Chapter 6

Study of Radon in Water, Soil-Gas and Dwellings

This chapter covers results of radon gas levels in the indoor environment, dissolved radon concentrations in some water samples, surface exhalation rates and soil gas radon for the study region. Solid state nuclear track detector based twin cup dosimeters have been used in this study for measuring radon, thoron and their progeny equilibrium factors. For dissolved radon concentrations in water samples, surface exhalation rates and soil gas radon AlphaGUARD radon monitor was used. Radon and its measurement techniques using Solid state nuclear track detectors and AlphaGuard have been introduced and explained in chapter 2.

6.1 Indoor Radon Study

Indoor radon levels often vary more than an order of magnitude over a period of a few hours, the use of long-term integrated track etch detectors, called Solid State Nuclear Track Detectors (SSNTDs) in determining average indoor radon levels is therefore widely preferred around the world. Plastic track detectors can be exposed for several months as these integrating devices are virtually independent of normal variations in temperature and humidity occurring indoors. Taking into account the large-scale fluctuations in radon levels and hence corresponding doses, the long term measurements are considered the best compromise to estimate the "average" value (Martz *et al*., 1991; Bochicchio, *et al*., 1997; Singh *et al*., 2005). Therefore, the present survey was planned for one-year to cover all weather related variations. In the present investigations, the SSNTDs have been used for indoor radon concentration measurements in studied regions. 52 houses in 36 locations of three districts (Faridkot, Muktsar and Ferozepur) of Punjab were chosen and installed with cup dosimeters.

Two major approaches, in general undertaken to estimate radiation dose associated to indoor radon exposure are: epidemiological assessment and physical

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dosimetry. The first approach is based on equality of detriments from epidemiological determinations whereas physical dosimetry estimates are model-dependent and derive conversion factors from the analysis of information on aerosol size distribution, unattached fraction, breathing rate, fractional deposition in the airways, mucous clearance rate, and location of the target cells in the airways (Jacobi, 1964; Hopke *et al*., 1992; ICRP, 1994). Radiation and tissue weighting factors are also taken into account. These models are widely used to assess doses from inhaled radionuclides. ICRP's Human Respiratory Tract Model (HRTM) is one such model (ICRP, 1994), which is used most to estimate the (absorbed) doses to regions of the lung and to systemic organs due to radon and decay products (Balashazy *et al*, 2002; Al-Jundi *et al.*, 2011; Marsh *et al*, 2011). HRT model due to ICRP divides the lung into three regions: the bronchial region (BB), the bronchiolar region (bb) and the alveolar interstitial (AI) region. Target cell layers within the BB and bb regions are identified. Absorbed dose to the bb region is given by the average dose to the target cell layer in that region. And for the BB region, two layers namely; one that contains basal cells and the other that contains secretory cells, are defined which lie at different depths. The HRTM defines the absorbed dose to the BB region as the average dose of these two layers.

According to ICRP, the tissue weighting factor for lung is 0.12; the radiation weighting factor for alpha particles is 20 (ICRP, 1991b). With these two weighting factors, and at an equilibrium factor of 0.4 as recommended by UNSCEAR, effective dose due to dosimetric estimate is about 3.5 times higher than that of epidemiological estimate (UNSCEAR, 2000; Jing Chen, 2005). Dose conversion factors 0.17 nSv per $Bqhm^{-3}$ for gas concentration (C_{Rn}) and 9 nSv per $Bqhm^{-3}$ for radon equilibrium equivalent concentration ($C_{Rn} \times F_R$) is recommended by UNSCEAR (Eq. 6.1). Similarly for thoron (C_{Tn}), the dose conversion factors recommended are 0.11 nSv per $Bqhm^{-3}$ for gas and 40 nSv per Bq hm^{-3} (Eq. 6.2). These values are found to lie between dosimetric and epidemiological dose conversion factors used for converting the gas and progeny concentrations, to annual effective inhalation dose (United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000; Harley *et al.*, 2005). F_R and F_T are the equilibrium factors for radon and thoron respectively. Internal and external exposures are taken considering the occupancy factor for the region. In general occupancy factor is taken as 0.8 making an exposure value of 7000 hours for exposure

inside the houses and 1750 hours for exposure outside. Under these considerations annual doses equations are:

$$D(mSv\,Y^{-1}) = C_{Rn}(0.17 + 9 \times F_R)\,7000\,\times\,10^{-6} \quad (6.1)$$

$$D(mSv\,Y^{-1}) = C_{Tn}(0.11 + 40 \times F_T)\,7000\,\times 10^{-6} \quad (6.2)$$

6.1.1 Experimental Technique

Twin cup solid state nuclear track detector cup dosimeters (Figure 6.1) have been in this study for measuring radon, thoron and progeny concentrations (Fleischer *et al*., 1980; Abu-Jarad and Fremlin, 1981; Mayya *et al.*, 1998). These dosimeters were deployed with LR-115 (type II) detectors inside each of the two chambers for cup mode exposure and a third film externally for bare mode exposure (Ramola *et al.*, 1998). Of the two detectors in chambers, one is exposed in filter mode and other in membrane mode. The dimensions (6.2 cm×4.1 cm) of the membrane cup are so chosen that tracks recorded on the detector in the membrane cup are only due to radon and its progeny region of influence of ^{218}Po alpha particles being within the cup volume. In the case of ^{214}Po, almost 100 % of the atoms will be deposited on the surface. Diffusion theory calculations have been performed to obtain the airborne concentration distribution of ^{218}Po inside the cup from freshly formed ^{218}Po atoms from the decay of radon inside the cup volume (Porstendorfer and Mercer, 1979; Tokonami, 1999). In the case of the filter cup, the detector records tracks due to radon, thoron and progeny nuclides. 14 % of the volume from the sphere of influence for ^{220}Rn atoms (E=6.28 MeV) lies outside the cup, hence the track registration from ^{220}Rn atoms is only 86 %. Due to shorter half-life (0.15 s) of ^{216}Po atom, it decays almost completely within the airspace itself. Exact calculations for ^{216}Po atoms show that only 77 % of the volume from the sphere of influence inside the cup is only contributing tracks. Region of influence for ^{212}Po lies entirely outside the cup space and does not contribute to the tracks. Third detector placed in bare mode registers alpha tracks due to both the gases and their alpha emitting daughters (^{218}Po, ^{214}Po and ^{216}Po, ^{212}Po). Resolved diagrams illustrating response of various α-emitters in the respective membrane filter and bare modes, calibration factors and methodology used in this work to convert tracks densities into gas and progeny concentrations are given elsewhere (Eappen and Mayya, 2004).

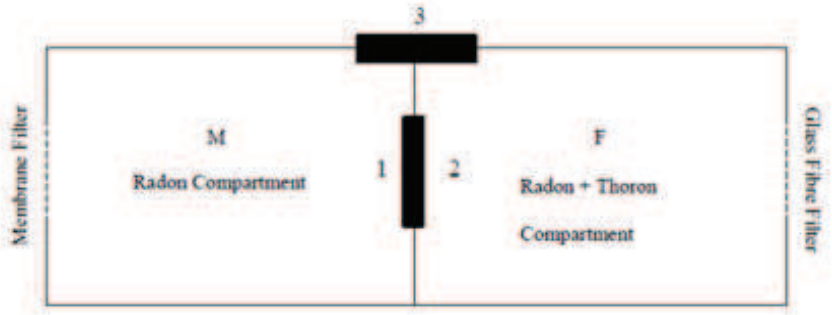

Figure 6.1 Twin cup radon- thoron dosimeter

Conversion Factors (CFs) used are: 0.02 tr cm^{-2} per Bq d m^{-3} for each of the species (species independent) in the bare mode exposure and 0.023±0.004 and 0.018±0.002 tr cm^{-2} per Bq d m^{-3}, respectively for ^{222}Rn and ^{220}Rn in the cup dosimeters. The tracks formed on the detectors are etched under specific etching conditions and counted using Optical microscope (Singh *et al.,* 2003). UNSCEAR dose conversion factors (Equations 6.1 and 6.2) are used to obtain annual inhalation dose due to exposure inside the dwelling. The bare card data was used in conjunction with cup data for computing the equilibrium factor using deposition velocities of particles inside the room and a root finding method for finding the ventilation rate via root finding method (Mayya *et al.*, 1998). Minimum Detection Level (MDL) for the method is computed based on background tracks obtained for the set of LR-115 films used in the study. MDL of 6.5 Bqm^{-3} is obtained from the average background counts of 10 tracks per cm^2.

