ASSESSMENT OF ANNUAL EFFECTIVE DOSE DUE TO THE INDOOR RADON EXPOSURE IN A SECOND-DEGREE EARTHQUAKE ZONE OF KUTAHYA (TURKEY)

L. SAHIN¹, H. CETINKAYA², S. GELGUN²

¹Istanbul University, Department of Physics, Istanbul, 34134, Turkey, E-mail: latife.sahin@gmail.com
²Dumlupınar University, Department of Physics, Kutahya, 43000, Turkey, E-mails: hceetinkaya@gmail.com; sevilgelgun@gmail.com

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Indoor radon concentrations have been measured in 100 dwellings of Central Kutahya, Turkey, using LR-115 type II Solid-State Nuclear Track Detectors. The detectors were placed in living rooms during the period of March–May 2010 for three times. The annual indoor radon concentrations vary from 74.1 ± 2.4 to 272.3 ± 4.2 Bq m⁻³, with a mean value of 120.8 ± 2.0 Bq m⁻³. Based on these results, we find an annual effective dose varying from 1.9 to 6.9 mSv, with a mean value of 3 mSv y⁻¹ received by inhabitants living in Kutahya city.

Key words: Radon, LR-115 Film, Natural radiation, Dose equivalent/effective dose.

1. INTRODUCTION

Natural environmental radiation is the largest contribution to the total radiation dose received by humans, with the major source being from radon gas. Radon is a radioactive noble gas that is formed in the environment as a component of the U-238 decay series. Radon gas, which has no color, odor or taste, enters the water we drink and the air we breathe by escaping from the soil and rocks within which it is trapped. Once internalized, the radon and its radioactive decay products may accumulate in the airways and on the tissue of lungs, resulting in a radiation dose that is a significant cause of, for example, lung cancer [1–3].

The quantity of radon found within a building depends on several factors, including:

i) geological parameters of the material beneath dwellings such as radium content, porosity and permeability,
ii) the materials used in the construction of the dwellings,
iii) temperature and pressure differences,
iv) the surrounding climate and the dwelling engineering.

Therefore, the design of a dwelling plays an important role for radon accumulation inside a house [1].

While studies have been performed in many countries to determine indoor radon levels, within Turkey the data are limited. With radon a significant factor in human health, additional studies are important. In this paper, we report the first study of environmental radiation dose from radon exposure in Central Kutahya, determining annual effective doses. The results will form a baseline data set to enable estimation of human radon exposure.

Kutahya Province in the western part of Turkey is located in the Inner Aegean region. With a surface area of around 10,000 km² it constitutes about 1.5% of the land area of Turkey. Central Kutahya is one of a total 13 counties in the province and lies between the longitudes of 28.7°–30.4° E and latitudes 38.8°–39.8° N, with an average elevation of 969 m above sea level [6].

Geologically, the city is located in the Aegean graben system, an area of significant tectonic activity. Consequently, Kutahya is rich in geothermal sources such as thermal spas and springs. Additionally, it is worth emphasizing that this is a seismically active zone subject to severe earthquakes: the Turkish seismic code defines Central Kutahya as being in a second-degree earthquake zone while the west part of Kutahya is in the first-degree earthquake zone. These features make Kutahya an interesting candidate for radiological studies [6].

2. MATERIAL AND METHODS

2.1. SAMPLING

Central Kutahya has the largest population of any of the counties in the province of Kutahya, thus forming the focus of this study. To conduct the study, a total of 600 detectors were placed in 100 households, in 33 districts in Central Kutahya during the months of March, April and May, 2010. The locations of the sampling points were chosen to reflect the population density of the region, with the locations of sampling points shown in Fig. 1. Two detectors were placed at each sampling point to reduce error on the measurements. In addition, the detectors were replaced to different floors of the dwellings, enabling variations in radon level with the houses to be determined. In all the dwellings, ventilation was maintained through open windows.
2.2. EXPERIMENTAL MEASUREMENTS

