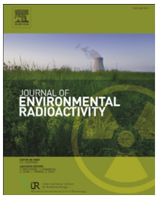
Journal of Environmental Radioactivity 140 (2015) 95–104

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad



An improved mathematical model for prediction of air quantity to minimise radiation levels in underground uranium mines

Durga Charan Panigrahi, Patitapaban Sahu, Devi Prasad Mishra*

Department of Mining Engineering, Indian School of Mines, Dhanbad 826 004, India

ARTICLE INFO

Article history:
Received 6 July 2014
Received in revised form
31 October 2014
Accepted 7 November 2014
Available online

Keywords:
Mathematical model
Underground uranium mine
Air quantity
^{222}Rn sources
Radon daughters
Inhalation exposure

ABSTRACT

Ventilation is the primary means of controlling radon and its daughter concentrations in an underground uranium mine environment. Therefore, prediction of air quantity is the vital component for planning and designing of ventilation systems to minimise the radiation exposure of miners in underground uranium mines. This paper comprehensively describes the derivation and verification of an improved mathematical model for prediction of air quantity, based on the growth of radon daughters in terms of potential alpha energy concentration (PAEC), to reduce the radiation levels in uranium mines. The model also explains the prediction of air quantity depending upon the quality of intake air to the stopes. This model can be used to evaluate the contribution of different sources to radon concentration in mine atmosphere based on the measurements of radon emanation and exhalation. Moreover, a mathematical relationship has been established for quick prediction of air quantity to achieve the desired radon daughter concentration in the mines.

1. Introduction

1.1. Radiation exposure in underground uranium mines

Uranium ore is mined either by opencast or underground mining methods depending on the size, depth, strike length, grade and other relevant characteristics of the ore deposit. During the mining and processing of uraniferous ore, the workers are exposed to radiation from uranium. It is a well known fact that the radiological hazards in underground uranium mines are more serious and difficult to tackle than in opencast mines due to ventilation problems. In uranium mines, the radiological hazard of the miners is primarily caused due to inhalation of radon (^{222}Rn) and its daughter products, which can contribute more than 50% of the total effective dose (Porstendorfer, 1994; UNSCEAR, 2000). The epidemiological studies revealed that prolonged exposure of underground uranium miners to radon and its daughter products leads to lung cancer (Grosche et al., 2006; Gulson et al., 2005; Tomasek, 2012).

The concentration of radon in underground uranium mine atmosphere mainly depends on the emissions of radon from the ore body, broken ore, backfill mill tailings and mine water. The radon exhalation from uranium ore mostly depends on several factors, viz. radium (^{226}Ra) content, porosity and moisture content of the ore and barometric pressure (Martin et al., 2002; Mudd, 2008; Rock and Walker, 1970; Strong and Levins, 1982; Thompkins, 1982). Broken ore piles are the sources of higher radon exhalation due to increased exposed surface area (Franklin et al., 1980; Lawrence et al., 2009; Washington and Regan, 1974). It has also been reported that radon exhalation from the backfill tailings is quantitatively more significant than from the uranium ore itself due to higher bulk porosity and enhanced surface area (Mishra et al., 2014). Mine water oozing out from uranium mineralised zones through the bore holes and fissures releases the dissolved radon into mine atmosphere (Misaqi, 1975).

1.2. Miners' risk of increased radon emanation

When a miner inhales the mine air, radon being a gas is exhaled along with the breathed out air. However, its decay 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. In mine atmosphere, the short-lived radon daughters interact with the aerosols and occur in two modes such as

---

* Corresponding author. Tel.: +91 9430191673; fax: +91 326 2296628, +91 326 2296563.
E-mail address: devi_agl@yahoo.com (D.P. Mishra).

http://dx.doi.org/10.1016/j.jenvrad.2014.11.008
0265-931X/© 2014 Elsevier Ltd. All rights reserved.

unattached and attached radon progeny. The short-lived radon progeny entering the mine air are usually positively-charged ions. They form ion groups (so-called clusters) with an activity median thermodynamic diameter (AMTD) lower than 10 nm in a short period of time (10–100 ms) with water, oxygen or other gases present in a traceable quantity in the air. These clusters are called unattached progeny (Porstendorfer, 2001). Since the unattached radon progeny exhibit a high rate of diffusion, they quickly become attached to existing aerosol particles in the atmosphere (the mean lifetime existence as free unattached ions is of the order of 10–50 s) (FRC, 1967). These aerosols, also called attached progeny, have the particle size range of 10–1000 nm (Dankelmann et al., 2001). The radon progeny in mine air are characterised by the potential alpha energy (PAE) collectively released by them.

The deposition characteristics of both unattached and attached fractions of radon decay products in the human respiratory tract are of considerable importance for the accurate estimation of inhalation radiation dose. A considerable portion of the unattached radon progeny gets deposited in the extra-thoracic and bronchial regions, whereas the attached radon progeny are deposited in different parts of the pulmonary region due to different sizes of the aerosols (Shimo et al., 1981). It has been reported that the unattached radon progeny are more easily deposited on the human respiratory lining and are largely responsible for radiation dose to the lungs because of their higher mobility than the attached progeny (El-Hussein et al., 1998; UNSCEAR, 2006). Further, the radon progeny decay completely *in situ* before they are translocated to other parts of the body by physiological process.

