Radiological Study of Radon Gas in Underground Goldmine

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ABSTRACT
Indoor radon concentrations were collected monthly over a period of one year in 10 different levels in an underground goldmine to determine the radiological impact on workers. The detectors were installed in batches within four quarters. The measurements were carried out using LR115 solid state nuclear track detectors. The results show that the activity concentration of radon in the underground mine ranges from a minimum of 2 Bqm^{-3} to a maximum of 284 Bqm^{-3} with a mean value of 58.51 Bqm^{-3}. The highest radon concentration was observed in the second quarter when the season was warm, and the lowest radon concentration was observed in the first quarter when the season was colder. The hazard indices, exposure rate, excess lung cancer risk and annual effective dose from the rock and soil samples possess no radiological hazard if used for building materials.
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Introduction

The underground mine environment is complex and variable. Radon, after being exhaled, decays to a more stable radionuclides: ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (Cousins et al., 2011). These radionuclides attach to the aerosol particles in the air, forming what is termed attached radon progeny. The fraction of radon progeny that does not attach to the aerosol particle in the air is termed the unattached state. In both cases, concentrations of these radon decay products increase rapidly with residence time of the air in the mine. If inhaled, both attached and unattached radon progenies may be deposited in the lung, especially in the upper respiratory tract, and irradiate the lung tissue as they decay. The entry of radioactive aerosol into the respiratory tract depends on their size; larger particles stop in the nasal cavity, while smaller aerosols reach the lungs (Planinic, Faj, Radolić, Šmit, & Faj, 1999). Epidemiological studies have revealed a strong correlation between lung cancer and exposure to radon (Yoon, Lee, Joo, & Kang, 2016). It was identified as a human lung carcinogen in 1986 by the World Health Organization – WHO. High concentration of radon is found in poorly ventilated structures and if the radon input from its sources is high, such as mines, caves, cellars, ancient tombs, and airtight houses. The inhaled radon passes from lungs into the blood and body tissues and may irradiate different soft tissue causing cancers such as lung cancer, kidney cancer and prostatic cancer. Radon has also been linked with melanoma and some childhood cancers. There is also a positive association between coronary heart disease and radon exposures where an elevated risk of mortality from coronary heart disease was observed among miners with accumulative radon exposure exceeding 1000 Working Level Month (WLM) (Bajwa & Virk, 1997; Hussein, 2008).

There are currently four goldmines in Ghana operating underground. Apart from the Obuasi underground goldmine, which some work has been done (Andam, 1992; Darko, Tetteh, & Akaho, 2005), there has not been any radiological impact assessment on the rest. Preliminary investigations indicate that the ventilation is poor, which makes it conducive to high radon levels. Some workers have complained about the quality of air inside the underground goldmine. It is therefore important to understand how much risk these workers may be exposed to and, therefore, how the risk can be avoided and minimized.

Despite increased interest and concern of the international scientific community on the importance of monitoring radon and its impact on public health, Ghana has not yet carried out any systematic studies on radon levels on a national scale. There are therefore no national regulations for residential and occupational radon protection. However, studies on the concentration levels of radon and its progeny in goldmines, industries (workplaces) and dwellings in Ghana are limited. This means that the average radon concentration levels and effective dose exposure to the entire population are not yet established. It is important to monitor this gas and its products in underground mines to assess the radiological hazards of the exposed workers. The knowledge of the radon distribution and its origin in mines is essential according to radiation-protection standards. In Ghana, studies on radon have been carried out over the past two decades. These studies have been independent and uncoordinated and have focused only on a few areas of interest (Andam, 1992; Darko et al., 2005; Nsiah-Akoto, Andam, Akiti, Flectcher, & Osei, 2019). The Subika underground goldmine is a new underground mine where there has been no radiological impact assessment. This means that the average radon concentration levels and effective dose to the entire population are not yet established.

To address this concern, the researcher aims to assess the radon and its progeny concentrations in the Subika underground goldmine to obtain reference data and information for regulatory authorities and other stakeholders to prepare the national regulations and standards for miners. This study is part of the Radon Project which is being conducted by the Ghana Atomic Energy Commission (GAEC) and the Nuclear Regulatory Authority (NRA). The set of data will contribute to limit occupational radiation exposure of workers and to obtain information and parameters to prepare the Ghana regulatory standards for miners.

