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Radon Exposure Study in Underground Mine Sites

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Abstract: The seepage of radon from the bowels of the earth is practically a natural process, and the accumulation of this gas can be observed in any closed ground spaces, underground mines, tunnels, underground garages, etc. That is why the measurement of radon concentrations is of interest not only to the mining industry and underground mines. For the present study, experimental measurements have been carried out for radon exposure in three underground mines using two methods for measuring radon content - digital (with an electronic device) and analytical (by placing CD/DVD plates). The analytical method is the placement of CD/DVD plates for measuring radon/thoron in underground sites (mining galleries, caves, etc.). The principle of the CD/DVD method is that it combines the high absorption capacity of the polycarbonate material of the discs with its track properties. This makes it possible to clarify the contribution of thoron and radon to the irradiation of miners and above-ground personnel. The digital method was carried out with the help of an electronic device, with which continuous monitoring of the concentration (volume activity) of radon in one of the underground sites was carried out and the results were compared with those from CD/DVD plates.

Keywords: Radon, Thoron, Radon detectors, Underground mines, Radon exposure

Introduction

Radon is a radioactive gas discovered in 1900 by the German physicist Friedrich Dorn. As a member of the uranium-radium decay chain, it is distributed everywhere across the Earth – in soils, rocks, minerals, water, and air (Samson et al., 2026; Sapmaz Il & İçhedef., 2026). As a gas, radon migrates through air pores and fissures, reaches the Earth's surface, and is released into the ambient atmospheric air. Some materials used in construction, such as concrete structures and rock cladding and linings in metro tunnels and similar confined spaces, can also be a source of radioactive radiation (Borisov, 2021). In enclosed spaces, it has the property of accumulating. Radon is a dominant factor in the exposure of the global population to natural radioactive sources and activities related to the mining and processing of uranium-bearing minerals (Dai et al., 2026). In 2009, the World Health Organization identified radon as the second most significant cause of lung cancer after smoking. Recognized as the most consequential occupational hazard faced by underground workers, chronic inhalation of radon decay products emerged decades ago as the dominant driver of lung cancer among mining populations, contributing a substantial share of premature deaths recorded across major mining cohorts worldwide (WHO, 2009; WHO, 2021b). The International Commission on Radiological Protection (ICRP) recommended that national radiation protection authorities introduce reference levels for radon concentrations in dwellings and workplaces (ICRP 137, 2017). Because uranium-bearing rock continuously emits radon gas as part of its natural radioactive decay chain, underground workings frequently trap this invisible, odorless contaminant at concentrations far above surface background levels, placing every worker who enters such spaces at measurable

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risk of chronic radiation exposure (Li et al. 2026). As a consequence of this, reference levels for radon exposure have been introduced in many European countries (EU Council Directive 2013/59/EURATOM, 2013). When higher radon levels are detected, it is necessary to take appropriate measures. Determining the radon level is achieved through direct measurement.

Modern health assessments for radon and thoron follow the International Commission on Radiological Protection (ICRP) Publication 137. These guidelines updated and essentially doubled previous dose coefficients, adopting an advanced dosimetry model rather than older epidemiological approximations. Modern Dose Conversion Coefficients (ICRP 137) see Table 1. For both dwellings and most indoor workplaces, the ICRP uses a standardized dose coefficient: Radon (^{222}Rn) Coefficient: 3 mSv per mJ h m^{-3} (approx. 10 mSv/WLM or 6.7 nSv per Bq h m^{-3}). Worker Exposure: For physical activities in specific workplaces (like tourist caves or confined spaces), the coefficient increases to 6 mSv per mJ h m^{-3} . Thoron (^{220}Rn): Doses from thoron progeny are typically calculated via site-specific biokinetic and respiratory models outlined in the Occupational Intakes of Radionuclides (OIR) series (ICRP 137, 2017; Rani et al., 2026).

Table 1. Effective doses from inhalation of radon and thoron in workplaces by a reference worker with an average breathing rate of $1, 2 \text{ m}^3 \text{ h}^{-1}$ (ICRP 137, 2017)

Exposure/place*	Unattached fraction, f_p	F	Effective dose per exposure†		
			mSv per WLM	mSv per mJ h m ⁻³	mSv per Bq h m ⁻³
<i>Radon (²²²Rn) gas + progeny</i>					
Indoor workplace	0.08	0.4	20	5.7	1.3 × 10 ⁻⁵
Mine	0.01	0.2	12	3.3	—
Tourist cave	0.15	0.4	24	6.7	1.5 × 10 ⁻⁵
<i>Thoron (²²⁰Rn) progeny</i>					
Indoor workplace	0.02	—	5.6	1.6	1.2 × 10 ^{-4‡}
Mine	0.005	—	4.8	1.4	1.0 × 10 ^{-4‡}

Note. f_p , unattached fraction in terms of the potential alpha energy concentration; F , equilibrium factor.

