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Radon concentration in coal mining in Corrales - Boyacá

Concentración de radón en la minería de carbón en Corrales - Boyacá

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ABSTRACT

The concentrations of radon ^{222}Rn can be quantified using active and passive measurements (in situ). This radioactive gas in enclosed spaces such as underground coal mines is a silent threat because inhaling it at high concentrations can induce lung cancer in workers exposed for extended periods. Currently, Colombia lacks protocols for the measurement and prevention of this radioactive gas. Therefore, the primary objective of this study is to measure the concentrations of ^{222}Rn to which the workers in the El Volcán coal mine, located in the municipality of Corrales in the Boyacá department of Colombia, are exposed. To achieve this, a radiological mapping was conducted inside the mine using nuclear track detectors placed within diffusion chambers. A total of 32 measurement points were monitored over a 60-day period, obtaining ^{222}Rn activity concentrations ranging from 700 to 2000 $\text{Bq}\cdot\text{m}^{-3}$. When compared to the permissible limits recommended by the ICRP, these measurements fall within the allowed range for enclosed spaces. These measurements were extrapolated to calculate the probability of radiological risk associated with lung cancer in this specific mine. In conclusion, the calculations show low concentrations of this radioactive gas, ^{222}Rn, and consequently, low doses absorbed by the personnel.

Keywords: (^{222}Rn), alpha, coal, LR-115, dosimetry, lung cancer risk.

RESUMEN

Las concentraciones de radón (^{222}Rn) se pueden cuantificar usando mediciones activas y pasivas (in situ). Este gas radiactivo en espacios cerrados como las minas subterráneas de carbón es un enemigo silencioso, debido a que su inhalación en altas concentraciones puede inducir un cáncer de pulmón en los trabajadores de este entorno cuando son sometidos a largos periodos de exposición. Actualmente Colombia no cuenta con protocolos de medición y prevención de este gas radiactivo, por lo que el principal objetivo de este trabajo es medir las concentraciones de ^{222}Rn a las cuales están expuestos los trabajadores de la mina de carbón El Volcán ubicada en el municipio de Corrales en el departamento de Boyacá, Colombia. Para esto, se realizó un mapeo radiológico al interior de la mina utilizando detectores de trazas nucleares ubicados al interior de cámaras de difusión. Un total de 32 puntos de medición fueron monitoreados durante un periodo de 60 días obteniendo tasas de dosis que oscilan entre $700-2000$ $\text{Bq}\cdot\text{m}^{-3}$, que al ser comparados con los límites permisibles recomendados por la ICRP encontramos que se encuentran dentro del rango permitido en espacios cerrados, estas mediciones fueron extrapoladas para calcular la probabilidad de riesgo radiológico asociado a cáncer de pulmón en esta mina en particular En conclusión, de los cálculos realizados encontramos bajas concentraciones de este gas radiactivo ^{222}Rn y por consiguiente baja dosis absorbidas por el personal.

Palabras Clave: Concentración de ^{222}Rn, alfa, carbón, LR$-$115, disimetría, riesgo de cáncer de pulmón.

1 INTRODUCTION

The concentration of (^{222}Rn) in coal mining is a matter of significance due to the public health issue it entails. Radon is a radioactive gas that naturally forms through the decay of uranium present in soil and rocks[1]. As coal is extracted, radon is released and can accumulate in the mine air, posing a health risk to workers. (^{222}Rn) is considered the second most important cause of lung cancer after tobacco[2]. Prolonged exposure to high concentrations of radon can significantly increase the risk of developing this disease, particularly among the population under study, in this case, the miners [3]. For this reason, it is essential to take measures to mitigate and reduce radon concentration in coal mines. Several strategies can be implemented to minimize exposure to (^{222}Rn) in coal mining. One of them is proper ventilation, which involves ensuring a constant and efficient airflow [4]. This is achieved by installing appropriate ventilation ducts that allow for a consistent airflow, ensuring effective removal of ^{222}Rn-contaminated air. Another crucial measure is continuous monitoring of ^{222}Rn concentration. This can be ensured by using real-time direct-reading measurement devices (DURRIDGE Company) capable of detecting and quantifying the presence of ^{222}Rn in the air. When such devices are not available, measurements can be conducted using diffusion chambers with nuclear track detectors LR-115 [5]. This measurement method proves to be highly efficient in ensuring measurements over extended periods (weeks to months), enabling the identification of areas with higher ^{222}Rn concentrations and the implementation of necessary measures to ensure radiological protection for workers, which is the measurement system used in this research. As mentioned earlier, the risk of developing lung cancer due to ^{222}Rn exposure depends on various factors: exposure rate, duration of exposure, and, when combined with smoking, results in a significantly elevated probability. Therefore, this study investigates the risk to which the workers of the El Volcán mine located in the municipality of Corrales in the department of Boyacá are exposed. The objective of this study is to determine the risk of lung cancer associated with the workers of the aforementioned mine. To achieve this, the concentration of ^{222}Rn is calculated at 32 points within the mine, allowing for the determination of concentration in Bq $\cdot$ m^{-3}, absorbed dose, equivalent dose, and, finally, lung-effective dose, which establishes the risk associated with contracting lung cancer.

