

# MEASUREMENT OF INDOOR RADON, THORON AND THEIR PROGENY LEVELS IN DWELLINGS OF AMBALA DISTRICT, HARYANA, NORTHERN INDIA USING SOLID STATE NUCLEAR TRACK DETECTORS

VIMAL MEHTA<sup>1,2,\*</sup>, S. P. SINGH<sup>2</sup>, R. P. CHAUHAN<sup>3</sup>, G. S. MUDAHAR<sup>2</sup>

<sup>1</sup>Department of Physics, M. M. University, Mullana (Ambala)-133 207, India

<sup>2</sup>Department of Physics, Punjabi University, Patiala-147 001, India

<sup>3</sup>Department of Physics, National Institute of Technology, Kurukshetra-136 119, India

Corresponding author: mehta\_vimal78@yahoo.co.in

*Received March 29, 2014*

Presence of radon, thoron and their decay products in household environment are considered a potential health hazard. Measurement of their levels is an important aspect to assess the threat they may pose to humans. Considering this their measurement from the dwellings of Ambala of Northern India has been carried out using passive technique. The indoor radon concentration varied from  $4.8 \pm 0.2 \text{ Bq m}^{-3}$  to  $29.1 \pm 1.4 \text{ Bq m}^{-3}$  with an average of  $13.0 \text{ Bq m}^{-3}$  while the thoron concentration in the same dwellings varied from  $1.2 \pm 0.1 \text{ Bq m}^{-3}$  to  $69.2 \pm 1.8 \text{ Bq m}^{-3}$  with an average of  $14.4 \text{ Bq m}^{-3}$  for the autumn season. The radon progeny levels in the dwellings under study varied from 0.52 to 2.80 mWL with an average of 1.40 mWL, while the thoron progeny levels varied from 0.03 to 1.87 mWL with an average of 0.39 mWL for the autumn season. The annual effective dose received by the inhabitants of these dwellings varied from 0.15 mSv to 2.30 mSv and depends upon the ventilation condition of the dwellings.

*Key words:* Radon; Thoron; progeny; SSNTD; dwellings; annual effective dose; ventilation.

## 1. INTRODUCTION

Uranium is ubiquitous in nature and can be found in trace amount in most rock and soil. Therefore, most rock and soil also contain thorium and radium. Due to differences in chemical forms, some limited separation can occur by the groundwater movement and other natural processes. The decay of radium leads to radon.  $^{222}\text{Rn}$  is the single gaseous isotope among the fourteen principal decay products composing the  $4n + 2$  natural decay series beginning with  $^{238}\text{U}$  and terminating in  $^{206}\text{Pb}$ . There are 35 known radon isotopes (all radioactive) with atomic mass numbers ranging from 195 to 229. However there are three major isotopes of radon - actinon ( $^{219}\text{Rn}$ ) with a half-life of 3.96 sec., thoron ( $^{220}\text{Rn}$ ) with a half-life 55.6 sec., and radon ( $^{222}\text{Rn}$ ) with a half-life 3.824 days [1]. These three isotopes of radon emit alpha particles of energy 6.82 MeV, 6.28 MeV and 5.48 MeV, respectively.

But because radon is a noble gas, a large portion of it is free to migrate away from radium. Depending on various geological and geophysical aspects and features of building materials, radon can migrate into the indoor air, which can lead to an increase in radon concentrations [2]. Radon contributes about half of the background radiation to which we are all exposed [3]. The primary sources of indoor radon are soils [4] and rocks source emanations, off-gassing of waterborne radon into a building, emanation from building materials, and entry of radon into a structure from outdoor air. Radon emanation from the soil depends upon its radium content and mineralogy, porosity, grain size, moisture content and permeability through host rock and soil [5].

Many researchers have reported the link between exposure to radon and its decay products in mining situations and an increased risk of lung cancer [6]. Due to these reported adverse health effects of inhaled radon and its progeny, International Commission on Radiological Protection (ICRP, 1993) has made recommendations for the control of this exposure in dwellings and work place [7]. Due to harmful effects of radon many workers have reported the values of indoor radon [8–11] from the different parts of the world and also from the different parts of India [12–14].

These types of studies are useful for the assessment of radiation dose received by the inhabitants and also for producing the data for producing the radon map of the country. Keeping these important points in mind the environmental monitoring of radon, thoron and their progeny in some dwellings of Ambala, Northern India has been carried out in the light of recommendations given by the International Commission on Radiological Protection (ICRP).