6.2 Radon in Water

Uranium, radium and radon are all soluble in water. The presence of radon in groundwater is predominantly due to the decay of radium found in rocks and soils and does not mainly originate from the radium dissolved in water. As is known, recoil effect during disintegration of ^{226}Ra atom taking place in mineral lattice is major driver for radon emanation. The distance which radon atom can move in a grain of normal density has been put at 0.02-0.07 μm (Durrani, and Ilic, 1997). Emanation of radon emanating from the soil grain to pore space increases with increasing water content in pores (Akerblom *et al*., 1990). Radon concentration in water is always greater than that in the

air in soil pores because of equilibrium relationship between ratio of radon in air to that in water. This leads to high concentrations of radon in groundwater used for drinking purposes. The un-dissolved radon has a tendency to escape from soil to the atmosphere. This process can occur by molecular diffusion or by convection (Schery *et al*., 1984). Radon present in surface waters, such as lakes and rivers, is readily released into outdoor air by agitation as it passes over rocks and soils. Groundwater from wells and boreholes usually contains higher radon concentrations than surface waters. Radon can also be generated within water distribution systems with high radium concentrations from radium adsorbed iron pipe scales (Field *et al*., 1995; Fisher *et al*., 1998a). Naturally occurring radionuclides in drinking-water usually give radiation doses higher than those provided by artificially produced radionuclides and are therefore of greater concern. Radon exposure from waterborne radon sources may occur either from ingestion or from inhalation of radon released from water and on average, 90% of the dose attributable to radon in drinking-water comes from inhalation rather than ingestion (UNSCEAR, 2000). Radon ingested in drinking-water will give a radiation dose to the lining of the stomach. Scientific studies have not shown a definitive link between consumption of drinking-water containing radon and an increased risk of stomach cancer (Ye *et al*., 1998; Auvinen *et al*., 2005).

Several well-established methods can be found to exist in literature for the collection and measurement of radon in water (Vitz, 1991; Field and Kross, 1996). Liquid scintillation counting and the de-emanation radon measurement techniques are the most prevalent methods for measuring radon concentrations in water (Lucas, 1957; Prichard and Gesell, 1977; Prichard *et al*., 1991). Direct gamma counting (Galli *et al*., 1999), Electret ion chambers (Kotrappa and Jester, 1993), and gas transfer by membranes (Freyer *et al*., 2003) are some of the other techniques used for measuring radon in water. Liquid scintillation counting (LSC) is the most sensitive and widely used method to measure radon in water. The popularity of liquid scintillation for radon analysis is due to several factors including the excellent accuracy and precision of the method, the low level of detection, the limited need for sample preparation, the ability to rapidly measure a large number of samples, and the ability of the counter to change samples while unattended. Because of the high solubility of radon in organic solvents,

properly collected water samples (Field and Kross, 1996) can be added directly to the scintillation cocktail (e.g. toluene, xylene, or mineral oil) to form a two-phase aqueous/organic system. The radon will be partitioned between the water/scintillation cocktail and the air space in the vial and will become available for measurement by LSC methods. The LSC technique quantifies the activity of radon and decay products from the rate of photons emitted from the scintillation fluid. Limitations of the LSC technique include the initial start-up cost to purchase the counter and the need to perform the analyses in a laboratory.

6.2.1 Experimental Technique

Subsurface water samples from 36 locations have been taken for gaseous radon concentration measurements using Aqua-kit attached with Alpha-Guard for monitoring the radon concentration in water taken from different potable water sources like tube-wells and hand-pumps. The setup consists of four components, the Alpha-Guard, Alpha-pump, emanation and safety vessel (Figure 6.2).

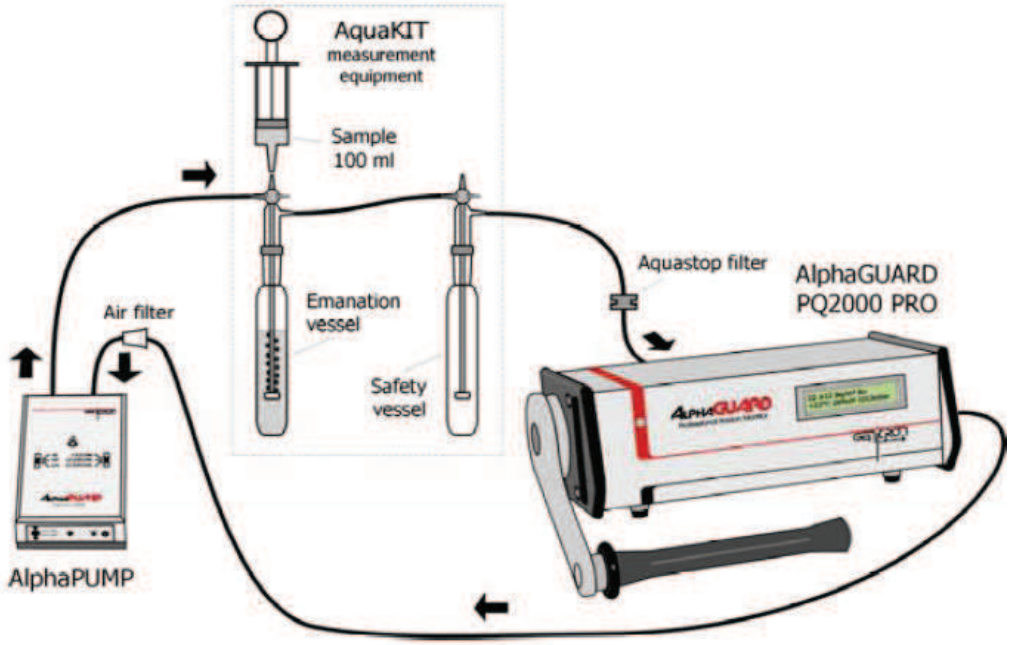

Figure 6.2 Experimental set-up for investigation of radon in water using aqua-kit (Adopted from Manual AlphaGUARD, Genitron Instruments)

Method is one of few on-site systems for radon-in-water analysis discussed in the literature, which use the effect of radon partitioning between water and air (Monnin and Seidel, 1998; Freyer *et al*., 2003; Dulaiova *et al*., 2005). The respective partitioning coefficient at room temperature for example, is about 0.25 (Kertes and Clever, 1979). Determination of the radon concentration in the water sample is based on the partitioning of radon from the water into the gas stream circling through the system. Radon solved in the liquid is gassed out and the equilibrium concentration generated in air in an emanation vessel is determined by Alpha-Guard (Schuberta *et al*., 2006). The continuous movement of air through the water (bubbling) extracts the radon until the radon concentration in the system has reached an acceptable background value. After radon equilibrium conditions between air and water are reached the gaseous radon concentration determined (C_{air}) is converted into the aqueous radon concentration in the water (C_{water}) using following Equation

$$C_{water}\left(\frac{Bq}{l}\right) = C_{air}\left(\frac{V_{air}}{V_{water}} + K_{\frac{water}{air}}\right) - C_0 \qquad (6.3)$$

The influential parameters are water sample volume (V_{water}), total air volume in the system (V_{air}), water/air partitioning coefficient at the given temperature ($K_{water/air}$), and if applicable radon background concentration in the gas cycle (C_0). The mean value of at least ten single equilibrium concentration readings, recorded minute by minute, should be used for C_{air} .

