Nuclear Technology & Radiation Protection: Year 2024, Vol. 39, No. 3, pp. 234-242

# DOSE AND RISK ASSESSMENT OF RADON IN THREE ROOMS WITH VARYING VENTILATION LEVELS USING RESRAD-BIULD SOFTWARE

by

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Scientific paper
https://doi.org/10.2298/NTRP2403234A

**Radon, a radioactive gas, poses a significant health risk when accumulated in indoor environments. This study measured radon concentrations in three rooms with varying ventilation levels over a 12-month period, utilizing a Corentium monitor, an alpha spectroscopy-based radon detection device. The objective was to assess the impact of seasonal variations on indoor radon levels. The results indicated that the highest radon concentration, approximately 42 Bqm$^{-3}$, was consistently observed in the closed room. In comparison, the partially closed room and the regularly occupied room with normal ventilation, had concentrations of 35 Bqm$^{-3}$ and 31 Bqm$^{-3}$, respectively. Across all three rooms, radon levels were lowest during the summer and peaked during the winter. The dose and risk associated with radon exposure were further analyzed using the RESRAD-BUILD computer code. All measured radon levels and associated doses were below the global safety limits. This study highlights the critical role of ventilation in controlling indoor radon levels and confirms that the environments studied remain within safe exposure thresholds.**

*Key words: radiological assessment, RESRAD- BIULD code, ventilation, meteorological parameter*

## INTRODUCTION

Indoor radon is a significant contributor to natural radiation exposure and poses a recognized health risk, particularly as a leading cause of lung cancer after smoking [1]. The accumulation of radon in indoor environments is influenced by various factors, including building materials [2], soil characteristics [3], and especially ventilation practices [1, 4, 5]. Understanding the relationship between indoor radon levels and ventilation is crucial for developing effective mitigation strategies. Many studies worldwide have explored various aspects of indoor radon exposure [6]. Some research has focused on understanding the influence of meteorological parameters, such as temperature, humidity, and wind speed, on indoor radon levels [7-10]. These studies highlight the complex interactions between environmental conditions and radon dynamics within buildings. Other research has concentrated on the health risks associated with radon [1, 11-13], particularly its role as a significant factor in lung cancer incidence, making it a critical public health concern. Additionally, some studies have examined different facets of radon, including its migration patterns, the effectiveness of mitigation strategies, and its interaction with building materials [14, 15]. There are numerous methods for calculating and analyzing radiation doses, each tailored to specific scenarios and types of radiation.

Over the years, various methods and software tools have been developed to assist the radiation dose calculations [16, 17], providing researchers and health professionals with robust and precise models for assessing radiation exposure. One of the most widely used tools is the RESRAD family of software, which includes RESRAD-BUILD, a specialized program designed for evaluating radiation doses and risks associated with indoor environments, particularly from radon [15, 18, 19]. RESRAD-BUILD is uniquely equipped to model complex scenarios involving different ventilation rates, room geometries, and building materials.

RESRAD-BUILD software is particularly valuable for radon dose and risk analysis because it allows users to define specific parameters, such as room volume and wall material composition, offering a detailed and accurate prediction of radiation exposure over time. This study analyses indoor radon concentrations in buildings under three different ventilation conditions. By comparing these different environments, the study aims to assess how ventilation impacts radon ac-

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cumulation. Furthermore, the study utilizes the RESRAD-BUILD computer code to evaluate the dose and associated risk of radon exposure over multiple periods, providing a comprehensive risk assessment. The primary objective of this research is to determine the effectiveness of ventilation in controlling indoor radon levels and to assess whether the radon doses in these environments fall within the recommended global safety limits.

## METHODS AND PROCEDURE

### Indoor radon measurement

Long-term radon concentrations were measured over a one-year period (2023) in three distinct rooms, all of equal volume but differing in their usage and ventilation conditions. *The first room (natural room)*: was located in a naturally ventilated residential building where occupants lived year-round. During the summer, the room was ventilated by opening windows and using an air conditioner. In winter, the windows were kept closed, and the room was heated. *Second room (partially closed)*: a room with no active ventilation system. This room remained sealed throughout the year, except for brief periods when the door was opened for small tasks, and then immediately shut. The windows remained shut at all times. *Third room (totally closed)*: this room was completely sealed for the entire year, with the door being opened only once per month to collect radon measurement data.

A Corentium radon monitor was used to measure indoor radon concentrations. This battery-operated device, an alpha spectrometer detector, can function for approximately two years and provides short-and long-term radon measurements. The monitor was placed in each room one meter above the ground to continuously monitor radon levels.

