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REVIEW PAPER

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SOURCES OF RADON AND ITS MEASUREMENT TECHNIQUES IN UNDERGROUND URANIUM MINES – AN OVERVIEW

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ABSTRACT

Purpose	This study aims to identify the potential sources of radon exhalation and its measurement in underground uranium mines to control the radiation levels within safe limits and protect miners from radiation hazards.
Methods	An extensive literature review on radon exhalation in underground uranium mines from various sources such as uranium ore, backfill tailings and mine water has been carried out. The influence of different important factors, viz. ore grade, porosity, grain size and moisture content on radon exhalation has been discussed in depth. Different methods for the measurement of radon exhalation from various sources in mines have also been presented in this paper.
Results	The review of literature revealed that the radon exhalation rate in porous uranium bearing rocks is less affected by the ore grade than in non-porous rocks. The exhalation of radon from backfill tailings is quantitatively more significant than from the uranium ore itself due to higher bulk porosity and enhanced surface area. Thus, porosity is the dominant factor that affects the rate of radon exhalation from rock surfaces into mine openings.
Practical implications	The knowledge of the sources of radon and quantitative estimation of radon from various sources will be very much useful in the planning and designing of ventilation systems in underground uranium mines. The accurate measurement of radon exhalation in underground uranium mines can be made by choosing the optimum size of accumulation chamber and a suitable radon build-up period in the chamber.
Originality/ value	The study portrays the important sources of radon and its measurement techniques in underground uranium mines based on an extensive literature review. The methods of measurement of radon exhalation from the ore body and backfill tailings in underground uranium mines, used by the authors of this paper, comparatively give more accurate results than previously used methods. Furthermore, the methods are more effective in terms of portability, cost and time for measuring the average radon exhalation across a large.

Keywords
underground uranium mine, radon exhalation, uranium-bearing ore, backfill tailings, mine water, accumulation technique

1. INTRODUCTION

Radium (^{226}Ra), a decay product of ^{238}U present in uranium ore, is a natural source of high radiation level in uranium mines. Since ^{226}Ra has a long half-life of 1600 ±7 y, it acts as an effective source of radon (^{222}Rn) gas with a relatively short half-life of 3.82 d in a mine atmosphere. ^{222}Rn decays to a series of short-lived decay products such as ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po in the mine atmosphere. When a miner inhales the mine air, radon being a gas, is exhaled along with the exhaled air. However, its daughter products, which are the atoms of heavy metals, deposit in the respiratory system and continue to irradiate the lung tissues even after one leaves the workplace. Additionally, short-lived radon daughters decay completely in situ before they are translocated to other parts of the body by physiological process. The potential hazards of radon daughters to workers in uranium mines have been well recognized (Grosche, Kreuzer, Kreisheimer, Schnelzer, & Tschense, 2006; Gulson, Mizon, Dickson, & Korsch, 2005; Ham, 1976). Although the inhalation hazard in uranium mines is principally due to radon daughters, this paper only concerns the migration of radon gas through pore spaces of the material into mine atmosphere. Since radon daughters are solid particles, they cannot migrate in the gas phase through the pore spaces. On reaching the mine atmosphere, radon decays to its daughter products, which migrate with aerosol particles. Schroeder and Evans (1969) have reported that the radon laden air remaining for a longer period in a mine develops higher radon daughter concentration.

A rapid air change causes the quick removal of radon gas from the mine's atmosphere, resulting in a lower quantity of its daughter products building up due to insufficient residence time. Therefore, the concentration of radon progeny in underground uranium mines greatly depends on the air exchange rate.

