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Determination of radon (^{222}Rn) activity concentration in the Institute of Radiation Protecion and Dosimetry, Rio de Janeiro, Brazil

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Abstract: Radon is a natural radioactive element responsible for around 40% of the annual dose from natural sources of radiation. It is considered the second leading cause of lung cancer by UNSCEAR. For these reasons, it is important to determine the concentration of radon in built environments. The aim of this study was to quantify the concentration of radon on the premises of the Institute of Radioprotection and Dosimetry (IRD/CNEN). Radon concentrations were measured using CR-39 solid-state nuclear trace detectors, which were exposed for 90 days in 20 of the Institute's buildings, including rooms, offices, bathrooms and laboratories. The laboratorial procedures were conducted at the Radon Laboratory of the Environmental and Occupational Radioprotection Division (DIRAD) of the IRD/CNEN. The statistical uncertainties were provided by the equipment manufacturer's software, and the effective dose calculations strictly followed the appropriate bibliographical references. The average radon concentration found was 86.4 Bq/m³, ranging from 6.5 Bq/m³ to 285.4 Bq/m³, demonstrating compliance with national regulations. Regarding the maximum annual effective dose, for a 5-hour working day, the values ranged from 0.13 mSv/year to 1.33 mSv/year. For an 8-hour working day, the values ranged from 0.21 mSv/year to 2.14 mSv/year. Based on the concentrations obtained, it was possible to check whether the Institute's facilities meet the requirements of standard CNEN NN 3.01, as well as calculating the maximum annual effective dose for two scenarios: 5-hour and 8-hour working days.

Keywords: Radon, CR-39, Radon activity concentration, Annual effective dose.

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Determinação da concentração de atividade dede radônio (^{222}Rn) no Instituto de Radioproteção e Dosimetria, Rio de Janeiro, Brasil

Resumo: Radônio é um elemento radioativo natural responsável por cerca de 40% da dose anual devido a fontes naturais de radiação. É considerado a segunda maior causa de câncer de pulmão pelo UNSCEAR. Por estes motivos, é importante determinar a concentração de radônio em ambientes construídos. Este trabalho teve como objetivo quantificar a concentração de radônio nas dependências do Instituto de Radioproteção e Dosimetria (IRD/CNEN). A medição da concentração de radônio foi realizada com detectores de traços nucleares de estado sólido CR-39, expostos por 90 dias em 20 prédios do Instituto, incluindo salas, escritórios, banheiros e laboratórios. Os trabalhos laboratoriais foram conduzidos no Laboratório de Radônio da Divisão de Radioproteção Ambiental e Ocupacional (DIRAD) do IRD/CNEN. As incertezas estatísticas foram fornecidas pelo software do fabricante do equipamento e os cálculos da dose efetiva seguiram rigorosamente as referências bibliográficas adequadas. A concentração média de radônio encontrada foi de 86,4 Bq/m³, variando entre 6,5 Bq/m³ e 285,4 Bq/m³, demonstrando a conformidade com a regulamentação nacional. No que se refere à dose efetiva anual máxima, para uma jornada de trabalho de 5 horas, os valores variaram entre 0,13 mSv/ano e 1,33 mSv/ano. Para uma jornada de 8 horas, os valores ficaram entre 0,21 mSv/ano e 2,14 mSv/ano. A partir das concentrações obtidas, foi possível verificar se as instalações do Instituto atendem às exigências da norma CNEN NN 3.01, assim como calcular a dose efetivida anual máxima para dois cenários: 5 horas e 8 horas de trabalho por dia.

Palavras-chaves: Radônio, CR-39, Concentração de atividade de radônio, Dose efetiva anual.

1. INTRODUCTION

Radiation protection and dosimetry are essential practices in environments where exposure to ionizing radiation can occur. These practices are particularly important in planned exposure situations, such as those found in the nuclear industry and in medical applications. In addition to planned exposure from artificial sources, there is growing concern about existing exposure situations involving natural radiation, such as that resulting from the decay of radioactive elements including uranium, thorium, and potassium-40 (^{40}K). Among these, radon gas (^{222}Rn), which originates from uranium decay, stands out for its public health relevance due to its carcinogenic potential, particularly when inhaled in enclosed environments [1].

Radon (^{222}Rn) is a noble, colorless, odorless, and tasteless gas resulting from the radioactive decay of ^{238}U [1]. Classified by the World Health Organization (WHO) as a Group 1 carcinogen, radon is, after smoking, one of the leading causes of lung cancer globally [2]. Epidemiological studies indicate that high concentrations of radon in indoor environments are directly associated with a significant increase in lung cancer risk. For instance, exposure to 100 Bq/m³ of radon gas increases cancer risk by approximately 8%. Additionally, in environments with radon concentrations between 100–199 Bq/m³, the incidence of cancer was 20% higher compared to those exposed to concentrations below 100 Bq/m³. Due to its characteristics, radon goes unnoticed and can only be detected through radiation measurements using appropriate detectors. This contributes to increased exposure among workers and the general public [2].