* The assumed aerosol distributions for the different workplaces are given in Tables A.3 and A.4 of Annex A.

† For radon, 1 WLM = $(6.37 \times 10^5/F) \text{ Bq h m}^{-3}$; for thoron, 1 WLM = $4.68 \times 10^4 \text{ Bq h m}^{-3}$ of equilibrium equivalent concentration of ^{220}Rn ; 1 WLM = 3.54 mJ h m^{-3} .

‡ In terms of mSv per Bq h m^{-3} of equilibrium equivalent concentration of ^{220}Rn .

The working and microclimate conditions in underground mining sites are different from those in buildings and in open atmospheric conditions. This specifics should be considered by selecting the preferred measurement methods and tools appropriate to these conditions. Air quality in underground sites and deep open-pit mines depends on a number of factors such as: internal combustion engine (ICE) operation, blasting and underground fires. etc. (Dinchev et al, 2014). This requires constant monitoring and installation of fire-detection and fire-protection systems (Makedonska et al 2019, 2025). The obtained data in an underground mine from various process monitoring are very complex and often require further data post-processing (Mischio H., & Krichler T. 2022). The underground environment is challenging for the measuring with CD/DVD detectors due to:

- High humidity (close to 100%) leading to condensation on the detectors (Günther et al., 2026)
- Explosive gases (NO_x , forming of acidic substances with moisture)
- High concentration of dust
- Blast waves of various intensity and force (Mollova, 2025);
- Curious or malicious personnel causing loss (damage) of detectors;

To compile a detailed map of radon levels in the air of the mine galleries and diagnose the efficiency of ventilation, the points at which simultaneous measurements must be carried out are numerous and distributed throughout the mine. When selecting a method to assess radon exposure, several critical factors must be considered, namely cost-effectiveness, environmental adaptability, and accessibility. Recent trends show a diversification of materials employed for long-term cumulative radon monitoring, integrating with conventional alpha-track techniques (Rathebe & Kholopo, 2024).

Method

The present study evaluates the effectiveness of analytical method with CD/DVD polycarbonate discs for passive radon monitoring in three underground mine sites. The analytical method for cumulative measurements of radon (^{222}Rn) and thoron (^{220}Rn): consists of placing CD/DVD plates for measuring radon/thoron in underground spaces and mine workings (mining galleries, caves, etc.). This includes specifying the influence of underground conditions on the readings of these detectors and comparing them with other methods for radon measurement including electronic devices and diffusion chambers (Dimitrov D., Pressyanov D, 2018). The method is based on specific ability of polycarbonate material, used for commercial CD/DVDs. This material is highly radon absorbent and has track-etch properties (Figure 1). In 2011 and following, the capacity of the CD/DVD method was expanded (Pressyanov et al., 2018, 2019, 2022, 2026) with the possibility of differential measurements of thoron ^{220}Rn , using a development of the CD-disk method and application in distinct conditions indoors and outdoors.

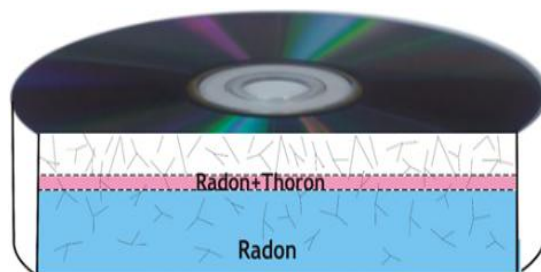


Figure 1. The principle of the CD/DVD method - Signal formation (Dimitrov D. 2020)

The main point of the method is that the time-integrated volumetric activity of radon can be determined from the density of α -particle traces at a strictly defined depth below the surface. At depth greater than $>76\mu\text{m}$, the signal is formed only from absorbed ^{222}Rn and its progeny (R-signal). Furthermore, at depth interval $64-76\mu\text{m}$ the signal is due to source connected to ^{220}Rn thoron (T –signal) namely ^{212}Po (decay product of ^{220}Rn) and from absorbed ^{222}Rn (R+T signal) (Figure 2). For the purpose of measuring ^{220}Rn the R-signal is used also to determine and subtract the ^{222}Rn contribution to the R+T signal in the first depth. The remaining “thoron component” (T-signal) is used to measure ^{220}Rn . This allows to eliminate the signal obtained from the progeny decay products in the environment and, after appropriate processing of the discs, to obtain a signal that is easy to register and read. The further treatment process of CD-DVDs like electrochemical etching (ECE) are described elsewhere (Pressyanov et al, 2022)