### Meteorological parameter measurement

Alongside radon measurements, additional environmental parameters such as indoor and outdoor temperature, humidity, and wind speed were also recorded to assess the impact of seasonal variations on indoor radon concentrations.

### Dose and risk estimation

After collecting the radon concentration data, the dose and risk associated with radon exposure were analyzed using the RESRAD-BUILD computer code. RESRAD is a computer code developed by the U.S. Department of Energy (DOE) for evaluating radiation doses and risks associated with residual radioactive materials [20]. It is widely used in environmental radiation protection and dose assessment. The RESRAD simulates the transport of radionuclides through various environmental pathways, including soil, air, water, and food. It calculates the radiation dose to individuals from different exposure routes, such as inhalation, ingestion, and direct radiation. The code can model radionuclide behavior over extended periods, assessing long-term exposure and risks. It estimates the potential dose to individuals living near or working on contaminated sites. Furthermore, the code is used to evaluate the health risks associated with exposure to residual radioactivity, supporting decisions for site release and land reuse.

Using the RESRAD software involves several steps, from preparing data to running simulations and interpreting results. After indoor radon has been measured for three different ventilation levels, the radon concentration is converted to its parent radionuclide, $^{226}$Ra. This conversion is performed by applying an equilibrium factor ($F$), which typically ranges from 0.3 to 0.7 depending on the specific ventilation and environmental conditions of the area under study [21]. The equilibrium factor represents the ratio of the actual radon progeny concentration in the air to the concentration in a theoretical equilibrium with radon gas. In practice, this factor accounts for the partial equilibrium typically observed between radon gas and its short-lived decay products (progeny). The equilibrium factor varies depending on environmental conditions, such as ventilation and particle attachment, but a standard value of 0.4 is commonly used in indoor air studies. To estimate the effective $^{226}$Ra concentration, the measured $^{222}$Rn concentration $^{222}$Rn is divided by the equilibrium factor (0.4), using the equation

$$^{226}\text{Ra} = \frac{^{222}\text{Rn}}{0.4} \tag{1}$$

Here, $^{222}$Rn is the concentration of radon gas (in Bqm$^{-3}$), and 0.4 reflects the assumed equilibrium factor for indoor environments. This calculation translates the measured radon levels into the $^{226}$Ra concentration in the underlying material, which is crucial for understanding the source strength of radon emissions. $^{226}$Ra serves as the parent isotope in the uranium decay chain with its concentration directly influencing radon generation. This conversion is particularly important for assessing radon risk and comparing results across different studies. This approach allows for the translation of measured radon levels into corresponding $^{226}$Ra concentrations, facilitating dose and risk assessments in models like RESRAD-BUILD, which require input data in terms of specific radionuclide concentrations [20]. Once the $^{226}$Ra values were obtained according to eq. (1), they were input into RESRAD- BUILD as the source term instead of radon. The software then simulated the radiological dose over 40 years to estimate long-term exposure risks to occupants. All other significant input data, such as building information, (including geometry, dimensions, layout, and materials of the building and rooms), the occupant scenario (*e.g.*, workers, residents), and environmental parameters, were also entered into the software. Also, the physical and chemical properties of building materials that may affect radionuclide transport and radiation shielding have been described. Furthermore, the time that occupants spend in different parts of the building has been specified. Inhalation, ingestion, external exposure, radon and relevant exposure pathways were defined. All the input data, as shown in tab. 1, were entered, and the dose and risk of different exposure pathways were simulated over a 40-year period to estimate long-term exposure risks to occupants.

## Statistical analyses

Finally, the results obtained from the RESRAD-BUILD model were exported to Microsoft Excel for further analysis. Statistical evaluations included calculating the mean values for indoor radon concentrations and temperature to assess their seasonal variations and trends under different ventilation conditions. Graphical representations were also created to visually interpret the impact of seasonal changes and ventilation scenarios on indoor radon levels and associated health risks. Additionally, the correlation coefficient was calculated to quantify the relationship between indoor radon concentrations and meteorological parameters, such as temperature, humidity, and wind speed, providing a clearer understanding of how these factors influence radon accumulation indoors.

