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Social Injustice in Colombian Labor for the Radioactive Effects of Radon Gas During Mining Exploration and Exploitation

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Abstract

This article delineates the State's omission, which should prioritize the general welfare and enhancement of the quality of life of all residents in Colombian territory, particularly in the context of workers in the mining sector, where these individuals, due to historical, social, and labor factors, find themselves in a state of marginalization social and legal. These workers are particularly vulnerable to the risk factors associated with radioactive exposure to radon gas (Rn 222) and its descendants, such as polonium 218 and 214 (Po) and lead 214 (Pb). It is crucial to acknowledge the studies conducted over the past five decades, which have elucidated the damages effects of radon gas in the mining sector. In Colombia, there is a paucity of research and studies focusing on this noble gas, as well as on the development of effective strategies for the monitoring and protection of workers in the context of the mining sector, where workers are exposed to significant risks associated with radioactive substances. The main objective of the article is to evaluate the radioactive effects of radon gas in the Colombian mining sector and the minimum guidelines for safety and health at work.

Keywords: decay, exposure, labor risks, mining, radioactive, radon

Introduction

The result of this article was partly the research, participation, and socialization of the research "radiation injury with radon gas in Colombian mining" that was carried out around the academic event called "European Summer School: radiation measurements and radiochemistry in the environment and decommissioning." This event was led by the Faculty of Physics and Engineering of the University of Strasbourg (France) in collaboration with the Institute of Nuclear Waste (INE) of the Karlsruhe Institute of Technology (Germany). The meeting addressed references to radiochemistry, the challenge of measuring low-level radioactivity, new instrumental techniques and measurement procedures for dosimetry and the handling of radioactive materials, such as the degree of exposure of certain radioactive chemical elements, including radon gas, and the consequences of not having adequate protection and monitoring. (European Summer School, 2024).

Mining generates a series of radioactive effects that are not well understood by the general public, particularly in the Colombian context. In the current year (2024), a request was made to the administrative authorities for information regarding the measures and protocols that are being

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implemented as public policy to prevent and promote occupational health and safety in Colombia in relation to the radiation caused by radon gas. The results of this request were surprising like the responses of the public entities in charge are equally surprising, as they state that they did not have an established protocol for measuring radon gas, since no alerts have been generated to indicate to the public authority that the competent authorities should carry out its control and monitoring.

The Colombian state's failure to implement a public policy in accordance with international recommendations, particularly those relating to the measurement and control of the effects of radon gas in the environment, especially in urban areas and workplaces, constitutes a flagrant omission like work in mining. This oversight is particularly disconcerting in light of the well-established carcinogenic properties of radon. The absence of comprehensive epidemiological monitoring, in conjunction with the absence of regulations aimed at preventing or mitigating the concentration of radon in the environment, further exacerbates the situation. **It is striking that no country in Central and South America does not have a national map of exposure to radon as a preventive measure to protect the well-being and integrity of human life.** This absence is particularly problematic, as it represents a critical aspect of the preventive measures that are essential to safeguard the well-being and integrity of human life (Giraldo, Ruano, Varela, Barros, & Pérez, 2020).

It is imperative to acknowledge the role of radon, a by-product of the radioactive decay or decomposition of uranium, in the deterioration of human health, particularly in confined and unventilated environments. The emission of alpha (α) particles by radon can result in the release of ionizing radiation, which poses a considerable threat to individuals exposed to it over an extended period. A salient example is that of mining workers, who face a heightened risk of developing lung cancer due to their lack of access to measures aimed at mitigating the associated risks. Moreover, there is a paucity of epidemiological studies that comprehensively analyze the safety and health of this demographic group in the workplace, thereby disregarding the incidence and damage affecting this particular segment of the mining workforce. A similar situation occurs in the case of illegal mines, where local and administrative bodies demonstrate inefficiency when it comes to controlling the exploration and exploitation of natural resources without imposing restrictions.

The dearth of knowledge and training in resource exploration engenders conditions conducive to exposure to toxic and radioactive substances whose concentrations and effects are not precisely measured. This is primarily due to the prevailing belief that radiation arises in the context of a nuclear disaster or the handling of radioactive materials such as plutonium or uranium. However, this is not the case. Human beings are constantly exposed to radiation from natural sources, such as the sun, as well as from medical procedures, including X-rays, CT scans, and radioactive treatments for tumors. The main objective of the article is to evaluate the radioactive effects of radon gas in the Colombian mining sector and the minimum guidelines for safety and health at work. These individuals are devoid of the safeguards provided by a comprehensive occupational health and safety management system, and public authorities have been complicit in the acquiescence of hazardous work practices. There is a conspicuous absence of regulatory oversight or research on exposure to radioactive hazards, such as radon gas.

Methodology

The research method is quantitative in nature and a socio-legal approach, which analyzes critical

reflection on the mining reality in Colombia, that is, it seeks to promote processes of transformation and social justice in relation to the interests, protection, safety, health conditions and dignified life of workers who are dedicated to the exploration and exploitation of mining resources. based on a critical study of the scientific literature that addresses radioactive risk factors, hazards and challenges, as well as the proposal of solutions in the field of occupational safety and health.

The methodology has been designed to provide a comprehensive understanding of the factors that affect the working conditions, human dignity, health and environment of those engaged in mining. This is achieved through a systematic review of the literature, following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (PRISMA) (Universidad de Navarra, 2020).