The concentration of radon in a mine atmosphere is considered to be indicative of the radiation hazards. The radon concentration in an underground uranium mine environment depends on emissions of radon from the ore body, broken ore, backfill tailings and mine water (Khan & Raghavayya, 1973; Mishra, Sahu, Panigrahi, Jha, & Patnaik, 2014; Raghavayya & Khan, 1973; Sahu et al., 2014). Radon atoms formed from ^{226}Ra within the solid grains may not be directly released into the atmosphere due to their low diffusion coefficients in solids. However, when radon atoms escape into the interstitial space between grains, they may be released to the surface. The release of radon atoms from the material to the atmosphere takes place by the following series of processes: a) Emanation – the process of movement of radon atoms from solid mineral grains to the interstitial space between the grains. b) Transport – the process of diffusion and advective flow causing movement of the emanated radon atoms through the material to the surface and c) Exhalation – the process of movement of radon atoms from the surface of the material to the atmosphere (Moed, Nazaroff, & Sextro, 1988).

The physical behaviour of radon in uranium ore is characterized by an emanation coefficient. Some of the radon atoms generated by the decay of radium contained in rock grains are not released into the pore spaces of rock because the radon atoms may travel a short distance and remain embedded in the same grain and/or they may travel across a pore space and become embedded in an adjacent grain. The fraction of radon atoms released from the radium-bearing rock grains into pore spaces of the rock is termed as emanation fraction or emanation factor or emanation coefficient of radon (Schumann, 1993; Tanner, 1980). The release of radon atoms from the material grains to pore spaces is caused due to processes such as recoil and diffusion (Hassan et al., 2011; Hosoda et al., 2008). Recoil is a process that when a radium atom decays to radon, the energy generated is strong enough to send the radon atom to a distance of about 40 nanometres (Tanner, 1980). Since the diffusion coefficient of radon gas in solid grains is very low, it is assumed that the release of radon is mainly due to the recoil process (Yang, Chou, Chen, Chyi, & Jiang, 2003).

This paper summarizes the sources of radon exhalation and its measurement techniques in underground uranium mines based on an extensive literature review. The main aim of this review is to identify the potential sources of radon exhalation and its measurement for reducing the radiation levels within the safe limits in underground uranium mines.

2. SOURCES OF RADON EXHALATION INTO A MINE ATMOSPHERE

Some important sources of radon exhalation into mine atmosphere in underground uranium mines, such as mine walls, broken ores, backfill tailings and mine water, are described below.

2.1. Mine walls

One of the major modes of entry of radon into the mine atmosphere is by diffusion through the mineral-bearing host rock and subsequent exhalation through the mine walls. Radon exhalation rate is expressed as a function of ore grade (Fusamura, & Misawa, 1964; Khan & Raghavayya, 1973). A study carried out by Sahu, Mishra, Panigrahi, Jha, and Patnaik (2013) also revealed a better correlation between the ore grade and radon exhalation rate as shown in Figure 1. Table 1 enlists the average radon exhalation rates of different lithological uranium ore types with different ore grades reported by various researchers. From this table, it may be observed that the radon exhalation rate in porous rocks is less affected by the ore grade than in non-porous uranium ores. Thompkins (1974) has also reported that the radon exhalation rate expressed as a function of ore grade alone has a poor correlation. However, a good correlation was obtained when the internal rock porosity was considered. Thus, unless the ore grades are extremely high, porosity and micro-fracture are the dominant factors that affect the rate of radon gas exhalation from rock faces into mine openings.

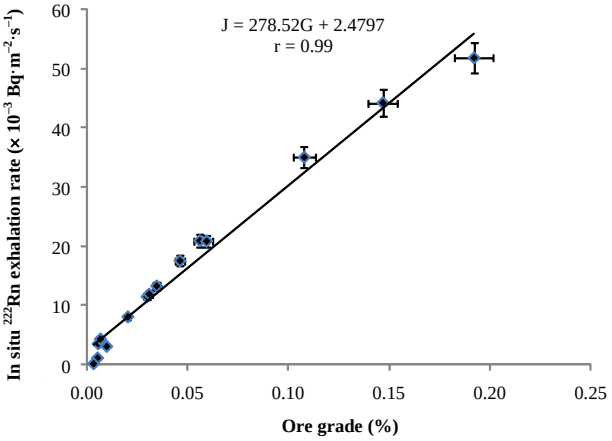

Fig. 1. The relationship of in situ radon exhalation rate with ore grade (Sahu, Mishra, Panigrahi, Jha, & Patnaik, 2013)