## RESULTS AND DISCUSSION

The results of this study provide insight into the seasonal variation of indoor radon concentrations and their corresponding doses under different ventilation conditions. Analysis of the data reveals distinct patterns in radon levels throughout the year, as well as significant differences in dose exposure based on the room's usage and ventilation practices. The results presented in fig. 1 illustrate the relationship between indoor radon concentrations over different months of the year. The two vertical coordinate axes, RC and WHO, represent the radon concentration values measured in houses with different ventilation systems and the average limit recommended by the WHO, respectively. Notably, radon levels peaked in winter, attributed to the stack effect, where warmer indoor air rises, causing radon from the ground to accumulate indoors. This effect is aggravated by a snowy barrier and tightly sealed houses [22]. Cold temperatures increase the pressure within the house, pulling more air in from the ground, thereby elevating the risk of radon entering it [2]. Conversely, the lowest radon concentrations were observed during the summer months, likely due to increased ventilation practices, such as opening windows, which reduce indoor radon levels. Figure 2 illustrates the total dose assessment across three different rooms with varying degrees of ventilation over one year. The room actively used and ventilated by humans during the day recorded the lowest dose, demonstrating the effectiveness of regular ventilation

**Table 1. Input parameter for RESRAD-BIULD simulation**

| | |
|---|---|
| Input source | |
| Radionuclide | $^{226}$Ra |
| Building parameter | |
| Room volume | 36 m$^3$ |
| Wall thickness | 0.2 m |
| Building exchange rate | 0.8 h$^{-1}$ |
| Deposition velocity | 0.00039 ms$^{-1}$ |
| Resuspension rate | $5 \cdot 10^{-7}$ s$^{-1}$ |
| Environmental and occupancy parameter | |
| Exposure duration | 365 days |
| Evaluation time | 40 year |
| Equilibrium factor | 0.4 |
| Receptor parameter | |
| No. of receptor | 1 |
| Breathing rate | 18 m$^3$d$^{-1}$ |