Given the data presented, the need to monitor and control radon concentrations in indoor environments becomes evident, especially in regions lacking detailed information about soil constituents. Measures such as adequate ventilation of enclosed spaces, the use of radon detectors, and the adoption of construction standards that incorporate mitigation strategies are essential to reducing the health risks associated with prolonged exposure to this gas [2]. In Brazil, however, radiological protection related to radon remains a little-explored area, with a lack of public policies effectively addressing risk mitigation.

The CNEN standard NN 3.01 sets a limit of 300 Bq/m³ for radon concentrations in indoor environments, in accordance with the guidelines of the World Health Organization (WHO). However, a lack of awareness in key sectors — such as civil construction and public health — hampers the adoption of simple and effective preventive measures, such as soil characterization, pre-construction measurements, and architectural design with enhanced ventilation systems. These actions can be crucial for reducing radon concentrations in indoor spaces

This topic becomes even more relevant considering estimates by the National Cancer Institute (INCA), which forecast approximately 32,560 new cases of trachea, bronchus, and lung cancer in Brazil annually from 2023 to 2025, with an estimated risk of 15.06 cases per 100,000 inhabitants. These numbers include 18,020 cases among men and 14,540 among women, corresponding to 17.06 and 13.15 new cases per 100,000 inhabitants, respectively. These data highlight the importance of studies that quantify radon exposure and assess its potential impacts on the health of the Brazilian population [4].

This study aims to measure radon concentrations in indoor environments at the Institute for Radiation Protection and Dosimetry (IRD). For this purpose, solid-state nuclear track detectors (CR-39) were used to support the optimization of the institution's radiological protection plan. Specific objectives include calculating the maximum annual effective dose from radon and its decay products, contributing to the improvement of the IRD's existing radiological protection plan.

2. MATERIALS AND METHODS

2.1. The detector CR-39

For this study, the CR-39 nuclear track detector, manufactured by Radosys, was used and placed inside the diffusion chamber (Figure 1). A total of 178 detectors were deployed, distributed across rooms, restrooms, and laboratories within the Institute of Radiation Protection and Dosimetry (IRD/CNEN), as shown in Table 1.

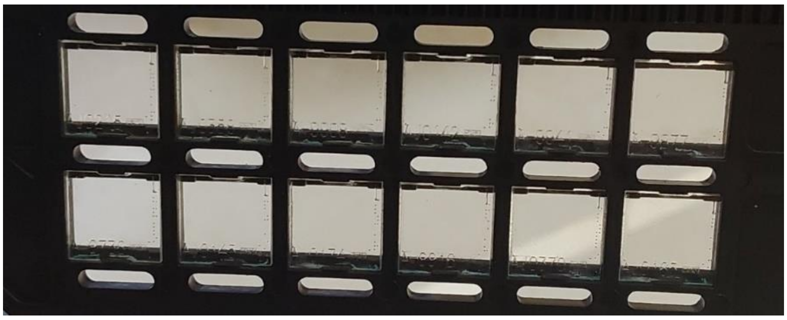
Figure 1: Diffusion chamber Radosys and CR-39 SSNDT detectors.

Table 1: Distribution of CR-39 detectors in IRD buildings.

Building	Quantity of detectors	Building	Quantity of detectors
1	12	11	3
2	23	12	7
3	3	13	16
4	19	14	5
5	22	15	5
6	3	16	7
7	5	17	17
8	2	18	9
9	2	19	6
10	3	20	9

When unsensitized, the CR-39 (figure 2) behaves like ordinary plastic. When alpha particles, resulting from radon decay, strike it, an ionization process occurs in which the incoming particle loses kinetic energy until it is fully stopped by the material. During this path, the previously unmarked plastic begins to show what is called a latent track, which can persist for years.

Figure 2: Detector Cr-39.



The Solid-State Nuclear Track Detectors (SSNTD) has several notable features, such as ease of installation, robustness, insensitivity to beta or gamma radiation, and low cost. Once developed, it can be stored without requiring any special treatment. Furthermore, the detector does not need an energy source to collect data.

2.2. The Development Process

According to the equipment manual, detector development process, also known as chemical etching, uses the following materials: 6.0 mol/L sodium hydroxide (NaOH), acetic acid 20 %, and distilled water.

The first step in the process is to add 4 liters of the NaOH solution into the RadoBath equipment from Radosys (Figure 3) [5].

The second stage of the procedure involves the development process. The solution must be heated to 90 °C, at which point the exposure timer is initiated. The detectors remain under continuous processing for a duration of 4.5 hours. All operational parameters are monitored and displayed in real time on the equipment (Figure 3).