Table 1. Radon exhalation rates of different lithological uranium ore types

Ore grade (% U_3O_8)	Rock type	Radon exhalation rate (Bq·m^{-2}·s^{-1})	Reference
0.051	Pre-Cambrian meta-sedimentary rocks	0.22–51.84 × 10^{-3}	(Sahu et al., 2013)
–	Igneous rock, very low porosity	0.2–2 × 10^{-3}	(Thompkins, 1982)
0.20	Medium to coarse-grained	5.25	(Rock & Beckman, 1977)
0.20	Sandstone	5.29	
0.05	50% sandstone, 50% siltstone, highly fractured	9.73	
0.30	Gneiss, with fractured zone	19.87	
0.25	Sandstone, 20% porosity	18.5	(Thompkins, 1974)
0.10	Conglomerates, 0.10% porosity	0.259	
–	Shale, intermediate porosity	5	(Tsivoglou & Ayer, 1954)

2.2. Broken ore

In underground uranium mines, radon is not only exhaled from the mine walls (ore body and waste rock) but also from the broken ores present in the stopes. The ore, fragmented during the course of mining operations, provides a source of higher radon exhalation due to the increased exposed surface area (Thompkins & Cheng, 1969). The radon exhalation rates of the Beaverlodge broken ore samples and waste rock samples varied in the ranges of 4.81 × 10^{-3} – 0.22 Bq·m^{-2}·s^{-1} and 0.2–5 × 10^{-3} Bq·m^{-2}·s^{-1} respectively (Cheng & Porritt, 1981).

Bossard et al. (1974) reported the radon emanation coefficient from ore samples varying in the range of 7–57%. The emanation coefficients of Canadian, Italian and Australian ores have been reported as 0.0197, 0.0097 and 0.0877 respectively (Thompkins, 1982). Sahu et al. (2013) have reported the average emanation fraction of 0.025 ±0.02 for Jaduguda uranium ore.

2.3. Backfill tailings

Mill tailings, the crushed uranium ore residue produced during the extraction of uranium from the ores, is used as backfill material in underground uranium mines. IAEA (2004) has reported that the mining and milling of uranium ores has resulted in the generation of about one billion tons of uranium mill tailings in 4000 mines worldwide. The commercial extraction of uranium from the ores generally involves leaching with sulphuric acid (H_2SO_4). Since the uranium content of ores is low, large amounts of mill tailings are discharged in the form of slurry during the processing of uranium ore in the mills. The slurried tailings are separated into coarser and finer fractions. The coarser fraction is sent back to underground uranium mines for backfilling the stoped out areas and the finer fraction is discharged into a geologically stable structure with proper embankment and barriers called tailings pond (Tripathi, Sahoo, Jha, Khan, & Puranik, 2008). Usually, uranium extraction efficiencies at commercial mills range from about 65 to 95% (Mudd, 2000). Since the solubilisation of ^{226}Ra from ore minerals in sulphuric acid is low, the tailings contain a significant amount of radium. IAEA (1992b) has reported that the tailings contain 99% of the radium present in the original ore in France. Thus they are a potential source of radon in mine air. The radon exhalation rates of backfill tailings have been variously reported by different authors (Table 2). From this table, it may be observed that the difference in these values may be due to variations in the ^{226}Ra content of the processed uranium ore, particle size and moisture content of the backfill tailings.

Table 2. Radon exhalation rates of mill tailings used as backfill in different underground uranium mines

Location	Radon exhalation rate ($Bq \cdot m^{-2} \cdot s^{-1}$)	Reference
Jaduguda uranium mine, India	1.01	(Mishra et al., 2014)
Canada	203.5	(Franklin, Washington, Kerkering, Montone, & Regan, 1982)
Jabiluka uranium mine, Australia	10	(Strong & Levins, 1982)
Spain	1.7 ± 0.04	(Escobar, Tome, & Lozan, 1999)
Northern Territory	6.5	(Bollhofer, Storm, Martin, & Tims, 2006)

Due to the smaller particle size (a few tens of microns) of backfill tailings and hence their larger specific surface area, the radium in tailings tends to be rich near the grain surface resulting in higher radon exhalation (Breitner, Arvela, Hellmuth, & Renvall, 2010; Sakoda, Ishimori, & Yamaoka, 2011). Thompkins (1982) reported that Dension (Canada) unclassified tailings released 19.19% of the contained radon, whereas the radon release rate diminished to 14.38% in the case of classified tailings. IAEA (1976) also reported that tailings of less than a 40 μm size fraction released 10–15 times more radon than the coarser fractions.

