Chapter

Radon in Underground Mines

Purushotham Tukkaraja, Rahul Bhargava and Srivatsan Jayaraman Sridharan

Abstract

Radon, a radioactive noble gas, is a decay product of uranium found in varying concentrations in all soils and rocks in the earth crust. It is colorless, odorless, tasteless, and a leading cause of lung cancer death in the USA. A study of underground miners shows that 40% of lung cancer deaths may be due to radon progeny exposure. In underground mines, radon monitoring and exposure standards help in limiting miners' exposure to radioactivity. Radon mitigation techniques play an important role in keeping its concentration levels under permissible limits. This chapter presents a review of the radon sources and monitoring standards followed for underground mines in the USA. Also, the different radon prediction and measurement techniques employed in the underground mines and potential mitigation techniques for underground mining operations are discussed.

Keywords: radon mitigation, radon measurement, underground mines, ventilation system

1. Introduction

Radon is a colorless, odorless, and tasteless inert gas. It can only be detected or measured with the help of special detectors. It can travel through cracks of the bedrock, soil, and through groundwater. In underground mines or underground structures, high concentrations of radon may be detected in the absence of adequate ventilation. In underground mines with uranium-bearing mineralization, radium 226 (radium's most stable isotope) is a natural source of radiation. Other isotopes of radon, such as radon 220 and radon 219, also exist naturally; however, because of the small amount and short lifetime, other isotopes are of less concern. Radium 226 decays into radon 222, which in turn decays into its short-lived radioactive daughters in the mine atmosphere. The uranium decay chain can be summarized as shown in **Figure 1**.

Until the late 1970s, radon and its daughter products were of concern only at uranium mines. A study conducted by Daniels and Schubauer in 2017 shows that the radon exposure varied widely among several working populations, most of whom were employed in industries unrelated to the uranium fuel cycle. With the recent advancement of scientific knowledge, there has been more interest and attention to the hazards in non-uranium mines, underground structures, and residential buildings. In the absence of control measures, occupational exposures outside the uranium fuel cycle (e.g., tourist cave workers, waterworks employees) can exceed those found in most uranium workers [1].

Dehnret [2] reported high radon concentrations in old underground workings in Germany and protective steps taken for miners' safety. Sahu et al. [3] reported

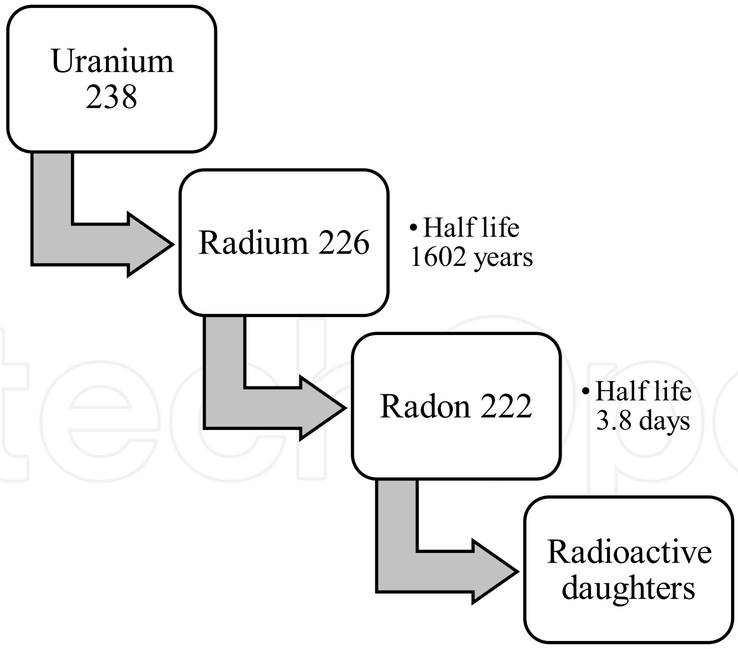

Figure 1.
Uranium decay chain.

the sources of radon, its emanation rate, and measurement techniques, particularly for underground uranium mines. Hu et al. [4] highlighted radon and radon progeny problems in Chinese uranium mines. In the United States, radon has been listed as the second major cause of lung cancer after tobacco [5]. A study of underground miners shows that 40% of lung cancer deaths may be due to radon progeny exposure [6]. MSHA has regulations for radon concentration in underground mines and sampling procedures depending on the concentration.

Considering the short half-life and the high radiation dose of radon gas and its daughter products, its mitigation in the underground environment becomes very important. In the absence of mitigation techniques, both the uranium and non-uranium mines (with uranium mineralization in the orebody) pose a serious threat to the personnel working in the underground environment.

