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Original Article

Indoor radon and thoron from building materials: Analysis of humidity, air exchange rate, and dose assessment

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ABSTRACT

Building materials contribute significantly to the indoor radon and thoron levels. Therefore, parameters that influence the exhalation rates of radon and thoron from building material need to be analyzed closely. As a preliminary study, the effects of humidity on exhalation rates were measured using a system with an accumulation chamber and RAD7 detector for Korean brick, Korean soil, and Indonesian brick. Resulting doses to a person who resides in a room constructed from the building materials were assessed by UNSCEAR method for different air exchange rates. The measurements have revealed that Korean brick exhaled the highest radon and thoron while Indonesian brick exhaled the lowest thoron. Results showed that for a typical low dense material, radon and thoron exhalation rate will increase until reached its maximum at a certain value of humidity and will remain saturated above it. Analysis on concentration and effective dose showed that radon is strongly affected by air exchange rate (ACH). This is showed by about 66 times decrease of radon dose from 0.00 h^{-1} to those of 0.50 h^{-1} ACH and decrease by a factor of 2 from 0.50 h^{-1} to those of 0.80 h^{-1}. In case of thoron, the ACH doesn't have significant effects on effective dose.

1. Introduction

Radon (^{222}Rn) and thoron (^{220}Rn) are the two most well-known isotopes of radon which are decay products of radium and thorium, respectively. Both are significant contributors in indoor radiation. They show huge variations in their existing levels in the environment. IAEA has specified and put them in the scope of natural sources of radiation for some specific provisions which exclude workplaces having planned exposure situation for uranium and thorium progeny and some specific buildings with high dwelling time for public [1].

In a microstructure level, most radon emerges on mineral surface layer and it can release from its initial grain locations. In some way they can emanate into spaces among the grains. The motion of the radon gas mainly depends on diffusion and advection on the atomic level and they fill pore spaces inside the material structure. In time, some of the radon gas will drift through the holes in the grain boundaries and then releases to the atmosphere. The characterization of this transfer process is crucial for the understanding of the following fate of the radioactive rare gas: either as trace substance distributed in the atmosphere or as build up impurity in the indoor environment [2].

The location of radon atoms released from radium atoms in a material is mainly divided into three cases. First, radon is produced from a radium atom that is present inside the grain and then terminates its path. Second, when radon is produced from area between grains in which radium exists, and the third is when radon terminate its path in an air gap inside grains. In this case, radon in the first case cannot be spread because it does not have a diffuse pathway, whereas in the second and third cases, radon pathways are nearly connected to the air gap, so it is possible to spread. The third case becomes important, when the gap is made up of water or air. When radon passing through air-filled pore, it is more frequent to bounce through the pore and into other areas. However, if water passes through an air-filled gap, the probability of radon to travel can be higher than in the air-filled gap, since water as a fluid can bring radon atom together with their flow. Therefore, the higher

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the moisture content of the air gap in the material, the higher the radon emission rate of the material [3]. More recent research tried to analyze radon exhalation rate variation with building material's granular size [4].

Researches on indoor radon concentration in relation to meteorological and atmospheric parameters had been done by many researchers and some characteristic of radon variation were tried to be inspected [5–8]. The observation told that temperature and porosity might have an influence on indoor radon values.

Even though the influence of humidity had been estimated, variation of indoor radon and thoron exhalation had been found in some specific samples [9,10]. Reverse effect of ventilation and temperature gradient on indoor equilibrium factor had been also numerically inspected [11].

Recently, pattern between indoor radon concentration and earthquake distribution were tried to be observed by some researchers and resulting an interesting hypothesis on possibility to predict low magnitude earthquake [12].

When relative humidity of the atmosphere is increased, the water percentage in the air is also increased and it will trigger higher deposition of vaporizers on indoor building surfaces. Consequently, it will decrease the ^{222}Rn and ^{220}Rn emanation rates and reduce the gas concentrations [13]. However, various values of radon and thoron in the environment indicates that the characteristics and influencing parameters of radon and thoron have not clearly found yet. In this current research, different values of humidity will be applied and their effect to ^{222}Rn and ^{220}Rn exhalation rate from building materials will be closely investigated. For further research, the influence of air exchange rate and the behavior of annual effective dose as a representative of radiological risk will be studied.

A German case control study on indoor radon [14] and the miners data extracted by extrapolation revealed that indoor radon exposure for some extent contributes to the lung cancer risk in a general population. Even though it cannot be ascertained how significant the influence of ^{222}Rn and ^{220}Rn on lung cancer, a more in-depth study of the exhalation of ^{222}Rn and ^{220}Rn especially inside room still needs to be done to dig deeper information considering that nowadays about 80% of human time is in room.

To get more information and higher benefit, three different building materials from Indonesia and Korea were chosen. Low dense Korean Hwangto brick made from clay, which is usually used to construct Korean houses; Korean Hwangto soil, which is usually used to plaster sauna house wall; and high dense fired type brick from Indonesia were chosen. Indonesia is an archipelago country that has more than 17,000 islands with one third of its territory is water [15]; while Korea is a subtropical country with land as its main territory. Various radon exposure in some geological characteristics, altitude variations, and earthquake prone areas have been studied by researchers [16].

The behavior characteristic of radon is influenced by many other parameters and many researches still cannot confirm it clearly. Therefore, to examine more deeply the parameters that affect radon derived from building materials, the analysis of the influence of humidity and air exchange rate was carried out in this current research. Furthermore, effective dose assessment came from radon and thoron were done to disclose radiological risk of them.

2. Materials and methods

2.1. Exhalation measurement

The rate of exhalation of ^{222}Rn and ^{220}Rn has been obtained by the technique of accumulation in sealed chamber equipped with RAD7. Before conducting measurement, the building materials were dried at 110 °C for about 48 h to remove the moisture. Later, all samples were immediately kept in a closed plastic bag for about thirty days to let them reach equilibrium. The properties of all samples were shown in Table 1.

The chamber of 30 × 30 × 30 cm has been constructed and characterized to be tight from leakage. To keep RAD7 in its dryness range, a desiccant was installed to the system between RAD7 inlet and the accumulation chamber. The smaller desiccant was chosen to compensate ^{220}Rn measurement. When the pump run, the same air will circulate repeatedly through the desiccant. This procedure will efficiently remove residual moisture from the RAD7. This does not introduce any fresh air, and so does not change the ^{222}Rn level in the instrument [17]. If the laboratory drying unit was used instead of the small drying tube, it created additional sampling delay, which allowed more of the ^{220}Rn to decay before reaching the RAD7, reducing the sensitivity of the measurement to about half that of the standard setup. Fig. 1 shows the experimental scheme for the exhalation measurement.