Theoretical Review

A comprehensive review of the extant literature was conducted to identify and analyze recent research on the effects of radon gas on the environment and human health, the consequences of ionizing radiation, and public policy guidelines related to occupational safety and health in the mining sector. A selection of academic articles, reports from international organizations, and case studies published in the last five years (2019-2024) was made, as well as the different responses of the Colombian administrative authorities on the consequences of radiation exposure on mining workers. The following databases were consulted for this review: Scopus, Google Scholar, and the repository of the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP). The selection of literature was based on the relevance and quality of the sources, ensuring that the selected studies are representative of the analysis of the mining reality in Colombian territory.

The research carried out by the medical scientific community on the relationship between exposure to low doses of ionizing radiation and health outcomes, particularly the development of lung cancer, is noteworthy, as is the scarcity of research on radon gas in Colombia:

- The scientific paper "Cancer mortality after low-dose exposure to ionizing radiation in workers in France, the United Kingdom and the United States" postulates a direct relationship between prolonged exposure to low doses of ionizing radiation, such as radon, and cancer mortality. The study notes that the occurrence of cancer mortality is associated with specific occupations and high levels of exposure (MBJ, 2023).
- The article "The impact of alternative historical extrapolations of diesel exhaust and radon exposure on miners" (Roel, Jay, and Aaron, 2020) describes the direct relationship between exposure to radon gas risk and lung cancer in underground miners (Roel, Jay, & Aaron, 2020).
- A seminal article by Messier (2016) offers a compelling example of the deleterious effects that the chemical element radon has on human health and the environment (Kyle P Messier, 2016).
- The research on "Radon and stomach cancer" provides a detailed analysis of the impact that radon, when diluted in water, has on stomach cells. The hypothesis suggests that the duration of radioactive exposure is prolonged due to the stomach's function in storing and processing food (Raquel Barbosa-Lorenzo, 2017).

- The critical scientific study, "Residential Radon in Manizales, Colombia: Results of a Pilot Study" is one of the few research papers that reveals the limited knowledge that public authorities and the community in general have about the effects of radon gas on health and the environment (Giraldo, y otros, 2021).
- The research study "Exploratory study of residential radon in Bogotá, Colombia, and surrounding municipalities" underscores the persistent threat of radon inhalation, which poses a significant risk of developing lung cancer. The study methodically investigates the concentration levels of the chemical element, the disintegration process, and the emission of alpha particles in urban residences (Dominguez, 2021).

Mining in Colombia

Mining exploitation requires greater state vigilance because more than half of the mining exploration and exploitation in Colombian territory is illegal, without environmental control and regulation, as well as a continuous lack of protection in the work of workers who are in the informal sector, oblivious to the minimum labor guarantees and coverage in comprehensive social security in health. occupational risks and pension, revealing a social and environmental injustice, which according to the report of the Ministry of Mines and Energy, during the period 2011 to 2022 a number of fatal accidents of 1,165 workers were registered in the mining formality, compared to the 1,778 miners who died in the informal sector (Ministerio de Minas y Energía, 2022). The Colombian state's acquiescence in the face of the inefficiency and delay of the territorial, administrative, and judicial entities in the fight against illegal mining has caused a series of environmental, social, and health damages. This phenomenon is exemplified in gold mining, where 85% of the precious metal is extracted illegally (Contraloría General de la República, 2022), contaminating water sources with mercury on a large scale, due to the inappropriate and harmful use of techniques that end up throwing quantities of toxic waste into rivers and stagnant bodies of swamps, lakes and lagoons, or spreading toxic metallic vapors into the atmosphere, in the process of purifying the precious metal through burning, generating collateral damage not only to the people who are dedicated to this activity but also to the communities and the environment, damages that are intended to be made invisible by the degree of responsibility of the State, because it does not assume the legal duty to regulate, control and monitor the exploration and exploitation of natural resources, generating a series of occupational diseases in the mining sector without any kind of epidemiological study, monitoring and protection of this part of the population (Gallo & Pico, 2017).

It is imperative to acknowledge that most of the mining practices in Colombia are clandestine in nature, particularly illicit mining, which engages in economic activities without conducting prior environmental impact studies, in violation of environmental regulations and licenses, and with a disproportionate reliance on techniques that are contrary to nature and the social conscience of environmental conservation (Defensoría del Pueblo, 2023). These practices have been identified as significant contributors to the social and environmental challenges facing the nation, including, but not limited to, deforestation, forced displacement, deregulation of labor law guarantees, and negligence in guaranteeing comprehensive social security coverage. The economic activity of mining in Colombia has had a detrimental social and environmental impact due to the polluting effects on water, soil, and air habitat, affecting biodiversity and survival (Ministerio de Ambiente y Desarrollo Sostenible, 2019).

Radon gas has been identified as a lung carcinogen, and scientific studies indicate that it is the

second leading cause of lung cancer after smoking in the Americas, where evidenced that between 1985 to 2018, lung cancer accounted for the highest mortality rate among men (American Cancer Society, 2024). However, epidemiological studies have revealed that women in Venezuela, Argentina, Colombia, and Brazil have higher mortality rates from lung cancer (Miranda, Piñeros, & Bray, 2019), suggesting a higher risk for people engaged in mining activities due to their exposure to radioactive radon (Seltenrich, 2019). A good reference the case study is the analysis presented by SENA in Colombian on the health risks to coal mine workers who are exposed to radon gas due to its high concentration and require constant monitoring of the air in the workplace, in relation to the scientific evidence of developing lung cancer due to prolonged exposure to radioactive decay of radon (Montañez, Sajo, & Martínez, 2024).

