Dijk and Jong (2001) values range from 0.02 to 15.8 $mBq.m^{-2}.h^{-1}$. The world average radon exhalation rate (UNSCEAR, 2000) is 57600 $mBq.m^{-2}.h^{-1}$ (0.016 $Bq.m^{-2}.s^{-1}$) which is also higher than the values observed in the present study. The radon exhalation rate is seen to increases (as compared to the dried samples) with moisture content up to 30%. At higher value of 45% moisture content, a decreasing trend is observed.

Both the formulae show the same trend of increase in exhalation rate with moisture content and yield results, which are in good agreement with each other. This increase in radon exhalation with moisture content may be explained as follow. As moisture content increases from 0% to 30% level, emanation from the grain increases which in turn results in an increase in the exhalation rate.

Table 5.8: Statistical analysis of the present data regarding the radon exhalation rate as a function of moisture contents applying student T-test was applied to the data.

| MC | Swabi | Mardan | Charsadda | Mohmand | Bajuar | Soil(All Samples) | Sand | Brick |
|---|---|---|---|---|---|---|---|---|
| 0-15% | 0.00179 | 0.00459 | 0.05294 | 0.00228 | 1.30E-05 | 3.77E-12 | 8.33E-07 | 0.00219 |
| 0-30% | 0.00474 | 0.00108 | 0.05356 | 0.00126 | 2.07E-04 | 8.25E-12 | 7.46E-07 | 4.83E-04 |
| 0-45% | 0.01286 | 0.0106 | 0.72212 | 0.00754 | 0.00407 | 4.76E-06 | 0.048 | 0.32223 |
| 15-30% | 0.13091 | 0.07831 | 0.87313 | 0.28154 | 0.91076 | 0.01618 | 0.01011 | 0.42907 |
| 15-45% | 0.51814 | 0.55611 | 0.04227 | 0.27321 | 0.01703 | 0.0011 | 0.00174 | 0.12312 |
| 30-45% | 0.13955 | 0.05729 | 0.00588 | 0.05625 | 0.02118 | 5.56E-06 | 3.70E-05 | 0.009 |

All values below 0.05 are significant

The recoiling radon nuclei from the alpha decay of radium atoms are more likely to stop in pore spaces if it contains water in the pore space. It may be noted here that radon does not "recoil" through the pore spaces; it goes through the porous material because it is an inert gas. Without water (i.e. 0% moisture content), the recoiling nuclei may travel through the less dense, air-filled pore space and become embedded in another grain. Once in the pore space, the atom is free to migrate out of the soil and thus radon exhalation increases with an increase in the moisture content.

However, when the pore space is completely filled with fluid, it causes a decrease in the radon exhalation rate because all fluid-filled (water) pore spaces inhibit the migration of emanated radon from the grain to the soil surface of the material and thus the exhalation decreases.

As moisture content was increased from 0% to 15%, 30% and 45%, on the average 34%, 46% and 13% increase was observed in the radon exhalation rate. Radon exhalation from samples increased up to 30% moisture content.

At 45% moisture content, a decreasing trend was observed. Radon exhalation rate at 45% moisture content is still higher than the exhalation rate from the dried samples.

Table 5.9: Published data concerning radon exhalation rate along with the present results.

| Investigators | Range of Values in $mBq.m^{-2}.h^{-1}$ |
|---|---|
| Al-Jarallah et al. | 120-131000 (.12 -13.1 $Bq.m^{-2}.h^{-1}$) |
| Shweikani and Hushari | 72000 - 32400000 (20±5 – 9000 ± 1000 m Bq. $m^{-2}.s^{-1}$) |
| Oufni | 3 -145 (0.003 - 0.145 $Bq.m^{-2}.h^{-1}$ ) |
| Levin et al. | Soil type A 3300 ( 3.3± 0.9 $Bq.m^{-2}.h^{-1}$) |
| | B 7900 (7.9± 2.1 $Bq.m^{-2}.h^{-1}$) |
| | C 3600 (3.6± 1.3 $Bq.m^{-2}.h^{-1}$) |
| Kumar et al. | 260-1500 (0.26 - 1.5 $Bq.m^{-2}.h^{-1}$) |
| Hafez et al. | 464 ($12.9 \times 10^{-5}$ $Bq.m^{-2}.s^{-1}$) |
| Sroor et al. | 14117.08-59436.25(338.81 -1426.47 $Bq.m^{-2}.d^{-1}$) |
| Amrani and Cherouati | 45-153(0.003 - 0.145 $Bq.m^{-2}.h^{-1}$) |
| Singh et al. | 246.63 -1100.00 |
| Maged & Ashraf | 11–223 |
| El-Bahi | 2549-7557 (61.19 - 181.39 $Bq.m^{-2}.d^{-1}$ ) |
| Yahong et al. | $10^{-3}$-$10^{-4}$ |
| Van Dijk | 0.02-15.8 |
| World average radon exhalation rate | 57600 (0.016 $Bq.m^{-2}.s^{-1}$) |
| Present Study | Soil (261) |
| | Sand (265) |
| | Brick (292) |

It was observed that from 0% to 15% moisture content, increase in exhalation rate was higher as compared with the increase of radon exhalation from 15-30% and 30-45% moisture contents. During the removal of the detectors from the sealed containers at higher moisture content, a layer of water content was found on the surface of the detector especially at 30 and 45% moisture content, which might have slightly affected the track registration efficiency of the CR-39 detector. However, it was very difficult to quantify this effect. In order to measure the radon exhalation rate, samples were first crushed and

then sieved. This phenomenon might also have some effect on the exhalation rate from these samples as compared to the undisturbed rocks/materials. As main factor of radon exhalation is the radium content in the materials and thus qualitatively it shows the behavior of the undisturbed rocks/materials.

The present data is reasonably in good agreement with the published data for Hong Kong (Yu et al., 1996). Fournier et al. (2005) have reported that radon exhalation sharply increases with water until the volumetric water content becomes higher than 30% for low porosity materials which is also in agreement with the present data. According to the paired T-test (see, table 5.8), change in the exhalation rate as a function of the moisture content is significant at 95% confidence level.

Cozmuta et al. (2003) have reported dependence of the radon-release rate on the moisture content for concrete under well controlled conditions. They have observed that the radon-release rate increases almost linearly up to moisture contents of 50% to 60% which are not in line with the present value (i.e. higher than the present values).The building materials selected have lower radon exhalation rate and are thus safe for use as construction materials.

## 5.5. Conclusions

To conclude, radon exhalation rate has been determined in soil, sand and brick samples collected from several districts of the NWFP, namely, Charsadda, Mardan and Swabi as well as Mohmand and Bajuar agencies, FATA, Pakistan. This study revealed that all the materials exhale radon with lower rate as compared to world average radon exhalation rate and would pose no serious threat if used in the construction of buildings. Effect of moisture content on the radon exhalation rate show that radon exhalation rate increases with an increase in the moisture content up to a certain level and then decreases with further increase in the moisture content. Radon exhalation rate measured using two different formulas are reasonably in good agreement. According to the paired T-test, change in the exhalation rate as a function of the moisture content is significant at 95% confidence level at 15%, 30% and 45% moisture contents.

# Chapter Six

# Measurement of Natural Radioactivity in Soil and other Building Materials

## 6.1. Introduction

Radioactivity is a part of our physical environment. The presence of natural radioactivity in soil and other building materials results in internal and external exposure to the occupants (Ahmad et al., 1997). Terrestrial radioactivity and the associated external exposure due to the gamma radiation depend primarily on the geological and geographical conditions and appear at different levels in the soils of each region (UNSCEAR 2000). The largest contribution to the radiation field is of natural origin: it is due to the cosmic rays, the natural radionuclides in soil and other building materials, radioactivity of the ground and the radioactive decay products of radon in the air. Naturally occurring building materials reflects the geological variations of their sites of origin, so their radiometric characterization provides a useful technique of acquiring better understanding of the local environment (Trevisi et al., 2005). Artificial radioactivity emitted from nuclear power plants, industrial plants and research facilities has smaller contribution to the overall radiation. These emissions are very small in normal operation, although large amounts of radioactivity can be released to the environment through accidents.

In view of the above discussion, it is highly desirable to determine natural radioactivity levels in the samples of soil and other building materials (e.g. brick, sand, marble and cement etc). In this regards, samples were collected from the Swabi, Mardan and the Charsadda districts of the North West Frontier Province (NWFP) Mohmand and Bajuar agencies of the federally administered tribal areas (FATA) Pakistan and analyzed in order to find its radiological significance. The prime objective of carrying out these

studies was to generate a baseline data for the selected area and then to set the standards and guidelines in the light of the international recommendations.

### 6.2. Measurements

In order to measure the natural radioactivity, P-type coaxial HPGe detector was used. Resolution and relative efficiency of the detector for 1332 keV from $^{60}$Co was 2.5 keV and 90 %, respectively. The details of the detector, its cooling system and calibration have been discussed in chapter 2.

For the gamma spectroscopy, a total of fifty (i.e. 10 samples from each district/agency) soil samples were collected from the Swabi, Mardan and Charsadda districts as well as from the Mohmand and Bajuar Agencies of the federally administered tribal areas (FATA), Pakistan.

The specific activities (A) for $^{226}$Ra, $^{232}$Th and $^{40}$K were calculated using the following relation.

$$A = \frac{C}{t \times P_r \times \eta} \tag{1}$$

Where '*C'* represents the net counts, t is the data collection time, $P_r$ is the emission probability and $\eta$ is the efficiency of the detector for the corresponding peak.

Radium equivalent activity ($Ra_{eq}$) was calculated using the following relation (OECD, 1979).

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \tag{2}$$

Where $A_{Ra}$, $A_{Th}$, $A_K$ are the activity concentrations of thorium, uranium and potassium respectively. Absorbed dose was calculated ($D_{air}$) at ground level using the following equation (UNSCEAR, 2000).

$$D_{air} = 0.462A_{Ra} + 0.604A_{Th} + 0417A_K \qquad \text{nGy h}^{-1} \tag{3}$$

The absorbed dose was converted into the annual effective dose using the conversion where the value of $Q$ is 0.7 $Sv.Gy^{-1}$ for environmental exposure to the gamma rays of moderate energy and $T$ is time of one year, i.e., 8760 hours.

Table 6.1: Natural radioactivity, radium equivalent activity in $Bq.kg^{-1}$, external and internal hazard indices and effective doses in the samples collected from the district Swabi.

| Location | $^{226}Ra$ ($Bq.kg^{-1}$) | $^{332}Th$ ($Bq.kg^{-1}$) | $^{40}K$ ($Bq.kg^{-1}$) | $Ra_{eq}$ ($Bq.kg^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Swabi | 54±3 | 56±3 | 710±55 | 190±12 | 0.51±.03 | 0.66±.04 | 0.54±.04 |
| Lahore(Anbar) | 21±1 | 42±3 | 454±36 | 117±8 | 0.32±.02 | 0.37±.02 | 0.33±.02 |
| Zaida(Dodher) | 24±2 | 40±2 | 349±28 | 108±7 | 0.29±.02 | 0.36±.02 | 0.31±.02 |
| Zaida | 34±2 | 61±3 | 714±55 | 176±11 | 0.48±.03 | 0.57±.04 | 0.51±.03 |
| Rashaka | 23±1 | 46±3 | 514±40 | 128±8 | 0.35±.02 | 0.41±.02 | 0.37±.02 |
| Rashaka(Q.K) | 34±2 | 48±3 | 450±35 | 137±9 | 0.37±.02 | 0.46±.03 | 0.39±.03 |
| Yar Hussain | 28±2 | 41±2 | 509±40 | 126±8 | 0.34±.02 | 0.42±.03 | 0.36±.02 |
| Dagi | 23±1 | 38±2 | 360±28 | 104±7 | 0.28±.02 | 0.34±.02 | 0.30±.02 |
| Gadoon | 16±1 | 34±2 | 320±26 | 65±4 | 0.18±.01 | 0.22±.01 | 0.25±.01 |
| Mangal Chai | 42±3 | 42±2 | 495±39 | 140±9 | 0.38±.02 | 0.49±.03 | 0.40±.03 |
| Minimum m | 16±1 | 34±2 | 320±26 | 65±4 | 0.18±.01 | 0.22±.01 | 0.25±.01 |
| Maximum | 54±3 | 61±3 | 714±55 | 190±12 | 0.51±.03 | 0.66±.04 | 0.54±.04 |
| AM±SD | 30±11 | 45±8 | 488±137 | 129±36 | 0.35±.10 | 0.43±.12 | 0.38±0.09 |
| GM±GSD | 28.15±1.2 | 44±1.09 | 471±1.15 | 124±1.16 | 0.34±1.16 | 0.41±1.17 | 0.37±1.13 |

$$E_{air}(mSv) = TQD_{air} \times 10^{-6} \qquad (4)$$

In order to limit the radiation dose to permissible dose equivalent limit of 1 $mSv.yr^{-1}$, a number of models are available in the literature (ICRP, 1990). Using the following relations external and internal hazard indices were calculated (Beretka and Matthew , 1985).

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (5)$$

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \quad (6)$$

Table 6.2: Natural radioactivity, radium equivalent activity in $Bq.kg^{-1}$, external and internal hazard indices and effective doses in the samples collected from the district Mardan.

| Location | $^{226}Ra$ ($Bq.kg^{-1}$) | $^{332}Th$ ($Bq.kg^{-1}$) | $^{40}K$ ($Bq.kg^{-1}$) | $Ra_{eq}$ ($Bq.kg^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Takht Bhai | 35±2 | 48±3 | 489±39 | 142±9 | 0.38±.03 | 0.48±.03 | 0.40±.03 |
| Kalamabad | 53±3 | 86±5 | 1018±79 | 255±17 | 0.69±.04 | 0.83±.05 | 0.73±.05 |
| H Khan Bagh | 34±2 | 48±3 | 485±39 | 140±9 | 0.38±.03 | 0.47±.03 | 0.40±.03 |
| Rustum | 33±2 | 51±3 | 424±33 | 138±9 | 0.37±.02 | 0.46±.03 | 0.39±.03 |
| Khairabad | 30±2 | 44±3 | 463±36 | 130±9 | 0.35±.02 | 0.43±.03 | 0.37±.02 |
| Nawan Killi | 38±2 | 57±3 | 638±50 | 169±11 | 0.46±.03 | 0.56±.04 | 0.48±.03 |
| Pat Baba | 26±2 | 36±2 | 417±32 | 109±7 | 0.29±.02 | 0.36±.02 | 0.31±.02 |
| Fazal Abad | 29±2 | 33±2 | 487±38 | 114±8 | 0.31±.02 | 0.39±.03 | 0.33±.02 |
| Toro | 17±1 | 17±1 | 633±50 | 89±6 | 0.24±.02 | 0.29±.02 | 0.27±.02 |
| Chargul | 23±2 | 36±2 | 262±22 | 95±6 | 0.26±.02 | 0.32±.02 | 0.27±.02 |
| Minimum | 17±1 | 17±1 | 262±22 | 89±6 | 0.24±.02 | 0.29±.02 | 0.27±.02 |
| Maximum | 53±3 | 86±5 | 1018±79 | 255±17 | 0.69±.04 | 0.83±.05 | 0.73±.05 |
| AM±SD | 32±10 | 46±18 | 532±202 | 138±48 | 0.37±.13 | 0.46±.44 | 0.40±0.14 |
| GM±GSD | 31±1.17 | 42±1.24 | 502±1.9 | 132±1.17 | 0.36±1.17 | 0.44±1.16 | 0.38±1.16 |

Where $A_{Ra}$, $A_{Th}$, $A_K$ are the activity concentrations of thorium, uranium and potassium, respectively. The error in the activity was calculated from the combined uncertainty in the efficiency of the detector, uncertainty in the net count rate, attenuation of the gamma rays by the sample. In the case of using two gamma rays peaks for the calculations of the activity, uncertainty in the yield was also included.

## 6.3. Results

### *6.3.1. Specific activities and radium equivalent activity*

Tables 6.1–6.8 show measured specific activities of $^{26}Ra$, $^{232}Th$, $^{40}K$ radium equivalent activity, external and internal hazard indices and effective doses. Their arithmetic means

(AM) and geometric means (GM) are also shown in these tables. As may be seen in table 6.1 $^{226}$Ra activity is found to vary from 16 ± 1 to 54 ± 3 Bq.kg$^{-1}$, $^{232}$Th activity from 61 ± 3 to 45 ± 8 Bq.kg$^{-1}$ and $^{40}$K activity from 488 ± 137 to 714 ± 55 Bq.kg$^{-1}$ in the district Swabi. Average radium equivalent activity for the district Swabi was 129 ± 36 Bq.kg$^{-1}$. In the district Mardan, $^{226}$Ra activity was found to vary from 17 ± 1 to 53 ± 3 Bq.kg$^{-1}$, whilst the average radium equivalent activity value was 138 ± 48 Bq.kg$^{-1}$.

Table 6.3: Natural radioactivity, radium equivalent activity in Bq.kg$^{-1}$ external and internal hazard indices and effective dose in the samples collected from the district Charsadda.

| Location | $^{226}$Ra (Bq.kg$^{-1}$) | $^{332}$Th (Bq.kg$^{-1}$) | $^{40}$K (Bq.kg$^{-1}$) | $Ra_{eq}$ (Bq.kg$^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Shara | 27±2 | 42±2 | 502±39 | 126±8 | 0.34±.02 | 0.41±.03 | 0.36±.02 |
| Pakban | 20±1 | 27±2 | 339±27 | 85±6 | 0.23±.02 | 0.29±.02 | 0.25±.02 |
| Pahlawan | 29±2 | 84±5 | 575±45 | 194±12 | 0.52±.03 | 0.60±.04 | 0.54±.04 |
| Zoorkandai | 21±1 | 33±2 | 728±57 | 125±9 | 0.34±.02 | 0.40±.03 | 0.37±.03 |
| Garangi | 22±1 | 34±2 | 248±21 | 90±6 | 0.24±.02 | 0.30±.02 | 0.25±.02 |
| Kharaqy | 37±2 | 39±2 | 477±38 | 129±9 | 0.35±.02 | 0.45±.03 | 0.37±.02 |
| Halimzai | 17±1 | 17±1 | 648±51 | 91±6 | 0.25±.02 | 0.29±.02 | 0.28±.02 |
| Sherpao | 45±3 | 67±4 | 652±51 | 191±12 | 0.52±.03 | 0.64±.04 | 0.54±.04 |
| Matta | 39±2 | 54±3 | 586±46 | 161±11 | 0.44±.03 | 0.54±.04 | 0.46±.03 |
| Umarzai | 34±2 | 47±3 | 472±38 | 137±9 | 0.37±.02 | 0.4±.036 | 0.39±.03 |
| Minimum | 17±1 | 17±1 | 248±21 | 85±6 | 0.23±.02 | 0.29±.02 | 0.25±.02 |
| Maximum | 45±3 | 84±5 | 728±57 | 194±12 | 0.52±.03 | 0.64±.04 | 0.54±.04 |
| AM±SD | 29±9 | 44±20 | 523±147 | 133±39 | 0.36±.11 | 0.43±.13 | 0.38±.11 |
| GM±GSD | 28±1.18 | 41±1.26 | 500±1.18 | 128±1.16 | 0.35±1.16 | 0.42±1.16 | 0.37±1.17 |

$^{232}$Th activity varied from 17 ± 1 to 86 ± 5 Bq.kg$^{-1}$ whilst $^{40}$K varied from 262 ± 22 to 1018 ± 79 Bq.kg$^{-1}$ in this district. In the district Charsadda $^{226}$Ra activity varied from 17 ± 1 to 45 ± 3 Bq.kg$^{-1}$, $^{232}$Th varied from 17 ± 1 to 84 ± 5 Bq.kg$^{-1}$ having an average value of 44 ± 20 Bq.kg$^{-1}$ whilst $^{40}$K varied from 248 ± 21 to 728 ± 57 Bq.kg$^{-1}$ with an average value of 523 ± 147 Bq.kg$^{-1}$. In the Mohmand agency $^{226}$Ra activity varied from 8 ± 1 to 30 ± 2 Bq.kg$^{-1}$, $^{232}$Th from 7 ± 1 to 34 ± 2 Bq.kg$^{-1}$ and $^{40}$K varied from 153 ± 13 to 795 ±

62 Bq.kg$^{-1}$. Average radium equivalent activity for this agency was found to be 78 ± 30 Bq.kg$^{-1}$.

In the Bajuar agency, $^{226}$Ra activity varied from 8 ± 1 to 34 ± 3 Bq.kg$^{-1}$, $^{232}$Th from 9 ± 1 to 64 ± 4 Bq.kg$^{-1}$and $^{40}$K varied from 220 ± 19 to 836 ± 65 Bq.kg$^{-1}$. Average radium equivalent activity for this agency was found to be 116 ± 42 Bq.kg$^{-1}$.

Table 6.4: Natural radioactivity, radium equivalent activity in Bq.kg$^{-1}$, external and internal hazard indices and effective doses in the samples collected from the Mohmand agency.

| Location | $^{226}$Ra (Bq.kg$^{-1}$) | $^{332}$Th (Bq.kg$^{-1}$) | $^{40}$K (Bq.kg$^{-1}$) | $Ra_{eq}$ (Bq.kg$^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Safi | 16±1 | 16±1 | 795±62 | 101±7 | 0.27±.02 | 0.32±.02 | 0.31±.02 |
| Qalakalai | 23±1 | 34±2 | 475±37 | 109±7 | 0.29±.02 | 0.36±.02 | 0.31±.02 |
| Narogha | 8±1 | 7±1 | 160±14 | 31±2 | 0.08±.01 | 0.10±.01 | 0.09±.01 |
| Sheikh Baba | 9±1 | 11±1 | 248±20 | 44±3 | 0.12±.01 | 0.14±.01 | 0. 13±.01 |
| Alingar | 27±2 | 34±2 | 153±13 | 88±6 | 0.2±.024 | 0.31±.01 | 0.24±.02 |
| Lakaro | 30±2 | 34±2 | 458±36 | 114±8 | 0.31±.02 | 0.39±.03 | 0.33±.01 |
| S.Khan koor | 24±1 | 34±2 | 369±29 | 100±6 | 0.27±.02 | 0.33±.02 | 0.29±.02 |
| Karkanai | 11±1 | 16±1 | 199±16 | 49±3 | 0.13±.01 | 0.16±.01 | 0.14±.01 |
| Qandari | 8±1 | 13±1 | 325±11 | 52±3 | 0.14±.01 | 0.16±.01 | 0.15±.01 |
| Ghalanai | 19±1 | 28±1 | 386±11 | 89±3 | 0.24±.01 | 0.29±.01 | 0.15±.01 |
| Minimum | 8±1 | 7±1 | 153±13 | 31±2 | 0.08±.01 | 0.10±.01 | 0.09±.01 |
| Maximum | 30±2 | 34±2 | 795±62 | 114±8 | 0.31±.02 | 0.39±.03 | 0.33±.01 |
| AM±SD | 18±8 | 23±12 | 357±193 | 78±30 | 0.21±.08 | 0.26±.10 | 0.23±0.09 |
| GM±GSD | 16±1.30 | 20±1.34 | 315±1.24 | 71.3±1.26 | 0.19±1.25 | 0.23±1.27 | 0.21±1.26 |

As may be seen in table 6.6, $^{226}$Ra activity varied from 9 ± 1 to 50 ± 3 Bq.kg$^{-1}$, $^{232}$Th activity varied from 6 ± 1 to 68 ± 4 Bq.kg$^{-1}$ and $^{40}$K activity varied from 77 ± 8 to 672± 52 Bq.kg$^{-1}$ in the brick samples which were collected from the selected area. Average radium equivalent activity for the brick samples is 129 ± 54 Bq.kg$^{-1}$.

In the sand samples (see table 6.7), $^{226}$Ra activity varied from 2 ± 1 to 31 ± 2 Bq.kg$^{-1}$ with an average value of 19 ± 9 Bq.kg$^{-1}$, $^{232}$Th activity varied from 6 ± 1 to 51 ± 3 Bq.kg$^{-1}$ having an average value of 30 ± 15 Bq.kg$^{-1}$ whilst $^{40}$K activity varied from 424 ± 33 to 1745 ± 135 Bq.kg$^{-1}$ with an average value of 769 ± 461 Bq.kg$^{-1}$. Variation in the

radium equivalent activity ranged from 43 ± 3 to 234 ± 16 Bq.kg$^{-1}$ with an average value of 121 ± 57 Bq.kg$^{-1}$. In the marble samples (see table 6.8), $^{226}$Ra activity varied from 1 ± 1 to 62 ± 4 Bq.kg$^{-1}$, $^{232}$Th activity varied from 1 ± 1 to 66 ± 4 Bq.kg$^{-1}$ and $^{40}$K activity varied from 25 ± 2 to 890 ± 69 Bq.kg$^{-1}$ whereas In marble samples radium equivalent activity varied from 24 ± 2 to 198 ± 13 with an average value of 67 ± 60 Bq.kg$^{-1}$.

Table 6.5: Natural radioactivity, radium equivalent activity in Bq.kg$^{-1}$, external and internal hazard indices and effective doses in the samples collected from the Bajuar agency.

| Location | $^{226}$Ra (Bq.kg$^{-1}$) | $^{332}$Th (Bq.kg$^{-1}$) | $^{40}$K (Bq.kg$^{-1}$) | $Ra_{eq}$ (Bq.kg$^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Delai | 28±2 | 40±2 | 503±39 | 124±8 | 0.34±.02 | 0.41±.03 | 0.36±.02 |
| Mashkanro | 9±1 | 18±1 | 220±19 | 51±4 | 0.14±01 | 0.16±.01 | 0.15±.01 |
| Sabagai | 8±1 | 15±1 | 836±65 | 94±7 | 0.25±.02 | 0.28±.02 | 0.29±.02 |
| Loisum | 23±2 | 37±2 | 410±33 | 108±7 | 0.29±.02 | 0.35±.02 | 0.31±.02 |
| Luyjuhar | 28±2 | 39±2 | 502±39 | 122±8 | 0.33±.02 | 0.40±.03 | 0.35±.02 |
| Tarakai | 9±1 | 9±1 | 518±41 | 61±4 | 0.17±.01 | 0.19±.01 | 0.19±.01 |
| Tangai | 25±2 | 35±2 | 386±30 | 105±7 | 0.28±.02 | 0.35±.02 | 0.30±.02 |
| Khar | 25±1 | 49± | 553±43 | 138±9 | 0.37±.02 | 0.44±.03 | 0.40±.02 |
| Zorbandar | 33±2 | 59±3 | 687±53 | 170±11 | 0.46±.03 | 0.55±.04 | 0.49±.03 |
| Mamond | 44±3 | 64±4 | 625±49 | 183±12 | 0.50±.03 | 0.61±.04 | 0.52±.03 |
| Minimum | 8±1 | 9±1 | 220±19 | 51±4 | 0.14±01 | 0.16±.01 | 0.15±.01 |
| Maximum | 44±3 | 64±4 | 836±65 | 183±12 | 0.50±.03 | 0.61±.04 | 0.52±.03 |
| AM±SD | 23±12 | 37±18 | 524±170 | 116±42 | 0.31±.11 | 0.38±.14 | 0.33±0.12 |
| GM±GSD | 20±1.36 | 31±1.38 | 496±1.20 | 108±1.23 | 0.29±1.23 | 0.35±1.24 | 0.31±1.22 |

In cement samples (table 6.9), $^{226}$Ra activity showed variation from 19 ± 1 to 34 ± 2 Bq.kg$^{-1}$, with an average value of 24 ± 6 Bq.kg$^{-1}$, $^{232}$Th activity varied from 13 ± 1 to 23 ± 1 Bq.kg$^{-1}$ with an average value of 18 ± 4 Bq.kg$^{-1}$ and $^{40}$K activity varied from 215 ± 17 Bq.kg$^{-1}$ to 282 ± 22 Bq.kg$^{-1}$ with an average of 244 ± 29 Bq.kg$^{-1}$. Radium equivalent activity varied from 58 ± 4 to 80 ± 5 Bq.kg$^{-1}$ with an average value of 68 ± 9 B.kg$^{-1}$.

### *6.3.2. External and Internal Indices*

External hazard indices from the soil samples collected from the district Swabi varied from 0.18 ± 0.01 to 0.51 ± 0.03 and internal indices varied from 0.22 ± 0.01 to 0.66 ± 0.04 with average values of 0.35 ± 0.10 and 0.43 ± 0.12, respectively. In the district Mardan, variation in the external indices was from 0.24 ± 0.02 to 0.69 ± 0.04 with an

average value of 0.37 ± 0.13, whilst internal hazard indices varied from 0.29 ± 0.02 to 0.83 ± 0.05 with an average value of 0.46 ± 0.44. In the district Charsadda, the external hazard indices varied from 0.23 ± 0.02 to 0.52 ± 0.03 with an average value of 0.36 ± 0.11 whilst internal hazard indices showed variation in the range of 0.29 ± 0.02 to 0.64 ± 0.04 with an average of 0.43 ± 0.13.

Table.6.6: $^{226}Ra$, $^{232}Th$, $^{40}K$ and $Ra_{eq}$, external and internal hazard indices and effective dose measured in brick samples which were collected from the districts Swabi, Mardan and Charsadda.

| Location | $^{226}Ra$ ($Bq.kg^{-1}$) | $^{332}Th$ ($Bq.kg^{-1}$) | $^{40}K$ ($Bq.kg^{-1}$) | $Ra_{eq}$ ($Bq.kg^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| MD | 46±3 | 68±4 | 667±52 | 195±13 | 0.53±0.03 | 0.65±0.04 | 0.56±0.04 |
| NR | 45±3 | 56±3 | 620±48 | 173±11 | 0.47±0.03 | 0.59±0.04 | 0.49±0.03 |
| SS | 14±1 | 16±1 | 672±52 | 88±6 | 0.24±0.02 | 0.27±0.02 | 0.27±0.02 |
| SB | 9±1 | 6±1 | 360±28 | 45±3 | 0.12±0.01 | 0.14±0.01 | 0.14±0.01 |
| PS | 14±1 | 15±1 | 77±8 | 41±3 | 0.11±0.01 | 0.15±0.01 | 0.12±0.01 |
| Mumtaz | 36±2 | 42±2 | 641±50 | 146±10 | 0.39±0.03 | 0.49±0.03 | 0.42±0.03 |
| GD | 31±2 | 47±3 | 510±40 | 138±9 | 0.37±0.02 | 0.46±0.03 | 0.39±0.03 |
| Star | 25±2 | 57±3 | 550±43 | 149±10 | 0.40±0.03 | 0.47±0.03 | 0.42±0.03 |
| PK | 34±2 | 42±2 | 554±43 | 136±9 | 0.37±0.02 | 0.46±0.03 | 0.39±0.03 |
| TB | 50±3 | 58±3 | 583±46 | 178±11 | 0.48±0.03 | 0.62±0.04 | 0.51±0.03 |
| Minimum | 9±1 | 6±1 | 77±8 | 41±3 | 0.11±0.01 | 0.15±0.01 | 0.12±0.01 |
| Maximum | 50±3 | 68±4 | 672±52 | 195±13 | 0.53±0.03 | 0.65±0.04 | 0.56±0.04 |
| AM±SD | 30±15 | 41±21 | 523±182 | 129±54 | 0.35±0.15 | 0.43±0.18 | 0.37±0.15 |
| GM±GSD | 27±1.3 | 33±1.5 | 463±1.4 | 115±1.33 | 0.31±1.33 | 0.38±1.33 | 0.33±1.31 |

In the Mohmand agency, the external hazard indices varied from 0.08 ± 0.01 to 0.31 ± 0.02 with an average value of 0.21 ± 0.08 whilst internal hazard indices showed variation which ranged from range of 0.10 ± 0.01 to 0.39 ± 0.03 with an average value of 0.26 ± 0.1. In the Bajuar agency, the external hazard indices varied from 0.14 ± 0.01 to 0.50 ± 0.03 with an average value of 0.31 ± 0.11 and internal hazard indices varied from 0.16 ± 0.01 to 0.61 ± 0.04 with an average of 0.38 ± 0.14.

Variation in the external hazard indices in brick samples (see table 6.6) ranged from 0.11 ± 0.01 to 0.53 ± 0.03 with an average value of 0.35 ± 0.15 whilst internal indices varied from 0.15 ± 0.01 to 0.65 ± 0.04 with an average of 0.43 ± 0.18. In the sand sample (see table 6.7), variation in the external indices was from 0.12 ± 0.01 to 0.63 ± 0.04 with an average value of 0.33 ± 0.15 and internal hazard indices varied from 0.12 ± 0.01 to 0.70 ± 0.05 with an average value of 0.38 ± 0.17. In marble samples (see table 6.8), variation in the external indices was from 0.07 ± 0.01 to 0.57 ± 0.04 with an average value of 0.18 ± 0.16 and internal hazard indices varied from 0.08 ± 0.01 to 0.65 ± 0.04 with an average value of 0.23 ± 0.20, respectively.

In the cement samples (table 6.9), external hazard indices varied from 0.16 ± 0.01 to 0.22 ± 0.01 with an average value of 0.19 ± 0.03 whilst internal hazard indices showed variation in the range of 0.21 ± 0.01 to 0.31 ± 0.02 with an average value of 0.25 ± 0.04.

### *6.3.3. Calculations of Effective Dose*

Annual effective dose form the soil and other building materials were calculated from the air absorbed doses using equation 4.

As may be seen in tables 6.1-6.5, in the district Swabi, annual effective dose varied from 0.25 ± 0.01 to 0.54 ± 0.04 mSv $yr^{-1}$. In the Mardan district, the variation was from 0.27 ± 0.02 to 0.73 ± 0.05 mSv $yr^{-1}$ (see tables 6.1-6.5). In the Charsadda district variation in the effective dose was from 0.25 ± 0.02 to 0.54 ± 0.04 mSv $yr^{-1}$. The effective dose equivalent in the Mohmand agency varied from 0.15 ± 0.01 to 0.52 ±.03 mSv $yr^{-1}$, and in the Bajuar agency the variation observed was in the range of 0.09 ± 0.01 to 0.33 ± 0.01 mSv $yr^{-1}$ with an average value of 0.23 ± 0.09 mSv $yr^{-1}$. As may be seen in tables 6.6 – 6.9, effective dose in the brick samples (see table 6.6), varied from 0.12 ± 0.01 to 0.56 ± 0.04 mSv $yr^{-1}$ with average value of 0.37 ± 0.15 mSv $yr^{-1}$. In the sand samples (see table 6.7), variation was from 0.14 ± 0.01 to 0.71 ± 0.05 mSv $yr^{-1}$ with an average value of 0.33 ± 0.15 mSv $yr^{-1}$.