In a transport process of porous materials, diffusion parameters such as sample thickness, z_0, and diffusion length, l_0, may influence indoor radon concentration. In a specific case consider that sample thickness is very small against diffusion length, $z_0 \ll l_0$, free exhalation, E, is not dependent on the diffusion length, but only on sample characteristics, in this case, surface area of the samples, S [18]. Typically, the diffusion length in porous material is above 0.25–0.30 m range [19,20]; this approximation will be applicable to a sample thickness of less than 0.05 m (note that the samples in this study are 0.024, 0.05, and 0.01 m, respectively).

Radon accumulation (C_{Rn}^{a}) inside chamber as a function of time is given as a combination of radon exhalation rate and removal rate as follow [18]:

$$\frac{dC_{Rn}^{a}}{dt} = \frac{Exh \cdot S}{V_c} + C_{Rn}^{B}\lambda_w - \lambda_{eff} \cdot C_{Rn}^{a} \tag{1}$$

In this equation, C_{Rn}^{B} is average background air radon, V_c is the chamber volume (m^3) and λ_{eff} is effective removal rate of radon. In chamber measurement, $\lambda_{eff} = \lambda + \lambda_b + \lambda_w$, where λ_b is radon back diffusion rate and λ_w is leakage rate (h^{-1}). The solution of the equation with boundary condition $C_{Rn}^{a}(0) = C_{Rn}^{0}$ is

$$C_{Rn}^{a}(t) = C_{Rn}^{0} \cdot e^{-\lambda_{eff} \cdot t} + \left(\frac{Exh \cdot A}{\lambda_{eff} \cdot V_c} + \frac{C_{Rn}^{B}\lambda_v}{\lambda_{eff}}\right)\left(1 - e^{-\lambda_{eff} \cdot t}\right) \tag{2}$$

considering that volume of samples is less than 10% of chamber volume and the chamber volume is much bigger than 1 L, than radon back diffusion can be assumed to be negligible [21,22]. Assuming the chamber is tight enough, the background radon should not affect radon inside chamber. The saturated radon concentration then can be stated as

$$\frac{Exh \cdot A}{\lambda_{eff} \cdot V_c} = C_{Rn}^{sat} \tag{3}$$

Considering the short half-life of ^{220}Rn, 10 min cycle time was set for 2 h measurement time. The measurement was performed in an air-conditioned room of about 23 °C and a specified value of relative humidity. To study the influence of humidity to exhalation rate, the measurement was performed in a range of humidity of 30–80%.

To get and control the needed humidity value, a different system loop was made. External controlled pump was installed between the accumulation chamber and Erlenmeyer flask. By pump assistance, the air flow rate and the homogeneity of the air environment

Table 1
Properties of building material samples.

Material	Type	Main contents	Dimension/size
Korean Brick	Mudbrick (humidity 55–60%)	silica, alumina, iron oxide	25 × 14 × 2.4 cm
Indonesian Brick	Fired brick	silica, alumina, iron oxide	21.5 × 9 × 5 cm
Korean Clay Soil	Clay	alumina, iron oxide, H_2O	600 g, $z_0 = 1$ cm

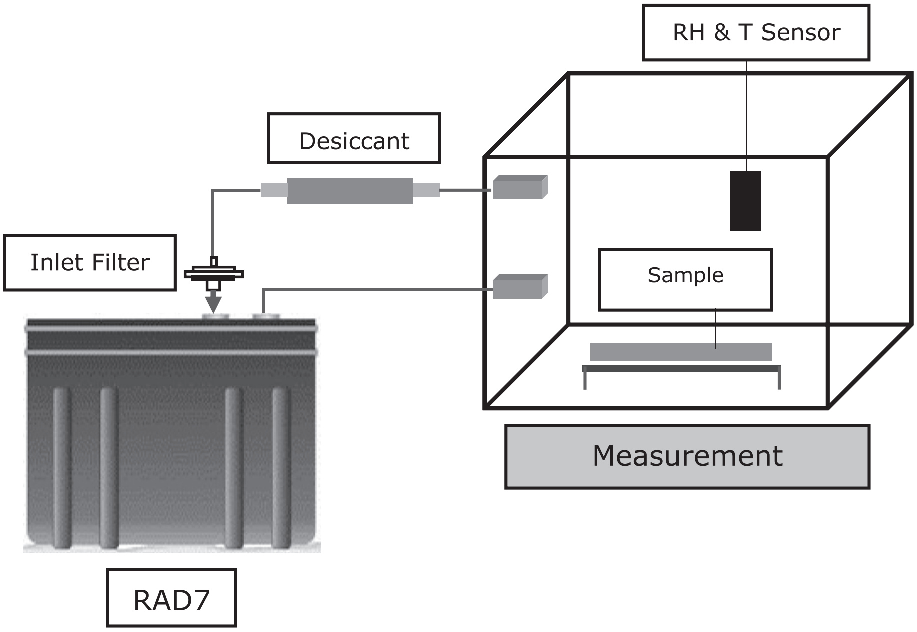

Fig. 1. System of an accumulation chamber and RAD7 detector for exhalation measurement.

can be maintained. Heated water in the flask was used as a supporting device to produce more vapor and increase the air humidity in case the pump was not strong enough to reach high humidity. Another purpose of this humidity system loop is to ensure the sample is exposed to the effects of air humidity. Therefore, the sample was stored inside the chamber with certain value of humidity for about 24 h before measured by RAD7. The humidity system is shown in Fig. 2.

Air exchange rate (ACH) is a function of air flow rate in comparation to chamber capacity that can compensate air inside it. Mathematically, it can be written as follow:

$$ACH = \frac{Air\ Flow\ Rate \bullet 60}{V_c} \tag{4}$$

where ACH is in h^{-1}, air flow rate is air that flow in and outside of the chamber ($L \bullet min^{-1}$), and V_c is chamber volume (L). By installing flow meter at the outflow path of chamber, the air flow rate can be measured easily. The change of radon concentration can be inspected by varying the ACH values using the controlled pump.

2.2. Dose assessment

In steady condition, ^{222}Rn and ^{220}Rn concentration caused by exhalation in indoor environment is influenced by the volume that is consumed by air, surface area that emit ^{222}Rn and ^{220}Rn, and air exchange rate that flows in and out of the room.