## 2. GEOLOGY OF STUDY AREA

Ambala is a part of Haryana which is the 16<sup>th</sup> largest state in India. This state has a very fertile land and is called the Green Land of India. The state is bordered by Uttar Pradesh in east, Punjab in west, Himachal Pradesh in north and Rajasthan in south. Union Territory of Delhi is landlocked on 3 sides by Haryana. Haryana can be divided into two natural areas; sub-Himalayan Terai and Indo-Gangetic plain. The plain is fertile and slopes from north to south with a height above sea level, averaging between 213 m to 274 m. For most parts of the year, climate of Haryana is extreme, summers are very hot and winters are extremely cold. Temperatures in summer generally shoot up to 47 °C and in winters the temperature ranges from 5 to 9 °C, occasionally dropping to freezing. The main geographical features of Haryana are the Yamuna-Ghaggar plain forming the largest part of the state, the Shivalik hills to the northeast, semi-desert sandy plain to the southwest and the Aravalli range in the south [15].

Ambala district of Haryana lies between 30° 10' to 31° 35' N and 76° 30' to 77° 10' E. Total geographical area of the district is 1574sq.km. The district area falls in Yamuna sub-basin of Ganga basin, and is mainly drained by the river

Tangri, Markanda and Beghna. The Indian metrological service divide the year into four seasons the relatively dry cool winter (Dec-March), the dry hot summer (March-June), rainy (June-Sept) and autumn (Sept-Dec). Similarly the climate of Ambala district can be classified as subtropical monsoon, mild & dry winter, hot summer and autumn. The normal annual rainfall of the district is 1076 mm, and is unevenly distributed over the area. The average rainy days are 44. The south west monsoon, sets in from last week of June and withdraws in the end of September, contributing about 2/3rd of normal annual rainfall. The district area is occupied by Indo-Gangetic alluvim. Physiographically the area is flat terrain, however a little part in the extreme northeastern area of the district is occupied by Siwalik hills. The area slopes towards southwest with an average gradient of 1.5m/km. The soils are non-calcareous and sandy loam on the surface, and loam to clayey loam at depth, and placed under the classification of soil as Udipsamments/Udorthents [16].

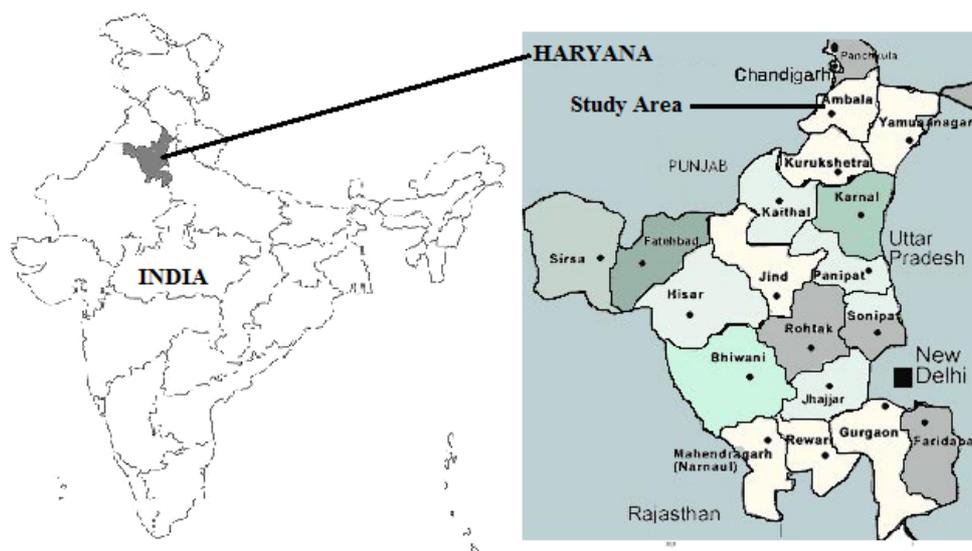


Fig. 1 – Location of the study area.

### 3. MATERIALS AND METHODS

Several methods are in use for measuring the radon and its daughter elements in dwellings but in this study the measurement of radon, thoron and their progeny levels has been done using twin chamber dosimeters cups. These twin cup dosimeters were developed and calibrated at Environmental Assessment Division, Bhabha Atomic Research Centre, Mumbai [17]. In this technique, LR-115 type II, strippable plastic track detector films of size (2cm x 2cm) are used. Pristine

LR-115 (cellulose nitrate, type-II, strippable, procured from DOSIRAD, France) is alpha sensitive plastic track detector. It is a 12  $\mu\text{m}$  thick film red dyed cellulose nitrate emulsion coated on inert polyester base of 100  $\mu\text{m}$  thickness. The specially designed twin cup dosimeter used here consists of two chambers of cylindrical geometry separated by a wall in the middle with each having a length of 4.5 cm and radius of 3.1 cm [18-19] as shown in Fig. 2. Also, there are large numbers of fine holes at the ends *i.e.* perforated ends are there so that free entry of air inside the chambers is possible. This dosimeter employs three SSNTDs out of which two detectors were placed in each chamber and a third one was placed on the outer surface of the dosimeter. One chamber is fitted with glass fiber filter so that radon and thoron both can diffuse into the chamber while in other chamber, a semi permeable membrane made of latex or cellulose nitrate, having a thickness of 25  $\mu\text{m}$  is used [18, 20-22]. The membrane mode measures the radon concentration alone as it can diffuse through the membrane but suppresses the thoron. The twin cup dosimeter also has a provision for bare mode enabling it to register tracks due to radon, thoron and their progeny in total.