The third step is neutralization. At this stage, 200 ml of acetic acid 20 % are added to neutralize the action of NaOH, and the neutralization program is selected on the equipment display. This process lasts 20 minutes [5].

The fourth step is the final rinse. Four liters of distilled water are used for the final washing of the equipment and detectors. This step is important to prevent unwanted stains on the detectors.

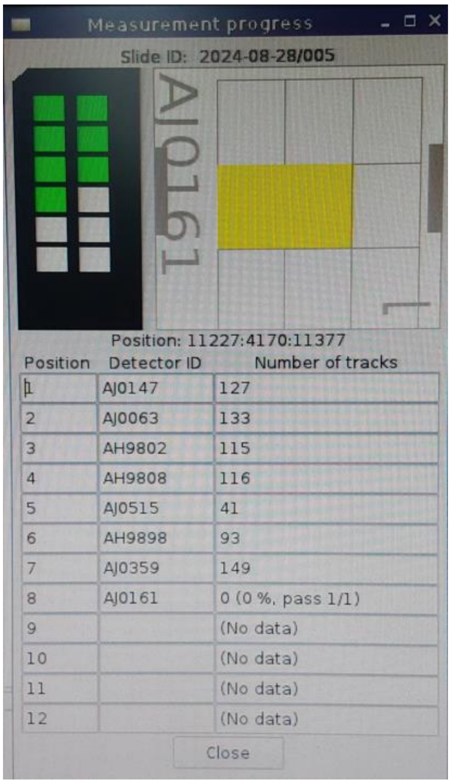
Figure 3: RadoBath.

2.3. Reading

The reading of the tracks on the CR-39 detectors is performed by the Radometer hardware (Figure 4) from Radosys, specifically through the optical microscope and processes integrated in the DMU-V6R software version RSV100. As previously mentioned, the interactions of alpha particles with the CR-39 can create latent tracks, which become visible after the development process. The equipment follows a programmed routine to read and count these tracks. Figure 5 shows the software layout during the reading process.

Figure 4: Radometer equipment for counting traces in CR-39 detectors.

Figure 5: Detector reading process.

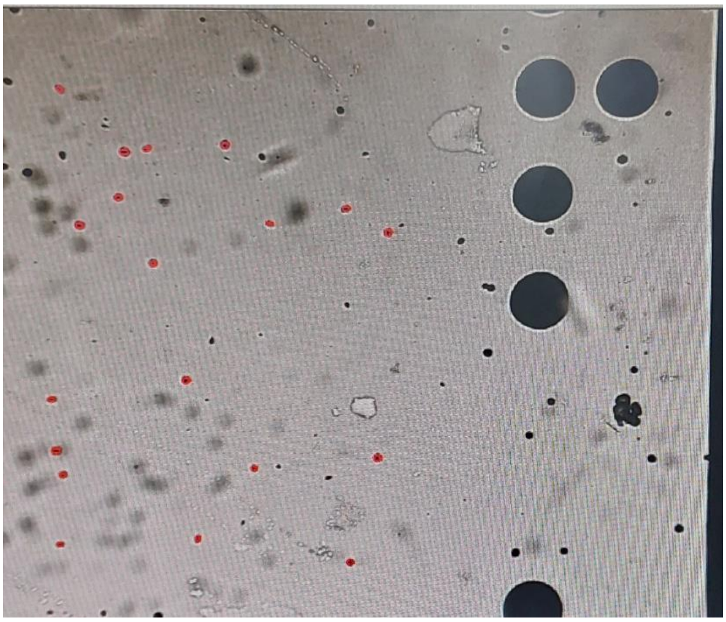


The following steps are then performed:

1. Equipment Calibration: After starting the operation, the system performs automatic calibration. This process adjusts the optical microscope and software, ensuring that subsequent measurements are accurate and consistent.
2. Detector Counting on the Slide: The equipment begins by verifying how many CR-39 detectors are positioned on the slide. This initial step is essential to ensure that the system has a clear view of all the samples that need to be analyzed.
3. Detector Identification: Each CR-39 detector has an individually engraved code, which the equipment reads to identify and record the specific sample. This ensures that the generated data is correctly associated with each detector.
4. Division into Quadrants: The software divides the CR-39 into nine quadrants, allowing for a more detailed and organized analysis of the detector surface. This division facilitates track mapping and ensures that the scanning occurs systematically.
5. Mapping and Identification of Tracks: The system maps the visible tracks in the quadrants, identifying the marks corresponding to alpha particle interactions. Only the tracks consistent with these interactions are considered for counting.
6. Track Counting in Quadrants: The equipment revisits each of the nine quadrants to count the identified tracks. Only valid tracks, i.e., those resulting from alpha particle interactions, are included in the final count. These are visually highlighted with red (Figure 6) dots to distinguish them from other marks in the image.