Materials and Methods

Description of Study Area

Location, Geology and Sampling Points of the Underground Mine

The Subika Underground Goldmine (SUG) area is located approximately 300 km northwest of the capital city, Accra, 107 km northwest of Kumasi, and 40 km south of the regional capital of Sunyani. The SUG is being developed at the southern end of a mineralized zone that extends approximately 70 kilometres (km) in the central portion of Ghana. The SUG is an underground pit operation located at Kenyasi in the Asutifi North District of the Brong Ahafo Region. The nearest industrial site or Mine is Mensin Gold Bibiani Limited at Bibiani about 70 km southwest of Ahafo (Plant Site coordinates: 7°02’00” N, 2°23’00” W).

The current economic evaluation of the Mine indicates that Subika Underground mine contains an inventory of approximately four million ounces of gold with an average grade of 4.5 g/t Au. The SUG has the potential to provide between 200 koz and 300 koz of gold annually at peak production, over a 15 to 18-year mine life.

The SUG is proposed to be ultimately an underground long-hole open stopping mine producing approximately two million tons of ore per annum. The Mine operations use trucking and ramp haulage to bring ore to the surface. The decline (twin portal) constructed during the exploration phase serves as the main access portals for the Underground Mine and they will be advanced as two separate declines from the main decline as mining progresses to access the ore deeper underground.

The Subika deposit is a typical example of an orogenic-style gold deposit.

Orogenic gold deposits occur in variably deformed metamorphic terranes formed during Middle Achaean to younger Precambrian, and continuously throughout the Phanerozoic. The host geological environments are typically volcano-plutonic or clastic sedimentary terranes, but gold deposits can be hosted by any rock type. There is a consistent spatial and temporal association with granitoids of a variety of compositions. Host rocks are metamorphosed to greenschist facies, but locally can achieve amphibolite or granulite facies conditions. Global examples of these deposits include Muruntau (Uzbekistan), Golden Mile (Australia), Hollinger-McIntyre-Moneta (Canada), Jamestown (USA), and Obuasi (Ghana).

The underground mine was constructed 1000 meters below the reference level and the sampling areas were within ten (10) different levels below the reference level. All levels indicate the depth of the underground goldmine from the reference level.

Deployment of Detectors at the Sampling Points

The radon gas measurement was done using radon detectors made up of LR-115 (type II strippable) cellulose nitrate detectors manufactured by Kodak Pathé in France. The detectors of area 2cm × 2cm were attached to a plastic dish with its sensitive side facing upwards and covered with a perforated plastic dish. The plastic dish with the radon detectors were installed at ten different locations of the Subika underground mine.

The detectors were planted in batches within the four quarters. The first quarter was between June to August 2018, the second quarter was between September to November 2018, the third quarter was between December 2018 to February 2019 and the fourth quarter was between March to May 2019. Each batch within the quarters was left at the sampling points for approximately four (4) weeks.

Forty (40) sampling points within the ten randomly selected points were chosen within the project site using a non- probability quota sampling. A total number of 40 dishes containing 80 detectors were deployed at the points for each batch (month) as shown in figure 11. In all a total number 320 detectors were deployed at the sampling points of which 20 of them were crushed by the heavy-duty vehicles underground leaving a total of 300 detectors to be analysed at the Nuclear Track detection Laboratory of Ghana Atomic Energy Commission.

Track Revelation

After exposure for one (1) month, the detectors were removed from the detector dish. 200 grams of sodium hydroxide pellet was weighed in a beaker with an electronic balance and the solution prepared in a 2L volumetric flask at the Nuclear Track Detection Laboratory of the Ghana Atomic Energy Commission as shown in figure 12. The detectors were then subjected to chemical etching in a 2.5 M concentration of sodium hydroxide solution at 60 ºC, for two hours in a constant temperature water bath to enlarge the latent tracks produced by alpha particles from the decay of radon. After the etching, the detectors were washed with running cold water for 20 minutes to stop the etching process, and then washed in distilled water for 15minutes. The detectors were then peeled whilst in the distilled water and air dried on a cardboard as shown in figure 13. After a few minutes of drying in air, the detectors were ready for track counting.

Image Acquisition and Counting of Tracks

The counting of tracks and the image acquisition was performed using a commercial scanner (Epson Perfection V600 Photo) manufactured in France, having 4800`x9600-dpi resolution and 48-bit for colour and 16-bit for grey maximum depth coupled to a laptop as shown in figure 24a. An important characteristic of the scanner is its double-lighting system. The films were inserted between two rigid transparent sheets on the scanner surface as shown in figure 24b. This arrangement provides a reasonably uniform illumination of the films, reducing the formation of folds and/or bubbles. The negative acquisition of the film image was carried out using 24-bit colour depth and 4800-dpi resolution. This choice produces an image that allows discerning appropriately tracks without requiring too much memory. A square area (1x1) cm^2 inside the exposed surface of the film was acquired.