2 METHODOLOGY

The research was conducted at the El Volcán mine in the municipality of Corrales, located in the Boyacá department at approximately 5°49’23” N and 72°49’23” W. The experimental measurements were carried out in two phases. The first phase involved active measurements using the MARKUS-10 equipment 1 [6], with the purpose of assessing radon concentrations in the soil and walls of the mine, values that served as a reference for subsequent measurements inside the mine tunnel. The second phase involved deploying 32 diffusion chambers, as shown in 2. These chambers were distributed from the entrance of the mine to a depth of approximately 120 m, with a spacing of approximately 4 m between them. A 60−day exposure time was necessary to achieve acceptable statistical results during the measurement period.

Fig. 1. MARKUS-10 equipment used for active measurements of ^{222}Rn concentration at the mine entrance.

The experimental setup in 2 is the result of a diffusion chamber model implemented by the research team. The manufacturing process of these chambers involves a PVC tube measuring 6 cm in length and 5.08 cm in diameter, housing the LR-115 detector [7] inside. These diffusion chamber were designed and built to estimate radon activity concentrations from the registered track densities in the detector.

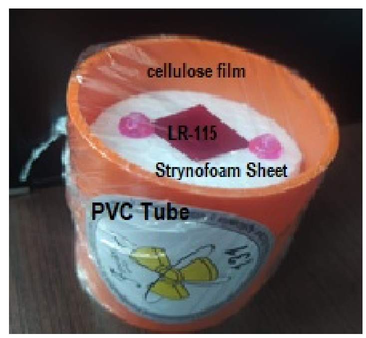

Fig. 2. Diffusion chamber used to house the LR-115 nuclear track detector, coated with a thin film of low-density linear polyethylene used as a moisture filter.

The next step after the exposure for the specified duration involved the collection of the diffusion chambers. For this purpose, the detectors were carefully removed and wrapped in aluminum foil to prevent contamination (moisture, dirt, additional radiation). Subsequently, they were transported to the laboratory, where they undergo a chemical development process known as ”etching” to enhance the trace left by the alpha particle when it impacts the detector, making possible to count nuclear tracks in an optical microscope under the transmission mode. For the etching process, a 2.5N NaOH solution was prepared, and the temperature was maintained at 60 $^{\circ}C$ in a water bath for 90 minutes.

In 3, the water bath device, branded as Beind model WX-12, used etching is shown. Subsequently, the detectors undergo a washing process with distilled water at the same temperature for 20 minutes, followed by a final wash at room temperature for 10 minutes.

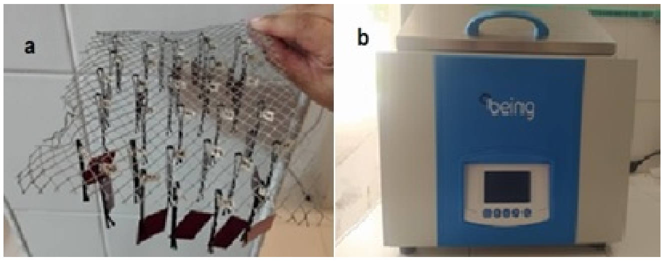

Fig. 3. a) Assembly of LR-115 detectors on a 15 x 20 cm mesh. b)Controlled water heater equipment, Beind model WX-12.