Ventilation plays a significant role by supplying fresh air and removing the contaminated air from the working areas, thereby minimizing the radon concentrations in the mine environment. In addition, an appropriate mining method and well-designed mining sequence can also help control radon gas in the mine atmosphere [4]. In this chapter, the different radon mitigation methods that are specific to the underground mining operations are discussed.

2. Sources of radon

Radium 226 decays into radon 222, which in turn decays into its short-lived radioactive daughters in the mine atmosphere. Common sources of radon emissions in underground mines are summarized in **Table 1**.

3. Radon monitoring

The concentration of radon gas is measured in units of picocuries per liter (pCi/L) or becquerels per cubic meter (Bq/m^3) of ambient air. Due to difficulties in measuring radon gas concentration, potential alpha particles per liter of air are usually measured. The ratio of all the short-lived radon daughters' activity to the

Sources	Remarks
Mine walls	In low/medium ore grades, porosity and micro-fractures are dominant factors affecting the rate of radon gas emanation.
Broken ore	Fragmented ore provides a source of higher radon emanation due to the increased exposed surface area.
Backfill tailings	Radon emanation rate increases with increasing water content up to a certain saturation level, and beyond the saturation level, it decreases with the increase in water content.
Mine water	Mine water carries radon from the mineralized rocks to mine openings and transports it to a considerable distance in the mine galleries.

Table 1.
Common sources of radon in underground uranium mines [3].

parent radon gas activity is called the equilibrium factor. The equilibrium factor is 1 when both are equal. Radon daughter activities are usually less than the radon activity, and hence, the equilibrium factor is generally less than 1. In artificially ventilated scenarios such as underground mines, the equilibrium factor is in the range of 0.4 to 0.5.

In the United States, radioactivity for radon decay products is measured in terms of Working Level (WL). A WL is defined as the concentration of short-lived radon daughters, representing 1.3 × 105 MeV of potential alpha particle energy while decaying to the stable Pb-210. The worker's prolonged exposure to radon daughters is expressed in Working Level Months (WLM). One WLM is equivalent to 1 WL exposure for 170 hours.

In underground mines as per the Mine Safety and Health Administration (MSHA) regulations, personnel shall not be exposed to air containing concentrations of radon daughters exceeding 1.0 WL. No person shall be permitted to receive

Type of mine	Radon daughter concentration level (a)	Frequency of monitoring
Uranium mine	a > 0.1 WL	Radon daughter concentration shall be determined at least every 2 weeks at random times in all working areas.
	a > 0.3 WL	Radon daughter concentration shall be determined weekly in that area until the concentration reaches 0.3 WL or less for 5 consecutive weeks.
	a < 0.1 WL (exhaust mine air sample)	Radon daughter concentration shall be determined by taking at least one sample in the exhaust mine air monthly.
Non-uranium mine	0.1 WL < a < 0.3 WL	Radon daughter concentration shall be determined at least every 3 months at random times until the concentration is below 0.1 WL in that area and annually thereafter.
	a > 0.3 WL	Radon daughter concentration shall be determined at least weekly in that area until the concentration drops to 0.3 WL or less for 5 consecutive weeks.
	a < 0.1 WL (exhaust mine air sample)	No further exhaust mine air sampling is required.
Houses	a > 0.04 WL (equilibrium factor of 1)	The EPA (Environmental Protection Agency) guidelines recommend the installation of radon mitigation systems.

Table 2.
Radon daughter exposure monitoring [7].

exposure over 4 WLM (Working Level Months) in any calendar year. In all mines, at least one sample must be taken in exhaust mine air by a competent person to determine whether concentrations of radon daughters are present [7]. **Table 2** provides the radon sampling frequency for uranium and non-uranium mines and households. Gamma radiation surveys shall be conducted annually in all underground mines where radioactive ores are mined. Gamma radiation dosimeters shall be provided to all personnel working in the area where gamma radiation exceeds 2.0 milliroentgens; annual individual gamma radiation exposure shall not exceed 5 Roentgen Equivalent Man [7].

4. Measurement techniques

The measurement techniques for radon can be classified based on a) whether the technique measures radon gas ^{222}Rn or its daughter products, b) time resolution, and c) radioactive detection of the type of emission resulting from radioactive decay—alpha, beta, gamma radiation. The commonly used methods for measuring radon and its daughter products are shown in **Figure 2**.

Active methods require electric power for measurements, whereas passive methods require no power. Measurements can be performed at specified intervals and data can be stored and read directly with active methods. In contrast, in the case of passive methods, integrated exposure concentrations can be measured, and data analysis requires special equipment. Time resolution techniques can be classified into three types, as shown in **Figure 3**.