Several investigators have reported that the emanation coefficient depends on the moisture content of the tailings (Mishra et al., 2014; Sahu et al., 2014). It has been found that the emanation coefficient of the tailings initially increases with moisture saturation before attaining the steady state as shown in Figure 4. This can be explained by the fact that the emanation coefficient of dry tailings is relatively low as most of the radon atoms escaping from particles bury themselves in adjacent particles. With an increase in moisture content, the pore water content of the tailings increases resulting in the termination of the recoiling of radon atoms in the pores. At a higher moisture content (above 5% by volume), few of these atoms penetrate into the adjacent grain particles and the emanation coefficient remains nearly constant with increasing moisture content up to saturation (Strong & Levins, 1982). It has also been reported that the emanation coefficient of saturated tailings is 2–6 times higher than in dry tailings (IAEA, 2013). Therefore, it is evident that the presence of moisture in the pore spaces of the tailings enhances the emanation coefficient.

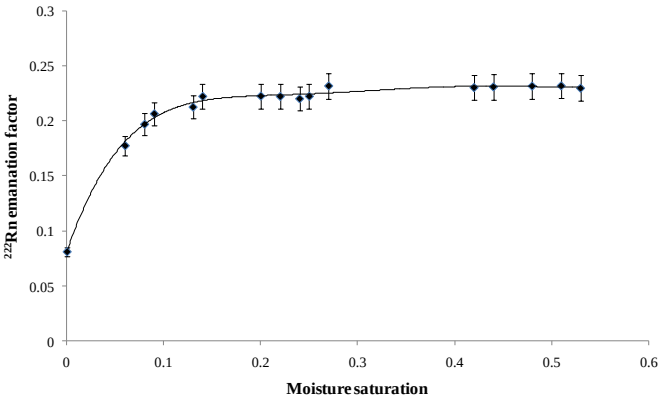

Fig. 2. Variation of ^{222}Rn emanation factor with moisture saturation of backfilled tailings (Sahu et al., 2014)

The radon exhalation rate from backfill tailings increases with increasing water content up to a certain saturation level and beyond the saturation level, it decreases with the increase in the water content as shown in Figure 3 (Sahu et al., 2014). While the highest radon exhalation was observed in the moist tailings, the lowest radon exhalation was found in saturated tailings. It may be explained by the effect of re-adsorption of the radon atoms on the surfaces of the pores of the rock under very dry condition and low diffusion coefficient in the tailings completely saturated with water resulting in a lower radon exhalation rate (IAEA, 1992a; Sahu et al., 2014).

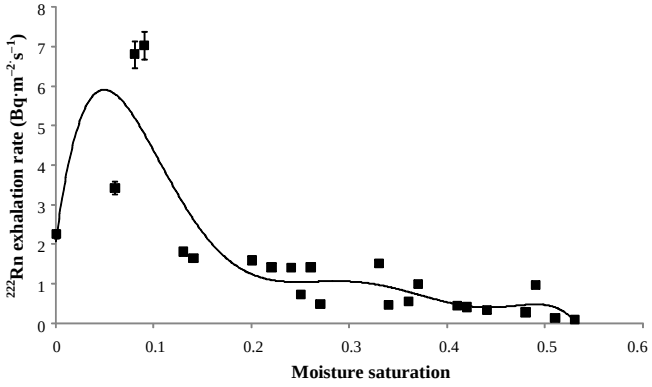

Fig. 3. Variation of ^{222}Rn exhalation rate with moisture saturation of the tailings (Sahu et al., 2014)