The next step involves the direct reading of the detectors. This process was conducted using a Leica 10X/18 optical microscope 4. The purpose of this reading is to identify and count the number of tracks recorded per field of view on each detector.

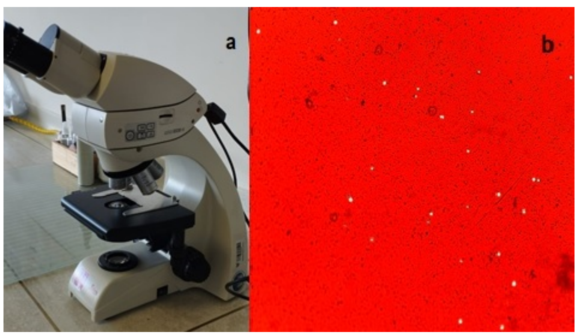

Fig. 4. a) Leica microscope b) Etched detector, magnification 10X/18

For track counting, initially, the entire detector is read, and it was concluded that by randomly selecting 5 fields of view, a weighted average very close to the total detector reading is obtained. After obtaining the weighted average number of density is calculated using equation 1.

$$\delta = \frac{\mathrm{NT}}{5 \cdot \mathrm{A}} \frac{\mathrm{Tracks}}{\mathrm{cm}^2} \quad (1)$$

Where δ tracks density, NT total number of tracks counted in the 5 observed fields of view, and A observed area in 1 cm^2.

Once δ is known, the effective exposure time **t** is calculated. For this calculation, the following relationship is taken into account: for one month of exposure corresponds to 1, in our case the effective exposure time was 60 days, therefore, t will be equal to 2. This density is multiplied by the calibration factor (CF), which in our case is 30.8Bq$\cdot$m $^{-3}\cdot$ tracks$^{-1}\cdot$cm^{-2} per month of exposure [8], calculating the concentration using equation 2.

$$\mathrm{C_{Rn}} = \frac{\delta}{\mathrm{CF} \cdot \mathrm{t}} [\mathrm{Bq} \cdot \mathrm{m}^{-3}] \quad (2)$$

Once the concentration of ^{222}Rn is known, the absorbed dose can be calculated using equation 3 [9]:

$$\mathrm{D_{Rn}} = \mathrm{C_{Rn}} \cdot \mathrm{D} \cdot \mathrm{H} \cdot \mathrm{F} \cdot \mathrm{T} [\frac{\mathrm{mGy}}{\mathrm{y}}] \quad (3)$$

Where D is the dose conversion factor, equal to $9 \cdot 10^{-6}$ [mSv$\cdot$ m^3/ h $\cdot$ Bq], H is the occupancy factor, which is 0.40 and depends on working time, F is the equilibrium factor, which is 0.50, and T is the occupancy time, which is 2000 h $\cdot$ y^{-1} [10].

With the absorbed dose, the equivalent dose (H_{Rn}) is then calculated using equation 4, obtained by multiplying the absorbed dose by the radiation weighting factor (W_R), in this case, for alpha particles, with a weighting factor of 20 [11].

$$\mathrm{H_{Rn}} = \mathrm{D_{Rn}} \cdot \mathrm{W_R} [\mathrm{mSv.y}^{-1}] \quad (4)$$

Once H_{Rn} is known, the effective dose can be calculated, which depends on the sensitivity of the organ or tissue. In this case, our organ at risk is the lung, with a weighting factor of $W_T = 0.12$ [11], and it is calculated using equation 5:

$$\mathrm{E_{Rn}} = \mathrm{H_{Rn}} \cdot \mathrm{W_T} [\mathrm{mSv.y}^{-1}] \quad (5)$$

Finally, the calculation of the cancer increment is performed, which is calculated using equation 6 [12]:

$$\mathrm{ELRC} = \mathrm{ERn} \cdot \mathrm{DL} \cdot \mathrm{RF} [\mathrm{mSv.y}^{-1}] \quad (6)$$

In Colombia, life expectancy (DL) according to DANE (National Administrative Department of Statistics in Colombia) is approximately 74 years. Furthermore, if we consider that the lifetime cancer risk increment is the difference between the number of people who develop or die from cancer in the exposed population and the number of people in a similar unexposed population [11], we can consider the risk factor (RF) to be 0.05 y^{-1} [13].