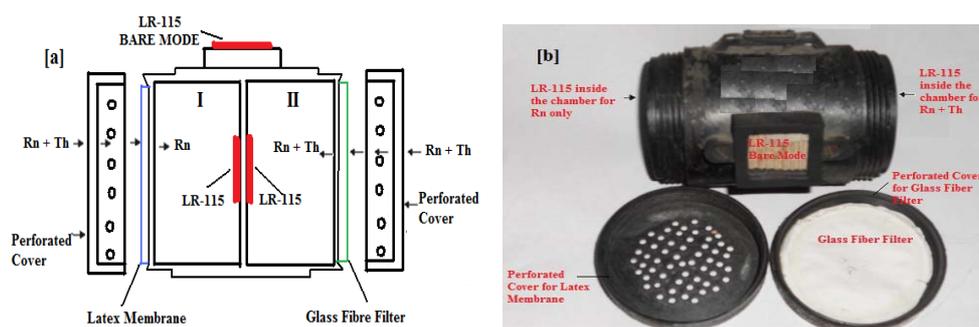


Fig. 2 – (a) Schematic diagram; (b) Actual twin cup dosimeter.

The plastic detectors LR-115 type II (2cm x 2cm) are loaded in the twin chamber dosimeters which provide three modes of exposure to determine radon, thoron and their progeny simultaneously [22–23]. The selection of the detector LR-115 is based on the fact that these detectors do not develop tracks originating from the alpha particles of the progeny deposited on them and hence ideally suited for air concentration measurements [24]. The dosimeters were suspended in the room at a height more than 2 m above the ground level and about 1 meter below the ceiling of the room to. The distance of the dosimeters from the walls was kept 2 meters. In case of the still air, the diffusion length of thoron is 2-3 cm, so the contribution of thoron for track formation on dosimeter is negligible but in the presence of convective transport of thoron due to natural intermixing of air, the thoron emitted from the wall is distributed in the whole room. Three different types

of dwellings were selected according to their ventilation conditions viz. average, below average and good ventilated. We have assumed a room with a door and without window as below average ventilated, with one window and a door as average ventilated and with more than two windows and a door as good ventilated. The building material of dwellings was similar and was having cemented walls and floorings. The dwellings monitored were from the different localities of the Ambala for a uniform distribution. The annual effective dose received by the inhabitants was looked into in the light of guidelines given by International Commission on Radiological Protection, 2009 [25].

The detectors were left exposed for a period of three months. At the end of the exposure time, the detectors were removed and subjected to a chemical etching process in 2.5 N NaOH solutions at 60°C for 90 minutes. The detectors were washed and immediately after the completion of washing, the red sensitive layer was stripped for counting using spark counter. The stripping was done by pinching one of the corners of the film between the thumb and the index finger and then pulling the sensitive layer in a direction parallel to the base until the two are completely separated. The tracks produced by the alpha particles were counted using a spark counter (Polltech Inst., Mumbai) as shown in Fig. 3. The etched sensitive layer of LR-115 detector acts as an insulating material, is placed between two electrodes of the spark counter forming a capacitor and covered with an aluminized plastic foil (a thin layer of aluminium evaporated onto Mylar backing). The aluminized side of the plastic foil is in contact with the thin detector. When a high voltage is applied an electrical discharge or spark takes place through a track-hole. The voltage pulse produced can easily be counted electronically by a scalar. The pre spark voltage is 900 V and spark voltage is 500 V in this experiment. The measured track density was converted into radon, thoron and their progeny concentrations using calibration factors as used by other researchers [17–18, 26].

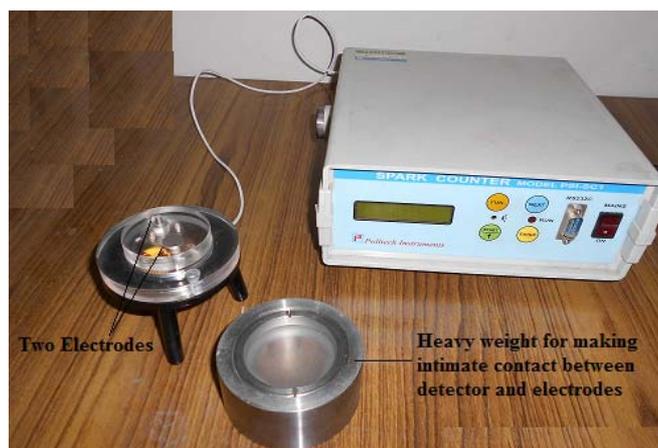


Fig. 3 – Polltech spark counter unit.