Determination of the Annual Effective Dose and Lung Cancer Risk

Radiation Dose Estimation

The exposure to radon daughters in the underground goldmine can be calculated on the basis of the measured radon concentration using the following equation and US EPA methodology (Pawel & Puskin, 2003; UNSCEAR, 2006).

$$ER = CR \times F \times n(2.7 \times 10^{-4}) \times 8760/170 \qquad (1)$$

where, ER is exposure to radon daughters in WLM /y, CR is the radon concentration in Bq m^{-3}, 2.7×10^{-4} is the factor for the conversion of radon concentration to the WL per Bq m^{-3}, F is the equilibrium factor (0.4 for indoor), n is the occupancy factor, 8760 indicates total hours in the year, and 170 indicates the total working hours per month.

The annual effective dose due to radon in the underground mining has been estimated using the following formula (Quarto, Pugliese, La Verde, Loffredo, & Roca, 2015):

$$DE = ER \times DCF \qquad (2)$$

where, DE is the annual effective dose (mSv y^{-1}) due to radon daughters, ER is the exposure to radon daughter in WLM y^{-1} as per equation (1) and DCF is the dose conversion factor (mSv per WLM). For the determination of effective doses for underground miners, the dose conversion factor of (DCF) of 5 mSv per WLM recommended by ICRP 65 has been used.

The excess lifetime cancer risk ($ELCR$) due to radon exposure of the population in the underground mine was determined using the following equation based on the methodology described in EPA report (Shoeib & Thabayneh, 2014)

$$ELCR = ER \times T \times FR \qquad (3)$$

where, E_R is the radon daughter exposure in WLM per year (calculated by Eq. 1), T is the average lifetime expectancy for Ghanaians (62.4) and world average (70) (WHO,2015), and F_R is the risk coefficient for exposure to ^{222}Rn gas in equilibrium with its progeny. Based on the recommendation of the ICRP (International Commission on Radiological Protection), F_R is 5×10^{-4} per WLM (Valentin, 2007).

Results and Discussion

Radiological Impact Assessment of Indoor Radon

The European Union (EU) has adopted the International Commission for Radiological Protection (ICRP) recommendations into its protection standards. Member states are required to develop national action plans for addressing the long-term health risks of radon exposure in workplaces (Daniels & Schubauer-Berigan, 2017). The EU recommends 300 Bq·m^{-3} for ^{222}Rn concentrations as a suitable radon Derived Reference Level (DRL) as shown in table 19, although provisions for selecting a different level have been offered. Ireland was first to respond by publishing the National Radon Control Strategy in 2014 (Dowdall, Fenton, & Rafferty, 2016). The plan established a workplace DRL of 400 Bq·m^{-3} for ^{222}Rn, measured over three consecutive months. Exceeding the DRL triggers immediate federal notification and evaluation by the employer to determine if remediation is justified. Remediation is mandatory if the average ^{222}Rn level exceeds 800 Bq·m^{-3}.

Table 1: Annual Radon Concentration (Bqm^{-3})

Level	Block	Annual Radon Concentration (Bqm^{-3})
800	EMP	49.51
810	YOD	58.89
840	YOD	62.96
880	YOD	71.56
790	EMP	50.48
820	SKY ACCN	54.57
960	YOD	50.00
1000	SKY DEC	48.15
920	YOD	61.18
1000	YOD	73.49
Annual Average		58.51

According to the results in table 11 the mean radon concentration of 58.51 Bqm^{-3} is lower than the radon concentration monitored in of the oldest mines in Ghana called the Obuasi mines, The dose reference level (DRL) set by the European union, a remedial action level of 1000 Bqm^{-3} set by the International Commission for Radiological Commission (ICRP), Radon concentration in caves in Czech Republic as well as an underground goldmine in Kosovo as shown in table 2. The difference in the radon concentration may be due to the different geology of each study area as well as the rate of ventilation since Kosovo mine reported a poor ventilation system at the mine (Hodolli, Bekteshi, Kadiri, Xhafa, & Dollani, 2015). However, radon emanation levels depend on the radon concentration in the soil and the underlying rocks structure in addition to other factors like grain size, mineralogy, porosity, permeability, moisture content as well as the age of the underground mine.