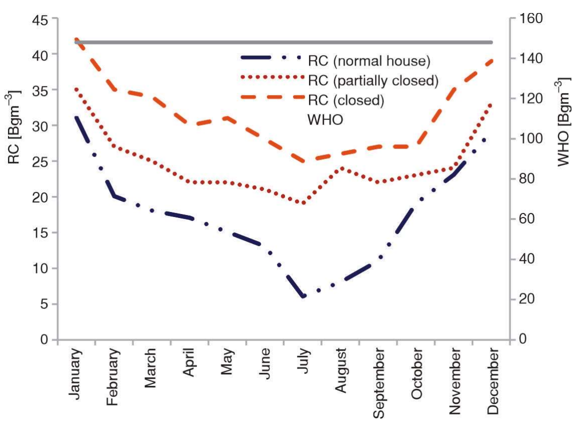


**Figure 1. Monthly variation of radon concentration over the year**

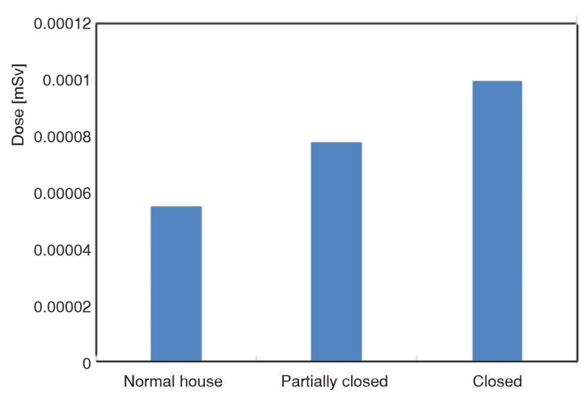


**Figure 2. Comparison of radiation dose across three buildings at different degrees of ventilation**

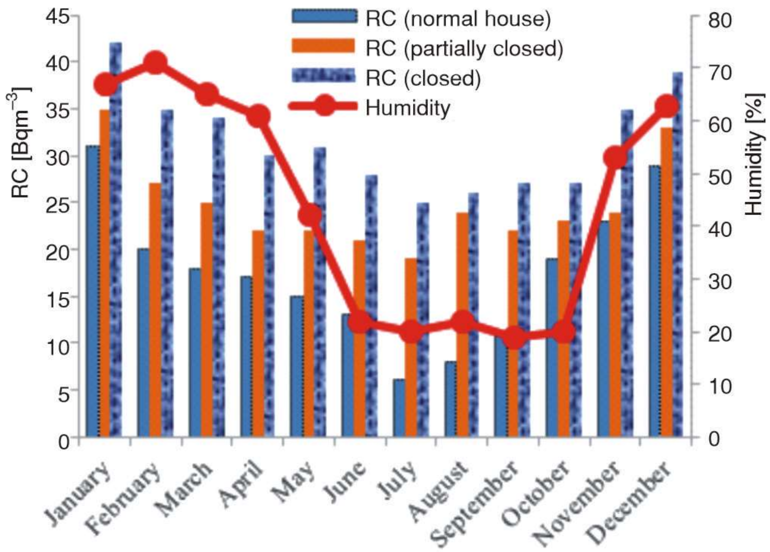


**Figure 3. Effect of humidity on monthly radon concentration variation**

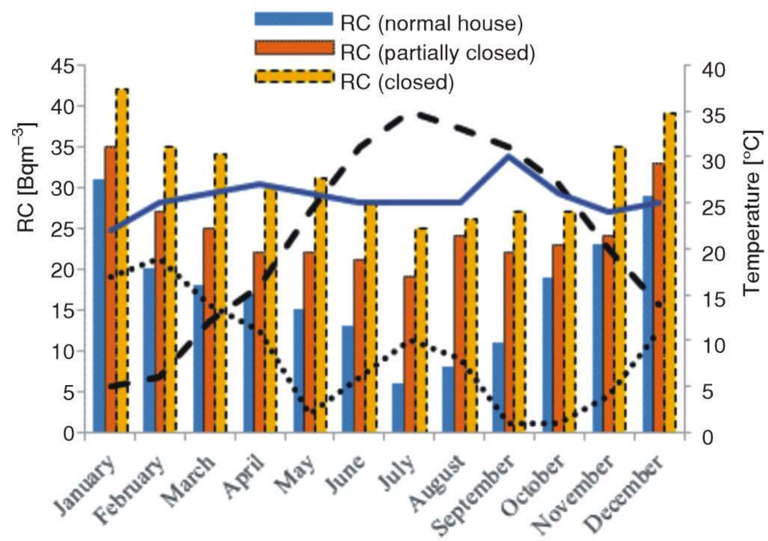


**Figure 4. The Correlation between temperature °C (indoor, outdoor, and temperature difference) and indoor radon concentration across different months of the year**

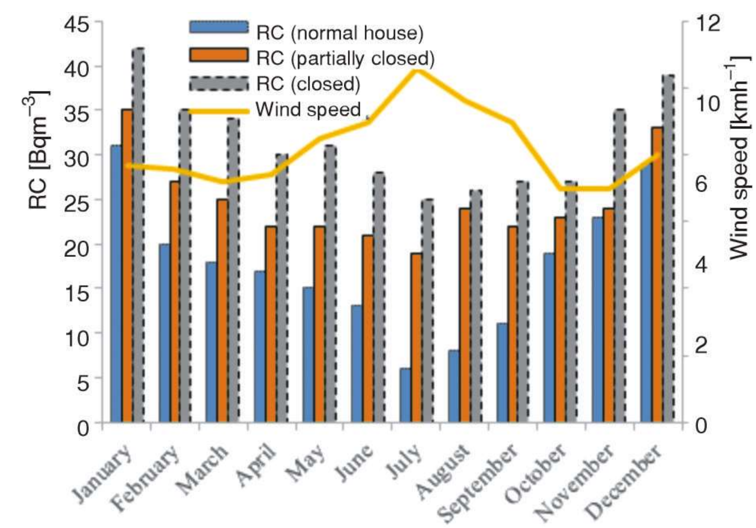


**Figure 5. Correlation between wind speed and indoor radon concentration across different months of the year**

in reducing radon exposure. Conversely, the closed room, which remained sealed most of the time, exhibited the highest radon dose, emphasizing the impact of poor ventilation on indoor radon accumulation and the associated health risks [23, 24].

Figures 3-5 illustrate the correlation between indoor radon levels and meteorological parameters. Figure 3 depicts the relationship between indoor radon and outdoor humidity. Our data show that indoor radon levels were lowest during the summer and highest in the winter suggesting a negative correlation between radon concentration and moisture, particularly in the summer months (June-August). Higher humidity levels may correspond to reduced radon levels due to lower soil gas permeability or increased air exchange in humid conditions. However, in closed environments, the impact is less evident. The correlation coefficient could range from –0.3 to –0.5, indicating a moderate inverse relationship. This seasonal variation reflects the intricate interplay between humidity and radon dynamics. High outdoor humidity often causes increased soil moisture, affecting radon migration [25]. Moist soil may either trap radon or create conditions where radon is more easily pushed into buildings due to pressure differences. Furthermore, elevated humidity can reduce the likelihood of opening windows for ventilation, leading to higher indoor radon levels as radon is not efficiently expelled.