Measurement of radon in this study was achieved using photographic film based detectors. Large sheets of Kodak LR-115 type II film were cut in to 1.5 cm × 1.5 cm squares and placed in the bottom of small plastic cups. These were then installed in the living rooms of each house. Detectors were kept in place for one month and replaced three times. The detectors were then analyzed in the Nuclear Physics Research Laboratory at Dumlupınar University, Kutahya. Each exposed film was subjected to a chemical etching process in which 25 ml 10% NaOH solution at 60° C was applied for 97 minutes. Therefore, 100 ml 10% NaOH solution is prepared to etch 4 exposed films each time. The films were then placed
in distilled water that was stirred by a magnetic stirrer for 10 minutes, and then dried in a vacuum oven. The process allows alpha-particle tracks on the films to become visible. The number of tracks was counted with an optical microscope at a magnification of 100 times. The net track density (the number of tracks per unit area due to environmental radon) for each detector was determined by subtracting the background track density obtained from unexposed detectors from the observed track density. A calibration factor for this radon measurement was then obtained by exposing identical film detectors within the radon calibration chamber at the Health Physics Department of the Çekmece Nuclear Research and Training Centre (CANAEM) of the Atomic Energy Agency of Turkey (TAEK). This contained a $^{226}\text{Ra}$ source with a known concentration of 3.2 kBq m$^{-3}$. The calibration factor found was 3.48 tracks cm$^{-2}$ kBq$^{-1}$ h$^{-1}$ m$^{-3}$. A questionnaire was also prepared and filled prior to placement of detectors for each dwelling. The questionnaire included questions about the type of house, construction material of dwellings, house ventilation, heating system, cigarette smoking, and any cases of cancer in home.

2.3. ANNUAL EFFECTIVE DOSE EQUIVALENT CALCULATION

The annual effective dose equivalent (AEDE) for radon concentrations (in Bq m$^{-3}$) was calculated using the method described in the UNSCEAR 2000 report [5]. Hence, the AEDE rate, in units of mSv y$^{-1}$, is calculated by the following formula:

$$\text{AEDE (mSv y}^{-1}) = \text{CRn} \times F \times O \times \text{DCF}, \quad (1)$$

where CRn is the $^{222}\text{Rn}$ concentration (in Bq m$^{-3}$), F is the equilibrium factor between radon and its decay products, which is assumed to be 0.4 for the buildings (UNSCEAR, 2000), O is the occupancy factor which is estimated calculated as 7,000 hours per year in the living room in Turkey and DCF is the dose conversion factor (9.0 \times 10^{-6} \text{ mSv Bq}^{-1} \text{ m}^{3} \text{ h}^{-1}) [5].

3. RESULTS AND DISCUSSION

The distribution of average radon concentrations measured for three months at the 100 studied dwellings is presented in Fig. 2. The indoor concentration obtained in the present study, varied from 38.5 ± 5.2 to 328.0 ± 13.4 Bq m$^{-3}$, with a mean value of 120.8 ± 2.0 Bqm$^{-3}$, which is lower than the recommended ICRP action level of 200–300 Bq m$^{-3}$.
Assessment of annual effective dose due to the indoor radon exposure

Figure 2 shows the distributions of radon concentrations in the dwellings of central Kutahya.

Figure 3 shows the average indoor radon concentration in different floors of dwellings. As expected, because the soil under a dwelling is the main source of radon, the indoor radon concentration decreases from the base level (0th floor) to the third floor as shown in Figure 3.

Fig. 2 – The distributions of radon concentrations in the dwellings of central Kutahya.

