Paper

Radon Concentrations in a Nuclear Reactor Center in Brazil

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Abstract—**Radiation workers are normally exposed to doses resulting from their day-to-day activities. Besides that, background radiation, such as radon, can contribute to the exposure rates. The radionuclide ^{222}Rn is a noble gas belonging to the uranium series, and its indoor concentration in the air depends on the exhalation from surrounding soil and the exhalation from building materials. Radon exhaling from porous building materials containing high uranium concentrations can become a significant exposure factor in areas with limited ventilation. The objective of this study was to evaluate the ^{222}Rn concentrations in the radiochemistry and radiometric laboratories in the nuclear reactor building of the Nuclear Reactor Center (CERPq) located in the Institute of Nuclear and Energy Research (IPEN), São Paulo, Brazil. Measurements were done using a Radon Gas Monitor, model RAD7, equipped with a solid-state alpha detector. A passive method (SSNTD) was also used, consisting of square pieces of C-39 foils (2.5 cm × 2.5 cm) placed within small diffusion chambers. The CR-39 detectors were etched in KOH 30% solution at 80 °C for 5.5 h in a constant-temperature bath. After etching, the detectors were washed, dried, and scanned using a microscope to obtain the track density measurements. The activity concentrations measured with both techniques varied from 52 to 103 Bq m^{-3} in the studied areas of the CERPq. These values may be compared to the reference level of 100 Bq m^{-3} established by the World Health Organization to ensure safety environments. Health Phys. 121(2):117–123; 2021**

Key words: ^{222}Rn; exposure, occupational; nuclear reactor

INTRODUCTION

THE MAIN source of exposure to ionizing radiation for the population comes from natural radioactivity, and radon and its progenies contribute with more than 50% of the annual effective dose received considering all natural sources of ionizing radiation (UNSCEAR 2010). Radon is a naturally occurring, colorless, and odorless radioactive gas. The most frequent and relevant isotope from an epidemiological point of view is ^{222}Rn, which has a half-life of 3.8 d and tends to accumulate indoors, particularly in places with low ventilation. When inhaled, the radioactive decay products of radon, mainly the short-lived descendants ^{218}Po and ^{214}Po, may cause irradiation in the lung. According to the World Health Organization's International Agency for Research on Cancer (IARC), radon is classified as a group 1 carcinogen (IARC 1998, 2012).

The World Health Organization (WHO), established in 2009, provides a reference level for residential radon of 100 Bq m^{-3}, and it set 300 Bq m^{-3} as the concentration that must not be surpassed in any case (WHO 2014). Indoor radon exposure includes not just dwellings but also workplaces. Workplaces that can be considered radon-prone areas include underground work areas and some specific industries.

Worldwide different radon levels are adopted as reference levels. The International Commission on Radiological Protection (ICRP 1993) suggests the action level for non-related radiation workers' values from 500 to 1,500 Bq m^{-3}, considering an equilibrium factor of 0.4 and dose conversion conventions. ICRP (2014) revised the suggested reference values to a range of 100 to 300 Bq m^{-3}, using the as low as reasonably achievable (ALARA) approach and a benchmark of 10 mSv y^{-1}. ICRP (2017) suggested new dose coefficients for radon and thoron using ICRP reference biokinetic and dosimetric models, with specified radiation and tissue weighting factors that should impact the derived reference level using the ALARA approach in the near future worldwide. The Health and Safety Executive of the United Kingdom adopts a radon action level of 400 Bq m^{-3} for workplaces based on advice from the National Radiological Protection Board (NRPB) (Dixon et al. 1996). Other countries established lower levels; for example, Estonia (Pahapill 2003) and the United States (USEPA 2016), where reference levels are 200 Bq m^{-3} and 150 Bq m^{-3}, respectively.