Figure 4 reveals a direct relationship between temperature and indoor radon levels. There appears to be a moderate positive correlation between temperature and radon concentration, particularly in closed conditions. Warmer months (*e. g.*, summer) show higher radon concentrations in closed environments, possibly due to increased radon release from soil and reduced ventilation. In contrast, the correlation may be weaker or negligible in partially or normally ventilated conditions due to better air exchange. A potential correlation coefficient for closed environments ranges from 0.4 to 0.6, suggesting a moderate relationship. This correlation is consistent with the known effects of temperature on radon dynamics. Temperature influences indoor radon levels through mechanisms such as the stack effect and ventilation practices. Additionally, reduced ventilation during colder periods exacerbates radon accumulation.

Figure 5 demonstrates the impact of wind speed on indoor radon levels. Wind speed seems to have a negative correlation with radon concentration. Months with higher wind speeds, such as July and August, correspond to lower radon levels, particularly in normal and partially closed conditions. This suggests that increased ventilation reduces radon accumulation indoors. In closed environments, the impact of wind speed is less significant. The estimated correlation coefficient between radon concentration and wind speed ranges from –0.5 to –0.7, indicating a strong inverse relationship. Wind speed affects radon concentrations through several mechanisms. High wind speeds can create pressure differentials between the interior and exterior of buildings, potentially increasing radon entry through foundation cracks and gaps [22]. Conversely, increased wind speed can enhance natural ventilation, which may dilute radon levels if windows or vents are open. The net effect of wind speed on indoor radon levels depends on the interplay between building structure, ventilation patterns, and soil permeability. Comparisons with global studies in tab. 2 underscore the variability in indoor radon levels across different regions and conditions. This comparison emphasizes the importance of localized assessments for a precise understanding and effective management of indoor radon exposure. The interactions between meteorological parameters and radon dynamics are multifaceted, requiring careful consideration of local environmental and building factors.

Figures 6-8 present the dose distribution across six distinct exposure pathways: external radiation, inhalation, deposition, air submersion, ingestion, and ra-

**Table 2. Nuclide dose details of radium, lead, and polonium in three rooms with varying ventilation levels**

| Type of ventilation | Nuclide detail of doses mSv | | |
|---|---|---|---|
| | $^{226}$Ra | $^{210}$Pb | $^{210}$Po |
| Normal house | $7.28 \cdot 10^{-5}$ | $1.47 \cdot 10^{-10}$ | $1.71 \cdot 10^{-12}$ |
| Partially closed | 0.000103 | $2.08 \cdot 10^{-10}$ | $2.4 \cdot 10^{-12}$ |
| Closed | 0.000132 | $2.65 \cdot 10^{-10}$ | $3.08 \cdot 10^{-12}$ |