In the marble samples (see table 6.8), variation in the effective dose was from 0.07 ± 0.01 to 0.57 ± 0.04 mSv $yr^{-1}$ with an average value of 0.20 ± 0.17 mSv. The

effective dose from the cement samples (see table 6.9) varied from 0.17 ± 0.01 to 0.23 ± 0.02 mSv $yr^{-1}$, with an average value of 0.20 ± 0.03 mSv $yr^{-1}$.

Table 6.7: $^{226}Ra$, $^{232}Th$, $^{40}K$ and $Ra_{eq}$, external and internal hazard indices and effective dose measured in the sand samples collected from Swabi, Mardan, Charsadda districts as well as Mohmand and Bajuar agencies.

| Location | $^{226}Ra$ ($Bq.kg^{-1}$) | $^{332}Th$ ($Bq.kg^{-1}$) | $^{40}K$ ($Bq.kg^{-1}$) | $Ra_{eq}$ ($Bq.kg^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Gandab Kawar | 26±2 | 51±3 | 1745±135 | 234±16 | 0.63±0.04 | 0.70±0.05 | 0.71±0.05 |
| Sheikh Baba | 22±1 | 43±3 | 1476±115 | 198±14 | 0.53±0.04 | 0.60±0.04 | 0.60±0.04 |
| Toro Nalai | 2±1 | 6±1 | 424±33 | 43±3 | 0.12±0.01 | 0.12±0.01 | 0.14±0.01 |
| S.Killi Kwar | 8±1 | 15±1 | 836±65 | 94±7 | 0.25±0.02 | 0.28±0.02 | 0.29±0.02 |
| Yaqurban | 19±1 | 24±1 | 483±38 | 90±6 | 0.24±0.02 | 0.30±0.02 | 0.27±0.02 |
| Lahore | 21±1 | 34±2 | 532±41 | 110±7 | 0.30±0.02 | 0.36±0.02 | 0.32±0.02 |
| Maniri | 31±2 | 47±3 | 510±40 | 138±9 | 0.37±0.02 | 0.46±0.03 | 0.39±0.03 |
| Tangai Kwar | 15±1 | 24±1 | 603±47 | 96±7 | 0.26±0.02 | 0.30±0.02 | 0.29±0.02 |
| Rustum Kwar | 21±1 | 16±1 | 548±43 | 86±6 | 0.23±0.02 | 0.29±0.02 | 0.26±0.02 |
| Zorbandar | 27±2 | 40±2 | 537±43 | 125±8 | 0.34±0.02 | 0.41±0.03 | 0.36±0.02 |
| Minimum | 2±1 | 6±1 | 424±33 | 43±3 | 0.12±0.01 | 0.12±0.01 | 0.14±0.01 |
| Maximum | 31±2 | 51±3 | 1745±135 | 234±16 | 0.63±0.04 | 0.70±0.05 | 0.71±0.05 |
| AM±SD | 19±9 | 30±15 | 769±461 | 121±57 | 0.33±0.15 | 0.38±0.17 | 0.33±0.15 |
| GM±GSD | 16±1.5 | 26±1.4 | 680±1.3 | 0.30±1.27 | 0.35±1.28 | 0.35±1.28 | 110±1.27 |

## 6.4. Discussion

The concentration of radionuclides understudy in the soil samples collected from different localities varied from area to area. For example, a minimum value of 8 ± 1 $Bq.kg^{-1}$ for $^{226}Ra$ was observed in samples from Naroga (Mohmand agency) and Sabagai (Bajuar agency) and maximum specific activity of 53 ± 3 $Bq.kg^{-1}$ in Kalambad (district Mardan) and 54 ± 3 $Bq.kg^{-1}$ was found in the Swabi city. $^{232}Th$ activity was found to be 7 ± 1 $Bq.kg^{-1}$ (Narogha), 9 ± 1 $Bq.kg^{-1}$ (Tarakai) in the Mohmand and Bajuar agencies, respectively to 84 ± 5 $Bq.kg^{-1}$, 86 ± 5 $Bq.kg^{-1}$ in the Pahlawan in the district Charsadda and Kalambad (Mardan), respectively. A minimum specific activity for $^{40}K$ was 153 ± 13 $Bq.kg^{-1}$ in the Alingar area of the Mohmand agency and a maximum value of 1018 ± 79 $Bq.kg^{-1}$ was observed in the Kalambad, district Mardan. Radium equivalent activity

showed variation from 31 ± 2 $Bq.kg^{-1}$ (Narogha) to 194 ± 12 $Bq.kg^{-1}$ in Pahlawan area of the district Charsadda and 255 ± 17 $Bq.kg^{-1}$ Kalamabad. If the measured radioactivity is compared with the geology of the area, it shows that alluvial soils have higher concentration of radioactive elements as compared to that of metabasites metamorphic and igneous rocks.

In general, average maximum specific activities for $^{226}Ra$, $^{232}Th$ and $^{40}K$ were observed in the district Mardan and minimum in the Mohmand agency. The areas of Narogha, Sheik Baba, Qandari of Mohmand agency and Maskano, Sabagai, Tarakai in Bajuar agency have little vegetation cover. The observed $^{226}Ra$ and $^{232}Th$ specific activities in the samples collected from Maskano, Sabagai, Tarakai, Narogha, Sheik Baba and Qandari were very low and thus are safe to use as building materials.

Table 6.10 shows the results of the current study along with other data reported for different parts of Pakistan. It may be seen in this table that average activities calculated in the present study lies within the reported values; however the measured values for $^{40}K$, in the present study are slightly higher than the world population weighted average value (420 Bq. $kg^{-1}$) as reported in the UNSCEAR 2000.

For $^{226}Ra$, overall average minimum and maximum activities of 18 ± 19 $Bq.kg^{-1}$ and 30 ± 15 $Bq.kg^{-1}$ were observed in marble and sand samples, respectively. In general, minimum average activities for $^{232}Th$ were 18 ± 4 and 18 ± 21 $Bq.kg^{-1}$ in cement and marble samples, respectively whereas maximum activity of 41 ± 21 $Bq.kg^{-1}$ was observed in the sand samples collected from the selected area.

As the specific activities, radium equivalent activity and internal and external hazard indices of the soil samples reported in this study are within the acceptable limit. Therefore the use of these soils in the construction of dwellings is considered to be safe for the inhabitants especially the soil of Mohmand agency which has relatively low values of specific activities as compared to the other districts/agency.

Similarly, measured specific activities of $^{226}Ra$, $^{232}Th$ and $^{40}K$ varied from sample to sample in the brick, sand, marble and cement samples. For example, both for $^{226}Ra$ and $^{232}Th$, minimum value of 1 ± 1 $Bq.kg^{-1}$ was observed in the marble samples

(Greenish). maximum value of 62 ± 4 (Dagi Mb) and (Pink M) 66 ± 4 Bq.kg$^{-1}$ was also observed in marble samples.

Table 6.8: $^{226}$Ra, $^{232}$Th, $^{40}$K and $Ra_{eq}$, external and internal hazard indices and effective dose measured in the marble samples collected from the selected area.

| Brand | $^{226}$Ra (Bq.kg$^{-1}$) | $^{332}$Th (Bq.kg$^{-1}$) | $^{40}$K (Bq.kg$^{-1}$) | $Ra_{eq}$ (Bq.kg$^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Yellow | 28±2 | 34±2 | 535±42 | 119±8 | 0.32±0.02 | 0.40±0.03 | 0.34±0.02 |
| Pink M | 41±3 | 66±4 | 819±64 | 198±13 | 0.54±0.03 | 0.65±0.04 | 0.57±0.04 |
| Dagi Mb | 62±4 | 2±1 | 25±2 | 66±4 | 0.18±0.01 | 0.34±0.02 | 0.19±0.01 |
| Black M | 34±2 | 54±3 | 665±52 | 161±11 | 0.44±0.03 | 0.53±0.03 | 0.46±0.03 |
| Dark Green | 10±1 | 8±1 | 93±8 | 29±2 | 0.08±0.01 | 0.11±0.01 | 0.08±0.01 |
| White Swabi | 7±1 | 7±1 | 115±9 | 27±2 | 0.07±0.01 | 0.09±0.01 | 0.08±0.01 |
| Off-White | 5±1 | 8±1 | 99±8 | 24±2 | 0.07±0.01 | 0.08±0.01 | 0.07±0.01 |
| Reddish | 6±1 | 7±1 | 98±8 | 24±2 | 0.06±0.01 | 0.08±0.01 | 0.07±0.01 |
| Greenish | 1±1 | 1±1 | 890±69 | 71±6 | 0.19±0.01 | 0.20±0.02 | 0.24±0.02 |
| Dark Brown | 8±1 | 15±1 | 56±5 | 34±2 | 0.09±0.01 | 0.11±0.01 | 0.09±0.01 |
| Br. Mardan | 6±1 | 8±1 | 103±8 | 25±2 | 0.07±0.01 | 0.08±0.01 | 0.07±0.01 |
| Light Brown | 11±1 | 8±1 | 94±8 | 30±2 | 0.08±0.01 | 0.11±0.01 | 0.09±0.01 |
| Minimum | 1±1 | 1±1 | 25±2 | 24±2 | 0.07±0.01 | 0.08±0.01 | 0.07±0.01 |
| Maximum | 62±4 | 66±4 | 890±69 | 198±13 | 0.54±0.03 | 0.65±0.04 | 0.57±0.04 |
| AM±SD | 18±19 | 18±21 | 299±328 | 67±60 | 0.18±0.16 | 0.23±0.20 | 0.20±0.17 |
| GM±GSD | 10±1.9 | 10±2 | 164±1.9 | 49±1.52 | 0.13±1.52 | 0.17±1.52 | 0.14±1.52 |

For $^{40}$K, minimum value of 25 ± 2 Bq.kg$^{-1}$ and a maximum of 1745 ± 135 Bq.kg$^{-1}$ (Gandab Kawar) were observed in marble and sand samples, respectively.

For $^{40}$K, average minimum value of 244 ± 29 Bq.kg$^{-1}$ was observed in brick samples whilst average maximum value of 769 ± 461 Bq.kg$^{-1}$ was observed in the cement samples. Average minimum radium equivalent value of 67 ± 60 Bq.kg$^{-1}$ was observed in the marble samples and maximum average value of 129 ± 54 Bq.kg$^{-1}$ was observed in sand samples. In table 6.11, present data of the sand, marble and cement samples have been compared with some other published data. As may be seen in table 6.11, $^{226}$Ra value of the present selected samples is slightly lower than those reported by the other groups.

Table 6.9: $^{226}Ra$, $^{232}Th$, $^{40}K$ and $Ra_{eq}$, external and internal hazard indices and effective dose measured in the cement samples collected from the area understudy.

| Brand | $^{226}Ra$ ($Bq.kg^{-1}$) | $^{332}Th$ ($Bq.kg^{-1}$) | $^{40}K$ ($Bq.kg^{-1}$) | $Ra_{eq}$ ($Bq.kg^{-1}$) | $H_{ex}$ | $H_{in}$ | Annual effective dose (mSv) |
|---|---|---|---|---|---|---|---|
| Chairman | 21±1 | 23±1 | 264±21 | 74±5 | 0.20±0.01 | 0.26±0.02 | 0.21±0.01 |
| Askari | 34±2 | 17±1 | 282±22 | 80±5 | 0.22±0.01 | 0.31±0.02 | 0.23±0.02 |
| Fuji | 19±1 | 16±1 | 215±17 | 58±4 | 0.16±0.01 | 0.21±0.01 | 0.17±0.01 |
| Cherat | 25±2 | 13±1 | 219±17 | 60±4 | 0.16±0.01 | 0.23±0.01 | 0.17±0.01 |
| Lucky | 20±1 | 21±1 | 240±19 | 69±5 | 0.19±0.01 | 0.24±0.02 | 0.20±0.01 |
| Minimum | 19±1 | 13±1 | 215±17 | 58±4 | 0.16±0.01 | 0.21±0.01 | 0.17±0.01 |
| Maximum | 34±2 | 23±1 | 282±22 | 80±5 | 0.22±0.01 | 0.31±0.02 | 0.23±0.02 |
| AM±SD | 24±6 | 18±4 | 244±29 | 68±9 | 0.19±0.03 | 0.25±0.04 | 0.20±0.03 |
| GM±GSD | 23±1.1 | 18±1.1 | 243±1 | 68±105 | 0.18±.105 | 0.25±1.05 | 0.19±1.05 |

However, specific activity of $^{232}Th$ in some samples is higher and in some samples lower than those of the reported values. In spite of this trend, present average value of $^{232}Th$ is still lower than the world population weighted average values. Specific activity of $^{40}K$ is on the higher side as compared to the other reported studies especially the values obtained from the sand samples in the present study; however it is still in the range of the reported values. Average activities calculated in the present study lies within the reported values and are also lower than the world population weighted average value as reported in the UNSCEAR 2000.

Specific activities, radium equivalent activity and internal and external hazard indices for all the selected samples are within the acceptable limits. Therefore, use of these materials in construction of dwellings may be considered safe for the inhabitants from a radiological point of view.

In general, soil has more mean activity concentrations of $^{226}Ra$, $^{232}Th$ and $^{40}K$ as compared to the brick, sand, marble and cement samples which were collected from the selected area whilst marble has the least concentration of the naturally occurring radionuclides. The results are comparable with those reported for some other parts of Pakistan.

Table 6.10: Comparison of the present values with some other data reported for other parts of Pakistan.

| Location | $^{226}$Ra (Bq.kg$^{-1}$) | $^{332}$Th (Bq.kg$^{-1}$) | $^{40}$K (Bq.kg$^{-1}$) | Reference |
|---|---|---|---|---|
| Faisalabad Barren soil | 24–29 | 49–54 | 499–604 | Tufail et al., 2006. |
| Faisalabad cultivated soil | 27–33 | 46–62 | 563–629 | Tufail et al., 2006. |
| Bahawalpur | 32.9±0.9 | 53.6±1.4 | 647.4±14.1 | Matiullah et al., 2004. |
| Punjab | 41 ±8 | 35 ±7 | 615 ±143 | Tahir(2005). |
| Nowshera | 44 | 56 | 668 | Khan, (2001). |
| Peshawar | 42 | 56 | 562 | Khan(1995). |
| Islamabad | 38 | 59 | 690 | Tufail(1991). |
| Lahore | 18 | 28 | 570 | Akhtar (2005). |
| NWFP and FATA | 26±9 | 39±20 | 485±450 | The present study |

Table 6.11: Comparison of the present study with other data reported for different parts of the world (All the activities are shown in Bq.kg$^{-1}$).

| Location | $^{226}$Ra (Bq.kg$^{-1}$) | $^{332}$Th (Bq.kg$^{-1}$) | $^{40}$K (Bq.kg$^{-1}$) | Reference |
|---|---|---|---|---|
| Sri Lanka, Brick | 35 | 72 | 585 | Hewamanna et al.,2005 |
| Pakistan, Marble | 27 | 26 | 58 | Tufail et al., 2000 |
| China, Cement | 64.7 | 48.7 | 161.3 | Xinwei, 2005 |
| Pakistan, Sand | 36.9-51.9 | 52.5-67.6 | 680-784 | Khan et al., 2005 |
| Egypt, Cement | 33± 17 | 14± 2.4 | 45± 26 | Mahmud, 2007 |
| Iran, Cement | 33 | 30 | 700 | Fathivand et al., 2007 |
| World Range | 17–60 | 11–64 | 140–850 | UNSCEAR, 2000 |
| World Population weighted Average | 32 | 45 | 420 | |
| Brick | 30±15 | 41±21 | 523±182 | The present study |
| Sand | 19±9 | 30±15 | 769±461 | The present study |
| Marble | 18±19 | 18±21 | 299±328 | The present study |

## 6.5. Conclusions

Mean activity concentrations of $^{226}Ra$, $^{232}Th$ and $^{40}K$ in soil sand, brick, marble and cement samples from the three districts and two Tribal Agencies were measured. The results are comparable with the values reported for the specific activities in some other parts of the country and also with worldwide findings. Radium equivalent activity external and internal hazard indices are well below the acceptable hazard limit of 370 Bq $kg^{-1}$ (OECD, 1979; Beretka and Mathew, 1985) and 1, respectively. Therefore, the use of these soils as building materials in the construction of dwellings may be considered to be safe for the inhabitants. For soil higher average $^{226}Ra$ contents were found in the Mardan district and lower values have been measured for the Mohmand agency. Over all higher average $^{226}Ra$ was measured in the soil as compared to other studied building materials. In other studied building materials, bricks samples have more $^{226}Ra$ as compared to the other materials. Least $^{226}Ra$ was observed in the marble samples. In soil samples relatively higher average $^{232}Th$ activity was measured for the Mardan, Swabi and Charsadda districts as compared to the Mohmand and Bajuar agencies. Low $^{232}Th$ contents were measured in the marble and cement samples studied while sand has intermediate values between marble, cement and soil samples. Higher $^{40}K$ was measured in the soil of the Mardan district while low values are reported for the soil samples form Mohmand agency. Highest average $^{40}K$ was measured in the sand samples collected form the studies area. Relatively higher radium equivalent was measured in the Mardan district, and Lower in the Mohmand agency.

# Chapter Seven

# Electrets as a Radon Progenies Dosimeter

## 7.1. Introduction

A number of active and passive devices are currently being used for the measurement of ionizing radiations. Most of the passive devices, although relatively cheaper, are suitable only for a long-term measurements. Reading of such passive detectors is time consuming and its sensitivity, in some cases, is relatively low (respond to specific band of energy), its reading requires a time delay due to processing requirements (etchings) and thus the results are not instantly available. Unlike other passive devices electret ion chamber (EIC) provides rapid results. EICs are used for accurate measurement of different types of radiation including indoor radon measurements (Dua et al.,1999 & 2002). According to US EPA estimates, 30% to 40%, of radon researchers in USA utilize the electret ionization chambers (Colle´ et al., 1995). In EICs, ionization current is integrated over a period of time by noting the drop in the surface voltage on electret that is placed inside an ion chamber. An electret is a sample of dielectric material (commonly Teflon) that carries a quasi-permanent electric charge.

As the amount of voltage drop on the electret provides an accurate correlation to the number of ions collected and hence to the total energy lost by the alpha-emitting isotope (Kasper, 1999). The EIC system is accurate and sensitive. The EIC system provides consistent, repeatable results that are, on average, within 5% accuracy. Aluminized Mylar window is used in case of measurement of alpha contamination on surfaces, to reduce the effect of dust (Dua , 1999; Sun et al., 2006).

The electret chambers may be reused again and again. The electrets are replaced after making 10 to 20 measurements until its voltage drops below 200V and it is then

recharged. EIC measurement performance is comparable to the scintillation technology.

The surface potential of electrets remains stable even under extreme conditions of relative humidity (Kotrappa et al., 1988; Mahat et al., 2001). In a study conducted in UK, at radon concentration of 500 Bq $m^{-3}$, the resulting perturbation was 3% over a 7-day deployment; at the typical value of 80 Bq $m^{-3}$ it approached to 22% (Denman et al., 2001).

Electrets are sensitive to gamma rays and on the presence of a high gamma background an error ranging up to about 20% may be introduced (Usman et al., 1999; Kim et al., 2003; Righi, and Bruzzi, 2006; Espinosa et al., 2005; Pilkte and Butus et al., 2005; Paulus et al., 2003; Martinez et al., 1998; Samer et al., 2007; Clouvas et al., 2006; Gervino et al., 2007; Fricke et al., 1999).

This chapter deals with the use of EIC in measuring the radon concentration, determining the equilibrium factor and unattached fraction. Before discussing the experimental details it would be informative to briefly discuss main components of the electrets and its calibration.

## 7.2. Components of E-PERMS

Electret-passive environmental radon monitor (E-PERM) system consist of three components (1) electrostatically charged Teflon called electrets (2) an ion chamber made of conductive plastics to which an electret can be loaded (3) a voltage reader to read the surface potential of the electrets.

7.2.1. Electrets: Electrets are made of Teflon which is electrically charged by a special process so that it retains the charge permanently. Electrets are of two types (a) positive (b) negative. The surface charge of the electret is neutralized by collection of ions from the surroundings and the surface voltage of the electrets decrease proportionally when these ions are collected on the electret surface.

7.2.2. The electret ion chamber: Nuclear radiation emitted by radon or other radioactive materials during decay generates ions in air. When this occurs in the fixed volume of the conductive plastic chamber, the ions are collected on the charged electrets which work as a mean of measuring radiations. Such instrument is called electret ion chamber.

7.2.3. The Electret Reader: To read the potential of the electret the electronic instrument called surface potential electret voltage reader (SPER) is used. This reader is able to read the potential drop of a minimum of one volt (1V). To measure the integrated drop of potential drop of the electret, before placing the electret in the chamber its initial voltage (I) is recorded, after exposure the final voltage (F) of the electret and the exposure time in days is recorded. The calibration factor (CF) for E-PERM is calculated which is linearly related to the electret voltage drop over a range of 150V to 750V to the average voltage during the exposure.


Figure 7.1: Electret ion chambers used for measurement of radon and thoron progeny deposited on the surface.

### 7.3. Principal of Measurement of Alpha Contamination

The surface EIC with its aluminized Mylar window is used to measure alpha radiation from the contaminated surfaces or alpha emitters deposited on its surface. Area monitored is 48.7 $cm^2$ and the response of electric ion chamber is for all the alpha radiations from different isotopes. The results are expressed in alpha counts per 100 $cm^2$ in $4\pi$ geometry.

The calibration factor for measurement of alpha contamination with ST electrets is given by the following relation.

$CF=0.0006416+2.4303\times10^{-7}\times(I+F)/2$ and the alpha contamination levels in unit of alpha disintegration per minute per 100 $cm^2$ is calculated by

$$A = \alpha(\text{dpm per } 100\ cm^2) = \frac{(I-F)\times 2.053}{CF\times T}$$

However when LT electrets are used the results may be multiplied by 11.5, if a window is used the result is multiplied by 1.794 (Part-II Section .4.Alpha Rev#0 ,1994). Electrets are sensitive to gamma radiation, to correct the electret readings for background gamma radiation; the background (BG) factor is introduced. BG depends on the chamber as well as on the place of measurement.

## 7.4. Alpha Contamination Electret Measurement System as Radon Progeny Dosimeter

### *7.4.1. Experimental Approach*

As stated above, special electret ion chambers (EICs) can be used for the measurement of surface alpha contamination (see Figure 7.1). However in the present study these alpha contamination chambers have been used in a novel approach to measure its performance for the measurement of airborne radon progeny concentration through surface deposited radon progeny. In these experiments surface electret ion chambers have been used in such a way that Mylar side was directed upward and ionization produced by deposited radon progenies have been measured instead of alpha contamination. In order to measure the performance factor (PF) of this alpha contamination chamber radon concentration was measured side by side using the standard chambers with short term electrets to determine the radon concentration. Experiments were performed using both short term (high sensitivity) and long term (low sensitivity) electrets.

To correct the readings for the gamma background and radon gas, an electret with plastic cover (see Figure 7.1) which blocks the detection of alpha was used for the subtraction of the effect gamma radiation on these chambers. During the measurement aerosols conditions of the room was changed (i.e. from normal aerosol conditions with no turbulence or aerosols generating activity) to the use of different types of aerosols generating activities like propane cooking, candle burning, cigarette smoking and fan and using different High Efficiency Particle Air (HEPA) filters and unattached fraction and equilibrium factor was measured.

### *7.4.2. Measurement of Radon using Electrets*

Commercially available E-PERMs were used to measure the indoor radon concentration during the experiments using alpha contamination chambers to measure the plate out

radon progeny concentration in the exposure room. As E-PERMs are sensitive to gamma rays therefore corrections were applied (Kotrappa and Stieff, 1992; 1993). In order to measure the radon using electrets two steps are involved. First the calibration factor (CF) was determined using the following formula

$$CF = \frac{Volts}{\frac{pCi}{l} \times day} = A + B \times \frac{(I + F)}{2}$$

Where A and B are constant for a particular E-PERM configuration and "I" and "F" are the initial and final voltages of the electrets exposed in the chamber. Radon concentration was then calculated by using the following relation

$$\mathrm{RnC}\left(\frac{pCi}{l}\right) = \frac{(\mathrm{I\text{-}F})}{\mathrm{CF} \times D} \text{-BG}$$

Where RnC is the radon concentration in units of $pCi.\ell^{-1}$ or in $Bqm^{-3}$ ($1\ pCi.L^{-1}$ $=37.5\ Bqm^{-3}$), "I" and "F" are the initial and final voltage readings of the exposed electret. In the present work standard chamber "S" having volume of 200ml was used. Different configurations are used for making measurements i.e. when short term electret (ST) used in S-chamber, the e-perm is called "SST" e-perm. When a long term (LT) is loaded into "S" chamber the electret is called "SLT" E-PERM. In the present study "SST" configuration was used. The background values for S chamber are 0.087 R/h.

SST electrets were exposed to indoor radon concentration in the exposure room and its initial and final voltages were noted along with the exposure duration. Blue labeled (Short-term) electret in Standards chamber (SST) calibration factor was found using the following calibration factor (see table 7.1).

$$CF = 1.69776 + 0.0057420 \times \frac{(I + F)}{2}$$

These calibration factors are used in the 200-750V range (Kotrappa, 1990). Electrets have the following components of error.

1. The system imperfection error, which include uncertainty in chamber volume, electret thicknesses and other component parameters. It is 5 % (Kotrappa et al., 1990).

2. Error component 2: the error of the electret reading. There can be an uncertainty of as much as 1 volt in both initial and final readings; the error in the difference of the two readings is 1.4 volts. the percentage =100×1.4/(I-F)

3. Error component 3: error due to gamma background. the maximum error is about 0.1 to 0.2 pCi.$\ell^{-1}$

4. Total error is Et=sqrt($E_1^2$+$E_2^2$+$E_3^2$)

Using standard radon chambers results obtained are shown in table 7.1. As can be seen from table 7.1 radon concentration as measured by using the short term high sensitivity electrets are stable and the variation between the different readings of the same exposure(run) is low. The exposure of four short term electrets on March 20, have radon concentration of 43 ± 6 pCi.$\ell^{-1}$, 44 ± 6 pCi.$\ell^{-1}$, 44 ± 5 pCi.$\ell^{-1}$ and 44 ± 5 pCi.$\ell^{-1}$ with standard deviation of ~ zero. Similar reading was obtained on March 30 and the two detectors showed the same value of 22 ± 4 pCi.$\ell^{-1}$ with no standard deviation.

The maximum variation among the reading of different electrets used in the same run was recorded in a run in which three electrets were exposed in which the two reading were 34 ± 8, 34 ± 8 pCi.$\ell^{-1}$ and the third one had value of 158 ± 8 pCi.$\ell^{-1}$. This high difference thought to be the accidental drop due to the touching of the surface of the electret by hand or some other conducting materials, which have caused this high difference in the voltage drop.

In majority of the cases more than one electrets were exposed to the indoor radon and the reading were in a very good agreement For example, the exposure of five electrets on March 11 for 0.33 days gave results of 36 ± 6, 32 ± 7, 34 ± 7, 33 ± 7 and 34 ± 6 pCi.$\ell^{-1}$ with an average of 34 ± 7 pCi.$\ell^{-1}$ and having standard deviation of only two. On March 12, exposure of five electrets for 0.71 days gave results of 58 ± 3 , 60 ± 3, 57 ± 3, 57 ± 3 and 70 ± 4 with an average of 60 ± 6 pCi.$\ell^{-1}$ and a standard deviation of this run is only 5. In total of 36 runs of experiments in which two or more than two electrets were exposed in the exposure room the standard deviation between different readings was less

than 10. In only three reading the standard deviation among the reading was higher than 10, which may be due to the accidental touching of the surface of the electrets which causes unwanted discharge of the surface. Measuring radon concentrations above 150 Bq $m^{-3}$ (i.e., 4 pCi.$\ell^{-1}$) the relative difference is normally less than 20% using electrets. The difference is mostly less than 10% for radon concentrations above (5.3 pCi $\ell^{-1}$) 200 Bq $m^{-3}$. If accurate results (variation 20%) are required for measurements made in time period of less than 6 months at low radon concentrations (below 200 $Bqm^{-3}$), L-chambers with short-term electrets (LST combination) should be used (Vargas and Ortega, 2001). E-PERMs show better performance at a very high radon concentration (Gervino et al., 2004). The E-PERM provides to be very good for measuring the indoor radon concentration.

### 7.5. Calculation of the Performance Factor for The Measurement of Radon Progeny

Alpha contamination chambers were exposed to radon progeny and radon measurements were carried out using both standard radon chambers and active detector for a suitable time (see table 7.1). The performance factor was calculated and inter-compared for different environmental conditions using the long-term electret for the measurement of radon progenies. Short-term electret with thick plastic top cover was used for the measurement of background. The readings from long-term electrets were multiplied by 12.5 (due to low sensitivity of the long term electrets) and then the calculations were performed (Manual of E-PERMS Part-II - II.4.Alpha Rev#0,1994).

For the measurement of normalized Voltage drop of the long-term electrets, the following relation was used.

$$NVPD = \frac{((12.5 \times F_{LT} - F_{ST}) - (12.5 \times I_{LT} - I_{ST}))}{T(Days)}$$

Normalized Voltage drop (NVPD), $F_{LT}$ = Final reading of long-term electret, $F_{ST}$ Final reading of short-term electret, $I_{LT}$ = Initial reading of long-term electret, $I_{ST}$ Initial reading T = Exposure time (in days).

Table 7.1: Radon concentration measurements made in the exposure room using standard electrets.

| ID | Initial Volts (VI) | Final Volts (VF) | Calib.Facotr | Exposure (Days) | Rn(pCi.ℓ$^{-1}$) | Rn(Bq.m$^{-3}$) | Av Rn |
|---|---|---|---|---|---|---|---|
| ST 9979 | 347 | 324 | 1.89 | 0.33 | 36±6 | 1335 | 34±7 |
| SQ 8344 | 431 | 410 | 1.94 | 0.33 | 32±7 | 1184 | |
| SQ8431 | 360 | 338 | 1.9 | 0.33 | 34±7 | 1270 | |
| SQ8293 | 315 | 294 | 1.87 | 0.33 | 33±7 | 1228 | |
| SK 3783 | 494 | 471 | 1.98 | 0.33 | 34±6 | 1276 | |
| ST 9979 | 324 | 246 | 1.86 | 0.71 | 58±3 | 2184 | 60±3 |
| SQ 8344 | 410 | 328 | 1.91 | 0.71 | 60±3 | 2239 | |
| SQ8431 | 338 | 261 | 1.87 | 0.71 | 57±3 | 2146 | |
| SQ8293 | 294 | 218 | 1.84 | 0.71 | 57±3 | 2147 | |
| SK 3783 | 471 | 374 | 1.94 | 0.71 | 70±4 | 2612 | |
| ST 9979 | 246 | 225 | 1.83 | 0.35 | 32±7 | 1203 | 34±7 |
| SQ 8344 | 328 | 306 | 1.88 | 0.35 | 33±7 | 1230 | |
| SQ8431 | 261 | 237 | 1.84 | 0.35 | 37±6 | 1374 | |
| SQ8293 | 218 | 197 | 1.82 | 0.35 | 32±7 | 1214 | |
| SK 3783 | 374 | 350 | 1.91 | 0.35 | 35±6 | 1326 | |
| SK 3783 | 350 | 293 | 1.88 | 0.63 | 47±3 | 1771 | 47±3 |
| ST 9979 | 217 | 193 | 1.82 | 0.35 | 36±6 | 1366 | |
| SQ 8344 | 303 | 278 | 1.86 | 0.35 | 37±6 | 1386 | |
| SQ8431 | 231 | 206 | 1.82 | 0.35 | 38±6 | 1418 | |
| SQ8293 | 182 | 159 | 1.8 | 0.35 | 35±6 | 1322 | |
| SK 3783 | 293 | 268 | 1.86 | 0.35 | 37±6 | 1390 | |
| Su0079 | 366 | 339 | 1.9 | 0.35 | 39±6 | 1471 | 37±6 |
| SQ 8344 | 278 | 206 | 1.84 | 0.65 | 60±4 | 2242 | |
| SQ8431 | 206 | 140 | 1.8 | 0.65 | 56±4 | 2098 | |
| SQ8293 | 159 | 96 | 1.77 | 0.65 | 54±4 | 2032 | |
| SK 3783 | 268 | 186 | 1.83 | 0.65 | 69±4 | 2570 | |
| Su0079 | 339 | 262 | 1.87 | 0.65 | 63±4 | 2356 | 60±4 |
| ST 9979 | 187 | 161 | 1.8 | 0.35 | 40±6 | 1497 | |
| SQ 8344 | 206 | 180 | 1.81 | 0.35 | 40±6 | 1488 | |
| SQ8431 | 140 | 116 | 1.77 | 0.35 | 37±6 | 1401 | |
| SQ8293 | 96 | 73 | 1.75 | 0.35 | 36±6 | 1361 | |
| SK 3783 | 186 | 154 | 1.8 | 0.35 | 49±5 | 1853 | |
| Su0079 | 262 | 231 | 1.84 | 0.35 | 47±5 | 1751 | 42±6 |
| SQ8424 | 461 | 386 | 1.94 | 0.63 | 61±4 | 2284 | |
| SU0025 | 452 | 374 | 1.94 | 0.98 | 40±3 | 1502 | |
| SU0081 | 267 | 198 | 1.83 | 0.98 | 37±3 | 1401 | |
| SU0007 | 184 | 114 | 1.78 | 0.98 | 39±3 | 1461 | 43±3 |
| SK3783 | 156 | 86 | 1.77 | 0.98 | 39±3 | 1475 | |
| SQ8424 | 386 | 364 | 1.91 | 0.31 | 36±7 | 1346 | 32±8 |
| SU0081 | 198 | 177 | 1.81 | 0.31 | 36±7 | 1362 | |
| SU0007 | 114 | 95 | 1.76 | 0.31 | 34±8 | 1263 | |
| SK3783 | 86 | 71 | 1.74 | 0.31 | 27±9 | 999 | |

(Table 7.1: continued )