6.3 Soil-Gas Radon and Surface Exhalation Rates

Soil-gas radon and surface exhalation rates have also been studied to complement and complete the analysis radon levels in the study region. The radon content in soil gas exhaling from the ground surface, volcanoes as well as in underground waters (*i.e.* in waters from wells that are hundreds of meters deep and springs along active fault zones) has found better application in important earthquake precursory studies (Martinelli *et al.*, 1995). Several studies have attempted to relate anomalous radon concentrations in soil gas and water with seismic events (Martinelli and Ferrari, 1991; Igarashi *et al*., 1995; Planinic *et al*., 2001; Hartmann and Levy, 2005; Yasuoka *et al*., 2006; Choubey *et al.*, 2007). Radon is considered a potential earthquake precursor since micro-fracturing and increased stress levels associated with an

earthquake event are thought to enhance the release of radon gas from rocks (Thomas, 1988).

Soil gas infiltration however, is also one of the most important sources of residential radon (Fisher *et al.*, 1998b; Brown *et al.,* 1993; Synnott *et al.*, 2006), since the most common way to enter a building is through pressure-driven transport of soil gas. Radon-flux and soil-gas measurement are therefore, useful for characterizing the potential for radon prior to construction, as well as for aiding a diagnostic assessment for mitigation. The measurement of ^{222}Rn concentration in water and soil, in principle, can be used as a method of evaluating the potential for elevated indoor ^{222}Rn concentrations (Iskandar *et al*., 2005).

Radon in air also comes from other sources, in particular radon entering the home from the underlying soil. Transfer of radon form soil into environment involves some of the same processes controlling the soil/air exchange of green house gases such as CH_4, CO_2 and NO_2. Radon, being noble gas does not undergo chemical reactions and its source term (Radium) is relatively well-known. Therefore studies of the radon exhalation are able to provide information on the pure transfer component of gaseous exchange between the soil and the atmosphere.

6.3.1 Experimental Technique

For soil-gas measurements, experimental set-up consisted of a soil gas probe and a pump connected to AlphaGuard as shown in Figure 6.3. The soil-gas probe consists of a drilling rod with a lost tip which is closed by a rivet and capillary probe. By means of a protective or machine hammer, the drilling rod can be hit into the ground, and a 1 m deep hole was drilled. Afterwards, the drilling rod has to be drawn up by 2-3 cm. The capillary probe is inserted into the drilling rod and pushed forward until a firm stroke is noticed. Herewith, the capillary probe penetrates the air-lock and pushes the rivet out of the tip of the probe. By this, an opening for sucking the air is created. Then by using Alpha-pump and radon progeny filters connected in series, soil-gas is sucked out of the surrounding ground area through the capillary probe and pressed into the ionization chamber of the Alpha-Guard monitor. The air-lock integrated in the probe tip enables the capillary probe to be driven in and out as in the respective measuring depth without atmospheric air getting into the tip of the probe. More details regarding experimental set-up and sampling procedure are published elsewhere. (Walia *et al.*, 2008).

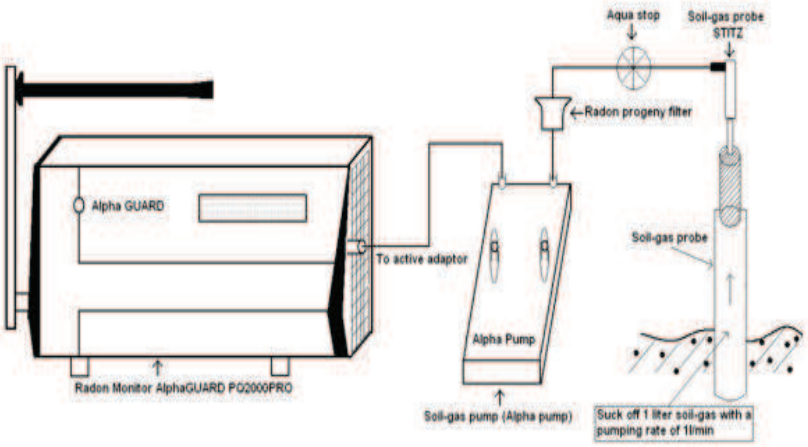

Figure 6.3 Experimental set-up for radon soil-gas measurement in the field using AlphaGUARD

In order to determine only radon ^{222}Rn concentration, the ionization chamber was kept closed tightly after filling it with soil-gas for about 10 min i.e. time needed for thoron (^{220}Rn) to decay away. For soil-gas measurements Alpha-Guard is operated in flow mode because of its fast response, high sensitivity and a wide dynamic range which is linear in nature.

Close-circuit analytic technique is used for measurement of surface radon exhalation rate consisting of a static accumulation chamber and Alpha-Guard (Figure 6.4). The air is circulated in the closed circuit until saturation were achieved in radon concentration, while radon accumulated was recorded every 10 min. The temporal variation of the volume averaged particle density of the radioactive gas in the chamber is a function of net flux of gas from the surface and the loss due to radioactive decay (Lehmann, 2004). This results in a linear initial increase in radon concentration with time in the box, which saturates later depending on the exhalation rate itself, disintegration constant of the gas and dimensions of the box. A typical curve is shown in Figure 6.5. The exhalation rate was calculated using expression (Vaupotić, *et al*., 2010)

$$E_{Rn} = \frac{V}{A} \times \frac{\Delta C}{\Delta T} \tag{6.4}$$

where,

E_{Rn} is the Radon exhalation rate in $Bqm^{-2}s^{-1}$; V is the Volume of accumulation box in m^3; A is the attachment area [m^2] of accumulation chamber and $\frac{\Delta C}{\Delta T}$ is the radon concentration gradient (slope) within linear region in $Bqm^{-3}s^{-1}$.

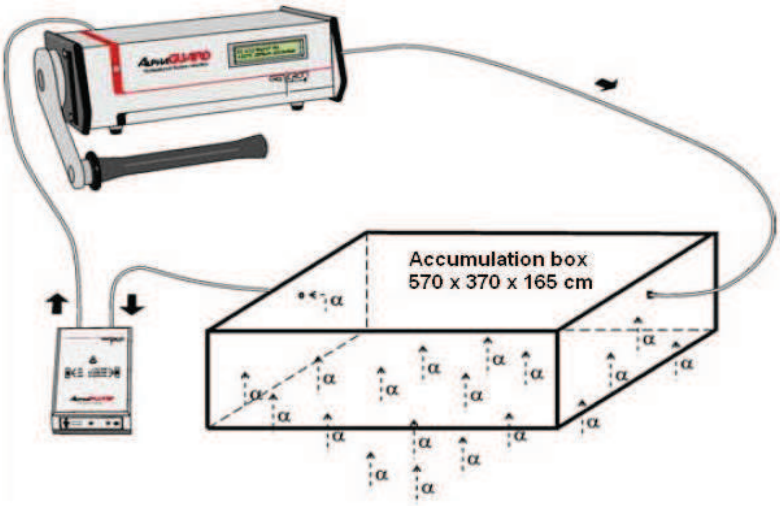

Figure 6.4 Experimental set-up for surface radon exhalation rate measurements (Adopted from Manual AlphaGUARD, Genitron Instruments)