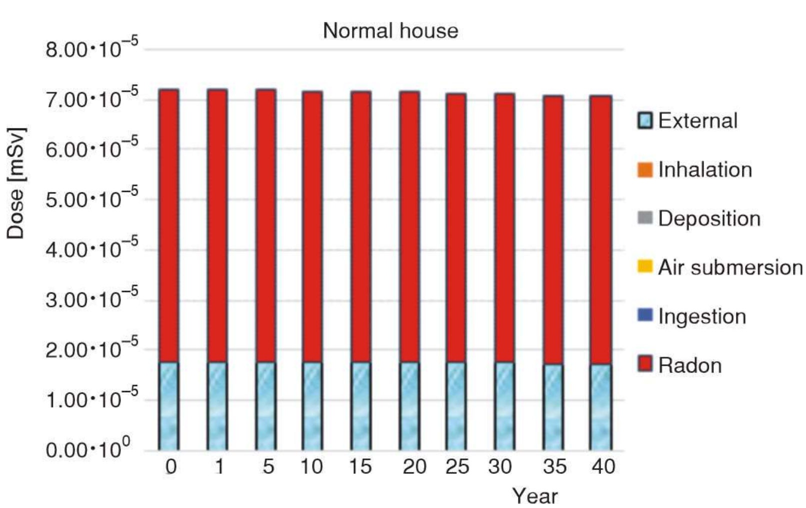


**Figure 6. Dose by time and pathway for nuclide in normal house**

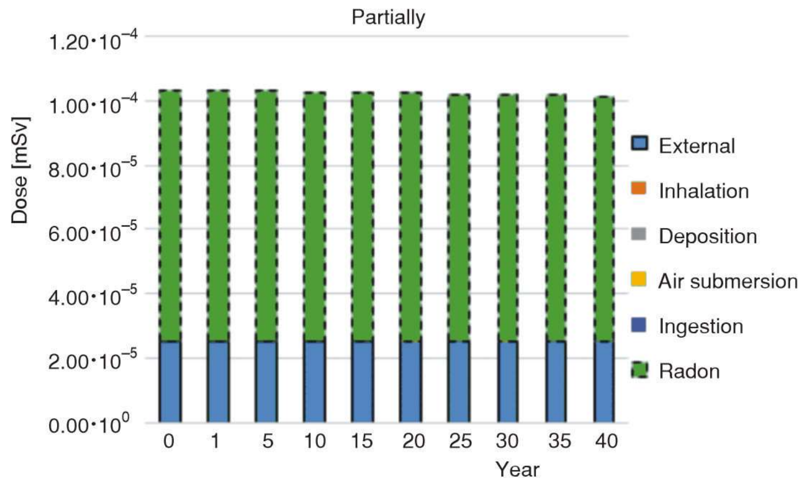


**Figure 7. Dose by time and pathway for Nuclide in partially ventilated**

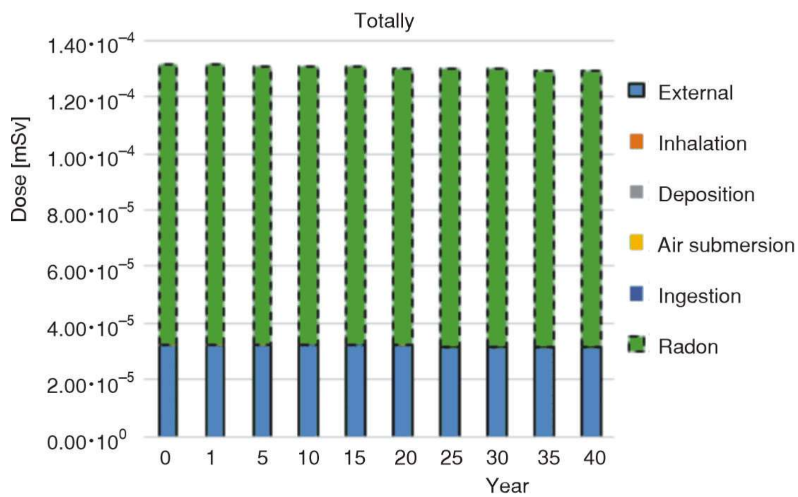


**Figure 8. Dose by time and pathway for nuclide in closed ventilation**

don. The data indicate that the dose absorbed by individuals is predominantly due to external radiation and radon exposure, with radon contributing approximately 75 % of the total dose. This significant contribution of radon is primarily due to the decay of $^{226}$Ra, which, given its long half-life, continues to influence radon levels over extended periods. The graphs further illustrate that the cumulative dose over 40 years remains relatively constant, with only a slight decrease observed, reflecting the persistent nature of $^{226}$Ra and its decay products. Moreover, the analysis shows that the distribution of doses across the various pathways remains consistent across all three ventilation scenarios: normal, partially closed, and totally closed. However, the total dose is higher in the closed ventilation scenario compared to the other two environments. This difference underscores the importance of ventilation in mitigating radon exposure, as the lack of air exchange in the closed ventilation scenario leads to higher radon accumulation and, consequently, a greater dose. The highest dose among all pathways is consistently from radon, emphasizing the critical need for managing radon levels in indoor environments to reduce long-term radiation exposure.

The risk assessment of radionuclides, as depicted in fig. 9 highlights that the primary risks to human health are associated with external radiation and radon exposure. Figures 10-12 further illustrate the specific risk contributions of radon over a 40-year period, compared to the cumulative risk from all other pathways combined. These figures consistently demonstrate that radon poses the most significant risk, overshadowing the contributions from other exposure pathways. The data indicate that managing radon exposure is crucial for minimizing long-term health risks from radionuclides. Fortunately, all the data from this study, including radon levels and the associated doses, fall well below the worldwide safety limits established by various health organizations [2]. Despite the significant contribution of radon to the overall dose and risk found in this study, the measured values remain within the acceptable range for human exposure. This finding is reassuring, as it indicates that, under the conditions studied, the indoor radon concentrations and the resulting doses do not pose a significant health risk according to global standards. In RESRAD-BUILD, the total radiation dose is calculated based on six primary pathways: external exposure, annihilation, deposition,

