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High Indoor Rn Concentration Mitigation in a Heritage Building: Case Study Analysis of the Applied Constructive Measures

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Abstract: Indoor radon (Rn) concentration is pointed out by the World Health Organization (WHO) as the second leading cause of lung cancer. Adopting mitigation measures based on ventilation procedures is an effective solution for most cases. However, the occurrence of abnormal concentrations of indoor Rn in heritage buildings, where most interventions are restricted, may lead to alternative remediation techniques. In these cases, constructive mitigation measures, such as the use of barrier membranes on the floor or specific coating mortars on the walls, can be adequate solutions. In the current investigation, two constructive measures were applied and analyzed sequentially. The preliminary long-term monitoring campaign registered extremely high indoor Rn concentration measurements. The application of a barrier membrane covering the floor of the test compartment allowed a 90% reduction in the average Rn concentration, but it nevertheless remained substantially above the recommended value of 300 Bq·m^{-3}. Subsequently, a coating mortar was applied on the walls. The combined measures contributed to a total reduction of 94% in the average indoor Rn concentration, which remains slightly above the recommended exposure limit. Despite the verified reduction and the apparent effectiveness of the measures, it is still necessary to carry out more monitoring campaigns to test their general applicability.

Keywords: indoor Rn concentration; constructive mitigation measures; Rn barrier membrane; anti-Rn slurry coating

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1. Introduction

The significance of buildings conservation and rehabilitation assumes growing importance in the valuation of built heritage [1]. This importance covers not only a theoretical and methodological approach but also assuming a practical and organizational focus [2]. The buildings' improvement that results from retrofitting must respect a multiplicity of values ranging from those of a cultural, historical, and social scope to those of an environmental and safety scope [3]. New issues and challenges emerge concerning intervention in buildings, which include a wide range of typologies, needs, problems, and values—tangible and intangible—and the development of norms, materials, diagnostic instruments, study methods and practices of intervention, management, and maintenance [4]. Furthermore, on the one hand, the ways in which built heritage is perceived by societies have evolved throughout time not only because of the gradual and active involvement of communities as an interested party but also due to the demand for a transformation that enables the adaptation to new uses, functions, and requirements [5]. On the other hand, the current socioeconomic pressure on historical heritage, associated above all with the progressive climate emergency and environmental crisis, brings added challenges around the care to be taken through the act of conserving and rehabilitating [6,7].

Based on this approach, a classified building of public interest housing a higher education institution was subject to a retrofitting process to promote Rn mitigation. Under this program, a technical room on the ground floor of the building was intervened in three evolutive stages: (i) in the first stage, the pavement was fully covered with a Rn protection membrane; (ii) in the second stage, the surrounding walls were coated with a Rn protection mortar; (iii) in a third stage, the cracks of doors and windows were sealed to prevent Rn migration from other adjacent rooms. This compartment works as a pilot to test Rn remediation solutions so that the most successful can be incorporated into the entire building.

Odorless, colorless, and tasteless, Rn is a radioactive gas formed by the decay of uranium, which is an unstable element, causing through this process the release of energy [8]. Rn is found in soil and granite-based building materials, and in Portugal, it is more common to find it in the northern areas and on the borders with Spain [9]. Rn is the greatest natural source of exposure of populations to ionizing radiation, and if this happens for prolonged periods, it can become a public health problem [10,11]. According to the World Health Organization (WHO), it is, in many countries, the second leading cause of lung cancer (after tobacco) [12–16]. Although it can be found on kitchen worktops, fireplace stones, concrete, and mortars incorporating granite aggregates, Rn enters the buildings through pipes or directly from the ground and walls of support and through cracks, gaps, and fissures [17]. In this case, the remediation procedures must involve not only covering all cracks and holes in pavements and walls in contact with the foundation soil but also allowing good air circulation daily by employing natural or mechanical ventilation [18–23].

To assess Rn risk exposure, rooms are generally classified according to the type of construction, with emphasis on the type of foundation or room elements in contact with the ground (basements totally or partially installed underground or ground floors concrete slabs laid directly on the ground) or floors raised above the ground over a space. The room classification is important since the Rn concentration is usually higher in rooms located close to the foundation soil, mainly in basements generally used as cellars, pantries, technical rooms, storerooms, and garages, that is, as spaces of less permanent or frequent occupancy. To evaluate Rn risk exposure, Decree-Law No. 108/2018 establishes in Portugal the legal regime for radiological protection, transposing Directive 2013/59/Euratom, which sets basic safety standards relating to protection against the dangers resulting from exposure to ionizing radiation. Namely, this applies to human activities in the presence of natural radiation sources leading to a significant increase in the exposure of workers or the population, to sources that lead to the presence of Rn inside buildings, external exposure to radiation from construction materials, and situations of prolonged exposure to this gas. With the entry into force of Decree-Law No. 108/2018, which took place on 2 April 2019, the Portuguese Environment Agency (APA) became the new competent authority in this matter.

In this way, the main objective of this research is to assess the result of the implementation of a set of Rn mitigation measures designed to remediate extraordinarily high indoor Rn levels in an ancient building, listed as National Architectural Patrimony, in a scenario where the use of mechanical ventilation systems for Rn mitigation is strongly constrained. For that, a room specifically selected on the ground floor of a building of heritage and architectural interest working as a school building was subject to a comprehensive indoor Rn assessment in three different stages by using long-term Rn tests over 3 months: (i) the first stage, including measurements performed before the implementation of any Rn mitigation measure; (ii) a second stage in which the in situ measurements were implemented after the pavement floor was covered by a Rn membrane barrier; (iii) and a third state comprehending measurements after the adoption of a wall cladding made of a Rn-proof mortar. The main purpose of this study is to analyze the impact of the adopted mitigation measures on indoor Rn concentration in a building located in the Alto Minho region northwest of Portugal, in which Rn monitors were installed on the ground floor. The monitored room is laid on a granite substratum bedrock, and the pavements, walls, and partitions are mainly built also with granite elements materials.