Grab sample technique: This technique involves measurement of ^{222}Rn in a discrete sample of air collected over a very short period of time (compared with the mean life of ^{222}Rn at a single point). Radon measuring instruments such as RAD7 can be used to measure ^{222}Rn and its daughters. When it is used in "sniffer" mode, in which radon is typically present with minimal growth of its progeny, a large number of measurements can be taken in a relatively less period of time [8].

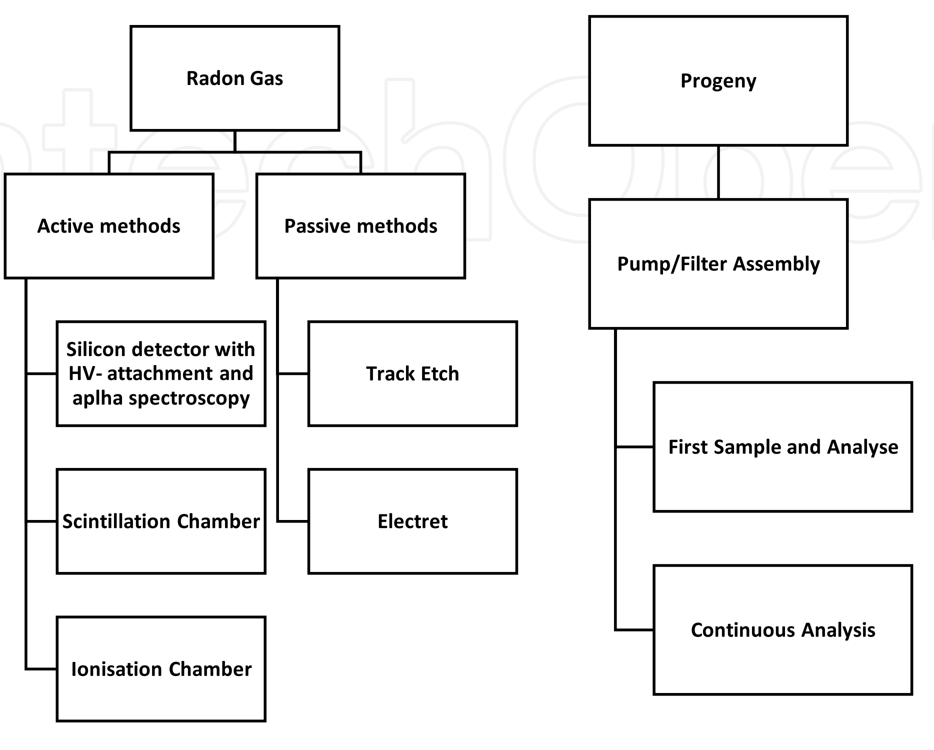

Figure 2.
Radon gas and daughter (progeny) product measurement methods [8].

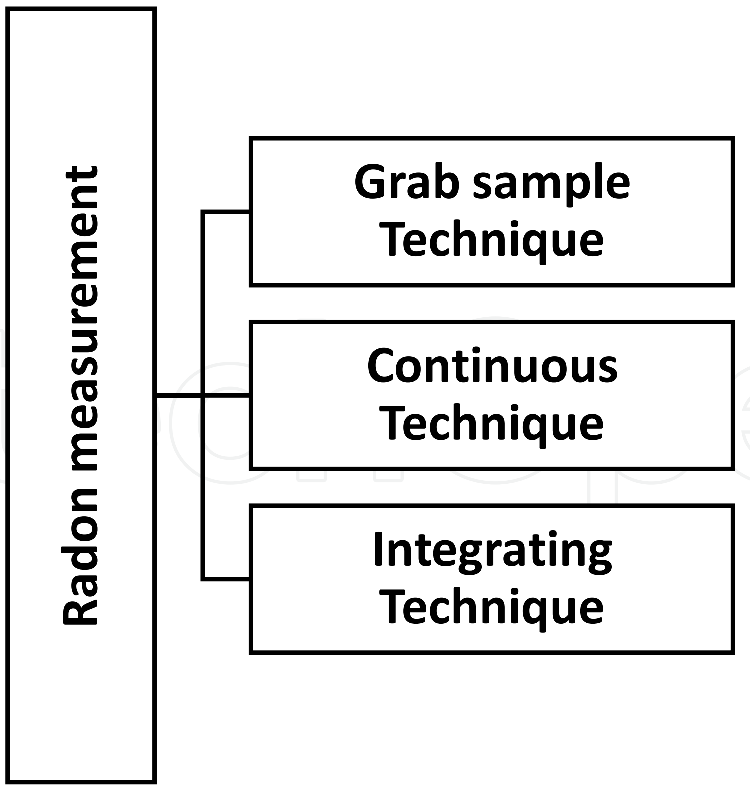

Figure 3.
Time resolution techniques for measuring radon and its daughter products [8].