3 RESULTS

When performing the direct reading of the detectors, the radon concentration was calculated at each measured point. It should be noted that point 1 is located at a depth of 120 m, and point 32 is located at the mine entrance. The data obtained is presented in Table 1.

From Table 1, the measured radon concentrations (C_{Rn}) at the 32 points within the mine range from 700 to 2000 Bq $\cdot$ m^{-3}. These values are slightly above the recommended values (1500 Bq $\cdot$ m^{-3}) for workplaces according to [11].

The C_{Rn} values reported in Table 1 are mostly above the limit set by [11] 1500 Bq $\cdot$ m^{-3}. However, exposure to radon in a workplace above 1000 Bq $\cdot$ m^{-3} should be taken into account in national regulations. In this regard, ICRP recommends defining this reference value and considering it as part of a worker's occupational radiation exposure.

Detector	δ cm^2	C_{Rn} $(Bq \cdot m^{-3})$
1	400	1120
2	450	1260
3	250	700
4	370	1036
5	320	896
6	260	728
7	340	952
8	420	1176
9	350	980
10	560	1568
11	380	1064
12	470	1316
13	380	1064
14	650	1820
15	680	1904
16	420	1176
17	680	1904
18	420	1176
19	390	1092
20	650	1820
21	350	980
22	480	1344
23	470	1316
24	370	1036
25	300	840
26	400	1120
27	360	1008
28	320	896
29	430	1204
30	620	1736
31	340	952
32	730	2044
Average	437.81	1225.88

Table 1. Traks density in cm^2 and radon concentrations in $Bq \cdot m^{-3}$ obtained at each of the 32 points located inside the El Volcán mine in the municipality of Corrales, Boyacá.

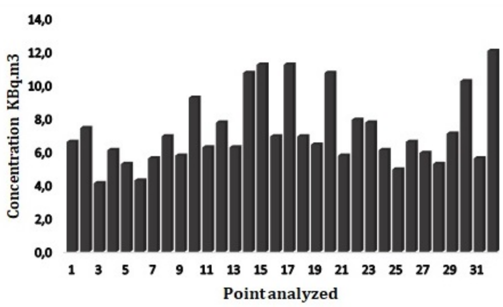

Fig. 5. Concentrations obtained in the El Volcán mine in the municipality of Corrales, Boyacá.

The results obtained, as shown in Figure 5, allow us to identify points with higher gas concentration. The point with the lowest concentration corresponds to point 3, with a value of 700 $Bq \cdot m^{-3}$ located at a depth of 112 m, while point 23, located at the mine entrance, exhibits the highest concentration at 2000 $Bq \cdot m^{-3}$. This value was corroborated with active measurements using the MARKUS-10 device at the mine entrance and surrounding areas, where indeed an increase in Rn gas concentration is evident. The average tracks density was 1225.9 $Bq \cdot cm^{-3}$.

The points with the highest concentration are $14, 15, 17, 20, 30$, and 32. However, it is not possible to establish symmetry in the measurements since the variation is random, as shown in Figure 5. Nevertheless, high readings were obtained in detectors located along the mine's central axis. This aspect may be related to the ventilation of the mine, in addition to assessing temperature changes within the galleries, where temperatures ranged between $19-24°C$. Ventilation and temperature are associated, since the higher the ventilation the lower the temperature and certainly the lower the radon concentration [14, 15].