Here, calibration factors are the quantities, which are used for converting the observed track density rates to the activity concentration of the species of interest. If  $T$  is taken as track density observed on a SSNTD due to exposure in a given mode to a concentration  $C$  of a given species for a time  $t$ , then in general we take

$$T = K \times C \times t \quad (1)$$

where we define  $K$  as calibration factor.

Therefore, following relations were used to determine the concentration of Radon  $C_R$ , thoron  $C_T$ , and progeny levels of radon  $C_R$  (WL) and that of thoron  $C_T$  (WL) [17-18, 26]

$$C_R = T_M / t K_{RM} \quad (2)$$

$$C_T = T_F - K_{RF} C_R / t K_{TF} \quad (3)$$

$$\text{Progeny levels of Radon (WL)} = C_R (\text{Bqm-3}) \times F_R / 3700 \quad (4)$$

$$\text{Progeny levels of Thoron (WL)} = C_T (\text{Bqm-3}) \times F_T / 3700 \quad (5)$$

Where  $T_M$  = track density in membrane compartment

$T_F$  = track density in filter Compartment

$t$  = total exposure time

$K_{RM}$  = Calibration factor for radon in membrane mode =  $0.021 \text{ tr cm}^{-2} \text{ d}^{-1} / \text{Bqm}^{-3}$

$K_{RF}$  = Calibration factor for radon in filter mode =  $0.023 \text{ tr cm}^{-2} \text{ d}^{-1} / \text{Bqm}^{-3}$

$K_{TF}$  = Calibration factor for thoron in filter mode =  $0.019 \text{ tr cm}^{-2} \text{ d}^{-1} / \text{Bq m}^{-3}$

$F_R$  = Equilibrium factor for Radon having value of 0.4

$F_T$  = Equilibrium factor for Thoron having value of 0.1

Indoor inhalation dose received due to  $^{222}\text{Rn}$  and its progeny, and  $^{220}\text{Rn}$  and its progeny, has been estimated using the following relation.

$$D = \{(0.17 + 9F_R) C_R + (0.11 + 32F_T) C_T\} \times 7000 \times 10^{-6} \quad (6)$$

Where  $F_R$  = equilibrium factor for radon = 0.4

$F_T$  = equilibrium factor for radon = 0.1 [27].

#### 4. RESULTS AND DISCUSSION

The measurement of indoor radon and thoron concentrations in some dwellings of Union Tertiary, Chandigarh were carried out by twin cup dosimeters. The results are listed in Table 1 for the autumn season for September 2013 to November 2013.

The indoor radon concentration in Ambala varies from  $4.8 \pm 0.2 \text{ Bq m}^{-3}$  to  $29.1 \pm 1.4 \text{ Bq m}^{-3}$  with an average of  $13.0 \text{ Bq m}^{-3}$  while the thoron concentration in the same dwellings varied from  $1.2 \pm 0.1 \text{ Bq m}^{-3}$  to  $69.2 \pm 1.8 \text{ Bq m}^{-3}$  with an average of  $14.4 \text{ Bq m}^{-3}$  for the autumn season. The radon progeny levels in the dwellings under study varied from 0.52 to 2.80 mWL with an average of 1.40 mWL,

while the thoron progeny levels varied from 0.03 to 1.87 mWL with an average of 0.39 mWL for the autumn season.

*Table 1*

Radon, thoron and their progeny levels in some dwellings of Ambala in autumn season