Table 2: Comparison of Radon Concentrations to International Standards and Published Work

Country	Radon Concentration (Bqm^{-3})	Location	Reference
Ghana	436.80	Obuasi Mines	Darko et al 2005
Kosovo	527.2	Underground gold mine	Hodolli et al 2015
Czech Republic	1000-7000	Caves	Hodolli et al 2015
ICRP	1000	Mines/Workplaces	ICRP 115
European Union (DRL)	300	Workplaces	Daniels & Schubauer-Berigan, 2017
This study	58.51	Subika Underground Mine (Newmont Ahafo)	Phd Thesis

In its most recent recommendations on radon exposure, the International Commission on Radiological Protection (ICRP) encouraged national authorities to set a radon reference level (RL) based on an annual effective dose within the range of 1 to 20 mSv for members of the public and workers alike (Lecomte et al., 2014). The ICRP suggested a benchmark of 10 mSv effective dose equivalent per year as a practical starting point for considerations by nations developing radon management strategies and recognized an effective dose conversion factor (DCF) for Radon and its short-lived decay product (RnDP) exposures of approximately 10 mSv per Working Level Month (WLM), where 1 WLM =3.54 $mJ{\cdot}h{\cdot}m^{-3}$. Thus, the derived reference level (DRL) is 1 $WLM{\cdot}y^{-1}$, or average annual ^{222}Rn concentration of about 200 and 800 $Bq{\cdot}m^{-3}$ at home and in the workplace, respectively.

The average values of exposure rate to radon daughters in this study as shown in table 1 is lower than the derived reference level (DRL) of 1 $WLM{\cdot}y^{-1}$ by the international Commission for radiological protection (ICRP) and the National Institute for occupational Safety and Health (NIOSH) as well as 4 $WLM{\cdot}y^{-1}$ by the US Mine Safety and Health Administration regulation as shown in table 2.

Generally, the radon soil concentrations at all the 10 locations in the underground goldmine fall below the reference levels from the international commission for radiological protection (ICRP) as shown in table 3.

Table 3: ICRP 115 and Task Group Reference Levels

Location	Reference levels (Bqm^{-3})
Homes	300
Workplaces	1000
Mines	1000
Building Work	300

Source: (Tirmarche et al., 2010)

Table 4: Annual Radon Exposure (WLM y^{-1}), Annual Effective Dose (mSv y–1) and Excess Lifetime Cancer Risk (%)

Level	Block	Annual Radon daughter exposure (WLMy^{-})	Annual Effective dose (mSvy^{-1})	Excess Life Cancer Risk ELCR (%) (Ghanaians)	Excess Life Cancer Risk ELCR (%) (Worldwide)
800	EMP	0.22	2.20	0.70	0.80
810	YOD	0.26	2.62	0.80	0.90
840	YOD	0.28	2.80	0.90	0.01
880	YOD	0.32	3.19	1.00	1.10
790	EMP	0.22	2.25	0.70	0.90
820	SKY ACCN	0.24	2.43	0.80	0.90
960	YOD	0.22	2.23	0.70	0.80
1000	SKY DEC	0.21	2.14	0.70	0.80
920	YOD	0.27	2.72	0.80	1.00
1000	YOD	0.33	3.27	1.00	1.10
Annual Average		0.26	2.61	0.80	0.90

Table 5: Comparison of Annual Radon Daughter Exposure (WLMy^{-1}) to Protection Standards and Guidance for Occupational Exposure to Radon Progeny

Agency	Covered Population	Annual Level (WLM·y^{-1})	Reference
ICRP (Guidance)	Workers/Public	1	Publication No. 126
NIOSH (Guidance)	Underground miners	1	Publication No. 88-101
MSHA (Regulation)	Underground miners	4	10 CFR Part 57

ICRP, International Commission for Radiological Protection
NIOSH, National Institute for Occupational Safety and Health
MSHA, Mine Safety and Health Administration
CFR, Code of Federal Regulations

The ICRP also recognized that planned occupational exposures above the reference level (RL) may be unavoidable. In those cases, the exposure should be treated as occupational and managed using a set of radiation protection requirements for radiation workers. However, a worker's annual effective dose from radon should be kept below 20 mSv after accounting for the exposure situation (e.g., equilibrium, occupancy, breathing rate, respiratory protection, etc.) as shown in table 4.

The values of annual effective doses calculated for radon inhalation by the underground workers in this study were found to vary in the range 2.20–3.27 mSvy^{-1} at the 10 different levels in the underground mine with a mean of 2.61mSvy^{-1}. The minimum value of the annual radon dose was in level 800 and the maximum value was in level 1000 YOD as shown in table 4.