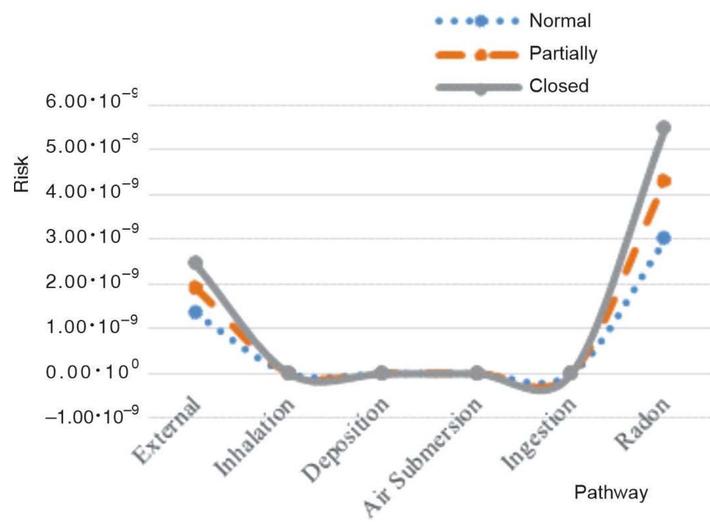


**Figure 9. Risk by pathway for different ventilation degree**

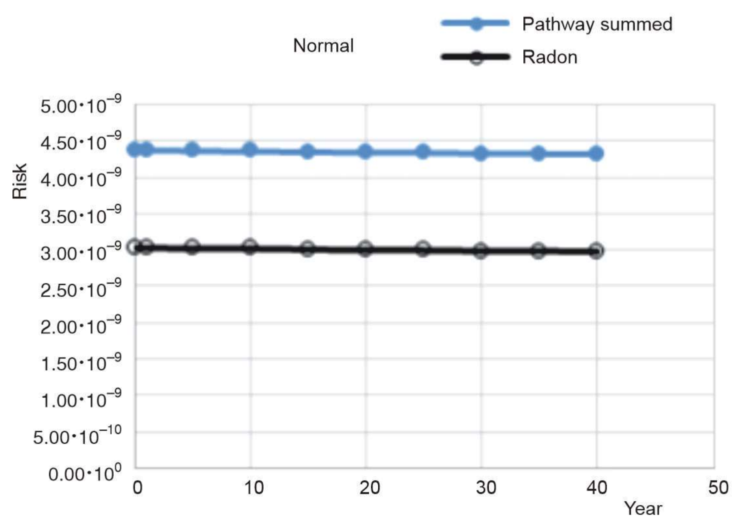


**Figure 10. Comparison between the risk of radon alone and all pathways summed in a normal house**

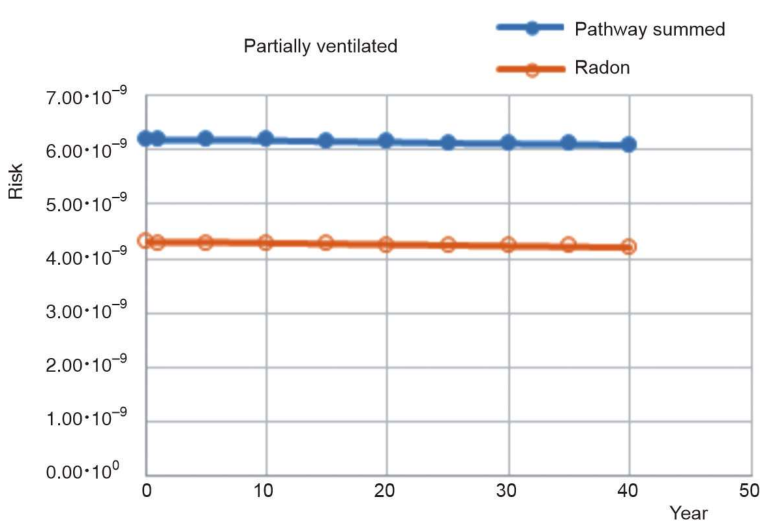


**Figure 11. Comparison between risk of the radon alone and all pathways summed in a partially ventilated house**

air submersion, ingestion, and radon inhalation. Among these, the radon inhalation and ingestion pathways typically contribute the highest dose values, while the contributions from the other four pathways are relatively minor. This disparity arises from the specific characteristics and exposure mechanisms of each route. Radon, as a radioactive gas, can accumulate in indoor environments, especially in poorly ventilated spaces, leading to significant exposure through inhalation. The decay products of radon emit alpha radiation, which has a high biological effectiveness and poses a significant health risk to lung tissue. Similarly, the in-