Detector	D_{Rn} $(mGy \cdot y^{-1})$	H_{Rn} $(mSv \cdot y^{-1})$	E_{Rn} $(mSv \cdot y^{-1})$	ELRC
1	4.03	80.64	9.68	35.80
2	4.54	90.72	10.89	40.28
3	2.52	50.40	6.05	22.38
4	3.73	74.59	8.95	33.12
5	3.23	64.51	7.74	28.64
6	2.62	52.42	6.29	23.27
7	3.43	68.54	8.23	30.43
8	4.23	84.67	10.16	37.59
9	3.53	70.56	8.47	31.33
10	5.64	112.90	13.55	50.13
11	3.83	76.61	9.19	34.01
12	4.74	94.75	11.37	42.07
13	3.83	76.61	9.19	34.01
14	6.55	131.04	15.72	58.18
15	6.85	137.09	16.45	60.87
16	4.23	84.67	10.16	37.59
17	6.85	137.09	16.45	60.87
18	4.23	84.67	10.16	37.59
19	3.93	78.62	9.43	34.91
20	6.55	131.04	15.72	58.18
21	3.53	70.56	8.47	31.33
22	4.84	96.77	11.61	42.96
23	4.74	94.75	11.37	42.07
24	3.73	74.59	8.95	33.12
25	3.02	60.48	7.26	26.85
26	4.03	80.64	9.68	35.80
27	3.63	72.58	8.71	32.22
28	3.23	64.51	7.74	28.64
29	4.33	86.69	10.40	38.49
30	6.25	124.99	15.00	55.50
31	3.43	68.54	8.23	30.43
32	7.36	147.17	17.66	65.34
Average	4.41	88.26	10.59	39.19

Table 2. Calculation of risk from the concentration of ^{222}Rn.

Now, if we analyze the results shown in Table 2, we find that H_{Rn} values would fall within the established limits for occupationally exposed workers of < 20 $mSv \cdot y^{-1}$ if they were exposed to photon or electron radiation. However, when D_{Rn} is affected by alpha radiation, as in this case, see column 3, we observe that H_{Rn} in some cases shows values exceeding 100 $mS \cdot y^{-1}$. This would correspond to the dose a worker occupationally exposed would receive over more than 5 years. These doses are considerably high when adjusted by the weighting factor for the organ at risk (lung), as shown in column 4, revealing that only this organ can receive over 10 mSv in a year [16].

4 CONCLUSIONS

On average, the concentrations of Radon (C_{Rn}) found in this study were 1226 $Bq \cdot m^{-3}$. When compared to the limits established by [11], which suggests that concentrations in workplaces, including mines, should be between 500 and 1500 $Bq \cdot m^{-3}$, it can be concluded that they are within the permitted limits. This result led us to calculate the doses received by the workers due to Rn^{222}.

When evaluating the absorbed dose (D_{Rn}), it is found that if a worker were located at the point with the highest C_{Rn} for $2000 h \cdot y^{-1}$, they would receive an absorbed dose of 4.4 mSv. This value would seemingly fall within the established limits for occupational exposures of < 20mSv [11] if the worker were exposed to gamma, electron, or neutron radiation. However, these levels do not apply to Colombian regulations for alpha radiation, whose weighting factor is 20. Therefore, the H_{Rn} is calculated to establish the actual equivalent dose the worker is exposed to. The mean value of HRn corresponds to 88 $\mathrm{mSv}\cdot\mathrm{y}^{-1}$, which is significantly higher than the limits set by the ICRP. This value may be lower if it is considered that the workers do not work 2000 $\mathrm{h}\cdot\mathrm{y}^{-1}$.

The focus of this study was to assess the effective dose that the lung would receive in a year, using the weighting factor of 0.12 suggested by ICRP-103 in 2007 [11]. This value corresponds to 10.5 $\mathrm{mSv}\cdot\mathrm{y}^{-1}$. This effective dose corresponds to the whole-body ERn that a worker receives in a year exclusively due to Rn^{222}. Therefore, the risk of developing long-term lung cancer remains present.

To assess the probability of long-term lung cancer, the calculation shown in Table 2 was performed, yielding a probability of 39%. However, this probabilistic calculation was done conservatively (2000 $\mathrm{h}\cdot\mathrm{y}^{-1}$), a situation that is not realistic if it is considered that mine workers do not exceed 1000 hours of work per year. Another important aspect is the variability of Rn^{222} emanation throughout the year.

It is worth noting that the El Volcán mine complies with all the regulations required by the Ministry of Mines and Energy for its operation, thus ensuring proper functioning and worker protection. However, the presence of Radon in the area cannot be denied due to the different geological characteristics it presents.

As a future task, the possibility of replicating this study in different areas of the department is proposed to obtain a radiological map and establish protocols and a range of permissible radon limits in mines at the national level. This is a direct responsibility of the state, which must establish its own reference level.