Measurements of average air exchange rate in residential room in three metropolitan cities of US was found to be between 0.61 and 0.88 h^{-1} [23]. In this research, it was assumed that the average air exchange rate is 0.80 h^{-1}, and the assessment was done in some variations from 0.00 to 0.80 h^{-1}. The relation between ^{222}Rn and ^{220}Rn concentration and their exhalation rate can be showed by the following formula [13,18]:

$$C_{Rn} = (Exh \times A) / ((\lambda + \lambda_W) \times V) \tag{5}$$

where A is the surface area considered to exhale ^{222}Rn and ^{220}Rn, which is assumed to be 22.90 m^2 in this scenario (about 40% of all room surfaces); λ_W is air removal rate due to exchange rate; and V is air volume of the room. In this assessment, it was simulated a room with 4.5 × 4 × 2.5 m in size and it was assumed the air volume is 80% of all total volume, thus it will be 36 m^3.

The annual effective dose resulted from indoor exposure is influenced by radon concentration (C_{Rn}), equilibrium factor (*F*, which is set to be 0.40 for ^{222}Rn and 0.02 for ^{220}Rn according to UNSCEAR research), and dwelling time in the room ($T = 7008$ h, assuming average human time is 80% inside rooms). The formula can be written as follows:

$$Dose = C_{Rn} \times F \times T \times EEC \tag{6}$$

where EEC is equilibrium-equivalent concentration to effective dose conversion (9 × 10^{-6} mSv y^{-1} per Bq m^{-3} for ^{222}Rn and 40 × 10^{-6} mSv y^{-1} per Bq m^{-3} for ^{220}Rn).

3. Results and discussion

3.1. Radon and thoron accumulation profile

Theoretically, ^{222}Rn has a specific characteristic of buildup called

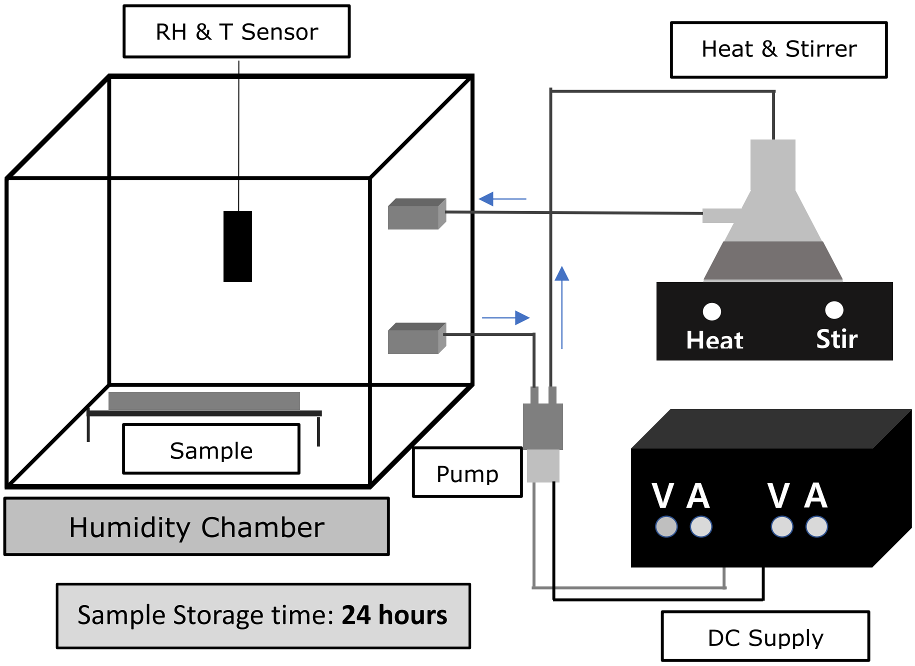

Fig. 2. System of humidity control for building material samples.

secular equilibrium. It is a situation where the parent nuclide, ^{226}Ra, has a very long half-life, and the product activity will grow to a level that is essentially identical to that of the parent [24]. the activity of ^{222}Rn reaches equilibrium with ^{226}Ra activity after about 6.7 half-lives [25]. Since the characteristic buildup curve of radon is already known, we can estimate radon value even before it reaches its 6 half-lives.

By inspecting the change of concentration continuously within time, RAD7 can assess and shows ^{222}Rn and ^{220}Rn concentration profile. If a sample is put into the accumulation chamber, the ^{222}Rn will exhale from it and the concentration will increase exponentially until it considered to reach its saturated region.

In case of ^{220}Rn, the concentration can reach stable condition very quickly just after the measurement was starting. The short half-live of thoron has limited the possibility of it to build up. The typical ^{222}Rn and ^{220}Rn profile in elapsed time, which is strongly related to their characteristic of half-life, can be seen in Fig. 3.

This ^{222}Rn and ^{220}Rn concentration profile confirms the advantage of RAD7 which is able to distinguish the different alpha-emitting daughters by their alpha energy.

Even though RAD7 has a significant advantage regarding its ability to do simultaneous measurement of ^{222}Rn and ^{220}Rn and relatively accurate in short measurement of ^{222}Rn and ^{220}Rn, analyzing the influence of air humidity to ^{222}Rn and ^{220}Rn exhalation rate is quiet challenging. Its basic measurement system that needs very low instrument humidity to maintain ^{222}Rn and ^{220}Rn counting results (below 10%), has caused this to be a contradictory obstacle to the research objective, investigating the effects of relative humidity on exhalation.

Separate system between radon exhalation measurement and humidity control explained in materials and methods section has been conducted successfully to avoid the problem of contradiction.

From the result of RAD7 measurement, we can conclude that the ^{222}Rn and ^{220}Rn measured profiles were satisfying the theoretical perspective of ^{222}Rn and ^{220}Rn.

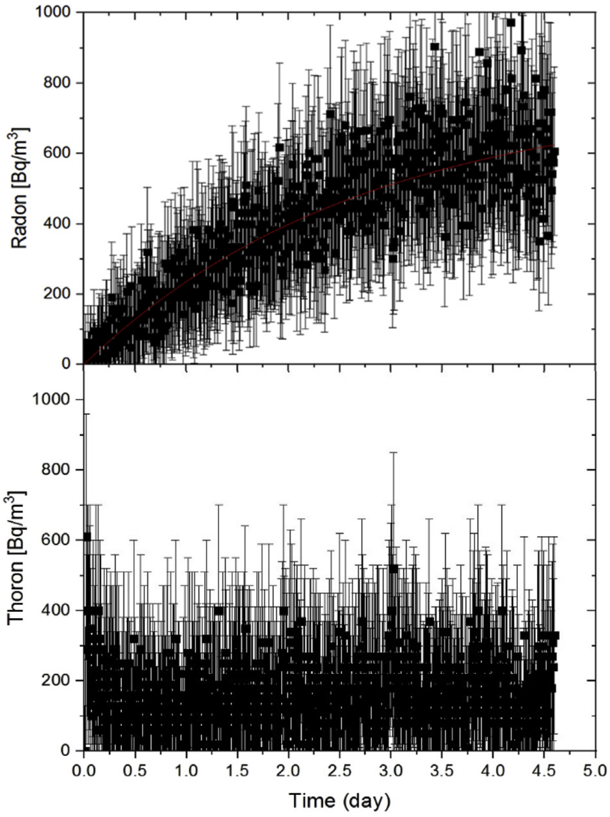

Fig. 3. Radon and thoron concentration as a function of time in an accumulation chamber.