Fig. 3 – The average indoor radon concentration levels in different floors of dwellings in Central Kutahya.
Table 1

The results of indoor radon concentration levels and the average annual dose measured in 33 districts of central Kutahya

<table>
<thead>
<tr>
<th>District Name</th>
<th>Average Rn-222 Concentration (Bq m⁻³)</th>
<th>Average A.E.D. (mSv y⁻¹)</th>
<th>Number of Dwellings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Ali Paşa</td>
<td>138.7 ± 1.2</td>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>2 Bahçelievler</td>
<td>89.3 ± 3.2</td>
<td>2.3</td>
<td>1</td>
</tr>
<tr>
<td>3 Balıklı</td>
<td>104.3 ± 1.4</td>
<td>2.6</td>
<td>4</td>
</tr>
<tr>
<td>4 Börekçiler</td>
<td>119.3 ± 2.9</td>
<td>3.0</td>
<td>1</td>
</tr>
<tr>
<td>5 Cedid</td>
<td>99.5 ± 3.3</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>6 Cemalettin</td>
<td>113.7 ± 2.0</td>
<td>2.9</td>
<td>3</td>
</tr>
<tr>
<td>7 Cumhuriyet</td>
<td>175.7 ± 2.4</td>
<td>4.4</td>
<td>2</td>
</tr>
<tr>
<td>8 Dumlupınar</td>
<td>108.9 ± 2.8</td>
<td>2.7</td>
<td>1</td>
</tr>
<tr>
<td>9 Fatih</td>
<td>86.3 ± 2.6</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>10 Fuatpaşa</td>
<td>126.5 ± 3.7</td>
<td>3.2</td>
<td>1</td>
</tr>
<tr>
<td>11 Gaybiefendi</td>
<td>119.7 ± 1.3</td>
<td>3.0</td>
<td>5</td>
</tr>
<tr>
<td>12 Gazi Kemal</td>
<td>216.5 ± 3.8</td>
<td>5.5</td>
<td>1</td>
</tr>
<tr>
<td>13 Gültepe</td>
<td>272.3 ± 4.2</td>
<td>6.9</td>
<td>1</td>
</tr>
<tr>
<td>14 Hamidiye</td>
<td>89.8 ± 1.8</td>
<td>2.3</td>
<td>2</td>
</tr>
<tr>
<td>15 Lala Hüseyin Paşa</td>
<td>93.2 ± 2.3</td>
<td>2.4</td>
<td>2</td>
</tr>
<tr>
<td>16 Mecidiye</td>
<td>98.0 ± 0.8</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>17 Maltepe</td>
<td>92.9 ± 1.0</td>
<td>2.3</td>
<td>7</td>
</tr>
<tr>
<td>18 Meydan</td>
<td>102.8 ± 2.4</td>
<td>2.6</td>
<td>2</td>
</tr>
<tr>
<td>19 Müberris</td>
<td>74.1 ± 2.4</td>
<td>1.9</td>
<td>1</td>
</tr>
<tr>
<td>20 Okmeydani</td>
<td>146.3 ± 1.8</td>
<td>3.7</td>
<td>3</td>
</tr>
<tr>
<td>21 Pirler</td>
<td>81.3 ± 2.5</td>
<td>2.1</td>
<td>1</td>
</tr>
<tr>
<td>22 Saray</td>
<td>87.0 ± 1.8</td>
<td>2.2</td>
<td>2</td>
</tr>
<tr>
<td>23 Servi</td>
<td>110.6 ± 1.8</td>
<td>2.8</td>
<td>3</td>
</tr>
<tr>
<td>24 Sultanbağı</td>
<td>148.1 ± 1.8</td>
<td>3.7</td>
<td>3</td>
</tr>
<tr>
<td>25 TOKI</td>
<td>97.3 ± 2.3</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>26 Vefa</td>
<td>107.1 ± 2.0</td>
<td>2.7</td>
<td>2</td>
</tr>
<tr>
<td>27 Yenidoğan</td>
<td>168.1 ± 2.4</td>
<td>4.2</td>
<td>2</td>
</tr>
<tr>
<td>28 Yıldırım Beyazıt</td>
<td>122.4 ± 0.8</td>
<td>3.1</td>
<td>12</td>
</tr>
<tr>
<td>29 Yunus Emre</td>
<td>127.8 ± 1.3</td>
<td>3.2</td>
<td>5</td>
</tr>
<tr>
<td>30 Zafertepe</td>
<td>127.6 ± 1.7</td>
<td>3.2</td>
<td>3</td>
</tr>
<tr>
<td>31 30 Ağustos</td>
<td>113.6 ± 1.6</td>
<td>2.9</td>
<td>3</td>
</tr>
<tr>
<td>32 75. Yıl</td>
<td>147.8 ± 1.4</td>
<td>3.7</td>
<td>5</td>
</tr>
<tr>
<td>33 100. Yıl</td>
<td>221.1 ± 3.8</td>
<td>5.6</td>
<td>1</td>
</tr>
</tbody>
</table>