Grab sampling technique for radon progeny involves drawing a known air volume through a filter and counting the alpha activity during or following the sampling. Usually, a known volume of air is drawn through a filter using an air sampling pump for very short sampling periods usually 5 minutes. Filters are counted for alpha particle emissions during mathematically determined periods after the sample is collected. There are three main methods available for counting these particles, namely the Kusnetz method, where the filter is counted once, and the modified Tsivoglou method, where the filter is counted three times to measure the decay. Another method, named the Rolle method, is quite popular in Canadian mines. It is similar to Kusnetz method but is more rapid, and the procedure differs only in the timing of filter counting after sample collection. **Figure 4** shows one of the MSHA recommended instruments for sampling radon progeny that works based on the Kusnetz method.

Continuous technique: This technique provides time series concentrations of ^{222}Rn in air samples; in this method, sampling and counting are performed simultaneously. Most of the continuous monitors are portable, and nearly all of those are designed to detect alpha radiation (by an ionization chamber, gross alpha counting, or alpha spectrometry). Specific ionization and scintillation chambers are shown in **Figures 5** and **6**, respectively.

Integrating technique: This technique provides the integrated concentration over a certain period of time. Such measurements are used to determine monthly or average ^{222}Rn . The passive detectors, which are expensive, are examples of integrating techniques [8].

Apart from measuring alpha particles during the decay of ^{222}Rn , radon concentrations are determined by measuring the beta activity during the decay of ^{214}Pb and ^{214}Bi by assuming secular equilibrium between ^{222}Rn and its progeny in the air. The beta activity is assayed with plastic scintillators mounted on photomultiplier tubes or the filter paper can be counted in a beta counter with the appropriate use of absorber film. Gamma spectrometry can also be used to determine radon concentrations by measuring the gamma activity during the decay of ^{214}Pb and ^{214}Bi .

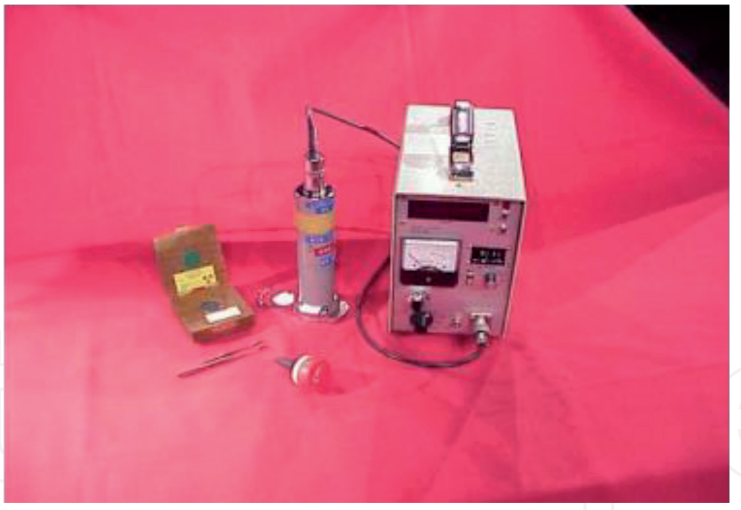

Figure 4.
Ludlum 2000 with accessories.

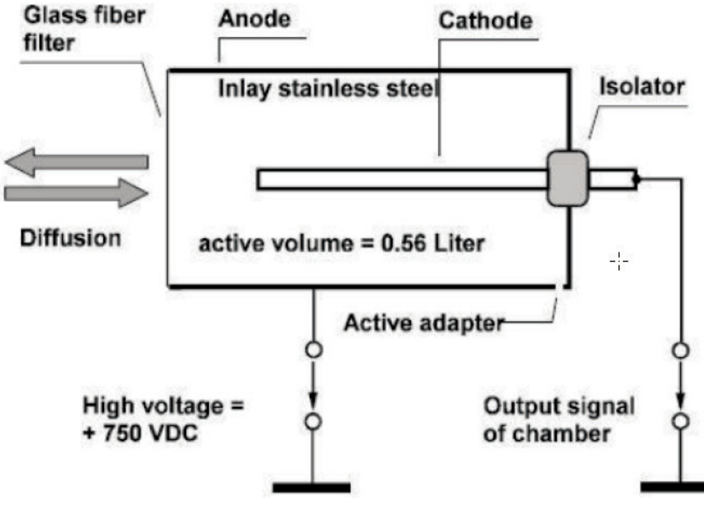

Figure 5.
Schematic diagram of an ionization chamber [9].