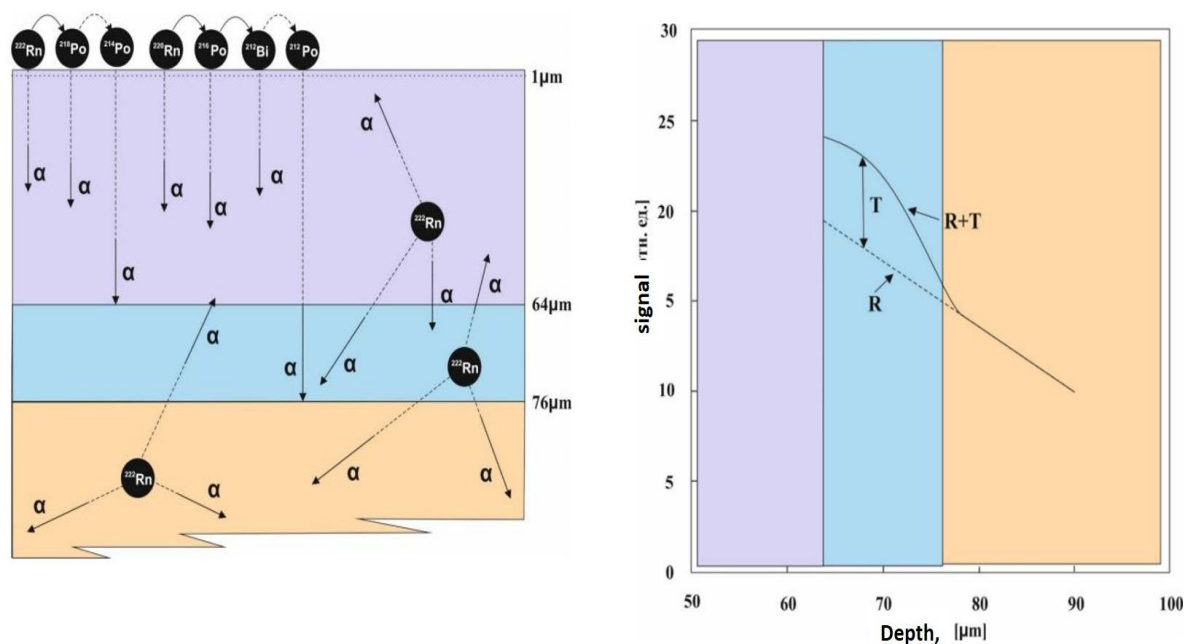


Figure 2. Radon and thoron signal depth distribution (Dimitrov D. 2020)

An important advantage of this method in an underground environment is that normal moisture condensation does not affect the measurement. The calibration factor depends on the temperature at the time of irradiation. The temperature influence can be reported, corrected if necessary. If it is not known, posteriori correction can be

applied. Other factors (pressure, dust, smoke, blast waves) do not affect the CD/DVD method. The CD/DVD method is sensitive and accurate enough to measure ^{222}Rn and ^{220}Rn in underground spaces and mines.

Experiments

Three study sites were selected for conducting the experiment: underground mines with distinct characteristics, varying geological conditions, and different types of extracted raw materials, mainly polymetallic ores (Table 2). Passive radon/thoron detectors were deployed across all three sites, with Site 3 featuring parallel measurements using an electronic radon monitor.

Table 2. Study sites characteristics

Mining site	Type	Ore extraction	CD number	Location
Site 1	Underground mine site	Gold - silver ores	28	Bulgaria
Site 2	Underground mine site	Lead – zinc ores	20	Bulgaria
Site 3	Underground mine site	Silver ore (Lead – zinc ores)	15	Germany

The geological conditions, as well as the characteristics of each mine site, are specific in terms of depth, type of ore, and microclimate characteristics (Table 3). The aim of the study is to compare the presence of radon/thoron under different conditions and to establish the applicability of the measurement method with CD/DVD discs.

Table 3. Experiment settings

Study site	Number of detectors	Exposition period	Temperature	Relative Humidity	Depth	Underground waters	Notes
Mine Site 1	28	6 months	11 – 14 °C	68 - 78% incl. shaft; 78 - 87 % galleries	From level 810 to 760	yes	
Mine site 2	20	3 months	15°C	dry	From level 460 to 240	no	
Mine site 3	15	3 months	10 °C	90% -95%	150 m	yes	*Digital Monitor

Description of Studied Mine Sites

Study Site 1 – Underground Mine Site for Extraction and Processing of Gold (Au) – Silver (Ag) Ores

Site 1 - is an underground mine located in the Western Srednogorje region, Western Bulgaria (Figure 3 and 4). The geological structure of the deposit area and its metallogenic specialization are determined by an Upper Cretaceous volcanic trough, filled with a thick layer of medium to basic volcanics and their tuffs, representing a small segment of the regional Banat-Srednogorje volcanogenic-metallogenic zone. The manifestations of mineralization of precious and non-ferrous metals are associated with partially exposed Upper Cretaceous porphyry stocks. Subsequently, the Upper Cretaceous volcanics and hydrothermal systems are covered by thicker Paleogene and Neogene sediments, folded into extensive synclinal structures. The occurrences of mineralization of precious and non-ferrous metals are associated with partially exposed Upper Cretaceous porphyry stocks. Subsequently, the Upper Cretaceous volcanics and hydrothermal systems were covered by thicker Paleogene and Neogene sediments, folded into extensive syncline structures..

