Effect of porosity on evaluation of radon concentration in soil samples collected from Sulaymania governorate, Iraq

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Abstract. In this study maximum concentration of radon in different location of soil samples collected from Sulaymania governorate has been determined depending on the porosity, pores in the soil, allow water and gases to flow through these media. The porosity of different soils has been determined by diffusing radon gas through these soils. The maximum values of porosity have been found in Kanikurda (0.48), but the minimum in Sheakh-mhiddin (0.40). The lower and higher values of concentration of radon have been found in Zargata (66.80 Bq m⁻³, (128.00) Bq m⁻³ in Sheakh-mhiddin. Result showed that the maximum values of specific density and bulk density have been found (1777.77, 1047.11) kg m⁻³ in Twiymallik, and minimum (1423.49, 777.22) kg m⁻³ in Malkani, respectively. Average value of specific density (1551.607 kg m⁻³, 64%) was higher than the average value of bulk density (876.4335 kg m⁻³, 36%), also the average value of maximum concentration of radon - Cmax (1813.859 Bq m⁻³, 95%) was higher than the average value of concentration of radon (98.529 Bq m⁻³, 05%).

1. Introduction

Radon is a naturally occurring radioactive gas. It originates from the decay of uranium, which is present in small quantities in all rocks and soils. Radon concentration in soil formed as a result of radioactive decay of the element uranium; radon is a colorless and odorless radioactive gas that is fairly abundant [1-3]. Radon is a radioactive gas which makes the primary contribution to the natural radiation to which people are exposed for that reason; great importance is attributed to the determination of radon concentration levels [4, 5]. Pores in the soil, sand and rocks allow water and gases to flow through these media. The porosity of different materials has been determined by diffusing radon gas through these materials. The change in the flux of the gas in the soil and sand has been measured by conducting a separate laboratory experiment for each medium based on the Solid State Nuclear Track Detection (SSNTD) technique. From the experimentally observed nuclear track density, and the porosity, of the media have been estimated with the help of an analytical model [6, 7]. Movement of radon through the earth is strongly influenced by moisture content and permeability of soil, porosity and degree of fracturing in rocks, as well as surface meteorological conditions. As a
result, the ease with which radon moves in pore spaces or fractures affects how much radon reaches
the earth's surface at any given location. Thus anomalously high concentrations of radon are often
found in soils such as that associated with geologic faults and active volcanoes [3, 8]. Radon will
transfer through the soil as "soil gas” or via water from underground supplies. The amount of radon in
the soil depends on soil chemistry. The amount of radon that escapes from the soil to enter the house
depends on the weather, soil porosity, soil moisture, and the suction within the house. The solid state
nuclear track detectors (SSNTDs)-technique is useful to investigate radon levels in different types of
soil. These levels are necessary to be known in the future planning in order to avoid indoor hazard
problems. The CR-39 plastic detector has been used in this work using a long-tube technique in order
to measure the radon concentration.

2. Characteristics of Soil

There are many properties of soil that influence the production and transport of radioactive gases
trough the soil, the one important of characteristics is porosity:
1- Porosity of Soil. 2- Grain-Size Distribution. 3- Moisture Content.
One of the factor to determin the maximum concentration of radon in the soil is porosity, therefore, to
measure the maximum concentration must be calculate, 1- The porosity of the soil samples, 2- The
specific density of the soil samples, 3- The bulk density for the soil samples 4- Concentration of radon
at the surface of the soil.

2.1. Porosity (ε)

Porosity (ε) is defined as the ratio of the pore volume to the total volume of the soil. It gives a measure
of the storage capacity of the material. The method used for determination of the total soil, porosity
was that one suggested by [9], where the total porosity of the soil can be calculated as;

\[ \text{Total porosity} = \frac{\text{Volume of pore}}{\text{Volume of soil}} \]

2.2. Specific density, Bulk density of the Soil sample

The specific density (ρs) of a material is defined as the mass per unit volume. The bulk density (ρb) of
the material shows how much soil would be packed as a whole into a specific volume. To determine
the specific density (ρs) using the following relation [10];

\[ \frac{M_w}{\rho_w} + \frac{M_s}{\rho_s} = \nu_f \]

Where:  \( M_w \) is mass of water added to soil (kg), \( M_s \) is mass of soil investigated (kg), \( \nu_f \) is measured
volume of combined soil and water (m³), \( \rho_w \) is density of water at the specific room temperature (kg
m⁻³) and \( \rho_s \) is specific density of the soil in (kg m⁻³).