2. Literature Review

The assessment of the health status of buildings necessarily includes the quantification of air quality parameters, which include the assessment of indoor Rn concentration since this radioactive element has been classified as harmful to health. Despite being generally associated with granite-type geological substrates, thus enhancing the probability of high indoor concentrations occurring in buildings, its presence can also occur in other types of substrates. Soils and rocks with lower emanation potential can also lead to high concentrations of indoor Rn, especially if combined with building characteristics that are conducive to the concentration of the gas inside, namely, for example, due to the lack of ventilation that promotes renovation of air or that presents an architectural configuration that works as a trap for the retention of the gas inside. Rizo-Maestre and Echarri-Iribarren [24], in a study carried out in Alicante (Spain), analyzed the indoor Rn concentration in underground buildings implanted in clayey soils, demonstrating that despite the Rn emanation potential of these soils being considerably lower than that of that what happens in granitic soils, the structure of the building enhances the accumulation of Rn in its interior. In this study, the authors identified Rn concentrations in the building selected for the study as five times higher than those registered in other similar buildings, demonstrating that the constructive typology of the buildings also plays a determining role in the concentration of indoor Rn.

Despite the growing interest in the topic, the number of works available on mitigation measures cannot be considered abundant. In fact, searches in the main bibliographic databases, such as *SCOPUS* or the *Web of Science*, mainly present works related to assessment. Studies related to mitigation actions, such as those presented by Sicilia et al. [25], in which the authors address the theme of transport, concentration patterns, and Rn mitigation techniques applied to confined spaces, tend to present solutions related to the ventilation of indoor spaces. In this specific case, the authors studied the effects of pressurizing and depressurizing the compartments on the Rn concentration, demonstrating that the introduction of fresh air diluted the Rn concentration, and the slight increase in the pressure reduced the entry of gas by the advection mechanism. The authors concluded that the depressurization technique was the least effective mitigation technique since this method contributes to the negative pressure created in the compartment facilitating the emanation of Rn from the soil. As a corollary of this study, the authors recommend that before applying any mitigation technique, it is necessary to study the space to be remediated and the possible impact on neighboring spaces, which is in the same line of several other authors [26–33].

The authors point to similar recommendations, continually reinforcing the need to ventilate spaces as a corrective measure so that, as recommended by Rizo-Maestre and Echarri-Iribarren [34], it is necessary to also account for the areas considered to have a low presence of Rn gas to achieve healthy constructions. These authors, who studied the high risk of low indoor air quality in poorly ventilated buildings, reinforced once again the need to establish procedures for the ventilation of spaces, especially in cases where, despite the geological substrate not being potentially rich in Rn, there are still conditions that enhance the accumulation of gas. Along the same lines, Martin Sánchez and Nuevo [35], in the study carried out on actions for remediation in areas with a large concentration of indoor Rn, analyzed working places in the region of Extremadura (Spain). As corrective measures, ventilation protocols were indicated as well as other measures, such as changing the location of the workstation or limiting the time spent in the most exposed places. Furthermore, as also concluded by Rizo-Maestre and Echarri-Iribarren [36], they reinforced the role of the constructive typology as one of the factors to be considered for the concentration of indoor Rn.

As seen from the available works, the focus has been on mitigation measures directed toward the ventilation of spaces. One of the first references reporting the use of barrier membranes is found in the study presented by Groves-Kirby et al. [37], where the authors compared the concentration of indoor Rn in houses with and without the placement of barrier membranes. Based on the obtained results, the authors recommended that mandatory testing be introduced for all new dwellings in Rn-affected areas. In the following years, other authors, such as Cosma et al. [38], Muñoz et al. [39], Khan et al. [40], Burghele et al. [41], Gong et al. [42], Gaskin et al. [43], and Sainz et al. [33], presented case studies of the application of barrier membranes, including comparative analyses between different types of materials. Concerning anti-Rn mortars, most studies were found to refer to their existence, but no case studies were found where their effectiveness was analyzed. No study investigated the use of two different constructive mitigation measures, justifying the novelty of the case study analyzed in this work.

3. Materials and Methods

3.1. Framework

To carry out this study, we selected a historic building called Mosteiro de Refóios do Lima, located in the parish of Refóios do Lima, municipality of Ponte de Lima, in the Alto Minho region (northern Portugal). The building, currently occupied by the Escola Superior Agrária of the Polytechnic Institute of Viana do Castelo (ESA IPVC), is classified as a national monument of architectural interest. Figure 1 shows the location of the building as well as its general overview. In its framework, the university campus of ESA IPVC has a total area of 17 hectares distributed by the main academic building, where the present study was carried out, as well as agricultural annexes, university residences, and agricultural production areas for animal exploitation. The main academic building, which dates to the 12th century, but has undergone various interventions and renovations over time and was built essentially in masonry using granite stone exploited in the abundant quarries in the region. The entire region is rich in several types of granitic rocks, with lithology dominating the region.