An inclined shaft is used for the exploration and extraction. The entrance is at elevation 811 with slope 1/7 (14 degree). The inclined shaft is a rectilinear construction, and it is planned to use it to cut the ore veins at Chor. 760. The total length of the inclined shaft will be 380 m. During the period of normal operation and exploration of the mine, it is planned to use a flank suction ventilation system after the construction of the ventilation systems at two ventilation chimneys, located respectively at the eastern and western ends of the mine field. The clean air flow enters the opening workings located centrally in the mine field and through the central chimney will enter the respective horizon, where the mining operations are concentrated. The amount of air required to ventilate the mine is limited by the diesel-powered machinery intended for use in underground conditions, as modern trends in mining mechanization are towards the transition to electric vehicles and the use of autonomous

control methods (Gorbounov, 2025; Hristova, 2024). The designed main ventilation system ensures an air flow rate between 110 and 120 m³/s.



Figure 3. Site 1 – Underground mine site with Au – Ag deposits



Figure 4. CD/DVD positions on underground mine site 1

Study Site 2: Underground Mine for Extraction and Processing of Lead (Pb) – Zinc (Zn) Ores

Mining site 2 is located in the Southeastern part of Bulgaria, which is rich in ore and non-ore minerals. The greatest economic importance is given to lead-zinc and polymetallic ores (Madan, Rudozem, Lucky, Madzharovo and Zlatograd deposits). Lead-zinc deposits have a vein origin, with some ore-bearing veins having a length of up to several kilometers (Fig. 5) and sometimes in very hard-to-access areas (Aleksandrova et. al., 2025). In addition to lead and zinc, the ores contain copper, pyrite, gold, silver and other valuable components. Polymetallic ores are formed from hot mineralized solutions, which rose through the cracks of the rocks 20-30 million years ago. Chromium ore is found in Krumovgrad and Asenovgrad regions, and uranium ore - in Smolyan region. Tungsten is mined in Velingrad region. The deposits of fluorite (near Mihalkovo) and marble (Velingrad region) are of economic importance. Of the non-metallic minerals in the Eastern Rhodopes, asbestos, trass, perlite, and zeolites are of greatest importance. Figure 6 shows the position of CD/DVDs detectors in mine site 2.