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| SQ8424 | 364 | 302 | 1.89 | 0.68 | 48±3 | 1784 | 46±3 |
| SU0025 | 369 | 302 | 1.89 | 0.68 | 51±3 | 1929 | |
| SU0081 | 177 | 121 | 1.78 | 0.68 | 45±3 | 1705 | |
| SU0007 | 95 | 39 | 1.74 | 0.68 | 47±3 | 1752 | |
| SK3783 | 71 | 25 | 1.73 | 0.68 | 38±4 | 1443 | |
| SQ8424 | 302 | 277 | 1.86 | 0.34 | 38±6 | 1429 | 30±8 |
| SU0081 | 121 | 99 | 1.76 | 0.34 | 35±7 | 1329 | |
| SU0007 | 39 | 24 | 1.72 | 0.34 | 25±9 | 920 | |
| SK3783 | 25 | 11 | 1.71 | 0.34 | 23±10 | 860 | |
| SQ8424 | 277 | 224 | 1.84 | 0.68 | 42±3 | 1560 | 40±3 |
| SU0025 | 297 | 241 | 1.85 | 0.68 | 44±3 | 1641 | |
| SU0081 | 99 | 54 | 1.74 | 0.68 | 37±3 | 1397 | |
| SK9979 | 161 | 113 | 1.78 | 0.68 | 39±3 | 1463 | |
| SQ8424 | 224 | 198 | 1.82 | 0.32 | 44±6 | 1662 | 41±6 |
| SU0025 | 241 | 215 | 1.83 | 0.32 | 44±6 | 1653 | |
| SU0081 | 54 | 35 | 1.72 | 0.32 | 34±8 | 1275 | |
| SK9979 | 113 | 90 | 1.76 | 0.32 | 41±6 | 1520 | |
| ST9995 | 355 | 333 | 1.9 | 0.71 | 15±6 | 581 | 16±6 |
| SQ0098 | 382 | 357 | 1.91 | 0.31 | 41±6 | 1554 | 44±6 |
| SQ 8366 | 346 | 320 | 1.89 | 0.31 | 44±6 | 1636 | |
| SQ276 | 435 | 408 | 1.94 | 0.31 | 44±6 | 1655 | |
| ST9995 | 333 | 306 | 1.88 | 0.31 | 46±6 | 1708 | |
| SQ0098 | 357 | 280 | 1.88 | 0.65 | 62±4 | 2343 | 60±4 |
| SQ 8366 | 320 | 246 | 1.86 | 0.65 | 61±4 | 2276 | |
| SQ276 | 408 | 334 | 1.91 | 0.65 | 59±4 | 2215 | |
| ST9995 | 306 | 238 | 1.85 | 0.65 | 56±3 | 2096 | |
| SQ0098 | 280 | 247 | 1.85 | 0.33 | 53±5 | 1995 | 52±5 |
| SQ 8366 | 246 | 216 | 1.83 | 0.33 | 49±5 | 1829 | |
| SQ276 | 334 | 300 | 1.88 | 0.33 | 54±5 | 2022 | |
| ST9995 | 238 | 207 | 1.83 | 0.33 | 51±5 | 1897 | |
| SQ0098 | 247 | 188 | 1.82 | 0.66 | 48±3 | 1796 | 44±3 |
| SQ 8366 | 216 | 157 | 1.81 | 0.66 | 48±3 | 1814 | |
| SQ276 | 300 | 240 | 1.85 | 0.66 | 48±3 | 1797 | |
| ST9995 | 207 | 167 | 1.81 | 0.66 | 33±4 | 1219 | |
| SQ0098 | 188 | 162 | 1.8 | 0.33 | 43±6 | 1627 | 44±6 |
| SQ276 | 240 | 213 | 1.83 | 0.33 | 44±6 | 1663 | |
| ST9807 | 420 | 392 | 1.93 | 0.33 | 44±5 | 1632 | |
| SU0101 | 381 | 353 | 1.91 | 0.33 | 44±5 | 1652 | |
| SQ276 | 213 | 126 | 1.8 | 0.69 | 69±4 | 2591 | 72±4 |
| ST9807 | 392 | 297 | 1.9 | 0.69 | 71±4 | 2680 | |
| SU0101 | 353 | 254 | 1.87 | 0.69 | 75±4 | 2830 | |
| ST9807 | 297 | 260 | 1.86 | 0.31 | 63±5 | 2367 | 64±5 |
| SU0101 | 254 | 215 | 1.83 | 0.31 | 68±5 | 2531 | |
| SU0022 | 306 | 270 | 1.86 | 0.31 | 61±5 | 2295 | |

(Table 7.1: continued )

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| ST9807 | 260 | 174 | 1.82 | 0.67 | 70±4 | 2620 | 71±4 |
| SU0101 | 215 | 126 | 1.8 | 0.67 | 73±4 | 2754 | |
| SU0022 | 270 | 183 | 1.83 | 0.67 | 70±4 | 2643 | |
| ST9807 | 174 | 152 | 1.79 | 0.32 | 37±7 | 1392 | 36±7 |
| ST9916 | 303 | 282 | 1.87 | 0.32 | 34±7 | 1273 | |
| SU0022 | 183 | 161 | 1.8 | 0.32 | 37±7 | 1388 | |
| ST9807 | 152 | 86 | 1.77 | 0.68 | 54±3 | 2015 | 61±4 |
| ST9916 | 282 | 206 | 1.84 | 0.68 | 60±4 | 2233 | |
| SU0022 | 161 | 74 | 1.77 | 0.68 | 71±4 | 2668 | |
| ST9807 | 86 | 66 | 1.74 | 0.32 | 35±7 | 1329 | 39±7 |
| ST9916 | 206 | 181 | 1.81 | 0.32 | 43±6 | 1606 | |
| SU0022 | 74 | 53 | 1.73 | 0.32 | 37±7 | 1403 | |
| ST9807 | 66 | 25 | 1.72 | 0.69 | 34±4 | 1257 | 36±4 |
| ST9916 | 181 | 128 | 1.79 | 0.69 | 42±3 | 1576 | |
| SU0022 | 53 | 13 | 1.72 | 0.69 | 33±4 | 1231 | |
| ST9807 | 127 | 108 | 1.77 | 0.31 | 34±8 | 1266 | 75±8 |
| ST9916 | 128 | 109 | 1.77 | 0.31 | 34±8 | 1266 | |
| SU0022 | 161 | 74 | 1.77 | 0.31 | 158±8 | 5919 | |
| ST9807 | 108 | 57 | 1.75 | 0.68 | 42±3 | 1571 | 41±3 |
| ST9916 | 109 | 60 | 1.75 | 0.68 | 40±3 | 1507 | |
| SJ5697 | 290 | 287 | 1.86 | 0.3 | 4±47 | 166 | 4±47 |
| SJ5697 | 287 | 265 | 1.86 | 0.67 | 17±6 | 633 | 17±6 |
| SJ5697 | 265 | 261 | 1.85 | 0.33 | 6±35 | 211 | 6±35 |
| SJ5697 | 243 | 228 | 1.83 | 0.99 | 7±9 | 275 | 7±9 |
| SJ5697 | 228 | 187 | 1.82 | 1 | 22±4 | 812 | 22±4 |
| SJ5697 | 228 | 187 | 1.82 | 1 | 22±4 | 812 | 22±4 |
| SJ5697 | 159 | 100 | 1.85 | 1.02 | 30±3 | 1140 | 32±3 |
| SBH346 | 561 | 492 | 2 | 1.02 | 33±3 | 1233 | |
| SB897 | 522 | 454 | 1.98 | 1.02 | 33±3 | 1229 | |
| SBH346 | 492 | 416 | 1.96 | 1.21 | 31±2 | 1167 | 32±2 |
| SB897 | 454 | 377 | 1.94 | 1.21 | 32±2 | 1197 | |
| SBH346 | 416 | 370 | 1.92 | 0.79 | 29±3 | 1096 | 28±3 |
| SB897 | 377 | 334 | 1.9 | 0.79 | 28±4 | 1034 | |

For the measurement of normalized voltage drop for short-term electret the following relation was used.

$$NVPD = \frac{((F_{ST} - F_{BG}) - (I_{ST} - I_{BG}))}{T(Days)}$$

$F_{BG,}$ $I_{BG}$ are the final and initial reading of the background.

Performance factor (PF) was calculated using the following relation

$$PF = \frac{NVPD}{C_{Rn}}$$

$C_{Rn}$ is radon concentration.

**7.6. Results and Discussion**

As may be seen in table 7.1 radon concentrations during the experiment was in the ranged from 30 pCi.ℓ$^{-1}$ to 60 pCi.ℓ$^{-1}$ (1125-2250 Bq.m$^{-3}$) with an over all average was 44 pCi.ℓ$^{-1}$. The duration of each experiment was 0.3 - 1 day. The results of NVPD and PF are shown in tables 7.2a –7.2c.

*7.6.1. Long-term Electrets*

The performance factor was also compared with the equilibrium factor and unattached fraction of the radon progenies. The results showed that long term electret can be used in the inverted form for the measurement of radon progenies as the voltage drop per pCi.ℓ$^{-1}$ of radon is such that in the case of long-term electret (less sensitive) duration of exposure may be kept relatively longer, in order to get a suitable voltage drop.

Three sets of long-term electrets were used in these experiments. As may be seen in table 7.2c, the performance factor calculated for the three long-term electrets varied from -1.1 to 11.0 V/d.pCi.ℓ$^{-1}$ (Volt per day per Pico Curie per liter) with an average of 2. 20 ± 5.6 V/d. pCi.ℓ$^{-1}$ for the electret labeled LL12059 (excluding the three failures) and form 0.49 to 13.64 with an average of 2.90 ± 2.7 V/d.pCi.ℓ$^{-1}$ (having one failure) for the LL2187 and for the electret labeled LL2257 the variation was from 0.52 to 12.51 V/d.pCi.ℓ$^{-1}$ with an average of 2.60 ± 2.2 V/d.pCi.ℓ$^{-1}$ while the average of all the three electrets for each run had variation from 0.5 to 12.51 V/d.pCi.ℓ$^{-1}$ with an over all average of 2.68 ± 2.1 V/d. pCi.ℓ$^{-1}$.

As may be seen in table 7.2c, there were only four times out of 108 readings that performance factor of the alpha contamination measurement detector was negative i,e

long-term electrets failed to work as a radon progeny monitor. The average of these electrets were in good agreement, showing that long term electret showed more fluctuations in the short term reading while for long term average there was relatively less fluctuations.

After analyzing the data for these electrets it may be concluded that in a higher radon progeny environment, the use of long-term electret as a radon progeny detector would be suitable while for low radon concentrations performance factor for short duration may be difficult carry out. However, if the sensitivity of voltage reader is enhanced from lower limit of one volt in the current voltage readers, to some lower values say millivolt (mV), then long-term electret can also be used in the low radon environments.

Table 7.2a: Voltage drop of different long term electrets used as radon progeny monitors (Volts).

| Device | IV1 | FV1 | FV2 | FV3 | FV4 | FV5 | FV6 | FV7 | FV8 | FV9 |
|---|---|---|---|---|---|---|---|---|---|---|
| SCM 668 | 390 | 380 | 339 | 323 | 298 | 287 | 253 | 240 | 207 | 194 |
| LL12059 | 507 | 501 | 493 | 492 | 486 | 482 | 475 | 470 | 459 | 457 |
| LL2187 | 488 | 486 | 473 | 471 | 466 | 463 | 454 | 450 | 440 | 438 |
| LL2257 | 437 | 433 | 424 | 421 | 412 | 410 | 403 | 400 | 388 | 387 |
| Device | FV10 | FV11 | FV12 | FV13 | FV14 | FV15 | FV16 | FV17 | IV18 | FV18 |
| SCM 668 | 172 | 160 | 137 | 127 | 98 | 84 | 56 | 44 | 364 | 335 |
| LL12059 | 450 | 448 | 439 | 435 | 427 | 427 | 414 | 414 | 414 | 407 |
| LL2187 | 433 | 428 | 422 | 418 | 408 | 404 | 393 | 389 | 389 | 381 |
| LL2257 | 376 | 372 | 369 | 365 | 355 | 353 | 340 | 339 | 339 | 330 |
| Device | FV19 | FV20 | FV21 | FV22 | FV23 | FV24 | IV25 | FV25 | FV26 | FV27 |
| SCM 668 | 320 | 275 | 259 | 215 | 205 | 172 | 294 | 280 | 250 | 235 |
| LL12059 | 402 | 389 | 385 | 375 | 373 | 361 | 361 | 358 | 348 | 342 |
| LL2187 | 376 | 366 | 360 | 349 | 345 | 335 | 335 | 332 | 326 | 322 |
| LL2257 | 325 | 310 | 306 | 297 | 296 | 285 | 285 | 281 | 275 | 270 |
| Device | FV28 | FV29 | FV30 | FV31 | IV32 | FV32 | FV33 | FV34 | FV35 | FV36 |
| SCM 668 | 203 | 197 | 186 | 181 | 482 | 473 | 433 | 396 | 354 | 330 |
| LL12059 | 332 | 331 | 328 | 327 | 326 | 322 | 315 | 304 | 295 | 291 |
| LL2187 | 316 | 314 | 311 | 310 | 308 | 306 | 297 | 288 | 281 | 275 |
| LL2257 | 263 | 262 | 258 | 257 | 256 | 253 | 244 | 235 | 226 | 222 |

Other possibility may be to use these low sensitivity electrets for a relatively longer duration measurements. Over all performance of these low sensitivity detectors

originally used for the measurement of alpha contamination, may also be used as radon progeny dosimeters and would thus work as alternative radon progeny monitor

*7.6.2. Short-term high sensitivity electrets*

The results of the short-term high sensitivity electrets are shown in table 7.3a – 7.3c. Table 7.3a shows the data of the voltage drop of the short term electret for different runs of the experiments

Table 7.2b: Normalized voltage drop (NVPD) in Volts/day of different long-term electrets used as radon progeny monitors.

| Electret | NVPD1 | NVPD2 | NVPD3 | NVPD4 | NVPD5 | NVPD6 | NVPD7 | NVPD8 | NVPD9 |
|---|---|---|---|---|---|---|---|---|---|
| LL12059 | 197 | 83 | -10 | 78 | 108 | 84 | 138 | 161 | 39 |
| LL2187 | 45 | 171 | 26 | 59 | 74 | 123 | 103 | 142 | 39 |
| LL2257 | 121 | 101 | 63 | 137 | 39 | 84 | 68 | 180 | -2 |
| Electret | NVPD10 | NVPD11 | NVPD12 | NVPD13 | NVPD14 | NVPD15 | NVPD16 | NVPD17 | NVPD18 |
| LL12059 | 98 | 38 | 134 | 125 | 170 | -47 | 201 | -36 | 86 |
| LL2187 | 60 | 149 | 78 | 125 | 206 | 120 | 163 | 115 | 104 |
| LL2257 | 172 | 112 | 22 | 125 | 206 | 37 | 201 | 2 | 123 |
| Electret | NVPD19 | NVPD20 | NVPD21 | NVPD22 | NVPD23 | NVPD24 | NVPD25 | NVPD26 | NVPD27 |
| LL12059 | 144 | 175 | 106 | 119 | 45 | 172 | 73 | 138 | 188 |
| LL2187 | 144 | 119 | 184 | 138 | 121 | 135 | 73 | 65 | 109 |
| LL2257 | 144 | 213 | 106 | 101 | 8 | 154 | 113 | 65 | 148 |
| Electret | NVPD28 | NVPD29 | NVPD30 | NVPD31 | NVPD32 | NVPD33 | NVPD34 | NVPD35 | NVPD36 |
| LL12059 | 135 | 21 | 39 | 24 | 41 | 48 | 93 | 104 | 33 |
| LL2187 | 63 | 60 | 39 | 24 | 16 | 73 | 70 | 67 | 64 |
| LL2257 | 81 | 21 | 57 | 24 | 29 | 73 | 70 | 104 | 33 |

Table 7.3b shows the normalized voltage drop during different runs of the experiment whereas table 7.3c shows the performance factor of the electret calculated for different runs during the experiment.

In order to measure the effect of orientation of the electret on its performance factor, the electrets were exposed in two orientation i.e., horizontal and vertical positions.

As can be seen in table 7.3c the performance factor of the detector placed in the horizontal orientation varied from 0.51 to 3.53 V/d.pCi.$\ell^{-1}$ for electret labelled A whilst for electret labeled B it varied from 0.45 to 3.37 V/d.pCi.$\ell^{-1}$ with an average varied from 0.48-3.45 V/d.pCi.$\ell^{-1}$.For the electrets exposed in the vertical position the values varied

from 0.51 to 4.8 V/d.pCi.$\ell^{-1}$ for electret C whilst for the other electret it varied from 0.74 to 3.81 V/d.pCi.$\ell^{-1}$. The average value of the performance factor in the vertical position varied from 0.62 to 4.31 V/d.pCi.$\ell^{-1}$. As may be seen in table 7.3c the performance factor of the electrets exposed in horizontal position is relatively higher as compared to those exposed in vertical positions. However this deviation in performance factor is not significant.

Table 7.2c: Performance factor in V/d.pCi.$\ell^{-1}$ of different long-term electrets used as radon progeny monitors**.**

| Electret | PF 1 | PF 2 | PF 3 | PF 4 | PF 5 | PF 6 | PF 7 | PF 8 | PF 9 |
|---|---|---|---|---|---|---|---|---|---|
| LL12059 | 5.9 | 1.4 | -0.3 | 1.7 | 2.9 | 1.4 | 3.3 | 3.7 | 1.2 |
| LL2187 | 1.4 | 2.8 | 0.8 | 1.2 | 2.0 | 2.0 | 2.5 | 3.4 | 1.2 |
| LL2257 | 3.6 | 1.7 | 1.9 | 2.9 | 1.0 | 1.4 | 1.6 | 4.3 | -0.1 |
| Average | 3.6 | 2.0 | 0.8 | 1.9 | 2.0 | 1.6 | 2.5 | 3.8 | 0.8 |
| % | 63% | 39% | 139% | 45% | 47% | 23% | 34% | 12% | 92% |
| | PF 10 | PF 11 | PF 12 | PF 13 | PF 14 | PF 15 | PF 16 | PF 17 | PF 18 |
| LL12059 | 2.1 | 1.3 | 3.3 | 3.1 | 11.0 | -1.1 | 3.4 | -0.7 | 1.9 |
| LL2187 | 1.3 | 4.9 | 1.9 | 3.1 | 13.3 | 2.7 | 2.7 | 2.2 | 2.4 |
| LL2257 | 3.8 | 3.7 | 0.5 | 3.1 | 13.3 | 0.8 | 3.4 | 0.0 | 2.8 |
| Average | 2.4 | 3.3 | 1.9 | 3.1 | 12.5 | 0.8 | 3.2 | 0.5 | 2.4 |
| % | 52% | 56% | 72% | 0% | 10% | 227% | 11% | 295% | 18% |
| | PF 19 | PF 20 | PF 21 | PF 22 | PF 23 | PF 24 | PF 25 | PF 26 | PF 27 |
| LL12059 | 3.3 | 2.4 | 1.7 | 1.7 | 1.3 | 2.8 | 1.9 | 3.8 | 2.5 |
| LL2187 | 3.3 | 1.7 | 2.9 | 1.9 | 3.4 | 2.2 | 1.9 | 1.8 | 1.5 |
| LL2257 | 3.3 | 3.0 | 1.7 | 1.4 | 0.2 | 2.5 | 2.9 | 1.8 | 2.0 |
| Average | 3.3 | 2.3 | 2.1 | 1.7 | 1.6 | 2.5 | 2.2 | 2.5 | 2.0 |
| % | 0% | 28% | 34% | 15% | 100% | 12% | 26% | 47% | 26% |
| | PF 28 | PF 29 | PF 30 | PF 31 | PF 32 | PF 33 | PF 34 | PF 35 | PF 36 |
| LL12059 | 3.3 | 4.7 | 2.3 | 4.2 | 1.3 | 2.2 | 2.9 | 3.3 | 1.1 |
| LL2187 | 1.5 | 13.6 | 2.3 | 4.2 | 0.5 | 3.3 | 2.2 | 2.1 | 2.2 |
| LL2257 | 2.0 | 4.7 | 3.4 | 4.2 | 0.9 | 3.3 | 2.2 | 3.3 | 1.1 |
| Average | 2.3 | 7.7 | 2.7 | 4.2 | 0.9 | 3.0 | 2.4 | 2.9 | 1.5 |
| | 41% | 68% | 24% | 0% | 44% | 22% | 17% | 23% | 42% |

Thus it may be concluded that orientation has insignificant effect on the performance of the electrets if used as a surface deposition activity monitor. Standard deviation for each run is shown in the table 7.3c. A maximum value of 34% and a

minimum value of 17% were recorded for the eight runs. These short-term electrets were found most suitable for the measurement of both high and low levels of radon progeny concentration. However, when high radon concentrations are present, short term measurement must be performed, otherwise the voltage drop may be too high .to the measurement will be inaccurate if the electret voltage is less than 150 V.

Table 7.3a: Voltage drop of different short-term electrets used as radon progeny monitors.

| Device | IV | FV1 | IV2 | FV2 | IV3 | FV3 | IV4 | FV4 | IV5 | FV5 | IV6 | FV6 | IV7 | FV7 | IV8 | FV8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HorzA | 368 | 258 | 517 | 348 | 460 | 422 | 412 | 392 | 392 | 361 | 352 | 173 | 568 | 541 | 537 | 449 |
| ABlk | 231 | 192 | 507 | 460 | 348 | 329 | 321 | 309 | 309 | 287 | 288 | 228 | 575 | 557 | 555 | 531 |
| HorzB | 480 | 319 | 446 | 328 | 477 | 437 | 503 | 483 | 483 | 449 | 337 | 135 | 569 | 545 | 541 | 455 |
| BBlk | 492 | 446 | 319 | 274 | 274 | 252 | 422 | 410 | 410 | 384 | 343 | 277 | 311 | 296 | 291 | 266 |
| VertC | 512 | 382 | 382 | 206 | 522 | 487 | 468 | 446 | 446 | 415 | 361 | 195 | 452 | 421 | 418 | 309 |
| CBlk | 294 | 256 | 256 | 214 | 471 | 451 | 440 | 428 | 428 | 406 | 336 | 273 | 572 | 559 | 554 | 532 |
| VertD | 506 | 345 | 488 | 353 | 500 | 458 | 444 | 427 | 427 | 392 | 391 | 189 | 458 | 423 | 420 | 328 |
| BDBLK | 594 | 549 | 549 | 500 | 353 | 332 | 324 | 311 | 311 | 289 | 327 | 264 | 325 | 307 | 303 | 280 |

Table 7.3b: Normalized voltage drop of different short-term electrets used as radon progeny monitors.

| | NVPD1 | NVPD2 | NVPD3 | NVPD4 | NVPD5 | NVPD6 | NVPD7 | NVPD8 |
|---|---|---|---|---|---|---|---|---|
| HorzA | 72.0 | 123.9 | 57.0 | 31.1 | 24.0 | 117.0 | 28.2 | 165.8 |
| HorzB | 116.6 | 74.1 | 54.0 | 31.1 | 21.3 | 133.7 | 28.2 | 158.0 |
| VertC | 93.3 | 136.1 | 45.0 | 38.9 | 24.0 | 101.2 | 56.3 | 225.3 |
| VertD | 117.6 | 87.3 | 63.0 | 15.6 | 34.7 | 136.6 | 53.2 | 178.7 |

An other series of measurements were also performed using short term electrets. The results obtained are shown in table 7.4a - 7.4c, below.

Table 7.3c: Performance factor (V/d. pCi.$\ell^{-1}$) of different short-term electrets used as radon progeny monitors.

| | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 | PF7 | PF8 |
|---|---|---|---|---|---|---|---|---|
| HorzA | 1.95 | 3.06 | 1.45 | 0.87 | 0.51 | 2.09 | 0.62 | 3.53 |
| HorzB | 3.15 | 1.83 | 1.37 | 0.87 | 0.45 | 2.39 | 0.62 | 3.37 |
| VertC | 2.52 | 3.36 | 1.14 | 1.09 | 0.51 | 1.81 | 1.24 | 4.80 |
| VertD | 3.18 | 2.16 | 1.60 | 0.43 | 0.74 | 2.44 | 1.17 | 3.81 |
| Average | 2.70 | 2.60 | 1.39 | 0.82 | 0.55 | 2.18 | 0.91 | 3.88 |
| Average H | 2.55 | 2.44 | 1.41 | 0.87 | 0.48 | 2.24 | 0.62 | 3.45 |
| Average V | 2.85 | 2.76 | 1.37 | 0.76 | 0.62 | 2.13 | 1.20 | 4.31 |
| Std.Div. | 22% | 28% | 14% | 34% | 23% | 13% | 37% | 17% |

Table 7.4a: Voltage drop of different short-term electrets used as radon progeny monitors.

| Device | IV | FV1 | FV2 | FV3 | FV4 | FV5 | FV6 | FV7 | FV8 | FV9 | IV10 | FV10 | FV11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SCQ497 | 719 | 710 | 707 | 680 | 654 | 571 | 481 | 389 | 337 | 276 | 494 | 468 | 451 |
| SCQ559 | 719 | 717 | 715 | 706 | 695 | 657 | 622 | 581 | 556 | 517 | 507 | 495 | 489 |
| SCQ553 | 698 | 697 | 695 | 675 | 649 | 563 | 473 | 380 | 328 | 269 | 260 | 237 | 220 |
| SCQ499 | 713 | 712 | 712 | 700 | 690 | 649 | 612 | 567 | 541 | 499 | 289 | 278 | 272 |
| SCQ480 | 721 | 720 | 716 | 694 | 671 | 597 | 516 | 430 | 382 | 325 | 295 | 270 | 249 |
| SCQ576 | 682 | 681 | 679 | 672 | 659 | 624 | 592 | 552 | 524 | 473 | 227 | 218 | 210 |
| SCQ542 | 725 | 723 | 721 | 701 | 677 | 597 | 510 | 406 | 351 | 293 | 323 | 300 | 283 |
| SCQ508 | 720 | 720 | 718 | 708 | 697 | 658 | 621 | 578 | 553 | 511 | 254 | 244 | 236 |

Table 7.4b: Normalized voltage drop of different short-term electrets used as radon progeny monitors**.**

| I.D | NVPD 1 | NVPD 2 | NVPD 3 | NVPD 4 | NVPD 5 | NVPD 6 | NVPD 7 | NVPD 8 | NVPD 9 | NVPD 10 | NVPD11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SCQ497 | 27.3 | 1.3 | 20.0 | 14.4 | 63.5 | 54.2 | 43.5 | 34.1 | 19.9 | 7.0 | 9.4 |
| SCQ553 | 0.0 | 2.5 | 8.9 | 15.4 | 63.5 | 52.3 | 40.9 | 32.8 | 15.4 | 6.0 | 9.4 |
| SCQ480 | 0.0 | 2.5 | 16.7 | 9.6 | 55.1 | 48.3 | 39.2 | 25.3 | 5.4 | 8.0 | 11.1 |
| SCQ542 | 7.8 | 0.0 | 11.1 | 12.5 | 57.9 | 49.3 | 52.0 | 37.9 | 14.5 | 6.5 | 7.7 |
| Average | 8.8 | 1.6 | 14.2 | 13.0 | 60.0 | 51.0 | 43.9 | 32.5 | 13.8 | 6.9 | 9.4 |

Table 7.4c: Performance factors in V/d.pCi.$\ell^{-1}$of different short term electrets used as radon progeny monitors.

| I.D | PF1 | PF2 | PF3 | PF4 | PF5 | PF6 | PF7 | PF8 | PF9 | PF10 | PF11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SCQ497 | 2.73 | 0.13 | 2.00 | 1.44 | 1.25 | 1.53 | 1.21 | 1.05 | 0.57 | 1.44 | 2.19 |
| SCQ553 | 0.00 | 0.25 | 0.89 | 1.54 | 1.25 | 1.47 | 1.14 | 1.01 | 0.44 | 1.24 | 2.19 |
| SCQ480 | 0.00 | 0.25 | 1.67 | 0.96 | 1.08 | 1.36 | 1.09 | 0.78 | 0.17 | 1.65 | 2.59 |
| SCQ542 | 0.78 | 0.00 | 1.11 | 1.25 | 1.13 | 1.39 | 1.44 | 1.17 | 0.41 | 1.34 | 1.79 |
| Average | 0.9 | 0.2 | 1.4 | 1.3 | 1.2 | 1.4 | 1.2 | 1.00 | 0.47 | 1.42 | 2.19 |
| Std.Div. | 147% | 77% | 36% | 20% | 7% | 5% | 13% | 16% | 18% | 12% | 15% |

The results of another experiment using short term electrets high sensitivity are shown in table 7.4a – 7.4c. As may be seen in table 7.4c, the performance factor varied from 0.13 to 2.73 V/d.pCi.$\ell^{-1}$ for electret labeled SCQ497. The performance factor varied in the

range 0- 2.19 V/d.pCi.$\ell^{-1}$ and 0- 2.59 V/d.pCi.$\ell^{-1}$ for electrets labeled SCQ553 and SCQ542, whilst for electret SCQ542 it varied from 0 to 1.79 V/d.pCi.$\ell^{-1}$. The average values varied from 0.2 to 2.19. The standard deviation varied from 0.05- 1.47 in different runs. These results show a good agreement among different runs and thus the alpha contamination detectors using short-term electrets can be used as radon progeny dosimeter. It also shows that the use of duplicate deposition detector is better from statistical point of view for reducing uncertainty in the readings and a better average value can be obtained.

### 7.7. Equilibrium and Unattached Fraction of Radon using E-RPISU

Equilibrium factor and unattached fraction of the radon progenies are the two important parameters required for the dose calculation. Radon entry and radon decay product distribution can vary with ambient weather and also with wind, temperature and aerosols conditions in the indoor environment. An increased percentage of unattached decay products leads to or results in a higher risk as compared to the aerosol-attached fraction (Porstendörfer, 2001**)**. Because the amount of radon decay products in the breathing space depends on aerosols particles and turbulence. US EPA relates radon levels to the radon decay product levels by assuming that 40% of the radon decay products produced remain in the air for inhalation. However, this factor can very between 0.1-0.9. Therefore, the simultaneous measurement of both radon and its progeny is desirable for producing an accurate estimate of radon progeny dose rate.

In order to measure unattached fraction and equilibrium factor of radon using E-PERMs an instrument called the Electret-Radon Progeny Integrating Sampling Unit (E-RPISU) was used (Kotrappa et al., 1989). This instrument can measure radon and its decay products simultaneously. The E-RPISU is composed of an air sampling pump, a flow meter and electret ion chambers, one for radon and two for radon progenies. The E-RPISU measures radon progeny with sampling heads (A and B), two flow-meters (A and B), flow-meter tamper resistant cap, ion chambers A and B), Box with pump and power supplies, time totalizer (no reset), power cord (110 V AC) and tubing.

## 7.8. Principle of Operation of E-RPISU

An air-sampling pump (0.3 to 0.6 liters per minute) is used to collect the radon progeny for a known sampling time on a 3.5 $cm^2$ filter sampler mounted on the side of an electret ion chamber. The flow rate of the pump is adjustable. Recommended flow rate is 0.3 to 0.6 liter per minute and the time is from 1 to 7 days. The filter paper and/or mesh is mounted in such a way that the collected progenies emit their radiation within the chamber. The alpha radiations emitted by the progenies are collected on the filter, which ionizes air in the electret ion chamber. The ions are continuously collected by the electret, providing integrated alpha activity collected on the filter paper. The initial and final readings of the electret, the flow rates and the duration of sampling recorded by the time totalizer are used in software to calculate the progenies concentration in terms of working level (WL) units (Progeny Group Limited ).

Once the progeny concentration and radon concentration are known, equilibrium ratios can be calculated using the standard procedures. In order to measure the unattached fraction of radon decay products, air is sampled through a wire mesh in housing B. A down line filter in system B allows for a balanced airflow through both systems. Using these values, radon progeny concentration on both the filter and mesh were calculated using the same procedure. The ratio of the result with mesh to that of filter gives the unattached fraction.

From the measured data of radon and progenies equilibrium factor and unattached fraction were calculated. Radon concentration in pCi (1 pCi = 37.5 $Bq.m^{-3}$) was calculated. Equilibrium factor $F = (PAEC)/C_{Rn}$ was calculated (Kotrappa et al., 1990). The results obtained using different aerosols conditions are shown in the table 7.5. As these measurements were performed under different environmental conditions, therefore, unattached fraction and equilibrium factor showed a wide range of variation. Maximum equilibrium factor of 87% and a minimum unattached fraction of 3% were measured under the smoky environment in the exposure room. One cigarette per hour was used in the Smoking 'Joe smoker' system for producing smoke in the indoor air of the exposure room.

Table 7.5: Equilibrium factor and unattached fraction of radon decay products using ERIPSU

| Conditions | Start | Stop | Days | ERIPSU F | ERIPSU f |
|---|---|---|---|---|---|
| Calm no particles | 3/27/2007 11:25 | 3/28/2007 9:00 | 0.90 | 3% | 55% |
| Calm no particles | 3/28/2007 10:00 | 3/29/2007 11:00 | 1.04 | 4.2% | 51% |
| Calm no particles | 3/29/2007 16:00 | 3/30/2007 9:00 | 0.71 | 2.9% | 86% |
| No particles | 3/30/2007 10:40 | 3/31/2007 11:00 | 1.01 | 11% | 78% |
| Air freshener | 3/31/2007 11:30 | 4/1/2007 15:40 | 1.17 | 17% | 64% |
| Candle (low) | 4/1/2007 16:00 | 4/2/2007 11:00 | 0.79 | 20% | 55% |
| Candle (two)+Bathmist | 4/2/2007 11:30 | 4/3/2007 14:00 | 1.10 | 21% | 10% |
| DJS UL West | 4/22/2007 12:00 | 4/24/2007 12:00 | 2.00 | 10% | 44% |
| DJS LL main | 4/24/2007 12:00 | 4/25/2007 16:00 | 1.17 | 6% | 91% |
| Xroom HEPA | 7/16/2007 10:20 | 7/17/2007 10:00 | 0.99 | 5% | 35% |
| HEPA+ion | 7/17/2007 13:22 | 7/18/2007 13:00 | 0.98 | 4% | 32% |
| Cooking | 7/19/2007 8:00 | 7/19/2007 16:00 | 0.33 | 74% | 7% |
| Smoking | 7/23/2007 10:00 | 7/23/2007 16:10 | 0.26 | 87% | 3% |
| Smoking | 7/24/2007 7:00 | 7/24/2007 16:00 | 0.38 | 61% | 3% |
| None/None | 8/16/2007 8:00 | 8/17/2007 8:25 | 1.02 | 13% | 33% |
| Candle | 8/17/2007 9:48 | 8/17/2007 17:28 | 0.32 | 83% | 6% |
| Propane | 8/23/2007 8:00 | 8/23/2007 18:40 | 0.44 | 56% | 9% |

Measurement performed under the calm conditions showed reduced equilibrium factor and higher unattached fraction. In this case, equilibrium factor varied from 3% to 13% and the unattached fraction varied from 33% to 86%. When Air freshener was used the equilibrium factor was measured as 17% and the unattached fraction was 64%, for low level of candle burning, equilibrium and unattached fraction were 20% and 55%, respectively.

Using Candle (two) + Bathmist the values for equilibrium ratio and unattached fraction were 21% and 10% respectively. When measurements were performed in an actual, occupied home environment (DJS House Collegeville MN a standard US home) the values obtained for equilibrium and unattached fractions were in the range of 6% - 10% and 44% - 91%, respectively.