| S. No | Ventilation condition | Radon conc. $C_R$ ( $Bq\ m^{-3}$ ) | Thoron conc. $C_T$ ( $Bq\ m^{-3}$ ) | Progeny levels of Radon $C_R$ (mWL) | Progeny levels of Thoron $C_T$ (mWL) | Annual Dose (mSV) |
|-------|-----------------------|------------------------------------|-------------------------------------|-------------------------------------|--------------------------------------|-------------------|
| 1     | Good                  | $5.8 \pm 0.2$                      | $3.7 \pm 0.1$                       | 0.63                                | 0.10                                 | 0.24              |
| 2     | Below average         | $5.3 \pm 0.2$                      | $8.8 \pm 0.4$                       | 0.57                                | 0.24                                 | 0.34              |
| 3     | Average               | $17.5 \pm 0.5$                     | $1.6 \pm 0.1$                       | 1.90                                | 0.04                                 | 0.50              |
| 4     | Good                  | $4.8 \pm 0.2$                      | $1.2 \pm 0.1$                       | 0.52                                | 0.03                                 | 0.15              |
| 5     | Below average         | $18.5 \pm 1.0$                     | $2.8 \pm 0.2$                       | 2.00                                | 0.08                                 | 0.55              |
| 6     | Average               | $16.9 \pm 0.7$                     | $8.2 \pm 0.4$                       | 1.80                                | 0.22                                 | 0.64              |
| 7     | Below average         | $25.9 \pm 1.2$                     | $69.2 \pm 1.8$                      | 2.80                                | 1.87                                 | 2.30              |
| 8     | Good                  | $6.3 \pm 0.3$                      | $13.4 \pm 0.6$                      | 0.68                                | 0.36                                 | 0.48              |
| 9     | Good                  | $5.3 \pm 0.2$                      | $22.8 \pm 0.7$                      | 0.57                                | 0.62                                 | 0.67              |
| 10    | Average               | $10.6 \pm 0.3$                     | $12.8 \pm 0.5$                      | 1.10                                | 0.35                                 | 0.58              |
| 11    | Below average         | $29.1 \pm 1.4$                     | $16.2 \pm 0.6$                      | 3.10                                | 0.44                                 | 1.14              |
| 12    | Average               | $21.2 \pm 0.9$                     | $6.5 \pm 0.3$                       | 2.30                                | 0.18                                 | 0.71              |
| 13    | Good                  | $5.3 \pm 0.2$                      | $20.3 \pm 0.9$                      | 0.57                                | 0.55                                 | 0.60              |
| 14    | Below average         | $12.7 \pm 0.4$                     | $16.8 \pm 0.8$                      | 1.40                                | 0.45                                 | 0.72              |
| 15    | Average               | $10.1 \pm 0.5$                     | $12.2 \pm 0.5$                      | 1.10                                | 0.33                                 | 0.55              |

Annual dose received by the inhabitants in the dwellings under study varied from 0.15 mSv to 2.30 mSv with an average of 0.68 mSv. In all the dwellings surveyed, the maximum annual effective dose (2.30 mSv/y) is found less than the lower limit of the action level (3 mSv/y) recommended by International Commission on Radiological Protection (ICRP).

Table 1 provides the whole information of the study area regarding the radon, thoron and their progeny levels. It also shows the amount of annual dose received by the occupants of these dwellings. The variation found in the radon concentration of different dwellings may be explained due to different ventilation rates, the nature and type of building material used during construction and the variation in the radioactive levels in the soil beneath the dwellings.

International Commission on Radiological Protection (ICRP, 1993) recommended the action levels range as 200-600  $Bq\ m^{-3}$  for dwellings [7]. However, in the 2007 recommendations, the AL concept was replaced with the concept of reference level (RL) [28]. WHO (2009) [29] recommends in regards of

RLs, that radon concentration should be less than  $100 \text{ Bq m}^{-3}$ , or, if this RL is not considered feasible for some countries, the chosen RL should not be more than  $300 \text{ Bq m}^{-3}$ . ICRP in 2009 recommended in regards to radon in dwellings, ICRP (2009) [25] reduced the upper value for the RL from  $600 \text{ Bq m}^{-3}$  and lower RLs should be considered according to local circumstances. As regards radon in workplaces,  $1000 \text{ Bq m}^{-3}$  was confirmed as the entry point for applying radiological protection requirements for planned exposures, whereas no value for RLs was anticipated. The values of indoor radon levels found in Ambala were below the lower limits of reference level as recommended by the ICRP, 2009 [25]. These values were also less than the world average of  $40 \text{ Bq m}^{-3}$  [27].

Table 2

Dependence of average annual dose on the ventilation conditions of the dwellings of Ambala

| S.No | Ventilation Condition | No. of dwellings | Average annual Dose (mSv) |
|------|-----------------------|------------------|---------------------------|
| 1    | Good                  | 5                | 0.43                      |
| 2    | Average               | 5                | 0.60                      |
| 3    | Below average         | 5                | 1.01                      |

Table 2 provides the information about the annual dose received by the occupants in different type of ventilation of dwellings. Fig. 2 shows the amount of annual dose received by the occupants according to their ventilation condition. It clearly shows that the dose received by the inhabitants of the poorly ventilated dwellings was on higher side in comparison to the average and good ventilated dwellings. This clearly indicates that the risk from radon can be reduced by lowering the radon level in the dwellings by increasing the ventilation. The high values of indoor radon in dwellings with poor ventilation were also reported recently [30].

Table 3 shows the values of radon concentration from different parts of Northern India. Table 4 shows the comparison of our indoor radon results with the other countries.

