Influence of Blasted Uranium Ore Heap on Radon Concentration in Confined Workspaces of Shrinkage Mining Stope

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Abstract. A calculation model for radon concentration in shrinkage mining stopes under various ventilation conditions was established in this study. The model accounts for the influence of permeability and area of the blasted ore heap, ventilation air quantity, and airflow direction on radon concentration in a confined workspace; these factors work together to allow the engineer to optimize the ventilation design. The feasibility and effectiveness of the model was verified by applying it to mines with elevated radon radiation exposure. The model was found to accurately changes in radon concentration according to the array of influence factors in underground uranium mines.

1. Introduction
Radon concentration is higher in underground uranium mines and is known to be a severe health hazard for miners. Mining activity results in the release of radon gas and its daughter products into confined workspaces, where miners may be exposed to high levels of radon in ore heaps or from other sources. Poor ventilation condition can severely threaten the health and safety of miners due to exposure to radioactive materials. There is urgent demand for workable techniques to quantify radon concentration in confined workspaces in order to design ventilation systems for blasted uranium ore heaps in shrinkage mining stopes.

Radon measurement techniques were first investigated in coal mines in Pakistan [1] and Western Turkey [2]. El-Fawal [3] established a calculation model for airflow, air pressure and radon/daughter concentration in mine ventilation networks. Sahu [4] evaluated the effect of various ventilation parameters on radon exposure to miners in underground uranium mines; airflow rate was considered the key parameter in controlling the radon/daughter concentrations in the mine. These researches have focused mostly on radon concentration measurement in assessing radiological hazards. Many have also explored the influence of ventilation parameters on radon concentration.

Data gathered in previous studies was utilized to build a calculation model for radon concentration in shrinkage mining stopes with various ventilation parameters. The calculation results may provide a workable reference for ventilation design in underground shrinkage uranium mines.

2. Mathematical Model

2.1. Calculating the radon release-diffusion-seepage migration in blasted uranium ore heap
The ore particles in blasted uranium ore heaps vary in size and can be roughly divided into n grades accordingly: \( r_1 < r_2 < r_3 < \ldots < r_n \). The equivalent radius of the \( i_{th} \) grade ore particles can be calculated as follows:

\[
\bar{r}_i = \left( \frac{r_{i \text{min}}^2 + r_{i \text{max}}^2}{2} \right)^{\frac{1}{2}}
\]

Where \( r_{\text{min}} \) and \( r_{\text{max}} \) is the minimum and maximum size of the \( i_{th} \) grade ore particles (m).

The mass fraction of the \( i_{th} \) grade ore particles is a function of the fractal dimension and particle size, it can be calculated as follows [5]:

\[
w_i = \frac{r_{i \text{max}}^{D_i - 1} - r_{i \text{min}}^{D_i - 1}}{r_{\text{max}}^{D_i - 1} - r_{\text{min}}^{D_i - 1}}
\]

Where \( D_i \) is the fractal dimension of the particle size distribution.

The bottom surface of uranium ore heap forms the origin of the coordinates and the top is the positive direction. Then the steady release-diffusion-seepage migration equation in the blasted uranium ore heap is as follows:

\[
\frac{D_i}{\eta_2} \frac{d^2 C}{dx^2} - \frac{v}{\eta_2} \frac{dC}{dx} - K_1 C + K_2 = 0
\]

\[
K_i = \lambda + \frac{3(1 - \eta_i) D_i \eta_i}{\eta_2} \sum_{j=1}^{n} w_j \left( \frac{\lambda_i}{D_i} \right) \frac{1}{r_i} - \frac{3(1 - \eta_i) D_i \eta_i}{\eta_2} \sum_{j=1}^{n} w_j \left( \frac{\lambda_i}{D_i} \right) \frac{1}{r_j}
\]

Where \( \eta_2 \) is ore heap porosity; \( K_i \) is equivalent radon decay constant of the medium; \( K_2 \) is equivalent radon release rate of the medium (Bq m\(^{-3}\) s\(^{-1}\)).

### 2.2. Determination of radon exhalation rate of blasted uranium ore heap

Figure 1 and 2 show shrinkage stope with ascensional and descensional ventilation respectively. The pressure difference between the top and bottom surface of the ore heap is formed during the ventilation period. The value of said pressure difference is approximately equal to the ventilation resistance of the stull-supporting raise, which can be calculated as follows:

\[
\Delta P = \frac{\alpha_i p L_o Q^2}{s^3}
\]

Where \( \alpha_i \) is the frictional resistance coefficient of the stull-supporting raise (Pa s m\(^{-2}\)); \( p \) is the stull-supporting raise perimeter (m); \( s \) is the stull-supporting raise area, (m\(^2\)); \( Q \) is the ventilation air quantity of the stope (m\(^3\) s\(^{-1}\)) and \( L_o \) is the stull-supporting raise length (m).