When aerosol sinks were used, the equilibrium ratio and unattached fraction also changed because both of them depend on the particle concentrations. For HEPA filter, the values were 5% and 35% and for HEPA filter + ionizer, they were 4% and 32% respectively. During cooking of meal, these values were 74% and 7%. For normal conditions these values were 13% and 33%, respectively. For candle burning, conditions equilibrium ratio and unattached fraction values were 83% and 6% respectively. When propane was burnt during the measurement equilibrium ratio and unattached fraction values were 56% and 9% respectively.

### 7.9. Conclusions

A series of measurements were performed to study the feasibility of using the electret ion chamber for the measurement of deposited radon progenies. The results showed that electret ion chambers can be used for this purpose. Both short-term and long term electret were studied. It was observed that for high levels of radon concentration, or for long term measurement low sensitivity (L type) electret is suitable whilst for short term measurement, or low levels of radon progeny concentration measurement, high sensitivity short term electrets can be used. Radon concentration measured using electrets showed very stable behavior and radon concentration derived from different electrets of the same exposure gave nearly the same results. The results of the long-term (low sensitivity) electrets showed more fluctuations than those of short-term (high sensitivity) electrets for short-term measurements. However, their long term average had less fluctuation. Use of the E-RIPSU for the measurement of equilibrium factor and unattached fraction show a wide range of variations depending on the indoor aerosols conditions. Under low aerosol conditions higher unattached fraction and lower value of the equilibrium factor was observed. The E-RIPSU electrets are convenient instrument for measuring the equilibrium factor and unattached fraction.

# Chapter Eight

# Development of Passive Thoron Progeny Dosimeter

## 8.1. Introduction

Thoron ( $^{220}$Rn) belongs to $^{232}$Th decay series. Due to its short-half-life of 55.5 seconds it is not able to travel far. Thoron can be eliminated from the monitoring system by introducing filters or other delaying techniques. The health effect of thoron had been underestimated as compared to the radon ($^{222}$Rn) in the past because of the difficulties in the calibration and measurement of thoron dosimeters (Tokonami, 2005). No epidemiological studies of thoron have been done. However in the recent studies in which radon and thoron released from building materials were measured indicated dose due to thoron and its decay products may be greater than the dose delivered due to radon in the indoor environment (Tuccimei and Norcia, 2006). Research work by Yamada et al. (2006) and others (Michikuni et al., 1994; Quanfu et al., 2004; Tokonami et al., 2002) have shown that thoron plays a very important role in risk evaluation due to two reasons. First, some conventional radon monitors are sensitive to thoron (Masahiro et al., 2006) so radon concentration may be affected by the presence of thoron (Tokonami, 2003; Doi et al., 1994; Shang et al., 1997; Yuan et al., 2004). Studies have shown that thoron was present to a considerable extent in the indoor environment (Doi and Kobayashi et al., 1994; Ma et al., 1997; Tokonami et al., 2002). Radiation exposure due to the inhalation of thoron progeny has been estimated to be of the order of 10 - 20% as that compared with the short-lived radon progenies (Yamasakit et al., 1995; Guo et al.,1992).

Cave dwellings and areas having high $^{232}$Th contents are suitable locations for studying indoor radon and thoron and the long-term health effects of radiation emitted by these isotopes. The longer-lived progenies, $^{212}$Bi ($T_{1/2}$ = 60.6 min) and $^{212}$Po ($T_{1/2}$ = 10.6 h) are never in equilibrium with the parent nuclide (Gargioni and Arnold, 2005).

Therefore thoron progenies cannot be estimated accurately from that of the gas itself using the equilibrium factor as in the case of radon. Therefore, direct measurement of the thoron progenies is preferable (Wiegand et al., 2000).

Significant correlation was found between the deposition rates, concentration of thoron progeny and the deposition velocity for attached radon progeny (Zhou and Iida, 2000) . The ratios of the indoor Potential alpha energy concentration (PAEC) ($^{220}$Rn) to indoor PAEC ($^{222}$Rn) ranged from 0.09 to 0.58, with an overall average ratio of 0.32 (Martz et al., 1990). Two sources of indoor thoron are (1) building materials and outside air and (2) soil beneath the house (Yanxia et al., 1992). According to the Schery the origin of thoron in the atmosphere is almost entirely due to the diffusion from the top few centimeters of the soil where thoron is produced (Schery,1990; Pearson and Spangler, 1991).

### 8.2. Effect of Deposition of Thoron

Dose delivered by radon/thoron depends not only on the radon/thoron gas concentration but also on the prevailing conditions in the indoor environment. Thoron concentration is mainly governed by the distance from the thoron source. The level of ventilation and the plating out of radon/ thoron daughters onto surfaces decides the extent of equilibrium between them (Ramola et al., 2003). Investigation has shown (Steinhäusler et al., 1975; Yarborough,1980) relation between radon and thoron concentrations and meteorological parameters. Deposition onto surfaces acts to reduce the airborne concentration of radon/thoron and their decay products, thereby reducing the amount available for deposition in the respiratory tract (Knutson, 1992). The importance of deposition as a removal process in the indoor air has been studied by several groups and more decay product activity is found on the surfaces than that found in the air (Maniyan et al., 1999; Porstendörfer, 1979; Pagelkopf and Porstendörfer, 2003).

### 8.3. Measurement Techniques of Thoron and its Progenies

The choice of the measurement techniques depends on whether measurement of thoron or its progenies would be performed on short term (hours to days) or long term basis. For short term measurements, active techniques are preferred, whilst for long-term measurements, passive techniques are suitable. George has summarized detection

systems for thoron and its progenies: pulse ionization chambers, electrets ionization chambers, scintillation detectors with zinc sulfide ZnS (Ag), alpha particle spectrometers with silicon diodes, surface barrier or diffused junction detectors, registration of nuclear tracks in solid-state materials and gamma-ray spectrometry with NaI (T1) scintillation crystals or germanium lithium (GeLi) detector (George, 1996). Long-term measurements of thoron concentrations can be carried out by radon and thoron discriminative measuring methods (Yonehara et al., 2005). A few of these techniques are briefly described below.

## 8.4. Thoron Measurement

### 8.4.1. *$^{220}$Rn Concentration using Lucus Cell*

Thoron concentration may be measured using the Lucas cell. One minute counting immediately after sampling followed by another counting after a delay of 5 min for a duration of 10 min. The counts in the first counting period due to radon and its progeny are calculated from the known radon concentration and then subtracted from the total counts obtained in the first counting period. The remaining counts are due to thoron and its progeny and are used to calculate the radon concentration. The overall uncertainty of this method lies between 10% and 20% ( Eappen et al., 2007).

### *8.4.2. Radon – Thoron Discriminative Monitors*

Radon – thoron discriminative monitors, was developed by Yamada and coworkers. Similarly Doi and co-workers have developed a $^{222}$Rn- $^{220}$Rn discriminative passive dosimeter that can estimate both radon and thoron concentrations at the same time. Two solid-state nuclear track detectors are used in this discriminative dosimeter (Masahiro et al., 1994; Misdaq, 2002). Passive detector like CR-39 was used for the measurement of equilibrium equivalent concentration radon and thoron in which air was drawn though a filter and then CR-39 were exposed to filter after a sufficient time delay so that all the radon progeny decayed out. Thus sampling and measuring time are separated by a definite interval (Tokonami et al., 2002). Determination of $^{218}$Po, $^{214}$Bi, $^{214}$Pb and $^{212}$Pb were carried out by total alpha particle counting. A minimum of 5 h delay was employed for taking the final counts for $^{212}$Pb.

### 8.4.3. *Thoron and Radon Concentrations Measurement Through Scintillation Cells*

Scintillation cell has been used for the measurement of thoron and radon concentrations

(Bigu et al., 1993). This technique is based on two measurements using the difference of the half-life between radon and thoron. Tokonami et al has developed a new technique for both radon and thoron concentration with a single scintillation cell. It is based on two measurements that use the difference in half life between radon and thoron (Tokonami et al., 2002; Hámori et al., 2006).

8.4.4. *Gamma rays Measurement*

Active sampling of thoron gas can be performed by using activated charcoal canisters, followed by measurement using the $^{212}$Pb γ peak with a high purity germanium (HPGe) detector (Bigu , 1986). A peak 239 keV gammas from $^{212}$Pb is usually used as it is very clearly identified in every spectrum, being one of the strongest natural lines. The nucleus $^{212}$Pb decays by emitting β particle with a half-life of 10.64 h to $^{212}$Bi, and 43.3% of the time gives off a γ-ray of energy 238.632 keV. There is also a weaker line at 300.1 keV (3.3%), which is also detected (Ernest Ho and. Measday,2005).

8.4.5. *Delayed Coincidence Technique for the Measurement of Thoron*

Delayed-coincidence and time-analysis (DC-TA) method is based on the use of the short decay half-life of 145 ms of $^{216}$Po in order to distinguish between thoron – $^{216}$Po pair counts and random coincidence pulses (i.e., chance coincidence). Generally Three time-windows in the DC-TA unit, whose opening durations are 150, 300 and 450 ms, are designed to start counting delayed pulses in each window from a trigger pulse (Iimoto et al., 2005).

8.4.6. *Beta Particles Counting Technique*

Thoron progeny concentration has been measured by using beta activity by conventional GM counters (Mohamed and El-Hussein,2005; Buzinny and Los, 2005). The counts of $^{216}$Po are proportional to the local thoron activity concentration $^{216}$Po due to its short half-life is always in equilibrium with the parents nuclide. $^{216}$Po counts by means of a solid-state detector can be used easily to obtain thoron concentration profiles (Nikezic et al., 2006; Leonard, 2005; Wiegand et al., 2000). The total counting efficiencies for the progeny of radon and thoron using beta counting are 20% – 30% (Papp and Dezső, 2006).

**Thoron progenies Measurement**

8.4.7. *Wire Screen Method*

The simple wire screen method provides a direct estimate of the unattached fraction from the screen count, or an indirect estimate from the difference between the reference and back-up filter counts(Khan et al., 1982). This technique can be used for active measurement of the thoron progenies concentrations (Cheng and Yeh, 1980).

*8.4.8. Low-pressure Berner Cascade Impactor Technique*

Attached and unattached activity size distributions of thoron and radon progeny can be collected using a low-pressure Berner cascade impactor technique. A single low-pressure impactor can cover a size range from approximately 30nm to micrometers (Mohamed and El-Hussein, 2005; Keskinen et al., 1999).

8.4.9. *Diffusion Samplers*

Diffusion Sampler is useful for measuring the unattached fractions of radon and thoron decay products (Kotrappa et al., 1975). To separate the contributions of radon and thoron two diffusion chambers one for recording the concentrations of radon while the other for recording the concentrations of ($^{222}$Rn + $^{220}$Rn), so that the difference between the signals recorded by the SSNTDs inside the two diffusion chambers would give the thoron concentration.

8.4.10. *High Efficiency Membrane or Glass Fiber Filters*

Thoron progeny can be collected by high efficiency membrane or glass fiber filter paper using any convenient combination of volumetric flow rate (2–10 $l.\text{min}^{-1}$) and time (up to 60 min), followed by alpha counting of the filter after a delay of suitable time (5 h) or more after the end of sampling. By that time, $^{212}$Pb (ThB), a beta emitter, is in transient equilibrium with its alpha-emitting daughters, enabling its air concentration at the time of sampling (Tokonami et al., 2004; Zhuo and Iida, 2000).

**8.5. Aim or Purpose of This Study**: From the above introduction about the different types of measuring instruments for the radon/thoron it is obvious that a number of instruments for the measurement of radon and thoron progenies are available using both active and passive techniques. However the instrument used for the measurement of

thoron progeny using passive surface deposition technique are very few. In most cases during the measurement of radon thoron is ignored which produces an error in the radon concentration. In this study efforts have been made to develop an instrument for measurement of thoron progeny working on the principle of surface deposition. Studies have also been be conducted about the surface deposition of radon/thoron progenies and air borne radon/thoron progeny concentration was also studied. It is easier to measure surface deposition and make relation for absorbed dose due to thoron in the air. Further details of development of passive thoron progeny dosimeter are given below.

## 8.6. Materials and Methods

### *8.6.1. Theory of Measurement of Radon Progeny Dosimeter using Solid State Nuclear Track Detector*

A variety of solid state nuclear track detectors are available, having different efficiencies for α- particle emitted from radon, thoron and its progenies (McLaughlin et al., 1992).

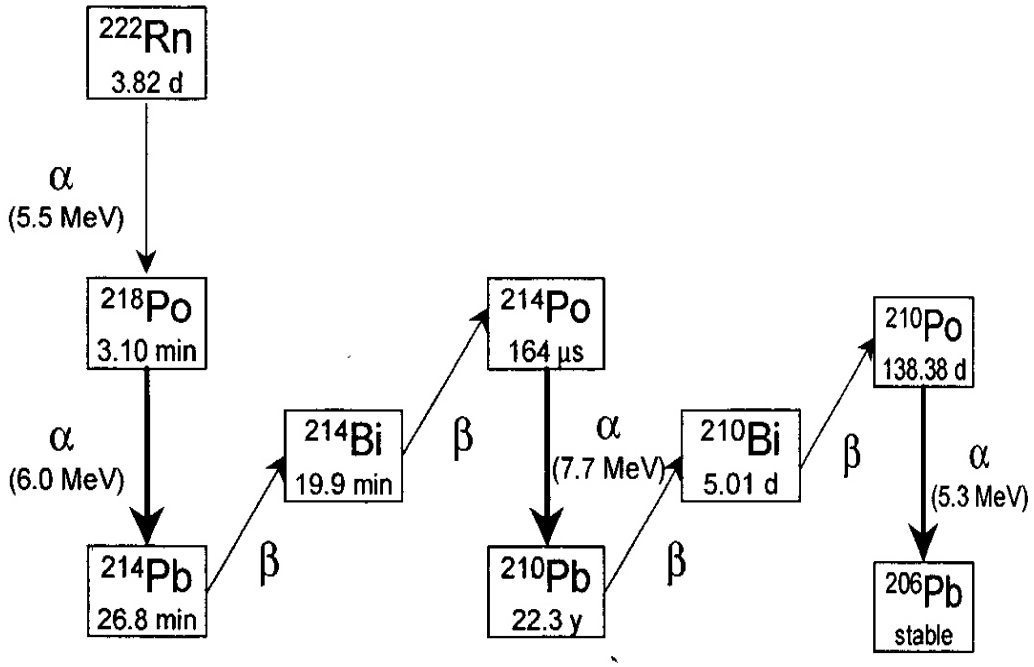



**Figure 8.1: Radon decay chain**

Widely used detectors in this regard are LR-115 and CR-39. LR-115 has sensitivity for a limited range of alpha energies, while CR-39 has capability to detect a wide range of α energies. Radon, thoron and their progenies are usually present in the indoor environment in the mixed form. Therefore measurement of thoron or its progenies in the mixed

environment causes difficulties. Thoron progenies have alpha energies in the range form 5.4 MeV to 8.8 MeV.

| Isotope | Half Life | Types of Radiation |
|---|---|---|
| $^{220}_{86}Rn$ **(Thoron gas)** | **55 s** | **α (6.29 MeV)** |
| $^{216}_{84}Po$ (Polonium) | 0.15 s | α (6.78 MeV) |
| $^{212}_{82}Pb$ (Lead) | 10.64 hrs | β, γ (0.35,0.58 MeV) |
| $^{212}_{83}Bi$ (Bismuth) | 60.6 min | α, β, γ (5.4-6.1, 0.08-2.26 MeV) |
| $^{212}_{84}Po$ (Polonium) | $0.34x10^{-6}$ s | α (8.8 MeV) |
| $^{208}_{85}Tl$ (Thallium) | 3.05 min | β, γ (1.25-2.37 MeV) |
| $^{208}_{82}Pb$ (Lead) | Stable | |

**Figure 8.2: Thoron decay chain**

This wide range of alpha energies is both help and a problem for its measurement. To measure only thoron progeny (i.e., $^{212}$Po) and block the remaining radon and thoron progenies using solid state nuclear track detector, absorbing filters are placed in front of the CR-39 detector. This filter functions as an energy absorber which absorbs alpha particles energy emitted from the radon progenies to very low (zero) efficiency region, and reduces thoron energy ($^{212}$Po) to a range which are still detected by CR-39. Using this technique, suitable filters were identified to detect only thoron progeny ($^{212}$Po) and attenuate the radon progenies. CR-39 detects wide range of energies, however the efficiency of the CR-39 is not uniform for the whole energy range; and it is maximum for alpha particles having 3-6 MeV energy. So selection of such filter had double advantage in this case, first it blocked the detection of unwanted radon and thoron progenies and secondly it also reduced the energy of the desired progeny ($^{212}$Po) to such a range for which CR-39 had relatively higher detection efficiency. It may be mentioned here to block all the radon progenies is easier, except $^{214}$Po which is a difficult task because it energy difference from the α from $^{212}$Po.

*8.6.2. Determination of Efficiency of Different Plastics/Filter as Energy Absorber*

Filtration of radon progenies energies also attenuates the energy of the desired progeny ($^{212}$Po), thus a tradeoff was required between the loss of efficiency of CR-39 and the

noise created by the unwanted radon /thoron progenies for the detection of alpha particle emitted by them. To select a suitable energy filter for the detection of $^{212}$Po, different types of plastics/ materials were studied for their ability to absorb some fraction of α-energy of the radon / thoron progenies. These materials were studied for their ability to absorb $^{214}$Po and attenuate $^{212}$Po to a desirable efficiency range.

To measure the efficiency/ability of these plastic materials $^{218}$Po, $^{212}$Po and $^{214}$Po sources were used (these sources were constructed in the Shaffer Environmental Radiation Laboratory St. John's University USA using Uranium Jars and Thorium Oxide gas mantles). Large area semiconductor diode detectors (SDD), analyzed with a computer-based alpha spectroscopy system (APTEC), were used for these measurements. The filter material was placed between the SDD and the $^{212}$Po or $^{214}$Po source. The materials that were selected had different thicknesses and had a wide range of absorbing ability. The materials tested as filtering/absorbing materials are shown in table 8.1.

Before measuring the efficiency of different plastics the APTEC system was calibrated. To calibrate the APTEC (Surface barrier detector) standard sources of $^{230}$Th and $^{241}$Am were used. The efficiency of the detector as calculated by using $^{230}$Th and $^{241}$Am with no distance (~1mm) between source and detector was 0.26. Using the flat source taking distance of 4 mm between the detector and the source the efficiency of the detector was measured as 0.19. To establish the energy calibration, $^{214}$Po and $^{212}$Po sources were placed under the SDD and the counts were collected for sufficient time to have a peak for the $^{214}$Po and $^{212}$Po. Selected plastics/materials were used to measure their efficiency for $^{218}$Po, $^{214}$Po and $^{212}$Po. Using these materials the residual energies of α particles emitted from $^{212}$Po and $^{214}$Po were measured. The results of different type plastics and other materials are shown in table 8.1 which shows that efficiency of these materials ranges from 0.01 to a maximum of 0.29.

Table 8.1: Efficiency of different materials for the detection of $^{218}$Po $^{214}$Po and $^{212}$Po.

| S.No. | Filter | Gauge | $^{218}$Po | $^{214}$Po | $^{212}$Po |
|---|---|---|---|---|---|
| 1. | Mylar | 8 | 0.25 | 0.16 | 0.04 |
| 2. | MM | 16 | 0.18 | 0.08 | 0.04 |
| 3. | 3M2708+M | 58.00 | - | - | - |
| 4. | CI75 | 75.00 | 0.19 | 0.22 | - |
| 5. | CI92 | 92.00 | 0.16 | 0.28 | - |
| 6. | CI75+2708 | 125.00 | 0.09 | 0.28 | - |
| 7. | 3M125 | 145.00 | 0.07 | 0.21 | - |
| 8. | FFMM | 200 | 0.00 | 0.02 | 0.08 |
| 9. | FFM | 200 | 0.01 | 0.04 | 0.15 |
| 10. | FFM_07 | 200 | - | - | 0.15 |
| 11. | 3M114 | 200.00 | 0.00 | 0.16 | 0.07 |
| 12. | 3M146_07 | 285.00 | - | - | 0.06 |
| 13. | 3MM | 250.00 | - | - | 0.03 |

## 8.7. Technical specifications and Construction Procedure of Surface Deposition Detectors

Analyzing the data in table 8.1 suitable filtering materials for the detection of radon and thoron were selected based on the principle of surface deposition detectors. A few Surface deposition detectors were constructed using (Glass Slide Mounts device Gepe) Gepe 35 mm slide mounts. CR-39 was used as track registration chip and was held in Gepe35 mm slide mounts with an 18 mm × 24 mm opening.

**Construction steps**: Two sets of the progeny surface deposition detectors were manufactured. One set was used for the monitoring of radon progenies, while the other was constructed for the monitoring of the thoron progeny.

The glass side (side which is used to fix the deposition detector with a glass or any other smooth surface) could also be used for the measurement of $^{210}$Po which consist of two portions, one portion consist of only Mylar layer and that “uncovered area” is more sensitive to natural contaminants in glass and the bottom is covered with a 12 mm wide strip of 3M2708 + Mylar that defines the $^{210}$Po sensitive area.

The room side area (side which is exposed to the surface deposition) which is $^{214}$Po sensitive is covered by 3M114 films; when developed these pits appear larger. $^{218}$Po and $^{214}$Po sensitive area are covered by CI-192 film. The track density will be higher in this region as the efficacy of CI-92 is high. The two regions are separated by scratched dashed line on the CR-39 chip. Metallized Mylar is used over the central opening of the Gepe using 3M 2175C double sticky mounting tape. On the inside of the holder, a 2 mm wide strip of 3M 2175C above and below the central opening was used. This is used for sticking it to the glass surface.

Room side of the thoron progeny detector (Which detects surface deposition of $^{212}$Po) consists of the following parts. For the room side/side exposed to the newly deposited radon progenies, a 10 mm × 25 mm strip of 3M 146_07 films was used to the bottom of the slide opening so that the film extends 1 mm onto edge opening. A 10 mm ×25 mm strip of CI-192 to the top of the slide opening so that the films meet but do not overlap at the centre of the opening. Covered both films with a 26 mm × 26 mm strip of Metallized Mylar over the central opening using the 3M 2175C tape to hold it in place. Metallized Mylar was used to remove the effects of light on the selected plastic.

The glass side of both radon and thoron progeny is same. For the construction of the thoron progeny detector room side**,** 10 mm × 25mm long strip of tape FF to the bottom of the slide opening so that the tape extends 1 mm onto edge of opening. The sticky side of the tape should be away from the holder. Attached a 10 mm × 25mm long strip of film 3M146_7 to the top of the slide opening so that the films meet but do not overlap at the centre of the opening. Covered the film with 26mm × 26 mm strip of Metallized Mylar over the central opening using the 3M 2175C and a special Mylar coated plastic adhesive tape **(**FFM) to hold it in place. A light coat of antistatic fluid is sprayed to offset the electrostatic charge on the chip.

### 8.8. Initial Testing of the New Surface Deposition Dosimeters

To test these newly assembled/developed surface deposition radon and thoron dosimeters for its ability to register tracks in the indoor environment, a small chamber containing high concentrations of radon was constructed. The small thoron chamber having dimensions of 58 cm × 30 cm × 27 cm and surface to volume ratio of 18.These

surface deposition detectors were exposed in it, in order to know the track density in each region. Two different sets of surface deposition detectors were made. In one set only thick plastic material was used and in the other sets two regions were made one of 3M146_7 region and the other part was made with CI-92 materials and were exposed to thoron and its progenies in the newly constructed small sized thoron chamber. Surface deposition detector was exposed to thoron and its progenies for 7 days in this chamber. During the exposure the thoron concentration in the chamber was measured using the Rad 7 active detector (Durridge Co, USA). Exposed surface deposition detectors in the test chamber were removed after the specified exposure time and its surface deposited activity of $^{212}$Po was measured using the APTEC system. The results obtained are shown in table 8.2. CR-39 detectors were removed form these deposition chambers and were etched in 6M NaOH solution for 6 hours at 75C° and were counted under using an optical microscope. Experiment for studying the tracks of $^{212}$Po in the thick region of the dosimeter (3M146) was repeated. The sensitivity of different regions of these surface deposition detectors are shown in the table 8.3 below for run-1.

Table 8.2: Surface deposited $^{212}$Po activity in different chambers.

| Experiment | Counts.s$^{-1}$ | Observed Surface Density | Efficiency of the detector | Actual Surface Density (Bq.mm$^{-2}$) |
|---|---|---|---|---|
| Small Chamber Run 1 | 2.70E-01 | 1.59E-04 | 1.81E-01 | 8.75E+02 |
| Small Chamber Run 2 | 2.30E-01 | 1.35E-04 | 1.81E-01 | 7.48E+02 |
| Medium Chamber | 1.64E-01 | 9.62E-05 | 1.81E-01 | 5.31E+02 |
| Exposure room | 5.80E-03 | 3.41E-06 | 1.81E-01 | 1.88E+01 |

The results of the exposure in the small chamber were good as there were enough track density on the thick filter portion of the detector. As may be seen in this table, average surface deposited activity in small chamber is very high as the thoron concentrations in the chamber were high. The corresponding track densities using CR-39 detectors were high.

Table 8.3: Track density in different regions of the surface deposition detector in the small thoron chamber (Run-1).

| S.No | Filter Materials | Average Tracks/FoV | Tracks.mm$^{-2}$ | Tracks.m$^{-2}$.s$^{-1}$ |
|---|---|---|---|---|
| 1 | 3M146-1 | 3.8 | 10.6 | 31 |
| 2 | 3M146-2 | 3.9 | 10.9 | 32 |
| 3 | 3M146-3 | 3.9 | 11.2 | 32 |
| 4 | 3M146-4 | 2.9 | 8.3 | 24 |
| Average | 3M146 Average | 3.6 | 10.3 | 30 |
| 1 | CI-92-1 | 16.2 | 46.0 | 130 |
| 2 | CI-92-2 | 16.8 | 47.6 | 140 |
| 3 | CI-92-3 | 14.1 | 40.1 | 120 |
| 4 | CI-92-4 | 15.8 | 44.7 | 130 |
| Average | CI-192 Average | 15.7 | 44.6 | 140 |
| 1 | 3M146-1 | 3.5 | 10.0 | 29 |
| 2 | 3M146-2 | 3.6 | 10.1 | 29 |
| 3 | 3M146-3 | 3.4 | 9.7 | 28 |
| 4 | 3M146-4 | 3.5 | 10.0 | 29 |
| Average | 3M146 Average | 3.5 | 9.9 | 31 |

The average activity in run 1 and run 2 (table 8.1) has the same trend as it was observed for the corresponding tack density observed in the exposed CR-39 detector track density (table 8.3 and 8.5). Radon and thoron concentration during these experiments in the small chamber are shown in table 8.4 and 8.6. After analysis of the data in the primary small chamber a new medium chamber with dimensions of 130 cm × 60 cm × cm 63 cm having Thorium Oxide mantles inside it for the production of thoron and its progenies. A small air circulation fan was also placed inside the chamber to circulate the air in the chamber. Surface deposition detectors were exposed inside the chamber for seven days and radon and thoron concentrations were measured during that period which are shown in table 8.7.

Table 8.4: Radon and thoron concentration in the small chamber (Experiment Run-1).

| Run | Date | Radon | Thoron | Run | Date | Radon | Thoron |
|---|---|---|---|---|---|---|---|
| 1 | 19-4-2007 | 369±154 | 14689±1106 | 16 | 20-4-2007 | 304±231 | 16317±1169 |
| 2 | 19-4-2007 | 279±152 | 17316±1210 | 17 | 20-4-2007 | 392±252 | 17168±1214 |
| 3 | 19-4-2007 | 269±156 | 17797±1228 | 18 | 20-4-2007 | 341±250 | 16835±1199 |
| 4 | 19-4-2007 | 433±198 | 14763±1114 | 19 | 20-4-2008 | 226±246 | 17168±1199 |
| 5 | 19-4-2007 | 270±185 | 16206±141 | 20 | 21-4-2007 | 492±276 | 18056±1243 |
| 6 | 19-4-2007 | 400±214 | 16650±1184 | 21 | 21-4-2007 | 381±276 | 18611±1262 |
| 7 | 19-4-2007 | 559±242 | 15873±1147 | 22 | 21-4-2007 | 279±364 | 20017±1291 |
| 8 | 19-4-2007 | 370±244 | 16650±1195 | 23 | 22-4-2007 | 278±555 | 21756±1362 |
| 9 | 19-4-2007 | 440±251 | 17538±1225 | 24 | 22-4-2007 | 276±374 | 20572±1325 |
| 10 | 20-4-2007 | 500±278 | 15873±1154 | 25 | 22-4-2007 | 231±275 | 19425±1273 |
| 11 | 20-4-2007 | 681±290 | 16354±1184 | 26 | 22-4-2007 | 259±522 | 20942±1336 |
| 12 | 20-4-2007 | 440±283 | 17057±1210 | 27 | 22-4-2007 | 270±514 | 22163±1373 |
| 13 | 20-4-2007 | 481±215 | 15873±1154 | 28 | 22-4-2007 | 275±555 | 20831±1321 |
| 14 | 20-4-2007 | 411±212 | 16946±1203 | 29 | 22-4-2007 | 280±485 | 20128±1310 |
| 15 | 20-4-2007 | 270±211 | 16798±1199 | 30 | 22-4-2008 | 293±514 | 23162±1402 |
| Average | | | | | | 358±299 | 18167±1184 |

After exposure these CR-39 detectors were removed and etched and its track densities were measured. The results are shown in table 8.8. As expected track density of different filtering materials was different according to their efficiencies. It is clear that 3M146 has average track density lower than the region were CI-92 is used as masking/filtering material for the CR-39. However the track density in each region was enough to be read conveniently. Measured radon and thoron concentrations show a consistent trend of high thoron consternation.

In the second experiment in medium chamber surface deposition detectors were exposed to thoron gave a similar trend as was in run-1 and 2 in the small exposure chamber. Exposing surface deposition dosimeter to high thoron concentrations for a week time produced a suitable number of tracks in CR-39 detector in the thick region (3M146).

Table 8.5: Track density in different regions of the surface deposition detector in the small thoron Chamber Run 2.

| Surface Deposition detector | Filter | Average Tracks/FoV | Tracks.mm$^{-2}$ | Tracks.m$^{-2}$.s$^{-1}$ |
|---|---|---|---|---|
| 1 | 3M146_1 | 3.2 | 9.0 | 35 |
| 2 | 3M146_2 | 3.2 | 9.1 | 35 |
| 3 | 3M146_3 | 3.3 | 9.3 | 36 |
| 4 | 3M146_4 | 3.5 | 9.9 | 38 |
| 3M146 Average | | 3.3 | 9.3 | 36 |
| 1 | CI-92-1 | 8.3 | 23.6 | 91 |
| 2 | CI-92-2 | 16.0 | 45.5 | 175 |
| 3 | CI-92-3 | 8.9 | 25.1 | 97 |
| 4 | CI-92-4 | 10.2 | 28.9 | 111 |
| CI-92 Average | | 10.8 | 30.7 | 120 |
| 1 | 3M146_1 | 3.7 | 10.5 | 40 |
| 2 | 3M146_2 | 4.3 | 12.0 | 47 |
| 3 | 3M146_3 | 3.9 | 11.1 | 43 |
| 3M146 Average | | 4.0 | 11.2 | 32 |

The results of the surface deposition detector in the medium exposure chamber show that different region of the detectors have different response to the surface deposition detector. Mainly there are two regions i.e. low sensitivity region of 3M146 masking material and high sensitivity region of CI-92 and 3M114. During these measurement radon and thoron concentration were measured and are shown in table 8.7.

After testing these surface deposition detectors in the small and medium chambers for the ability to register track on the CR-39, these deposition dosimeters were exposed in the exposure room which is a standard room with the dimensions 255 cm × 300 cm × 365 cm. Thorium oxide gas mantle were placed in four different locations for the production of thoron and its progenies and Natural Uranium Jars for the production of radon . These surface deposition detectors were exposed for 15 days. During this experiment thoron concentration was in the range of 3-10 pCi $\ell^{-1}$ (100 – 3700 Bq.m$^{-3}$).

Table 8.6: Radon and thoron concentration in the small chamber (Run-2).

| Date | Thoron | Radon |
|---|---|---|
| 23/4/2007 | 20128±1295 | 551±254 |
| | 20720±1332 | 422±248 |
| | 21571±1369 | 444±255 |
| 24/4/2007 | 20276±1295 | 322±174 |
| | 20683±1332 | 218±170 |
| | 21386±1332 | 366±189 |
| 25/4/2007 | 17538±1221 | 400±167 |
| | 18167±1221 | 407±174 |
| | 17834±1221 | 429±194 |
| 26/4/2007 | 16317±1184 | 292±161 |
| | 18167±1258 | 407±176 |
| | 18611±1258 | 251±175 |
| 27/4/2007 | 16761±1184 | 274±149 |
| | 18796±1258 | 281±163 |
| | 18500±1258 | 370±174 |
| Average | 19030±1268 | 362±188 |

During the exposure Rad 7 active detector was used to measure the radon and thoron concentration in the exposure room and the results obtained are shown in table 8.9. The results (table 8.10) showed that the thick region of the dosimeter has sufficient sensitivity for the determination of thoron progeny in the indoor environment if the detectors were exposed to the thoron progenies for a sufficiently long time.

Analyzing these initial results of the surface deposition detector in the small and medium chambers in the exposure room, in the next step more surface deposition detectors were assembled for the exposure in the real indoor environment in USA and Pakistan. Deposition pattern of the radon and thoron progenies depend on the ultrafine particles in the atmosphere. Therefore, a series of experiments were performed to study the airborne radon/thoron progenies under different aerosols conditions.