As (\( \rho_s \)) calculated, the bulk density (\( \rho_b \)) can be calculated using the relation [10];

\[ \rho_b = \rho_s (1-\epsilon) \]

Specific density (\( \rho_s \)) and bulk density (\( \rho_b \)) then can be used to determine the creation rate of radon or
the integrated radon exposure.

2.3. Concentration and Emanation rate of Radon

Radon molecules can escape from grains of soil by diffusion or recoil into the soil pores. This process
is called emanation [11]. The emanation rate depends on many physical parameters. The internal soil
structure, grain size of soil, type of mineralization and the pore volume determine the value of the
emanation coefficient, defined as the fraction of the generated radon that enters the soil pores. The
emanation rate of radon from the material can be calculated from the following equation [12];

\[ V = \rho/t \]

Where \( \rho \) is the track density and \( t \) is the time of exposure.
The radon concentration in the pore space cannot be calculated unless the calibration factor is known [13]. The calibration factors for radon \( K_{\text{Radon}} = 0.025 \, \text{(track cm}^{-2}/\text{(Bq m}^{-3}\text{h}^{-1})} \). Determination of gross alpha contamination (concentration) in soil can be calculated by the following equation [14];

\[
CS (\text{Bq m}^{-3}) = K (\rho_S/T_S) \]

Where, \( \rho_S \) is track density (number of track cm\(^{-2}\)) of distributed in soil, \( T_S \) is exposure time of detectors in soil, \( K \) is calibration factor. Pico-Curies per liter (pCi \text{L}^{-1}) is a historical unit still commonly used, with 1 pCi \text{L}^{-1} = 37 \text{Bq m}^{-3} [15].

3. Maximum Concentration of Radon

The concentration at the surface is much less than the maximum constant concentration \( C_{\text{max}} \) underground. By assuming the soil is uniform and can be approximated as one-dimensional with the \( Z \)-axis originating at the surface of the soil and increase downwards. So, we have;

\[
C_{\text{Rn}} \rightarrow C_{\text{max}}(\text{Rn}) \quad \text{as} \quad Z \rightarrow \infty
\]

\[
C_{\text{Rn}} \rightarrow C_{\circ}(\text{Rn}) \quad \text{as} \quad Z \rightarrow 0 \quad (\text{at the surface})
\]

Using the relations presented and described in [10]. (Spellman, 2004) to getting the final formula and used for calculating the maximum concentration \( C_{\text{max}} \) of radon as following;

\[
C_{\text{max}} = 0.009 \, C_{\circ}(\text{Rn}) \rho_s (1 - \varepsilon)/\varepsilon \quad \text{...............................} \quad (6)
\]

The Equation (6) was determined by relations;

\[
C_{\text{max}} = S/\lambda \quad \text{..................................................(i)}
\]

\[
S = \eta \rho_s \varepsilon A_{Ra} \lambda (1 - \varepsilon)/\varepsilon \quad \text{.................................(ii)}
\]

\[
\eta = \text{RnERaC/ARa} \quad \text{..................................................(iii)}
\]

\[
\text{RnERaC} = C_{\text{Rn}}V_a/G[1-(1-e^{-\lambda t_s})/\lambda t_s]^{-1} \quad \text{.........................} \quad (\text{iii})
\]

Where, \( \eta \) = Radon emanation coefficient.

\( \rho_s \) = Specific density of the soil (kg m\(^{-3}\)).

\( \lambda \) = Radon decay constant \( (2.1 \times 10^{-6} \, \text{s}^{-1}) \).

\( A_{Ra} \) = Radium activity.

\( \varepsilon \) = Porosity of the soil.

\( S \) = Creation rate of radon.

\( \text{RnERaC} \) = The Radon Emanation\(^{226}\text{Ra} \) Concentration.

\( V_a \) = Air volume in the tube.

\( G \) = Mass of the soil samples in grams.

\( t_s \) = Exposure of time.

\( C_{\circ}(\text{Rn}) \) = Radon concentration of the soil sample.

\( C_{\text{max}} \) = Maximum concentration of radon, (Bq m\(^{-3}\)) unit.