2.4. Mine water

Mine water coursing though the mineralised zones dissolves radon present in the rock capillaries. Under normal temperature and pressure conditions, the solubility of radon in water is low. However, under the enormous pressure of overburden, the solubility of radon increases considerably. When this water enters the mine through bore holes and fissures, the dissolved radon is released into the mine atmosphere as the pressure on it is suddenly reduced. Table 3 presents the concentrations of dissolved radon in different sources of two Indian underground uranium mines. The concentration of radon dissolved in water may approach a level much higher than the concentration in the voids filled with air. Since the flow of water from the pore spaces of the material into mine is more rapid than the diffusion process that occurs in dry material, the net transport of radon into a wet mine could be greater than that of the dry mine where the only mechanism for radon transport is gaseous diffusion. Since the volume-distribution concentration of radon in water to air is about 0.3 at normal mine atmosphere, the radon-rich flowing water transfers the radon to the mine air till the radon concentration in air is approximately 3 times more than that of the concentration in water. It has been reported that the dissolved radon concentration in water varies in the range of 19.13×10^3 - 3×10^6 Bq·m^{-3} inside uranium mines (Bossard et al., 1974; Bossard, 1982). Andrews and Wood (1972) reported that water percolating through the uranium ore body released radon in the concentration range of 3.7×10^5 - - 3.7×10^6 Bq·m^{-3} in uranium mines. Khan (1979) reported that approximately 75% of the total dissolved radon in water is released into the mine atmosphere.

Table 3. Concentrations of dissolved radon in different sources of two Indian underground uranium mines (Raghavayya, 1976)

Water source	Radon concentration (× 10^3 Bq·l^{-1})	
	Mine No. 1	Mine No. 2
Bore holes and drill holes	2.27	4.12
Fissures in the walls	0.79	9.0
Seepage from the walls	0.47	5.66
Open drains and pool	0.45	0.5

Table 4 presents the depletion of radon with distance during the flow of water along mine galleries. From this table, it may be observed that significant quantities of radon remain waterborne even after the flowing of water to a distance of more than 20 m. Thus, it may be concluded that mine water not only carries radon from the mineralised rocks to mine openings but also transports it to a considerable distance in the mine galleries. The non-uniformity in the radon depletion with respect to distance travelled may be attributed to the variation in the degree of turbulence caused by obstacles in the path of flow. When the radon-rich water flows in smooth and undisturbed channels, the depletion is lower than when it falls from a height and flows in uneven channels. Disturbances caused by the movement of mine workers and mining equipment may also enhance the depletion process.

Table 4. Depletion of radon with distance during the flow of water along mine galleries (Khan, 1979)

Source	Water flow rate (l/min)	^{222}Rn concentration (×10^2 Bq·l^{-1})			
		at source	10 m downstream	20 m downstream	30 m downstream
1	30	1.99	1.46	0.91	0.53
2	30	4.44	0.95	0.24	0.16
3	2	2.75	2.61	2.51	2.28

The release of radon into the mine air from different sources of radon-rich water has been illustrated in Table 5. From the table, it may be observed that the concentration of radon in the air is higher at the vicinity of water sources and it decreases with an increase in the distance from the water source due to dilution caused by large volumes of air. The non-uniformity in air contamination levels is probably due to the combined effect of non-uniform depletion rates and variations in ventilation rates at different locations. From the table, it may also be observed that the radon concentration in air released from mine water is more pronounced in poorly ventilated areas.

Table 5. Release of radon into mine air from different sources of radon-rich water (Khan, 1979)

Source	Water flow rate (l/min)	Radon concentration in water (× 10^2 Bq·l^{-1})	Radon level in air (Bq·l^{-1})			Remarks
			5 m upwind	at the source	5 m downwind	
1	15	3.03	1.48	3.42	2.04	Poor ventilation
2	1	2.15	1.83	2.15	2.42	
3	2.5	1.26	2.86	3.34	3.15	
4	2	2.74	0.19	0.30	0.28	Good ventilation
5	30	0.85	0.19	0.28	0.28	
6	3	19.24	1.30	1.48	1.57	

3. METHODS OF MEASUREMENT OF RADON EXHALATION RATE IN MINES

Different methods have been used by several investigators for the measurement of radon exhalation rate from uranium ore and backfill tailings. The details of some of the methods highlighting their merits and demerits are presented below.