Table 8.7: Radon and thoron concentration in the medium sized thoron chamber.

| S.No | Run ID | Date | Radon | Thoron |
|---|---|---|---|---|
| 1. | 6101 | 7/5/2007 | 68±74 | 3922±588 |
| 2. | 6102 | 7/5/2007 | 69±79 | 3534±574 |
| 3. | 6103 | 7/5/2007 | 99±85 | 3356±555 |
| 4. | 6201 | 8/5/2007 | 174±103 | 6401±740 |
| 5. | 6202 | 8/5/2007 | 138±101 | 6142±733 |
| 6. | 6203 | 8/5/2007 | 187±118 | 5439±692 |
| 7. | 6301 | 8/5/2007 | 107±121 | 4921±655 |
| 8. | 6302 | 8/5/2007 | 149±138 | 4884±662 |
| 9. | 6303 | 8/5/2007 | 159±138 | 4884±662 |
| 10. | 6401 | 9/5/2007 | 175±128 | 5069±666 |
| 11. | 6402 | 9/5/2007 | 80±119 | 4736±651 |
| 12. | 6403 | 9/5/2007 | 199±131 | 4514±636 |
| 13. | 6601 | 10/5/2007 | 146±111 | 6882±770 |
| 14. | 6602 | 10/5/2007 | 309±143 | 7363±807 |
| 15. | 6603 | 10/5/2007 | 139±118 | 7363±807 |
| 16. | 6801 | 11/5/2007 | 97±99 | 6290±740 |
| 17. | 6802 | 11/5/2007 | 79±106 | 7178±792 |
| 18. | 6803 | 11/5/2007 | 118±114 | 6808±770 |
| 19. | 7001 | 12/5/2007 | 29±90 | 4995±662 |
| 20. | 7002 | 12/5/2007 | 110±104 | 5883±722 |
| 21. | 7003 | 12/5/2007 | 139±120 | 5439±699 |
| 22. | 7201 | 13/5/2007 | 107±97 | 3848±585 |
| 23. | 7202 | 13/5/2007 | 209±121 | 4699±651 |
| 24. | 7203 | 13/5/2007 | 129±109 | 4773±655 |
| 25. | 7401 | 14/5/2007 | 156±107 | 5735±707 |
| 26. | 7402 | 14/5/2007 | 189±123 | 5254±685 |
| 27. | 7403 | 14/5/2007 | 129±127 | 5143±681 |
| | Average | | 137±112 | 5387±687 |

## 8.9. Measurement of Particle Concentration

Dose due to $^{222}Rn/^{220}Rn$ airborne progenies not only depends on Radon/$^{220}Rn$ concentration but also depends on the attachment of the progenies to aerosols. Ultrafine particles contribute little to the total mass but are present in a very high number concentration. Particles of this size can almost unrestrictedly enter into the lungs and results in a greater inflammatory potential (Martell, 1983).

Table 8.8: Track density in different regions of the surface deposition detector in the medium size thoron chamber.

| Surface Deposition detector | Filter | Average Tracks/FoV | Tracks.mm$^{-2}$ | Tracks.m$^{-2}$.s$^{-1}$ |
|---|---|---|---|---|
| 1. | 3M146-1 | 4.3 | 12.3 | 20 |
| 2. | 3M146-2 | 5.0 | 14.1 | 23 |
| 3. | 3M146-3 | 4.6 | 12.9 | 21 |
| | Average | 4.6 | 13.1 | 22 |
| 1. | CI-192-1 | 10.1 | 28.7 | 48 |
| 2. | CI-192-2 | 8.9 | 25.3 | 42 |
| 3. | CI-192 -3 | 10.4 | 29.5 | 49 |
| | Average | 9.8 | 27.9 | 46 |
| 1. | 3M146-1 | 5.2 | 14.8 | 24 |
| 2. | 3M146-2 | 5.7 | 16.1 | 27 |
| 3. | 3M146-3 | 5.2 | 14.8 | 24 |
| | Average | 5.4 | 15.2 | 25 |
| 1. | 3M114-1 | 38.4 | 108.8 | 180 |
| 2. | 3M114-2 | 24.6 | 69.8 | 115 |
| 3. | 3M114-3 | 26.1 | 73.9 | 122 |
| | Average | 29.7 | 84.2 | 139 |
| 1. | CI-192-1 | 15.0 | 42.5 | 70 |
| 2. | CI-192-2 | 16.7 | 47.3 | 78 |
| 3. | CI-192 -3 | 15.7 | 44.5 | 74 |
| | Average | 15.8 | 44.8 | 74 |

In order to measure these affect in indoor environment ultrafine particles were measured on an hourly basis using the CPC P-track system. Ultrafine particle counter uses the condensation particle counting (CPC) technique (TSI MN, USA).

Table 8.9: Radon and thoron concentration in the exposure room during the exposure of the Surface Deposition Detectors in the room (15 days).

| S.No | Radon | Thoron | S.No | Radon | Thoron |
|---|---|---|---|---|---|
| 1. | 19±135 | 58±148 | 1. | 48±97 | 67±133 |
| 2. | 0±197 | 48±170 | 2. | 0±118 | 54±144 |
| 3. | 10±158 | 54±158 | 3. | 50±178 | 68±164 |
| 4. | 0±289 | 47±193 | 4. | 19±138 | 53±151 |
| 5. | 0±158 | 54±158 | 5. | 30±118 | 60±144 |
| 6. | 30±158 | 60±158 | 6. | 10±118 | 48±144 |
| 7. | 0±77 | 39±125 | 7. | 0±135 | 53±148 |
| 8. | 20±40 | 54±108 | 8. | 0±158 | 40±158 |
| 9. | 40±79 | 64±128 | 9. | 10±0 | 48±48 |
| 10. | 39±38 | 63±105 | 10. | 0±77 | 39±125 |
| 11. | 40±40 | 64±108 | 11. | 10±138 | 48±151 |
| 12. | 10±79 | 48±128 | 12. | 0±98 | 40±136 |
| 13. | 10±193 | 47±167 | 13. | 0±77 | 39±125 |
| 14. | 40±396 | 64±220 | 14. | 0±197 | 40±170 |
| 15. | 20±197 | 54±170 | 15. | 0±138 | 40±151 |
| 16. | 0±58 | 39±116 | 16. | 0±174 | 8±161 |
| 17. | 20±316 | 68±202 | 17. | 0±98 | 40±136 |
| 18. | 0±197 | 54±170 | 18. | 20±79 | 54±128 |
| 19. | 0±295 | 148±477 | 19. | 145±19 | 97±93 |
| 20. | 10±140 | 48±153 | 20. | 218±118 | 115±144 |
| 21. | 10±98 | 47±135 | 21. | 239±59 | 119±118 |
| 22. | 39±174 | 63±161 | 22. | 19±97 | 58±133 |
| 23. | 30±59 | 60±118 | 23. | 0±158 | 40±158 |
| 24. | 69±138 | 76±151 | 24. | 10±138 | 48±151 |
| 25. | 10±77 | 47±125 | 25. | 0±77 | 47±125 |
| 26. | 10±178 | 48±164 | 26. | 10±178 | 48±164 |
| 27. | 10±178 | 48±164 | 27. | 20±79 | 54±128 |
| 28. | 10±135 | 47±148 | 28. | 825±38 | 199±105 |
| 29. | 10±178 | 54±164 | 29. | 607±59 | 176±118 |
| 30. | 20±138 | 54±151 | 30. | 544±59 | 168±118 |
| 31. | 10±97 | 47±133 | 31. | 48±116 | 67±141 |
| 32. | 40±59 | 64±118 | 32. | 50±98 | 68±136 |
| 33. | 30±98 | 60±136 | 33. | 40±79 | 64±128 |
| 34. | 19±97 | 53±133 | 34. | 136±193 | 97±167 |
| 35. | 20±59 | 54±118 | 35. | 109±414 | 88±224 |
| 36. | 20±98 | 54±136 | 36. | 129±79 | 94±128 |
| 37. | 29±116 | 58±141 | 37. | 729±97 | 189±133 |
| 38. | 20±316 | 54±202 | 38. | 1110±296 | 232±198 |
| 39. | 10±414 | 54±224 | 39. | 327±97 | 137±128 |
| 40. | 19±97 | 53±133 | Average | 80±136 | 67±149 |

Table 8.10: Track density in different regions of the surface deposition detector in the exposure room.

| Filter | Average /FoV | Tracks.mm$^{-2}$ | Tracks.m$^{-2}$.s$^{-1}$ |
|---|---|---|---|
| 3M146-1 | 1.2 | 3.4 | 6 |
| 3M146-2 | 1.5 | 4.2 | 7 |
| 3M146-3 | 1.7 | 4.7 | 8 |
| Average 3M146 | 1.5 | 4.1 | 7 |
| 3M114-1 | 2.1 | 6.1 | 10 |
| 3M114-2 | 2.2 | 6.3 | 10 |
| 3M114-3 | 2.1 | 5.9 | 10 |
| Average 3M114 | 2.2 | 6.1 | 10 |
| 3M146-1 | 1.8 | 5.1 | 8 |
| 3M146-2 | 1.4 | 4.0 | 7 |
| 3M146-3 | 1.6 | 4.6 | 8 |
| Average 3M146 | 1.6 | 4.6 | 8 |
| FFM-1 | 5.8 | 16.4 | 27 |
| FFM-2 | 2.6 | 7.3 | 12 |
| FFM-2 | 4.2 | 12.0 | 20 |
| Average FFM | 4.2 | 11.9 | 20 |
| CI-92-1 | 6.6 | 18.8 | 31 |
| CI-92-2 | 7.3 | 20.7 | 34 |
| CI-92-3 | 6.4 | 18.1 | 30 |
| Average CI-92 | 6.8 | 19.2 | 32 |

The following different aerosol generating activities were performed in the indoor environment.

- High Efficiency Particle Air (HEPA) filter: To remove the fine and ultrafine particle form the indoor environment

- HEPA filter with ionizer: the ionizer generates negative ions and thus the attachment rate may be increased. This phenomenon reduces the particles concentration to very low level.

- Candle burning for a specified period of time
- Propane cooker: propane cooker was used for a specific period of time.
- Cigarette smoking: The Joe smoker system was used to produce smoke in the exposure room for a specified period of time

Particle concentrations show a long range of variation depending on the aerosol generating source/sink usage in the room. The particles concentrations are reduced to very low number when the indoor environment has HEPA filter working along with ionizer. In some cases the particles concentrations are reduced to such an extent that the general empirical relation defined/derived by Porstendoerfer et al., $f_p = 150 / Z(cm^3)$ was not valid and the particles concentrations reduced to less than 100 per $cm^3$ (Porstendörfer, 2001, 1996 &1994; Porstendörfer and Reineking, 1999). Using the HEPA filter only the particles concentrations is in the range of 100-300 ($cm^3$). Thus unattached fraction of thoron /radon is high and is in the range of 60 - 90%. When aerosol generating activity is taking place in the indoor environment the particles concentration increases to very high number. Consequently the unattached fraction is reduced. The unattached fraction ranges from 0.0001- 0.2. The particle concentrations can be divided mainly into two categories. (1) low levels log Z ~2 - 3 and (2) high levels log Z ~4 - 5. The low levels occurs when there is no aerosol generating activity is taking place in the indoor environment or the aerosol sink like HEPA filter or HEPA filter ionizer is operating in the indoor environment. High aerosols conditions occur during the operation of a fan or some cooking or smoking activity taking place. Candle burning or cigarette smoking produces very high levels of ultrafine particles. Indoor particle concentrations increase from $10^3$ to $10^5$ per $cm^3$, the-attached fraction of airborne radon decay products increases progressively and the deposition on the surfaces decreases. A single burning cigarette in a closed room gives rise to particle concentrations of $10^3$ to $10^5$ per $cm^3$, because of rapid coagulation; most of the radon decay products are associated with large particles of low mobility. In the smoke-filled rooms, airborne radon progeny approach equilibrium with radon limited only by ventilation rate and particle sedimentation (detailed description of the measurements is given in the later section).

As may be seen in table 8.11 that ultrafine particle concentration is very high during the cooking and burning activities in the indoor environment and the corresponding equilibrium factor and unattached fraction have been varied accordingly. Unattached fraction calculated using filter and mesh and the empirical relation that $f_p$ =150/Z($cm^{-3}$) are in good agreement. However, unattached fraction calculated using filter is relatively lower as compared to that derived by using the empirical relation. In normal conditions when no activity is taking place in the indoor environment ultrafine particles reduces to low concentration levels.

## 8.10. Surface deposition Rates of Radon and Thoron

In order to measure surface deposition of radon /thoron progenies in the indoor environment, smooth surfaces were exposed to a steady radon /thoron levels and different types of aerosol producing environment for several hours, during which the activities of the short-lived radon progenies /thoron progenies reached equilibrium with its parents.

A protocol was required for determining these equilibrium activities for all four short-lived progenies on a glass surface in the case of radon and $^{212}$Pb, $^{212}$Bi-$^{212}$Po in the case of thoron. As $^{214}$Pb and $^{214}$Bi and $^{212}$Pb are beta emitters, a model for extrapolating their activities was constructed. Since the lifetime of $^{214}$Po is very short (half-life = 0.164 μs), it is always in equilibrium with the longer-lived parent $^{214}$Bi (half-life = 19.7 min).

A spreadsheet was used to accept as input the raw data from the specified detectors, perform the necessary corrections and output the initial activities (equilibrium values) of $^{218}$Po, $^{214}$Pb, and $^{214}$Bi-$^{214}$Po in the case of radon progenies. After experimental consideration, the protocol developed by Dumm (Dumm, 2005) was used. This protocol contains a practical set of counting intervals that minimize uncertainty. In the case of thoron, the element of interest was $^{212}$Pb which has a large half life of 10.6 hrs for which a protocol was developed to collect the count for one hour as after 10 min there were few counts.

A calibrated computerized APTEC alpha-spectroscopic multi-channel analyzer and Science Applications International Corporation **(**SAIC) ® Alpha Analyzers of model AP-2 were used for these measurements

Table 8.11: Ultrafine particles concentration equilibrium factor and unattached fraction of radon and thoron progenies.

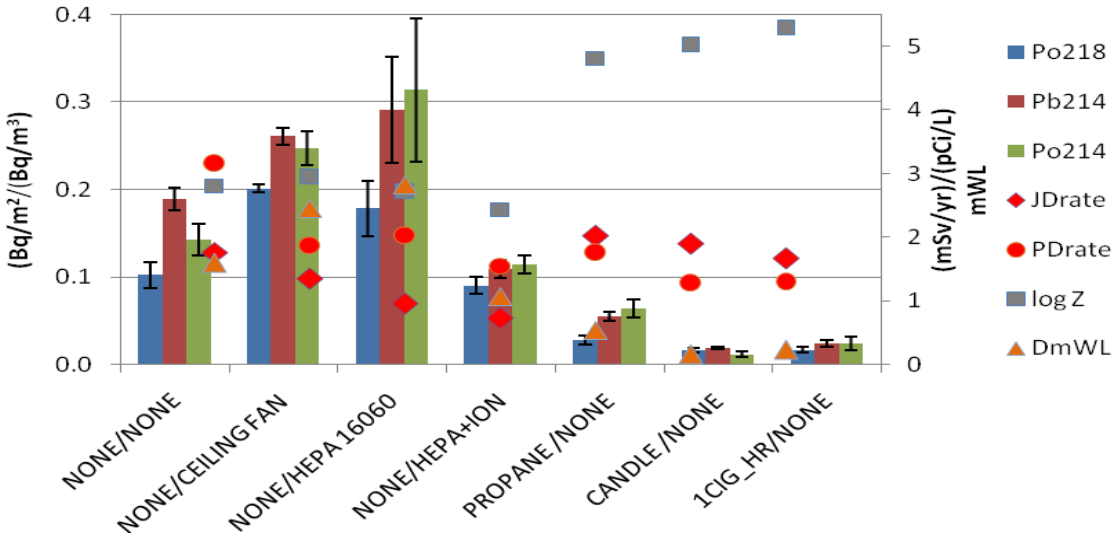
| Aerosol Type | F $^{222}$Rn( Filter) | F $^{220}$Rn Filter) | F $^{222}$Rn Mesh | F $^{220}$Rn Mesh | fp $^{222}$Rn | fp$^{222}$Rn | Z.cm$^{-3}$ | Unattached by P-Track |
|---|---|---|---|---|---|---|---|---|
| propane cook+Candle | -0.77±-0.97 | 0.20±0.06 | 0.21±0.32 | 0.003±0.002 | -0.365 | 0.015 | 116416 | 0.001288 |
| propane cook+Candle | -0.12±-0.25 | 0.46±0.15 | -0.09±-0.09 | 0.009±0.004 | 0.407 | 0.019 | 179571 | 0.000835 |
| propane cook+Candle | 1.84±0.67 | 0.11±0.04 | 0.26±0.23 | 0.002±0.002 | 0.125 | 0.015 | 164428 | 0.000912 |
| propane cook+Candle | 0.26±0.2 | 0.51±0.16 | -0.06±-0.07 | 0.008±0.004 | -0.272 | 0.015 | 86550 | 0.001733 |
| prop ck+1Cig+Can | 0.52±0.28 | 0.12±0.04 | -0.07±-0.1 | 0.003±0.002 | -0.163 | 0.024 | 191608 | 0.000783 |
| Candle Filter | 0.8±1 | 0.28±0.09 | 0.02±0.3 | 0.001±0.002 | 0.025 | 0.003 | 187933 | 0.001248 |
| Candle+1Cig | 1.94±0.54 | 0.15±0.05 | -0.01±-0.13 | 0.002±0.002 | -0.007 | 0.016 | 120233 | 0.000798 |
| propane cook | 0.17±0.14 | 0.10±0.03 | -0.01±-0.05 | 0.001±0.001 | -0.092 | 0.011 | 166275 | 0.000902 |
| propane cook | 0.94±0.34 | 0.15±0.05 | 0.07±0.11 | 0.002±0.002 | 0.073 | 0.015 | 104341 | 0.001438 |
| propane cook+Candle | 0.59±0.23 | 0.15±0.05 | -0.01±-0.08 | 0.004±0.002 | -0.009 | 0.025 | 110966 | 0.001352 |
| propane cook | -0.26±-0.26 | 0.16±0.05 | -0.12±-0.07 | 0.001±0.001 | 0.312 | 0.007 | 5545 | 0.027051 |
| propane cook | -0.36±-0.22 | 0.11±0.04 | -0.08±-0.07 | 0.001±0.001 | 0.185 | 0.010 | 61035 | 0.002458 |
| propane cook | 0.94±0.44 | 0.52±0.16 | 0±0.13 | 0.007±0.003 | 0.005 | 0.013 | 67315 | 0.002228 |
| candle only | 0.13±0.31 | 0.10±0.03 | -0.03±-0.13 | 0.004±0.002 | -0.335 | 0.037 | 88134 | 0.001702 |
| propane cook | -0.43±-0.21 | 0.45±0.14 | 0.13±0.07 | 0.001±0.002 | -0.441 | 0.003 | 188758 | 0.000795 |
| propane cook+candle | -0.04±-0.17 | 0.11±0.03 | 0.03±0.07 | 0.003±0.002 | -5.817 | 0.030 | 150950 | 0.000994 |
| propane cook | 0.65±0.22 | 0.14±0.04 | 0.04±0.06 | 0.002±0.002 | 0.054 | 0.015 | 158233 | 0.000948 |
| propane cook | 0.76±0.22 | 0.09±0.03 | 0.01±0.05 | .00044.00044 | 0.014 | 0.005 | 169583 | 0.000885 |
| propane cook | -0.13±-0.09 | 0.01±0.00 | -0.06±-0.03 | .00013±.0001 | 0.312 | 0.012 | 195733 | 0.000766 |
| propane cook | 0.16±0.36 | 0.13±0.04 | 0.05±0.14 | 0.004±0.002 | 0.231 | 0.027 | 143441 | 0.001046 |
| propane cook | -0.83±-0.28 | 0.35±0.11 | -0.06±-0.08 | 0.007±0.004 | 0.068 | 0.019 | 72483 | 0.002069 |
| propane Lighter | 0.94±0.26 | 0.21±0.07 | 0.01±0.08 | 0.009±0.004 | 0.009 | 0.042 | 101326 | 0.00148 |
| propane cook | -1.41±-0.58 | 0.48±0.15 | -0.09±-0.19 | 0.005±0.004 | 0.062 | 0.011 | 118000 | 0.001271 |
| propane cook | 0.88±1.56 | 0.07±0.02 | -0.44±-0.72 | 0.004±0.002 | -0.038 | 0.055 | 43017 | 0.003487 |
| propane cook | -1.1±-0.61 | 0.34±0.11 | -0.02±-0.22 | 0.01±0.004 | -0.002 | 0.027 | 34106 | 0.004398 |
| propane Lighter | -8.02±-2.21 | 0.19±0.06 | -0.25±-0.67 | 0.008±0.005 | 0.030 | 0.041 | 65304 | 0.002297 |
| propane Lighter | -0.03±-0.18 | 0.45±0.14 | -0.01±-0.08 | 0.011±0.005 | 0.281 | 0.025 | 147233 | 0.001019 |
| propane cook | 0.81±0.6 | 0.22±0.07 | -0.07±-0.25 | 0.008±0.004 | -0.090 | 0.037 | 33924 | 0.004422 |
| propane cook | 0.04±0.26 | 0.15±0.05 | -0.01±-0.11 | 0.006±0.003 | -0.273 | 0.038 | 101222 | 0.001482 |
| Candle | 0.24±0.18 | 0.17±0.05 | 0±0.08 | 0.005±0.004 | 0.017 | 0.032 | 117425 | 0.001277 |
| Candle | -0.17±-0.47 | 0.20±0.06 | 0.24±0.2 | 0.006±0.003 | 3.420 | 0.030 | 70055 | 0.002141 |
| none | 0.4±0.21 | 0.11±0.03 | 0.07±0.12 | 0.014±0.005 | 0.156 | 0.119 | 581 | 0.258176 |
| none | 0.06±0.28 | 0.16±0.05 | -0.11±-0.15 | 0.015±0.006 | 2.114 | 0.084 | 681 | 0.220264 |
| none | -0.46±-0.32 | 0.09±0.03 | 0.02±0.21 | 0.02±0.007 | -0.048 | 0.180 | 926 | 0.161987 |
| none | 0.5±0.41 | 0.06±0.02 | 0.18±0.25 | 0.015±0.005 | 0.271 | 0.189 | 819 | 0.18315 |
| propane cook | -0.12±-0.35 | 0.06±0.02 | -0.48±-0.26 | 0.013±0.005 | 0.799 | 0.180 | 477 | 0.314465 |
| none | 0.56±0.26 | 0.04±0.01 | 0.56±0.21 | 0.01±0.004 | 0.501 | 0.200 | 1876 | 0.079957 |
| Candle | -0.16±-0.73 | 0.10±0.03 | -0.15±0.49 | 0.014±0.006 | 0.488 | 0.127 | 9900 | 0.015152 |

Summarized results for radon are shown in Figure 8.3. It is clear from this Figure that surface deposited activity depends on the aerosols conditions in the indoor air. For similar indoor radon concentrations but different aerosols conditions, the surface deposited

activities showed large variations. (see appendix A, B, C and D). Using the calibration information $^{218}$Po, $^{214}$Pb, and $^{214}$Bi-$^{214}$Po activities in case of radon and $^{212}$Pb and $^{212}$Bi - $^{212}$Po for thoron progenies activities on the surfaces were calculated using different aerosols conditions (for further details , reader is referred to appendices A to D).

It may be seen in Figure 8.3 that under normal conditions, average normalized surface deposited $^{218}$Po varies from 0.016 which is for the candle on/off conditions (Candle is on for odd hours and reading in even hours) to 0.201 when ceiling fan was operating. As may be seen in the graph when HEPA filter and HEPA+IONIZER are used as aerosol sinks, particles concentrations are reduced and the surface deposition is increased.

Figure 8.3: Normalized surface deposition rate of radon progenies under different aerosols conditions.

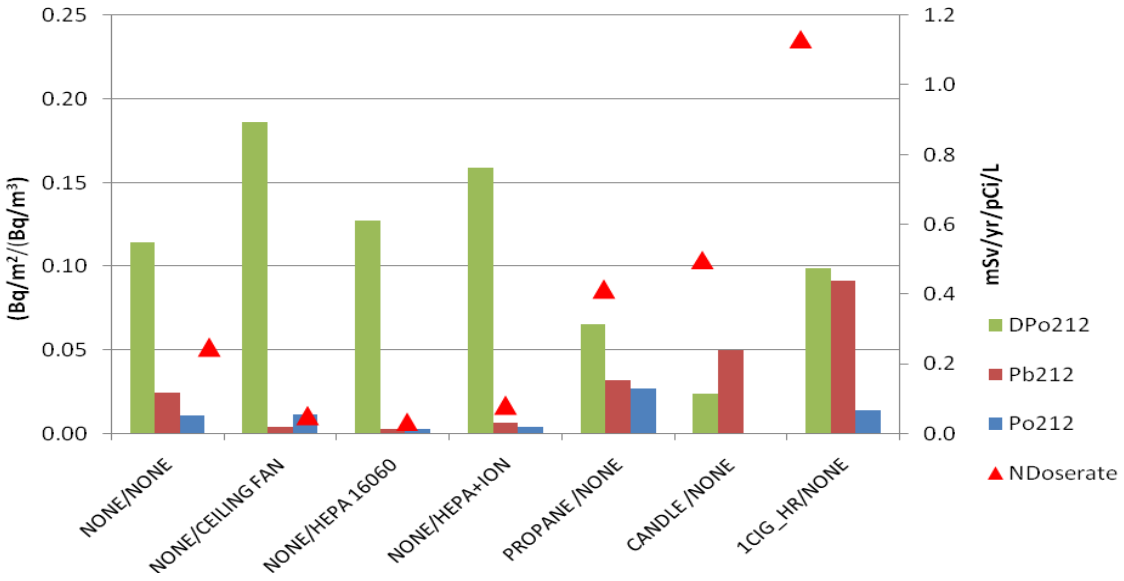



Candles, propane, cooking and cigarette smoking increases the particles concentrations and reduces surface deposition. Candle burning produces more ultrafine particles and reduces the surface deposition. A similar trend was observed for $^{214}$Pb and $^{214}$Po. ( i.e., when aerosol generating activity was taking place surface deposition rate decreased and vice versa).

When thoron was used in the indoor environment and the experiments were repeated for different aerosol sources and sink the average. Results obtained from these experiments are shown in Figure 8.4.

In the absences of aerosol source and sinks, average normalized surface deposited $^{212}$ Pb-$^{212}$ Bi had a value of 0.179, and maximum deposition of 0.291 occurs when the ceiling fan is on, for propane cooking the normalized deposition was 0.102 and a minimum value of 0.037 occurs for candle burning. Similarly for $^{212}$Po minimum deposition of 0.024 was measured for propane cooking and maximum deposition value of 0.186 was obtained for HEPA filter. Qualitatively, the behavior of radon and thoron progenies is similar. When aerosol sink was used, the particles concentration was reduced and the deposition rate increased accordingly. When aerosol generating activity was taking place, the deposition was least as more particles were available to keep the aerosol particles suspended in the ambient air.

Figure 8.4: Normalized surface deposition rate of thoron progenies under different aerosols conditions.

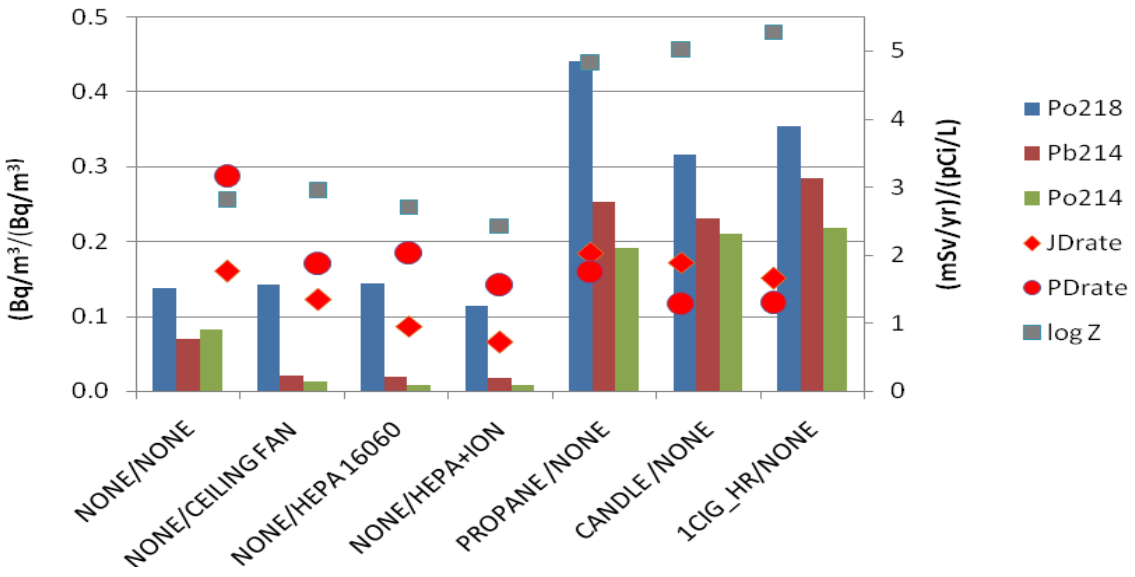


## 8.11. Air borne Progeny Fraction Measurement

*8.11.1. Measurement of unattached fraction using Ludlum scintillation detector*

To correlate the airborne radon/thoron progenies attached to the aerosols or unattached fraction of the progenies activity to the surface deposited activity, airborne progenies activity was measured simultaneously with the surface deposited activity using the active *Ludlum scintillation detector* system. For these measurements two different protocols were used due to the difference of half lives of radon and thoron progenies. For the measurement of radon progenies, the Tsivoglou method was used which is based on the one minute counting interval for 50 min for the concentration of $^{218}$Po, $^{214}$Pb, and $^{214}$Bi-$^{214}$Po after sampling of 5 min. The results obtained are shown in figure 8.5.

Figure 8.5: Normalized airborne radon progenies for different aerosols conditions.




As may be seen in the Figure 8.5 the behavior of airborne radon progeny is opposite to the surface deposited activity. Under the high aerosol conditions the airborne radon progenies concentration is lower on mesh and filter. The concentrations of radon progenies in air attached or unattached form were calculated using the data of unattached

fraction is calculated. For $^{218}$Po normalized airborne radon progenies have maximum value of 0.441 for Propane On-Off/None aerosols conditions and a minimum value of 0.138 was for normal conditions was recorded and this normalized value was 0.143 when the ceiling fan was on. For airborne $^{214}$Pb the maximum value of 0.284 was recorded for cigarette smoking and 0.253 occurred for the propane cooking conditions, and a minimum value of 0.010 was calculated for the None/HEPA + Ionizer was on conditions. Similarly, the airborne $^{214}$Po maximum value of 0.219 was measured for cigarette smoking and a minimum value of 0.009 was measured for None/HEPA+ Ionizer on conditions. This behavior of radon progenies are just opposite to the surface deposition pattern. Thus aerosol sources increase the airborne radon progenies and decrease the deposition phenomena as the available particles for the attachment have been increased and thus attached fraction was also higher.

For the measurement of thoron progeny the counting protocol developed by KBP was used (Khan and Philips, 1986; Khan et al.,1982). In the KBP total counting time (CT) is limited to 5.5 h after the beginning of sampling. Airborne concentrations of radon and thoron daughters are measured directly from the number of counts due to the alpha disintegrations on the filter which is taken in five successive time intervals after the end of sampling 10 min sampling, 2 minutes delay). 50% cutoff of the screen was measured using the relation provided by Knutson et al.,(2001, 1996&1994; Porstendörfer and Reineking, 1999, Reineking and Porstendörfer, 1986) this data the required flow rate was calculated for the pumping through the screen and a backup filter. Screen was used to collect unattached particles and the backup filter was used to collect the aerosols attached fraction of the radioactive radon/thoron progenies particles in the indoor air. These calculations may be extended to radon and thoron daughter working levels by the use of following equations,

$$RnWL = \frac{1.03C_1 + 5.07C_2 + 3.73C_3}{1000}$$

$$RnWL = \frac{123.19C_4 + 12.67C_5}{1000}$$

$$RSWL = \frac{[(91.03S_1)^2 + (5.07S_2)^2 + (3.73S_3)^2]^{1/2}}{\text{RnWL} \times 1000}$$

$$RSTWL = \frac{[(123.19S_4)^2 + (12.67S_5)^2]^{1/2}}{\text{TnWL} \times 1000}$$

The time-weighted averages of $^{218}$Po, $^{214}$Pb, and $^{214}$Bi - $^{214}$Po $^{212}$Pb and $^{212}$Bi concentrations during sampling, are $C_1$, $C_2$, $C_3$, $C_4$, $C_5$, and $S_1$, $S_2$, $S_3$, $S_4$, $S_5$ are standard deviations in concentration in measurements respectively.

During the grab sampling using filter and screen, Rad 7 was used to measure the radon and thoron concentration.

$$F = \frac{\text{Radon Progeny concenteration in mWL}}{\text{Radon concenteration in pCi } \ell^{-1}}$$

$^{220}$Rn equilibrium factor was calculated using:

$$\text{Equilibrium factor (Tn) } F = \frac{\text{Thoron Progeny concenteration in mWL}}{\text{Thoron concenteration in pCi } \ell^{-1}}$$

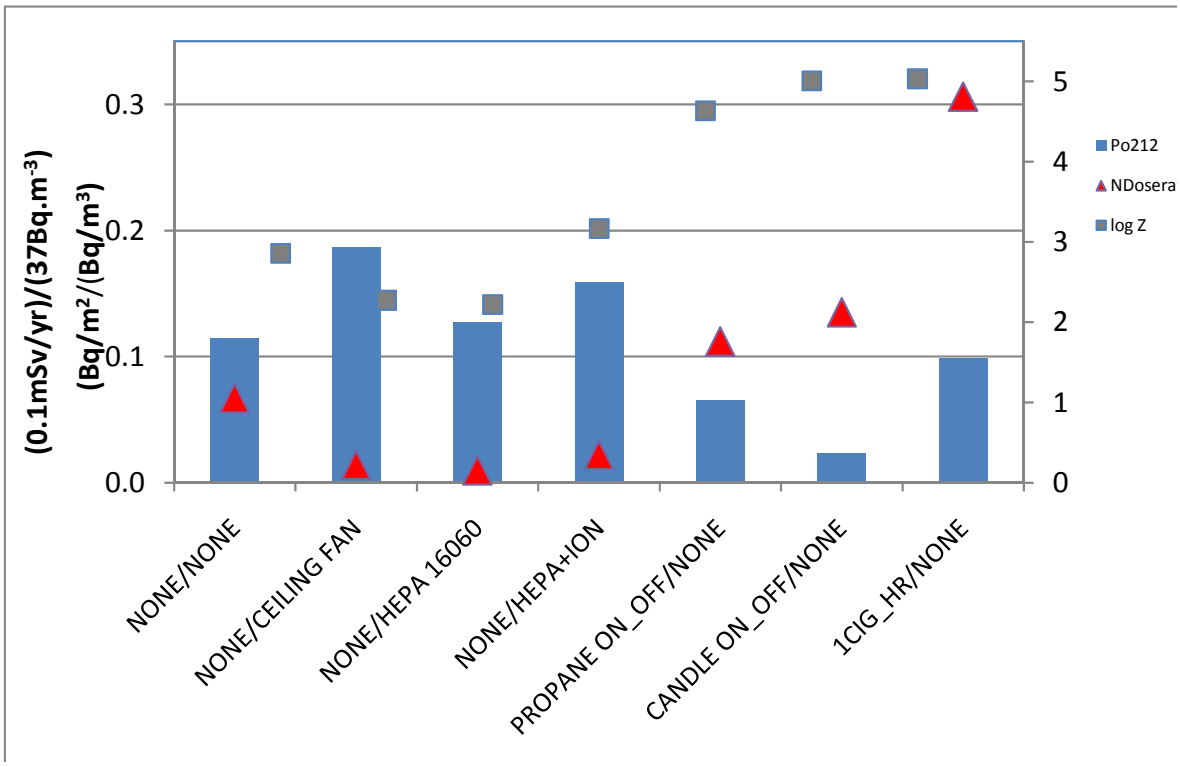
Same procedure (Protocol) was used for the measurement of filter and screen. Unattached fraction of radon and thoron was calculated using the following relation

$$f_p = \frac{(\text{Rn or Tn mWL on screen})}{((\text{Rn or Tn mWL on screen}) + (\text{Rn or Tn mWL on filter}))}$$

Thoron progeny concentration measured using the above mentioned protocol by KPB is shown in the appendix A, B,C and D. Airborne progeny concentration of thoron depends on the aerosols activity generated or present in the environment. It may be borne in mind that due to the relatively long half life of $^{212}$Pb the time required to attain equilibrium between thoron progenies is relatively longer than radon. About 24 h are required in

order to measure thoron progeny before the conditions of the exposure room is changed. Summery results of the normalized thoron progenies are shown in Figure 8.6.