1.3. Mathematical model of reducing radiation exposure

Because of the uncertainties in lung dosimetry, the concept of working level (WL) was introduced as a measure of workers exposure to radon daughters in uranium mines. One WL is defined as the concentration of radon decay products in air having a potential alpha energy concentration of 1.3×10^5 MeV l^{-1} (2.08×10^{-5} J m^{-3} in SI unit) and corresponds to 3700 Bq m^{-3} of ^{222}Rn in equilibrium with its decay products (ICRP, 1993). The growth of radon daughters in mine atmosphere mainly depends on the residence time of radon gas in the mine, which in turn depends on the ventilation rate. A rapid air change causes quick removal of radon gas from mine atmosphere, resulting in less build-up of its daughter products due to insufficient residence time. Haasbroek and Du Toit (1973) reported that a 55% increase in ventilation resulted in 17% reduction in time taken by the air to reach underground working places from the surface, which in turn resulted in 43% reduction in the WL in a South African mine. Schroeder and Evans (1969) proposed the following formula to calculate the radon residence time to achieve the desired radiation levels in mine atmosphere:

$$T = \sqrt[1.85]{\frac{8065 R_D V_t}{E_t}} \tag{1}$$

where T is the radon residence time (min), R_D is the radon daughter working level (WL), V_t is the volume of stope (l) and E_t is the radon production rate (pCi min^{-1}). However, this formula utilises the older units, which are not acceptable in recent days and may require unit conversion. Also, this formula is only valid for the prediction of ventilation requirement when the intake air to the stope is uncontaminated with radon. In reality, the air entering the stope in a uranium mine invariably contains some radon and radon daughters, which in turn further increases the radon daughter concentration in the stope. Therefore, in the case of radon contaminated intake air, the formula proposed by Schroeder and Evans (1969) may underestimate the ventilation requirement to achieve the desired radiation levels in mine atmosphere. Moreover, in their paper, the systematic derivation of the formula has not been provided and hence it is very difficult for the readers to understand. Also, it is unclear how the relationship between the growth of WL and residence time was obtained. Thus, it necessitates an improved mathematical model for accurate prediction of air quantity for achieving the desired radiation levels in underground uranium mines depending on the quality of intake air.

2. Methodology

2.1. Mathematical model for prediction of potential alpha energy concentration (PAEC)

The radon gas exhaling from various sources into underground uranium mine atmosphere produces a complex mass of radon daughters over a period of time. The growth of radon daughters from the parent radon in mine atmosphere can be studied by assuming the air containing pure radon initially. ^{222}Rn decays to its short-lived daughter products such as ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po with the progress of time. Let, the number of atoms of ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po at time 't' be N_1, N_2, N_3 and N_4 respectively and their corresponding decay constants are λ_1, λ_2, λ_3 and λ_4. The values of λ_1, λ_2, λ_3 and λ_4 are 0.227, 0.0258, 0.035 and 70.43 min^{-1} respectively. The growth of ^{218}Po from ^{222}Rn at a small time interval 'dt' is given in Eq. (2)

$$\frac{dN_1}{dt} = N_0\lambda_0 - N_1\lambda_1 \tag{2}$$

Similarly, for ^{214}Pb, we can write

$$\frac{dN_2}{dt} = N_1\lambda_1 - N_2\lambda_2 \tag{3}$$

and so on for successive decay products. Where N_0 is the number of ^{222}Rn atoms (222 atom) and λ_0 is the decay constant of ^{222}Rn. The equations for successive decay products in the series form the complete mathematical basis for the complicated integral solutions, which are collectively called the "Bateman equation". These equations can be solved only with a small error (<1%) by considering the parent radon source as constant with time, because the mean life of radon is about 200 times longer than that of any of its short-lived decay products. Hence, the solutions for the growth of activity of each short-lived decay product accumulating in the parent radon, which maintains a constant activity 'C_0', are given below.

The activity concentration of ^{218}Po from the radon during the build-up time 't' is given in Eq. (4)

$$C_1 = C_0\left(1 - e^{-\lambda_1 t}\right) = C_0\left(1 - e^{-0.227t}\right) \tag{4}$$

where C_1 is the activity concentration of ^{218}Po ($=N_1\lambda_1$), C_0 is the initial radon concentration ($=N_0\ \lambda_0$) and t is the build-up time (min).

The total activities from the nth decay product during the same build-up time 't' can be generalised as

$$C_n = C_0 \sum_{i=1}^{n} \frac{\prod_{j=1\neq i}^{n} \lambda_j}{\prod_{j=1\neq i}^{n} (\lambda_j - \lambda_i)} \left(1 - e^{-\lambda_i t}\right) \tag{5}$$