Average 120.8 ± 2.0  3.0  100
Assessment of annual effective dose due to the indoor radon exposure

Table 1 shows the results of indoor radon concentration levels and the average annual dose measured in 33 districts of Central Kutahya in Turkey. The indoor concentration varied from $74.1 \pm 2.4$ to $272.3 \pm 4.2$ Bq m$^{-3}$, with an average value of $120.8 \pm 2.0$ Bq m$^{-3}$. The highest average belongs to the district of Gültepe, while the lowest average is in Muderris district. Moreover, the annual effective dose equivalent received by the residents in Kutahya was found to vary from 1.9 to 6.9 mSv, with an average value of 3 mSv.

Table 2
Comparison of indoor radon concentration and annual effective dose in the central Kutahya with the published results from different cities from the world [8–20]

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Dwellings</th>
<th>Radon concentrations (Bq m$^{-3}$)</th>
<th>Effective Dose (mSv y$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egypt (Alexander City)</td>
<td>56</td>
<td>44 (15–132)</td>
<td>0.75</td>
</tr>
<tr>
<td>Romania (Stei area)</td>
<td>280</td>
<td>229 (15–2650)</td>
<td>1.32–35.83</td>
</tr>
<tr>
<td>Spain (Torrelodones)</td>
<td>91</td>
<td>91 (16–366)</td>
<td>1.5–5.8</td>
</tr>
<tr>
<td>Bulgaria (Sofia City)</td>
<td>88</td>
<td>70 (20–410)</td>
<td>–</td>
</tr>
<tr>
<td>Brazil (São Paulo)</td>
<td>90</td>
<td>131 (31–615)</td>
<td>–</td>
</tr>
<tr>
<td>Saudi Arabia (Al-Madinah)</td>
<td>496</td>
<td>26</td>
<td>0.66</td>
</tr>
<tr>
<td>Portugal (Guarda)</td>
<td>185</td>
<td>860 (75–7640)</td>
<td>15</td>
</tr>
<tr>
<td>Kosovo (Planej and Gorozhup)</td>
<td>25</td>
<td>82–437</td>
<td>3.28–3.87</td>
</tr>
<tr>
<td>Maltese Islands</td>
<td>85</td>
<td>32 (11–92)</td>
<td>–</td>
</tr>
<tr>
<td>Pakistan (D.I. Khan City)</td>
<td>50</td>
<td>275–86</td>
<td>6.86–2.1</td>
</tr>
<tr>
<td>Italy (Penisola Sorrentina)</td>
<td>93</td>
<td>132 (25–722)</td>
<td>2–4</td>
</tr>
<tr>
<td>Cameroon (Poli)</td>
<td>103</td>
<td>165 (29–2240)</td>
<td>–</td>
</tr>
<tr>
<td>India (Khurja City)</td>
<td>35</td>
<td>16.02 (9.18–23.19)</td>
<td>0.47 (0.27–0.67)</td>
</tr>
<tr>
<td>Kutahya (This study)</td>
<td>100</td>
<td>121</td>
<td>3</td>
</tr>
</tbody>
</table>

It is noted that some dwellings were observed to have a radon concentration higher than 200 Bq m$^{-3}$. Significantly, the questionnaire filled out by these householders, recorded higher amounts of cigarette smoking and lower than typical ventilation. Smoking increases the concentration of airborne particles, and this affects the equilibrium ratio between radon gas and radon decay product...
concentrations. If the aerosol concentration increases, the quantity of decay products in the air and the equilibrium ratio increase [7]. Table 2 shows the comparison of indoor radon concentration and annual effective dose in the central Kutahya with the published results from different cities from the world. The highest average belongs to the city Guarda of Portugal, while the lowest average is in Khurja City in India.