Figure 8.6: Airborne thoron progenies in the exposure room under different aerosols conditions.




The results show that normalized airborne $^{212}$Pb has a maximum value of 0.091 when aerosol generating activity of cigarette smoking (light smoking is taking place) was taking place and a minimum average value of 0.003 was recorded when the ceiling fan was on. For the airborne normalized thoron progeny, minimum value of ~0.0001 was obtained for candle burning and a value of 0.003 for the conditions when HEPA+Iionizer was used as an aerosols sink and a maximum value of 0.027 was recorded for candle burning conditions.

*8.11.2. Radon and Thoron Progeny Equilibrium and Unattached Fraction*

As mentioned earlier, the protocols developed by Tsivoglou and Kusnetz were used for the measurement of the equilibrium factor and unattached fraction using the screen and backup filter. Tsivoglou method provides information about the concentrations of the

individual radon daughters through three alpha counts intervals. The first count is taken from second minute till fifth minute (2-5), the second from sixth till twentieth minute (6-20) and the third from twenty first till thirtieth (21-30) minutes after sampling. From the counts concentrations of the individual radon daughters ($^{218}$Po, $^{214}$Pb, and $^{214}$Bi) and the working level concentration were calculated. The total counting interval for these methods is about 50 minutes and the counting interval are (2-5), (6-20), (21-30) minutes.

Indoor $^{222}$Rn/$^{220}$Rnn was measured using Rad 7 for which the equilibrium attached and unattached concentrations of $^{218}$Po, $^{214}$Pb, $^{214}$Bi - $^{214}$Po. $^{212}$Bi - $^{212}$Po were calculated. Equilibrium factor for radon varied from 3% to 32% which were for the conditions of the ceiling fan and when HEPA 16060 filters were used as sinks for the ultrafine particles in the indoor environment. Unattached fraction varied from 2% for candle on-off to 68% when HEPA 16060 was in use and 67% for HEPA+ Ionizer air filters was used as a sink for the ultrafine particles. Unattached ratio (Uratio) was measured by multiplying the equilibrium factor and unattached fraction. The results varied from 0.5% to 2.3% which were for candle burning and normal aerosols conditions, respectively.

Equilibrium factor measured in the exposure room for the thoron under different aerosols conditions varied from 0.3% to 8.7% which were for the None / HEPA1606 and 1 Cig-hr / None aerosols conditions respectively. These results indicted that equilibrium factor depends on the aerosols sources/sinks. When ultrafine particles are reduced due to the presence of its sink, equilibrium factor is low, whilst for higher aerosols conditions it is high. Unattached fraction for thoron varied from 4.1% to 69.7% which were observed for 1 Cig-hr/None and HEPA1606 respectively. Environmental thoron levels are an order of magnitude lower than those of radon (Yu et al.,1998).

### 8.12. Calibration Factor for the New Thoron Surface Deposition Dosimeters

The calibration and conversion factor were calculated from the efficiency of different regions of the detector for the detection of surface deposited $^{218}$Po, $^{214}$Po and $^{212}$Po. Calculations were performed as follows

$$S^{218}Po = \frac{\left( \frac{Tracks.m^{-2}s^{-1} \times 0.94 \times (Trmm^2 \text{ on Thin filter (CI-92)} - 1.15 \times Trmm^2 \text{ on Thick filter (3M114)} \times \text{Efficiency of thin filter (CI-92) for } ^{214}Po)}{\text{Efficiency of thick filter for (3M114) } ^{214}Po} \right)}{\text{Efficiency of thin filter for (CI-92) } ^{218}Po}$$

$$S^{214}Po = \frac{Trmm^2 \text{ on Thick filter (3M114)} \times Tracks.m^{-2}s^{-1}}{\text{Efficiency of thick filter (3M114) for } ^{214}Po}$$

$$S^{212}Po = \frac{Trmm^2 \text{ on Thick filter (3M146-7)} \times Tracks.m^{-2}s^{-1}}{\text{Efficiency of thick filter (3M146-7) for } ^{212}Po}$$

Thin filter

$$S^{212}Po = \frac{Tracks.m^{-2}s^{-1} \ (Trmm^2 \text{ on Thick filter (3M146-7)} - 1.15 \times Trmm^2 \text{ on Thick filter (3M114)} \times \text{Efficiency of thick filter (3M146-7) for } ^{214}Po}{\text{Efficiency of thin filter (FFM\_7) for } ^{212}Po}$$

For calculation of radon a calibration factor of 19.6 tracks.mm$^{-2}$.d$^{-1}$ /37 Bq.m$^{-3}$ to determine the radon concentration and for thoron calibration factor of 33.533 tracks.mm$^{-2}$.d$^{-1}$ / 37 Bq.m$^{-3}$ concentrations was used.

The results show that $S^{218}Po$ varied from 0.1 ± 0.01 to 8.9 ± 3.5 which were recorded in Anbar Swabi and Islamabad area, respectively. However the uncertainty in the $S^{218}po$ is high and in some case the relation gave negative values due to high uncertainty. $S^{214}Po$ varied from 0.7 ± 0.2 in I-9 Islamabad to 19.1 ± 5.5 Bq.m$^{-2}$ in Narogha Mohmand agency, respectively.

$S^{212}Po$ in the case of thoron was calculated using Thick filter and the values varied from 1.9 ± 0.8 Bq.m$^{-2}$ in I-9 Islamabad to 28.7 ± 11.5 Bq.m$^{-2}$ in Ziarat Mohmand agency, respectively. $S^{212}Po$ measured using thin filter corrected for $^{214}Po$ gave relatively lower value because the $^{214}Po$ corrections is overestimated and therefore in the present study only Thick filter data was used for the measurements of surface deposited activity and dose calculation of the thoron progenies. However for very low concentration radon environment where thoron concentration is sought to be measured thin filter data can also be used.

### 8.13. Dose from Thoron Progeny

The dose conversion factor for radon is derived using two approaches, i.e., epidemiological and dosimetric approaches. However, it can not be used for thoron due to the lack of epidemiological data. Only the dosimetric approach has been used for its

dose calculations. ICRP in its latest publication addressing thoron decay products (TnDP) where assumed DCF was 0.52 based on dosimetric approach available in 1987. UNSCEAR in its 1988 report uses value of 0.42 Sv per $Jhm^{-3}$ to all the organs considering occupancy of 100% and for 80%, occupancy the lung dose was 0.35 Sv per $Jhm^{-3}$. IAEA in its 1996 basic safety standards assumed a DCF equal to 0.48 Sv per $Jhm^{-3.}$ In the 1996 Council Directive of the European Union, a DCF of 0.5 Sv per $Jhm^{-3}$. In ICRP 65 the DCF for TnDP is 0.3 and 0.4 Sv per $Jhm^{-3}$ for dwellings and work places, respectively (Nuccetelli and Bochicchio,1998).

In the report of UNSCEAR 1993 the annual effective dose from thoron and its progeny was evaluated to be 75$\mu$Sv, only 6% of that of radon and its progeny. The annual effective dose from thoron and its progenies was evaluated to be up to 9% of that of radon and its progenies in the report of UNSEEAR 2000. As the half-life of thoron progeny ($^{212}$Pb, 10.64 h) is much longer than that of radon progeny, and the alpha energy emitted from thoron progeny is high ($^{212}$Po, 8.8 MeV), the effective dose per unit equilibrium equivalent concentration of thoron progeny is near 4.4 times higher than that of radon progenies. It is not possible to use only the concentration of the gas in dose evaluation, since the concentration is strongly dependent on the distance from the source (UNSCEAR, 1993). Using the equilibrium equivalent concentrations, the annual effective dose may be derived as:

Indoors: 0.3 Bq $m^{-3}$ (EEC) × 7,000 h × 40 nSv (Bq h $m^{-3}$)$^{-1}$ = 0.084 mSv.

Outdoors: 0.1 Bq $m^{-3}$ (EEC) × 1,760 h × 40 nSv (Bq h $m^{-3}$)$^{-1}$ = 0.007 mSv.

The value of 40 nSv (Bq h $m^{-3}$) is for equilibrium equivalent concentrations of thoron, for evaluating exposures both indoors and outdoors (ICRP Publication50, 1987). The dose to organs other than lungs due to the transfer of $^{212}$Pb from the lungs is significant due to the long half-life of $^{212}$Pb. Due to the unit exposure to thoron progeny, about 20% of the dose that they receive from the same exposure to radon progeny (Comparative dosimetry, 1991; Guo et al., 2001).

Table 8.12: Indoor radon, thoron and their progenies concentration and the dose delivered by thoron progeny.

| House No | Location | Rn | Tn | $S^{218}Po$ | $S^{214}Po$ | $S^{212}Po$ thick | $S^{212}Po$ thin | D Rate $mSv.yr^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| 1. | Islamabad | 56 | 26 | 1.7±0.7 | 2.9±0.8 | 3.4±1.4 | 1.6±0.6 | 0.10 |
| 2. | Swabi | 30 | 15 | -0.6±-0.2 | 2.3±0.7 | 5.6±2.2 | 1.8±0.7 | -0.19 |
| 3. | Bachai | 78 | 155 | 0.8±0.3 | 3.5±1.0 | 5.6±2.2 | 3.4±1.4 | 1.63 |
| 4. | Naziabad | 56 | 67 | 2.9±1.1 | 1.8±0.5 | 4.9±1.9 | 2.6±1.0 | 0.53 |
| 5. | Kaddi | 93 | 70 | 4.8±1.9 | 1.8±0.5 | 7.7±3.1 | 4.7±1.9 | 0.38 |
| 6. | Rashaka | 70 | 30 | -1.4±0.6 | 3.3±0.9 | 8.7±3.5 | 4.1±1.6 | -0.21 |
| 7. | Mathra1 | 59 | 59 | 2.3±0.9 | 2.4±0.7 | 4.2±1.7 | 2.1±0.8 | 0.48 |
| 8. | Mathra2 | 78 | 85 | 1.5±0.6 | 2.2±0.6 | 4.3±1.7 | 3.1±1.2 | 0.81 |
| 9. | Sparliwand | 63 | 56 | 2.1±0.8 | 3.0±0.9 | 4.3±1.7 | 2.7±1.1 | 0.43 |
| 10. | Nilore | 63 | LLD | 0.6±0.2 | 1.7±0.5 | 2.8±1.1 | 2.2±0.9 | LLD |
| 11. | I-9 Islamabad | 33 | 19 | 8.9±3.5 | 0.7±0.2 | 1.9±0.8 | 0.5±0.2 | 0.12 |
| 12. | Alipur Isd | 37 | 22 | L | L | 4.3±1.7 | 2.8±1.1 | L |
| 13. | Mamta | 85 | 78 | -5.3±-2.1 | 7.8±2.2 | 5.1±2.0 | 1.0±0.4 | L |
| 14. | Daudshah | 89 | 152 | -2.5±-1.0 | 4.5±1.3 | 3.8±1.5 | -0.1±0.0 | 1.71 |
| 15. | Sardcheena | 56 | LLD | 2.9±1.1 | 5.1±1.5 | 4.6±1.8 | 4.6±1.8 | LLD |
| 16. | Marghuz | 52 | 15 | 1.2±0.5 | 2.1±0.6 | 2.2±0.9 | 0.6±0.2 | -0.15 |
| 17. | Zaida | 59 | LLD | 1.9±0.8 | 2.1±0.6 | 5.4±2.2 | 4.3±1.7 | LLD |
| 18. | Dhodher | 48 | 74 | 1.5±0.6 | 2.7±0.8 | 3.9±1.6 | 1.2±0.5 | 0.69 |
| 19. | Kalabat | 41 | 78 | 1.9±0.8 | 2.5±0.7 | 4.3±1.7 | 2.5±1.0 | 0.72 |
| 20. | Mainai | 59 | 44 | 1.7±0.7 | 1.0±0.3 | 2.2±0.9 | 1.4±0.5 | 0.42 |
| 21. | Anbar | 59 | 67 | 0.1±0.0 | 2.0±0.6 | 3.0±1.2 | 2.7±1.1 | 0.66 |
| 22. | Khwar | 70 | 137 | -1.4±-0.6 | 4.8±1.4 | 5.9±2.4 | 2.2±0.9 | 1.37 |
| 23. | Qala | L | L | 0.4±0.2 | 5.6±1.6 | 6.4±2.6 | 3.4±1.4 | L |
| 24. | Ziarat | L | L | -3.7±-1.5 | 7.9±2.3 | 28.7±11.5 | 18.1±7.2 | L |
| 25. | Manasab | 59 | 307 | -1.3±-0.5 | 1.6±0.5 | 4.8±1.9 | 3.3±1.3 | 3.66 |
| 26. | Narogha | 59 | 196 | -11.2±-4.5 | 19.1±5.5 | L | L | L |
| 27. | Rupat | 74 | 33 | -0.4±-0.2 | 4.0±1.2 | 6.3±2.5 | 5.7±2.3 | -0.01 |
| 28. | Rustum1 | 122 | 63 | -1.3±-0.5 | 5.0±1.5 | 5.6±2.2 | 1.7±0.7 | 0.43 |
| 29. | Wah | 48 | 89 | -0.5±-0.2 | 2.3±0.7 | 3.2±1.3 | 1.8±0.7 | 0.94 |
| 30. | Rawalpindi | 56 | LLD | -1.1±-0.4 | 2.4±0.7 | 2.4±0.9 | 0.6±0.3 | L |
| 31. | Nawankilli | 41 | 52 | 1.2±0.5 | 1.4±0.4 | 2.3±0.9 | 0.8±0.3 | 0.52 |
| 32. | Rustum2 | 48 | 44 | L | L | L | L | L |
| 33. | Birikao | 52 | 144 | 0.5±0.2 | 2.4±0.7 | 3.9±1.5 | 1.7±0.7 | 1.60 |
| 34. | Gulbahar | 68 | LLD | 2.3±0.9 | 4.9±1.4 | 2.8±1.1 | 0.5±0.2 | LLD |
| 35. | Habib | 67 | 26 | 0.9±0.4 | 2.2±0.6 | 4.7±1.9 | 1.9±0.8 | 0.01 |
| 36. | Sufaid Dheri | 63 | 37 | -2.9±-1.2 | 4.3±1.2 | 3.4±1.4 | 0.3±0.1 | 0.25 |
| 37. | Chargul | 48 | 148 | -0.1±0.0 | 0.9±0.3 | 5.3±2.1 | 3.1±1.2 | 1.56 |
| 38. | Taja | 63 | 67 | -0.7±-0.3 | 3.5±1.0 | 3.2±1.3 | 0.3±0.1 | 0.65 |
| 39. | Khairabad | 85 | LLD | 2.1±0.8 | 3.0±0.9 | 6.2±2.5 | 2.1±0.8 | LLD |
| 40. | Amjad Rustum | 85 | 67 | 1.1±0.4 | 5.0±1.4 | 4.3±1.7 | 0.4±0.2 | 0.57 |
| Min | | 30 | 15 | 15 | 1 | 2 | 0.3 | 0.01 |
| Maximum | | 122 | 307 | 307 | 19 | 29 | 18 | 3.66 |
| Average | | 62 | 79 | 79 | 4 | 5 | 3 | 0.84 |
| ST.Dev. | | 18 | 63 | 63 | 3 | 4 | 3 | 0.78 |

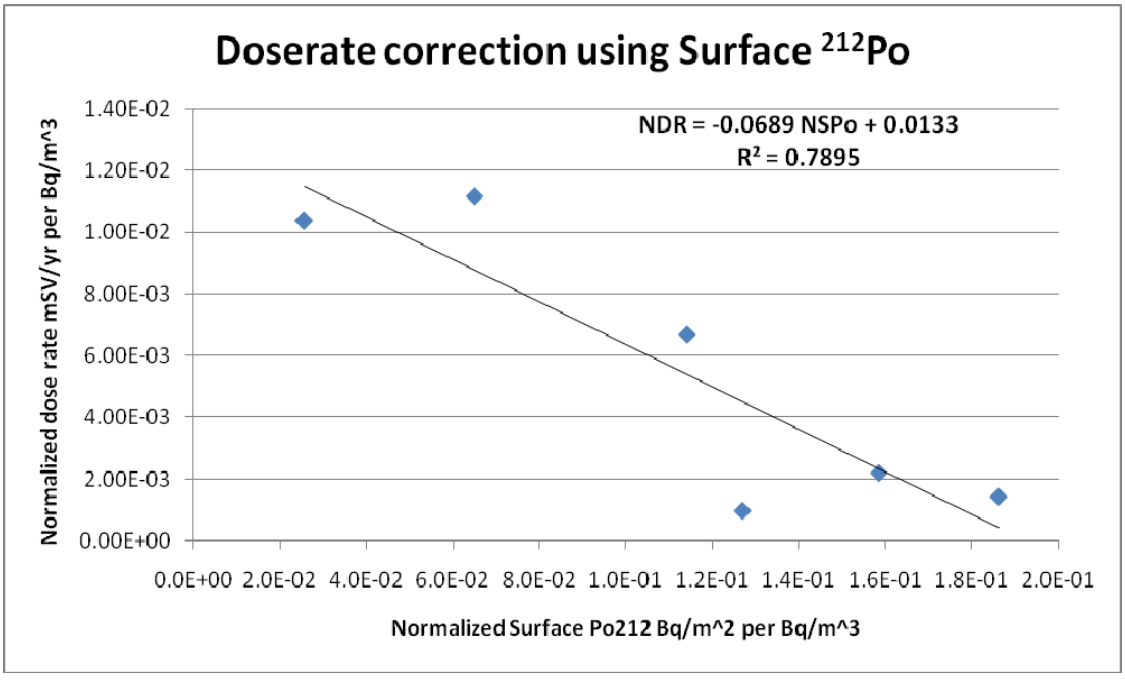
Dose conversion factor (DCF) for thoron progeny was calculated by Nikezic et al., as 4.5 mSv.WLM$^{-1}$, which is three times smaller than that for $^{220}$Rn radon progeny (Nikezić, 2007).

The effective dose per EETC was about four times larger than the effective dose per equilibrium equivalent concentration for radon (EERC) (Ishikawa et al., 2007). Based on the measurements in the exposure room under various aerosols conditions a relation was derived to calculate the thoron progeny dose rate per year (DR).

In this relation both thoron gas concentration (TnG) and the surface deposited $^{212}$Po activity density (S$^{212}$Po) from the newly surface deposition t dosimters; either thick filter alone or thin filter corrected for $^{214}$Po) were used in the following relationship:

DR (mSv/yr) = 0.013× TnG -0.069× S$^{212}$Po.

The results of the study conducted in different parts of Pakistan using the newly developed surface deposition dosimeter showed that thoron can not be ignored during measurement of the indoor radon concentration as in some cases its concentration is high and delivers dose to such an extent which when added to the dose delivered by radon, may exceeded the limits defined by the US EPA or NRPB UK.



In the present study the dose rate varied from 0.1 to 3.66 $mSv.yr^{-1}$ with an average of 0.84 ± 0.78 $mSv.yr^{-1}$. The study showed that thoron concentration in some cases may be very high and thus should not be ignored while measuring radon concentration.

## 8.14. Conclusions

To conclude, a new thoron progeny dosimeter has been developed using the surface deposition principles. The study showed that using suitable filter radon and thoron progenies can be measured discriminatively in the mixed environment using passive technique. Calibration and initial laboratory test were performed which showed very good results. The results showed that this technique is reliable and inexpensive and is suitable for the large area monitoring of the thoron progenies. Aerosols sources and sinks are the main factors for determining the airborne and surface deposited activity of the radon and thoron progenies. In the low aerosols environment unattached fraction is higher resulting in low equilibrium factor. Any cooking or burning activity in the indoor environment increases the number of ultrafine particles very quickly which influences the unattached fraction and equilibrium factor of radon and thoron progenies. Ultrafine particles concentration varies very quickly with the operation of aerosol source or sink. A relation has been established for the measurement of dose of the thoron progeny. Field measurement of the of the radon and thoron progenies in different localities of Pakistan showed that thoron concentrations are high and thus while measuring indoor radon thoron concentration should also be measured.

# Chapter Nine

# Conclusions and Future Recommendations

This chapter presents a brief summary and main conclusions of the studies carried out during this PhD project. The present thesis is based on the experimental work carried out in the field and in the Laboratory. The first two chapters described basic introductory techniques of the solid state nuclear track detectors, materials and methods used during the experimental work and geographic geological information about the area studied. Experimental work consists of two parts. In the first part CR-39 based NRPB (HPA) dosimeters were exposed in dwellings of the selected areas of Pakistan in order to measure the seasonal and spatial variations of the indoor radon levels. Measurements of natural radioactivity in the different soil and building materials which were collected form the selected areas were performed. Experiments about the radon exhalations and the effect of moisture contents on the radon exhalation rate were also performed. In the second part of the experimental work, efforts were concentrated on the development of a passive thoron progeny dosimeter.

## 9.1. Conclusions

According to the review of different studies performed in Pakistan for the measurement of natural radionuclides, a wide variation was noted in the reported data. Most of these studies were conducted to measure the health hazards associated with the natural radioactivity present in the soil and other building materials. Limited data is available in Pakistan concerning the use of the natural radioactivity for the exploration of uranium and other related minerals deposits in different types of rocks and soil. In the majority of the studies related to the natural radioactivity high purity germanium detectors (HPGe) were used whereas in some cases, relatively low resolution NaI (Tl) detector has also been used using spectrum stripping technique. Fission track dating technique has also been used to measure naturally occurring uranium in rocks and water samples. In order to

measure the elemental concentration of the radionuclides in food and vegetable samples, INAA has also been reported.

The lowest reported values for $^{226}Ra$, $^{232}Th$ and $^{40}K$ were as 1.45 $Bq.kg^{-1}$, 1.16 and 7 $Bq.kg^{-1}$, whilst the highest were 799 $Bq.kg^{-1}$, 124 $Bq.kg^{-1}$ and 1272 $Bq.kg^{-1}$, respectively. Reported range of the uranium concentration in water samples is from 0.03 ± 0.01 $\mu g.\ell^{-1}$ (0.0004 ± 0.0001 $Bq.kg^{-1}$) to 6.67 ± 0.14 $\mu g.\ell^{-1}$ with an average value of 1.36 ± 0.05 $\mu g.\ell^{-1}$ (0.0170 ± 0.0006 $Bq.kg^{-1}$).

Etched track detectors for measuring radon are the dosimeters of choice, first, because they are passive and thus need no power supply and second because they measure total radon exposure, allowing averaging of the radon concentration over long time.

From the analysis of the results of the indoor radon levels variation observed in the houses surveyed of the selected area may mainly be due to the local geological formations on which these houses are built as well as ventilation system of the houses. The present work revealed that the Charsadda district and the Bajuar agency have relatively higher indoor radon levels as compared to the other studied areas. Mud houses (houses use unbaked bricks) have relatively higher indoor radon as compared to the houses which are made of the baked bricks and cement. As the cement used in Pakistan has relatively low radioactive nuclides contents, annual arithmetic mean of the present study (72 ± 32 Bq $m^{-3}$) lies within the published values of the indoor radon reported for different countries.

Using the ICRP recommended maximum constraint limit of 600 Bq $m^{-3}$ (ICRP-65), EPA action level of 4 pCi. $\ell^{-1}$ (148 Bq $m^{-3}$) or NRPB (HPA), UK limit of 200 Bq $m^{-3}$ (NRPB, 1990) , yearly arithmetic mean values measured in the present studies of all the districts/agencies are below the recommended limits of ICRP, NRPB (HPA), UK or US EPA limits. Only in few cases the individual values of indoor radon in bedrooms or drawing rooms in the four seasons exceeded NRPB and US EPA limits.

The yearly average indoor radon values in bedrooms exceeded the EPA limit whilst no drawing room value crossed the limits. Weighted average indoor radon

concentration in one house exceeded the EPA limit, no value was higher than the NRPB (HPA) and ICRP limits. Individual values of the indoor radon showed more fluctuations showed as compared to the weighted average data. In the seasonal data, wide variation in the indoor radon levels in the different seasons was observed. Highest and lowest average indoor radon levels were observed in the winter and summer seasons, respectively.

Highest seasonal correction factor of 1.33 ± 0.3 and 1.32 ± 0.47 has been found for drawing rooms and bedrooms of the Mardan and Swabi districts in the summer season, respectively. This is ~18% higher than the overall seasonal correction factor. Seasonal correction factor is higher in spring and summer seasons and lower in winter and autumn seasons. The difference in the seasonal correction factors of bedroom and drawing rooms is not statistically significant.

Comparison of the results of yearly and seasonally exposed detectors indicated more fluctuation in the individual values of the drawing room. Yearly exposed detectors gave average values of 23%, ~19% and ~25% lower than the seasonally measured values in the Swabi, Mardan and Charsadda districts, respectively.

In the Mohmand agency the average yearly values was ~10% lower than the seasonally measured values. In the Bajuar agency, a similar trend was observed. Heat and humidity in the presence of oxygen in the air can affect the sensitivity of the etched-track detector during their use to measure radon. The magnitude of the effect depends on the detector materials, etching conditions and counting techniques. The reason of relatively low track density/ indoor radon levels from the yearly exposed detector as compared to the seasonally measured values, apart from other reason may due to the fact a layer of dust may be formed on the surface of CR-39 detector which causes reduced efficiency of CR-39 for the registration of tracks, as some of the low energy alpha may be absorbed in the dead layer of the dust above the CR-39 detectors. Seasonally measured values were comparable to that of the yearly measured values and there was ~13% difference between them.

Annual effective dose to the inhabitants of the area was with in the limits; however for radiation the ALARA principle should prevail, therefore care must be taken

while using relatively high radioactive contents materials in construction of buildings. Excess lung cancer risk was calculated using the local occupancy factor. As the occupancy factor of the area was 40% lower than that given in the ICRP or other international documents, therefore the effective dose and excess lung cancer risk was also 40% lower than that if high occupancy factor.

It is worth mentioning here that in Pakistan, ICRP recommended limits are adopted by the Pakistan Nuclear Regulatory Authority (PNRA) Pakistan. However, so far, no limits have been defined for the indoor radon concentration levels by the PNRA. At some stage PNRA has also to define indoor radon exposure limits and must take into consideration the environmental and economic conditions of Pakistan. It is suggested that the values recommended by the ICRP may be adopted in this regard.

Exhalation rate has been calculated from the soil sand and brick samples which were collected from the selected area using two different relations and the results showed that relation derived by Rehman et al. yields relatively lower exhalation rate (~6 - 13 % less) as compared to that given by Abu-Jarad et al. From dried soil samples higher average radon exhalation rate of 304 ± 93 $mBq.m^{-2}.h^{-1}$ was found in the samples collected from the district Charsadda whereas lower value of the average radon exhalation rate of 228 ± 60 $mBq.m^{-2}.h^{-1}$ was observed in the district Swabi. From the dried sand samples higher average radon exhalation rate of 291 ± 13 $mBq.m^{-2}.h^{-1}$ was found in the samples collected from the district Charsadda.

Using different moisture contents levels, higher average radon exhalation rate was observed at 15% moisture content from the sample collected from the Bajuar agency with an average value of 392 ± 50 $mBq.m^{-2}.h^{-1}$. Minimum value of 327 ± 35 $mBq.m^{-2}.h^{-1}$ was found in the samples collected form the Mardan district. At 30% moisture content, average minimum of 377 ± 91 $mBq.m^{-2}.h^{-1}$ was observed for the Charsadda whilst a maximum average value of 397 ± 124 $mBq.m^{-2}.h^{-1}$ was observed from the soil samples collected from the district Swabi.

Using 45% moisture content the lower average value of 294 ± 47 $mBq.m^{-2}.h^{-1}$ was observed in the samples from the district Charsadda whilst higher value of 340 ± 53 $mBq.m^{-2}.h^{-1}$ was observed in samples which were collected form the Bajuar agency

respectively. Radon exhalation rate increases (as compared to the dried samples) with moisture content up to 30%. At higher value of 45% moisture content, a decreasing trend is observed. As moisture content is increased from 0% to 15%, 30% and 45%, on the average 34%, 46% and 13% increase was observed in the radon exhalation rate. It was observed that from 0% to 15% moisture content, increase in the exhalation rate was higher as compared with the increase of radon exhalation from 15-30% and 30-45% moisture content. According to the paired T-test, change in the exhalation rate as a function of the moisture content is significant at 95% confidence level. Taking dried samples as a baseline data, the change in the exhalation rate is significant for the moisture content of 15%, 30% and 45% at 95% confidence level. Between 15% and 30% moisture content, the change in exhalation rate is significant for soil and sand samples. For 30% - 5% moisture content, exhalation rate is significant in soil, sand and brick samples. The building materials studied have lower radon exhalation rate and are safe therefore for use as construction materials.

Concentration of natural radionuclides in the soil, sand, brick and cement samples collected from different localities of the selected area varied from sample to sample. A minimum value of $8 \pm 1$ Bq.kg$^{-1}$ was observed for $^{226}$Ra in the samples collected from the Naroga in the Mohmand and the Sabagai in the Bajuar, Agencies and maximum specific activity of $53 \pm 3$ Bq.kg$^{-1}$ and $54 \pm 3$ Bq.kg$^{-1}$ was found in the Swabi city and Kalambad the district Mardan, respectively. $^{232}$Th activity varied from $7 \pm 1$ Bq.kg$^{-1}$ in the Mohmand to $84 \pm 5$ Bq.kg$^{-1}$, $86 \pm 5$ Bq.kg$^{-1}$ in the Pahlawan in the district Charsadda and Kalambad Mardan, respectively. $^{40}$K activity varied from $153 \pm 13$ Bq.kg$^{-1}$ in the Alingar area of the Mohmand agency to a maximum value of $1018 \pm 79$ Bq.kg$^{-1}$ in the Kalambad district Mardan. Radium equivalent activity showed variation from $31 \pm 2$ Bq.kg$^{-1}$ to $255 \pm 17$ Bq.kg$^{-1}$. In general, average maximum specific activities for $^{226}$Ra, $^{232}$Th and $^{40}$K were observed in the samples which were collected from the district Mardan and minimum in the Mohmand agency. The areas of Narogha, Sheik Baba, Qandari of the Mohmand agency and Maskano, Sabagai, Tarakai in the Bajuar agency had little vegetation cover. The observed $^{226}$Ra and $^{232}$Th specific activities in the samples from Maskano, Sabagai, Tarakai, Narogha, Sheik Baba and Qandari were very low and thus safe as building materials. $^{40}$K in the present study is slightly higher than the world

population weighted average value (420 $Bq.kg^{-1}$) as reported in the UNSCEAR 2000. Specific activities, radium equivalent activity and internal and external hazard indices of the soil samples reported in this study are within the acceptable limit and therefore the use of these soils is safe in the construction of dwellings.

Measured specific activities of $^{226}Ra$, $^{232}Th$ and $^{40}K$ in the brick, sand, marble and cement samples showed a wide variation. $^{226}Ra$ and $^{232}Th$, minimum value of 1 ± 1 $Bq.kg^{-1}$ was observed in the marble samples of Greenish color. Maximum value of 66 ± 4 $Bq.kg^{-1}$ was also observed in Pink-M marble samples. $^{40}K$ showed wide variation ranging from 25 ± 2 $Bq.kg^{-1}$ to 1745 ± 135 $Bq.kg^{-1}$ which were observed in the marble and sand samples, respectively. $^{226}Ra$ varied from 18 ± 19 $Bq.kg^{-1}$ to 30 ± 15 $Bq.kg^{-1}$. A relatively lesser average of $^{232}Th$ was18 ± 4 in the cement samples whereas maximum activity of 41 ± 21 $Bq.kg^{-1}$ was observed in the sand samples collected from the selected area. For $^{40}K$, average minimum value of 244 ± 29 $Bq.kg^{-1}$ was observed in the brick samples whilst average maximum value of 769 ± 461 $Bq.kg^{-1}$ was observed in the cement samples. Averaged minimum radium equivalent value of 67 ± 60 $Bq.kg^{-1}$ was observed in the marble samples and maximum averaged value of 129 ± 54 $Bq.kg^{-1}$ was observed in sand samples. Average activities calculated in the present study lies within the reported values and are also lower than the world population weighted average value as reported in the UNSCEAR 2000. Specific activities, radium equivalent activity and internal and external hazard indices for all the studied samples are within the acceptable limits.

In general, soil has higher mean activity concentrations of $^{226}Ra$, $^{232}Th$ and $^{40}K$ as compared to the brick, sand, marble and cement samples, which were collected from the area while marble has the least concentration of the naturally occurring radionuclides. Radium equivalent activity external and internal hazard indices are well below the acceptable hazard limit of 370 Bq $kg^{-1}$ and 1, respectively.

Using standard radon chambers, radon concentration was measured using the short-term high sensitivity electrets in the exposure room. The results showed that electret ion chamber (EIC) were stable and the variation between the different readings of the same exposure (run) is very low.

In majority of the cases there seems a reasonably good agreement between the values of the different electrets exposed to the same environment. The exposure of five electrets for 0.33 day gave results of 36 ± 6, 32 ± 7 pCi.$\ell^{-1}$, 34 ± 7 pCi.$\ell^{-1}$, 33 ± 7 pCi.$\ell^{-1}$ and 34 ± 6 pCi.$\ell^{-1}$ with an average value of 34 ± 7 pCi.$\ell^{-1}$ and having standard deviation of only two. Measuring radon concentrations above 148 Bq.m$^{-3}$(i.e. 4 pCi.$\ell^{-1}$) the relative difference was normally less than 20% using electrets. Low radon concentrations (below 200 Bqm$^{-3}$). Electret-passive environmental radon monitors (E-PERM) show better performance higher indoor radon concentration.