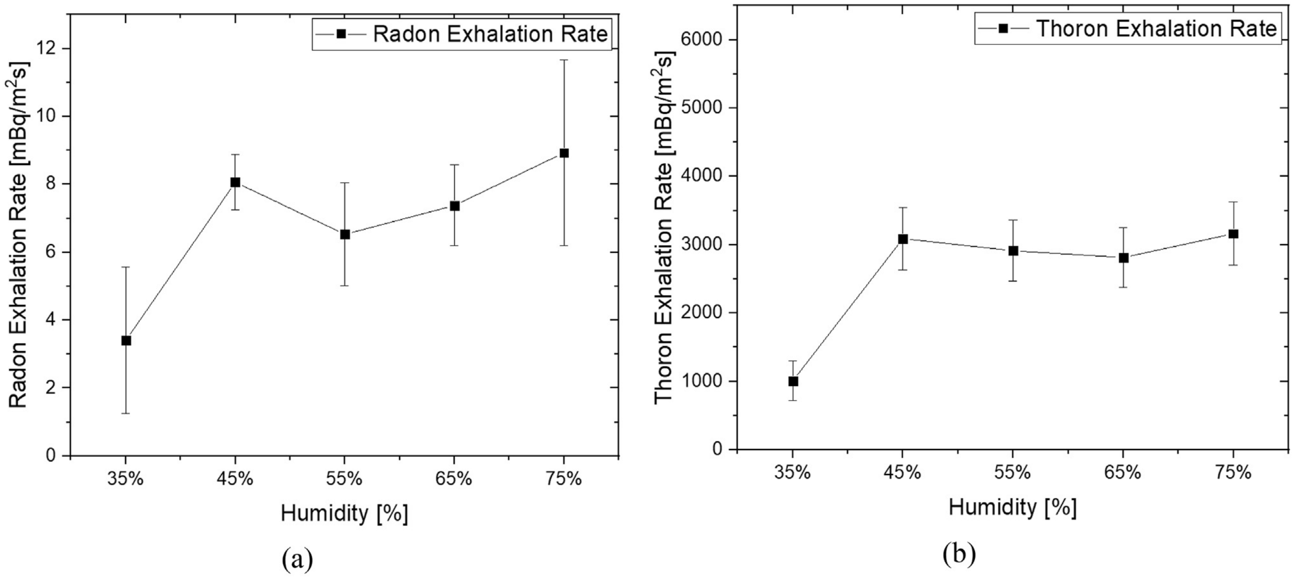

Fig. 4. Radon (a) and thoron (b) exhalation rate of Korean brick in various level of air humidity.

3.2. Humidity influence on radon and thoron exhalation rate

The effect of the humidity on exhalation rates for the three different building materials – Korean Hwangto brick, Indonesian brick, and Korean Hwangto soil can be seen in Figs. 4–6 for radon and thoron, respectively. The highest radon exhalation rate was found from the Korean brick, while the Korean soil was found to be the lowest. From the figures it can be inferred that for typical low dense material, radon and thoron exhalation rate will increase until a certain value of humidity and finally find its saturation region. For Korean brick, the maximum exhalation rate was reached at humidity of 45%. In case of Korean soil, the exhalation rate increased slower than that of Korean brick and reached its maximum at 65% humidity. Slower increase of Korean soil exhalation rate might be caused by the different structure of its grain size than Korean brick. Air humidity might only deposit and influence thin surface of Korean brick while it might gradually infiltrate deeper surface of Korean soil. For Indonesian brick, the radon exhalation rate resulted from the measurement was decreasing until minimum on 55% of humidity and then increasing again above the value. The decreasing trend might occur due to aerosol barrier caused by increasing humidity before it can release from grain boundaries. In case of thoron, the very low exhalation resulted made it difficult to inspect the trend.

Main difference among radon experiments usually lies in several things such as accumulation chamber volume, detectors, measurement methods, inspected parameters, and the type of samples. Considering experimental situations and conditions involved, this experimental result was analyzed and compared to other experiments. In general, it can be concluded that the results of this study are quite similar to the results of other studies [13,26]. Even though it has similar trend, the results of Janik did not show strong changes on the exhalation rate. This might be caused by the use of a very large chamber volume. In this research, a tight and

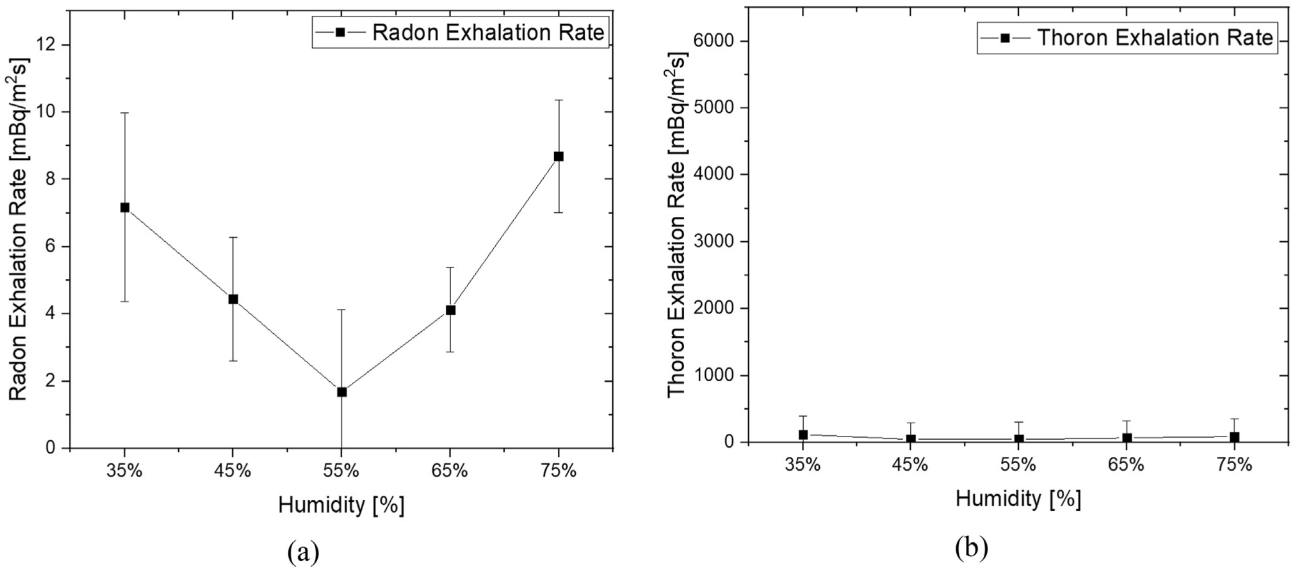

Fig. 5. Radon (a) and thoron (b) exhalation rate of Indonesian brick in various level of air humidity.