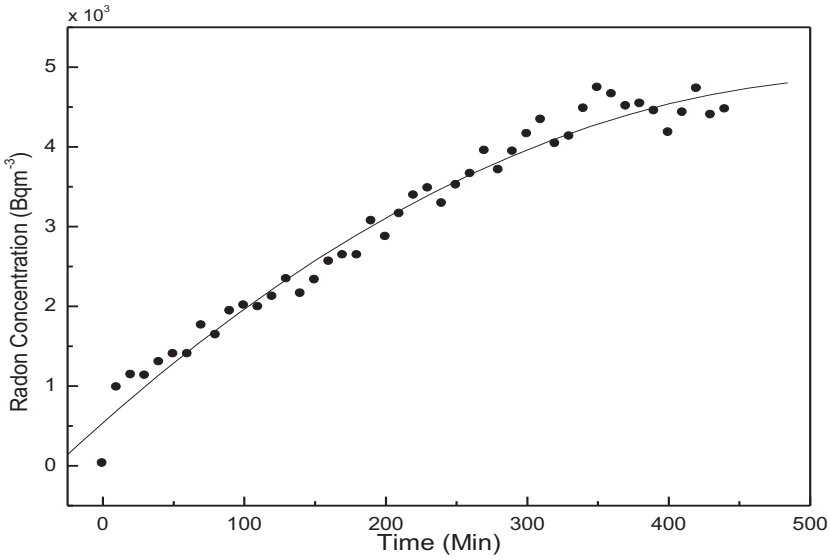

Figure 6.5 Curve showing temporal radon build-up from soil surface in accumulation box

The results obtained by different researchers reveal that, radon concentration in soil may vary over a wide range depending on weather conditions, climatic factors, and soil type including diurnal variation (Durrani, and Ilic, 1997; Schubert *et al*., 2002). The variations in the soil-gas and water radon may be due to radium content and distribution, porosity and density of soil, underlying bedrocks, and meteorological parameters (barometric pressure, rain, etc.), which can be minimized (King, 1986). For this, all measurements were made in similar climatic and environmental conditions so that variation in meteorological parameters like temperature, pressure and relative humidity is small.

6.4 Results and Discussion

Indoor Radon

The annual average radon and thoron concentrations (Bqm^{-3}) and their equilibrium factors for the given study region determined using cup dosimeters are presented in Table 6.1. Radon (^{222}Rn) concentration varied from 21.4 to 79.4 Bqm^{-3} with an average 47.5 Bqm^{-3} and geometric mean of 45.2 Bqm^{-3} (GSD 1.39). Thoron (^{220}Rn) concentration varied from 6.5 Bqm^{-3} to 58.4 Bqm^{-3} with a mean value of 23.2 Bqm^{-3} and geometric mean of 19.3 Bqm^{-3} (GSD 1.88). It could be therefore inferred that both radon and thoron levels are higher compared to respective national geometric mean values 23 Bqm^{-3} and 12 Bqm^{-3} (Ramachandran *et al*., 2003) and the values of 40 (Arithmetic mean) and 30 Bqm^{-3} (Geometric mean) of the distribution of worldwide indoor radon (UNSCEAR, 2000). Figure 6.6 shows the frequency distribution graph of thoron to radon ratio for the dwellings. The graph indicates that almost 80 % of the results show thoron to radon ratio above 10% indicating the presence of slight excess of thoron in the area compared to normal background region.

Indoor Radon and thoron values obtained for the study region in the present investigation are compared with those reported in different Indian regions in Table 6.2. Apart from these region specific studies, national surveys have been carried out in India to study indoor radon levels in Indian dwellings (Subba Ramu *et al*., 1988;

Ramachandran *et al*., 1990). In one such survey comprising 1200 dwellings, an overall national geometric mean of 4.2 mWL of indoor radon has been reported (Subba Ramu *et al.*, 1991). The unit 'working level' is used to evaluate exposure due to a mixed field of radon, thoron and their decay products in certain equilibrium (called Potential Alpha Energy Concentration-PAEC), introduced in section 1.8.2.1. One working level unit is that concentration of mixture of these α-emitters that produce 1.3×10^5 MeV of alpha radiation per liter of air. Corresponding Rn progeny working levels are then determined with the formula (Subba Ramu *et al.*, 1991):

$$WL_R = C_R F_R/370 \qquad (6.5)$$

In terms of mWL units, indoor ^{222}Rn concentration varied from 2.31-8.58 mWL, with an average 5.14 mWL, which is higher than national average value of 4.2 mWL. Table 6.3 compares ^{222}Rn PAEC values for the different countries in the world, (assuming an average value 0.4 for the Rn equilibrium factor) with the present study. As seen in this table, values of indoor ^{222}Rn concentration varied from 1.1 to maximum 28.4 mWL. Comparatively higher values 28.4 mWL, 21.6 mWL and 11.4 mWL have been reported for Sweden, China and Switzerland respectively, while moderate to low values are reported for other countries (UNSCEAR, 1988).

Annual internal inhalation dose has been calculated by two approaches. The first approach is by following the UNSCEAR 'F' values and the second approach is by using the 'F' values derived from the bare card tracks in combination with the cup tracks. Values of radon and progeny equilibrium factors (F_{Rn}) and thoron and progeny equilibrium factors (F_{Tn}) have been calculated using root finding method (Mayya *et al*., 1988) and ranged as 0.17- 0.70 and 0.01-0.39 for radon and thoron respectively. Results for the inhalation doses computed by two approaches are presented in bar diagram form in Figure 6.7.

Table 6.1 Table for indoor radon, thoron concentration and annual doses in dwellings from Faridkot, Ferozepur and Muktsar districts of Punjab

Name of location	Rn Conc. (Bqm^{-3})	Tn Conc. (Bqm^{-3})	Rn and progeny equilibrium Factor (F_{Rn})	Tn and progeny equilibrium Factor (F_{Tn})	Annual Dose (mSv)	Annual Dose using UNSCEAR equilibrium Factors (mSv)
Faridkot city	53.6	29.9	0.22	0.02	1.07	1.84
Kotkapura	72.0	16.4	0.44	0.06	2.56	2.15
Ramana	42.3	21.9	0.51	0.09	2.40	1.46
Jaito	55.1	38.5	0.49	0.08	3.25	2.06
Bhagtuana	52.1	6.5	0.59	0.14	2.30	1.45
Karirwali	71.4	24.6	0.27	0.02	1.58	2.25
Machaki	45.0	9.9	0.19	0.02	0.68	1.33
Sadik	68.8	30.8	0.24	0.21	1.46	2.26
Mallan	52.1	18.8	0.58	0.14	3.26	1.67
Kauni	55.1	26.8	0.42	0.06	2.27	1.87
Mukatsar city	52.9	32.4	0.29	0.03	1.49	1.88
Marh Mallu	55.1	12.2	0.54	0.11	2.59	1.65
Rupana	47.6	6.7	0.24	0.02	0.83	1.35
Aulakh	52.1	21.6	0.32	0.03	1.45	1.70
Pind Malout	61.3	46.3	0.27	0.03	1.68	2.30
Malout City	79.4	34.6	0.39	0.05	2.80	2.63
Badal	50.0	50.9	0.21	0.02	1.17	2.04
Kabbarwal	41.4	7.5	0.42	0.05	1.34	1.21
Balluana	49.0	20.8	0.29	0.03	1.25	1.60
Abohar	46.0	23.9	0.33	0.03	1.42	1.57
Nihal Khera	30.6	29.0	0.60	0.15	3.35	1.27
Fazilka	53.6	50.2	0.19	0.02	1.07	2.11
Behakbobla	47.9	58.4	0.21	0.02	1.19	2.09
Bambha Battu	38.3	11.2	0.45	0.07	1.50	1.19
Bagge Ke	21.4	14.7	0.60	0.16	1.97	0.80
Jalalabad	52.1	13.1	0.56	0.12	2.68	1.58
Jiwan Arain	39.7	14.8	0.44	0.06	1.59	1.28
Pindi	23.0	28.9	0.41	0.05	1.38	1.05
Lakho ke	29.1	18.3	0.23	0.02	0.62	1.03
Khai Kheme Ki	21.4	16.4	0.56	0.12	1.78	0.83
Ferozepur city	56.7	6.5	0.51	0.09	2.14	1.59
Khosa Dal Singh	33.7	21.9	0.49	0.08	1.95	1.23
Zira	42.9	36.4	0.20	0.02	0.86	1.64
Khui Khera	37.0	9.3	0.21	0.02	0.60	1.11
Bhadana	26.5	10.3	0.70	0.39	3.20	0.86
Makhu	52.9	15.5	0.17	0.01	0.71	1.61
Range	21.4-79.4	6.5-58.4	0.17-0.70	0.01-0.39	0.60-3.35	0.80-2.63
Average	47.5	23.2	0.38	0.07	1.76	1.60
Median	49.5	21.2	0.40	0.05	1.54	1.60
GM	45.2	19.3	0.35	0.05	1.58	1.53
GSD	1.39	1.88	1.53	2.48	1.63	1.35