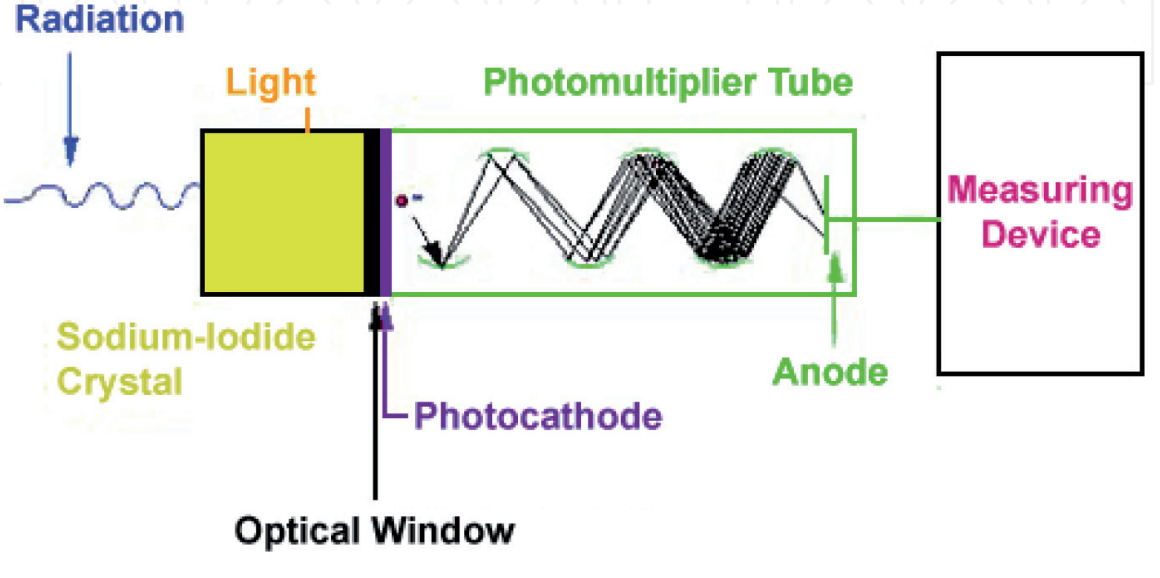

Figure 6.
A typical scintillation detector [10].

5. Prediction techniques

There are a few traditional approaches for predicting radon flux such as uninterrupted short-term monitoring to represent radon concentration over an extended period and laboratory investigations. These methods do not apply to all cases. Recently, Kayode et al. [11] developed an approach for predicting radon flux from fractured rocks, a discrete fracture network (DFN) model that can predict radon transport through fractures considering diffusion, advection, and radon generation with radon decay.

6. Mitigation methods

Some of the important techniques to mitigate radon gas in underground mines are discussed below.

6.1 Sealant coating

The major sources of radon gas in non-uranium underground mines (with uranium mineralization) are the drift walls, floor, and roof. Shotcreting or applying radon sealants to the walls and roof effectively minimizes radon gas emissions into the mine atmosphere. The effectiveness of sealant coating in controlling the radon gas depends on the size of the capillary in which the acrylics (contained in the sealants) form barriers to prevent the escape of radon gas [12].

6.2 Bulkhead

Isolation of mined-out areas using bulkheads is one of the popular methods of controlling radon gas emissions into the active mine workings. Bulkheads prevent the contaminated air of mined-out regions containing high radon gas concentrations from mixing with the fresh air. Loring and others [13] reported that styrofoam and shotcrete/concrete bulkheads are used in a panel cave mine for a temporary and permanent sealing purpose, respectively. These bulkheads are installed at a 60-degree layback angle of the planned cave area to minimize damage to the bulkheads during the caving process. As the bulkheads are not leak proof, bleeder pipes creating a negative pressure inside the bulkhead area and connected to the main exhaust ventilation system can also be an effective measure [13]. **Figure** 7 shows the typical designs of bulkheads.

6.3 Mine pressurization by mechanical ventilation

Mine pressurization can also play an important role in controlling radon gas emissions in underground workings, especially near-working faces. In a forced ventilation system, which is considered quite effective for control of radon gas in the mine environment, fresh air is pumped into underground workings with the help of fans; this follows the path of least resistance taking the contaminants along with it and out of the mine. In the forced ventilation system, the direction of seepage is toward the rock surface, causing less radon to be released.