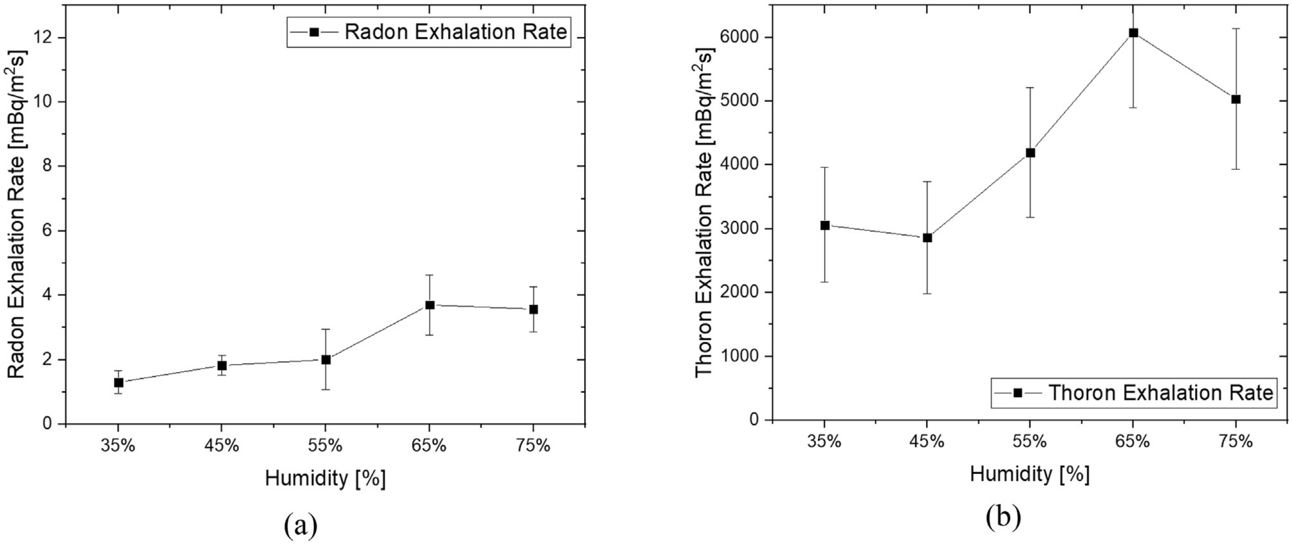

Fig. 6. Radon (a) and thoron (b) exhalation rate of Korean soil in various level of air humidity.

small chamber was used to ensure that the exhalation measured by RAD7 was an exhalation that really came from the sample.

The effect of humidity can be explained from a microstructural perspective. The increase of humidity will increase aerosol existence on the surface of the sample which form a thin coating on grain surface at a certain value of humidity. A thin coating in pore spaces between grains can increase the direct-recoil fraction relative to air-filled pores because of the shorter recoil distance in water. However, if the humidity is increased more the thicker coating will reduce the radon diffusion [27].

In case of Indonesian brick, very low exhalation of thoron was observed. In a solid material, thoron exhalation mainly depends on the structure characteristic of the sample materials. From the results, it can be concluded that the Indonesian brick has relatively tight and dense structure inside which reduce the possibility of thoron to release to the atmosphere. This result confirms that the porosity of Indonesian brick is lower than those of Korean brick and soil.

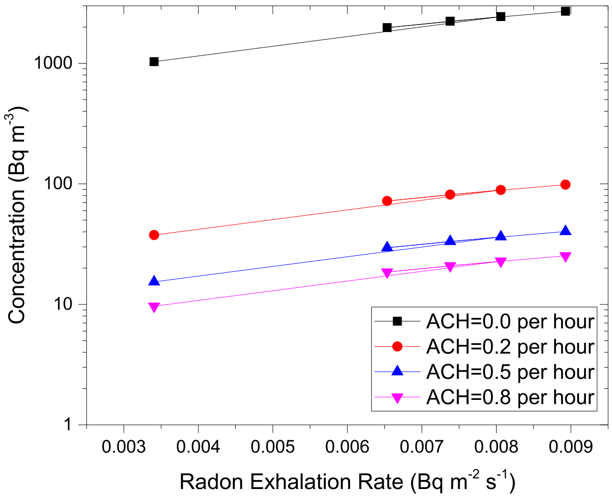

Fig. 7. The influence of air exchange rate to radon concentration in Korean Hwangto brick.

3.3. Air exchange rate influence on radon and thoron

Inspecting Fig. 7, the influence of air exchange rate to the concentration of radon can be inspected. In a chamber or room, radon exhalation rate mainly depends on the chamber air volume, surface of possible radon source, concentration of radon, and effective decay constant of radon. The effective decay constant may include radon decay constant and air exchange rate of the chamber. The small decay constant of radon and the big air exchange rate has caused the dependence of the system to the air exchange rate.

It can be seen from Fig. 7, with the same value of radon exhalation rate, concentration of radon will be very high if there is no ventilation in the room. It was caused by the accumulation of radon inside the room without possibility to come out before its decay. In addition, with 0.2 h^{-1} air exchange rate, the concentration of radon falls about 27 times from those of 0.0 h^{-1}. We can conclude that the bigger air flow in and out of the room the lower the ability of radon to accumulate.

In case of thoron, its short half life has caused it to have a big decay constant. Consequently, air exchange rate doesn't have much effect on its effective decay constant. With the same room condition, Fig. 8 shows that the concentration of thoron doesn't change much at any air exchange rate value. On the graph, it can be seen that the concentration values at different air exchange rate values are almost overlapping. It can be said that thoron has low ability to accumulate, with or without air flow in and out of the room.

3.4. Dose assessment of radon and thoron

From Table 2 and Table 3, observation results of annual effective dose resulted from some ^{222}Rn and ^{220}Rn exhalation values are emerged and their relationship with the change of air exchange rate are investigated.