Fundamentals of Radioactivity

Atoms are defined by their mass number, denoted Z , and their atomic number, denoted A . When these two numbers are specified for an atom of an element, the term "nuclide" is used; radioactive nuclides are classified as "radionuclides," defined as unstable nuclei. The atoms on the planet are largely stable due to the balance between their neutron particles and the protons in their nucleus. However, radioactive material has a degree of instability in its atomic nuclei because the number of protons and neutrons in the nucleus is not enough to keep the particles together. During the process of disintegration, the material emits radioactive particles, a phenomenon referred to as radioactive decay. The transformation of an unstable nucleus into a more stable form is accompanied by the emission of energy in the form of particles, that is to say, radiation. It is noteworthy that most radioactive elements do not undergo direct disintegration into a stable nucleus; rather, they undergo a series of successive disintegrations until they reach a stable derivative nuclide. Consequently, a disintegration chain is defined as a sequence of chemical elements into which an atom is transformed during the process of radioactive disintegration. This sequence is designated as a radioactive family (IAEA, 2024).

It is imperative to acknowledge that radioactivity can be either natural or artificial in origin. Natural radioactivity is attributed to cosmic rays and radionuclides that have been identified in the Earth's environment since its formation. Notable examples of the latter category include the radioisotopes of uranium-238, thorium-232, potassium-40, and radon, which are produced by the disintegration of uranium present in soil and rocks. In contrast, artificial radioactivity is the result of human intervention, specifically the destabilization of stable atoms by methods such as particle bombardment.

The quantification of radioactivity in a material is achieved by measuring its activity, which quantifies the rate of atomic disintegration in a sample. The unit of measurement for this quantity is the becquerel (Bq), which quantifies the number of disintegrations that occur per second. The temporal progression of the activity of a radionuclide is governed by an exponential law, and the half-life is defined as the time required for the activity to decrease by half. While the activity measurement quantifies the level of radioactivity, it does not directly reflect the potential biological damage that radiation can cause. The magnitude of radiation damage is determined not only by the amount of radiation, but also by its energy and type. During the disintegration process, an atom can emit various types of particles, including alpha particles (consisting of two protons and two neutrons), beta particles (electrons or positrons), and gamma rays (photons).

The energy of the emitted particle is typically measured in electron volts (eV), where 1 eV corresponds to 1.60×10^{-19} J. When a stable atom is struck by a particle, it is possible that one

of its electrons in the orbitals is expelled. This process is known as ionization, which results in the transformation of the stable atom into an ion. Consequently, the ion exhibits increased chemical reactivity, meaning it becomes more susceptible to chemical reactions and, therefore, affects the stability of the matter that has been irradiated. The classification of radiation as ionizing is contingent upon its possession of sufficient energy, typically exceeding 10 electron volts, to induce ionization.

The phenomenon of ionization is defined as the process by which radiation deposits energy into matter, and its effects can be multifaceted. In biological tissues, ionization can damage cells, causing their death or irreversible damage. Furthermore, the ions produced in biological tissues can initiate chemical reactions, thereby generating a cascade of biological effects. Consequently, continuous and high exposure to ionizing radiation can be detrimental to human health and the environment. The concept of dose, expressed in the International System of Units (SI) in Gray (Gy), is used to quantify the energy deposited by radiation in a material. This unit of measurement quantifies the energy absorbed per unit mass, with 1 Gy being equivalent to 1 J/kg (IAEA, 2018).

However, it is crucial to note that the biological effects can vary significantly even with the same absorbed dose, depending on the type of radiation involved (alpha, beta, gamma). For instance, alpha radiation possesses a comparatively large and heavy atomic number compared to other forms of radiation. While it exerts a high ionizing effect, its penetration capacity is limited in materials or organisms. The damage it inflicts is limited to the initial micrometers of the tissue it impacts, i.e., a few cells. Consequently, alpha particles are unable to traverse the skin or other superficial layers of the body with ease. However, if these particles are emitted internally, for example, by a radionuclide ingested or inhaled by the subject, they have the potential to inflict considerable damage to the internal components of the body, including cells and tissues. In contrast, beta radiation consists of charged particles, including electrons (beta-) and positrons (beta+). Beta particles possess a smaller size and mass compared to alpha particles, which affords them a greater penetrating power. These particles have the capacity to traverse the epidermis and tissue layers, though their movement is impeded by more compact materials such as glass or plastic. Finally, gamma radiation, being of a photonic nature, is distinct from the preceding types of radiation. The photons associated with this type of radiation possess low energy, akin to X-rays. The penetrating power of gamma photons is such that high-density materials, such as lead, are used to attenuate them.

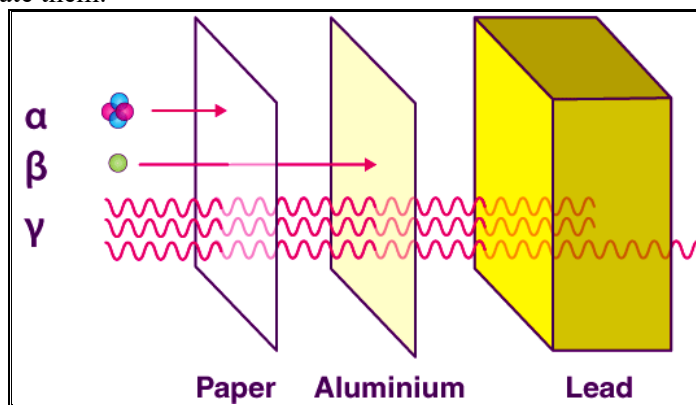


Figure 1. Ionizing effect penetration capacity into materials.