3.1. By measuring the radon concentration at two locations

Thompkins and Rajhans (1967) described a method for the estimation of the radon exhalation rate in underground uranium mines. In this method, uncontaminated air is supplied at different velocities through a raise of uniform cross-section and 30 to 50 m long. Filtered air samples are collected in Lucas flasks at two locations separated by a known distance at predetermined time intervals. Radon exhalation rate 'J' (Bq·m^{-2}·s^{-1}) is calculated using the following relation:

$$J = \frac{(C_2 - C_1)Q}{PL} \tag{1}$$

where C_1 is the initial radon concentration in one location (Bq·m^{-3}), C_2 is the final radon concentration in another location (Bq·m^{-3}), Q is the airflow rate (m^3·s^{-1}), P is the perimeter of the stope (m) and L is the length of the stope (m). However, this method is not suitable where the stopes are interconnected and large uncertainties in the results may be observed due to various mining operation conditions, contamination of intake air and air leakage.

3.2. Charcoal canister method

Lawrence, Akber, Bollhofer, and Martin (2009) used charcoal canisters for measuring the radon exhalation rate. These canisters are filled with 25 g of activated charcoal and then heated in an oven for 24 h prior to desorption of any previously adsorbed ^{222}Rn. After removal from the oven, the canisters are sealed and taken to the sampling location where they are unsealed, upturned and pressed firmly into the ground to about 1 cm depth to ensure a good seal between the edge of the canister and the ground. The canisters are again

sealed after collecting the sample for four to five days and then sent to the laboratory. The activity of ^{222}Rn adsorbed on the charcoal is determined by counting the gamma particles emitted from ^{214}Pb and ^{214}Bi using a gamma spectrometer with a NaI(TI) crystal housed in a sealed castle. The ^{222}Rn exhalation rate is determined using the following equation (Bollhofer, Storm, Martin, & Tims, 2006):

$$J = \frac{Rt_c\lambda^2 \exp(\lambda t_d)}{\varepsilon a[1-\exp(-\lambda t_e)][1-\exp(-\lambda t_c)]} \quad (2)$$

where J is the radon exhalation rate (Bq·m^{-2}·s^{-1}), R is the net count rate after background subtraction during the counting period "t_c" (counts s^{-1}), t_c is the counting period (s), λ is the decay constant of radon (s^{-1}), t_d is the delay period from the end of exposure to the beginning of the counting interval (s), ε is the counting efficiency of the system (counts s^{-1}·Bq^{-1}), a is the area of the canister (m^2) and t_e is the period of exposure of the charcoal in the canister (s). A lower detection limit of 1.11×10^{-3} Bq·m^{-2}·s^{-1} for a four-day exposure period by using charcoal canister has been reported by Countess (1977).

Although this method is simple and cheap, the charcoal canisters can only be used to measure the radon exhalation rate over a very limited area and for a limited period of time. It may also give high uncertainties in the results under various environmental conditions of atmospheric pressure, temperature and humidity. Furthermore, some amount of adsorbed radon will be lost during the period between the exposure time and measuring time due to the decay before the γ – ray spectroscopy measurement.

3.3. The flow method

Some researchers measured the average radon exhalation over a large area of the tailings by circulating air under a collector through a charcoal bed (Freeman, 1981). Pacific Northwest Laboratory (PNL) developed a re-circulating, pressure balanced, flow-through radon exhalation measuring system that uses a 76 × 122 × 5 cm (9300 cm^2 surface area) aluminium tent to cover the area to be measured. The system utilizes a diaphragm vacuum pump to draw air through a drierite column to remove water vapour and through a filter to remove particulates. The air is then passed through an activated carbon trap to remove radon. The carbon trap consists of a 4.8 cm diameter convoluted tube filled with 400 g of 8–12 mesh size activated carbon. This trap can absorb 99.9% of the radon in the air that is circulating through the trap at a rate of 2 litres per minute at temperature of 44°C (Hartley et al., 1980). The system is sealed to tailings by pushing the lip of the tent into the tailings. After about four hours of sampling, the ^{222}Rn activity concentration is determined by counting the gamma particles emitted from ^{214}Pb and ^{214}Bi using an intrinsic germanium gamma-ray spectrometer and the radon exhalation is then determined from the radon concentration value.