For the quantification of tracks on the detectors, the criterion of performing five readings and taking the average of these five readings as the final value was adopted. After counting the tracks, the data was entered into an Excel spreadsheet (Microsoft Inc.) and were statistically processed.

Figure 6: Appearance of the CR-39 detector under the microscope, showing the traces in the detector reading process.



2.4. Annual Effective Dose from Radon

Radon gas dosimetry can be interpreted in different ways. As presented in [7], there are known models for calculating the effective dose, some of which even consider the average breathing rate. However, the most widely used approach is the calculation of the Annual Effective Dose from radon and its decay products. For this process, Equation 1 was used.

$$\text{Annual Effective Dose} = \text{CRn} * \text{E} * \text{D} * \text{T} \qquad \text{Eq (1)}$$

Where:

CRn is the Radon Concentration – Bq/m^3

E is the equilibrium factor. – 0.4 for the radon equilibrium factor in indoor environments

D is the conversion factor – 9 nSv/ $(Bq \cdot h \cdot m^3)$

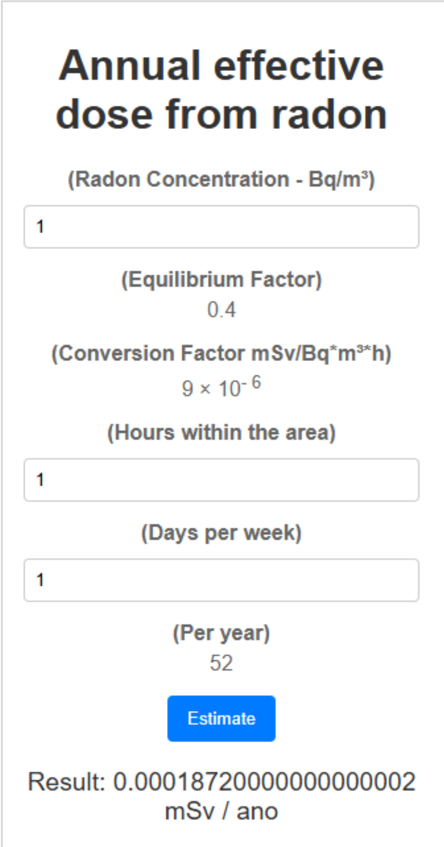
T is the time. – The exposure time in hours.

According to [7], recent determinations of the equilibrium factor for radon in indoor environments generally confirm the typical value of 0.4. Measurements in enclosed spaces show a range from 0.1 to 0.9, with most results within a 30% margin of the reference value. Similarly, the dose conversion factor for radon, based on epidemiological studies and physical dosimetry, varies between 6 and 15 nSv/(Bq·h·m^3) In this context, UNSCEAR [7] establishes a value of 9 nSv as appropriate for calculating the average effective dose. Another important factor is the exposure time, a variable that should be adjusted according to the specific scenario, as the exposure period will depend on the activities conducted in the analyzed location. In Brazil, the standard work shift is 8 hours per day, with variations in other work schedules.

In this study, we chose to calculate the maximum annual effective dose in two distinct scenarios: one with a 5-hour daily shift, 5 days per week, over 52 weeks, and another with an 8-hour daily shift over the same period.

For each building, the highest radon concentration measured in each area was used. Thus, 20 maximum annual doses will be calculated, considering both 5-hour and 8-hour daily shifts, from Monday to Friday, over 52 weeks. It is assumed that the worker is exposed throughout the entire year. To assist with the calculations, an HTML file (Figure 7) was developed containing all the previously mentioned information. In this HTML, the value of 9×10^{-6} was applied as the conversion factor to express the result in millisieverts (mSv).

Figure 7: HTML developed by the author for dose calculation.



2.5. Quality of Results

In 2024, the Radon Laboratory participated in an intercomparison exercise organized by the Environmental Radioactivity Laboratory at the University of Cantabria, Spain. This exercise was conducted in accordance with the evaluation criteria established in the ISO/IEC 17043:2023 standard. The following parameters were used for result assessment:

Eref: Reference exposure value.

Xi: Exposure value reported by participant i.

μ(Eref): Uncertainty associated with the reference value.

μ(Xi): Uncertainty declared by participant i.