Source: International Atomic Energy Agency (IAEA, 2020)

In order to account for the disparate properties of the particles and to quantify the biological damage independently of these characteristics, the concept of equivalent dose, measured in sievert (Sv), is employed. This measure of radiological protection is calculated by multiplying the absorbed dose (in Gy) by specific weighting factors that depend on both the type of radiation and the tissue affected. This approach enables a more precise estimation of the damage induced by radiation, irrespective of the specific type of radiation.

Within the framework of radiological protection, two primary categories of exposure are recognized: external and internal. External exposure occurs when a radiation source is outside the body. In this case, the greatest risks are due to beta and gamma emissions because of their greater penetrating power. Conversely, internal exposure occurs when a radioactive source enters the body through ingestion, contact with wounds, or inhalation. In the presence of a radioactive gas, such as radon, the primary risks are associated with alpha emissions, which possess a high ionizing capacity and can directly compromise the internal regions of the lungs after inhalation.

To assess the radiological risk posed by gaseous sources, it is essential to estimate the concentration of activity in the air, expressed in becquerels per cubic meter (Bq/m³). This concentration is then used to quantify the damage to the human body through inhalation and immersion. Conversion coefficients, which are specific to the radionuclide present in the gas, are applied to calculate the dose rate expressed in microsieverts per hour ($\mu\text{Sv/h}$)/(Bq/m³). The application of these conversion coefficients facilitates the determination of the equivalent dose rate, which is expressed in $\mu\text{Sv/h}$. The conversion coefficients for activity and equivalent dose are derived from studies and physical models that analyze the deposition of energy in biological tissues.

Despite the long-standing presence of research in the scientific community concerning the study of radiation and its effects, the topic remains largely unexplored or unaddressed by the general public, particularly those engaged in the exploration and extraction of natural resources. This dearth of knowledge is particularly problematic for individuals engaged in the exploration and extraction of natural resources, where the state and the companies operating within this sector bear the responsibility for ensuring the well-being of laborers, who are obligated to provide care, study, measurement, and epidemiological monitoring of the effects to which workers are exposed. They must also control risk factors and demand measures to control, mitigate, and reduce radioactive accumulation and exposure. A salient example of this is radon gas, which, upon inhalation, serves as a vehicle for the entrapment of radioactive materials and its descendants within the pulmonary system.

Radiation Protection Guidelines and Standards

The overarching objectives of radiation protection legislation are threefold: to guarantee safety in the administration of ionizing radiation, to safeguard public health, and to protect the environment. These regulations are rooted in principles established by international bodies such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP). The legislation stipulates exposure limits for workers and the general population, along with monitoring and control practices to ensure that radiation levels remain within safe limits. For instance, the international standard "Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards" (IAEA, 2016).

In the context of mining operations, radiation protection is of particular importance due to

exposure to natural sources of radioactivity, in particular uranium, thorium, and radon. Legislators have outlined safety measures, including risk assessment and environmental monitoring, to ensure the protection of miners and surrounding communities (Ministerio de Minas y Energía, 2015).

Radon: Risks and Considerations in Radiation Protection:

Radon (Rn) is a chemical element that is located in the P block of the periodic table. It is identified by the atomic number 86 and the symbol Rn, and belongs to the group of noble gases. Radon's atomic mass is 222, comprising 86 protons and 136 neutrons, along with 86 electrons in a neutral state.

Radon gas is classified as part of the uranium (U) and thorium (Th) decay series. Uranium is found in nature in the form of several isotopes, and each of them follows radioactive decay chains. Specifically, the U-238 isotope undergoes a disintegration process that gives rise to the generation of Rn-222, which has a half-life of 3.8 days. Furthermore, U-235 undergoes a disintegration chain that results in the appearance of Rn-219, with a half-life of 4 seconds. Finally, in the thorium decay chain, which originates from Th-232, Rn-220 is produced, with a half-life of 55 seconds. Consequently, radon isotopes occur in nature as progeny of uranium and thorium, which are inherently present in various rocks and soils on Earth. Furthermore, the progeny of radon contains isotopes of polonium, bismuth, and lead. These resulting elements ultimately become solid particles that can easily attach themselves to dust or pollution in the environment and to liquid particles in rainwater that fall to the ground or into water sources (IAEA, 2013).