Nuclear and radiation-related workers may be exposed to higher doses in the daily execution of their activities,

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which is the reason why, in Brazil, the normal exposure limit to these individuals is 20 mSv y^{-1}, while for members of the public, the dose increment is limited to 1 mSv y^{-1} (CNEN 2011). Although the general contribution of Rn isotopes that arises from nuclear energy production is lower than 1% of the total dose (UNSCEAR 2010) (the combination of all natural and anthropogenic sources), there is little data on the radon levels in nuclear and radioactive workplaces other than uranium mining (Matshusa and Makgae 2017; Zhou et al. 2019; Ajayi et al. 2019).

The objective of this paper was to assess the radon concentrations in the radioactive laboratories and nuclear installations of the Centro do Reator de Pesquisa—CERPq, a part of the Instituto de Pesquisas Energéticas e Nucleares—IPEN, located in the city of São Paulo, Southwest Brazil.

MATERIALS AND METHODS

The CERPq houses the nuclear research reactor IEA-R1 and radiochemical and radiometric laboratories. From the regional geological point of view, the IEA-R1 reactor is located in the Sedimentary Basin of São Paulo, which corresponds to one of the units of the Continental Rift of Southeast Brazil, a tectonic feature of the Cenozoic age developed on lands of the Ribeira Folds Belt, which consists of metamorphic rocks, migmatites, and granitoids. The metropolitan region of São Paulo has climatic transition characteristics because it is located practically on the Tropic of Capricorn (23.5 °S). Using the Köppen climate classification criterion, this region is of the Cwa type, which is equivalent to a hot and humid subtropical climate with dry winters (total rainfall in the driest month is below 30 mm, the average temperature of the hottest month is above 22 °C, and the average temperature of the coldest month is below 18 °C).

The IEA-R1 reactor is used in radioisotope production, neutron irradiation for neutron activation analysis, and material characterization. Most of these characterizations are performed in the CERPq installations. A simplified scheme of the CERPq is shown in Fig. 1. Radon measurements were performed in buildings 2 and 3. None of these buildings has an underground workplace.

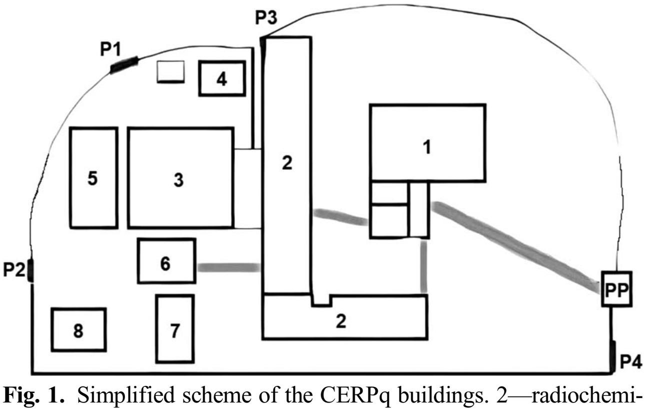

Fig. 1. Simplified scheme of the CERPq buildings. 2—radiochemical and radiometric laboratories, 3—IEA-R1 reactor.

The IEA-R1 is an open pool-type reactor installed in an all-closed building with thick walls and a controlled ventilation system to avoid the air flowing to the outside. The air inside the reactor building is controlled by an air conditioner system. At every hour, 10,000 m^3 of external air is mixed with 36,000 m^3 of indoor air, totaling 46,000 m^3 that circulates in the building. In this building, two ^{222}Rn measurements were done, one in the hall of the reactor pool (R1 and R2) and one measurement in the nuclear physics laboratory installed on the first floor (FF) of the reactor building for conducting experiments demanding neutron flux. The radiometric laboratories are used for gamma counting of the irradiated samples for neutron activation analysis. One measurement was done in each of the rooms 126, 128, and 130, located in building 2 of Fig. 1. In these rooms, the air is controlled by a central air conditioning system, and the doors remain closed most of the time. The radiochemical laboratories, also located in building 2, rooms 134, 135, 136, 137, and 226, are used mainly for sample preparation that happens before irradiation in the neutron activation analysis and for counting afterward. Room 139 is used to store non-radioactive material. Some of these rooms have simple air conditioning systems that are not continuously turned on. The windows of all the laboratories remain closed almost the entire time.