**Figure 1.** Schematic diagram of ascensional ventilation in shrinkage mining stope

**Figure 2.** Schematic diagram of descensional ventilation in shrinkage mining stope
The length of the stope’s stull-supporting raise can be calculated as follows:

\[ L_0 = \frac{H}{\sin \theta} = L_i \]  

(5)

Where \( H \) is the vertical height of the blasted uranium ore heap (m); \( \theta \) is ore body obliquity; \( L_i \) is the thickness of blasted uranium ore heap (m).

The air seepage velocity in the blasted uranium ore heap can be calculated through ‘Darcy law’. In ascentional ventilation, then radon exhalation rate of the top surface of the blasted uranium ore heap is:

\[
J_{sx} = \frac{\eta_2 D_2 K_2 [b_1 e^{h L_i} + b_2 e^{-b_2 L_i} - (b_1 + b_2) e^{(h-b_2) L_i}]}{K_1 (e^{h L_i} - e^{-b_2 L_i})} \]  

(6)

\[
b_1 = \left( \frac{\alpha_j k p Q^2}{\mu^2} + 4 K_1 D_2 \eta_i^2 \right)^{\frac{1}{2}} + \frac{\alpha_j k p Q^2}{\mu^3} \]  

\[
b_2 = \left( \frac{\alpha_j k p Q^2}{\mu^2} + 4 K_1 D_2 \eta_i^2 \right)^{\frac{1}{2}} - \frac{\alpha_j k p Q^2}{\mu^3} \]  

Where \( D_2 \) is the radon diffusion coefficient of the blasted uranium ore heap (m\(^2\) s\(^{-1}\)). The radon diffusion coefficient can be calculated as follows [6]:

\[ D = D_0 \eta \exp(-6 m n - 6 m_{\text{air}}) \left( \frac{T}{273} \right)^{0.75} \]  

(7)

Where \( D_0 \) is the radon diffusion coefficient of air (m\(^2\) s\(^{-1}\)); \( T \) is absolute temperature (K); and \( m \) is water saturation in porous media.

The radon exhalation rate of the blasted uranium ore heap bottom surface is:

\[
J_{sx} = \frac{\eta_2 D_2 K_1 [b_1 e^{h L_i} + b_2 e^{h L_i} - (b_1 + b_2)]}{K_1 (e^{h L_i} - e^{-b_2 L_i})} \]  

(8)

During descentional ventilation, radon exhalation rate of the top surface of the blasted uranium ore heap is:

\[
J_{sx} = \frac{\eta_2 D_2 K_2 [b_1 e^{h L_i} + b_2 e^{h L_i} - (b_1 + b_2)]}{K_1 (e^{h L_i} - e^{-b_2 L_i})} \]  

(9)

The radon exhalation rate of the blasted uranium ore heap bottom surface is:

\[
J_{sx} = \frac{\eta_2 D_2 K_1 [b_1 e^{h L_i} + b_2 e^{-b_2 L_i} - (b_1 + b_2) e^{(h-b_2) L_i}]}{K_1 (e^{h L_i} - e^{-b_2 L_i})} \]  

(10)

Under the effect of ventilation, radon diffusion is negligible if air seepage plays a dominant role in radon migration through the blasted uranium ore heap. The radon exhalation rate of the heap under the effect of ventilation can then be described as follows:

\[
J_{dvi} = \frac{\alpha_j k p Q^2 K_2}{K_1 \mu s^3} \left[ 1 - \exp \left( - \frac{K_1 \eta_j \mu s^3}{\alpha_j k p Q^2} L_1 \right) \right] \]  

(11)

2.3. Radon concentration calculation model in confined shrinkage mining stope workspace

When calculating radon concentration in confined workspaces, as shown in Figures 2 and 3, the air inlet of the confined workspace sits at starting point 0 and the radon concentration at the point \( L \) meters from the air inlet is calculated as follows:
\[
C(L) = C_0 e^{-\frac{J\lambda}{WQ}L^2} + \int_0^L \left( J_{\text{dual}}W + 2J_{\text{w}}H + J_{\text{d}}W \right) e^{-\frac{1}{WQ}(J\lambda + \lambda^2)H} dx
\]

\[
= C_0 e^{-\frac{J\lambda}{WQ}L^2} + \frac{(J_{\text{dual}}W + 2J_{\text{w}}H + J_{\text{d}}W)}{\lambda W \left( 1 - e^{-\frac{1}{WQ}(J\lambda + \lambda^2)H} \right)}
\]

(12)

Where \( C_0 \) is the air inlet radon concentration (Bq m\(^{-3}\)); \( J_w \) and \( J_d \) is the radon exhalation rate of surrounding rock and the top ore body (Bq m\(^{-2}\) s\(^{-1}\)); \( W \) is the width of the workspace (m); \( H \) is the height of workspace (m); \( \lambda \) is the radon decay constant (s\(^{-1}\)); \( Q \) is air quantity (m\(^3\)s\(^{-1}\)).