Studies [13] have shown that a successful blend of positive and negative pressure systems in a panel cave mine effectively reduces the radon gas concentrations at the production level. Negative pressure on the cave top minimizes the escape of radon gas from the broken ore to the production levels. Positive pressurization in the undercut levels also reduces the escape of radon gas into the working

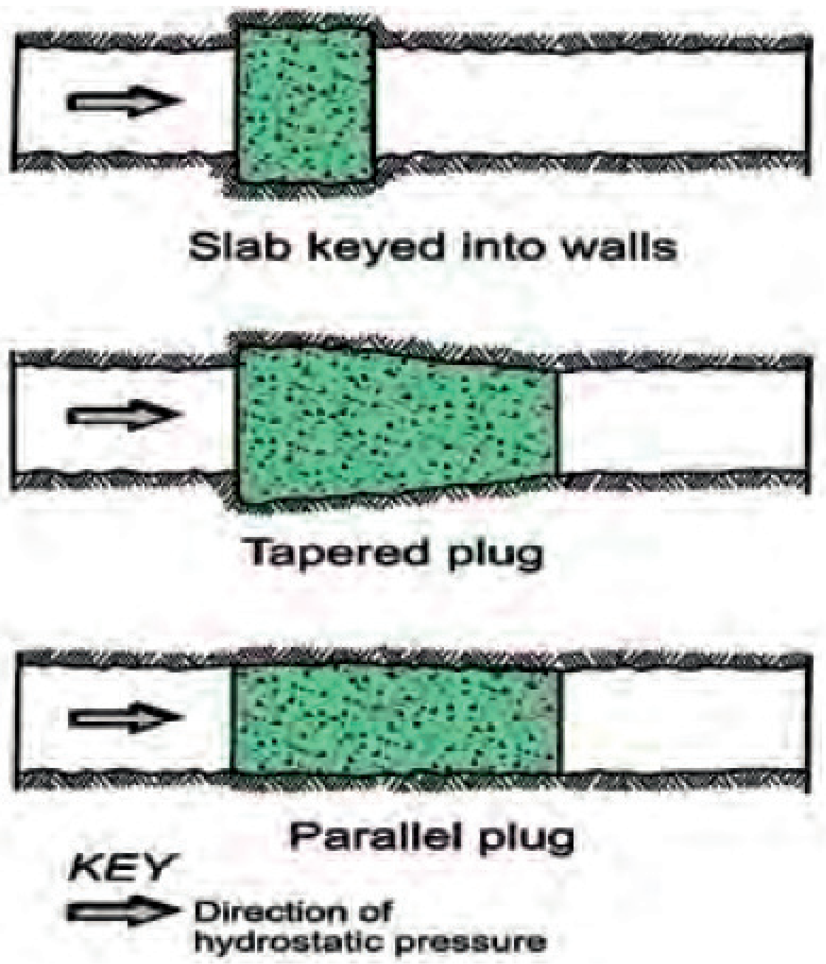

Figure 7.
Typical designs of bulkheads [14].

areas. Mine pressurization greatly depends on the porosity and permeability of the broken rock/ore for its effectiveness in controlling radon concentrations in the underground environment. **Figure 8** shows a typical cave ventilation system in a block/panel cave mine.

Computational fluid dynamic (CFD) simulation studies by Kayode et al. [15] showed the effect of an undercut ventilation system on radon gas distribution in the production drift and cave. It was observed that the air flowing through the cave transports some of the radon generated within the cave into the production drift, increasing the production drift concentration. However, in the absence of undercut ventilation, radon concentration decreases significantly within the production drift

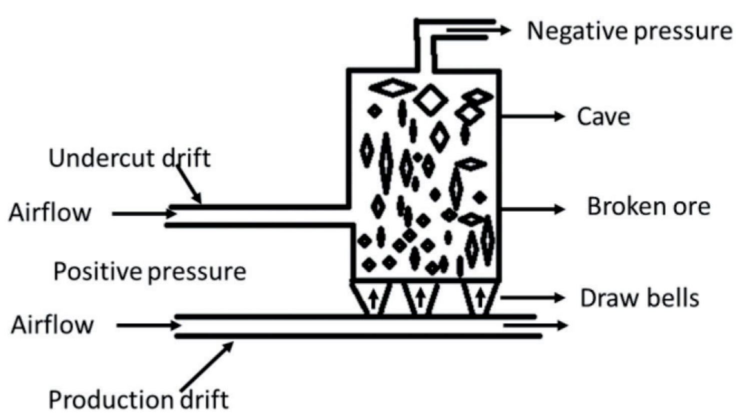

Figure 8.
A typical cave ventilation system in a panel/block cave mine.

but increases inside the cave. The radon growth through the production drifts is nonlinear due to differences in the source of radon. Maintaining a negative pressure on top of the cave and undercut pressurization significantly reduces radon concentration in the production drift. However, maintaining a negative pressure on top of the cave is not very effective without undercut pressurization. An increase in air volume flow rate reduces radon concentration through the production drifts; based on the drift configuration for radon source, different empirical relationships relate airflow and working level for each drift.