Radon measurements

Radon measurements in the air of the laboratories and in the hall of the reactor pool were done using two different methodologies: RAD7 and solid-state nuclear track detectors (SSNTD).

RAD7

RAD7 (Model: RAD7; Durridge Co., Billerica, MA) is a solid-state ion-implanted silicon alpha detector. The detector converts alpha radiation directly to an electric signal allowing discrimination of alpha particles by energy. The radon activity concentrations are determined by the decay of ^{218}Po and ^{214}Po trapped inside a chamber cell of 0.7 L. A calibration accuracy of the instrument is guaranteed by the manufacturer with a calibration precision better than 5% (Durridge 2019).

SSNTD

Nuclear solid-state track detectors (SSNTDs) are solid materials that present grooves on the surface when exposed to a defined radiation. Among the commercially available track detectors, the CR-39 was chosen because it presents better optical quality since it is transparent, and it allows a contrast between the produced track and the plastic body itself. After exposure, the detectors underwent a chemical attack with potassium hydroxide solution, 30% (w/v), for 5.5 h at 80 °C. The tracks in the detector were observed using a ZEISS Axiolmager light microscope for a transmitted light model, with an increase of 10×. The equipment was connected to a video camera Zeiss ICC-1 (Karl Zeiss AG, Oberkochen, Germany), connected to a microcomputer with a HP 29-inch monitor.

Radon-222 (^{222}Rn) concentration was calculated according to eqn (1) (Mayya et al. 1998), taking the density of tracks (tracks cm^{-2}), the exposure time, and the calibration factor that relates the track density in the surface of the detector and the concentration of radon:

$$C_{Rn} = \frac{D}{kt}, \qquad (1)$$

where:

C_{Rn} = ^{222}Rn concentration (Bq m^{-3});

k = calibration factor (tracks cm^{-2} per Bq m$^{-3\ \mathrm{d}-1}$);

D = Net track density (discounting the density relative to background radiation in the detectors; tracks cm^{-2}); and

t = exposure time (d).

The calibration factor was obtained experimentally by exposing the SSNTDs to a known ^{222}Ra concentration generated by a calibrated source of ^{226}Ra. In this case, the value was 0.0672 tracks cm^{-2} per Bq m^{-3} d^{-1}.

Effective dose calculation

Effective dose calculation is based on the latest effective dose coefficient (EDC) of 3 mSv per mJ h m^{-3} recommended by ICRP 137 (2017). The corresponding EDC for Rn-222 activity concentration in equilibrium is 1.67 × 10^{-5} mSv per Bq m^{-3} h.

The effective doses were calculated using eqn 2. The calculations used an equilibrium factor of 0.4 as recommended by ICRP 137 (2017) for indoor workplaces, considering an unattached fraction of 0.8 in terms of the potential alpha energy concentration.

$$E = c \times F \times CRn \times \Delta t, \qquad (2)$$

where:

E = effective dose (mSv);

