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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.

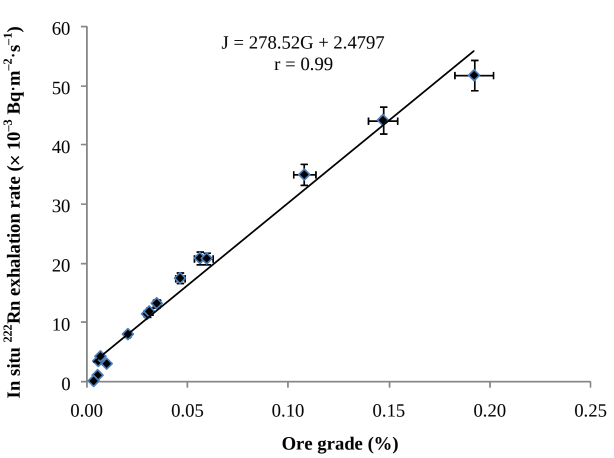

Fig. 1. The relationship of in situ radon exhalation rate with ore grade (Sahu, Mishra, Panigrahi, Jha, & Patnaik, 2013)

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

Ore grade (% U_3O_8)	Rock type	Radon exhalation rate ($Bq \cdot m^{-2} \cdot s^{-1}$)	Reference
0.051	Pre-Cambrian meta-sedimentary rocks	$0.22–51.84 \times 10^{-3}$	(Sahu et al., 2013)
–	Igneous rock, very low porosity	$0.2–2 \times 10^{-3}$	(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 $4.81 \times 10^{-3} – 0.22\ Bq \cdot m^{-2} \cdot s^{-1}$ and $0.2–5 \times 10^{-3}\ Bq \cdot m^{-2} \cdot s^{-1}$ respectively (Cheng & Porritt, 1981).