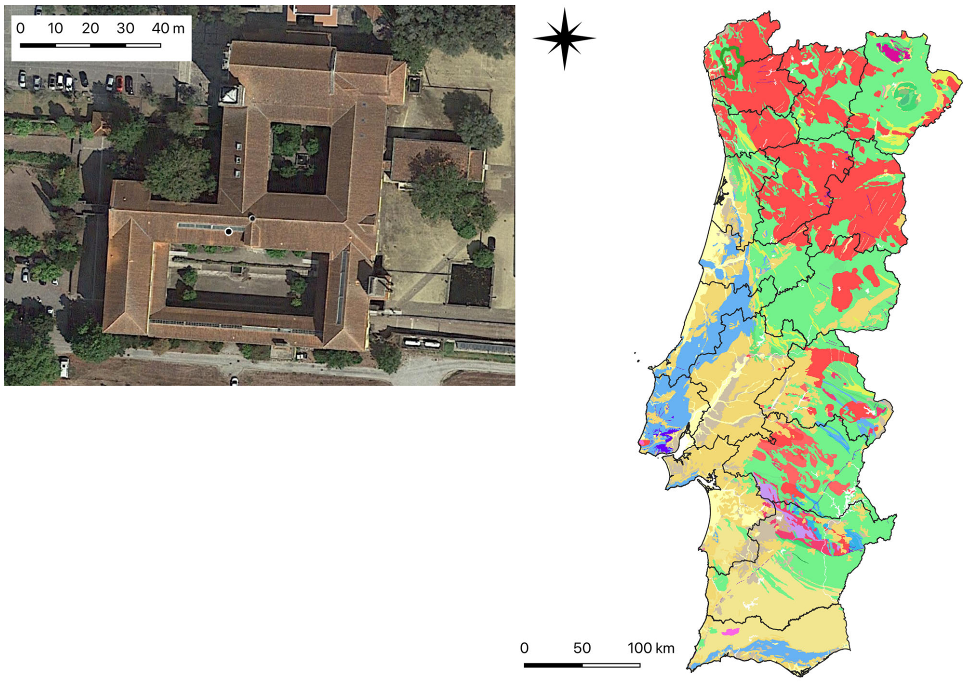


Figure 1. Location of the ESA IPVC academic building. The green circle shows the location of the municipality of Ponte de Lima. The simplified geological representation of Portugal shows the distribution of the granitic rocks (red) and the associated metamorphic rocks (light green) usually associated with high indoor Rn potential. The black dot in the main building highlights the position of the room where the indoor Rn concentration measurements were taken.

In fact, in the region, there is an abundance of granite-type lithologies, namely, two-mica granites with feldspar megacrystals (locally known as "horse tooth"), which are deeply fractured by a system of faults with N-S orientation. This intense fracture of the rocks must be the origin of the high concentrations of Rn that are verified in the region, where the Rn emanation potential is very significant, greatly contributing to the high concentrations of indoor Rn [44,45]. The original builders implemented the structure respecting the topography of the land so that it evolves as in terraces along the slope. The main entrance is at a level that accompanies the entire N exposure, while the opposite side, exposed to S, is at a lower level by about 6 m, culminating in an interior patio flanked by buildings now for educational use but which once functioned as storage rooms. Figure 2 shows a section (A,B) with N-S direction. It is schematically demonstrated that the compartment selected for carrying out the present monitoring study of the indoor Rn concentration is in direct contact with the geological substrate (soil and rock) on the pavement and partially on the walls. View (A) refers to the main entrance of the building, exposed to the N, and view (B) presents the opposite facade, exposed to the S, where it is visible the difference in level between Floor-1 and the inner patio with a difference of six meters in the level.

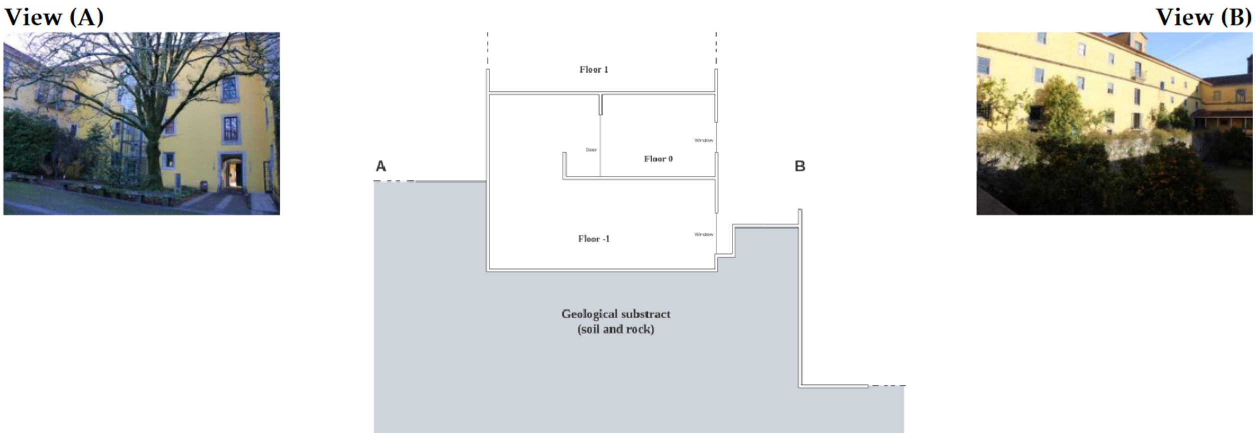


Figure 2. Section of the implantation of the building on the geological substratum. Views from each side of the main academic building of ESA IPVC, where view (**A**) refers to the main entrance of the building, exposed to the N, and view (**B**) presents the opposite facade, exposed to the S, where it is visible the difference of six meters between Floor -1 and the inner patio.

3.2. Monitoring and Data Acquisition

Indoor Rn concentration monitoring was carried out in a compartment located on Floor-1 of the ESA IPVC academic building. The compartment in question is located in the SW corner of the building, with the floor laid over the geological substrate and at least two walls in contact with the geological substrate. The compartment, which currently does not have any use involving the presence of people, may have been used as a storage room in the past and occupies an area of 12.6 m^2 and a volume of 34 m^3. Monitoring occurred between 13 March 2019 and 16 November 2021, as shown in Figure 3. Figure 4 shows the sequence of works carried out in the different phases.

Monitoring took place in three phases, which correspond to the indoor Rn concentration measurement campaigns, interspersed with the tasks of placing constructive measures for Rn migration, namely the application of the barrier membrane and the mortar. Phase II comprises an additional monitoring campaign to ascertain the impact of air circulation through the door that separates the compartment from the rest of Floor-1. Thus, Phase I corresponds to the preliminary assessment with the subsequent application of the barrier membrane. Phase II comprises the indoor Rn concentration assessment, followed by sealing the compartment door and a new indoor Rn concentration assessment campaign. Phase III begins with applying the coating mortar on the compartment walls and the subsequent assessment of the indoor Rn concentration. For the assessment of the indoor

Rn concentration, two AirThings Corentium Plus Rn Monitor probes, model QRI, were used. The two identical probes were used in all monitoring stages, so it is assumed that the error associated with the measurements is always similar. Table 1 presents the technical specifications of the probes used in the monitoring campaigns.