The criteria adopted for data analysis include the percentage difference (D%) and the zeta-score (ζ):

Percentage Difference (D%): Represents the percentage discrepancy between the reported value and the reference value, which may indicate values below or above the reference.

$$D\ (\%) = 100\ \frac{X_i - E_{ref}}{E_{ref}} \quad \text{Eq (2)}$$

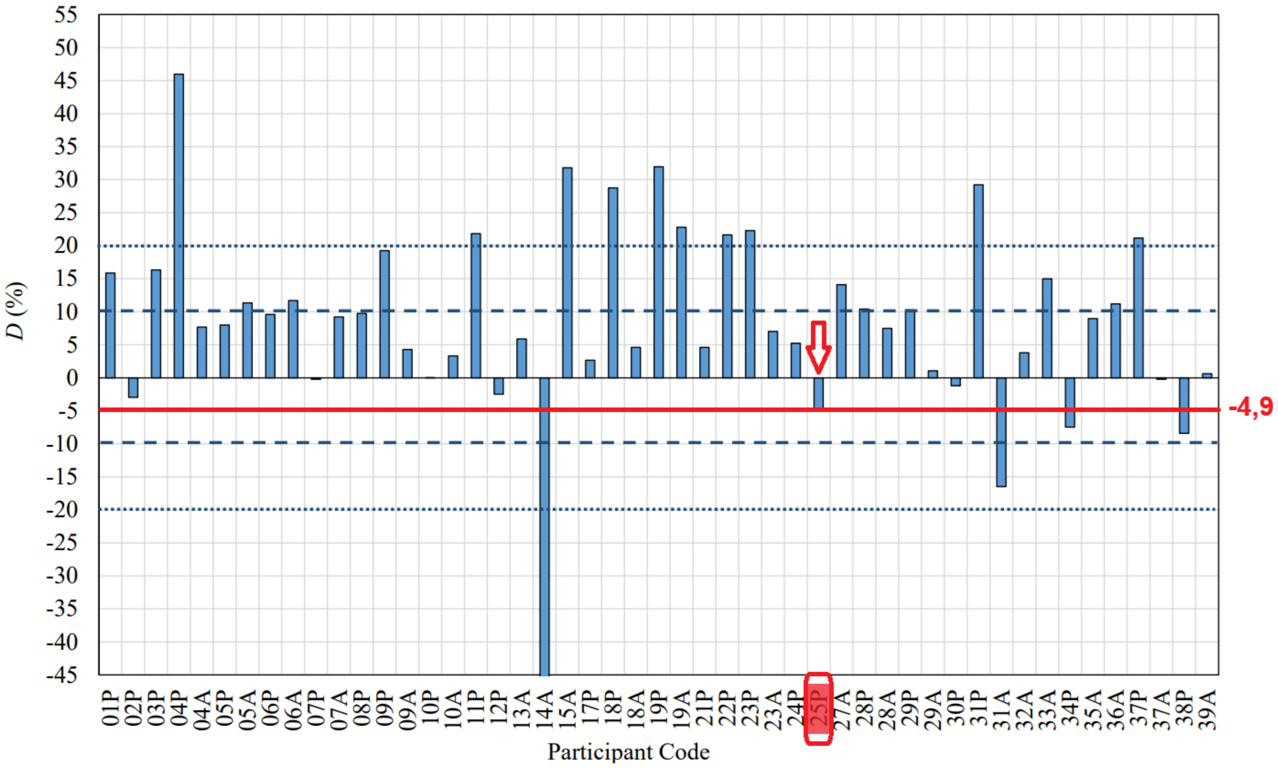
Zeta-score (ζ): Assesses the difference between the value reported by the laboratory and the reference value, considering the combined uncertainty (k = 1) of both values.

$$\zeta = \frac{|X_i - E_{ref}|}{\sqrt{u^2(X_{i)} + u^2(E_{ref})}} \quad \text{Eq (3)}$$

The results obtained by the Radon Laboratory demonstrated satisfactory performance:

Percentage Difference (D%): The calculated value was −4.9%, which falls well within the tolerance limit of ±10%, as established by the evaluation criteria (Figure 8).

Figure 8 : Percentage Difference (D%) Results.



Zeta-score (ζ): The obtained value was 0.6, classified as satisfactory, as illustrated in Figure 9. The evaluation criteria for this indicator are as follows:

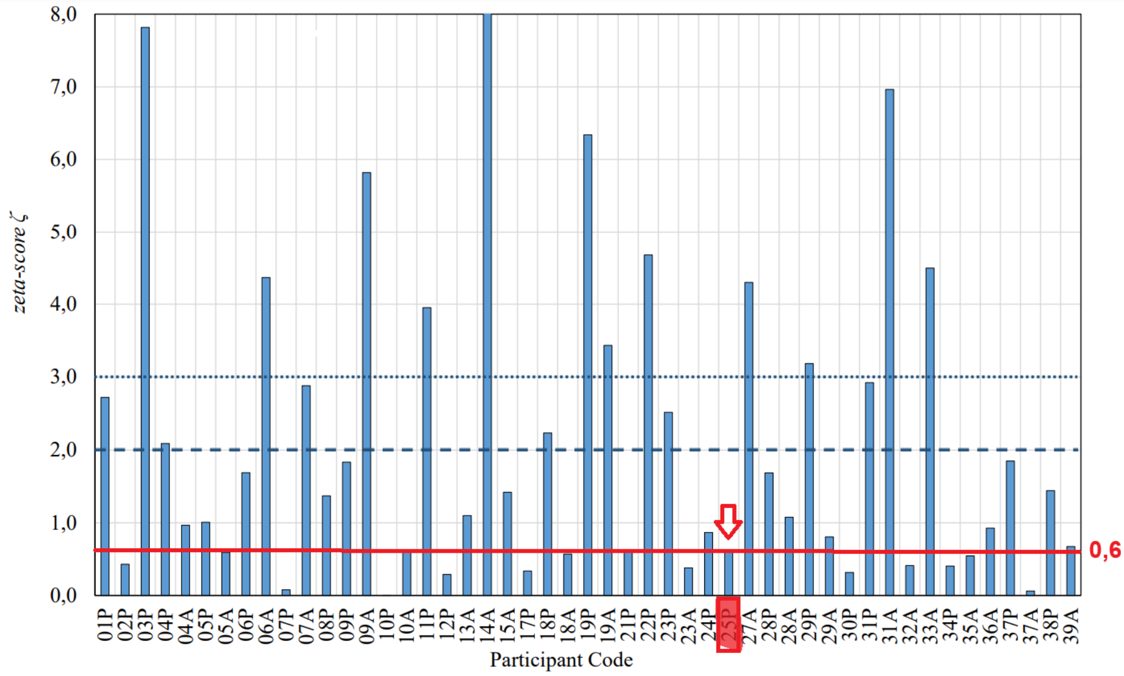
$\zeta \leq 2$: Satisfactory result.

$2 < \zeta < 3$: Questionable result.

$\zeta \geq 3$: Unsatisfactory result.

Based on these results, it is concluded that the Radon Laboratory at IRD obtained reliable measurements using CR-39 passive detectors, reinforcing the quality of its radon monitoring procedures.

Figure 9 : Zeta-score Test Results.



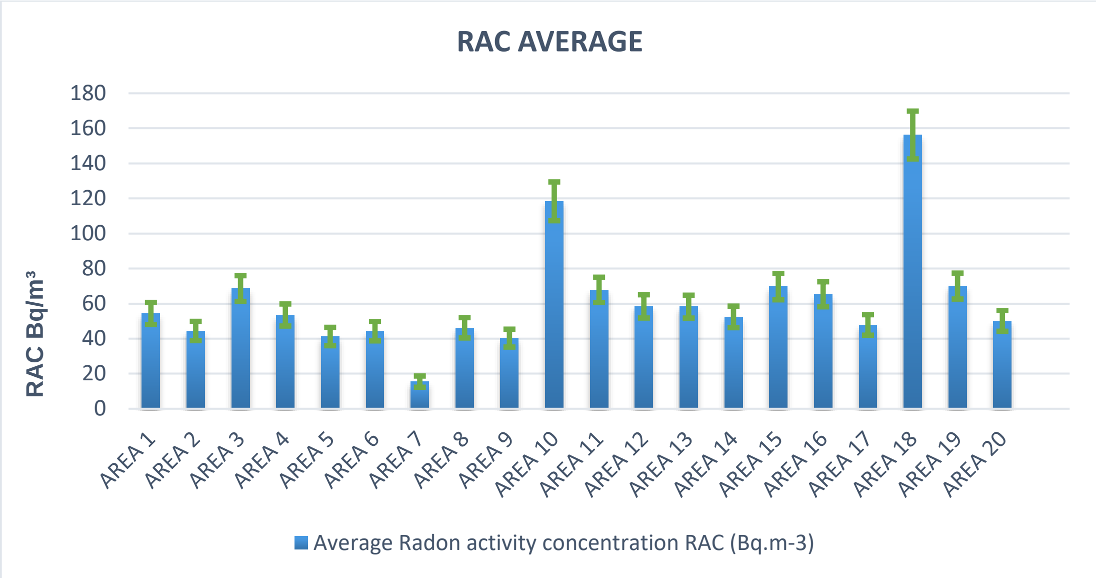
3. RESULTS AND DISCUSSIONS

After the installation, exposure, development, and track counting processes for the detectors, the 178 CR-39 detectors used provided valid data, which will be presented below.

To ensure information security, the results presented here include only the detector code, the average radon concentration, and the average uncertainty, thereby preserving the identities of individuals who use the rooms or laboratories.

Figure 10 shows a histogram of the average radon concentration in detectors exposed in each building of the IRD. It can be observed that the average radon concentration was 57.53 Bq/m³ with standard deviation of 38.87. Among the 178 detectors exposed, 164 recorded concentrations below 100 Bq/m³, corresponding to approximately 92.1% of the samples, thus meeting WHO recommendations. Concentrations between 100 Bq/m³ and 200 Bq/m³ were recorded in 10 detectors, representing 5.6% of the total. For concentrations between 200 Bq/m³ and 300 Bq/m³, 4 detectors were found, or 2.3% of the samples. No values above 300 Bq/m³ were observed.