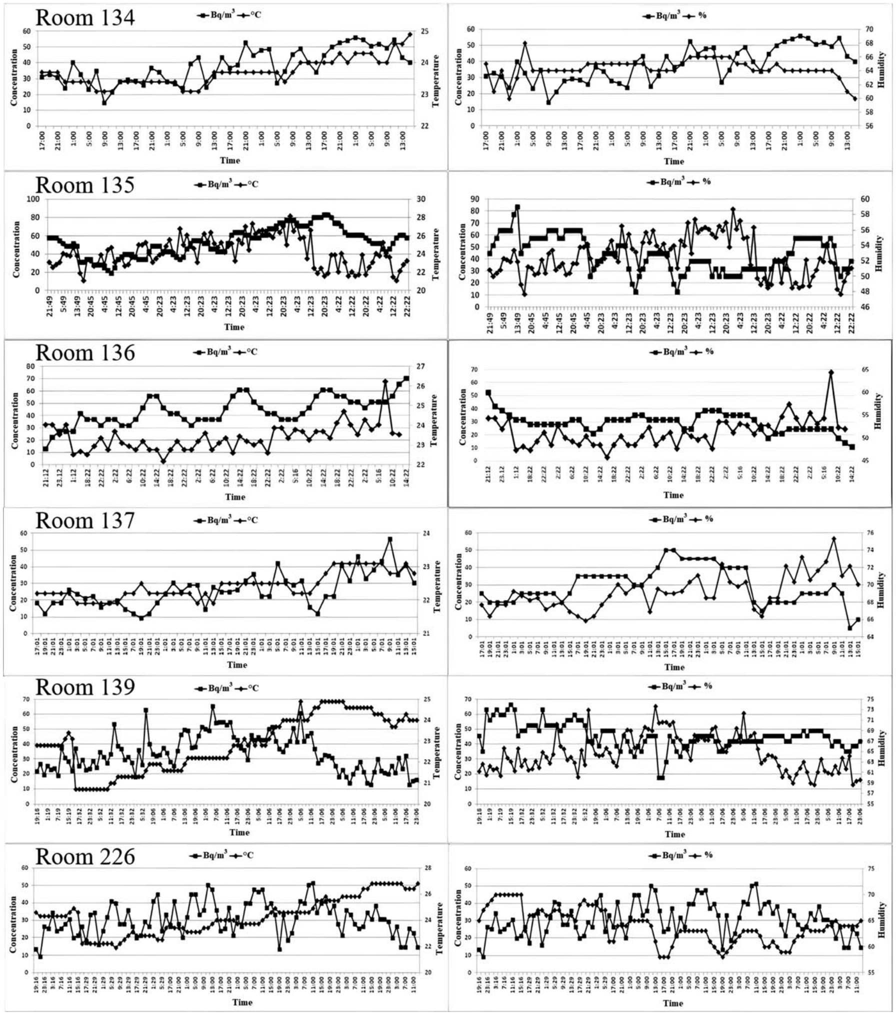

Fig. 2. Radon concentration (Bq m^{-3}), temperature (°C), and humidity (%) in the radiochemical laboratories.

c = effective dose coefficient (mSv m^3 h^{-1} Bq);
F = equilibrium factor;
CRn = average radon activity concentration (Bq m^{-3}) measured during a period of time; and
Δt = exposure duration (h).

RESULTS AND DISCUSSION

Fig. 2 shows the results of RAD7 measurements for the radiochemical laboratories. Fig. 3 shows the results for the radiometric laboratories and Fig. 4 for the hall of the reactor pool and in the nuclear physics laboratory on the first floor of the building. RAD 7 also provides information on the temperature and humidity. The results together with the ^{222}Rn concentrations are summarized in Table 1.

Even without a strict control, the temperature and humidity of the radiochemical laboratories in Brazil do not vary to a great extent. The variation of temperature is lower than 6% and, for the humidity, lower than 5% for all the radiochemical laboratories. The mean values of ^{222}Rn concentration in the air of these laboratories varied from 23 to 42 Bq m^{-3}. The highest values for ^{222}Rn concentration were observed in room 135, reaching 82 Bq m^{-3}.

In the radiometric laboratories, temperature is controlled by a central air conditioning system. The mean values varied from 19.4 to 21.4 °C for the three rooms, lower than the mean temperature of the radiochemical laboratories that varied from 22.3 to 25.3 °C. Humidity was lower in the radiological laboratories (varying from 48.2 to 63.2%) than in the radiochemical ones (variation of 52.8 to 69.9%). The mean values of ^{222}Rn concentration varied from 36 to 43 Bq m^{-3} with the higher values observed in room 126, reaching 89 Bq m^{-3}.

The hall of the reactor pool (R1 and R2) and the physics laboratory of the first floor (FF) presented temperature and humidity variations lower than 7.8% and 11.1%, respectively. The mean values of ^{222}Rn concentrations varied from 48 to 51 Bq m^{-3}, and the highest values that reached 83 Bq m^{-3} were observed on the first floor.