Núcleo	Modo de desintegración	Periodo de semidesintegración	Energía desprendida (MeV)	Producto de desintegración
U 238	α	4.468 · 10 ⁹ a	4,270	Th 234
Th 234	β^-	24,10 d	0,273	Pa 234
Pa 234	β^-	6,70 h	2,197	U 234
U 234	α	245500 a	4,859	Th 230
Th 230	α	75380 a	4,770	Ra 226
Ra 226	α	1602 a	4,871	Rn 222
Rn 222	α	3,8235 d	5,590	Po 218
Po 218	α 99.98 % β^- 0.02 %	3,10 min	6,115 0,265	Pb 214 At 218
At 218	α 99.90 % β^- 0.10 %	1,5 s	6.874 2.883	Bi 214 Rn 218
Rn 218	α	35 ms	7.263	Po 214
Pb 214	β^-	26.8 min	1.024	Bi 214
Bi 214	β^- 99.98 % α 0.02 %	19.9 min	3.272 5.617	Po 214 Tl 210
Po 214	α	0.1643 ms	7.883	Pb 210
Tl 210	β^-	1.30 min	5.484	Pb 210
Pb 210	β^-	22.3 a	0.064	Bi 210
Bi 210	β^- 99.99987% α 0.00013%	5.013 d	1.426 5.982	Po 210 Tl 206
Po 210	α	138.376 d	5.407	Pb 206
Tl 206	β^-	4.199 min	1.533	Pb 206
Pb 206	-	estable	-	-

Figure 2. Desintegration data

Source: Cuaderno de Cultura Científica (CCC, 2020)

As demonstrated in the above figure, the sequence of radioactive decays originating in uranium-238 is represented, along with the half-life values of each element. It is noteworthy that, with the exception of radon 222 (Rn), all elements are present in solid form. Radon's descendants emit alpha radiation (α), characterized by their diminutive size and substantial mass. The skin effectively prevents exposure to these particles; however, if they penetrate the respiratory system through inhalation, they become lodged in a specific part of the body, leaving their descendants in solid form. Subsequent to this, the descendants undergo a process of energy release within the lungs, resulting in the emission of alpha radiation and the initiation of ionizations that affect cellular structures (IAEA, 2019). This, in turn, leads to the uncontrolled fragmentation of mutated cells. It is important to note that radon and its radioactive progeny can enter the body through inhalation or ingestion, adhering to the walls of the stomach and intestine, where they begin radioactive decay and emit alpha particles. Secondly, radon has a brief half-life and can be expelled through exhalation; however, radon particles can persist, affecting DNA and causing mutations in the lungs or Chronic Obstructive Pulmonary Disease (EPA, 2024).

The highest concentrations of the chemical element radon are found in the subsoil, which can be extracted from a depth of one meter. This gas exits the atmosphere through the pores of the crust, particularly in sandy soils where high proportions of the gas are emitted, contrasting with clayey or compact soils. The rate of dissipation of radon gas in the environment is so rapid that it poses

no significant threat. However, it does not occur in confined, unventilated spaces, where the gas concentration increases to a level that constitutes a real risk to human health, as is the case in mines, caves, and water treatment dams (OMS, 2021).

As expected, radon levels are elevated in regions exhibiting high uranium concentrations in rock formations. The initial recognition of the potential dangers associated with inhalation of radon progeny occurred in the context of uranium mines. However, it is important to note that high radon concentrations are not exclusive to uranium mines. Given the ubiquity of uranium ores in the earth's crust, they are often discovered in the vicinity of other commercially viable ores. The identification of substantial radon concentrations in numerous mines have necessitated better ventilation and greater control of the radon level, especially in locations previously considered free of radiological hazards.

Consequently, radon has emerged as a significant radiological hazard for individuals engaged in mining operations. This hazard originates from various sources, including controlled mine drilling, mining operations, and internal mine explosions. These activities invariably generate substantial amounts of airborne dust, rock fragments, and fine particles. These materials continuously release radon. The presence of particles in the air leads to a significant adhesion of radon's descendants to these particles, thereby increasing the health risks associated with this combination. Mitigation of these risks can be achieved by implementing water spraying or optimizing air circulation. It is imperative to acknowledge that ventilation in mines is typically mandatory to mitigate the risk of silicosis, the predominant occupational disease affecting hard rock miners. However, given the tendency of radon to accumulate in dead-end tunnels and in unworked regions of the mine, it is imperative to provide additional and flexible ventilation systems. Furthermore, it is essential to implement continuous measurement and monitoring campaigns to evaluate the concentration of radon in the air (Cothorn & Smith, 1988).

The magnitude of radioactive activity is quantifiable in Becquerels per cubic meter (Bq/m^3), which serves as a metric for the rate of radioactive decay per second of the radioactive atoms present in a cubic meter of air. The concentration of radon gas in an open space can vary from 5 to 15 Bq/m^3 , but in urban environments such as buildings, houses, schools, and offices, the concentration level can vary from 10 to over 10,000 Bq/m^3 (CTE, 2022). Individuals may reside or work in locales with elevated radon levels without being cognizant of the threat, this poses a significant health risk due to the high radioactivity of radon, which can have harmful effects on human health when inhaled in substantial quantities for prolonged periods. Prolonged and indoor exposure to radon gas has been associated with the development of lung cancer and substantial cellular damage (American Cancer Society, 2024).

The World Health Organization (WHO) has established parameters for radon concentration, where the WHO characterizes radon concentration as low when it is less than 100 Bq/m^3 , average when it is between 100 and 200 Bq/m^3 , and high when it is greater than 200 Bq/m^3 . The WHO has indicated that the maximum allowable concentration level should not exceed 300 Bq/m^3 (WHO, 2015). For the United States, the maximum allowable concentration level is 4 picoCuries per Liter (pCi/L), which, when converted to Bq/m^3 , is equivalent to 148 Bq/m^3 (EPA, 2016).