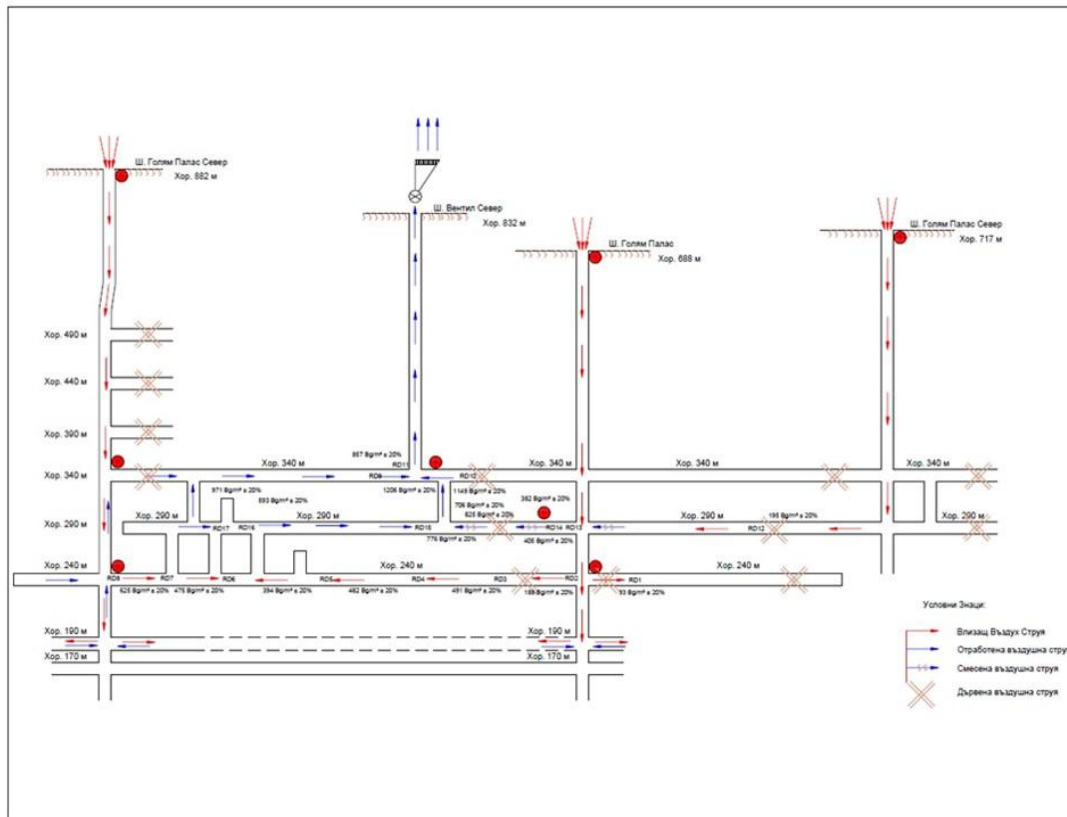


Figure 5. Site 2 – Underground mine site with Pb – Zn ore deposits

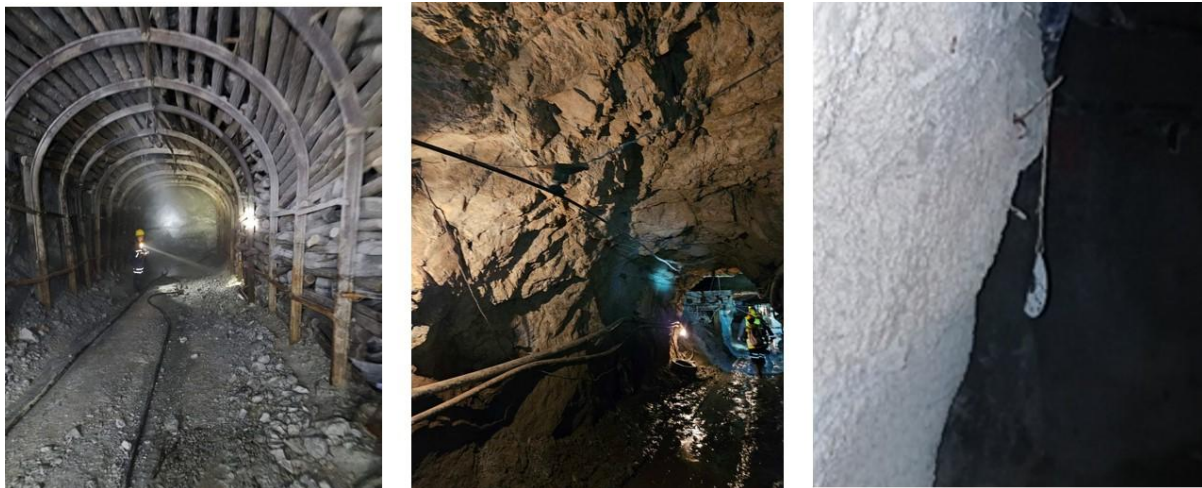


Figure 6. CD/DVD positions on underground mine site 2

Study Site 3: Underground Lead (Pb) – Zinc (Zn) Mine for Silver Ore (Ag) Extraction

The underground mine 3 is a lead-zinc deposit containing silver on the territory of Germany (Figure 7 and 8). The deposit is the most important ore deposit for the region in terms of its spatial extent, the quantities of ore mined and the metals extracted from it, its importance to the economic history of the region and the extent of geological research (Table 4). Geologically, it is a polymetallic, hydrothermal vein ore deposit of late Silurian to Silurian age with over 1100 known galleries. The galleries were the subject of mining activity from the late Middle Ages to the last third of the 20th century. Silver was the main extracted metal during most of the production periods. In addition, lead and zinc, as well as small amounts of copper, gold and trace metals, were of economic importance during the last periods of the mine's operation.

Table 4. Study site 3 – ore deposits composition

Ore type	Mineral	Chemical formula	Specific notes
Metallic ores	Galena	PbS	Basic Pb ore with high Ag content
	Sphalerite	ZnS	zinc sulfide mineral
	Pyrite	FeS ₂	Major raw material for sulfuric acid production; Low Au content – can be economically viable
	Arsenopyrite	FeAsS	
Silver (Ag) ores	Chalcopyrite	CuFeS ₃	Most abundant Cu content ore.
	Argentite	Ag ₂ S	Up to 87% Ag content
	Proustite	Ag ₃ [AsS ₃]	
	Argyrodite	Ag ₈ GeS ₆	Up to 74% Ag content and 6% Ge content
Non-metallic ores (rock minerals)	Quartz	SiO ₂	Nno economic importance; some of its variants are rock crystal, amethyst, agate, chalcedony
	Baryte	BaSO ₄	Due to high density is used as raw material for drilling
	Fluorite	CaF ₂	Collectable value – color variety and crystallisation
	Calcite	CaCO ₃	Collectable value



Figure 7. CD/DVD positions on underground mine site 3.