The results of the radon concentration measured with CR-39 are shown in Table 2, together with the mean concentration obtained with the RAD7 detector for comparison. Generally, the concentrations obtained with CR-39 are higher than those obtained with RAD7. The statistical differences between the results were evaluated by *t*-test resulting in a *t* value higher than 0.05 for the 95% confidence interval. Results obtained with RAD7 are mean values of measurements taken every 5 h for 1 wk during the month of November, while the ones obtained with CR-39 are the integrated values covering a period of 3 mo (November until February). This difference in the time of data collection can be responsible for the observed differences. Espinosa et al. (2013), in an intercomparison of indoor radon measurements using nuclear track detectors and different dynamic recording systems, also found lower radon concentrations for RAD7 compared to

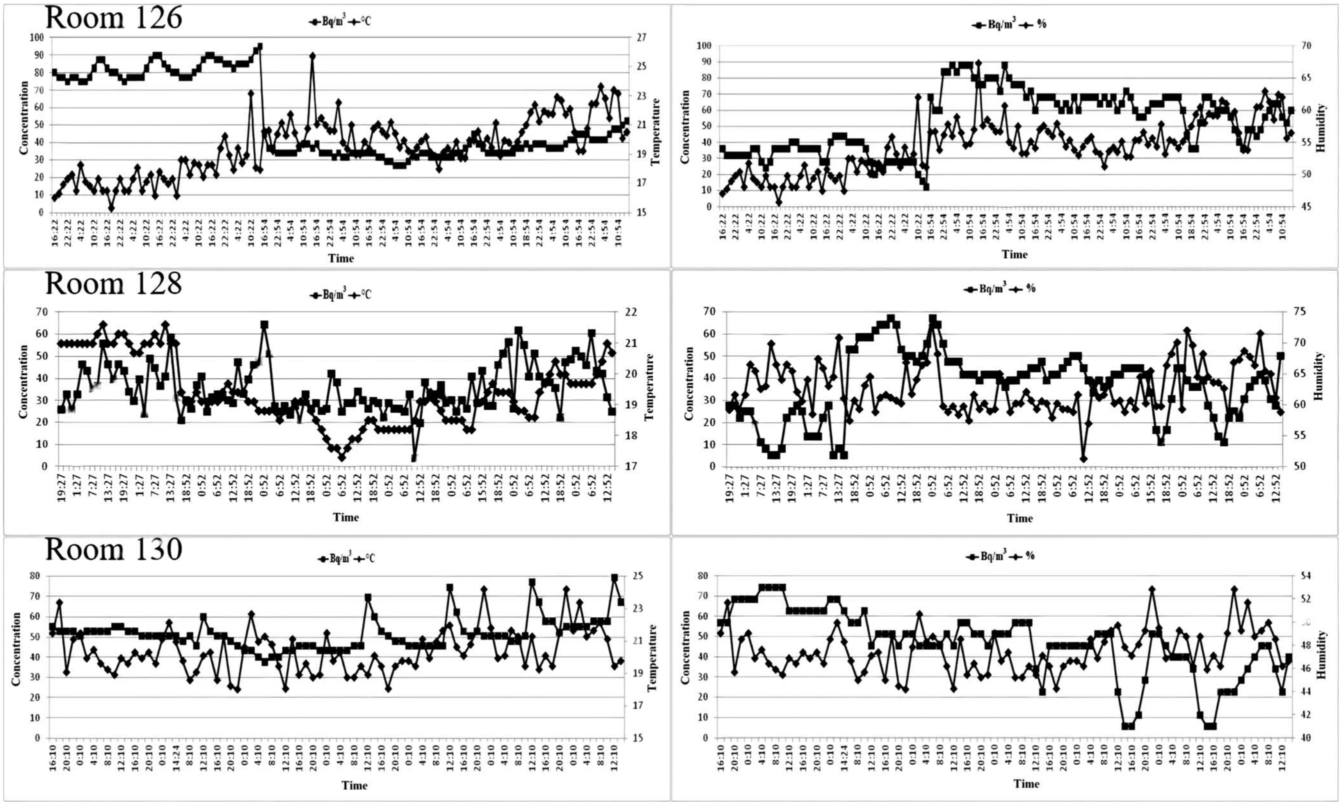

Fig. 3. Radon concentration (Bq m^{-3}), temperature (°C), and humidity (%) in the radiometric laboratories.