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REFERENCES

[1] Clement, Christopher H and Tirmarche, M and Harrison, JD and Laurier, D and Paquet, F and Blanchardon, E and Marsh, JW. Lung cancer risk from radon and progeny and statement on radon. *SAGE Publications Sage UK: London, England* vol. **40**, pp. 1-64, 2010.

[2] Seltenrich, N. Radon risk: A global estimate of radon's contribution to lung cancer. *Environmental Health Perspectives*, vol. **127(2)**, 024001, 2019.

[3] Lubin, JH, Boice Jr, JD, Edling, C., Hornung, RW, Howe, GR, Kunz, E. and Pierce, DA. Cáncer de pulmón en mineros expuestos al ^{222}Rn y estimación del riesgo por exposición en interiores. *JNCI: Revista del Instituto Nacional del Cáncer*, vol. **87(11)**, pp. 817-827, 1995.

[4] Zeeb, H., and Shannoun, F. *Manual de la OMS Sobre el Radón en Interiores: Una perspectiva de salud Pública*. Organización Mundial de la Salud. 2015.

[5] Rojas-Arias, N., Sandoval-Garzón, M. A., Medina-Higuera, J. D., Sajo-Bohus, L., and Martínez-Ovalle, S. A. Seasonal variation of the S-index as it relates to the concentration of ^{222}Rn inside a bunker that stores radioactive material. *Applied Radiation and Isotopes*, vol. 162, **109173**, 2020.

[6] Jacobs, W. (n.d.). Analytics.com.de: Willkommen auf der internetpräsenz von radon analytics - messgeräte für Radon. radon. `https://www.radon-analytics.com/index.php?show=markus10` [Fecha de acceso:20.09.2023]

[7] Dositometría de Radiación Ionizantes. Dosirad. (n.d.). `http://dosirad.com/` [Fecha de acceso:22.09.2023]

[8] Sandoval-Garzón, M. A., Ávila-Abril, L. A., Garcia-Rodriguez, A. M., Bermúdez, M. A., Martínez- Ovalle, S. A., and Sajo-Bohus, L. A new graph of soil Rn-gas transport: Radon-rose plot. *Applied Radiation and Isotopes*, vol. **169**, 109521, 2021.

[9] Muñoz, B. E. L., and García, J. L. I. Radiactividad natural y artificial en nuestro entorno. *Ciencia*, **1** pp. 6-16, 2004.

[10] Eappen, K. P., and Mayya, Y. S. Calibration factors for $LR-115$ (type-II) based ^{222}Rn thoron discriminating dosimeter. *Radiation measurements*, vol. **38(1)**, pp. 5-17, 2004.

[11] ICRP-103, *ICRP publication 103*. Ann ICRP, vol. 37(2.4), 2, 2007.

[12] Aguilar Aguilar, A. J. Determinación de los niveles de ^{222}Rn presentes en la mina subterránea *El Señor de Roma* en el cantón Zaruma-El Oro, *Ecuador (Bachelor's thesis)*. 2018.

[13] ICRP, I. *Publication 61: Annual limits on intake of radionuclides for workers based on the 1990 recommendations*. 1990.

[14] Darby, S., Hill, D., Deo, H., et al. Radón residencial y cáncer de pulmón: resultados detallados de un análisis colaborativo de datos individuales de 7.148 personas con cáncer de pulmón y 14.208 personas sin cáncer de pulmón de 13 estudios epidemiológicos en Europa. *Revista escandinava de trabajo, medio ambiente y salud*, pp. **1-84**, 2006.

[15] Krewski, D., Lubin, JH, Zielinski, JM, Alavanja, M., Catalan, VS, William Field, R.and Wilcox, HB. Un análisis combinado de estudios de casos y controles en América del Norte sobre radón residencial y cáncer de pulmón. *Revista de Toxicología y Salud Ambiental, Parte A* , vol. **69 (7-8)**, pp. 533-597, 2006.

[16] Lubin, JH, Wang, ZY, Boice Jr, JD, Xu, ZY, Blot, WJ, De Wang, L. y Kleinerman, RA. Riesgo de cáncer de pulmón y radón residencial en China: resultados agrupados de dos estudios. *Revista internacional de cáncer* , vol. **109 (1)**, pp. 132-137, 2004.