Figure 10 : Average concentration



The histogram in Figure 11 indicates that radon concentrations at the Institute follow a normal distribution, with some outlier values highlighted. These outliers typically correspond to areas that remain without forced ventilation for most of the time and also lack natural ventilation. This condition is particularly common in spaces that remain closed for extended periods, likely due to strict access control, which often results in a lack of air exchange for many hours—or even days.

Figure 11 : Histogram of radon concentration .

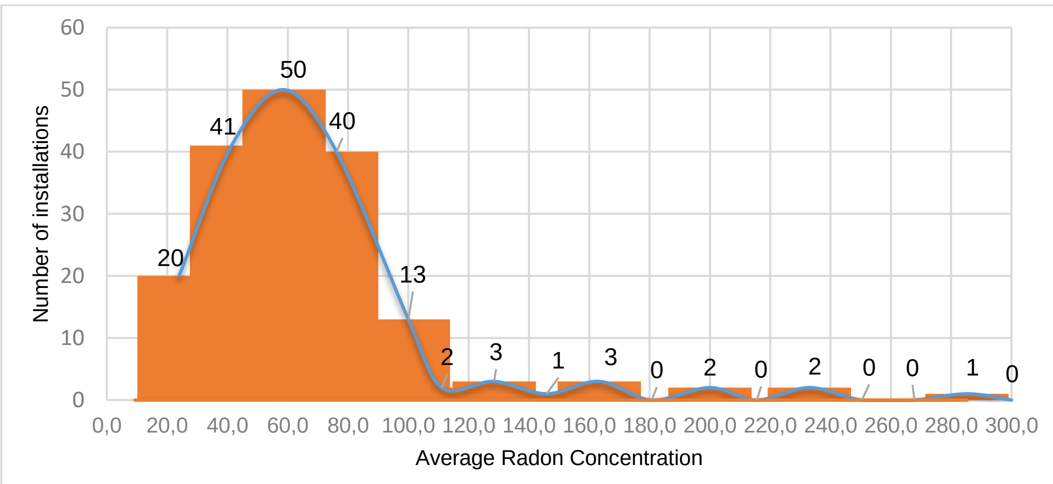
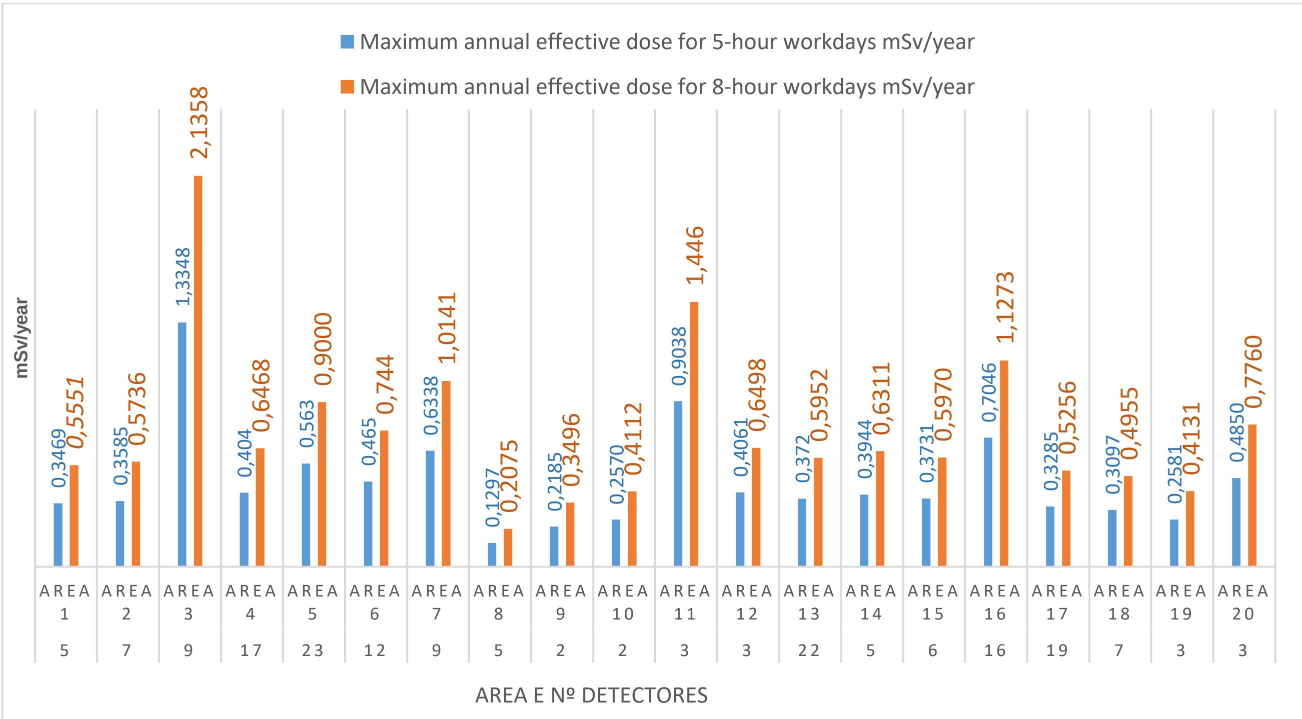