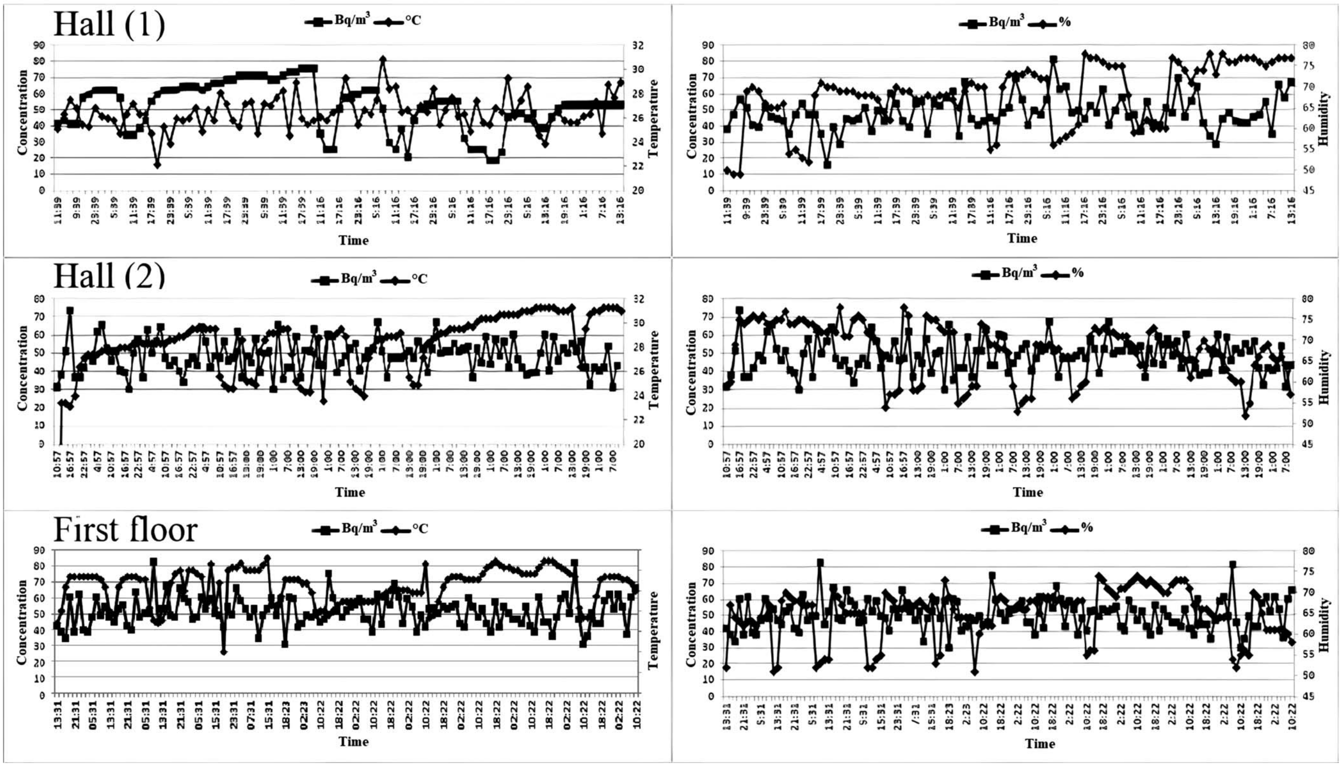

Fig. 4. Radon concentration (Bq m^{-3}), temperature (°C), and humidity (%) in the hall of the reactor pool [two measurements (1) and (2)] and the laboratory of the reactor first floor.