The knowledge of airflow behavior and system characteristics is vital in ventilating the block cave operations and reducing radon concentrations. Using field observations and laboratory experiments (scale model studies), Pan [16] investigated the effects of porosity, material size combinations, additional fan, ventilation devices, and undercut structure on cave airflow resistance. The study found that the cave airflow resistance increases with a decrease in porosity and particle size, additional fan operation, regulator installation, and air gap reduction in the undercut drifts. An additional fan operation can contribute extra total airflow through the system, but regulators will not increase the total airflow in the system; the air gap observed in the undercut drifts might lead to less airflow through the production drifts.

Rahul et al. [17] investigated the effect of changes in the bulk porosity of the broken rock on the cave airflow resistance using the computational fluid dynamics (CFD) approach. This study reveals that porosity plays a vital role in changing the resistance offered by the broken rock to the airflow leaking into the cave. The airflow resistance increases as the porosity of the broken rock pile decreases. The resistance of the block cave mine changes dynamically with the bulk porosity of the broken rock.

Jha et al. [18] studied the utility of different fans in reducing the radon concentration within the drifts using a physical scale model and CFD simulations. It was observed that the combination of main and cave fan is optimal in minimizing the gas concentration within the drifts. Observations of the scaled model also show that a fully operational cave fan significantly reduced the gas concentrations within the drifts. The study suggests using main fan in conjunction with a cave fan to minimize the gas concentration within the drift.

Erogul et al. [19] investigated the impact of air gap geometries on cave resistance and radon emissions using the CFD approach. This study reported an interesting airflow behavior within the air gap zone; initially, the airflow resistance increases up to a certain height and drops as the air gap height increases further.

6.4 Radon adsorption on activated carbon

Radon gas can be adsorbed by activated carbon, commonly known as a charcoal bed. The capacity of a charcoal bed to adsorb radon depends on the temperature and moisture content of the incoming air. Karunakara et al. [20] demonstrated that a coconut shell-based activated charcoal system can be used for designing effective and reliable radon mitigation systems. Degassing properties of the charcoal indicate its reusability potential. Adsorption of radon by activated carbon can also significantly reduce ventilation air requirements. **Figure 9** shows the experimental setup for studying radon adsorption in a charcoal bed.

6.5 Ground freezing

Mine water is another source of radiation in underground mines. Artificial ground freezing is an excavation support method that involves the use of refrigeration to convert *in situ* pore water into ice [21]. Yun and others [22] reported that artificial ground freezing, to form a frozen curtain between the water-bearing

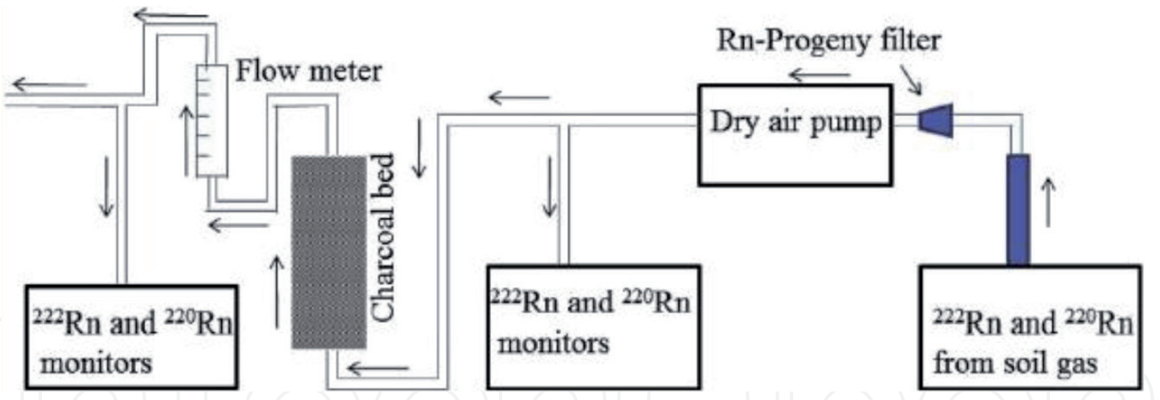

Figure 9.
Experimental setup for studying radon adsorption in charcoal bed [20].

sandstone and the ore body at McArthur River mining operation in Canada, helped prevent high-pressure, radon-bearing water from entering into the mine workings. **Figure 10** shows a schematic of a typical ground freezing technique.

6.6 Choice of mining method and ventilation system

The choice of mining method and the type of mechanical ventilation significantly impact the control of radon gas emissions into the underground mine atmosphere. **Table 3** provides the type(s) of effective ventilation systems to be used for various mining methods for controlling radon emissions in underground mines.