Figure 12 presents the maximum annual effective dose, calculated based on the highest radon concentration measured in each building. It is important to emphasize that these calculations are based on the highest positive concentration recorded; however, the detector that measured this concentration was not necessarily placed in a location where a worker typically remains for 5 or 8 hours per day. The analysis encompassed a range of environments, including offices, restrooms, and fountain bunkers.

The graph illustrates the maximum potential annual dose that a worker could receive in each building, considering two work shift scenarios. It can be observed that AREA 3 presents the highest dose, reaching 2.14 mSv/year for the 8-hour daily shift, followed by AREA 11 with 1.45 mSv/year. The same trend is observed in the 5-hour daily shift scenario, with AREA 3 presenting 1.33 mSv/year and AREA 11 reaching 0.90 mSv/year.

Figure 12: Distribution of the Maximum Annual Effective Dose.



For a comparative analysis, two studies were considered. The first, published in the *Brazilian Journal of Radiation Sciences*, titled "Evaluation of indoor radon gas levels in three Brazilian municipalities located in the state of Minas Gerais" [13], utilized 577 radon detectors distributed between urban and rural areas of Poços de Caldas. The results showed that 76% of the samples had concentrations between 20 and 140 Bq/m³, while 123 analyzed locations exceeded 200 Bq/m³. Regarding the standards established by NN 3.01, 9.2% of the samples showed values above 300 Bq/m³. The second study, "Human Exposure to Indoor Radon: A Survey in the Region of Guarda, Portugal" [14], published in *Radiation Protection Dosimetry* (Volume 154, Issue 2, April 2013), was conducted in the Guarda region of Portugal, an area with granite rock formations. For this study, 179 passive detectors were used, distributed in urban and rural areas. At the time of publication, Portuguese legislation stipulated a legal limit of 400 Bq/m³ for radon in private spaces. The results indicated that two-thirds of the analyzed locations had concentrations within the legal limit of 400 Bq/m³, while more than a third recorded concentrations above 800 Bq/m³. As previously discussed, the heterogeneity of the results can be attributed to various factors, already mentioned, that influence radon concentration in enclosed spaces.

Comparing the concentrations obtained at the IRD with the results from these studies, it can be observed that the values for the Institute fall within the range of occurrence and below the limit for residences according to CNEN NN. 3.01.

Measurements of radon concentration in indoor environments are intrinsically linked to the geological characteristics of the studied area. When conducting indoor measurements, in addition to the soil type, it becomes necessary to consider additional factors that can significantly influence the results, leading to substantial variations between nearby locations. Among these factors are socioeconomic aspects that impact construction models, housing standards, building materials used, the use of ventilation equipment, and population habits, such as whether windows are kept open. It is also essential to observe climatic factors, especially if the measurements were taken during drier, rainy, or winter periods. These variables may account for differences in radon concentration levels in neighboring regions.

4. CONCLUSIONS

This study aimed primarily to determine the concentration of radon-222 in the facilities of the Institute of Radioprotection and Dosimetry, with the specific objective of calculating the maximum annual effective dose from radon and its decay products, contributing to the existing radiological protection plan at the Institute.

By exposing CR-39 passive detectors for three months, followed by a chemical development process and track counting, the activity concentration of radon-222 in the air was determined for most of the server rooms and laboratories at the Institute.

The average activity concentration for the entire Institute was calculated to be 86.4 Bq/m^3, varying between 6.5 Bq/m^3 and 285.4 Bq/m^3. As demonstrated in the scientific literature on the subject, rooms and laboratories with better ventilation (using air conditioning or natural ventilation) clearly exhibit lower radon activity concentrations compared to those with poorer ventilation.

A dose calculation was performed for two scenarios: occupancy of the room for 5 hours per day and for 8 hours per day. In the first scenario, the values ranged from 0.13 mSv/year to 1.33 mSv/year, with an average of 0.45 mSv/year. For the second scenario, the values ranged from 0.21 mSv/year to 2.14 mSv/year, with an average of 0.72 mSv/year. The maximum annual effective dose was calculated based on the highest values from each area, and this dose was entirely associated with radon and its decay products.

It is important to note that, according to Brazilian regulations, no room or laboratory at the Institute of Radioprotection and Dosimetry exhibited an activity concentration exceeding the limit (300 Bq/m^3), thus the levels of radon activity concentration are in compliance with NN 3.01.

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CONFLICT OF INTEREST

The authors declare that there were no conflicts of interest.

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