CR-39. The authors explained that the lower values can be due to the presence of an integrated humidity filter in the RAD7, and ionized radon atoms may adhere to water molecules present in the cellar atmosphere, being retained by the filter (Cerda-Zorrilla 2012). It is important to highlight that the air conditioning systems installed in the measured rooms run all year long, so there is no difference among seasons.

Radon-222 measurements made by Reis and Campos (2016) found radon concentrations varying from 2,601 to 6,133 (Bq m^{-3}) in samples of IPEN soil. These values are in the same range reported by Barbosa et al. (2014) for soils from São Paulo state (2.31 to 15.07 kBq m^{-3}) and below other measurements made in different soil pedologies, varying from 12.1 to 51.4 kBq m^{-3}, in the region of the city of Belo Horizonte, also located in Southwest Brazil (Lara et al. 2015). The ^{222}Rn concentration values in the air found in all the CERPq environments measured seem not to be affected by the Rn soil concentrations, probably due to the thickness of the walls and foundations of the building, since the construction material and the air itself were the main contributors to the radon amount observed.

Table 3 shows a compilation of ^{222}Rn activity concentrations in dwellings, workplaces, and underground workplaces in different parts of the world for comparison. Despite the differences in the two measurement methods, the ^{222}Rn concentration determined in the laboratories of the CERPq and in the hall of the reactor pool are in the same range as those observed for dwellings and workplaces, yet are much lower than radon concentrations measured in underground workplaces and caves. Also, whatever the measurement technique used, the values are below or equal to the reference level for residential radon of 100 Bq m^{-3} recommended by the World Health Organization (WHO 2009),

Table 1. Minimum, maximum, mean values, and standard deviation of ^{222}Rn activity concentration, temperature, and humidity in the CERPq.

	Radiochemical labs						Radiometric labs			Reactor		
	134	135	136	137	139	226	126	128	130	R1	R2	FF
Concentration (Bq m^{-3})												
min	15	11	8	9	13	9	8	20	24	16	30	30
max	56	82	68	57	65	51	89	65	74	81	74	83
mean	38	42	23	26	34	31	38	36	43	48	49	51
SD	11	16	11	10	12	9	16	10	11	10	9	9
Temperature (°C)												
min	23.1	21.9	22.8	21.9	20.7	21.9	18.2	17.3	19.7	22.5	23.1	20
max	24.9	28.3	26.4	23.1	24.9	26.8	26.4	21.6	24.9	30.1	31.3	29.2
mean	23.7	25.3	24.7	22.4	22.9	24.3	21.4	19.4	21.4	27.0	28.4	26.5
SD	0.4	1.5	0.7	0.4	1.3	1.4	2.7	1.1	1.0	2.0	2.2	1.7
Humidity (%)												
min	60	48	48	65	60	58	48	52	41	49	52	51
max	68	59	60	74	74	70	67	74	53	78	78	74
mean	64.3	52.8	53.4	69.9	68.0	64.0	58.3	63.2	48.2	68.1	67.6	64.8
SD	1.5	2.3	2.1	2.1	2.4	3.2	4.8	5.5	2.9	7.6	6.7	6.0

Table 2. Radon concentration (Bq m^{-3}) obtained by RAD7 and CR-39, and dose assessment (mSv y^{-1}) for the laboratories and reactor hall of CERPq.

	C (Bq m^{-3})		
	RAD7	CR-39	E (mSv y^{-1})
Radiochemical labs			
134	38	74	0.44
135	42	52	0.31
136	23	59	0.35
137	26	54	0.32
139	34	66	0.39
226	31	63	0.38
Radiometric labs			
126	38	67	0.40
128	36	60	0.36
130	43	72	0.43
Reactor			
R1	48	90	0.54
R1	49	102	0.61
FF	51	103	0.72

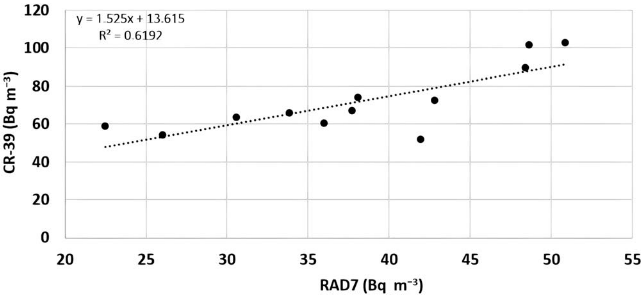

Fig. 5. Linear regression obtained for radon concentration (Bq m^{-3}) measured by RAD7 and CR-39.