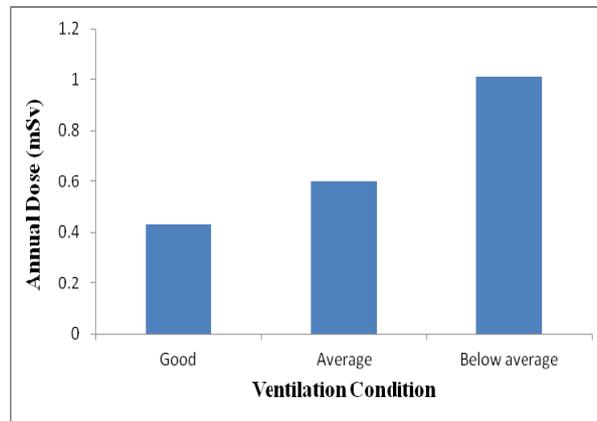


Fig. 4 – Dependence of annual dose received by the Ambala occupants on ventilation conditions.

Table 3

Comparison of indoor radon with different parts of Northern India

| S. No | Region        | Technique used  | Annual average indoor radon values ( $\text{Bq m}^{-3}$ ) $\pm$ S.D | Reference            |
|-------|---------------|-----------------|---|----------------------|
| 1     | Amritsar      | Bare Mode       | $121.7 \pm 48.3$  | [31]                 |
| 2     | Bathinda      | Bare Mode       | $153.6 \pm 31.3$  | [12]                 |
| 3     | Jalandhar     | Bare Mode       | $124.5 \pm 39.0$  | [32]                 |
| 4     | Patiala       | Bare Mode       | $92.6 \pm 9.0$  | [33]                 |
| 5     | Sangrur       | Bare Mode       | $63.2 \pm 7.9$  | [33]                 |
| 6     | Panchkula     | Bare Mode       | $51.8 \pm 7.3$  | [34]                 |
| 7     | Yamunanagar   | Bare Mode       | $118.03 \pm 11.2$   | [34]                 |
| 8     | Kurukshetra   | Bare Mode       | $40.33 \pm 7.3$   | [34]                 |
| 9     | Una           | Bare Mode       | $34.6 \pm 12.2$   | [35]                 |
| 10    | <b>Ambala</b> | <b>Twin cup</b> | <b><math>13.0 \pm 8.0</math></b>                                    | <b>Present Study</b> |

Table 4

Comparison of indoor radon with different countries

| S. No | Region         | Average indoor radon values ( $\text{Bq m}^{-3}$ ) | Reference     |
|-------|----------------|--|---------------|
| 1     | India (Ambala) | 13.0   | Present study |
| 2     | USA            | 46   | [36]          |
| 3     | Romania        | 112, 105   | [37, 11]      |
| 4     | France         | 68   | [38]          |
| 5     | Spain          | 86   | [39]          |
| 6     | Greece         | 41   | [40]          |
| 7     | Turkey         | 130  | [41]          |

|    |              |       |      |
|----|--------------|-------|------|
| 8  | Saudi Arabia | 18.4  | [42] |
| 9  | Egypt        | 65.97 | [43] |
| 10 | Yemen        | 42    | [44] |

## 5. CONCLUSIONS

In the present study we have measured the values of radon, thoron and their progeny levels in the indoor environment of some dwellings of Ambala district in Northern India. Annual effective dose has also been calculated for the occupants of these dwellings. The conclusions of the present study are as follows:

- The overall average value of radon in the present study is found to be  $13.0 \text{ Bq/m}^3$  and is lower than the world average value of  $40 \text{ Bq/m}^3$  of indoor radon level. The present values of indoor radon are lower than the reference level as recommended by ICRP. It is also clear from Table 3 that the radon levels in the dwellings of Ambala district are close to other values of indoor radon levels of nearby areas of Northern India as measured by other research groups.
- The maximum value of radon progeny level is found to be 3.10 mWL and is found below the action limit of 21.50 mWL for Indian dwellings [45, 46].
- The values of annual effective dose in dwellings of study area are found to be lower than the worldwide average radiation dose of 2.4 mSv. The effective dose received by the residents in the study area lies below the range of 3–10 mSv per year<sup>-1</sup> as recommended by ICRP.
- The ventilation conditions of the dwellings play an important role in order to decide the values of indoor radon/thoron concentration and effective dose. In general, the radon concentration values are found to be higher in dwellings with poor ventilation.