The performance factor calculated for the alpha contamination monitors using electrets showed that long term electret can be used in the inverted form for the measurement of radon progenies. Because the voltage drop per pCi.$\ell^{-1}$ of radon is such that for less sensitive electrets duration of the exposure may be kept relatively longer, in order to get a suitable voltage drop.

The average performance factor calculated for the three long-term electrets varied from 0.5 to 12.51 V/d.pCi.$\ell^{-1}$ with an over all average of 2.68 ± 2.1 V/d.pCi.$\ell^{-1}$. Only four times out of 108 runs the performance factor of the alpha contamination measurement chambers using long-term electrets failed to work as a radon progeny monitor. Long term electret showed more fluctuations in the short term reading whilst long term average had relatively less fluctuations.

In a higher radon progenies environment, the use of long-term electret as a radon progeny dosimeter would be suitable whilst for low radon concentrations, performance factor for short duration may be difficult to carry out. The performance of these low sensitivity detectors originally used for the measurement of alpha contamination may also be used as radon progeny dosimeters. In order to measure the effect of orientation of these electrets on its performance, electrets were exposed in the horizontal and vertical positions. For electrets exposed in the vertical position performance factor values varied from 0.51 to 4.8 V/d.pCi.$\ell^{-1}$ whilst for the other electret varied from 0.74 to 3.81 V/d.pCi.$\ell^{-1}$. The average value of the performance factor in the vertical position varied from 0.62 to 4.31 V/d.pCi.$\ell^{-1}$.

The performance factor of the electrets exposed in horizontal position was relatively higher as compared to those exposed in vertical positions. However, this deviation in performance factor was not significant. These short-term electrets were found most suitable for the measurement of both high and low levels of radon progeny concentration. For high radon concentration short term measurement must be performed otherwise the voltage drop may be much higher and may reach to unacceptably lower values near to zero.

Electret-radon Progeny Integrating Sampling Unit (E-RPISU) was used to measure unattached fraction and equilibrium factor of radon. Measured unattached fraction and equilibrium factor showed a wide range of variation. Maximum equilibrium factor of 87% and a minimum unattached fraction of 3% were measured in the smoky environment in the exposure room. Measurement performed under the calm conditions, equilibrium factor varied from 3% to 13% and the unattached fraction varied from 33% to 86%. When aerosol sinks were used, the equilibrium factor and unattached fraction also changed for HEPA filter as 5% and 35% and for HEPA filter + ionizer it were 4% and 32%, respectively. The results showed that the E-RIPSU electrets are convenient instrument for measuring the equilibrium factor and unattached fraction.

In order to develop a new thoron progeny dosimeters, different plastics and other materials were studied. Consequently a suitable set of materials were selected for the development of thoron dosimeter. In this study efforts have been made to develop an instrument for the measurement of thoron progeny working on the principle of surface deposition.

Using this technique, suitable filters were identified to detect only thoron progeny ($^{212}$Po) and attenuated the radon progenies. To block all the radon progenies is easier, except $^{214}$Po which is a difficult task because its energy difference is low as compared to the alpha energy of $^{212}$Po. 3M146_07 was used as thick filter for the surface deposited activity of $^{212}$Po.

In the absence of the aerosol source and sink, average normalized surface deposited $^{212}$Pb-$^{212}$Bi has a value of 0.179 and maximum deposition of 0.291 occurred when the ceiling fan was on. Qualitatively the behavior of radon and thoron progeny is

similar. When aerosol sink was used, the particles concentration was reduced which resulted in an increase in the deposition rate.

Due to the difference of half lives of radon and thoron progenies two different protocols were used. It is confirmed that airborne radon progeny concentration is opposite to the surface deposited activity. Under the high aerosol conditions, the airborne radon progeny concentration was lower on mesh filter. Aerosol sources increases the airborne radon progeny and decreases the deposition phenomena as the available particles for the attachment have been increased and thus attached fraction was also higher. Normalized airborne $^{212}Pb$ had a maximum value of 0.091 when aerosol generating activity of cigarette smoking (light smoking is taking place) was taking place and a minimum average value of 0.003 was recorded when the air fan was on.

Equilibrium factor measured in the exposure room for the thoron under different aerosols conditions varied from 0.3 to 8.7 % which were for the NONE / HEPA1606 and 1 Cig-Hr / None aerosols conditions respectively.

$S^{214}Po$ varied from 0.7 ± 0.2 in I-9 Islamabad to Narogha Mohmand 19.1 ± 5.5 $Bq.m^{-2}$.

$S^{212}Po$ in the case of thoron was calculated using thick filter and the observed values varied from 1.9 ± 0.8 in I-9 Islamabad to 28.7 ± 11.5 in Ziarat Mohmand agency. In the case of lower radon environment thoron concentration is measured, thin filter data may also be used. Based on the measurements in the exposure room under various aerosols conditions, following relation was derived to calculate the thoron progeny dose rate per year (DR).

$$DR\ (mSv/yr) = 0.013 \times TnG - 0.069 \times S^{212}Po.$$

TnG = Thoron gas concentration and $S^{212}Po$ surface deposited $^{212}Po$ activity density from the newly surface deposition thoron dosimeters. In the light of results obtained from the study conducted in different parts of Pakistan using the newly developed surface deposition it may be concluded that thoron concentration can not be ignored

## 9.2. Future Recommendations

- Indoor radon levels were measured in some selected areas of Pakistan and therefore it is recommended that those areas which have not been studied so far should be studied.

- Due to the unavailability of active detectors these measurements were performed using only passive detectors, therefore daily and short term variations could not be studied. Therefore, if suitable active detectors are comprehensive study should be conducted to study short term variations in the indoor radon levels.

- Using active detectors measurement of the radon attached and unattached fraction in the different indoor environment should be measured.

- Using active detectors for the measurement of radon exhalation rate field measurements should be performed in order to reduce the effect of crushing on the radon exhalation rate.

- Further experiments are needed to perform to study the Electret ion chamber for the measurement of radon and thoron progenies.

- The study of the surface deposition thoron dosimeter showed that further studies are needed to be performed to know the thoron contribution to the radiation dose.

- Intercomparison of the newly developed thoron progeny dosimeter with other thoron progenies dosimeter is recommended.

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# APPENDICES

Appendix A: Surface deposited radon progenies in $Bq.m^{-2}$ measured using active detector and smooth glass surfaces.

| Experiment Run ID | Aptec | Surface Activity ($Bq.m^{-2}$) | SA1 | SA3 |
|---|---|---|---|---|
| 71607A | $^{218}Po$ | 243±61 | 129±23 | 236±34 |
| Run 1 | $^{214}Pb$ | 1366±84 | 309±39 | 224±44 |
| | $^{214}Bi$- $^{214}Po$ | 1487±58 | 307±27 | 447±31 |
| Run 2 | $^{218}Po$ | 218±41 | 196±29 | 558±45 |
| | $^{214}Pb$ | 440±50 | 472±47 | 452±47 |
| | $^{214}Bi$- $^{214}Po$ | 519±34 | 454±33 | 433±32 |
| Run 3 | $^{218}Po$ | 294±43 | 207±28 | 344±38 |
| | $^{214}Pb$ | 407±50 | 243±42 | 360±44 |
| | $^{214}Bi$- $^{214}Po$ | 531±34 | 391±29 | 406±30 |
| Run 4 | $^{218}Po$ | 260±38 | 224±27 | 287±34 |
| | $^{214}Pb$ | 394±41 | 424±35 | 391±40 |
| | $^{214}Bi$- $^{214}Po$ | 324±28 | 181±23 | 290±27 |
| Run 5 | $^{218}Po$ | 375±47 | 244±30 | 422±42 |
| | $^{214}Pb$ | 558±53 | 294±42 | 411±47 |
| | $^{214}Bi$- $^{214}Po$ | 577±37 | 371±29 | 462±33 |
| 71707A | $^{218}Po$ | 143±30 | 203±26 | 108±25 |
| Run 1 | $^{214}Pb$ | 167±33 | 133±30 | 116±33 |
| | $^{214}Bi$- $^{214}Po$ | 245±23 | 202±21 | 256±23 |
| Run 2 | $^{218}Po$ | 92±27 | 46±16 | 109±23 |
| | $^{214}Pb$ | 321±34 | 167±30 | 174±29 |
| | $^{214}Bi$- $^{214}Po$ | 211±23 | 182±20 | 175±20 |
| Run 3 | $^{218}Po$ | 76±28 | 84±19 | 163±26 |
| | $^{214}Pb$ | 135±35 | 67±28 | 160±29 |
| | $^{214}Bi$- $^{214}Po$ | 292±25 | 184±20 | 171±20 |
| Run 4 | $^{218}Po$ | 277±34 | 68±17 | 188±28 |
| | $^{214}Pb$ | 314±30 | 207±26 | 147±28 |
| | $^{214}Bi$- $^{214}Po$ | 128±20 | 106±17 | 153±19 |
| Run 5 | $^{218}Po$ | 153±30 | 106±20 | 201±28 |
| | $^{214}Pb$ | 159±34 | 182±30 | 230±30 |
| | $^{214}Bi$- $^{214}Po$ | 253±24 | 189±21 | 163±20 |
| Run 6 | $^{218}Po$ | 329±38 | 152±23 | 170±24 |
| | $^{214}Pb$ | 177±36 | 150±32 | 195±28 |
| | $^{214}Bi$- $^{214}Po$ | 275±25 | 221±22 | 150±19 |
| Run7 | $^{218}Po$ | 289±37 | 131±22 | 266±29 |
| | $^{214}Pb$ | 424±39 | 187±30 | 253±30 |
| | $^{214}Bi$- $^{214}Po$ | 271±26 | 178±20 | 159±20 |
| 71807A | $^{218}Po$ | 245±35 | 103±21 | 148±27 |
| Run 1 | $^{214}Pb$ | 394±38 | 281±33 | 423±35 |
| | $^{214}Bi$- $^{214}Po$ | 250±25 | 202±22 | 194±23 |
| Run 2 | $^{218}Po$ | 168±32 | 104±20 | 150±26 |
| | $^{214}Pb$ | 472±38 | 161±31 | 315±34 |

| | | | | |
|---|---|---|---|---|
| | $^{214}$Bi- $^{214}$Po | 230±25 | 214±22 | 204±23 |
| Run 3 | $^{218}$Po | 122±26 | 140±23 | 153±26 |
| | $^{214}$Pb | 375±30 | 45±30 | 133±31 |
| | $^{214}$Bi- $^{214}$Po | 113±19 | 235±22 | 222±22 |
| 71907A | $^{218}$Po | 55±16 | 32±13 | 63±17 |
| Run 1 | $^{214}$Pb | 98±18 | 55±20 | 62±21 |
| | $^{214}$Bi- $^{214}$Po | 49±12 | 93±14 | 99±15 |
| Run 2 | $^{218}$Po | 61±20 | 8±10 | 45±17 |
| | $^{214}$Pb | 109±23 | 64±21 | 41±23 |
| | $^{214}$Bi- $^{214}$Po | 108±16 | 97±15 | 129±16 |
| Run 3 | $^{218}$Po | 39±26 | 56±15 | 61±18 |
| | $^{214}$Pb | 294±36 | 5±20 | 62±22 |
| | $^{214}$Bi- $^{214}$Po | 257±25 | 107±15 | 109±15 |
| Run 4 | $^{218}$Po | 75±19 | 21±11 | 33±16 |
| | $^{214}$Pb | 186±21 | 9620±20 | 73±22 |
| | $^{214}$Bi- $^{214}$Po | 53±13 | 80±14 | 113±16 |
| 71907B | $^{218}$Po | 295±49 | 351±36 | 628±49 |
| Run 1 | $^{214}$Pb | 689±61 | 491±53 | 674±54 |
| | $^{214}$Bi- $^{214}$Po | 791±42 | 605±37 | 564±37 |
| Run 2 | $^{218}$Po | 645±59 | 265±32 | 557±47 |
| | $^{214}$Pb | 891±65 | 492±49 | 614±53 |
| | $^{214}$Bi- $^{214}$Po | 846±45 | 491±34 | 535±36 |
| Run 3 | $^{218}$Po | 521±52 | 525±42 | 617±47 |
| | $^{214}$Pb | 711±57 | 529±53 | 597±49 |
| | $^{214}$Bi- $^{214}$Po | 623±39 | 565±36 | 436±33 |
| Run 4 | $^{218}$Po | 609±59 | 500±43 | 629±51 |
| | $^{214}$Pb | 861±66 | 638±61 | 850±61 |
| | $^{214}$Bi- $^{214}$Po | 878±45 | 801±42 | 719±42 |
| Run 5 | $^{218}$Po | 712±59 | 418±38 | 711±53 |
| | $^{214}$Pb | 1012±63 | 740±53 | 537±57 |
| | $^{214}$Bi- $^{214}$Po | 701±42 | 496±35 | 694±40 |
| 72107A & B | $^{218}$Po | 5±7 | 41±12 | 30±11 |
| Run 1 | $^{214}$Pb | 51±10 | 18±8 | 23±8 |
| | $^{214}$Bi- $^{214}$Po | 11±6 | 11±5 | 11±5 |
| Run 2 | $^{218}$Po | 47±12 | 4±6 | |
| | $^{214}$Pb | 43±9 | 30±10 | |
| | $^{214}$Bi- $^{214}$Po | 5±5 | 14±6 | |
| Run 3 | $^{218}$Po | 47±15 | 40±12 | -15±5 |
| | $^{214}$Pb | 23±15 | 34±11 | 36±13 |
| | $^{214}$Bi- $^{214}$Po | 49±10 | 197±7 | 34±9 |
| Run 4 | $^{218}$Po | 110±20 | 1±7 | 49±14 |
| | $^{214}$Pb | 46±16 | 39±14 | 65±15 |
| | $^{214}$Bi- $^{214}$Po | 51±11 | 44±10 | 38±10 |
| 72307A | $^{218}$Po | 61±20 | 5±6 | 15±9 |
| | $^{214}$Pb | 67±23 | 44±9 | 22±10 |
| | $^{214}$Bi- $^{214}$Po | 115±16 | 7±5 | 21±7 |
| Run 2 | $^{218}$Po | 8±7 | 3±6 | 14±9 |
| | $^{214}$Pb | 61±9 | 20±12 | 30±11 |

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|---|---|---|---|---|
| | $^{214}$Bi- $^{214}$Po | 2±5 | 32±8 | 25±8 |
| Run 3 | $^{218}$Po | 103±21 | 37±12 | 87±19 |
| | $^{214}$Pb | 10±18 | 59±15 | 64±22 |
| | $^{214}$Bi- $^{214}$Po | 78±13 | 40±10 | 109±15 |
| 72407A | $^{218}$Po | 27±20 | 11±9 | 13±13 |
| | $^{214}$Pb | 31±27 | 84±18 | 96±20 |
| | $^{214}$Bi- $^{214}$Po | 183±19 | 62±12 | 79±14 |
| Run 2 | $^{218}$Po | 34±11 | 16±8 | 23±11 |
| | $^{214}$Pb | 48±9 | 34±10 | 47±15 |
| | $^{214}$Bi- $^{214}$Po | 4±5 | 14±6 | 42±10 |
| Run 3 | $^{218}$Po | 3±8 | 29±10 | 28±11 |
| | $^{214}$Pb | 48±11 | 33±8 | 38±11 |
| | $^{214}$Bi- $^{214}$Po | 22±15 | 3±4 | 18±7 |
| Run4 | $^{218}$Po | 37±18 | 16±8 | 86±18 |
| | $^{214}$Pb | 81±13 | 45±10 | 37±16 |
| | $^{214}$Bi- $^{214}$Po | 18±7 | 12±6 | 53±11 |
| Run 5 | $^{218}$Po | 42±15 | 62±14 | 69±15 |
| | $^{214}$Pb | 23±16 | -5±13 | 49±10 |
| | $^{214}$Bi- $^{214}$Po | 63±11 | 46±9 | 6±6 |
| 81607 ONE/NONE | $^{218}$Po | 192±39 | | 267±34 |
| Run 1 | $^{214}$Pb | 584±49 | | 314±41 |
| | $^{214}$Bi- $^{214}$Po | 453±33 | | 340±28 |
| Run 2 | $^{218}$Po | 314±41 | 27±19 | 303±34 |
| | $^{214}$Pb | 247±44 | 229±45 | 186±34 |
| | $^{214}$Bi- $^{214}$Po | 425±30 | 484±32 | 251±24 |
| Run 3 | $^{218}$Po | 221±38 | 18127± | 212±31 |
| | $^{214}$Pb | 365±44 | 145±41 | 363±39 |
| | $^{214}$Bi- $^{214}$Po | 404±30 | 419±30 | 281±26 |
| Run 4 | $^{218}$Po | 369±45 | 104±23 | 355±39 |
| | $^{214}$Pb | 567±50 | 421±45 | 233±44 |
| | $^{214}$Bi- $^{214}$Po | 474±34 | 417±31 | 439±31 |
| Run 5 | $^{218}$Po | 306±45 | 113±24 | 222±34 |
| | $^{214}$Pb | 721±54 | 200±45 | 560±46 |
| | $^{214}$Bi- $^{214}$Po | 555±37 | 483±32 | 386±31 |
| Run 6 | $^{218}$Po | 327±41 | 91±23 | 449±41 |
| | $^{214}$Pb | 308±44 | 351±45 | 401±42 |
| | $^{214}$Bi- $^{214}$Po | 414±30 | 430±31 | 332±28 |
| Run7 | $^{218}$Po | 253±45 | 106±22 | 371±39 |
| | $^{214}$Pb | 471±56 | 290±38 | 264±44 |
| | $^{214}$Bi- $^{214}$Po | 683±39 | 289±26 | 418±30 |
| Run8 | $^{218}$Po | 445±50 | 88±21 | 164±31 |
| | $^{214}$Pb | 554±54 | 232±40 | 350±43 |
| | $^{214}$Bi- $^{214}$Po | 605±37 | 357±28 | 390±30 |
| Run 9 | $^{218}$Po | 211±43 | 161±26 | 381±38 |
| | $^{214}$Pb | 554±55 | 264±40 | 428±40 |
| | $^{214}$Bi- $^{214}$Po | 634±38 | 351±28 | 272±26 |
| Run10 | $^{218}$Po | 178±44 | 239±31 | 460±44 |

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|---|---|---|---|---|
| | $^{214}$Pb | 521±57 | 210±48 | 381±52 |
| | $^{214}$Bi- $^{214}$Po | 701±39 | 563±34 | 603±36 |
| Run11 | $^{218}$Po | | 107±23 | 262±36 |
| | $^{214}$Pb | | 503±44 | 462±48 |
| | $^{214}$Bi- $^{214}$Po | | 371±30 | 469±33 |
| 81707A Candle | $^{218}$Po | 101±27 | 14±12 | 46±20 |
| Run 1 | $^{214}$Pb | 34±30 | 37±25 | 12±31 |
| | $^{214}$Bi- $^{214}$Po | 236±22 | 159±18 | 255±22 |
| Run 2 | $^{218}$Po | 5±11 | 2±7 | 4±11 |
| | $^{214}$Pb | 38±16 | 34±13 | 6±17 |
| | $^{214}$Bi- $^{214}$Po | 54±11 | 35±9 | 75±12 |
| Run 3 | $^{218}$Po | 34±11 | 4±6 | 38±13 |
| | $^{214}$Pb | 34±8 | 4±9 | -6±12 |
| | $^{214}$Bi- $^{214}$Po | 7±5 | 19±6 | 41±9 |
| Run 4 | $^{218}$Po | 27±12 | 37±12 | 8±10 |
| | $^{214}$Pb | 0±11 | 35±14 | 59±15 |
| | $^{214}$Bi- $^{214}$Po | 33±8 | 45±10 | 45±10 |
| Run 5 | $^{218}$Po | 29±11 | 4±6 | 17±9 |
| | $^{214}$Pb | -3±10 | 7±10 | -2±7 |
| | $^{214}$Bi- $^{214}$Po | 27±7 | 24±7 | 15±5 |
| Run 6 | $^{218}$Po | 23±9 | -8±2 | 17±9 |
| | $^{214}$Pb | 49±7 | 8±8 | 3±8 |
| | $^{214}$Bi- $^{214}$Po | -3±4 | 13±5 | 14±5 |
| Run 7 | $^{218}$Po | 56±14 | 15±9 | 17±9 |
| | $^{214}$Pb | 31±11 | -8±11 | 1±8 |
| | $^{214}$Bi- $^{214}$Po | 20±7 | 37±8 | 15±5 |
| Run 1 FAN | $^{218}$Po | 521±57 | 88±24 | 259±37 |
| | $^{214}$Pb | 1034±67 | 291±50 | 378±50 |
| | $^{214}$Bi- $^{214}$Po | 875±46 | 602±36 | 560±35 |
| Run 2 | $^{218}$Po | 315±42 | 290±33 | 396±42 |
| | $^{214}$Pb | 527±47 | 590±50 | 400±50 |
| | $^{214}$Bi- $^{214}$Po | 408±32 | 473±34 | 530±34 |
| Run 3 | $^{218}$Po | 625±57 | 275±33 | 567±48 |
| | $^{214}$Pb | 725±61 | 382±50 | 328±54 |
| | $^{214}$Bi- $^{214}$Po | 741±41 | 537±34 | 668±38 |
| Run 4 | $^{218}$Po | 441±52 | 117±27 | 542±48 |
| | $^{214}$Pb | 891±60 | 562±55 | 830±58 |
| | $^{214}$Bi- $^{214}$Po | 672±41 | 626±38 | 637±39 |
| Run 5 | $^{218}$Po | 302±49 | 331±36 | 427±41 |
| | $^{214}$Pb | 760±61 | 878±58 | 413±46 |
| | $^{214}$Bi- $^{214}$Po | 758±42 | 618±39 | 436±32 |
| Run 6 | $^{218}$Po | 812±65 | 216±33 | 530±47 |
| | $^{214}$Pb | 936±69 | 741±63 | 572±55 |
| | $^{214}$Bi- $^{214}$Po | 964±47 | 822±43 | 613±38 |
| Run 7 | $^{218}$Po | 344±49 | 220±32 | 780±55 |
| | $^{214}$Pb | 554±57 | 557±57 | 656±60 |
| | $^{214}$Bi- $^{214}$Po | 707±40 | 693±39 | 722±41 |
| Run 8 | $^{218}$Po | 563±56 | 274±33 | 525±46 |

| | | | | |
|---|---|---|---|---|
| | $^{214}$Pb | 1226±64 | 555±51 | 548±51 |
| | $^{214}$Bi- $^{214}$Po | 677±42 | 511±35 | 512±35 |
| Run 9 | $^{218}$Po | 708±51 | 243±31 | 600±49 |
| | $^{214}$Pb | 467±51 | 496±48 | 530±54 |
| | $^{214}$Bi- $^{214}$Po | 530±35 | 464±33 | 600±37 |
| Run 10 | $^{218}$Po | 524±46 | 189±30 | 371±42 |
| | $^{214}$Pb | 732±55 | 376±54 | 545±55 |
| | $^{214}$Bi- $^{214}$Po | 549±37 | 669±38 | 625±38 |
| Run 1 PROPANE | $^{218}$Po | 76±22 | | 1±14 |
| | $^{214}$Pb | 276±28 | | 106±25 |
| | $^{214}$Bi- $^{214}$Po | 111±18 | | 137±17 |
| Run 2 | $^{218}$Po | 86±18 | 45±14 | |
| | $^{214}$Pb | 108±16 | 35±19 | |
| | $^{214}$Bi- $^{214}$Po | 33±10 | 91±14 | |
| Run 3 | $^{218}$Po | 93±24 | 46±14 | |
| | $^{214}$Pb | 113±28 | 61±19 | |
| | $^{214}$Bi- $^{214}$Po | 168±19 | 76±13 | |
| Run 4 | $^{218}$Po | 96±23 | 16±12 | 36±15 |
| | $^{214}$Pb | 146±25 | 138±25 | 60±21 |
| | $^{214}$Bi- $^{214}$Po | 114±17 | 120±17 | 105±15 |
| Run 5 | $^{218}$Po | 74±22 | 79±17 | 28±16 |
| | $^{214}$Pb | 132±26 | 10±21 | 90±25 |
| | $^{214}$Bi- $^{214}$Po | 144±18 | 122±16 | 135±17 |
| Run 6 | $^{218}$Po | 100±25 | 102±19 | 57±18 |
| | $^{214}$Pb | 150±29 | 117±24 | 133±24 |
| | $^{214}$Bi- $^{214}$Po | 181±20 | 112±16 | 117±17 |
| Run 7 | $^{218}$Po | | 32±13 | 53±18 |
| | $^{214}$Pb | | 154±22 | 103±26 |
| | $^{214}$Bi- $^{214}$Po | | 80±15 | 143±18 |
| Run 8 | $^{218}$Po | 203±30 | 52±17 | 96±24 |
| | $^{214}$Pb | 183±30 | 152±33 | 167±33 |
| | $^{214}$Bi- $^{214}$Po | 181±21 | 253±23 | 242±a |

Appendix B: Surface deposited radon and thoron progenies in $Bq.m^{-2}$ measured using active detectors and smooth glass surfaces.

| | Propane cook | | | | Cigarette smoke | | | |
|---|---|---|---|---|---|---|---|---|
| | APTEC | AP-1 | AP-2 | AP-3 | APTEC | AP-1 | AP-2 | AP-3 |
| $^{218}Po$ | 31 | 32 | 29 | 85 | 26 | 96 | 39 | 25 |
| $^{214}Po$ | 6 | 1 | 10 | 14 | 9 | 14 | 9 | 19 |
| $^{212}Po$ | 29 | 37 | 31 | 52 | 32 | 112 | 26 | 32 |
| $^{212}Po$ Act | 32.5 | 44.6 | 41.4 | 58.7 | 35.9 | 139.4 | 34.5 | 34.8 |
| $^{218}Po$ | 32 | 45 | 35 | 40 | 52 | 26 | 22 | 33 |
| $^{214}Po$ | 16 | 1 | 6 | 18 | 20 | 3 | 3 | 6 |
| $^{212}Po$ | 28 | 31 | 22 | 35 | 77 | 27 | 23 | 20 |
| $^{212}Po$ Act | 31.4 | 37.0 | 29.1 | 38.4 | 86.3 | 31.8 | 30.8 | 21.9 |
| $^{218}Po$ | 21 | 34 | 42 | 44 | 23 | 27 | 33 | 60 |
| $^{214}Po$ | 5 | 2 | 8 | 8 | 9 | 3 | 4 | 10 |
| $^{212}Po$ | 27 | 26 | 30 | 59 | 34 | 26 | 33 | 48 |
| $^{212}Po$ Act | 30.3 | 30.6 | 40.1 | 67.5 | 38.1 | 30.5 | 44.7 | 54.4 |
| $^{218}Po$ | 36 | 30 | 41 | 46 | 31 | 26 | 22 | 30 |
| $^{214}Po$ | 14 | 1 | 2 | 13 | 5 | 1 | 3 | 6 |
| $^{212}Po$ | 64 | 54 | 8 | 46 | 20 | 21 | 14 | 20 |
| $^{212}Po$ Act | 71.7 | 66.3 | 9.9 | 51.8 | 22.4 | 24.3 | 18.2 | 21.9 |
| $^{218}Po$ | 50 | 43 | 42 | 24 | 37 | 34 | 45 | 45 |
| $^{214}Po$ | 12 | 1 | 8 | 2 | 7 | 3 | 4 | 5 |
| $^{212}Po$ | 39 | 38 | 30 | 18 | 22 | 25 | 24 | 11 |
| $^{212}Po$ Act | 43.7 | 45.9 | 40.1 | 19.9 | 24.7 | 29.2 | 32.1 | 11.5 |
| $^{218}Po$ | 20 | 53 | 36 | 28 | 17 | 25 | 39 | 77 |
| $^{214}Po$ | 16 | 3 | 6 | 9 | 3 | 2 | 3 | 23 |
| $^{212}Po$ | 27 | 43 | 32 | 35 | 22 | 13 | 58 | 83 |
| $^{212}Po$ Act | 30.3 | 52.1 | 43.1 | 39.2 | 24.7 | 14.0 | 79.6 | 94.3 |
| $^{218}Po$ | 15 | 46 | 36 | 32 | 25 | 32 | 60 | 37 |
| $^{214}Po$ | 8 | 3 | 6 | 11 | 11 | 3 | 3 | 7 |
| $^{212}Po$ | 13 | 27 | 32 | 33 | 19 | 25 | 28 | 33 |
| $^{212}Po$ Act | 14.6 | 31.8 | 43.1 | 36.7 | 21.3 | 29.2 | 37.8 | 37.1 |
| $^{218}Po$ | 64 | 60 | 54 | 40 | 20 | 23 | 28 | 37 |
| $^{214}Po$ | 18 | 2 | 16 | 13 | 7 | 16 | 10 | 9 |
| $^{212}Po$ | 43 | 35 | 36 | 37 | 22 | 13 | 14 | 24 |
| $^{212}Po$ Act | 48.2 | 42.0 | 47.9 | 41.2 | 24.7 | 13.3 | 17.7 | 26.3 |
| $^{218}Po$ | 32 | 26 | 38 | 37 | 35 | 37 | 34 | 37 |
| $^{214}Po$ | 13 | 3 | 7 | 12 | 12 | 8 | 11 | 16 |
| $^{212}Po$ | 40 | 31 | 34 | 48 | 14 | 16 | 13 | 16 |
| $^{212}Po$ Act | 44.8 | 36.9 | 45.8 | 54.2 | 15.7 | 17.5 | 16.2 | 16.3 |
| $^{218}Po$ | 50 | 45 | 56 | 36 | 20 | 24 | 51 | 46 |
| $^{214}Po$ | 18 | 3 | 7 | 8 | 6 | 1 | 6 | 6 |
| $^{212}Po$ | 56 | 26 | 35 | 52 | 33 | 13 | 25 | 40 |
| $^{212}Po$ Act | 62.7 | 30.5 | 47.2 | 59.3 | 37.0 | 14.1 | 33.3 | 45.4 |
| $^{218}Po$ | 24 | 33 | 27 | 35 | 16 | 22 | 31 | 37 |
| $^{214}Po$ | 7 | 1 | 3 | 9 | 2 | 1 | 3 | 7 |
| $^{212}Po$ | 27 | 13 | 21 | 41 | 17 | 25 | 24 | 33 |
| $^{212}Po$ Act | 30.3 | 14.1 | 28.0 | 46.3 | 19.0 | 29.3 | 32.2 | 37.1 |
| $^{218}Po$ | 27 | 30 | 30 | 27 | 32 | 28 | 36 | 31 |
| $^{214}Po$ | 12 | 2 | 4 | 8 | 7 | 1 | 6 | 11 |
| $^{212}Po$ | 37 | 37 | 4 | 41 | 16 | 24 | 31 | 31 |
| $^{212}Po$ Act | 41.5 | 44.6 | 4.2 | 46.4 | 17.9 | 28.1 | 41.7 | 34.4 |
| $^{218}Po$ | 37 | 48 | 48 | 47 | 16 | 26 | 37 | 37 |
| $^{214}Po$ | 9 | 9 | 7 | 7 | 0 | 1 | 3 | 3 |
| $^{212}Po$ | 28 | 28 | 41 | 40 | 10 | 13 | 33 | 9 |
| $^{212}Po$ Act | 31.4 | 32.7 | 55.6 | 45.3 | 11.2 | 14.1 | 44.8 | 9.3 |
| $^{218}Po$ | 22 | 42 | 32 | 34 | 26 | 47 | 29 | 38 |
| $^{214}Po$ | 11 | 4 | 4 | 9 | 2 | 12 | 1 | 1 |
| $^{212}Po$ | 33 | 45 | 24 | 46 | 20 | 23 | 3 | 18 |
| $^{212}Po$ Act | 37.0 | 54.6 | 32.1 | 52.2 | 22.4 | 26.2 | 3.0 | 20.0 |
| $^{218}Po$ | 31 | 48 | 39 | 35 | 13 | 41 | 26 | 22 |
| $^{214}Po$ | 3 | 1 | 9 | 5 | 3 | 1 | 2 | 8 |
| $^{212}Po$ | 22 | 18 | 22 | 32 | 7 | 26 | 19 | 26 |
| $^{212}Po$ Act | 24.7 | 20.4 | 28.9 | 36.1 | 7.8 | 30.6 | 25.3 | 28.8 |
| $^{218}Po$ | 29 | 33 | 30 | 28 | 32 | 33 | 37 | 20 |
| $^{214}Po$ | 6 | 4 | 7 | 10 | 3 | 2 | 7 | 5 |
| $^{212}Po$ | 22 | 35 | 29 | 27 | 9 | 17 | 18 | 16 |
| $^{212}Po$ Act | 24.7 | 41.9 | 38.8 | 29.8 | 10.1 | 19.1 | 23.5 | 17.3 |
| $^{218}Po$ | 26 | 31 | 32 | 136 | 24 | 29 | 41 | 24 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $^{214}$Po | 13 | 3 | 3 | 12 | 7 | 4 | 2 | 13 |
| $^{212}$Po | 34 | 28 | 27 | 37 | 21 | 6 | 18 | 10 |
| $^{212}$Po Act | 38.1 | 33.1 | 36.4 | 41.3 | 23.5 | 5.0 | 23.9 | 9.6 |
| | 39.7 | 40.7 | 38.1 | 47.4 | 26 | 29.1 | 31.7 | 30.6 |