According to UNSCEAR (2006), the worldwide average dose due to inhalation of radon and its decay product is 1.15 mSv y^{-1}. The ICRP suggested a benchmark of 10 mSv effective dose equivalent per year as a practical starting point for considerations by nations developing radon management strategies.

Therefore, the dose received by the underground workers is above the worldwide average dose limit and lies below the suggested benchmark of ICRP for nations developing radon management strategies as well as the annual effective dose of occupationally exposed workers as shown in table 5.

The National Council on Radiation Protection and Measurements (NCRP) first published recommendations on radon exposure in 1984. The NCRP advised against exceeding an excess risk of death from lung cancer of 2% or greater over the lifetime of any individual exposed to enhanced levels of radon as shown in table 5. Using the underground miner epidemiologic data available at the time, the NCRP related this risk to Radon and its short-lived decay product (RnDP) exposures of 2 WLM·y^{-1}.

The mean excess lung cancer risk estimated by this work in table 20 was found to range between 0.7% and 1% with an average value of 0.8% for Ghanaian workers and a range of 0.8% and 1.1% with an average value of 0.9% for other nationals. The average of Excess Lifetime Cancer Risk (ELCR) is less as compared to the National Council for Radiation Protection and Measurement (NCRP) over the lifetime of any individual exposed to enhanced levels of radon (Pawel & Puskin, 2003). It is also less than the estimated excess lifetime lung cancer risk for continuous exposure at the United States Environmental Protection Agency (US EPA) of 2.3% for the U.S. population, 4.1% for ever-smokers, but higher than 0.73% for never smokers and the worldwide value 0.29 × 10-^{9} % from UNSCEAR as shown in table 5.

Table 6: Comparison of Annual Effective Dose and Excess Life Time Cancer Risk to International Standards and Published.

Agency	Covered Population	Annual Effective dose ($mSvy^{-1}$)	Excess Life Cancer Risk ELCR (%)	Reference
ICRP	Occupationally exposed workers	20	-	Publication No. 65
	Nations developing radon management strategies.	10	-	Publication No. 65
UNSCEAR (worldwide average value)	Individual exposed to enhanced radon	1.15	0.29 × 10-^{9}	UNSCEAR, 2006
NCRP	Individual exposed to enhanced radon		2.00	Report No. 77
US EPA	US population	-	2.30	Pawel & Puskin, 2003
	Ever Smokers	-	4.10	
	Never Smokers	-	0.73	

ICRP, International Commission for Radiological Protection
UNSCEAR, United Nations Scientific Committee on Atomic Radiation
NCRP, National Council for Radiation Protection and Measurement
US EPA, United States Environmental Protection Agency

Conclusion

This study was aimed at assessing the level of indoor radon and naturally occurring radioactive materials in underground goldmine in Ghana. Radon gas was present within the underground goldmine.

The average values of exposure rate to radon daughters were lower than the derived reference level (DRL) of 1 WLM·y^{-1} by the international Commission for radiological protection (ICRP) and the National Institute for occupational Safety and Health (NIOSH) as well as 4 WLM·y^{-1} by the US Mine Safety and Health Administration regulation. The effective dose received by the underground workers is above the worldwide average dose limit (1.15 mSv y^{-1}) but lies below the suggested benchmark of ICRP (10 $mSvy^{-1}$) for nations developing radon management strategies but was higher than the annual effective dose of 1$mSvy^{-1}$ for the members of the public. The Excess Lifetime Cancer Risk (ELCR) was less as compared to the National Council for Radiation Protection and Measurement (NCRP) over the lifetime of any individual exposed to enhanced levels of radon (Pawel & Puskin, 2003). It is also less than the estimated excess lifetime lung cancer risk for continuous exposure at the United States Environmental Protection Agency (US EPA) of 2.3% for the U.S. population, 4.1% for ever-smokers, but higher than 0.73% for never smokers and the worldwide value 0.29 × 10-^{9} % from UNSCEAR.

Generally, the radon soil concentrations at all the locations fall below the reference levels (1000 Bqm^{-3}) set by the international commission for radiological protection (ICRP). The measured radon concentration will be used as part of a reference data for regulatory authorities to set reference levels for underground workers.

Recommendation

The levels of Radon concentration at the underground gold mine appears to be low but may present a potential long-term health risk to occupationally exposed workers due to stochastic effect of radiation. Nonetheless, as a new underground goldmine, monitoring of indoor radon for deeper levels is recommended. In addition, further indoor radon testing after some years would enable a determination of the indoor levels and support the implementation of additional radon gas mitigation measures, if required. This will ensure that the occupationally exposed workers at the underground work with no radon gas health hazard.

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