Currently, the world average natural effective dose is considered about 2.4 mSv y^{-1} [28]. With 52% global natural radiation comes from radon, about 1.25 mSv respectively, it is confirmed that radon is one of the biggest contributors. ICRP recommendation of radon lower limit (3–10 mSv y^{-1}) is referred to assess the obtained value [29].

By applying UNSCEAR formula to analyze the annual effective dose received by humans from measured radon concentrations

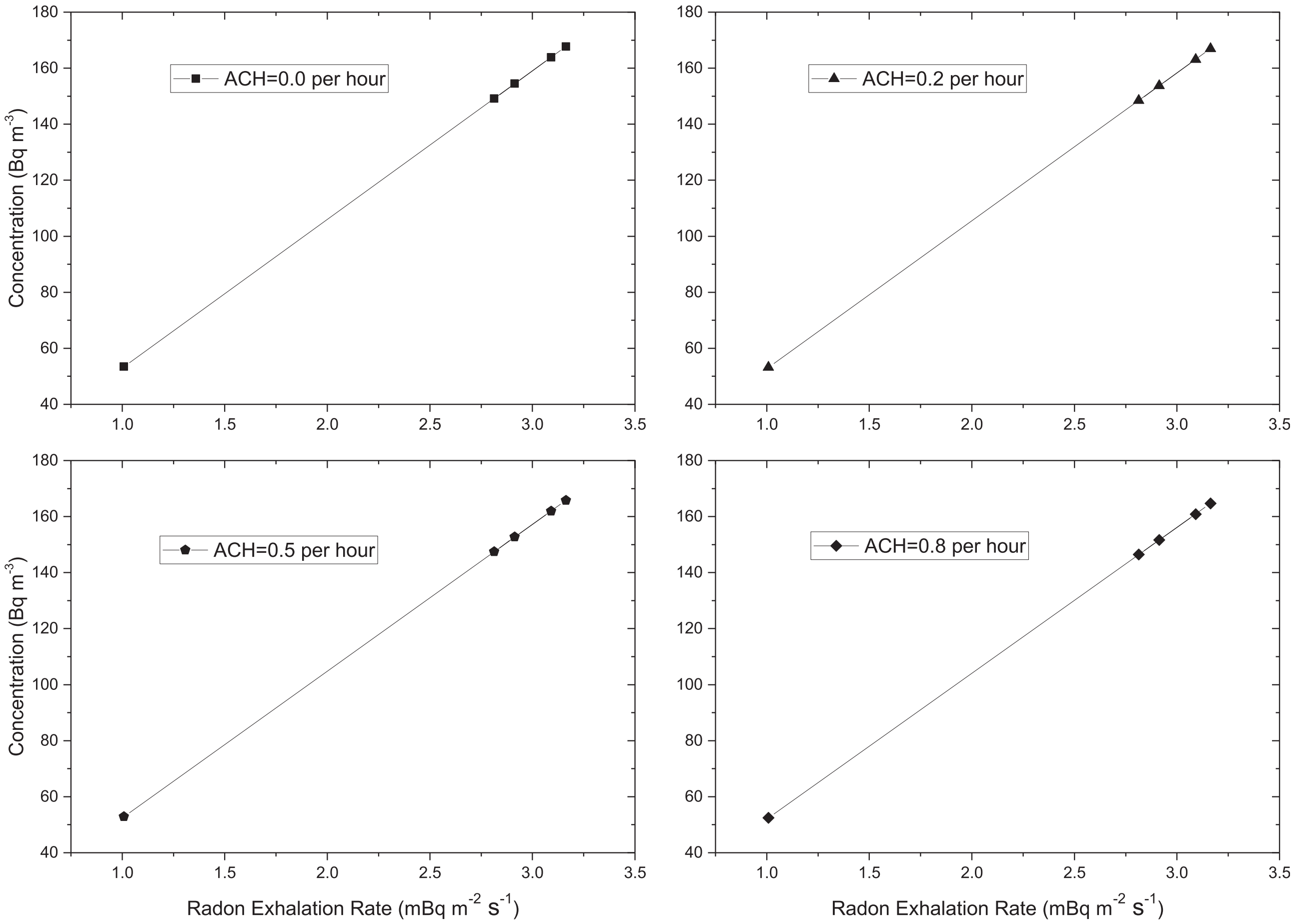

Fig. 8. The influence of air exchange rate to thoron concentration in Korean Hwangto brick.

Table 2
Radon concentration and effective dose of building materials calculated for different humidity, exhalation, and air exchange rate.

Material	RH (%)	Exhalation rate (mBq.m^{-2}. s^{-1})	Concentration (annual effective dose) Bq.m^{-3} (mSv. y^{-1})		
			Air exchange 0.0 h^{-1}	Air exchange 0.5 h^{-1}	Air exchange 0.8 h^{-1}
Korean Brick	35	3.41 ± 2.15	1032.01 (26.04)	15.37 (0.39)	9.66 (0.24)
	45	8.06 ± 0.81	2441.46 (61.59)	36.36 (0.92)	22.86 (0.58)
	55	6.53 ± 1.52	1979.21 (49.93)	29.48 (0.74)	18.53 (0.47)
	65	7.38 ± 1.19	2235.78 (56.41)	33.3 (0.84)	20.93 (0.53)
	75	8.93 ± 2.74	2704.38 (68.23)	40.28 (1.02)	25.32 (0.64)
Indonesian Brick	35	7.17 ± 2.80	2171.86 (54.79)	32.35 (0.82)	20.33 (0.51)
	45	4.44 ± 1.83	1345.63 (33.95)	20.04 (0.51)	12.60 (0.32)
	55	1.69 ± 2.44	510.64 (12.88)	7.61 (0.19)	4.78 (0.12)
	65	4.13 ± 1.26	1250.30 (31.54)	18.62 (0.47)	11.70 (0.30)
	75	8.69 ± 1.68	2633.19 (66.43)	39.22 (0.99)	24.65 (0.62)
Korean Clay Soil	35	1.30 ± 0.35	393.78 (9.93)	5.87 (0.15)	3.69 (0.09)
	45	1.82 ± 0.30	551.30 (13.91)	8.21 (0.21)	5.16 (0.13)
	55	2.00 ± 0.93	605.82 (15.28)	9.02 (0.23)	5.67 (0.14)
	65	3.70 ± 0.94	1120.77 (28.28)	16.69 (0.42)	10.49 (0.26)
	75	3.57 ± 0.69	1081.39 (27.28)	16.11 (0.41)	10.12 (0.26)

inside the room using the sample, characteristics of ^{222}Rn and ^{220}Rn in indoor environment can be known and examined.