Results and Discussion

Figure 9 graphically presents the measured data for radon concentrations in the three underground mining sites compared to the maximum recommended threshold level of 300 Bq/m³ for homes and work exposure. In relation to this norm, radon fluctuations, as well as its exceedance, can be noted. The data obtained in Mine site 1 are with low radon content as presented on the graphic below. This low radon concentrations are caused by the positioning of the CD/DVDs near the entrance of the mine and the minor depth. The installed ventilation system ensures the necessary fresh air supply. The study mine site 1 is at the early stages of exploitation. Further radon exposure measurements are to be considered in the future.

Significant levels of radon were detected from the obtained data at Site 2, which is associated with the great depth and at places ineffective ventilation. In 85% of the disks, a radon signal accumulation above 300 Bq/m³ was reported, and in two of the points there was a detected signal values that surpass the 1000 Bq/m³ occupational threshold, especially in workings that lack robust mechanical ventilation or rely on natural airflow alone. Mine 2 has currently ceased operations

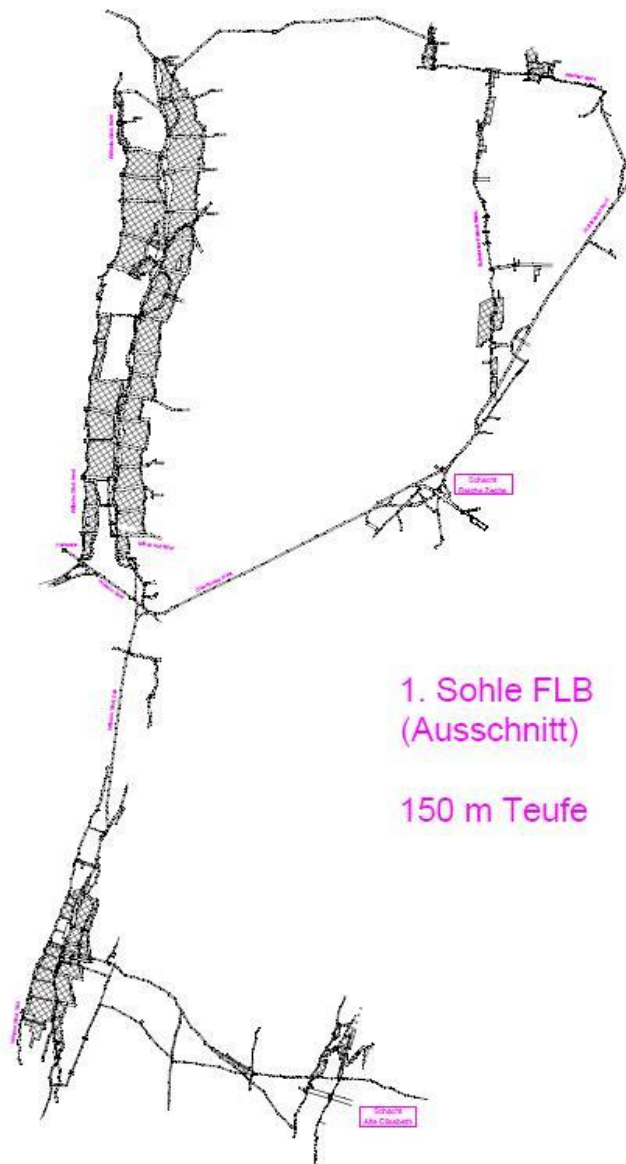


Figure 8. Site 3 – Underground mine site with Pb – Zn ore deposits and Ag extraction