Results

In the latter half of 2024, a request for information was made to various government entities within the Colombian state, including the National Mining Agency, the National Environmental

Licensing Authority, the Ministry of Labor, the Ministry of Environment and Sustainable Development, the Colombian Geological Service, and other entities such as the National Cancer Institute, Ecopetrol, and the Ministry of Health, where at the end of the year 2024 government entities never gave a concrete answer to the request for statistical data, public policy guidelines, follow-ups, and epidemiological studies on the effects of radon gas on the health of workers in the mining sector. This evasive and irresponsible behavior on the part of the administration is particularly alarming, as it underscores its apparent avoidance of its constitutional and legal duty to seek the well-being and improvement of the quality of life of all residents in Colombian territory. The National Mining Agency was the only government entity that attempted to respond to the twelve requirements requested:

"3. I request a report on the way in which the management, control and measurement of radon gas in the open-pit, surface, pleasure, underground and underwater mining sector is monitored in the last three and a half years, 2021, 2022, 2023 and 2024."

Answer:..... From this, it can be deduced that there is no exhaustive statement of the possible polluting gases that may occur in the development of underground mining activities and that must be subject to monitoring, which must be defined in the Occupational Health and Safety Management System, SG-SST., whose compliance is also verified by the mining authority.

To date, the mining authority has not established a protocol for measuring the reference gas. This is due to the fact that no alerts have been generated to indicate to the mining authority that it should carry out its control and monitoring by the competent authorities.

In light of the radioactivity associated with radon gas, it is imperative to establish comprehensive monitoring, licensing, and control procedures for all activities pertaining to the utilization of radioactive materials. This includes the design, construction, commissioning, operation, and decommissioning of radioactive and nuclear facilities, as well as the possession, exploration, extraction, production, storage, transportation, trade, import, and export of radioactive minerals and radioactive and nuclear materials for use in medicine, industry, scientific research, and other areas. The management of radioactive waste by public and private users at the national level is also the responsibility of the Colombian Geological Service, in accordance with the provisions of Article 1. According to Decree 1073 of 2015, the mining and energy sector is subject to specific regulations. Consequently, he was transferred for the response within the scope of his competencies under file No. 20243600161381 of August 8, 2024.

7. I request a report from those public and private entities that are dedicated to the study, analysis and monitoring of the consequences and effects of radon gas on the health and environment of the open-pit, surface, pleasure, underground and underwater mining sector in the last three and a half years, 2021, 2022, 2023 and 2024.

Answer: Given that the competence to issue a timely and substantive pronouncement on the request corresponds to the Colombian Geological Service and the National Institute of Health, under Dockets Nos. 20243600161381 and 20243600161361 of August 8, 2024, they were transferred for the pertinent matters.

8. I request a report on the training provided by the State through public and private entities on the effects of radon gas on health and the environment of the open-pit, surface, pleasure, underground and underwater mining sector of the last three and a half years, 2021, 2022,

Answer: Given that the competence to issue a timely and substantive pronouncement on the request corresponds to the Colombian Geological Service and the National Institute of Health, under Dockets Nos. 20243600161381 and 20243600161361 of August 8, 2024, they were transferred for the pertinent matters.

9. I request a report on the training provided by the Occupational Risk Administrators on the effects of radon gas on the health and environment of the open-pit, surface, pleasure, underground and underwater mining sector of the last three and a half years, 2021, 2022, 2023 and 2024.

Answer: Given that the competence to issue a timely and substantive pronouncement on the request corresponds to the Colombian Geological Service, the National Institute of Health and the Ministry of Labor, under file Nos. 20243600161381, 20243600161361 and 20243600161391 of August 8, 2024, they were transferred for the pertinent matters.

11. I request an epidemiological report on the effects of radon gas on the health of workers engaged in open-pit, surface, pleasure, underground and underwater mining in the last three and a half years, 2021, 2022, 2023 and 2024.

Answer: Given that the competence to issue a timely and substantive pronouncement on the request corresponds to the Colombian Geological Service and the National Institute of Health, under Nos. 20243600161381 and 20243600161361 of August 8, 2024, they were transferred for the pertinent matters" (Agencia Nacional de Minería, 2024).

However, the Colombian Geological Service has not fulfilled its mission obligations to generate and disseminate geoscientific and nuclear knowledge concerning the water cycle, climate change, geological dynamics, mineral and energy resources of the subsoil, in order to achieve the well-being and balance of the country's geosystem. The entity is required to control, manage, measure, and monitor radon gas in mining activities, but the entity repeatedly states that this is not a mission assigned to it by law:

"**3.** A report is hereby requested that details the manner in which the management, control, and measurement of radon gas have been monitored in the open-pit, surface, pleasure, underground, and underwater mining sectors over the past three and a half years, specifically in 2021, 2022, 2023, and 2024.

The Colombian Geological Service has not monitored the management, control, and measurement of radon gas in mining activities, and is unaware of whether any entity does so. This is taking into account that it is not a mission activity assigned to the entity.

7. I request a report from those public and private entities that are dedicated to the study, analysis and monitoring of the consequences and effects of radon gas on the health and environment of the open-pit, surface, pleasure, underground and underwater mining sector of the last three and a half years, 2021, 2022, 2023 and 2024.

The Colombian Geological Service has not carried out a study, analysis and monitoring of the consequences and effects of radon gas on health and the environment and does not know if any entity does so, since these are tasks outside our missionary competences.

8. I request a report on the training provided by the State through public and private entities

on the effects of radon gas on the health and environment of the open-pit, surface, pleasure, underground and underwater mining sector of the last three and a half years, 2021, 2022, 2023 and 2024.