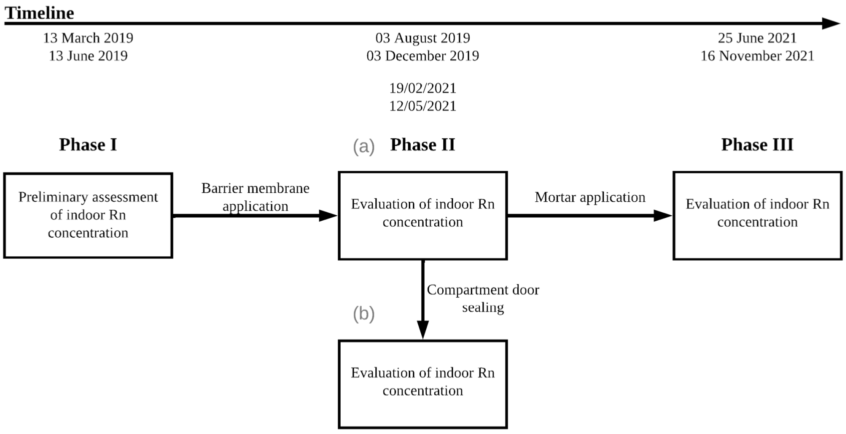


Figure 3. Organization of the works carried out during the monitoring process of the indoor Rn concentration in the compartment selected for the present case study.

Figure 4. A sequence of works carried out. (**a**) Initial appearance before the execution of the tasks; (**b**) barrier membrane application; (**c**) sealing of the outer compartment door; (**d**) application of mortar to the compartment walls.

Table 1. Technical specifications of the AirThings Corentium Plus Rn Monitor probes, model QRI, used in the different phases of monitoring the indoor Rn concentration.

Rn Sampling	Passive Diffusion Chamber
Detection method	Alpha spectrometry
Detector	1 silicon photodiode
Diffusion time constant	25 min
Measurement range	0–50,000 Bq·m^{-3}
Sampling rate	1 h
Operation environment	4 °C to 40 °C 5% RH to 85% RH non-condensing 50 kPa to 110 kPa
Temperature	0.336 °C resolution, ±1 °C accuracy
Humidity	0.5% RH resolution, ±4.5% accuracy
Barometric pressure	0.01 kPa resolution, ±1 kPa accuracy

The purpose of using the two probes to monitor the indoor Rn concentration was to check that there were no errors associated with the equipment. After each monitoring campaign, the data were analyzed by comparing the means and variances of each group. For this purpose, the Student's *t*-test was used to compare means, and the F-Snedecor statistical test was used to compare variances. For each of the four measurement campaigns, the results obtained by applying the Student's *t*-test and F-Snedecor tests were consistently higher than 0.5, not rejecting the null hypothesis (H0). In this way, it is concluded that there are no statistically significant differences between the means of the two data groups and no differences between the variances, which are supposedly equal. As there are no statistically significant differences, the data sets can be merged by determining the average value of each corresponding pair of measurements, starting to use only one data set for each phase of the indoor Rn concentration monitoring campaigns.

4. Results and Discussion

The results obtained in the three stages of the indoor Rn concentration monitoring, already transformed by merging the sets acquired by the two probes, are presented in Table 2.

Table 2. Summarized data obtained from the monitoring phases of indoor Rn concentration, carried out from 13 March 2019 to 16 November 2021.

	Phase I	Phase II (a)	Phase II (b)	Phase III
Monitoring period	13 March 2019 to 13 June 2019	3 August 2019 To 3 December 2019	19 February 2021 To 12 May 2021	25 June 2021 To 16 November 2021
Nr. of measurements	2205	2180	1970	3457
Average value	6459 Bq·m^{-3}	637 Bq·m^{-3}	9052 Bq·m^{-3}	373 Bq·m^{-3}
Standard deviation	3883 Bq·m^{-3}	475 Bq·m^{-3}	2572 Bq·m^{-3}	207 Bq·m^{-3}
Min. value	134 Bq·m^{-3}	22 Bq·m^{-3}	59 Bq·m^{-3}	4 Bq·m^{-3}
Max. value	18,738 Bq·m^{-3}	3407 Bq·m^{-3}	15,312 Bq·m^{-3}	1129 Bq·m^{-3}

Phase I monitoring, which took place between 13 March 2019 and 13 June 2019, accounted for a total of 2205 measurements at one-hour intervals, with an average indoor Rn concentration of 6459 Bq·m^{-3} and a standard deviation of 3853 Bq·m^{-3}. Such a high standard deviation indicates an equally high variance of the values obtained, evidenced by the minimum value recorded, 134 Bq·m^{-3}, and the maximum value recorded, 18.738 Bq·m^{-3}. In other words, there was a difference of 18.604 Bq·m^{-3} between the lowest and highest values for the indoor Rn concentration inside the compartment, indicating a significant fluctuation in the results. When carrying out the distribution of measurements obtained by successive intervals of 300 Bq·m^{-3}, it was verified that only four values fall within the interval (0; 300) Bq·m^{-3}. Only 0.002% are below the recommended threshold for occupant exposure, while 99.998% are above the recommended exposure value. Figure 5 shows the distribution of results obtained by categories with successive increments of 300 Bq·m^{-3}.

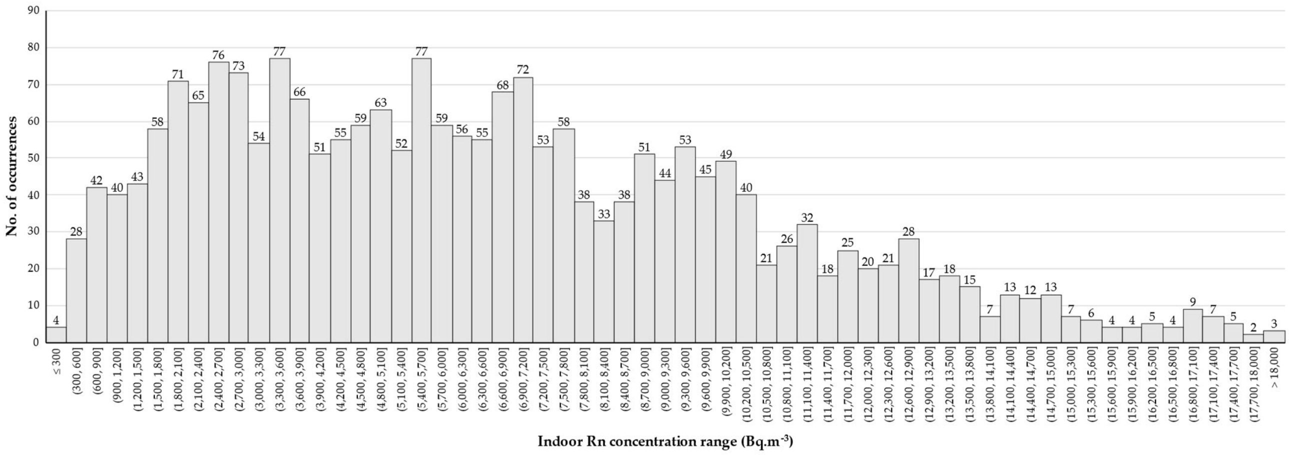


Figure 5. Distribution of measurements made in the preliminary assessment of Rn concentration in the compartment.