For the most extreme case, a room without air exchange rate (ACH = 0.00 h^{-1}), the highest effective dose received by human due to indoor radon was obtained from Korean brick, which was about 68.23 mSv y^{-1}. It can be inferred that without ventilation, radon can accumulate and give a very high exposure to population. When air exchange rate was increased to be 0.50 h^{-1}, the effective dose decreased significantly to about 1.02 mSv y^{-1}, which is already below world average radon value. And if the air exchange rate was increased again to be 0.80 h^{-1}, the effective dose will decrease more to be about a half of those of 0.50 h^{-1}, to become 0.64 mSv y^{-1}. From the obtained results, it can be concluded that air ventilation can reduce the effective dose caused by indoor radon very effectively.

In case of thoron, the highest effective dose due to indoor thoron also came from Korean brick, which was about 0.94 mSv y^{-1}, with

Table 3
Thoron concentration and effective dose building materials calculated for different humidity, exhalation, and air exchange rate.

Material	RH (%)	Exhalation rate (mBq.m^{-2}. s^{-1})	Concentration (annual effective dose) Bq.m^{-3} (mSv. y^{-1})		
			Air exchange 0.0 h^{-1}	Air exchange 0.5 h^{-1}	Air exchange 0.8 h^{-1}
Korean Brick	35	1008.51 ± 289.45	53.46 (0.30)	52.85 (0.30)	52.49 (0.29)
	45	3090.99 ± 458.90	163.85 (0.92)	161.98 (0.91)	160.87 (0.90)
	55	2913.93 ± 444.09	154.47 (0.87)	152.7 (0.86)	151.66 (0.85)
	65	2813.84 ± 439.31	149.16 (0.84)	147.45 (0.83)	146.45 (0.82)
	75	3164.13 ± 462.44	167.73 (0.94)	165.81 (0.93)	164.68 (0.92)
Indonesian Brick	35	120.26 ± 11.86	6.37 (0.04)	6.30 (0.04)	6.26 (0.04)
	45	45.09 ± 10.71	2.39 (0.01)	2.36 (0.01)	2.35 (0.01)
	55	45.09 ± 10.91	2.39 (0.01)	2.36 (0.01)	2.35 (0.01)
	65	67.65 ± 10.97	3.59 (0.02)	3.55 (0.02)	3.52 (0.02)
	75	90.19 ± 11.43	4.78 (0.03)	4.73 (0.03)	4.69 (0.03)
Korean Clay Soil	35	3060.79 ± 52.32	162.25 (0.91)	160.39 (0.90)	159.30 (0.89)
	45	2859.89 ± 51.03	151.60 (0.85)	149.87 (0.84)	148.84 (0.83)
	55	4195.29 ± 59.03	222.39 (1.25)	219.84 (1.23)	218.35 (1.22)
	65	6074.32 ± 68.49	322.00 (1.81)	318.31 (1.78)	316.14 (1.77)
	75	5034.36 ± 63.93	266.87 (1.50)	263.81 (1.48)	262.02 (1.47)

0.0 h^{-1} air exchange rate. Even without ventilation, thoron gave a very low contribution to the indoor exposure which is already below world average value. A big decay constant of thoron has made air ventilation not so influential in reducing thoron exposure. The short half-life of thoron also makes it difficult to accumulate inside a room. The proof can be seen on the effective dose of 0.50 and 0.80 h^{-1} air exchange rates. At 0.50 h^{-1} air exchange rate, the effective dose due to indoor thoron was about 0.93 mSv y^{-1}; while at 0.80 h^{-1}, it resulted 0.92 mSv y^{-1}. From all effective dose obtained from three different value of ACH (0.00, 0.50, and 0.80 h^{-1}), it was found almost the same value of effective dose, which was 0.94, 0.93, and 0.92 mSv y^{-1} respectively. In other words, the change of air exchange rate does not change the effective dose caused by indoor thoron exposure at all.

Even though thoron is relatively inert to ACH, thoron can still be a big concern if the building material used originally contains high thorium concentration. In this case, the thoron value may provide high indoor exposure.

4. Conclusions

Building materials contribute significantly to the indoor radon and thoron levels. Therefore, parameters that influence the exhalation rates of radon and thoron from building material need to be analyzed closely. As a preliminary study, the effects of humidity on exhalation rates were measured using a system with an accumulation chamber and RAD7 detector for Korean brick, Korean soil, and Indonesian brick. Resulting doses to a person who resides in a room constructed from the building materials were assessed by UNSCEAR method for different air exchange rates.

The exhalation measurements show that Korean brick exhales the highest concentration of radon and thoron, while Indonesian brick exhales very low thoron concentration (almost negligible). From the results, it can be inferred that for low dense material, radon and thoron exhalation rate increases with increasing humidity until a certain level of humidity and then find its saturated region. In case of high dense material, such as the Indonesian brick, the decreasing trend may be resulted.

From the effective dose assessment, it shows that radon has a very close relationship with the air exchange rate (ventilating process). Without ventilation (ACH $= 0.00$ h^{-1}), radon can accumulate and give a very high effective dose beyond world average value (1.25 mSv y^{-1}). By changing the air exchange rate from 0.00 to 0.50 h^{-1}, it can decrease the effective dose about 66 times. While 0.80 h^{-1}, the average air exchange rate used globally, it can decrease more than a half of those of 0.50 h^{-1}.

In case of thoron, the effective dose is still below world average value for both Korean brick, Indonesian brick, and Korean soil. In addition, the air exchange rate doesn't have significant effect to thoron concentration and effective dose. In this situation, it can be considered safe. However, if construction material has high thorium content, the thoron should not be neglected since it's relatively inert from air exchange rates.

It has been recognized that RAD7 is an active detector used by many researchers in radon measurement. The main superiorities of RAD7 are its ability to do simultaneous measurement of ^{222}Rn and ^{220}Rn, real time continuous measurement and spectrum analysis, and its fast response and recovery time after each measurement. However, from this research it is found out that the need to maintain the instrument humidity below 10% is contradictive with the research objective that needs to increase chamber humidity. Consequently, maintaining stable humidity become one restriction that will not be found in passive detector.

Considering the results of this study, it will be important for brick manufacturer to control the density of produced brick in order to enhance the safety of public and environment related to radon. In addition, fired-typed brick seems to have better safety in relation to reduced radon exhalation rates. Also, it is shown that the increased ACH from simple operation of a cheap ventilation pump will decrease radon dose greatly. The culture of ventilation use should be promoted for probable residence area radon dose reduction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] International Atomic Energy Agency (IAEA), Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna, IAEA, Vienna, 2014. https://doi.org/STI/PUB/1578.