The Colombian Geological Service has not carried out training on the effects of radon gas on health and the environment and does not know if any entity does so, since these are activities that are not assigned to the entity's mission competencies.

11. I request an epidemiological report on the effects of radon gas on the health of workers engaged in open-pit, surface, pleasure, underground and underwater mining in the last three and a half years, 2021, 2022, 2023 and 2024.

The Colombian Geological Service lacks the expertise necessary to conduct epidemiological studies. It should be noted that the Technical Directorate of Laboratories of the Colombian Geological Service has conducted investigations in underground mines, specifically in Guaico (Cisneros, Antioquia) in 2022 and El Vinagre (Puracé, Cauca) in 2023, which are dedicated to the extraction of gold and sulfur, respectively. The primary objective of these investigations is to identify gases that could potentially emit electromagnetic and ionizing radiation to which mining personnel could be exposed in these subterranean environments.

To this end, comprehensive measurements have been conducted to ascertain the presence of radioactive isotopes, specifically ^{222}Rn (radon) and ^{220}Rn (thoron), in the ambient air. In addition, in situ measurements of other critical gases, including CO, H₂S, O₂, CO₂, CH₄, and NO₂, have been made. Furthermore, the studies encompass the measurement of physical variables such as air temperature, relative humidity, atmospheric pressure, lighting, and the presence of gases and levels of ionizing radiation in the environment.

This research underscores the necessity to implement preventive measures to safeguard the health of personnel entering mines from the potential impacts of toxic, asphyxiating, flammable, explosive, and radioactive gases present underground. The studies provide detailed justifications for the measurements taken in each work area and offer a theoretical framework on gases, natural isotopes, mining, public health, and the accumulation of radioactive isotopes in mining activities. The methodology, results, and recommendations emphasize the critical importance of establishing a continuous monitoring system in mining operations to ensure the safety of personnel and the integrity of the environment (Servicio Geológico Colombiano, 2024)

The National Authority of Environmental Licenses (ANLA) offered a cursory general overview of the licenses currently issued by the Colombian government for the exploration and exploitation of the open-pit mining sector, evading precision, coherence, and exhaustiveness answer for each question. A similar situation can be observed with the Ministry of Environment and Sustainable Development, which avoided the respective questions, and the depth of the information requested, although it did recognize the absence of epidemiological studies and public policy guidelines to protect mining workers:

“..... In accordance with the foregoing, it is indicated that this Ministry, and in particular the Directorate of Environmental, Sectoral and Urban Affairs, is responsible for proposing environmental standards and general regulations on productive activities that may directly or indirectly generate environmental damage, including mining activities. Nor is there information on the study, analysis and monitoring of the consequences and effects. Likewise,

no training has been carried out on the effects of radon gas on the health and environment of the open-pit, surface, pleasure, underground and underwater mining sector" (MADS, 2024)

The Ministry of Labor, in accordance with its legal obligations, is responsible for formulating, implementing, and supervising public policies related Colombian labor law. The objective of these policies is to improve the quality of life of all residents in Colombian territory, where such the effectiveness of conditions labour, fair, and decent work, however, the response of this government entity has been characterized by inaction and a lack of responsibility, as evidenced by its statements:

"The Directorate of Occupational Risks of the Ministry of Labor responded to the concern as follows:

The Directorate of Occupational Risks of the Ministry of Labor gives general guidelines that do not include the direct solution of specific problems or the analysis of particular actions, in this case defining *the effects of radon gas on the environment of the mining sector in the open pit, surface, pleasure, underground and submarine of the last three and a half years. 2021, 2022, 2023 and 2024*. This competence in relation to environmental effects is in charge of the Ministry of Environment and Sustainable Development, which is why it is recommended to raise the request to this ministerial portfolio.

On the other hand, we would like to quote what was defined by the World Health Organization in terms of:

"Radon is a naturally occurring radioactive gas that can be found in high concentrations in indoor spaces, such as homes and workplaces, it can be found in enclosed spaces where it tends to have higher concentrations, especially in poorly ventilated places. The presence of radon gas indoors is a preventable risk factor that can be avoided through effective national policies and regulations." Geneva, WHO (2009).

We invite the petitioner to consult the WHO Handbook on Radon Indoors (Buildings): A Public Health Perspective, which presents policy measures to reduce health risks from exposure in homes. WHO Handbook on Indoor Radon: A Public Health Perspective. Geneva, WHO (2009).

In response to your specific question of giving a report on the training provided by the Occupational Risk Administrators on the effects of radon gas on health, we inform you of the following:

Decree 1072 of 2015 defines:

In accordance with the aforementioned standard, the Ministry of Labor has issued general regulations in the labor field such as Resolutions 0312/2019 (minimum standards), 491/2020 (confined spaces) and 773/2021 (globally harmonized system), which express the obligation of the employer, workers and occupational risk administrators, in relation to the identification of hazards and risk assessment in the workplace. in terms of specific prevention of chemical risk (gases).

In the case of the Occupational Risk Management Entities, they have the obligation to provide training and promotion and prevention services to companies and to the Joint Committees or Occupational Health and Safety Watchdog (COPASST) on issues related to Occupational Health and Safety in accordance with the provisions of Article 11 from Law

1562 of 2012 about permanent monitoring of working conditions and effective risk control.