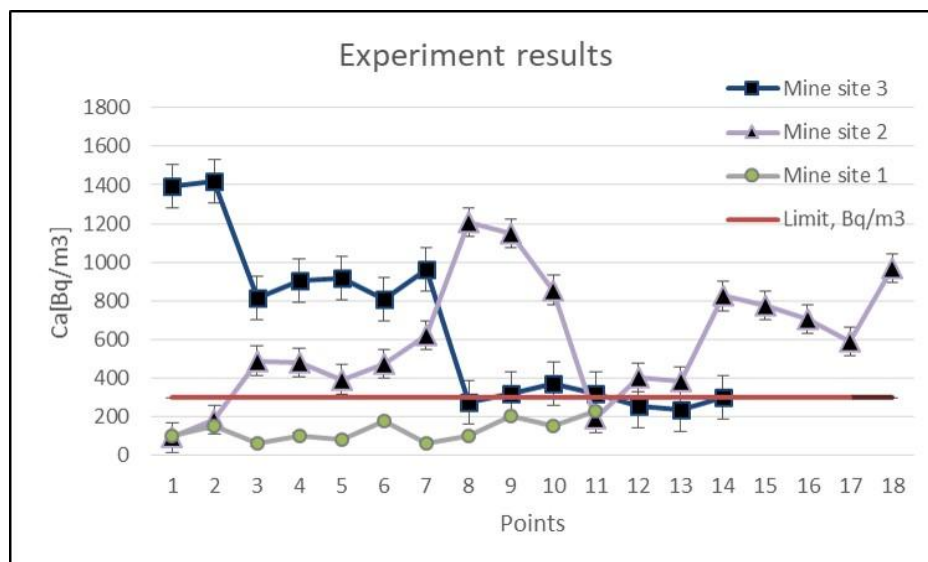


Figure 9. Result comparison for all experimental mine sites

Result Analyse for Mine Site 3

On particular interest are the data acquired in Site 3. The measured values are in wide range, from exceeding both 300 Bq/m³ and 1000 Bq/m³ thresholds. Due to the conditions in the mine 3 – low temperature (less than 10 degree Celsius) and high humidity (approximately 98 %), the radon signal (²²²Rn) on the CD/DVDs is considered relatively weak and hence the higher uncertainty of the radon measurement. In parallel with the passive time-integrated CD/DVD method independent control measurements were conducted using an active electronic device at four geographically randomized sampling points (Figure 10). The sampling points are in the proximity of corresponding polycarbonate detectors (Figure 11).

lfd. Nr.	Messort	Kurzzeichen	letzte Messung	C _{RN}	F	Dosis _h	Dosis ₂₀₀₀	Dosis _{0,4h}	Dosis _{0,4,2000}
				[Bq/m ³]		[μSv]	[mSv]	[μSv]	[mSv]
8	WMS 8		07.01.2020	419	0.02	0.06	0.13	1.33	2.67
9	WMS 9		03.12.2019	353	0.02	0.06	0.11	1.12	2.25
13	WMS 13		22.08.2019	1135	0.19	1.69	3.39	3.61	7.22
15	WMS 15		21.08.2019	836	0.25	1.65	3.31	2.66	5.32