It may be mentioned here that the flow system measures the radon exhalation in a shorter time period than the charcoal canister. So a single measurement using the flow system would probably not provide an accurate estimate of the average radon exhalation when compared to a single measurement using the charcoal canister. In other words, the charcoal canister method is more effective than the flow method in terms of cost and effort for measuring the average radon exhalation across a large area.

3.4. Accumulation method

In the accumulation method, the quantitative estimation of the radon exhalation rate from the materials is made by measuring the build-up of radon activity concentration in the accumulation chamber. Thompkins and Cheng (1969) have used the accumulation method for measuring the in situ radon exhalation rate from the ore wall in an underground uranium mine. In this method, they prepared different sampling points by cutting a flat surface of 1 m × 1 m × 12 cm deep on the ore wall. A steel frame was mounted on the flat area of the wall and cemented in that position. The frame was connected to the steel chamber, which was provided with several valves. The chamber served for the accumulation of radon exhaled from the ore. The chamber was initially flushed with compressed air to remove the radon gas and the valves were then closed. Air samples were collected from the chamber at intervals of several hours up to a maximum of 50 hours for the determination of radon exhalation rate. However, this method is very complex, expensive and time consuming when arranging the experimental setup.

Raghavayya and Khan (1973) used a drum of about 25 l capacity and 600 cm^2 cross-sectional area opened at one end for determination of radon exhalation rate from the mill tailings used as backfill in underground uranium mines. A tube provided with stopcock was fitted onto the closed end of the drum though a rubber cork. The drum was partially buried in the backfilled tailings up to a depth of approximately 20 cm, so that the radon gas exhaling through the surface of backfill material filled into the enclosed volume without leakage. An initial air sample was drawn with a scintillation flask soon after burying the drum and the second air sample was drawn after some hours in order to determine the radon concentration in each sampling. The radon exhalation rate was then deduced from initial and second radon concentration values. However, this technique also has some limitations like the occurrence of back diffusion and leakage of air due to a longer experiment period giving rise to uncertainty in the results (Mayya, 2004). Since the height of the drum is large, radon may not mix uniformly inside the drum and hence it may require employing a small fan inside the drum for proper mixing. In addition, the larger size of the drum is not convenient from the point of view of portability, especially for large scale field study inside the mine.

Jha, Khan, and Mishra (2001) measured the radon exhalation from uranium mill tailings using a method similar to that used by Raghavayya and Khan (1973). They used a small cylindrical steel chamber of 2 l capacity for the accumulation of exhaled radon for about 30–60 min. The open end of the chamber was placed tightly over the radon exhaling surface and the closed end was provided with a swagelok. However, Mayya (2004) reported the extent of underestimation of radon exhalation value in this method. The underestimation of radon exhalation may be due to the small size of the accumulator resulting in the back diffusion phenomenon at the interference between tailings and accumulator. Hence it requires corrections for the accurate estimation of radon exhalation.

Keeping this in mind, the authors used the simple, quick and less expensive techniques giving low uncertainties in the

measurements of radon exhalation rate from the ore body and backfill tailings. The authors had measured the radon exhalation rate from the ore body in the mine by making drill holes which acted as the accumulation chambers in which the radon exhaled from the ore body was allowed to accumulate for 1 day. The air sample was then drawn with the scintillation cell to determine the radon activity concentration (Sahu et al., 2013). In the case of backfill tailings, the radon exhalation rate was measured using a cylindrical accumulation chamber of 17 cm diameter and 30 cm height, which was partially buried in the tailings (Sahu et al., 2014). Radon exhaled from the tailings was allowed to accumulate in the chamber for less than 1 h in order to avoid the back diffusion effect and air leakage. The radon exhalation rate was calculated using the following relation:

$$J = \frac{\lambda(V_s + V_e)(C_t - C_0 e^{-\lambda t})}{A(1 - e^{-\lambda t})} \quad (3)$$

where C_0 is the initial radon concentration at $t = 0$ (Bq·m^{-3}), C_t is the radon concentration after time 't' (Bq·m^{-3}), t is the radon build-up time (s), V_s is the volume of scintillation cell (m^3), V_e is the effective volume of accumulation chamber (m^3) and λ is the decay constant of radon (s^{-1}).

4. MEASUREMENT OF RADON RELEASED FROM MINE WATER

The dissolved radon concentration in mine water is measured using the emanometry technique (Raghavayya, Iyenger, & Markose, 1990). In this method, the water sample is collected in airtight plastic bottles with minimum disturbance. The water sample is then transferred into the radon bubbler by vacuum transfer technique. Radon is collected in the Lucas cells by bubbling air through the water. Radon in the cell is then estimated by conventional counting techniques.

The contribution of mine water to radon concentration in mine air can be calculated by comparing the radon concentration of upstream water to that of the downstream water of a particular location given by the relation (Misaqi, 1975)

$$E = q\,(C_{up} - C_{down}) \quad (4)$$

where E is the radon released from water (Bq·min^{-1}), q is the flow of water (l·min^{-1}), C_{up} is the radon concentration in water upstream (Bq·l^{-1}) and C_{down} is the radon concentration in water downstream (Bq·l^{-1}).

5. SUMMARY AND CONCLUSIONS

The knowledge concerning the sources of radon and quantitative estimation of radon from various sources are of great value for controlling the radiation levels within safe limits in underground uranium mines. This paper presents an overview of radon exhalation sources and its measurement techniques in underground uranium mines. In underground uranium mines, the exhalation of radon from various sources depends on several factors such as ore grade, porosity, grain size and moisture content. The review of literatures revealed that the radon exhalation rate in porous uranium bearing rocks is less affected by the ore grade than in non-porous rocks. The exhalation of radon from the backfill tailings is quantitatively more significant than from the ore itself due to higher bulk porosity and enhanced surface area. Thus, porosity is the dominant factor that affects the rate of radon gas exhalation from rock faces into mine openings. Flowing water through uranium-bearing minerals is also a potential source of radon in the mine atmosphere. The concentration of radon in mine air due to flowing water depends on the degree of turbulence in the path of water flow and airflow rate.

The measurement of radon exhalation from various sources is essential when taking necessary measures to reduce the radiation levels to safe limits and protect the miners from radiation hazards. Several researchers have measured the radon exhalation in underground uranium mines using different sizes of accumulators. The demerit of using smaller accumulator is that it gives rise to larger back diffusion effects, which in turn affects the radon exhalation. On the other hand, large size accumulators are not convenient from the point of view of portability, especially for larger scale field studies inside the mine. Similarly, in the case of accumulators with greater height, the uniform mixing of radon may not take place and hence it may require a small fan for the proper mixing and uniform distribution of radon. Furthermore, it has also been reported that, for a longer build-up period of radon in the accumulation chamber, back diffusion may occur and the correction factor may be more significant, which reduces exponentially with a decrease in the build-up time of radon in the chamber. Thus, it is advisable to choose the optimum size of the accumulator and a suitable build-up period of radon for the measurement of radon exhalation in underground uranium mines to avoid the back diffusion effect in the accumulator.

Finally, it is worth mentioning that since high radon risk has also been reported in other non-uranium mines such as coal, gold, copper and manganese mines (Chałupnik et al., 2002; Doyi, Oppon, Glover, Gbeddy, & Kokroko, 2013; ICRP, 1993; Jamil & Ali, 2001; Kavasi et al., 2011; Patnaik et al., 2014; Veiga, Melo, Koifman, & Amaral, 2004), the measurement of radon exhalation should be carried out in these mines for controlling the radiation levels to safe limits.

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