ICRP 65, Health and Safety Executive of the United Kingdom, and US levels.

Fig. 5 shows that the concentrations obtained by RAD7 and CR-39 measurements present a good correlation with a correlation coefficient of 0.79 being the first, approximately 50% lower than the second.

The effective dose for radon inhalation is also presented in Table 2. Those doses were calculated using the ^{222}Rn concentration obtained from the CR-39 measurements, since they are higher than the ones obtained by the RAD7, following the principle of drawing the worst-case scenario. The higher doses are observed for the reactor pool area and the laboratory located on the first floor of the reactor building. According to UNSCEAR (2008), the average worldwide effective dose due to radon inhalation is 1.26 mSv y^{-1}. The radon concentrations found for all CERPq areas, both radioactive and nuclear, are below this value.

Besides the rooms measured with both methodologies, two others were measured only with a CR-39 track detector: rooms 132 and 133. The first one is used as a place for the decaying of the irradiated samples, and the second is used to open the aluminum capsules inside with the samples that are irradiated. The radon concentrations were 55 and 56 Bq m^{-3}, respectively, and the effective doses were 0.33 mSv y^{-1} for both rooms.

CONCLUSION

The control of radon exposure is of prime importance for the general population and in particular for radioactive and nuclear workplaces, since these places may involve a higher risk of radiation exposure by the very nature of the activity. Radon concentrations were measured in radiochemical and radiometric laboratories, in the hall of the reactor pool, and in a physics laboratory installed in the

Table 3. Radon concentration (Bq m^{-3}) found in residences, workplaces, underground, and caves.

Place	Classification	Mean	Range	Ref.
Palakkad, India	Dwelling	28.1	15–79	Ramsiya et al. 2017
Al-kharj, Saudi Arabia	Dwelling	114	67–488	Maghraby et al. 2014
	Workplace	76	46–267	Maghraby et al. 2014
South-Dayi, Ghana	Indoor	34.9	11.6–111	Ansre et al. 2018
Eastern Sicily, Italy	Indoor	53	24–126	Catalano et al. 2012
Brisbane, Australia	Workplace	10.5	0.7–86.6	Alharbi and Akber 2015
Catalonia, Spain	Workplace, Underground		< 1–12900	Font et al. 2008
Mexico City, Mexico	Dwelling	28		Espinosa et al. 2009
	Workplace	123		Espinosa et al. 2009
Guadalajara	Dwelling	80		Espinosa et al. 2009
	Workplace	160		Espinosa et al. 2009
Monterrey	Dwelling	42		Espinosa et al. 2009
	Workplace	69		Espinosa et al. 2009
Stanterg, Kosovo	Workplace, underground	281.4	60–748	Espinosa et al. 2009
Italy	Workplace, Underground	723	7–43919	Carelli et al. 2009
São Paulo, Brazil	Caves (PETAR)		515–6607	Albergi et al. 2005

same building of the IEA-R1 reactor at CERPq using an active alpha particle detector (RAD7) and the passive CR-39 detector. Mean concentration values were in the range of 31 to 51 Bq m^{-3} with RAD7 measurements and 52 to 103 Bq m^{-3} with CR-39 measurements. These concentrations are in the same range as the ones observed for dwelling, non-radioactive, and non-nuclear workplaces, and are also lower than the concentrations that can be found underground and in caves. The annual effective doses are in the range of 0.31 to 0.72 mSv, with the highest observed values reaching almost 50% of the average worldwide effective dose due to radon inhalation.

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