Table 6.2 Summary of indoor radon/thoron concentrations in different regions of India

S. No.	Indoor Radon (Bqm^{-3})	Indoor Thoron (Bqm^{-3})	Study Area/region	Reference
1.	17.7-101.6 (GM- 46.3)	0.47-69.94 (GM- 12.90)	Mizoram (North-Eastern India)	Rohmingliana *et al*., 2010
2.	0.2-19.8	0.3-45.9	Orissa (Eastern India)	Sulekha Rao and Sengupta, 2010
3.	21.7-33.3	10.9-30.1	Madhya Pradesh and Chhatisgarh (Central India)	Kher *et al*., 2008
4.	5-137	4-160	Budhakedar, Garhwal Himalaya (Northern India)	Prasad *et al*., 2008
5.	17-311 (GM- 52.8)	-	Andhra Pradesh (South-Eastern India)	Sreenath Reddy *et al*., 2008
6.	95.61-202.18 (GM- 153.61)	-	Bathinda (North-Western India)	Singh *et al*., 2005
7.	166 (max) (AM- 68)	95 (max) (AM- 33)	Shillong, Meghalaya (North-Eastern India)	Mishra *et al*., 2004
8.	12.2-165.6	1.0-74.9	Guwahati, Shillong, Agartala (North-Eastern India)	Dwivedi *et al*., 2001
9.	156.11-635.42	-	Kullu (Northern India)	Singh *et al*., 2001
10.	19.7-146.3	9.1-70.7	Hamirpur, Una, (Himachal Pradesh) (Northern India)	Virk and Sharma, 2000
11.	45.4-65.0 (AM- 56.3)	-	Coastal Karnataka (South-Western India)	Narayana *et al*., 1998
	21.4-79.4 (GM- 45.2)	**6.5-58.4 (GM- 19.3)**	**South-Western Punjab (North-Western India)**	**Present Study**

Table 6.3 ^{222}Rn PAEC values reported for different countries in the world (UNSCEAR, 1988)

Country	No. of dwellings	Average (mWL)	Type of measurement
Austria	729	2.4	Grab sampling: Four times a year
Canada	13413	1.9	Grab sampling of progeny
China	896	21.6	Grab sampling of progeny
Finland	8150	8.3	Passive and active (Grab sampling) methods
Germany	5970	3.5	Passive method
Hungary	833	3.2	Grab sampling of progeny
India	1208	4.2	SSNTD (LR-115)
Netherland	1000	3.0	Passive method
Poland	201	1.1	Grab sampling
Sweden	191	28.4	Passive method
Switzerland	123	11.4	Passive method
UK	2300	1.9	Passive method
USA	552	6.6	Passive and active (Grab sampling) methods
Present study	**52**	**5.14**	**SSNTD (LR-115)**

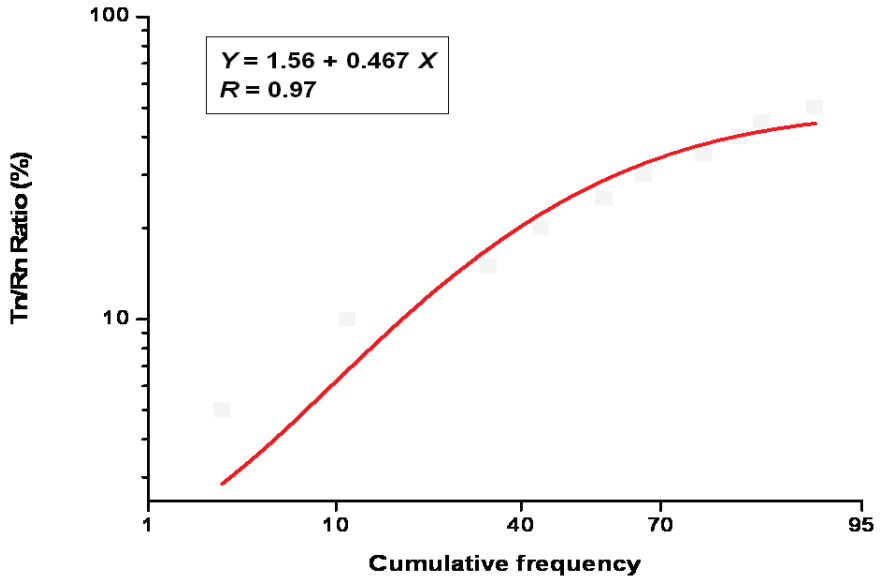

Figure 6.6 Graph showing frequency distribution graph of thoron to radon ratio in dwellings

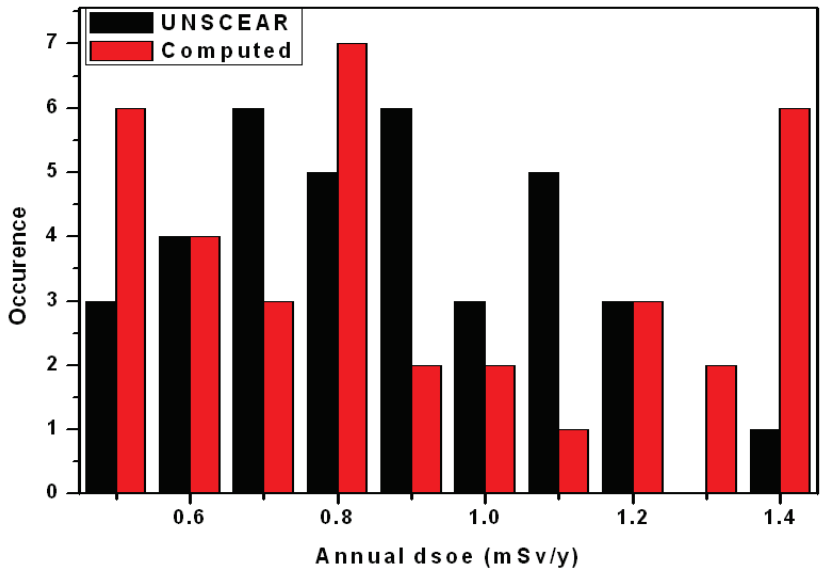

Figure 6.7 Frequency bar graph for annual internal inhalation doses using UNSCEAR approach and computed equilibrium factors

Figure 6.8 shows the frequency distribution of the doses. The annual dose by UNSCEAR approach varied from 0.80 to 2.63 $mSvy^{-1}$ with average 1.60 $mSvy^{-1}$ (GM-1.53, GSD-1.35), while the dose computed using bare card approach showed the values from 0.60 to 3.35 $mSvy^{-1}$ with average 1.76 $mSvy^{-1}$ (GM-1.58, GSD-1.63). In a countrywide survey, radon and thoron have been calculated to yield an annual inhalation dose of 1.11 mSv (GM) (Ramachandran *et al*., 2003). It can be concluded therefore, that inhalation doses for the study region due to radon and its daughter products is in line with global approximate value of 2 mSv (200 mrem) and slightly higher than national geometric mean.