[2] J. Yang, H. Busen, H. Scherb, K. Hürkamp, Q. Guo, J. Tschiersch, Modeling of radon exhalation from soil influenced by environmental parameters, Sci. Total Environ. 656 (2019) 1304–1311, https://doi.org/10.1016/j.scitotenv.2018.11.464.

[3] N.B. of Standards, Radon Transport through and Exhalation from Building Materials : A Review and Assessment, 1981. Washington.

[4] D. Ji, Z.Y. Xu, Y.T. Zhang, Influence of humidity on building material's radon exhalation rate, Appl. Mech. Mater. 433–435 (2013) 2085–2090, https://doi.org/10.4028/www.scientific.net/AMM.433-435.2085.

[5] L.M.O. Martins, M.E.P. Gomes, L.J.P.F. Neves, A.J.S.C. Pereira, The influence of geological factors on radon risk in groundwater and dwellings in the region of Amarante (Northern Portugal), Environ. Earth Sci. 68 (2013) 733–740, https://doi.org/10.1007/s12665-012-1774-0.

[6] A. Kumar, S. Sharma, R. Mehra, S. Narang, R. Mishra, Assessment of indoor radon, thoron concentrations, and their relationship with seasonal variation and geology of Udhampur district, Jammu & Kashmir, India, Int. J. Occup. Environ. Health 23 (2017) 202–214, https://doi.org/10.1080/10773525.2018.1450326.

[7] M. Pirsaheb, F. Najafi, L. Hemati, T. Khosravi, H. Sharafi, Data on the effect of geological and meteorological parameters on indoor radon and thoron level-case study: kermanshah, Iran, Data Br 18 (2018) 1945–1951, https://doi.org/10.1016/j.dib.2018.04.122.

[8] M. Schubert, A. Musolff, H. Weiss, Influences of meteorological parameters on indoor radon concentrations (222Rn) excluding the effects of forced ventilation and radon exhalation from soil and building materials, J. Environ. Radioact. 192 (2018) 81–85, https://doi.org/10.1016/j.jenvrad.2018.06.011.

[9] M.Y.M. Ali, M.M. Hanafiah, M.F. Khan, Potential factors that impact the radon level and the prediction of ambient dose equivalent rates of indoor micro-environments, Sci. Total Environ. 626 (2018) 1–10, https://doi.org/10.1016/j.scitotenv.2018.01.080.

[10] B. Collignan, E. Powaga, Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor radon activity concentration, J. Environ. Radioact. 196 (2019) 268–273, https://doi.org/10.1016/j.jenvrad.2017.11.023.

[11] R. Rabi, L. Oufni, Evaluation of indoor radon equilibrium factor using CFD modeling and resulting annual effective dose, Radiat. Phys. Chem. 145 (2018) 213–221, https://doi.org/10.1016/j.radphyschem.2017.10.022.

[12] J.W. Kim, H.Y. Joo, R. Kim, J.H. Moon, Investigation of the relationship between earthquakes and indoor radon concentrations at a building in Gyeongju, Korea, Nucl. Eng. Technol. 50 (2018) 512–518, https://doi.org/10.1016/j.net.2017.12.010.

[13] M. Janik, Y. Omori, H. Yonehara, Influence of humidity on radon and thoron exhalation rates from building materials, Appl. Radiat. Isot. 95 (2015) 102–107, https://doi.org/10.1016/j.apradiso.2014.10.007.

[14] H.E. Wichmann, J. Heinrich, M. Gerken, M. Kreuzer, J. Wellmann, G. Keller, L. Kreienbrock, Domestic radon and lung cancer—current status including new evidence from Germany, Int. Congr. Ser. 1225 (2002) 247–252, https://doi.org/10.1016/S0531-5131(01)00552-0.

[15] A.C. Syuryavin, M.M. Nirwono, S.H. Lee, Reviewing the prescriptive-based regulation of the continental shelf territory of Indonesia for regulating security of radioactive sources, in: Int. Conf. Secur. Radioact. Mater. W. Forw. Prev. Detect, 2018. Vienna.

[16] A.C. Syuryavin, S.Y. Han, S.H. Lee, How to regulate radon: case study of radon exposure in Korea and Indonesia, in: Korean Nucl. Soc. Autumn Meet. Yeosu, 2018. Yeosu.

[17] Durridge, RAD7 Radon Detector User Manual, 7.4.0, 2015. Billerica.

[18] J.L. Mas, J.P. Bolivar, R. Garcı, I. Lo, A Short-Time Method to Measure the Radon Potential of Porous Materials, vol. 67, 2009, pp. 133–138, https://doi.org/10.1016/j.apradiso.2008.07.015.

[19] G. Keller, B. Hoffmann, T. Feigenspan, Radon permeability and radon exhalation of building materials, Sci. Total Environ. 272 (2001) 85–89, https://doi.org/10.1016/S0048-9697(01)00669-6.

[20] S.A. Mujahid, S. Hussain, A.H. Dogar, S. Karim, Determination of porosity of different materials by radon diffusion, Radiat. Meas. 40 (2005) 106–109, https://doi.org/10.1016/j.radmeas.2005.04.006.

[21] C. Samuelsson, Closed-can exhalation method for measuring radon, J. Res. Natl. Inst. Stand. Technol. 95 (1990) 167–169, https://doi.org/10.6028/jres.095.019.

[22] IAEA, Measurement and Calculation of Radon Releases from NORM Residues, 2013.

[23] N. Yamamoto, D.G. Shendell, A.M. Winer, J. Zhang, Residential air exchange rates in three major US metropolitan areas: results from the relationship among indoor, outdoor, and personal air study 1999-2001, Indoor Air 20 (2010) 85–90, https://doi.org/10.1111/j.1600-0668.2009.00622.x.

[24] G.F. Knoll, Radiation Detection and Measurement, fourth ed., John Wiley & Sons, Michigan, 2010 https://doi.org/10.1017/CBO9781107415324.004.

[25] J.E. Martin, Physics for Radiation Protection, third ed., Second, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2013, https://doi.org/10.1002/9783527667062.

[26] E. Stranden, A.K. Kolstad, B. Lind, The influence of moisture and temperature on radon exhalation, Radiat. Protect. Dosim. 7 (1984) 55–58.

[27] R.R. Schumann, D.E. Owen, S. Asher-Bolinder, Weather Factors Affecting Soil-Gas Radon Concentrations at a Single Site in the Semiarid Western, U.S., 1988, p. 54.

[28] Unscear, Sources, Effects and risks of ionizing radiation. https://doi.org/10.2307/3577647, 2008.

[29] International Commission on Radiological Protection (ICRP), ICRP (international commission on radiological protection). Protection against radon-222 at home and at work (ICRP publication N^{o} 65). https://doi.org/10.1080/09553009414551371, 1993.