4. Methodology

4.1. Preparation of soil samples

Twenty different soil samples were collected from the surface of the earth from different locations (20 locations) for Sulaymanya governorate. The samples were cleaned from strange things and rocks, and then the samples were dried very well at temperate of nearly 45 °C for several days in order to get rid of humidity in them. The samples were grind and pulverized several times and mixed very well by a mixer and sieved through a fine mesh (~ 0.5mm) in order to obtain a homogenous grain size
distribution powder. Each sample separated in a plastic can, labeled according to the location and sealed well and stored for about five weeks prior for farther measurements. Long-tube is a plastic cylinder, made from PVC (Poly Vinyl Chloride), in the form of cylinder of (2mm) thickness, a diameter of tube (6 cm) and long of tube (11 cm) [16] with solid state nuclear detectors (SSNTDs) of CR-39, with (2cm× 1cm) dimension. 60 gm from each soil samples for the 20 locations under the study were placed in one end of the long-tube at 11 cm at the bottom (soil samples) of the tube, one of its ends is closed and the CR-39 detector would adhere on it to detect the α-particle radiation emitted from the soil, as shown in Fig. 1.

![Figure 1. The design of tube technique to determine the concentration of radon in the soil.](image)

The samples were left at room temperature for 35 days exposure time. After exposure the detectors were etched chemically in 6.25N solution of NaOH at (70 ± 1) °C for 4.5 hours. The tracks were counted for detectors using an optical microscope. The number of tracks was measured in the area of the field view and the track density is calculated by the relation in [17].

4.2. **Porosity and the density of the soils**

Sixty grams from each soil samples was weighted and transferred to measuring volume cylinder. The mass of the soil as well as the dry volume of the soil were recorded. All of the weighted contents were then transferred to another measuring beaker containing water, the volume of water was (50 cm³), then left to stand for about an hour. The total porosity of the soil then calculated using equation (1). The measured porosity soils from different locations, as shown in Table 1.

| No. | Location          | Volume of soil (cm³) | Volume of soil and water (cm³) | Pore (vol.) of soil (cm³) | Porosity of soil (ε) |
|-----|-------------------|----------------------|--------------------------------|--------------------------|-----------------------|
| 1   | Rzgari            | 48                   | 82                             | 22                       | 0.45 ± 0.04           |
| 2   | Twiymallik        | 51                   | 85                             | 21                       | 0.41 ± 0.04           |
| 3   | Zargata           | 50                   | 81.5                           | 23.5                     | 0.47 ± 0.03           |
| 4   | Azadi             | 51                   | 84                             | 22                       | 0.43 ± 0.04           |
| 5   | Ebrahim-basha     | 50.5                 | 83                             | 22.5                     | 0.44 ± 0.04           |
| 6   | Cani-Aiscan       | 48                   | 80                             | 23                       | 0.47 ± 0.04           |
| 7   | Riayia            | 48.5                 | 83.5                           | 20                       | 0.41 ± 0.04           |
To determine the specific density ($\rho_s$), a mass of soil ($M_s$) was weighted then transferred into a measured beaker. Before that, the beaker filled up to 450 cm$^3$ of tap water [10] with mass ($M_w$) was weighted. Equation (2) has been used for calculating the specific density ($\rho_s$) for forty soil samples that presented in the Table 2. And the specific density ($\rho_s$) was calculated; the bulk density ($\rho_b$) can be calculated using equation (3), as shown in the Table 2.

| No. | Location     | (M$_s$) mass of sample (gm) | (M$_w$) mass of water (gm) | (V$_f$) volume of $W_s+ S_s$ (cm$^3$) | $\rho_s$ (kg m$^{-3}$) | $\rho_b$ (kg m$^{-3}$) |
|-----|--------------|-----------------------------|-----------------------------|-----------------------------------|----------------------|----------------------|
| 1   | Rzgari       | 40                          | 449                         | 476                               | 1481.48              | 817.77               |
| 2   | Twiymallik   | 40                          | 448.5                       | 472                               | 1777.77              | 1047.11              |
| 3   | Zargata      | 40                          | 449.0                       | 475                               | 1536.48              | 815.38               |
| 4   | Azadi        | 40                          | 448.5                       | 476                               | 1454.54              | 827.63               |
| 5   | Ebrahim-basha| 40                          | 449.2                       | 473                               | 1680.67              | 932.77               |
| 6   | Cani-Aiscan  | 40                          | 449.5                       | 475                               | 1568.63              | 817.26               |
| 7   | Riayia       | 40                          | 449.0                       | 477                               | 1428.57              | 839.99               |
| 8   | Khabat       | 40                          | 448.8                       | 476                               | 1470.59              | 817.65               |
| 9   | Kareazawshk  | 40                          | 448.9                       | 476.5                              | 1449.27              | 815.94               |
| 10  | Sarchnar     | 40                          | 449.5                       | 473.5                              | 1666.66              | 891.16               |
| 11  | Sarwari      | 40                          | 449.2                       | 475.5                              | 1520.91              | 900.38               |
| 12  | Bakhteari    | 40                          | 449.0                       | 474.5                              | 1568.63              | 919.22               |
| 13  | Hawara-barza | 40                          | 448.5                       | 476                               | 1454.54              | 840.72               |
| 14  | Malkani      | 40                          | 448.9                       | 477                               | 1423.49              | 777.22               |
| 15  | Hawari- taza | 40                          | 449.6                       | 472.5                              | 1746.72              | 957.20               |
| 16  | Beakra-jow   | 40                          | 449.5                       | 473                               | 1702.13              | 1014.47              |
| 17  | Sheakh-mhiddin| 40                         | 449.3                       | 475                               | 1556.42              | 927.62               |
| 18  | Ablilak      | 40                          | 448.0                       | 474.6                              | 1502.76              | 896.24               |
| 19  | Eiskan       | 40                          | 448.8                       | 475                               | 1526.72              | 854.76               |
| 20  | Kani-kurda   | 40                          | 449.6                       | 476.5                              | 1515.15              | 818.18               |