Inhalation dose in the present work complied with annual effective dose due to indoor radon in the neighboring Bathinda district (1.63- 3.45 $mSvy^{-1}$) (Singh *et al*., 2005). Indoor concentration with maxima as high as 146.3 Bqm^{-3} and 70.7 Bqm^{-3} for radon and thoron respectively, in the uranium mineralization zones (Hamirpur, Una) of Himachal Pradesh are found reported (Virk and Sharma, 2000). Corresponding average annual effective dose reported in this study 8.67 μSvh^{-1} (60.69 $mSvy^{-1}$) for this area. Higher annual effective doses (4.50-12.38 $mSvy^{-1}$) in this area have also been confirmed in a later study (Singh *et al*., 2005). There are in fact, numerous examples where higher indoor radon concentrations have been found due to presence of local mineralization. In the monazite rich areas of Kerala, Chougaonkar *et al*. (2004) reported a mean annual inhalation dose of the order 1.5 $mSvy^{-1}$. Higher indoor radon concentration due to the underlying lignite in the dwellings of the suburbs of Prigtina is another example (Jakupi *et al*., 1997). In an important study, Reddy *et al*. (2003) conducted baseline studies of radon and thoron concentration levels and doses in and around the Lambapur and Peddagattu areas in Nalgonda district, Andhra Pradesh (India), to predict higher concentrations of uranium as a viable source for commercial extraction.

Indoor radon values correlated with uranium contents at these locations (given in chapter 4) with a correlation coefficient of 0.48, shown in Figure 6.9. Interestingly, magnitude of correlation coefficient obtained here, is very much similar to that reported in a previous indoor study (r^2=0.47) in the neighboring Bathinda region (Singh *et al*., 2005). A higher correlation coefficient (r^2=0.91) between uranium in soil and indoor radon concentrations however, was reported in a similar study carried in some areas of Himachal Pradesh, India (Singh *et al.*, 2002).

Radon in Soil-gas, Water and Exhalation Rates

The values of radon concentration in soil-gas, water and exhalation rates for the same 36 locations in the study area are given in Table 6.3. Figures 6.10, 6.11 and 6.12 show the distribution of radon soil-gas, water-dissolved radon concentration and exhalation rates at these locations. Annual dose due to radon in water have also been calculated. The radon concentration in soil-gas and water varied from 1.9–16.4 and 5.01–11.6 $kBqm^{-3}$. The minimum to maximum values of exhalation and dose rates due to radon in water found were 7.48–35.88 $mBqm^{-2}s^{-1}$ and 13.42–31.08 μSvy^{-1} respectively.

The range of radon concentration in soil-gas 1.9–16.4 $kBqm^{-3}$ is lesser than 0.3 to 35.8 $kBqm^{-3}$ reported in some parts of Northern Punjab (Singh *et al*., 2010). Still higher values of soil gas radon (up to 82.2 $kBqm^{-3}$) attributed to tectonic activity have been measured in the Dehar lineament of Nurpur area, Himachal Pradesh, India using LR-115 plastic track detectors (Singh *et al*., 2006). The recorded values of radon concentration in water are within the recommended maximum contaminant level (MCL) of 11 Bql^{-1} recommended by US Environmental Protection Agency **(**USEPA**,** 1999b), except one of the locations (location 4), where radon concentration just exceeded the limit with a value 11.6 Bql^{-1}. Information of radon levels in sources of drinking water, particularly household water is helpful for protection of general public from consequences of excessive radiation exposure.

Radon concentration in water samples of varying sources have been reported worldwide. Ramsar (Iran) is one such important area in the world, where transportation of natural radioactivity due to ^{238}U natural series and its decay products is reflected in terms of higher radon in water and brought to the surface by water of hot springs. In a study all of the water supplies from this region have been found with radon concentration greater than 10 Bql^{-1} (Mowlavi *et al*., 2009). In their study for radon in groundwater from Arizona, in the southwest United States, Barnett *et al*. (1994) found 65 % samples with ^{222}Rn concentrations above 11 Bql^{-1} of the 362 specimens analysed. Very high values (in the range 1.0-653.5 Bql^{-1}) of radon concentration in the water samples from thermal springs of Siwalik Himalaya have been reported (Bajwa *et al*., 2005). Radon concentration in the range 25.4- 92.5 Bql^{-1} in the ground water of Doon valley in outer Himalaya are reported elsewhere (Choubey *et al*., 2003).

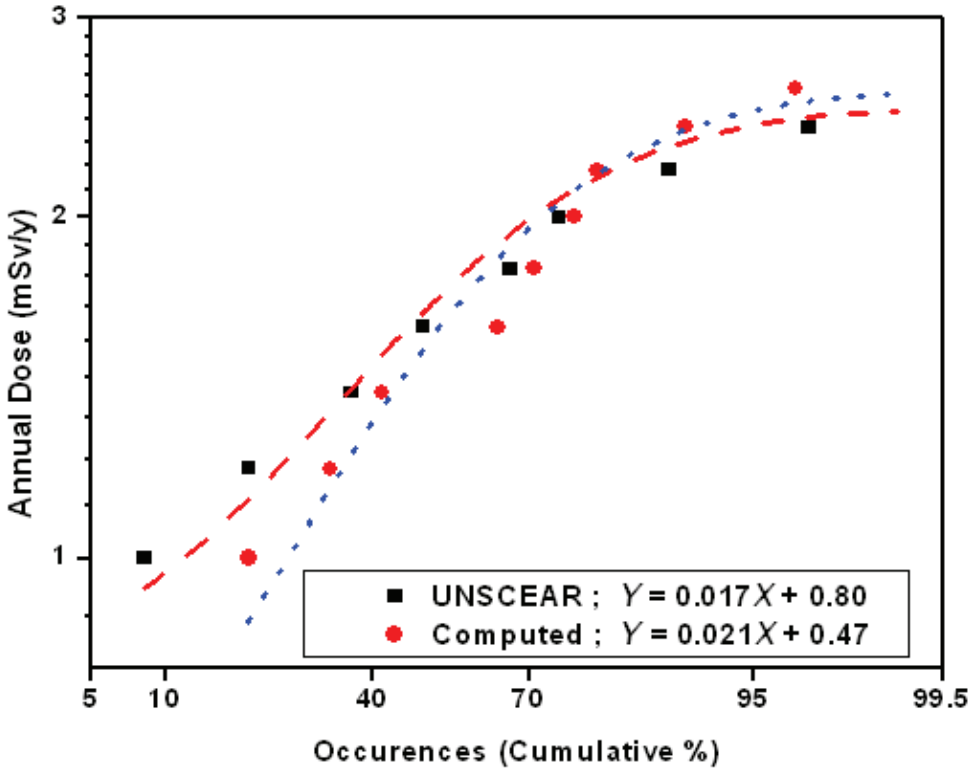

Figure 6.8 Commulative frequency distribution for respective UNSCEAR and computed doses

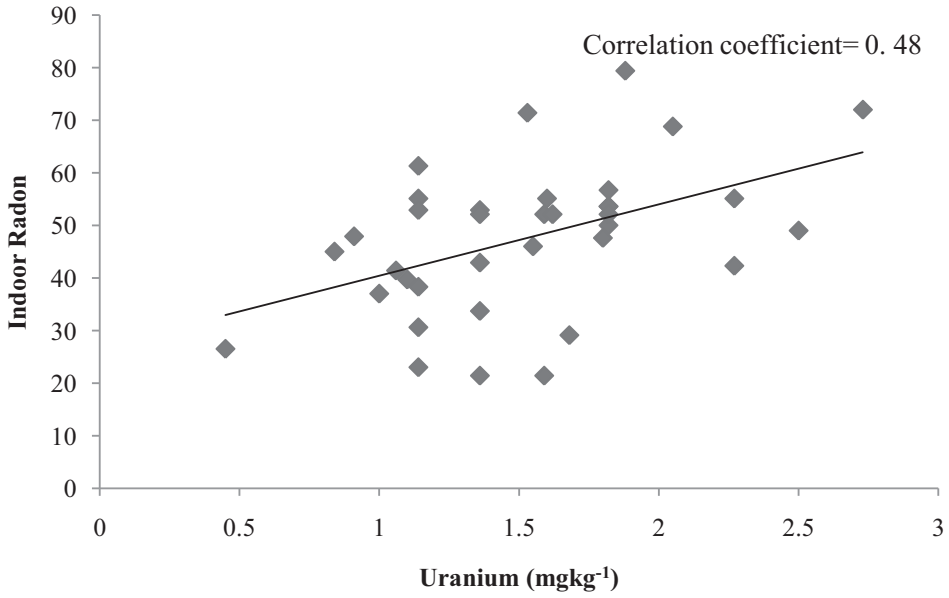

Figure 6.9 Correlation of Indoor radon with uranium concentration in soil samples for the 36 study locations of the study region