Figure 10. Electronic device results

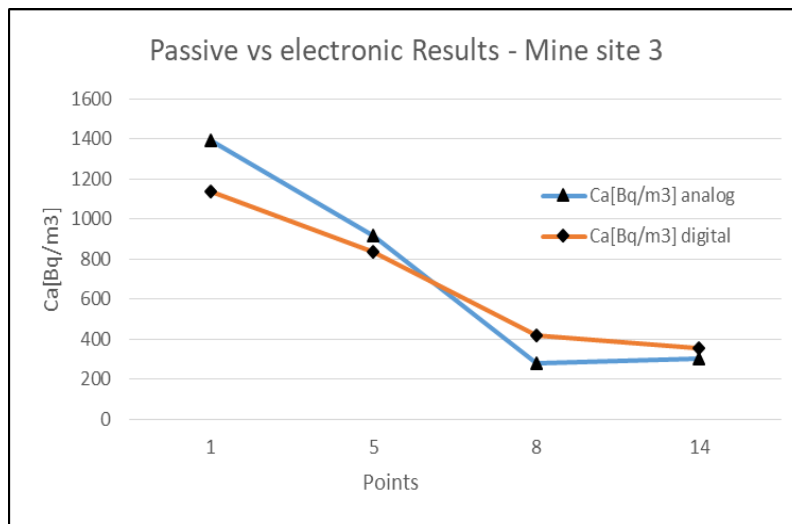


Figure 11. Results comparison - passive vs. electronic detector

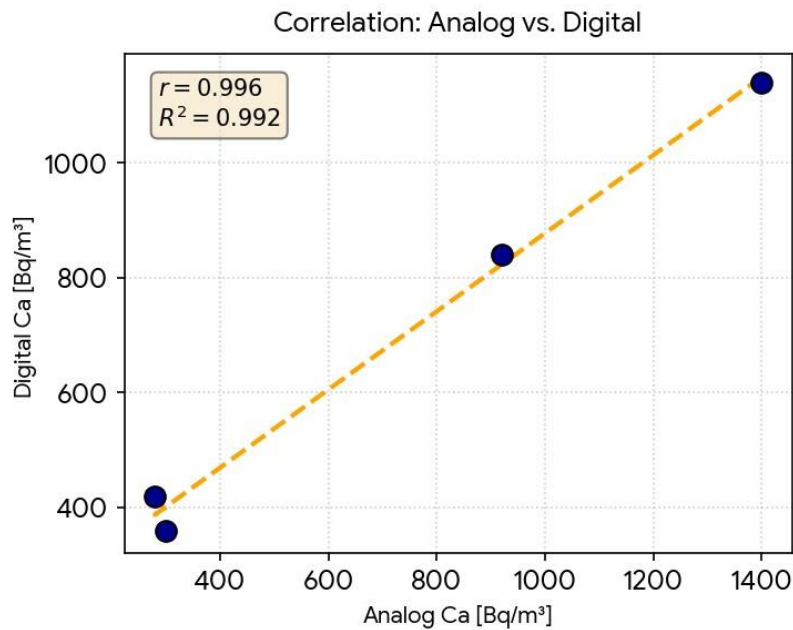


Figure 12. Result correlation - passive vs. electronic detector

These active readings were used to independently verify the accuracy of the passive CD/DVD method. Result comparison of the two independent measurement techniques (CD/DVD method vs. digital device) are in high agreement with $r = 0.996$, demonstrating the high validity of both approaches. (Figure 12). Furthermore, the analysis of thoron (^{220}Rn) concentrations results in notable findings. Radiometric evaluation of the passive detector disks revealed elevated (^{220}Rn) thoron signal. These data indicate that the atmospheric airborne radioactivity within this specific mine site is predominantly driven by a high contribution of thoron, as illustrated in Figure 13.

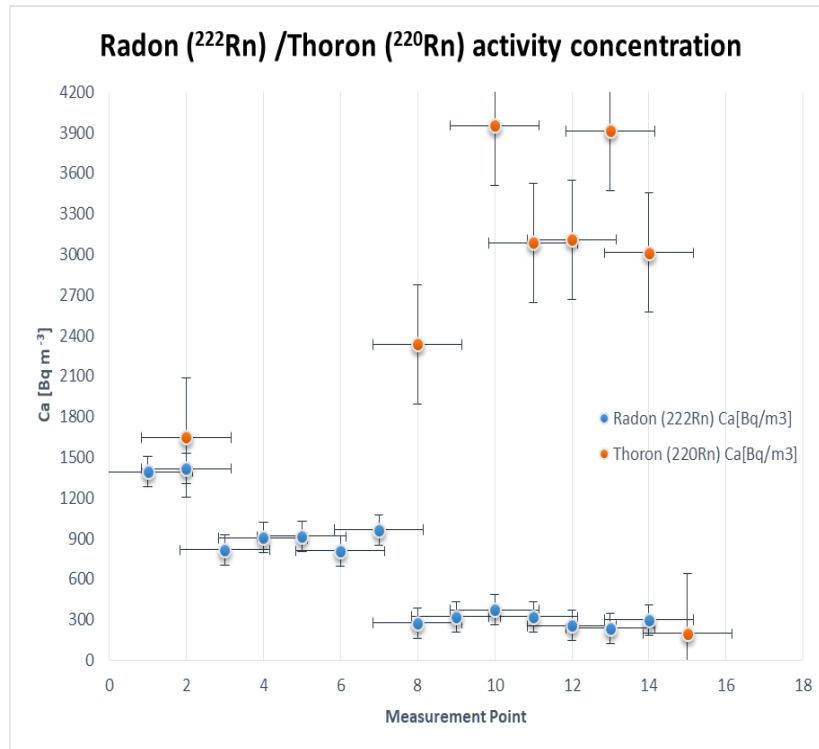


Figure 13. Radon/Thoron activity concentration

The measurement is based on tracking alpha particles from a short-lived progeny with decay energies between 7.8 and 8.8 MeV, recorded at a defined depth within the CD/DVD matrix. These tracks are assigned to (^{212}Po), a decay product of (^{220}Rn). Evaluation revealed an elevated track density in the DVDs exposed at site 3. This accumulation is presumably driven by the mineralogical profile of the mine rocks (Table 4). Consequently, it is pertinent to evaluate alternative techniques for thoron registration.

Conclusion

The application of CD/DVD polycarbonate discs as detectors for radon and thoron exposure demonstrates their capability to provide reliable results under extreme environmental conditions, including high humidity, dust, and smoke. This enables long-term cumulative measurements in underground mines, regardless of the severe conditions. Measuring radon and thoron levels in underground mines is of critical importance due to several key factors: the carcinogenicity of alpha radiation emitted by radon, the specific nature of the underground environment, restricted ventilation, and the rapid accumulation of hazardous concentrations.

Historically, thoron was overlooked as a radiological hazard due to its short half-life. Its half-life is approximately 56 seconds, compared to 3.8 days for radon, which led to the past assumption that it would decay before reaching the occupational zone. However, the actual risk of thoron manifests when the source material is in close proximity to the worker—as is typical in mining operations—allowing thoron to reach the breathing zone in substantial volumes. Its progeny are highly radiotoxic, and the resulting radiation workload can be comparable to, or even exceed, that of radon. One of the most effective mitigation strategies for reducing these underground gases is forced ventilation. Therefore, comprehensive measures to maintain safe radon and thoron levels in underground mines must integrate the control of ventilation systems, optimization of airflow dynamics, and continuous atmospheric monitoring.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest.

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