(Appendix B: Continued)

| Progenies | Candle On/Off | | | | Fan Experiment | | | | HEPA | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | APTEC | AP-1 | AP-2 | AP-3 | APTEC | AP-1 | AP-2 | AP-3 | APTEC | AP-1 | AP-2 | AP-3 |
| $^{218}$Po | 34 | 33 | 45 | 47 | 35 | 53 | 34 | 59 | 47 | 68 | 38 | 47 |
| $^{214}$Po | 4 | 4 | 7 | 3 | 3 | 12 | 13 | 18 | 15 | 12 | 22 | 14 |
| $^{212}$Po | 14 | 15 | 21 | 24 | 38 | 59 | 36 | 39 | 36 | 61 | 60 | 69 |
| $^{212}$Po Act | 15.7 | 16.5 | 27.7 | 26.9 | 42.6 | 72 | 48.1 | 43.1 | 40.3 | 74.6 | 80.8 | 78.7 |
| $^{218}$Po | 17 | 17 | 24 | 41 | 22 | 45 | 73 | 46 | 67 | 32 | 46 | 76 |
| $^{214}$Po | 4 | 2 | 7 | 8 | 8 | 8 | 11 | 15 | 23 | 9 | 17 | 22 |
| $^{212}$Po | 14 | 10 | 16 | 33 | 25 | 60 | 29 | 43 | 54 | 35 | 61 | 77 |
| $^{212}$Po Act | 15.7 | 10.2 | 20.7 | 37 | 28 | 73.5 | 38.5 | 48.1 | 60.5 | 41.6 | 82.7 | 87.3 |
| $^{218}$Po | 31 | 29 | 26 | 30 | 59 | 77 | 61 | 22 | 18 | 17 | 38 | 60 |
| $^{214}$Po | 5 | 1 | 1 | 8 | 19 | 10 | 17 | 15 | 8 | 7 | 4 | 15 |
| $^{212}$Po | 18 | 21 | 19 | 23 | 67 | 50 | 39 | 28 | 29 | 18 | 55 | 65 |
| $^{212}$Po Act | 20.2 | 24.3 | 25.4 | 25.3 | 75.1 | 60.7 | 52 | 30.5 | 32.5 | 20.1 | 75.4 | 73.9 |
| $^{218}$Po | 24 | 22 | 24 | 35 | 31 | 35 | 42 | 33 | 32 | 64 | 50 | 59 |
| $^{214}$Po | 19 | 2 | 6 | 1 | 8 | 3 | 11 | 25 | 16 | 11 | 18 | 23 |
| $^{212}$Po | 29 | 11 | 12 | 15 | 17 | 26 | 39 | 51 | 36 | 60 | 60 | 71 |
| $^{212}$Po Act | 32.5 | 11.5 | 15.2 | 16.5 | 19 | 30.5 | 52.5 | 56.5 | 40.3 | 73.4 | 81.2 | 80.2 |
| $^{218}$Po | 16 | 31 | 23 | 26 | 41 | 54 | 44 | 34 | 78 | 46 | 41 | 60 |
| $^{214}$Po | 3 | 5 | 5 | 4 | 20 | 5 | 12 | 7 | 18 | 13 | 16 | 23 |
| $^{212}$Po | 21 | 12 | 19 | 24 | 40 | 72 | 18 | 20 | 66 | 59 | 57 | 80 |
| $^{212}$Po Act | 23.5 | 12.6 | 25 | 26.8 | 44.8 | 89 | 23.1 | 21.8 | 74 | 72 | 77.2 | 90.7 |
| $^{218}$Po | 38 | 38 | 34 | 27 | 41 | 56 | 54 | 33 | 59 | 69 | 40 | 26 |
| $^{214}$Po | 4 | 6 | 5 | 2 | 20 | 13 | 23 | 14 | 26 | 8 | 10 | 6 |
| $^{212}$Po | 20 | 19 | 8 | 14 | 60 | 47 | 30 | 56 | 67 | 68 | 19 | 39 |
| $^{212}$Po Act | 22.4 | 21.4 | 9.7 | 15.3 | 67.2 | 56.7 | 38.9 | 63.4 | 75.1 | 83.7 | 24.6 | 44.2 |
| $^{218}$Po | 14 | 41 | 43 | 32 | 39 | 58 | 35 | 73 | 52 | 23 | 59 | 46 |
| $^{214}$Po | 6 | 2 | 5 | 10 | 13 | 6 | 14 | 18 | 13 | 6 | 13 | 25 |
| $^{212}$Po | 13 | 9 | 16 | 19 | 35 | 29 | 20 | 55 | 38 | 20 | 51 | 58 |
| $^{212}$Po Act | 14.6 | 8.9 | 20.9 | 20.4 | 39.2 | 34.2 | 25.7 | 61.9 | 42.6 | 22.7 | 69 | 64.8 |
| $^{218}$Po | 7 | 56 | 19 | 20 | 75 | 68 | 30 | 63 | 47 | 32 | 45 | 49 |
| $^{214}$Po | 6 | 1 | 6 | 2 | 22 | 14 | 15 | 9 | 7 | 4 | 17 | 8 |
| $^{212}$Po | 14 | 14 | 12 | 13 | 81 | 44 | 32 | 40 | 55 | 30 | 50 | 35 |
| $^{212}$Po Act | 15.7 | 15.3 | 15.2 | 14.1 | 90.8 | 52.8 | 42.4 | 45.1 | 61.6 | 35.5 | 67.3 | 39.3 |
| $^{218}$Po | 19 | 27 | 53 | 12 | 39 | 73 | 28 | 42 | 47 | 54 | 48 | 49 |
| $^{214}$Po | 3 | 3 | 10 | 10 | 9 | 14 | 13 | 11 | 5 | 9 | 21 | 22 |
| $^{212}$Po | 9 | 7 | 14 | 12 | 43 | 61 | 45 | 26 | 69 | 51 | 61 | 68 |
| $^{212}$Po Act | 10.1 | 6.3 | 17.7 | 12.2 | 48.2 | 74.5 | 60.7 | 28.5 | 77.3 | 62 | 82.3 | 76.8 |
| $^{218}$Po | 10 | 15 | 18 | 27 | 48 | 53 | 37 | 41 | 62 | 33 | 41 | 45 |
| $^{214}$Po | 5 | 1 | 1 | 5 | 11 | 10 | 14 | 15 | 24 | 9 | 19 | 22 |
| $^{212}$Po | 12 | 9 | 12 | 14 | 36 | 61 | 28 | 39 | 51 | 43 | 47 | 77 |
| $^{212}$Po Act | 13.4 | 9 | 15.6 | 15 | 40.3 | 74.7 | 36.9 | 43.4 | 57.1 | 51.8 | 63 | 87.3 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{218}$Po | 15 | 34 | 32 | 38 | 39 | 83 | 59 | 55 | 36 | 53 | 63 | 82 |
| $^{214}$Po | 3 | 3 | 7 | 3 | 6 | 12 | 21 | 15 | 15 | 11 | 19 | 16 |
| $^{212}$Po | 5 | 10 | 8 | 13 | 48 | 99 | 43 | 60 | 38 | 51 | 48 | 66 |
| $^{212}$Po Act | 5.6 | 10.1 | 9.5 | 14 | 53.8 | 123 | 57.2 | 68 | 42.6 | 61.9 | 64.4 | 75 |
| $^{218}$Po | 9 | 38 | 44 | 45 | 45 | 80 | 36 | 34 | 74 | 35 | 75 | 66 |
| $^{214}$Po | 4 | 3 | 6 | 4 | 25 | 9 | 13 | 19 | 18 | 11 | 18 | 20 |
| $^{212}$Po | 9 | 13 | 6 | 5 | 69 | 86 | 48 | 35 | 73 | 46 | 52 | 64 |
| $^{212}$Po Act | 10.1 | 14 | 6.8 | 4.5 | 77.3 | 106.6 | 64.9 | 38.3 | 81.8 | 55.5 | 70 | 72.3 |
| $^{218}$Po | 11 | 15 | 15 | 26 | 48 | 81 | 46 | 29 | 42 | 55 | 46 | 45 |
| $^{214}$Po | 0 | 2 | 16 | 3 | 15 | 13 | 15 | 10 | 14 | 11 | 7 | 6 |
| $^{212}$Po | 6 | 5 | 15 | 11 | 46 | 63 | 48 | 44 | 26 | 49 | 35 | 33 |
| $^{212}$Po Act | 6.7 | 3.8 | 18.5 | 11.6 | 51.5 | 77.1 | 64.7 | 49.7 | 29.1 | 59.4 | 47.2 | 37.2 |
| $^{218}$Po | 22 | 47 | 16 | 38 | 38 | 51 | 43 | 42 | 57 | 83 | 46 | 34 |
| $^{214}$Po | 4 | 1 | 5 | 2 | 14 | 9 | 12 | 21 | 13 | 30 | 13 | 22 |
| $^{212}$Po | 5 | 9 | 4 | 7 | 51 | 55 | 44 | 66 | 59 | 84 | 28 | 54 |
| $^{212}$Po Act | 5.6 | 9 | 4.1 | 7 | 57.1 | 67.1 | 59.4 | 74.5 | 66.1 | 102.9 | 36.9 | 60.3 |
| $^{218}$Po | 15 | 42 | 25 | 31 | 80 | 46 | 61 | 41 | 27 | 39 | 36 | 44 |
| $^{214}$Po | 2 | 1 | 3 | 5 | 38 | 8 | 21 | 11 | 17 | 5 | 11 | 20 |
| $^{212}$Po | 10 | 7 | 7 | 8 | 107 | 33 | 49 | 35 | 45 | 24 | 30 | 54 |
| $^{212}$Po Act | 11.2 | 6.4 | 8.5 | 7.9 | 119.9 | 39.2 | 65.6 | 39.1 | 50.4 | 27.9 | 39.9 | 60.5 |
| $^{218}$Po | 23 | 35 | 38 | 14 | 57 | 43 | 32 | 54 | 73 | 44 | 82 | 81 |
| $^{214}$Po | 1 | 2 | 9 | 3 | 13 | 12 | 9 | 17 | 19 | 10 | 28 | 24 |
| $^{212}$Po | 7 | 6 | 11 | 7 | 59 | 55 | 47 | 30 | 51 | 43 | 55 | 62 |
| $^{212}$Po Act | 7.8 | 5.1 | 13.5 | 7 | 66.1 | 66.9 | 63.8 | 32.6 | 57.1 | 51.8 | 73.4 | 69.5 |
| $^{218}$Po | | | | | 27 | 49 | 33 | 38 | 44 | 53 | 39 | 61 |
| $^{214}$Po | | | | | 13 | 9 | 6 | 23 | 13 | 8 | 16 | 24 |
| $^{212}$Po | | | | | 27 | 45 | 60 | 40 | 51 | 49 | 40 | 57 |
| $^{212}$Po Act | | | | | 30.3 | 54.4 | 82.2 | 43.8 | 57.1 | 59.5 | 53.4 | 63.7 |
| | 14.4 | 11.5 | 15.8 | 16.3 | 56 | 67.8 | 51.5 | 46.4 | 52.5 | 53.1 | 60.5 | 64.5 |

(Appendix B: Continued)

| | None | | | | HEPA+ION | | | | Candle (Repeat) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | APTEC | AP-1 | AP-2 | AP-3 | APTEC | AP-1 | AP-2 | AP-3 | APTEC | AP-1 | AP-2 | AP-3 |
| $^{218}$Po | 49 | 39 | | 42 | 58 | 57 | 68 | 48 | 40 | 17 | 39 | 39 |
| $^{214}$Po | 31 | 16 | | 15 | 25 | 9 | 6 | 14 | 9 | 1 | 8 | 23 |
| $^{212}$Po | 51 | 34 | | 32 | 71 | 52 | 41 | 69 | 19 | 4 | 17 | 46 |
| $^{212}$Po Act | 57.1 | 40.0 | | 35.2 | 79.6 | 63.3 | 55.7 | 78.7 | 21.3 | 2.6 | 22.0 | 50.9 |
| $^{218}$Po | 34 | 45 | 33 | 24 | 55 | 48 | 40 | 42 | 23 | 30 | 29 | 28 |
| $^{214}$Po | 12 | 12 | 12 | 12 | 24 | 7 | 10 | 12 | 8 | 2 | 5 | 14 |
| $^{212}$Po | 42 | 38 | 30 | 43 | 63 | 51 | 52 | 32 | 24 | 10 | 13 | 47 |
| $^{212}$Po Act | 47.1 | 45.3 | 39.8 | 48.4 | 70.6 | 62.1 | 70.7 | 35.5 | 26.9 | 10.2 | 16.7 | 52.9 |
| $^{218}$Po | 48 | 30 | 31 | 48 | 90 | 52 | 45 | 37 | 14 | 24 | 2 | 26 |
| $^{214}$Po | 21 | 27 | 9 | 20 | 29 | 6 | 8 | 17 | 0 | 3 | 25 | 9 |
| $^{218}$Po | 42 | 65 | 32 | 28 | 71 | 71 | 32 | 52 | 2 | 27 | 11 | 27 |
| $^{214}$Po | 47.1 | 78.9 | 42.9 | 30.0 | 79.6 | 87.6 | 42.9 | 58.5 | 22.0 | 31.8 | 12.2 | 29.9 |
| $^{212}$Po | 33 | 32 | 35 | 44 | 36 | 46 | 60 | 32 | 32 | 21 | 30 | 32 |
| $^{212}$Po Act | 8 | 4 | 13 | 14 | 17 | 4 | 14 | 24 | 10 | 0 | 5 | 2 |
| $^{218}$Po | 20 | 18 | 22 | 49 | 66 | 54 | 48 | 29 | 24 | 8 | 21 | 6 |
| $^{214}$Po | 22.4 | 20.3 | 28.6 | 55.2 | 74.0 | 66.1 | 64.8 | 30.8 | 26.9 | 7.8 | 27.8 | 5.9 |
| $^{212}$Po | 46 | 30 | 41 | 24 | 59 | 68 | 29 | 44 | 28 | 31 | 22 | 26 |
| $^{212}$Po Act | 21 | 10 | 18 | 9 | 31 | 8 | 7 | 22 | 3 | 11 | 3 | 2 |
| $^{218}$Po | 49 | 33 | 18 | 18 | 81 | 71 | 20 | 42 | 18 | 23 | 20 | 27 |
| $^{214}$Po | 54.9 | 39.0 | 22.6 | 19.3 | 90.8 | 87.5 | 26.3 | 46.3 | 20.2 | 26.3 | 26.6 | 30.5 |
| $^{218}$Po | 31 | 43 | 72 | 34 | 54 | 71 | 54 | 36 | 10 | 26 | 44 | 27 |
| $^{214}$Po | 14 | 14 | 20 | 4 | 18 | 7 | 4 | 7 | 5 | 2 | 3 | 7 |
| $^{212}$Po | 49 | 25 | 36 | 41 | 52 | 60 | 52 | 42 | 10 | 21 | 9 | 10 |
| $^{212}$Po Act | 54.9 | 28.7 | 47.5 | 46.7 | 58.3 | 73.6 | 71.2 | 47.6 | 11.2 | 24.2 | 11.3 | 10.1 |
| $^{218}$Po | 43 | 50 | 30 | 36 | 49 | 57 | 53 | 36 | 20 | 41 | 45 | 20 |
| $^{214}$Po | 18 | 19 | 12 | 14 | 11 | 3 | 11 | 14 | 2 | 4 | 3 | 6 |
| $^{212}$Po | 50 | 45 | 40 | 47 | 46 | 44 | 27 | 44 | 10 | 14 | 21 | 15 |
| $^{212}$Po Act | 56.0 | 53.8 | 53.8 | 52.9 | 51.5 | 53.4 | 35.7 | 49.3 | 11.2 | 15.2 | 28.0 | 16.1 |
| $^{218}$Po | 30 | 4 | 38 | 59 | 39 | 56 | 29 | 27 | 23 | 28 | 16 | 25 |
| $^{214}$Po | 9 | 18 | 13 | 17 | 27 | 6 | 5 | 8 | 3 | 0 | 9 | 6 |
| $^{218}$Po | 46 | 35 | 41 | 85 | 52 | 43 | 18 | 30 | 18 | 3 | 11 | 3 |
| $^{214}$Po | 51.5 | 41.2 | 55.1 | 97.2 | 58.3 | 52.0 | 23.7 | 33.5 | 20.2 | 1.4 | 13.5 | 2.0 |
| $^{212}$Po | 33 | 36 | 37 | 70 | 86 | 69 | 45 | 45 | 29 | 19 | 16 | 23 |
| $^{212}$Po Act | 14 | 2 | 17 | 19 | 37 | 14 | 4 | 14 | 5 | 2 | 0 | 4 |
| $^{218}$Po | 23 | 46 | 42 | 71 | 67 | 89 | 35 | 46 | 19 | 11 | 18 | 13 |
| $^{214}$Po | 25.8 | 56.0 | 56.1 | 80.6 | 75.1 | 110.1 | 47.5 | 51.7 | 21.3 | 11.5 | 24.1 | 13.9 |
| $^{212}$Po | 52 | 32 | 51 | 46 | 67 | 40 | 35 | 41 | 5 | 33 | 27 | 25 |
| $^{212}$Po Act | 16 | 13 | 16 | 24 | 25 | 7 | 6 | 10 | 0 | 1 | 2 | 7 |
| $^{218}$Po | 36 | 40 | 49 | 82 | 55 | 38 | 41 | 29 | 12 | 9 | 14 | 9 |
| $^{214}$Po | 40.3 | 47.8 | 66.0 | 93.0 | 61.6 | 45.6 | 55.7 | 32.1 | 13.4 | 9.0 | 18.3 | 8.9 |
| $^{218}$Po | 44 | 44 | 50 | 32 | 45 | 56 | 56 | 69 | 18 | 35 | 45 | 15 |
| $^{214}$Po | 17 | 16 | 20 | 15 | 16 | 4 | 7 | 19 | 4 | 2 | 6 | 5 |
| $^{212}$Po | 46 | 47 | 63 | 43 | 51 | 53 | 37 | 50 | 10 | 9 | 10 | 10 |
| $^{212}$Po Act | 51.5 | 56.5 | 85.2 | 48.1 | 57.1 | 64.8 | 50.0 | 55.9 | 11.2 | 8.9 | 12.4 | 10.3 |
| $^{218}$Po | 65 | 46 | 50 | 32 | 42 | 39 | 35 | 50 | 21 | 22 | 18 | 17 |
| $^{214}$Po | 17 | 8 | 20 | 15 | 16 | 10 | 8 | 21 | 5 | 4 | 4 | 5 |
| $^{212}$Po | 51 | 22 | 63 | 43 | 42 | 23 | 39 | 49 | 13 | 11 | 12 | 10 |
| $^{212}$Po Act | 57.1 | 25.2 | 85.2 | 48.1 | 47.1 | 26.3 | 52.7 | 54.6 | 14.6 | 11.4 | 15.4 | 10.3 |
| $^{218}$Po | 41 | 45 | 32 | 39 | 33 | 51 | 35 | 73 | 13 | 8 | 28 | 22 |
| $^{214}$Po | 13 | 11 | 12 | 17 | 16 | 7 | 6 | 16 | 4 | 3 | 4 | 7 |
| $^{218}$Po | 41 | 43 | 42 | 48 | 49 | 49 | 29 | 65 | 9 | 9 | 17 | 13 |
| $^{214}$Po | 45.9 | 51.7 | 56.6 | 53.8 | 54.9 | 59.6 | 38.9 | 73.8 | 10.1 | 8.9 | 22.3 | 13.6 |
| $^{212}$Po | 47 | 30 | 51 | 51 | 40 | 37 | 55 | 51 | 20 | 22 | 16 | 17 |
| $^{212}$Po Act | 7 | 7 | 6 | 18 | 38 | 10 | 7 | 22 | 3 | 2 | 6 | 0 |
| $^{218}$Po | 39 | 39 | 31 | 47 | 56 | 38 | 49 | 84 | 7 | 6 | 10 | 9 |
| $^{214}$Po | 43.7 | 46.8 | 41.7 | 52.5 | 62.7 | 45.4 | 66.7 | 95.5 | 7.8 | 5.1 | 12.4 | 9.6 |
| $^{212}$Po | | | | | 63 | 67 | 51 | 50 | 19 | 29 | 21 | 19 |
| $^{212}$Po Act | | | | | 22 | 5 | 4 | 33 | 8 | 1 | 2 | 7 |
| $^{218}$Po | | | | | 79 | 42 | 32 | 76 | 14 | 8 | 9 | 10 |
| $^{214}$Po | | | | | 88.5 | 50.8 | 43.3 | 85.1 | 15.7 | 7.7 | 11.3 | 10.1 |
| $^{218}$Po | | | | | | | | | 15 | 32 | 38 | 32 |
| $^{214}$Po | | | | | | | | | 8 | 2 | 1 | 2 |
| $^{212}$Po | | | | | | | | | 8 | 11 | 9 | 9 |
| $^{212}$Po Act | | | | | | | | | 9.0 | 11.5 | 11.4 | 9.4 |
| | 46.8 | 45.1 | 48.6 | 54.3 | 67.3 | 63.2 | 49.7 | 55.3 | 16.4 | 12.1 | 17.9 | 17.8 |

Appendix C: Airborne attached and unattached radon progenies in $Bq.m^{-3}$

| $^{218}Po$ | $^{214}Pb$ | $^{214}Po$ | $^{218}Po$ | $^{214}Pb$ | $^{214}Po$ | Total |
|---|---|---|---|---|---|---|
| -5±34 | 7±11 | 13±11 | 208±58 | 21±15 | 12±17 | 203 |
| 77±39 | 37±12 | -13±13 | 354±62 | 24±14 | -13±17 | 431 |
| 1±42 | 12±13 | 23±14 | 115±47 | -1±11 | 18±13 | 116 |
| 40±35 | 36±12 | -5±12 | 83±42 | 5±11 | 16±12 | 123 |
| -12±43 | 30±14 | 23±15 | 227±50 | 9±11 | -1±13 | 215 |
| -30±36 | -2±11 | 31±12 | 263±53 | 12±12 | -5±14 | 234 |
| 72±44 | 46±14 | -2±15 | 167±45 | 23±12 | -5±13 | 239 |
| -21±33 | 1±10 | 16±11 | 197±53 | 28±14 | 0±15 | 176 |
| -37±34 | -3±10 | 25±11 | 249±51 | -5±10 | -1±13 | 212 |
| 77±106 | 142±33 | 154±36 | 271±65 | 21±17 | 20±19 | 348 |
| 67±105 | 164±34 | 142±36 | 235±68 | 11±17 | 41±20 | 302 |
| -29±84 | 49±25 | 126±28 | 198±55 | 23±14 | 9±16 | 169 |
| 695±163 | 348±49 | 254±53 | 98±47 | 9±12 | 20±14 | 793 |
| 278±159 | 324±49 | 333±53 | 50±40 | 7±11 | 18±12 | 328 |
| 658±177 | 500±55 | 299±59 | -40±42 | 16±14 | 39±15 | 618 |
| 1250±248 | 913±77 | 646±83 | 125±53 | 26±15 | 20±16 | 1375 |
| -22±59 | 29±18 | 56±20 | 317±64 | 27±16 | 4±18 | 295 |
| 27±59 | 28±18 | 43±19 | 361±63 | 33±15 | -11±17 | 388 |
| 50±57 | 49±18 | 24±19 | 380±65 | -5±13 | 6±17 | 430 |
| 183±55 | 33±15 | -2±16 | 80±58 | 1±15 | 44±18 | 263 |
| 23±56 | 27±17 | 40±18 | 479±72 | 56±18 | -27±20 | 502 |
| 415±163 | 325±50 | 333±54 | -8±24 | -2±7 | 13±8 | 407 |
| 958±231 | 752±72 | 606±77 | 16±31 | 2±9 | 13±10 | 974 |
| 685±220 | 576±67 | 639±73 | -1±33 | 21±11 | 11±12 | 684 |
| 838±255 | 933±80 | 814±86 | 75±39 | 13±11 | 7±12 | 912 |
| 204±156 | 383±50 | 310±53 | 48±32 | 9±9 | 4±10 | 252 |
| 959±222 | 814±70 | 483±74 | -20±27 | 12±9 | 11±10 | 939 |
| 666±205 | 646±64 | 464±69 | 19±31 | 20±10 | 6±11 | 685 |
| 633±175 | 407±54 | 337±58 | 34±26 | 19±9 | -4±9 | 666 |
| 563±152 | 261±45 | 249±49 | 52±28 | 5±7 | 1±8 | 615 |
| 968±237 | 780±74 | 655±79 | 62±31 | 16±9 | -2±10 | 1029 |
| 345±183 | 406±57 | 466±61 | 43±29 | 32±10 | -8±10 | 388 |
| 847±201 | 568±62 | 428±67 | 66±33 | 21±10 | -3±10 | 913 |
| 178±102 | 122±31 | 105±34 | 337±70 | 18±17 | 20±20 | 516 |
| 150±108 | 160±34 | 120±36 | 265±82 | 30±22 | 71±25 | 416 |
| 217±108 | 154±34 | 107±36 | 605±80 | 68±20 | -30±22 | 822 |
| 141±120 | 186±38 | 164±41 | 685±91 | 65±23 | -7±25 | 826 |
| -44±102 | 84±32 | 174±34 | 554±85 | 108±23 | -22±25 | 510 |
| 72±73 | 75±23 | 51±25 | 617±87 | 44±21 | 3±24 | 689 |
| 204±106 | 137±33 | 109±35 | 482±81 | 78±22 | -3±24 | 686 |
| 76±75 | 50±23 | 69±25 | 341±67 | 23±16 | 8±19 | 417 |
| 92±71 | 49±21 | 55±23 | 261±67 | 28±17 | 25±20 | 354 |
| 212±113 | 179±36 | 120±38 | 563±82 | 68±21 | -15±23 | 775 |
| 475±121 | 303±39 | 34±41 | 454±82 | 46±21 | 21±24 | 929 |
| 615±201 | 509±62 | 417±67 | -1±46 | 22±14 | 36±16 | 614 |
| 846±234 | 553±71 | 634±77 | -5±27 | 9±9 | 11±9 | 841 |
| 282±186 | 386±58 | 442±63 | 85±35 | 31±11 | -9±11 | 367 |
| 1382±260 | 898±81 | 602±86 | 21±42 | 17±13 | 24±14 | 1403 |
| 1126±285 | 920±88 | 921±95 | 101±36 | 17±10 | -5±10 | 1227 |
| 934±250 | 785±78 | 661±84 | -10±34 | 9±10 | 21±11 | 924 |
| 1150±268 | 984±84 | 702±90 | 77±37 | 35±12 | -7±12 | 1227 |
| 54±61 | 39±19 | 28±20 | 232±50 | 19±12 | -10±13 | 286 |
| 22±73 | 33±22 | 69±24 | 225±52 | 20±13 | -2±15 | 247 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 96±69 | 66±22 | 27±23 | 203±51 | 11±12 | 3±14 | 299 |
| 18±52 | 25±16 | 23±17 | 236±57 | 2±13 | 16±16 | 254 |
| -24±44 | 10±14 | 24±15 | 261±57 | 7±13 | 6±15 | 237 |
| 83±69 | 17±19 | 51±22 | 317±60 | 21±14 | -6±16 | 400 |
| 448±107 | 198±33 | 16±35 | 25±42 | 18±13 | 22±14 | 473 |
| 329±154 | 226±47 | 274±51 | 34±44 | 20±13 | 25±15 | 363 |
| 395±161 | 327±50 | 254±54 | 203±63 | 60±18 | 11±20 | 599 |
| 426±180 | 444±57 | 325±61 | 196±59 | 52±17 | 7±18 | 622 |
| 908±159 | 448±50 | 67±52 | 317±62 | 69±17 | -24±18 | 1225 |
| 1204±270 | 923±84 | 720±90 | 149±62 | 65±19 | 17±20 | 1353 |
| 411±185 | 409±58 | 379±62 | 131±57 | 7±15 | 37±17 | 542 |

Appendix D: Airborne attached and unattached radon and thoron progenies in $Bq.m^{-3}$

| $^{218}Po$ | $^{214}Pb$ | $^{214}Po$ | $^{212}Pb$ | $^{212}Bi$ | $^{218}Po$ | $^{214}Pb$ | $^{214}Po$ | $^{212}Pb$ | $^{212}Bi$ |
|---|---|---|---|---|---|---|---|---|---|
| 33±25 | -6±9 | -15±7 | 6±1 | 20±8 | 6±9 | 0±3 | -1±2 | 0.5±0.2 | 2±2 |
| -60±25 | -6±11 | 12±9 | 13±1 | 17±11 | 12±8 | 7±3 | 3±2 | 1.4± | -6±3 |
| 3±18 | 3±7 | 9±6 | 6±1 | -3±7 | 17±11 | -5±3 | -6±3 | 0.7±0.3 | 6±3 |
| -4±16 | 10±8 | 7±6 | 6±1 | -3±7 | 12±7 | 0±2 | -2±2 | 0.5±0.2 | 0±2 |
| -27±19 | 0±9 | 5±7 | 8±1 | 8±8 | 9±8 | -5±3 | -8±2 | 0.3±0.2 | 7±3 |
| -24±17 | 5±8 | 11±7 | 7±1 | 0±8 | 7±8 | 3±3 | 3±2 | 1.2±0.3 | -4±3 |
| -6±15 | 14±7 | 16±6 | 6±1 | -11±6 | 15±9 | 8±3 | 4±3 | 1.8±0.3 | -7±3 |
| 13±9 | 0±2 | -3±1 | 0±0 | 1±1 | 3±8 | 2±3 | 1±2 | 0.7±0.2 | 0±2 |
| 3±10 | -4±2 | -2±2 | 0±0 | 5±2 | -10±5 | 2±3 | 6±2 | 1.30.3± | -3±3 |
| -11±5 | -4±2 | -1±2 | 0±0 | 5±2 | -4±4 | -3±2 | -2±2 | 0.5±0.2 | 4±2 |
| -4±8 | -2±2 | -2±2 | 0±0 | 4±2 | 18±10 | -3±3 | -6±2 | 0.3±0.2 | 5±2 |
| -26± | 0±2 | 7±2 | 1±0 | -1±2 | 30±12 | 5±3 | 3±3 | 1.7±0.3 | -6±3 |
| -8± | -4±3 | -5±2 | 0±0 | 6±3 | -13±8 | 4±3 | 8±3 | 1.3±0.3 | -3±3 |
| 58±39 | 29±16 | 22±13 | 28±2 | -7±16 | 4±8 | -2±2 | -1±2 | 0.6±0.2 | 2±2 |
| 70±42 | 24±18 | 19±15 | 34±2 | -2±17 | -7±1 | 0±3 | 0±2 | 1±0.3 | 1±3 |
| 1±30 | 4±14 | -1±11 | 19±1 | 16±13 | -6±5 | 4±3 | 5±2 | 1.1±0.3 | -3±3 |
| 73±38 | 43±16 | 33±13 | 28±2 | -25±15 | -4±4 | 1±2 | 1±1 | 0.4±0.2 | 0±2 |
| 73±47 | 33±21 | 11±17 | 45±2 | 8±20 | -4±4 | -2±2 | -2±2 | 0.2±0.2 | 3±2 |
| 18±16 | -6±4 | -1±4 | 2±0 | 5±4 | -4±5 | 0±2 | -1±2 | 0.5±0.2 | 2±2 |
| -3±9 | -4±4 | -4±3 | 1±0 | 6±4 | 10±7 | 4±2 | 1±2 | 0.9±0.2 | -3±2 |
| -11±9 | 9±4 | 15±3 | 3±0 | -11±4 | -2±6 | -1±2 | 0±2 | 0.2±0.1 | 1±2 |
| -11±11 | 4±4 | 7±3 | 2±0 | -2±3 | -15±2 | -3±2 | 1±2 | 0.1±0.1 | 3±2 |
| -15±6 | 1±3 | 2±3 | 1±0 | 2±3 | 15±11 | -3±2 | -2±2 | 0.4±0.2 | 2±2 |
| -41±26 | -17±13 | -4±10 | 15±1 | 28±12 | -2±4 | -3±3 | -3±2 | 0.4±0.2 | 4±2 |
| -9±32 | -17±15 | -10±12 | 22±1 | 33±15 | -3±5 | 4±3 | 5±2 | 1.6±0.3 | -4±3 |
| 36±28 | 8±12 | -2±10 | 16±1 | 6±12 | 8±7 | -3±2 | -4±2 | 0.3±0.2 | 4±2 |
| 51±31 | 25±12 | 9±10 | 16±1 | -6±12 | 2±7 | -1±2 | -4±2 | 0.1±0.2 | 4±2 |
| -33±24 | 11±13 | 8±10 | 17±1 | 7±12 | -14±3 | -2±3 | -1±2 | 0.7±0.2 | 4±3 |
| 6±42 | 0±19 | 6±16 | 37±2 | 28±18 | 3±7 | 2±3 | 0±3 | 1.3±0.3 | 0±3 |
| 9±8 | 4±2 | 3±2 | 1±0 | -4±2 | -12±1 | -4±2 | -2±1 | -0.2±0.1 | 5±1 |
| -5± | -3±2 | -5±2 | 0±0 | 5±2 | 10±8 | -3±2 | -2±2 | 0.2±0.2 | 2±2 |
| -1±4 | -2±2 | 0±2 | 0±0 | 1±2 | -2±5 | 10±2 | 8±2 | 1.3±0.3 | -8±2 |
| -4±4 | -1±3 | -3±2 | 1±0 | 3±3 | 1± | 6±2 | 1±2 | 0.9±0.2 | -3±2 |
| -6±5 | -3±3 | -2±2 | 0±0 | 4±3 | 5±6 | 2±2 | 1±2 | 0.8±0.2 | -2±2 |
| -7±4 | -3±2 | -5±1 | 0±0 | 5±2 | 7±9 | 2±2 | 3±2 | 0.8±0.2 | -3±2 |
| 25±34 | 19±14 | 14±11 | 19±1 | 1±13 | 7±8 | 4±2 | 3±2 | 0.9±0.2 | -3±2 |
| -19±45 | 29±20 | 19±16 | 41±2 | 19±19 | 0±4 | 5±2 | 5±2 | 0.9±0.2 | -5±2 |
| 122±67 | 92±17 | 79±15 | 25±1 | -17±15 | -1±7 | 4± | 4±2 | 1±0.3 | -3±2 |
| 7±34 | 24±15 | 13±12 | 24±1 | 2±15 | -4± | 4±2 | 2±2 | 0.8±0.2 | -2±2 |
| -35±44 | 19±20 | 18±16 | 39±2 | 23±19 | 2±3 | 1±2 | -1±1 | 0.2±0.1 | 0±1 |
| 19±26 | -6±11 | -3±9 | 12±1 | 14±11 | -7±2 | 5±3 | 4±2 | 1.2±0.3 | -3±3 |
| 18±30 | 0±14 | -11±11 | 19±1 | 21±14 | 0±6 | -3±2 | -3±2 | 0.2±0.2 | 4±2 |
| -28±29 | -5±13 | 2±11 | 18±1 | 20± | 12±7 | 4±2 | 1±2 | 0.8±0.2 | -3±2 |
| -5±39 | 2±18 | -12±15 | 312± | 37±17 | -5±5 | 2±3 | 1±2 | 0.8±0.3 | 0±3 |
| 11±26 | 15±12 | 5±15 | 14±1 | 2±11 | 7±9 | -3±4 | -3±3 | 1.4±0.3 | 3±4 |
| 22±33 | 14±14 | 14±12 | 21±1 | 1±14 | 4±6 | -3±2 | -4±2 | 0.3±0.2 | 4±2 |
| 15±32 | 25±15 | 11±13 | 27±1 | -2±15 | 6±6 | 1±2 | 0±2 | 0.6±0.2 | 0±2 |
| 52±28 | -14±11 | -16±9 | 12±1 | 23±11 | 10±8 | 5±3 | 2±2 | 1.1±0.3 | -4±3 |