Table 6.3 Radon concentration in radon in water with corresponding doses, soil-gas and exhalation rates

S. No	Name of the Location	Mean Radon Concentration in soil-gas (Bqm^{-3})	Mean Radon Concentration in water (Bqm^{-3})	Mean Radon exhalation rate ($mBqm^{-2}sec^{-1}$)	Water radon dose rate (μSvy^{-1})
1	Faridkot city	10300±689	8570±570	18.1±1.8	22.97
2	Kotkapura	7500±547	8560±569	14.3±1.5	22.94
3	Ramana	7804±175	7960±450	10.1±1.5	21.33
4	Jaito	7578±568	11600±690	23.7±1.7	31.09
5	Bhagtuana	16400±1070	5010±600	35.9±2.3	13.43
6	Karirwali	6650±520	6030±580	19.6±1.8	16.16
7	Machaki	4130±31	7240±650	17.5±1.6	19.40
8	Sadik	2560±254	6040±610	14.8±1.5	16.19
9	Mallan	6200±549	8570±710	21.5±1.7	22.97
10	Kauni	8010±651	9820±740	25.0±1.8	26.32
11	Mukatsar city	2600±366	7500±730	21.1±1.7	20.10
12	Marh Mallu	7840±691	7060±660	28.3±1.9	18.92
13	Rupana	3930±445	7040±630	19.6±1.6	18.87
14	Aulakh	7469±161	5220±480	30.1±2.0	13.99
15	Pind Malout	2120±435	8800±840	10.5±1.5	23.58
16	Malout City	2930±212	6010±590	9.9±1.5	16.11
17	Badal	5560±15	6070±600	12.8±1.5	16.27
18	Kabbarwal	2650±28	7010±620	14.0±1.5	18.79
19	Balluana	2530±21	6550±620	15.1±1.5	17.55
20	Abohar	2410±21	8180±740	20.1±1.7	21.92
21	Nihal Khera	3542±19	7040±630	22.6±1.8	18.79
22	Fazilka	1900±174	6140±590	11.2±1.5	16.46
23	Behakbobla	3881±108	6220±630	20.5±1.7	16.67
24	Bambha Battu	9250±266	5980±580	30.3±2.0	16.03
25	Bagge Ke	4410±183	8000±720	18.2±1.6	21.44
26	Jalalabad	3730±191	8890±840	7.5±0.8	23.83
27	Jiwan Arain	3324±84	7120±650	9.9±1.5	19.08
28	Pindi	10600±715	6140±590	30.0±2.0	16.46
29	Lakho ke	4030±447	7270±650	14.1±1.5	19.48
30	Khai Kheme Ki	11700±615	8580±720	31.9±2.1	22.99
31	Ferozepur city	6690±524	8810±850	11.2±0.9	23.61
32	Khosa Dal Singh	4930±486	8200±740	13.7±1.5	21.98
33	Zira	4000±116	6770±630	13.2±1.5	18.14
34	Khui Khera	4110±112	5830±590	20.5±1.7	15.62
35	Bhadana	3840±224	5100±610	10.3±1.5	13.67
36	Makhu	3360±271	6100±530	7.3±1.4	16.35
	Min	1900±174	5010±600	7.5±0.8	13.43
	Max	16400±1070	11600±690	35.9±2.3	31.09
	Average	5568±3212	7250±1433	18.2±7.5	19.43±3.84

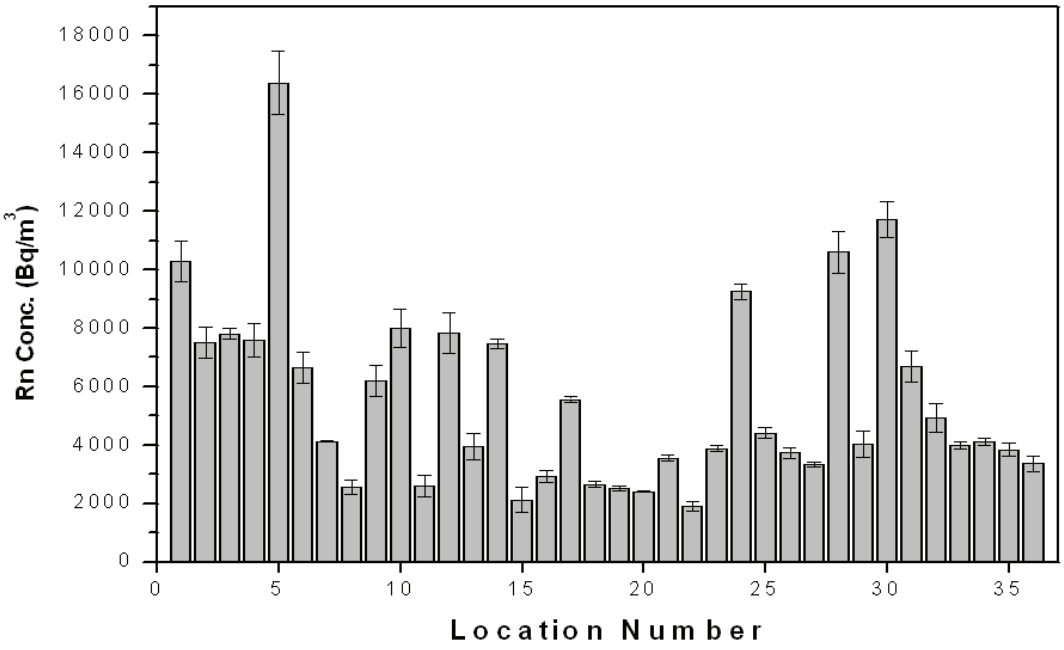

Figure 6.10 Bar graph of radon concentration in soil-gas at different locations of the study region

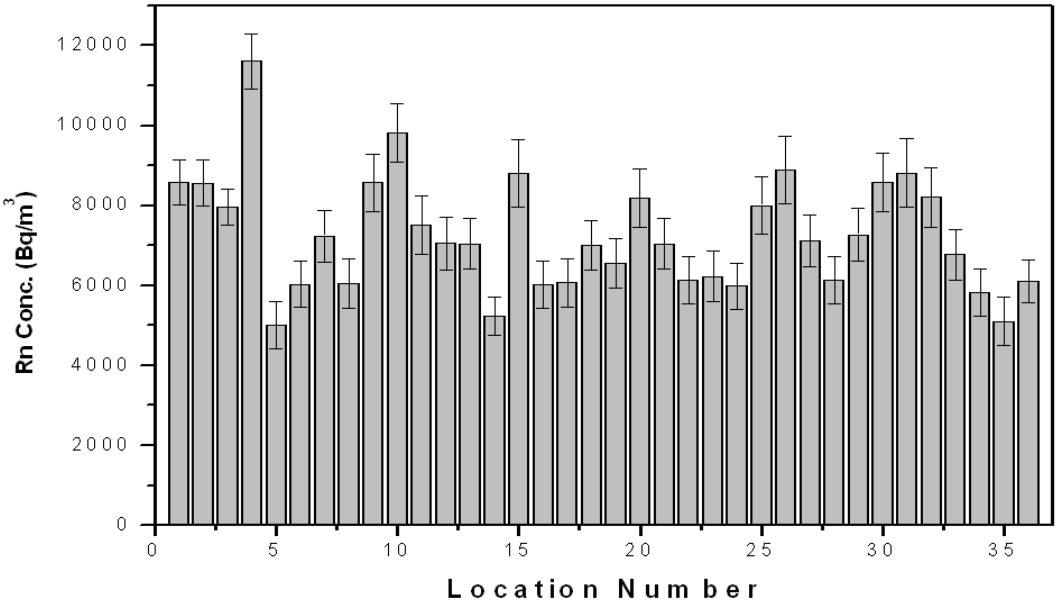

Figure 6.11 Bar graph of radon concentration in water at different locations of the study region