6.7 Personal respiratory protection

It is an indirect mitigation technique. In the environments where radon daughters' concentration exceeds 1.0 WL, miners should wear respirators approved by the National Institute for Occupational Safety and Health (NIOSH). The use of personal respiratory protection against radon daughters must be limited to temporary situations

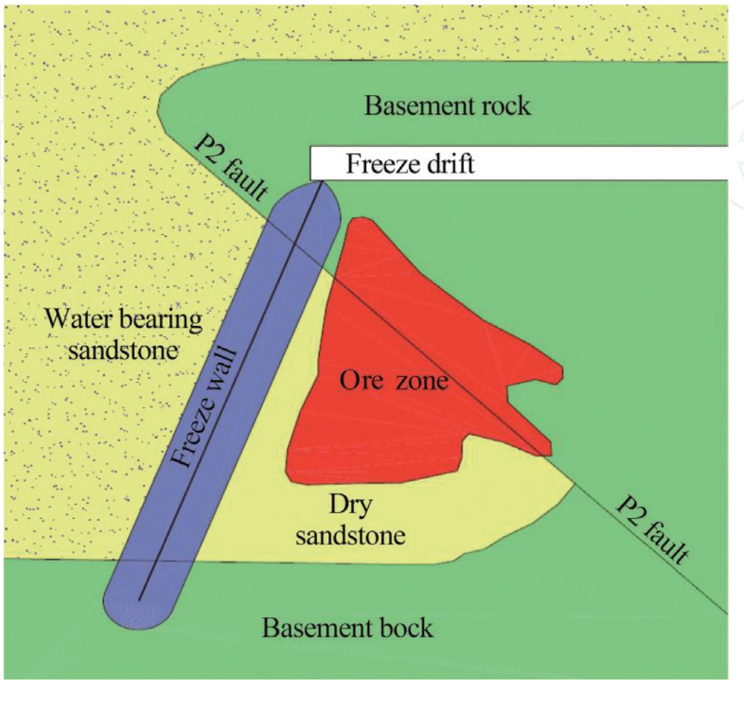

Figure 10.
Typical freeze wall insulation [22].

Mining methods	Mining types	Ventilation types
Cut and fill	Dry packing	Both forced and exhaust ventilation systems can be used.
	Hydraulic flushing	Both forced and exhaust ventilation systems can be used. Measures should be taken to control the release of radon from the seeping water.
Open stope	Shrinkage stoping	Downward forced ventilation can be used here to prohibit the release of radon. The air inlets are installed on the upper parts of the deposits. Local fans are installed where the amount of air introduced is inadequate.
	Breast stoping	Both forced, and exhaust ventilation systems can be used. However, the amount of air required at working faces increases as the number of mined-out areas increases.
Caving	Slicing	Forced ventilation and local fans should be used.
	Sublevel caving	Forced ventilation should be used.
	Block/panel caving	The combination of forced and exhaust ventilation systems.

Table 3.
Mining methods and ventilation types [4].

where engineering controls have not been developed or for maintenance and investigative work. For exposures up to 10 WL, proper filter-type respirators are available where concentrations of radon daughters exceed 10 WL, air devices, or face masks containing absorbent material capable of removing both radon and its daughters [7].

6.8 Dust control and miscellaneous measures

Airborne radon progeny (daughters) has an electrical charge associated with it; so, it can be attached to dust and other particles, which can be inhaled into the lungs of mineworkers who work in the dusty environment, particularly near the working faces. Some of the best practices that can help control radon levels in the mine atmosphere include implementing appropriate dust control measures by using air filters, measuring the performance of blasting practices at the end of the shift, and minimization of main/auxiliary fan shutdowns. Abd et al. [23] showed that the radon diffusion coefficient and diffusion length reduce significantly with increased water saturation of the material. This phenomenon can be used to reduce the rate of radon diffusion into the mine air.

7. Summary

Several radon mitigation techniques, particularly bulkheads and sealant coating, are being successfully used in the underground mines in the United States. Activated charcoal bed and oxidizing agents are also viable options for treating the contaminated air locally, especially at the difficult mine working faces. The feasibility of the application of these agents in the challenging mine environment needs a greater in-depth study.

Even though sealant coatings and bulkheads effectively control radon gas concentrations in the active working areas, improvements to reduce the costs and design of application of sealants and bulkheads can be performed.

Activated charcoal beds present a viable option for radon mitigation, but a pilot study in the mine environment can be more helpful to understand their applicability and effectiveness.

The use of strong oxidizing agents to remove radon from the contaminated mine air can also be a possibility. However, high humidity and temperature conditions in the mine atmosphere might limit the applicability of a corrosive oxidizing agent inside the mine.

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