As can be seen from the distribution of results in the previous figure, the need to apply a mitigation measure to correct the indoor Rn concentration becomes evident. In this specific case, given the situation of structural confinement in which the compartment is located, there is no possibility of natural ventilation since the compartment does not have any opening to the outside except for the access door. However, using the door to ventilate the space does not seem to be recommended since it could contribute to increasing the Rn concentration in cabinets occupied by ESA IPVC administrative services staff. Thus, the option fell on the use of a barrier membrane to be applied over the floor to prevent the entry of Rn and its accumulation inside the compartment. In this case study, it was decided to use a Monarflex RMB350 barrier membrane with the technical specifications shown in Table 3.

Table 3. Technical specifications of Monarflex RMB350 (http://www.necoflex.is, accessed on 10 October 2022).

Elongation	19%
Tear resistance	405 N
Water vapor transmission	0.03 g·m^{-2}·d^{-1}
Color tone	Red (top side) and black (underside)
Thickness	0.35 mm

After applying the barrier membrane and also covering the baseboards of the walls, a new monitoring of the indoor Rn concentration was carried out, which took place from 3 August 2019 to 3 December 2019, totaling 2180 measurements with an interval of an hour. The results show an average value of 637 Bq·m^{-3}, with a standard deviation of 475 Bq·m^{-3}. In addition, at this stage, the high variance of the results obtained became evident, with a minimum recorded value of 22 Bq·m^{-3} and a maximum value of 3407 Bq·m^{-3}. As can be seen in Figure 6, the distribution of measurements by successive intervals with increments of 300 Bq·m^{-3} already presents a configuration different from that previously observed in Phase I, with the results being distributed in a more balanced way and already showing a significant reduction in the indoor Rn concentration. As can be seen, the average value registered shows a decrease of 90.14% compared to the average value verified in the preliminary assessment of Phase I.

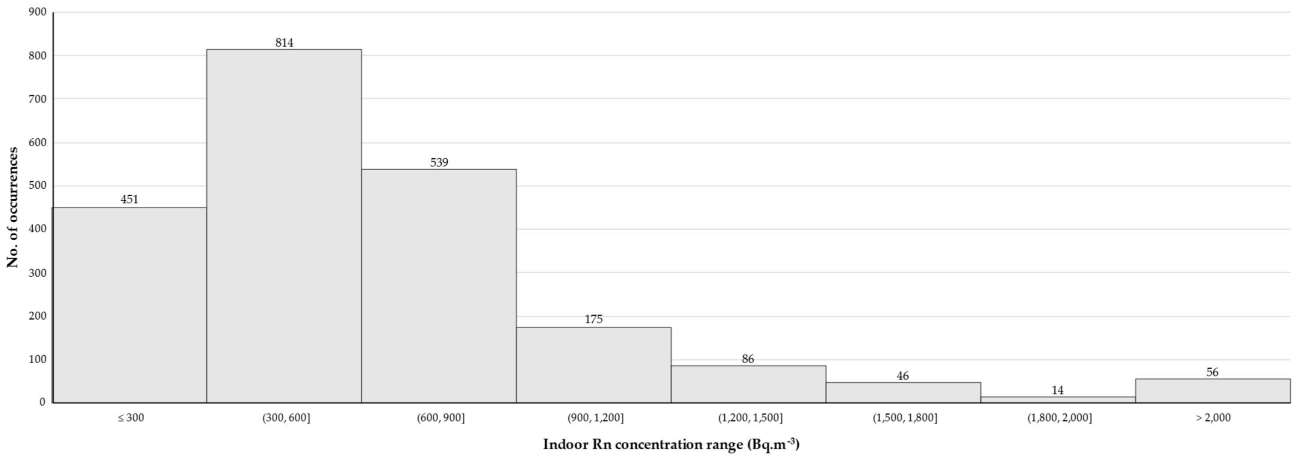


Figure 6. Distribution of measurements performed in the evaluation of the Rn concentration in the compartment after application of the barrier membrane.

In fact, after applying the barrier membrane, it appears that 20.69%, corresponding to 451 occurrences, are within the interval (0; 300) Bq·m^{-3} and that only 2.57%, corresponding to 56 occurrences, are in the class >2000 Bq·m^{-3}. Most of the results, 76.71%, corresponding to 1674 occurrences, are included in the interval (300; 2000) Bq·m^{-3}. However, despite the significant decrease in the indoor Rn concentration, it was observed that in most situations, the values continued to be above the recommended value of 300 Bq·m^{-3} although no longer showing the peaks of 18,000 Bq·m^{-3} recorded in Phase I. In this way, the effectiveness of the barrier membrane in mitigating the concentration of indoor Rn can already be confirmed. However, it is still not at the recommended value for human exposure.

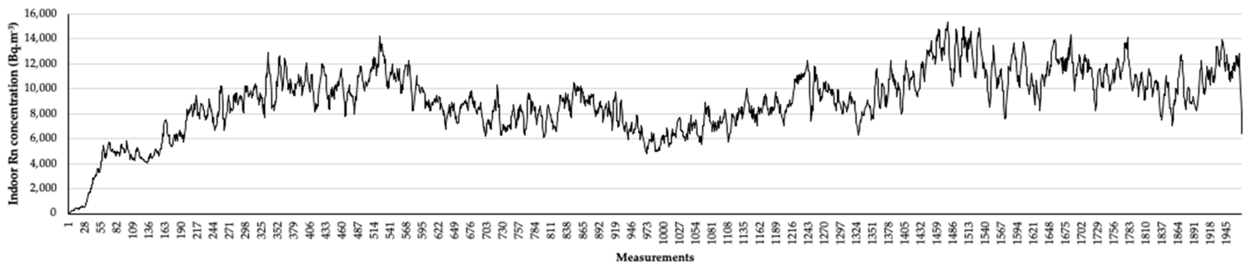
In the course of these results obtained in Phase II, it was considered suitable to confirm the impact that the compartment door could have on the final balance of the indoor Rn concentration through the circulation of air from other compartments. That is, we proceeded to verify whether the concentration of indoor Rn still registered in the compartment could be related to Rn coming from adjacent compartments and not just from the floor and walls of the compartment. For this purpose, the compartment access door was sealed with the same barrier membrane used to insulate the floor.