Mean weight=0.44±0.04

5. Result and Discussion
The diffusion of the gas radon produced in soil is different and depending on many factors; one important is the porosity of soil. In this work, the experimental procedure is preferred since it gives the more reasonable values of porosity which is very important in concentration estimation. The porosity of the all soil samples were measured in the laboratory using the experimental procedure calculated by equation (1). The experimental results are shown in the Table 1; the values of porosities are agreement with value of porosity by Kirk et al. [18]. The maximum values of porosity have been found in Kanikurda (0.48). But the minimum values of porosity have been found in Sheakh-mhiddin (0.40). The (specific and bulk) density of the soil samples have been measured experimentally by using the equations (2) and (3), the result showed the maximum values of specific density and bulk density have been found (1777.77, 1047.11) kg m⁻³ in Twiymallik and the minimum values of specific density and bulk density have been found (1423.49, 777.22) kg m⁻³ in Malkani, respectively, also the average value of specific density (1551.607 kg m⁻³, 64%) higher than the average value of bulk density (876.4335 kg m⁻³, 36%) in the same weight of soil samples, as shown in Table 2 and Figures 2, 3.

Figure 2. The relation between the specific density and bulk density of soil samples.
The lower and higher values of track density and emanation rate for radon gas have been determined for different locations (soil samples), the lower values of track density and emanation rate for radon was found in Zargata (13.99 track cm\(^{-2}\) \(\times\) 102, 1.67 track cm\(^{-2}\) h\(^{-1}\)) and the higher values of track density and emanation rate for radon (26.91 track cm\(^{-2}\) \(\times\) 102, 3.20 track cm\(^{-2}\) h\(^{-1}\)) was found in Sheakh-mhiddin, as shown in Table 3.