## REFERENCES

1. G. Milic, L. Gulan, P. Bossew, B. Vuckovic, Z.S. Zunic, *Indoor radon mapping: a survey of residential houses of Kosovo and Metohija*, Rom. Journ. Phys., **58**, Supplement, S180–S188 (2013).
2. E.S. Armencea (Mutoiu), A. Armencea, B. Burghela, A. Cucos (Dinu), C. Malos, T. Dicu, *Indoor radon measurements in Bacau County*, Rom. Journ. Phys., **58**, Supplement, S189–S195 (2013).
3. C.R. Cothorn, W.L. Lappenbusch, *Drinking-water contribution to natural background radiation*, Health Physics **50**, 33–47 (1986).
4. G. Akerblom, P. Andersson, B. Clavensjo, *Soil gas radon: a source for indoor radon daughters*, Radiat Prot Dosim **7** (1–4), 49–54 (1984).
5. I. Barnet, *Indoor radon probability calculated from the Czech soil gas radon data in a grid net for the European Geogenic Radon Map construction: test of feasibility*, Environ Earth Sci **66**, 1149–1153 (2012).
6. D.C. Thomas, K.G. McNeill, C. Dougherty, *Estimates of lifetime lung cancer risks resulting from Rn progeny exposure*, Health Physics **45** (5), 825–846 (1985).

7. ICRP (1993) (International Commission on Radiological Protection) (Oxford: Pergamon Press) ICRP Publication No. 65 (1993).
8. Auvinen Anssi, Mäkeläinen Ilona, Hakama Matti, Castrén Olli, Pukkala Eero, Reisbacka Heikki, Rytömaa Tapio, *Indoor radon exposure and risk of lung cancer: a nested case—control study in Finland*, JNCI J Natl Cancer Inst **88** (14), 966–972 (1996).
9. William J Blot, Zhao-Yi Xu, John D Jr. Boice, Dong-Zhe Zhao, Betty Jane Stone, Jie Sun, Li-Bing Jing, Joseph F. Jr. Fraumeni, *Indoor radon and lung cancer in China*. JNCI J Natl Cancer Inst **82** (12), 1025–1030 (1990).
10. M. Doi, S. Kobayashi, K. Fujimoto, *A passive measurement technique for characterization of high-risk houses in Japan due to enhanced levels of indoor radon and thoron concentrations*, Radiat Prot Dosim **45** (1-4), 425–430 (1992).
11. L.E. Muntean, C. Cosma, A. Cucos, T. Dicu, D.V. Moldovan, *Assessment of annual and seasonal variation of indoor radon levels in dwelling houses from Alba County, Romania*, Rom. Journ. Phys., **59**, 163–171 (2014).
12. S. Singh, M. Kumar and R. K. Mahajan, *The study of indoor radon in dwellings of Bathinda district, Punjab, India and its correlation with uranium and radon exhalation rate in soil*. Radiat Meas **39**, 535–542 (2005).
13. R. P. Chauhan, *Monitoring of radon, thoron and their progeny in dwellings of Haryana*, Indian J Pure & Appl Phys **48**, 470–472 (2010).
14. Deepak Verma, M. Shakir Khan, *Assesment of indoor radon, thoron and their progeny in dwellings of bareilly city of northern india using track etch detectors*, Rom. Journ. Phys., **59**, 172–182 (2014).
15. L. Bhandari and S. Kale (eds): *Indian states at a glance “Haryana”*, New Delhi, Pearson Education (2009).
16. S. A. Khan, *Ground water information booklet Ambala district*: Central Ground Water Board, Ministry of Water Resources, Government of India, Publication 2007; 1–26.
17. Y. S. Mayya, K. P. Eappen and K. S. V. Nambi, *Methodology for mixed field inhalation dosimetry in monazite areas using a twin-cup dosimeter with three track detectors*, Radiat Prot Dosim **77**(3), 177–184 (1998).
18. K.P. Eappen, Y.S Mayya, *Calibration factors for Ir-115 (Type II) based radon thoron discriminating dosimeter*, Radiat Meas **38**, 5–17 (2004).
19. Reddy Yadagiri. P., Reddy K. Viney Kumar, Reddy Gopal, Reddy Rama K., *J. Environ. Geochemistry* 8,104 (2005).
20. F.H. Abdel and G. Somogy, *Determination of radon and thoron permeability through some plastics by track technique*, Nucl. Tracks **12**, 697 (1986).
21. Wafaa Arafa, *Permeability of Radon-222 through Some Materials*, Rad. Meas. **35**, 207 (2002).
22. T.V. Ramachandran, K.P. Eappen, R.N. Nair, A.N. Shaikh, Y.S. Mayya and V.D. Puranik, *Distribution pattern of radon and thoron levels and inhalation dose rates in Indian dwellings*, Proc. 12<sup>th</sup> National Symp. on Environment 192 (2003).
23. K.K. Dwidevi, R. Mishra, S.P. Tripathy, A. Kulshreshtha, D. Sinha, A. Srivastva, P. Deka, B. Bhatta Charjee, T.V. Ramachandran and K.S.V. Nambi, *Radiat. Meas.* **33** (2001) 7.
24. S.A. Durrani and R. Ilic (Eds.), *Radon Measurement by Etched Track Detectors*, World Scientific, Singapore 387 (1997).
25. International Commission on Radiological Protection (2009). Statement on radon. ICRP Ref 00/902/09. Available on: [www.icrp.org/consultation\\_page.asp](http://www.icrp.org/consultation_page.asp).
26. Sannappa J., Chandrashekera M.S., Sathish L.A., Paramesh L. and Venkataramaiah P., *Study of background radiation dose in Mysore city, Karnataka State, India*, Radiat. Meas. **37** (2003) 55.
27. UNSCEAR: Sources and Effects of Ionizing Radiation. Report to the General Assembly with Scientific Annexes, United Nations Scientific Committee on the Effects of Atomic Radiation, New York (2000).