Phase II(b) monitoring took place between 19 February 2021 and 12 May 2021, with a total of 1970 measurements with an interval of one hour, with an average value of 9052 Bq·m^{-3} being recorded and with a standard deviation of 2572 Bq·m^{-3}. Once again, the variance of the results is very high, with a minimum recorded value of 59 Bq·m^{-3} and a maximum value of 15,312 Bq·m^{-3}, that is, presenting results similar to those verified in the preliminary monitoring carried out in Phase I. However, when analyzing the evolution of the results through their projection in the graph shown in Figure 7a and comparing it with the evolution of the results obtained in the preliminary evaluation assessment, which is shown in Figure 7b, the different disposition of the results obtained is notable, indicating a cumulative tendency. This tendency is confirmed through the distribution of the results obtained by the class intervals, as seen in Figure 8.

As can be seen, the frequency distribution of occurrences is concentrated in the intervals between (4200; 14.100) Bq·m^{-3}, indicating a particular cumulative trend in the concentration of indoor Rn. Even at first glance, the distribution of the results may show an approximation to a normal distribution of the data obtained. However, by applying the one-sample Kolmogorov–Smirnov test to all data sets, with the null hypothesis being that the distribution of the data is normal, it was confirmed that none of the data sets follows the normal distribution since the significance levels obtained are more significant than 0.05 in all situations, rejecting the null hypothesis. Although they do not follow a normal distribution, the data obtained in Phase II(b) are the closest to this distribution, as shown in

Figure 9c, indicating that this difference concerning the other sets of data may be associated with the cumulative trend caused by the confinement of the compartment.

(**a**)



(**b**)

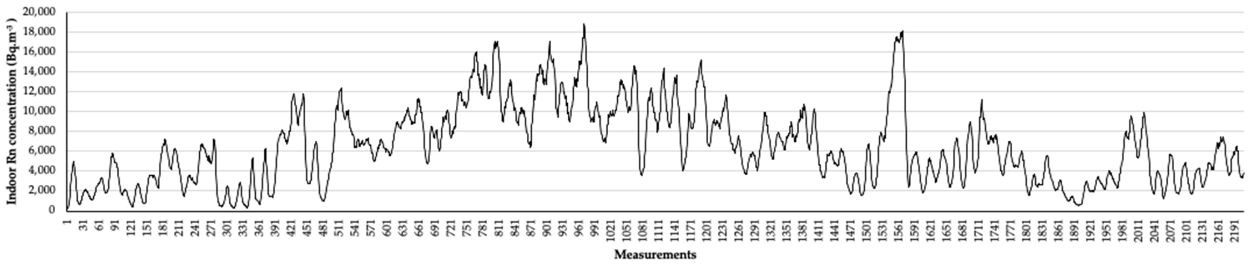


Figure 7. Evolution of indoor Rn concentration measurement results. (**a**) After compartment door sealing; (**b**) results of the preliminary assessment in Phase I.

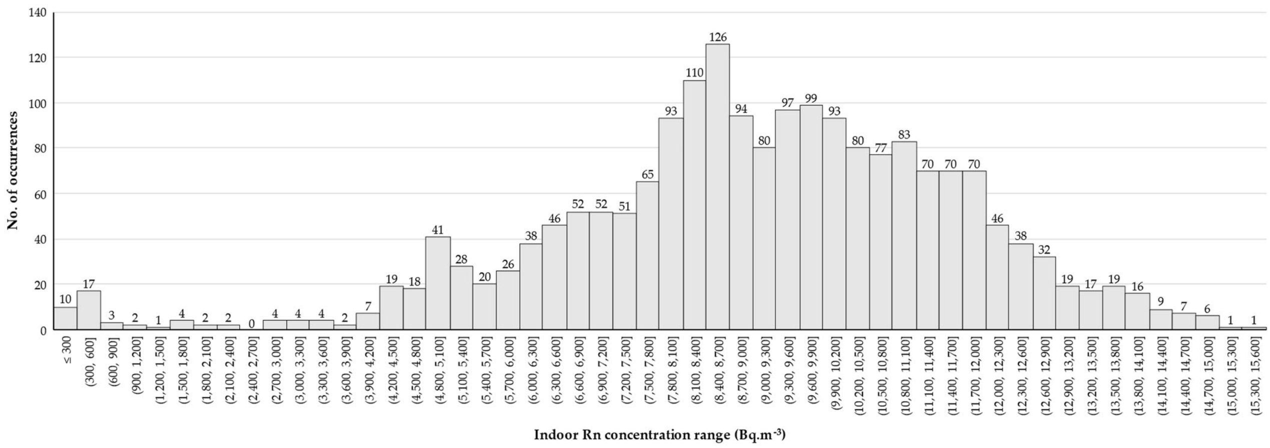


Figure 8. Distribution of indoor Rn concentration measurements in the compartment after sealing the door.

It will most likely be the compartment that contributes to the transfer of Rn to the adjacent compartments through the access door if conditions of pressure differences or displacement of air masses are verified. This situation also confirms that applying the barrier membrane does not eliminate the emanation of Rn, justifying the adoption of additional mitigation measures, such as applying a coating mortar for the walls. In the present situation, it was chosen to use an anti-Rn slurry coating. The selected option is a two-component permanently elastic polymer cement sealing suspension intended for waterproofing various concrete and reinforced concrete construction elements and whose technical specifications are presented in Table 4.