The radon decay constant is \( 2.1 \times 10^{-6} \) (s\(^{-1}\)), the length of the workspace does not exceed 100 m, and air velocity in the workspace is above 0.25 (m s\(^{-1}\)), so Equation (12) can thus be simplified as follows:

\[
C = C_0 + \frac{1}{\lambda W \left( 1 - e^{-\frac{1}{WQ}(J\lambda + \lambda^2)H} \right)} \leq C_{\text{lim}}
\]

(13)

Again, the length of the confined workspace is \( L_2 \). If in ascentional ventilation - \( J_{\text{dual}}=J_{\text{w}} \). The exhaust radon concentration increment in the confined workspace-caused by the blasted uranium ore heap can be calculated as follows:

\[
\Delta C_{\text{ex}} = \frac{J_{\text{w}}W L_2}{Q}
\]

(14)

Under descentional ventilation, \( J_{\text{dual}}=J_{\text{d}} \), so the exhaust radon concentration increment of workspace caused by the blasted uranium ore heap is calculated as follows:

\[
\Delta C_{\text{ex}} = \frac{J_{\text{d}}W L_2}{Q}
\]

(15)

3. Results and Discussion

3.1. Determining parameters

Here, we assume that the uranium ore grade is 0.5%, the value of \( \alpha_w \) is 9 (Bq m\(^{-3}\) s\(^{-1}\)), ore particle size is 0.03 m, particle size distribution fractal dimension is 2.0, ore porosity is 0.035, ore humidity is 0.333, ore temperature is 20 (℃), \( \alpha_f \) is 0.05 (Pa s m\(^{-2}\)), workspace height is 2 (m).

The top and bottom surfaces of the blasted uranium ore heap have the same area \( S_t = 200 \) (m\(^2\)).

3.2. Influence of ventilation airflow directions on radon concentration increment in confined workspaces

For simplicity, we assume that the height of blasted ore heap is 20 (m) regardless of changes in other parameters.

**Figure 3.** Variation curves of radon concentration increment in confined workspaces of shrinkage mining stope with different ventilation airflow

**Figure 4.** Variation curves of height of blasted uranium ore heap with radon concentration increment caused by ore heap exhalation
Figure 3 shows that in ascensional ventilation, as ventilation air quantity increases from 1 to 2 (m³ s⁻¹), ventilation increases the velocity of radon exhalation to the point where the amount of radon emitted is less than the amount of radon exhaled. When the air quantity is over 2 (m³ s⁻¹), however, the amount of radon emitted is greater than the amount of radon exhaled. With descentional ventilation, when ventilation air quantity is from 1 to 2 (m³ s⁻¹), radon concentration increment in the workspace gradually decreases. When ventilation air quantity is from 2 to 12 (m³ s⁻¹), radon concentration increment is close to 0. When permeability is invariable, the variations in radon concentration with ascensional ventilation are greater than with descentional ventilation.

3.3. Height of blasted uranium ore heap affects radon concentration in confined workspaces

Figure 4 shows that when air quantity is 6 (m³ s⁻¹) and permeability is 1×10⁻⁸ (m²), the radon concentration increment with ascensional ventilation increases as ore heap height increases. With descentional ventilation, radon concentration increment stays close to 0 regardless of heap height.

3.4. Blasted uranium ore heap area affects radon concentration increment in the confined workspaces

Figure 5 shows that when air quantity is 6 (m³ s⁻¹) and permeability is 1×10⁻⁸ (m²), the radon concentration changes as the heap area increases. As area increases, however, the variation tendency of radon concentration increment in the workspace gradually decreases. Although the area of blasted uranium ore heap has nothing to do with the exhalation rate, it does alter the radon exhalation area.

3.5. Influence of permeability on radon concentration increment in confined workspaces

Figure 6 shows that radon concentration in the workspace under ascensional ventilation gradually increases until leveling off as heap permeability increases. With descentional ventilation, radon concentration decreases as permeability increases until it nears 0. Under ascensional ventilation, the airflow forces radon exhalation from the ore heap into the workspace. The higher the heap permeability, the more radon is exhaled. The opposite effects occur with descentional ventilation.

3.6. Frictional resistance coefficient affects radon concentration increment in confined workspace
Figure 7. Variation curves of different frictional resistance coefficient with radon concentration increment caused by ore heap exhalation

Figure 7 shows that when air quantity is 6 (m³ s⁻¹) and permeability is 1 × 10⁻⁸ (m²), radon concentration increment continuously increases under ascensional ventilation as frictional resistance coefficient increases; the growth rate gradually decreases over the curve. Under descentional ventilation, the radon concentration is less influenced by frictional resistance coefficient.

4. Conclusions
A calculation model for radon concentration as-affected by source and ventilation conditions was established in this study for application in shrinkage mining stopes. The radon exhalation rate with varying airflow parameters was determined accordingly. The model accounts for the source of radon in the underground uranium mine, and allows the engineer to predict changes in radon concentration based on an array of influence factors. The height, area, and permeability of the heap are positively correlated with radon concentration increment under ascensional ventilation in the workspace; ventilation air quantity has the opposite effect. Radon concentration increases to greater extent under ascensional ventilation than descentional ventilation. These observations may be used as a reference for ventilation design to control radon in shrinkage mining stopes.

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