To define the training provided by the Occupational Risk Administrators, it is necessary for the petitioner to establish the economic activity and the departments where he wishes to know this data, however, he may make the query through the Fasesolda website, in his capacity as representative of the country's insurance companies, this has a group in which he brings together the Occupational Risk Administrators -ARL- of Colombia (Ministerio de Trabajo, 2024).

Finally, the incongruous response of the Colombian Oil Company, classified as the second largest company in Latin America in exploration and exploitation of natural resources, evading the questions that were asked through a right of petition where it is asked the policies of the Occupational Health and Safety Management System related to the protection of workers to the degree of radioactive exposure of radon gas, stating:

“1. I request a statistical report on the number of people who have developed lung cancer in the trade or profession of hydrocarbon exploration and mining in the years 2021, 2022, 2023, and 2024.

“We clarify that Ecopetrol's corporate purpose is the development, in Colombia or abroad, of industrial and commercial activities corresponding to or related to hydrocarbon exploration, among others, and does not include mining activities.

For the years 2021 to 2024, we are not reporting cases of occupational lung cancer associated with hydrocarbon exploration.”

2. I request a report on the measures and protocols implemented as public policy to prevent and promote Occupational Health and Safety in Colombian territory regarding the radiation exposure caused by radon gas.

“Ecopetrol S.A. Its corporate purpose is the development, in Colombia or abroad, of industrial and commercial activities corresponding to or related to the exploration of hydrocarbons, exploitation, refining, transportation, storage, distribution and marketing of hydrocarbons, their derivatives and products and in no case is it within our scope or corporate purpose to issue measures and protocols as public policies related to radiation associated with radon gas” (ECOPETROL, 2024).

The State's response must be forceful, as the International Atomic Energy Agency has stated about it is imperative to implement safety protocols to mitigate the radiological risks that potentially impact workers and the general public. States are bound by both national and international obligations pertaining to the safeguarding of human life, health, and the environment. It is incongruous and irresponsible for government authorities to shirk social responsibility by failing to provide for the design, implementation, and monitoring of public policies that control and prevent the radioactive risk factors caused by radon gas and its descendants in mining (IAEA, 2022).

The Colombian State must assume primary responsibility for ensuring workplace safety and health by implementing regulatory measures and guidelines that control and mitigate radioactive exposure to radon, a carcinogen, in the absence of adequate personal protective equipment, proper ventilation, and rotating work shifts during the workday to limit prolonged exposure. These guidelines must encompass the involvement of a professional expert in occupational safety

and health, an adequate and relevant occupational safety and health management system, active breaks, training against the risks of radioactive exposure, and effective radon detectors and monitoring instruments. In accordance with international standards for exposure levels, national regulatory guidelines must be followed among these national guidelines is Resolution 18-1434 of 2002 from the Colombian Ministry of Mines and Energy on radiological protection and safety, where established permissible exposure concentration levels of 400 Bq/m³. This resolution is reiterated in Resolution 3032 of 2022 from the Ministry of Labor determining the guide for the identification labour of high risk and requires public authorities to monitor and comply with the Colombian legal framework.

Conclusions

Employees engaged in mining operations are exposed to radioactive risk factors that are not widely recognized, and these factors have the potential to adversely affect human health and the environment. In this regard, government entities bear the responsibility of establishing public policies aimed at promoting safety and health in the workplace, with a particular focus on mitigating the radioactive effects caused by radon.

However, the Colombian state's acquiescence has enabled the circumvention of constitutional and legal commitments aimed at ensuring the well-being and enhancement of the quality of life of all residents. This failure to comply with international recommendations aimed at protecting and preventing accidents or occupational diseases among individuals exposed to constant ionizing radioactive risks is evident. This inconsistency in its duties and in the social aims of the state is evident.

A substantial proportion of mining activities in Colombia is conducted in subterranean settings, characterized by a paucity of adequate technology and environmental protection measures. This environment fosters widespread illegal mining, which operates beyond the confines of environmental regulations and licensing frameworks. Consequently, mine workers are subjected to substandard working conditions, with inadequate legal safeguards and comprehensive coverage for protection against occupational risks and social security.

Radon is one of the most danger human carcinogens. The carcinogenicity of radon is convincingly documented through epidemiologic studies of underground miners, all showing a markedly increased risk of lung-cancer, but there is a high level of ignorance regarding the radioactive effects of radon on the health of mining workers, and the Colombian government must commit to fulfilling its legal obligations to protect its workers. This ignorance should be reduced as an improved understanding develops cellular events in the induction of lung cancer at low levels of exposure to radon.

A notable concern is the issue of radon gas, which emanates from the disintegration of uranium present in rocks. During the radioactive decay process, radon emits alpha (α) particles of ionizing radiation, which pose a threat to human health, particularly for individuals who are exposed to these particles in confined spaces with inadequate ventilation or protective measures. This exposure has been linked to the development of lung cancer, as there are currently no established measures to mitigate the associated risks. Furthermore, there is a paucity of epidemiological studies that have examined the impact of occupational health and safety on the general population.

Governmental entities are urged to formulate a public policy of promotion, prevention, and

protection against ionizing radioactive hazards such as radon, which can cause carcinogenic effects, through regulatory guidelines that stipulate the elements of personal protection, adequate ventilation, rotating work shifts during the working day to limit prolonged exposure, a professional expert in occupational health and safety, an adequate and relevant occupational health and safety management system, active breaks, training against the risks of radioactive exposure, and effective monitoring instruments and radon detectors.

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