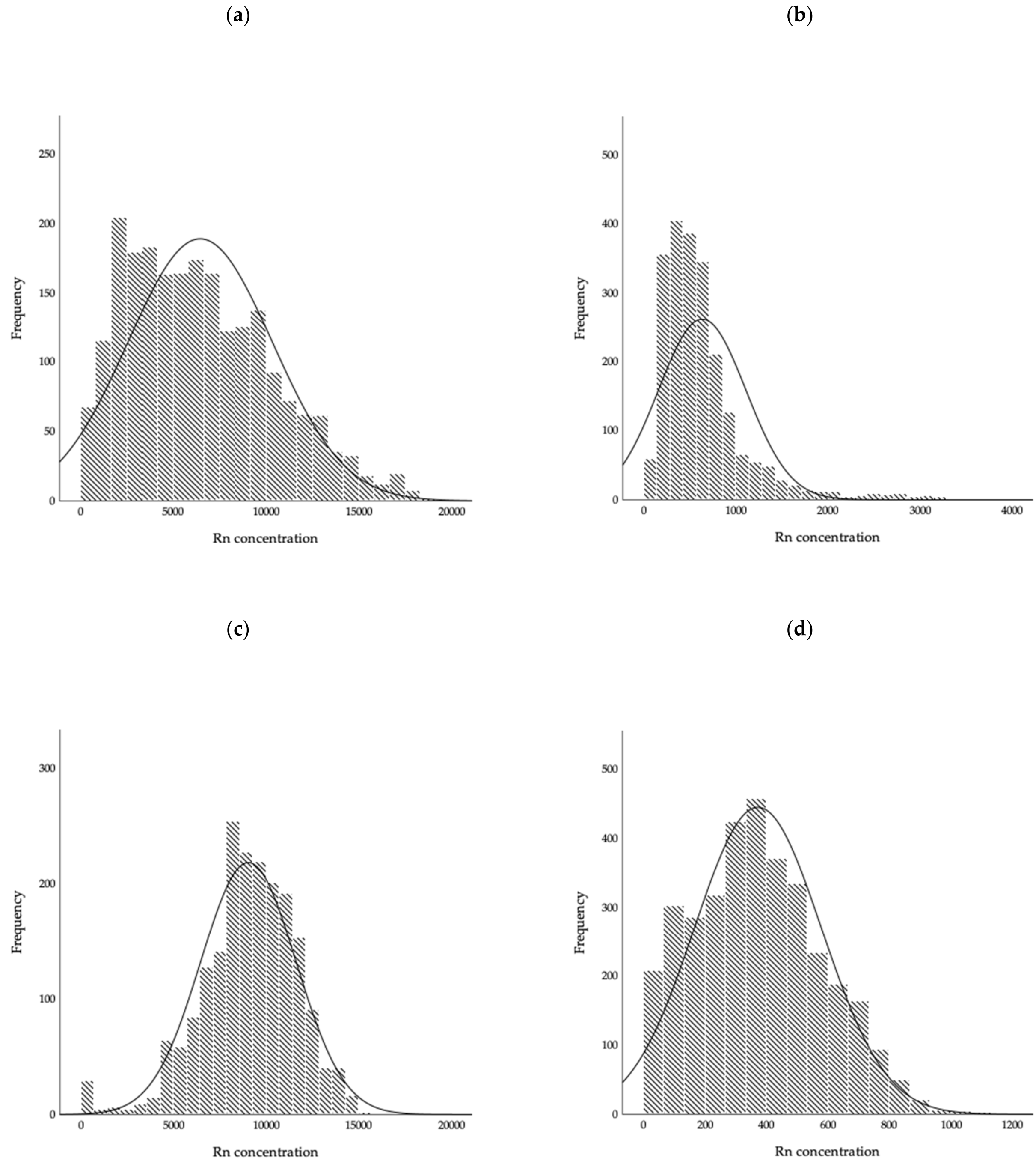


Figure 9. Histograms of the frequency distribution of occurrences. (**a**) Preliminary Phase I Assessment; (**b**) evaluation after application of the barrier membrane in Phase II(a); (**c**) evaluation after sealing the compartment door in Phase II(b); (**d**) evaluation after applying the coating mortar in Phase III.

Phase III occurred between 25 June 2021 and 16 November 2021, totaling 3457 measurements, with an interval of one hour, an average value of 373 Bq·m^{-3}, and a standard deviation of 207 Bq·m^{-3}. There is still significant variance in the results, with a minimum value of 4 Bq·m^{-3} and a maximum value of 1129 Bq·m^{-3}. However, despite the results' variability, the range is much smaller than those seen in previous phases. Frequency analysis, shown in Figure 10, demonstrates a very significant reduction in the concentration of indoor Rn after applying the coating mortar on the walls, with a decrease of 41.44% concerning the monitoring carried out after the application of the barrier membrane.

Table 4. Physical and mechanical parameters of WATERFIN PV (http://www.betosan.cz, accessed on 6 December 2022).

Color of Dry Component	Non-Standard Grey/White
Color of the Liquid Component	White
Color of coating	Grey/White
Minimum film-generating temperature of liquid component (°C)	>1
Tensile strength (MPa)	>1.5
Yield ability (%)	>30
Vapor resistance (m)	<4
Water tightness (under both negative and positive effects of water pressure)	>8 bars (80 m water column)
Coefficient of Rn diffusion D ($m^2 \cdot s^{-1}$)	$9.4 \times 10^{-12} \pm 0.5 \times 10^{-12}$