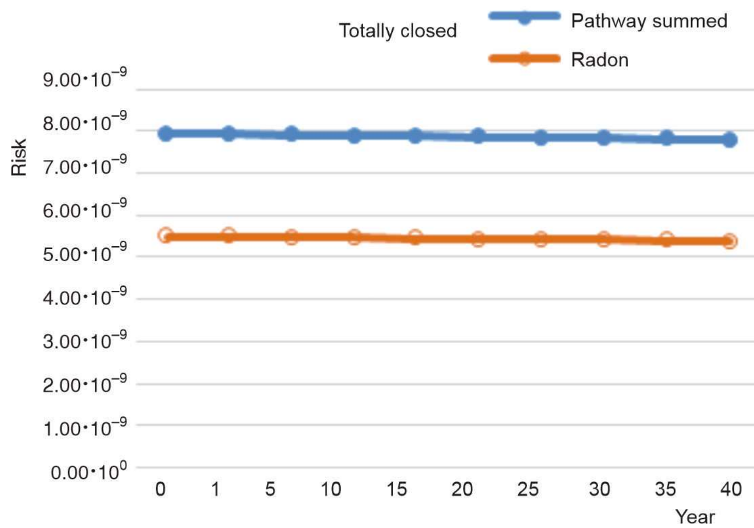


**Figure 12. Comparison between the risk of radon alone and all pathways summed in a closed ventilation house**

gestion pathway contributes substantially to the dose when food, water, or dust contaminated with radionuclides is consumed. This results in internal exposure, as radionuclides can concentrate in specific organs, such as iodine in the thyroid, leading to sustained radiation effects. In contrast, the external, annihilation, deposition, and air submersion pathways contribute minimally due to the lower intensity of their exposure mechanisms in typical scenarios. External exposure and air submersion depend on the presence and energy of gamma-emitting radionuclides, which may not be dominant in most building environments. Deposition and annihilation effects are limited unless there is significant contamination or the presence of positron-emitting radionuclides. Overall, the dominance of radon and ingestion pathways in dose contribution highlights the importance of controlling indoor radon levels and preventing contamination of food and water sources to mitigate radiological health risks effectively. The consistent observation of radon being the primary contributor to dose and risk, as seen in fig. 6-12, further emphasizes the importance of monitoring and managing radon levels. However, the fact that these levels are below the international thresholds highlights the effectiveness of current building practices and ventilation in maintaining safe indoor environments. These results suggest that, while vigilance is necessary, the existing conditions in the studied environments are adequate for protecting human health over the long term.

## CONCLUSION

This study measured indoor radon levels in three rooms with different ventilation conditions: one room occupied by humans with seasonal ventilation (open windows in summer and sealed in winter), another room partially closed, and a third room completely closed. The results indicated that indoor radon levels were lowest during the summer when ventilation was highest, and reached their maximum during the winter when ventilation was minimized. Additionally, the closed room exhibited the highest radon concentrations due to radon accumulation over time. The study also found that meteorological parameters significantly influenced indoor radon levels, with a positive correlation between radon levels and wind speed, and a negative correlation with atmospheric pressure. The dose and risk associated with radon exposure were assessed using the RESRAD-BUILD computer code, which confirmed that all measured radon levels and doses were below the safety thresholds recommended by the World Health Organization. These findings suggest that while indoor radon levels can vary significantly with ventilation and environmental conditions, the rooms studied maintained radon concentrations within safe limits, highlighting the importance of proper ventilation in radon mitigation strategies.

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Received on September 26, 2024
Accepted on December 10, 2024

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## ПРОЦЕНА ДОЗЕ И РИЗИКА ОД РАДОНА У ТРИ ПРОСТОРИЈЕ СА РАЗЛИЧИТИМ НИВОИМА ВЕНТИЛАЦИЈЕ ПОМОЋУ RESRAD-BIULD СОФТВЕРА

Радиоактивни гас радон представља значајан ризик по здравље када се акумулира у затвореним срединама. У раду су приказана мерења концентрације радона у три просторије са различитим нивоима вентилације током периода од дванаест месеци, користећи Corentium монитор, уређај за детекцију радона заснован на алфа спектроскопији. Циљ је био да се процени утицај сезонских варијација на ниво радона у затвореном простору. Резултати су показали да је највећа концентрација радона око 42 $Bqm^{-3}$, доследно уочена у затвореној просторији. За поређење, делимично затворена просторија и просторија која се редовно користи са нормалном вентилацијом имају концентрације од 35 $Bqm^{-3}$ и 31 $Bqm^{-3}$, респективно. У све три просторије нивои радона били су најнижи током лета и достизали врхунац током зиме. Доза зрачења и ризик повезан са изложеношћу радону анализирани су коришћењем RESRAD- BIULD рачунарског програма. Сви измерени нивои радона и повезане дозе били су испод глобалних безбедносних граница. Овај рад наглашава критичну улогу вентилације у контроли нивоа радона у затвореном простору и потврђује да проучавана окружења остају унутар безбедних прагова изложености.

*Кључне речи: радиолошка процена, RESRAD-BIULD програм, вентилација, метеоролошки параметар*