### Table 3. Radon Estimation in the soils samples

| No. | Location       | \(\rho_s\) (kg/m\(^3\)) | \(\rho_b\) (kg/m\(^3\)) | \text{Con. of } {}^{222}\text{Rn} \text{ Bq m}^{-3} | \text{Con. of } {}^{222}\text{Rn} \text{ pCi L}^{-1} |
|-----|----------------|--------------------------|--------------------------|---------------------------------|--------------------------|
| 1   | Rzgari         | 19.33                    | 2.30                     | 92.00                           | 2.49                     |
| 2   | Twiymallik     | 24.83                    | 2.95                     | 118.00                          | 3.19                     |
| 3   | Zargata        | 13.99                    | 1.67                     | 66.80                           | 1.80                     |
| 4   | Azadi          | 18.44                    | 2.19                     | 87.60                           | 2.37                     |
| 5   | Ebrahim-basha  | 17.65                    | 2.10                     | 84.00                           | 2.27                     |
| 6   | Cani-Aiscan    | 19.94                    | 2.37                     | 94.80                           | 2.56                     |
| 7   | Riayia         | 17.22                    | 2.05                     | 82.00                           | 2.21                     |
| 8   | Khabat         | 15.66                    | 1.86                     | 74.40                           | 2.01                     |
| 9   | Kareazawskh    | 21.32                    | 2.53                     | 101.20                          | 2.73                     |
| 10  | Sarchnar       | 23.05                    | 2.74                     | 109.60                          | 2.94                     |
| 11  | Sarvari        | 20.55                    | 2.45                     | 98.00                           | 2.65                     |
| 12  | Bakhteari      | 20.94                    | 2.49                     | 99.60                           | 2.69                     |
| 13  | Hawara-barza   | 18.59                    | 2.21                     | 88.40                           | 2.39                     |
| 14  | Malkani        | 19.55                    | 2.33                     | 93.20                           | 2.52                     |
| 15  | Hawari- taza   | 18.38                    | 2.18                     | 87.20                           | 2.35                     |
| 16  | Beakra-jow     | 24.08                    | 2.98                     | 119.43                          | 3.23                     |
| 17  | Sheakh-mhiddin | 26.91                    | 3.20                     | 128.00                          | 3.46                     |
| 18  | Abllakh        | 23.55                    | 2.80                     | 112.00                          | 3.03                     |
| 19  | Eiskan         | 22.65                    | 2.69                     | 107.60                          | 2.91                     |
| 20  | Kani-kurda     | 22.16                    | 2.63                     | 105.52                          | 2.85                     |
The lower and higher values of concentration in Bq m\(^{-3}\) for radon have been calculated for different locations (soil samples), the lower values of concentration for radon was found in Zargata (66.80 Bq m\(^{-3}\)), and higher values of concentration for radon was found (128.00) Bq m\(^{-3}\) in Sheakh-mhiddin. The maximum concentration of radon has been estimated through the values of the soil porosity, the specific density, bulk density and the concentration of radon for each soil sample, using the Equation 7. The high concentration of radon estimated are given in Table 4 and Figures 4, 5, was lower than maximum concentration of radon, also the average value of maximum concentration of radon - \(C_{\text{max}}\) (1813.859 Bq m\(^{-3}\)), 95% was higher than the average value of concentration of radon (98.529 Bq m\(^{-3}\), 05%) in the same weight of soil samples.

**Table 4.** The maximum concentration of radon in the soil samples.

| No. | Location       | Cons of Radon Bq m\(^{-3}\) | Cons of Radon Bq m\(^{-3}\) |
|-----|----------------|-------------------------------|-------------------------------|
| 1   | Rzgari         | 92.00                         | 1511.42                       |
| 2   | Twymallik      | 118.00                        | 2705.66                       |
| 3   | Zargata        | 66.80                         | 1030.51                       |
| 4   | Azadi          | 87.60                         | 1513.93                       |
| 5   | Ebrahim-basha  | 84.00                         | 1521.91                       |
| 6   | Cani-Aiscan    | 94.80                         | 1455.70                       |
| 7   | Riayia         | 82.00                         | 1504.65                       |
| 8   | Khabat         | 74.40                         | 1233.10                       |
| 9   | Kareazawshk    | 101.20                        | 1700.59                       |
| 10  | Sarchnar       | 109.60                        | 1891.47                       |
| 11  | Sarwari        | 98.00                         | 1946.41                       |
| 12  | Bakhteari      | 99.60                         | 1990.30                       |
| 13  | Hawara-barza   | 88.40                         | 1585.02                       |
| 14  | Malkani        | 93.20                         | 1732.50                       |
| 15  | Hawari-taza    | 87.20                         | 1661.97                       |
| 16  | Beakra-jow     | 119.43                        | 2699.06                       |
| 17  | Sheakh-mhiddin | 128.00                        | 2645.11                       |
| 18  | Abllakh        | 112.00                        | 1929.19                       |
| 19  | Eiskan         | 107.60                        | 1735.60                       |
| 20  | Kani-kurda     | 105.52                        | 1527.91                       |

**Figure 4.** The relation the concentration and maximum concentration of radon in the soil and number of location under study.
The porosity of these materials is found to be in good agreement with the data presented in [18]. The integrated radon exposure depends strongly on the density and the porosity of the soil, radon moving through soil pore spaces and rock fractures near the surface of the earth usually escapes into the atmosphere. Where a house or other building is present, however, radon may migrate into these structures, and accumulate indoors in sufficient quantities to pose a health hazard [19]. An increase in the porosity will provide more air space within the concrete for radon travel, thus reducing its resistance to radon transport. An increase in porosity results in the size or quantity of void spaces available for air flow [20].

6. Conclusions
This study presented to determine radon concentration of the soil at the surface and underground. The diffusion of the gas radon produced in soil is different and depending on many factors; one important is the porosity of soil. The maximum values of porosity have been found in Kanikurda (0.48). But the minimum values of porosity have been found in Sheakh-mhidddin (0.40). The integrated radon exposure depends strongly on the density and the porosity of the soil, they used in the estimation of the maximum concentration of radon.

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