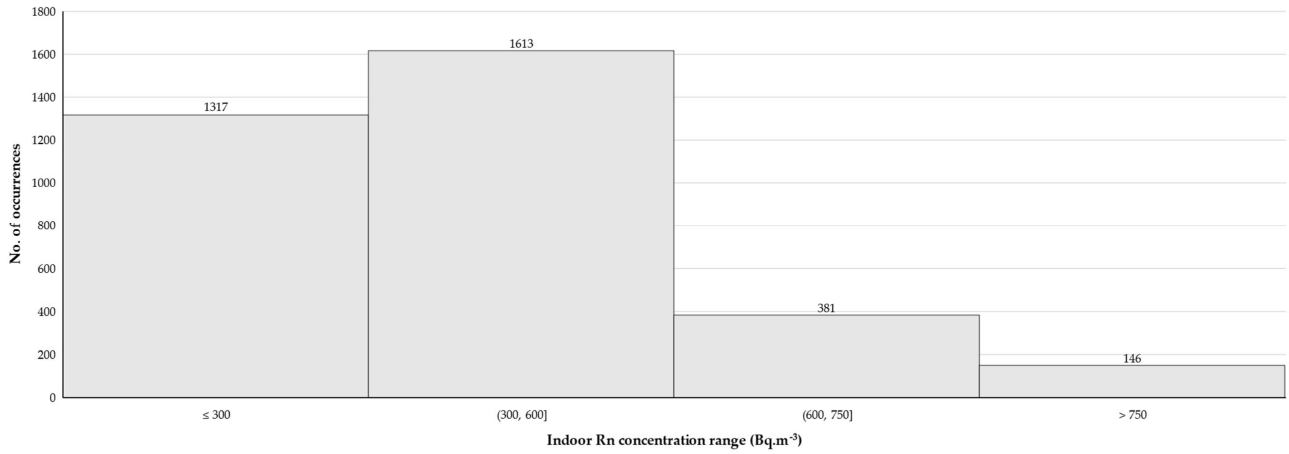


Figure 10. Distribution of measurements taken in the evaluation of Rn concentration in the compartment after mortar application.

After applying the coating mortar to the compartment walls, about 38.90%, corresponding to 1317 occurrences, coincided with the interval (0; 300) $Bq \cdot m^{-3}$, while 4.22%, corresponding to 146 occurrences, coincided with the class >750 $Bq \cdot m^{-3}$. However, 57.68%, corresponding to 1994 occurrences, were still above the recommended value for human exposure in the interval (300; 750) $Bq \cdot m^{-3}$.

The combination of the two constructive measures in the present case study corresponds to a reduction of 94.23% of the concentration of indoor Rn in the compartment. As can be seen in Figure 11, which shows the superimposition of the evolution of the data collected in the different stages of monitoring the concentration of indoor Rn after the application of constructive measures, a very significant attenuation of the levels of Rn in the indoor air is confirmed.

Despite the reduction of about 94% of the indoor Rn concentration, the results obtained continue to show a tendency for the occurrence of values above the recommendation of 300 $Bq \cdot m^{-3}$. However, although the results remain above 300 $Bq \cdot m^{-3}$, this does not mean that the recommended measures are not efficient but rather that these types of actions may present different levels of effectiveness depending on whether they are applied in extreme situations, as is the case shown in this state, or in more common situations, in which the registered values are lower. It is also important to consider the possibility that these constructive measures are more efficient if applied in cases where new buildings are constructed, in locations where the Rn emanation potential is recognizably high, and in conjunction with other types of measures, namely, the existence of airboxes and ventilation systems, both natural and forced, to promote indoor air renewal and dispersion of Rn concentration. At the same time, the adoption of measures for the continuous monitoring of the indoor Rn concentration, namely through IoT systems, will allow the anticipation of the moments in which the indoor Rn concentration exceeds the recommended values, transforming it into a risk situation for the users of indoor spaces.

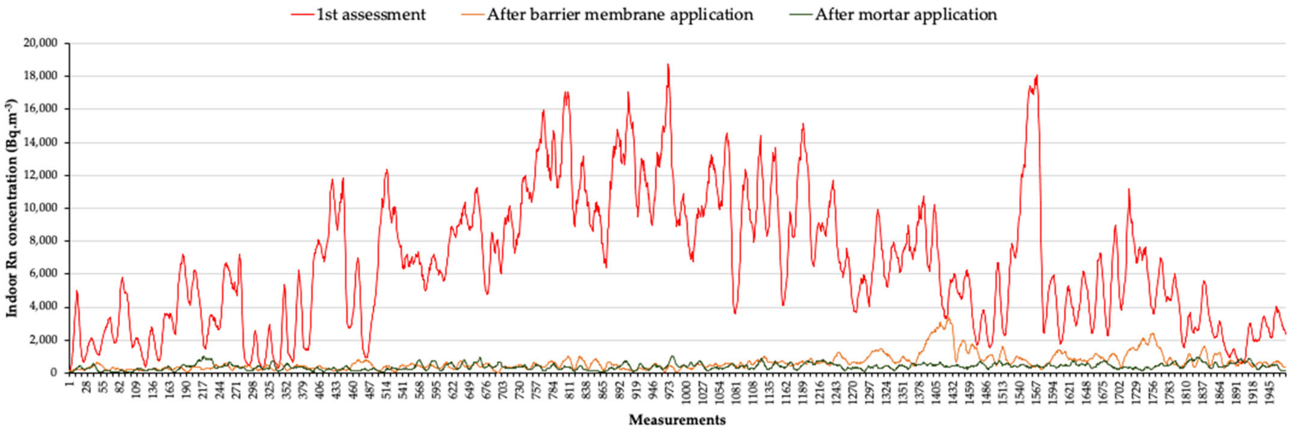


Figure 11. Evolution of the data collected in the different indoor Rn concentration monitoring phases.

5. Conclusions

The remediation of problems related to indoor air quality in buildings is increasingly a concern for the occupants of these spaces because, when associated with this air quality, health problems can be associated. Exposure to Rn is identified by the World Health Organization (WHO) as the second leading cause responsible for the occurrence of lung cancer, so the exposure of occupants of buildings with high concentrations of indoor Rn is a source of growing concern, both in buildings intended for housing, such as in-service buildings. However, if, in most cases, the solution involves natural or mechanical ventilation of spaces, other situations where air renewal procedures are not possible require other constructive measures to be taken. The application of constructive measures, such as opening windows or installing forced ventilation systems, may not be allowed, as these are buildings of architectural and heritage interest that are classified as monuments, with restrictions on interventions and renovations. For this reason, the use of measures applicable indoors, such as barrier membranes, which can be hidden under the floor, and wall-covering mortars, which can be hidden under paint or another type of finish, can contribute to mitigating the concentration of indoor Rn and reducing the dose of natural radiation to which occupants are exposed. In the case analyzed, a 94% reduction in the abnormal values of the indoor Rn concentration was achieved with the combination of two constructive measures. Despite the effectiveness of the measures used, the concentration of indoor Rn was still higher than the recommended value, which makes it necessary to carry out new tests and monitoring campaigns in other scenarios with different levels of concentration of indoor Rn as a way of validating the effectiveness of this type of constructive solution in a generalized way.

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