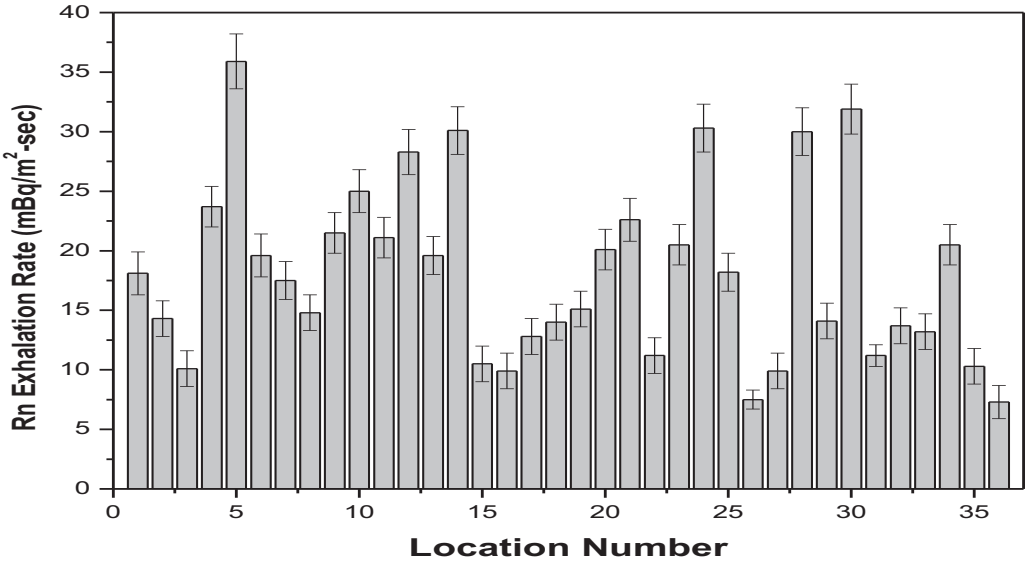

Figure 6.12 Bar graph of radon exhalation rates at different locations of the study region

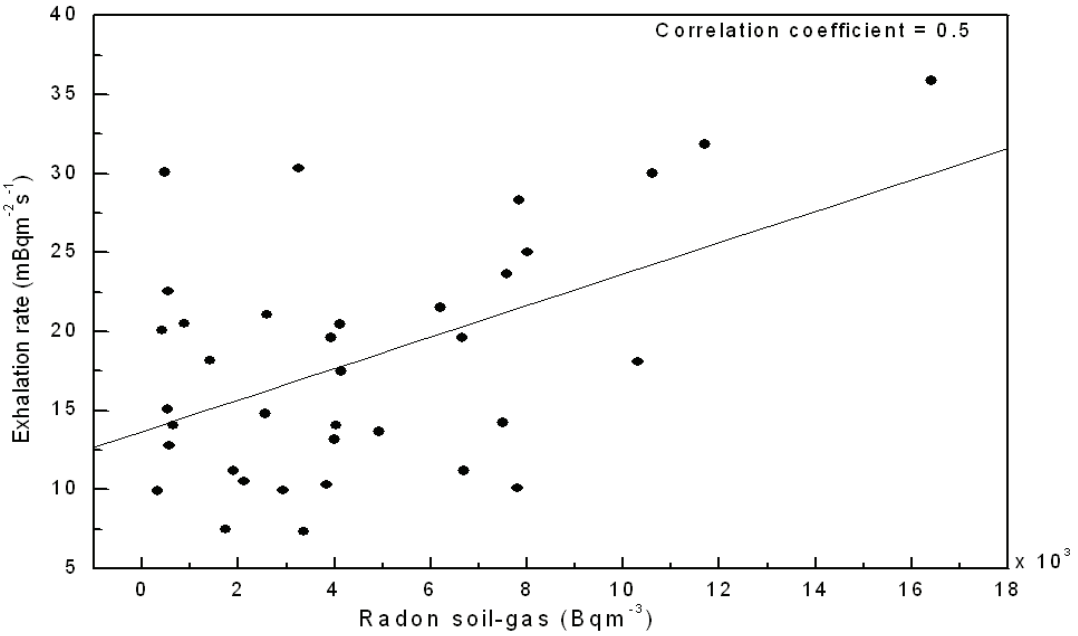

Figure 6.13 Correlation of exhalation rate with radon soil-gas

The measurement of ^{222}Rn concentration in water and soil is used for evaluating the potential for elevated indoor ^{222}Rn concentrations (Iskandar, 2005; Choubey *et al.*, 2007). Radon dissolved in water contributes indoor air through degassing. The percentage of radon present in drinking-water that is released into indoor air will depend on local conditions, such as the total consumption of water in the house, the volume of the house and its ventilation rate, and is likely to be highly variable. According to one of the estimates a radon concentration of 1000 Bql^{-1} in drinking-water discharged from a tap or shower increases the indoor radon concentration by 100 Bqm^{-3} (NAS, 1999a). Since the levels of radon in water in the present investigations are much lesser (5.01–11.6 Bql^{-1}), water radon is not a dominant contributor to indoor radon here.

The annual effective doses due to radon concentration in water rangin from 13.42–31.08 μSvy^{-1} are less than 0.1 $mSvy^{-1}$ for all the samples, as recommended by WHO, 2004 and the EU Council, 1998 (EUC, 1998; WHO, 2004). Radon concentration of 1 $kBqm^{-3}$ in water causes an annual approximate total effective dose of 2.68 μSv for adults including both its inhalation and ingestion (Mowlavi *et al*., 2009).

The calculated average radon exhalation rate has been 18.17 $mBqm^{-2}sec^{-1}$, much less than that of world average (33 $mBqm^{-2}s^{-1}$) given by UNSCEAR 2000 (UNSCEAR, 2000). The maximum of exhalation did not coincide with the maximum of soil-gas. This may be due to the dependence of radon transport through soil on various local parameters like permeability, grain size distribution, degree of compaction and water content etc (Rogers and Nielson, 1991). This is evident from Figure 6.13, showing only an intermediate value of correlation coefficient (0.5) between radon exhalation rates and soil-gas values.

6.5 Conclusions

1. Average indoor radon and thoron levels in Fridkot, Ferozepur and Muktsar of South-Western region of Punjab have been found to be higher compared to respective national average values 23 Bqm^{-3} and 12 Bqm^{-3} and global radon average value of 30 Bqm^{-3}. Inhalation doses for the study region due to radon and its daguther products are in lines with global approximate value of 2 mSv.
2. The radon concentration in soil- gas varied as 1.9-16.4 $kBqm^{-3}$. Soil- gas radon concentrations do not have very much relation with human health except when abnormally high. Present values are absolutely normal.
3. Radon concentrations in water recorded as 5.01-11.6 $kBqm^{-3}$ and are within the recommended safe limit of 11 Bql^{-1}. Corresponding annual effective doses have been found to be less than recommended limit of 0.1 $mSvy^{-1}$ for all the samples.
4. Radon exhalation rate which ranged as 7.48-35.88 $mBqm^{-2}s^{-1}$ averaged at 18.17 $mBqm^{-2}sec^{-1}$, lesser than world average value (33 $mBqm^{-2}s^{-1}$).