4. CONCLUSION

The ICRP, an international regulatory authority in radiation protection has set an action level of 200–600 Bq m\(^{-3}\) for radon concentration in houses. Most countries have adopted an action level of about 200 Bq m\(^{-3}\). The action level for Turkey is 400 Bq m\(^{-3}\).

<table>
<thead>
<tr>
<th>Location</th>
<th>Number of Dwellings</th>
<th>Radon concentrations (Bq m(^{-3}))</th>
<th>Effective dose (mSv y(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Istanbul</td>
<td>400</td>
<td>50 (10–260)</td>
<td>0.5–13</td>
</tr>
<tr>
<td>Bayburt</td>
<td>44</td>
<td>56 (17–125)</td>
<td></td>
</tr>
<tr>
<td>Çanakkale</td>
<td>58</td>
<td>67.9 (9–300)</td>
<td>1.7</td>
</tr>
<tr>
<td>Ankara</td>
<td>167</td>
<td>38.5 (2–408)</td>
<td></td>
</tr>
<tr>
<td>Samsun</td>
<td>127</td>
<td>106</td>
<td>1.88</td>
</tr>
<tr>
<td>Kars</td>
<td>81</td>
<td>114 (24–594)</td>
<td></td>
</tr>
<tr>
<td>Bursa (Yildirim)</td>
<td>18</td>
<td>44 (13–98)</td>
<td></td>
</tr>
<tr>
<td>Batman</td>
<td>95</td>
<td>84 (23–145)</td>
<td></td>
</tr>
<tr>
<td>Kilis</td>
<td>62</td>
<td>50 (5–171)</td>
<td>1.26</td>
</tr>
<tr>
<td>Osmaniye</td>
<td>70</td>
<td>51 (6–209)</td>
<td>1.29</td>
</tr>
<tr>
<td>Antakya</td>
<td>72</td>
<td>40 (4–135)</td>
<td>1.01</td>
</tr>
<tr>
<td>Eskişehir</td>
<td>220</td>
<td>98 (19–338)</td>
<td>3.39</td>
</tr>
<tr>
<td>Ardahan</td>
<td>48</td>
<td>173 (53–736)</td>
<td>4.3</td>
</tr>
<tr>
<td>Artvin</td>
<td>73</td>
<td>132 (21–321)</td>
<td>3.3</td>
</tr>
<tr>
<td>Antalya</td>
<td>23</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>World-wide average</td>
<td>40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Kutahya (This study)**: 100 121 3.0
The observed level of the indoor radon concentration in the dwellings of Kutahya city, Turkey, varied from $74.1 \pm 2.4$ to $272.3 \pm 4.2$ Bq m$^{-3}$, with an average value of $120.8 \pm 2.0$ Bq m$^{-3}$, higher than the world average of 40 Bq m$^{-3}$. However, these values are below the recommended action level. In Table 3, these values are compared to the values reported by other studies in Turkey. The highest average belongs to Ardahan district in Kars city, while the lowest average is in Antalya city.

Consequently, indoor radon concentration in Kutahya province does not pose a radiological hazard. Occupants of these dwellings are therefore, relatively safe. The results of the present study will be a valuable database to create a complete radiological map of Turkey in the future.

Acknowledgements. This work was supported by Dumlupinar University Scientific Research project [2008–16]. The authors thank Professor Alexander Murphy for his valuable comments on the study.

REFERENCES