28. International Commission on Radiological Protection: The 2007 recommendations of the International Commission on Radiological Protection: Publication 103, Annals of ICRP, **37** (2–4) (2007)1.
29. World Health Organization. WHO Handbook on Indoor Radon: A Public Health Perspective, Geneva, (2009).
30. R. Mehra, P. Bala, *Assessment of radiation hazards due to the concentration of natural radionuclides in the environment*, Environ Earth Sci 2013; DOI 10.1007/s12665-013-2493-x
31. H. Singh, J. Singh, S. Singh and B.S. Bajwa, *Regional variations pattern of indoor radon levels in some areas of Punjab and Haryana*, Radiat. Prot. Dosim. **130** (2), 257 (2008).
32. K. Badhan, R. Mehra and R.G. Sonkawade, *Measurement of radon concentration in ground water using RAD7 and assessment of average annual dose in the environs of NITJ, Punjab, India*, Indian J Pure & Appl Phys **48**, 508 (2010).
33. R. Mehra, S. Singh and K. Singh, *A study of uranium, radium, radon exhalation rate and indoor radon in the environs of some areas of the Malwa region, Punjab*, Indoor Built Environ. **15** (5), 499 (2006).
34. K. Kant and S.K. Chakarvarti, *Radiological impact of airborne radon and its progeny in dwellings*, Indian J. Pure Appl. Phys. **42**, 157 (2004).
35. H.S. Virk and N. Sharma, *Indoor radon/thoron survey report from Hamirpur and Una districts, Himachal Pradesh, India*, Appl Radiat Isotopes **52**, 137 (2000).
36. EPA (U.S. Environmental Protection Agency), *National Residential Radon Survey. Vol. 1: national and regional estimates*, Report prepared for the Office of Radiation Programs by Lucas, R.M., Grillo, R.B. and Kemp, S.S. (1992c).
37. Szacsvai K., Cosma C. and Cucos A., *Indoor radon exposure in Cluj-Napoca city Romania*. Rom. Journ. Phys. **58**, S273–S279 (2013).
38. Baysson H., Billon S., Laurier D., Rogal A. and Tirmarche M., *Seasonal correction for estimation radon exposure in France dwellings*. Radiat Prot Dosim **104(3)**, 245–252 (2003).
39. UNSCEAR, United Nation Scientific Committee on the Effects of Atomic Radiation. Sources and Effects of Ionizing Radiation, United Nations: New York (1993).
40. H. Papaefthymiou, A. Mavroudis and P. Kritidis, *Indoor radon levels and influencing factors in houses of Patras, Greece*, Journal of Environmental Radioactivity **66**, 247–260 (2003).
41. N. Celik, U. Cevik and B. Kucukomeroglu, *Determination of indoor radon and soil radioactivity levels in Giresun, Turkey*, Journal of Environmental Radioactivity **99**, 1349–1354 (2008).
42. S. Ferdoas and Al-Saleh, *Measurements of indoor gamma radiation and radon concentrations in dwellings of Riyadh City, Saudi Arabia*, Applied Radiation and Isotopes **65**: 843–848 (2007).
43. H. A. Abdel Ghany, *Variability of radon levels in different rooms of Egyptian dwellings*, Indoor and Built Environ **15** (2), 193 (2006).
44. A. H. Khayrat, M. I. Al-Jarallah, X. Fazal-ur-Rehman, and F. Abu-Jarad, *Indoor radon survey in dwellings of some regions in Yemen*, Radiat Meas **36**, 449–451 (2003).
45. Ramachandran T. V., *Indoor radon levels in India: current status of the coordinated nationwide study using passive detector technique*, Proceedings of XI<sup>th</sup> National Symposium on SSNTD Amritsar, 50 (1998).
46. Ramachandran T. V., Lalit B. Y. and Mishra U. C. *Measurement of radon permeability through some membranes*. Nucl. Tracks Radiat. Meas. **13**, 81–84 (1987).