Modeling of an Optimized Multilayer Cover Design for a Uranium Mill Tailings Disposal - 11607

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ABSTRACT

This paper presents a computer based algorithm to evaluate the performance of an engineered cover design for a uranium tailings disposal. The developed research was applied to a specific case study, the Urgeiriça uranium mining site located in the central north region of Portugal.

A multi-layer cover design was proposed in the remediation program for this site to be placed above the tailings disposal. The tailings composition is highly heterogeneous, in particular for radium concentration which varies between 3,000 and 67,000 Bq/kg. A value of 7.21 $Bq.m^{-2}.s^{-1}$ was calculated for radon exhalation through the tailings, considering an average radium concentration of 12,900 Bq/kg.

The cover was designed to mitigate the releases of radon gas to the surface and to minimize water infiltration to the mill tailings. An algorithm was developed to simulate the radon flux attenuation given by an arbitrary cover providing as an output the radon flux exhalation through the cover system. In addition, it is also possible to estimate the thickness of the cover that allows a radon flux inferior to the acceptable one, to accomplish legal limits.

The algorithm is based on the diffusion theory describing the long-term radon transport through the tailings and the cover's material and it was implemented in Matlab. The algorithm was simulated for the multi-layer cover design proposed in the remediation program, for an optimized multilayer cover design, and another simulation was done to accomplish a defined threshold.

The cover proposed in the remediation program, with 5.15 meters thickness, eliminated almost all the radon exhalation (99.82%). The optimized multilayer cover with 3 or 2 meters could achieve similar results: the radon exhalation decreases, respectively 99.55% or 96.39%. To accomplish the legal limits a cover system with 1 meter would be enough to reduce the average radon exhalation to the defined threshold.

INTRODUCTION

Usually the environmental remediation of a uranium mining site includes, along with many other activities, the design and implementation of an engineered cover to contain radioactive and non-radioactive materials from the tailings disposal. The cover system must also provide long-term stabilization and control of the tailings in order to minimize or eliminate radiation health hazards to the public. In practice, the major concern is to reduce radon exhalation to near-background levels also preventing geochemical reactions to occur within the radionuclides.

This paper presents a computer based algorithm to evaluate the long term efficiency of an engineered cover design for the remediation of a uranium tailings disposal. The developed research was applied to a specific case study, the Urgeiriça uranium mining site located in the central north region of Portugal. Approximately 13 ha of uranium mill tailings with an estimated volume of 1 460 000 m^3, were left as part of the legacy of the uranium mining and milling in this region. Also, two other contamination focuses were part of the legacy: a deposit of waste rock containing some low-grade ore and a few tons of high-grade uranium ore that were not milled [1].

The remediation project for this site included transferring the deposits of ore and waste rock into the tailings pile. It also included the geotechnical stabilization of the tailings area, confined in-situ by a concrete support structure with a deep drainage system, and sealed off with a multi-layer cover composed by geological and synthetic materials over the surface of the tailing deposit [1]. The cover was designed to mitigate the releases of radon gas to the surface and minimize water infiltration to the mill tailings. The cover also had the purpose of stopping the infiltration of gaseous oxygen preventing the formation of acid mine drainage. These were the relevant impacts needed to be mitigated.

SITE DESCRIPTION

The Urgeiriça mine is located near Canas de Senhorim, Nelas in central Portugal (Figure1). The Urgeiriça mine was active from 1913 to 1991 and until 1944 the ore was mined for radium extraction. After World War 2, in order to face the international demand for uranium, the purpose of this mine changed recovering only uranium as a radioactive substance [1].

The Urgeiriça ore processing plant was built in 1951 and it was used to process not only the ore from this mine but also from 62 others uranium mines exploited in Portugal at the time. The solid wastes produced in this facility were disposed in three main locations: a tailings pile with 1.46 million m^3 on 13.3 ha, known as “Old Dam”; a deposit of waste rock containing some low-grade ore, extracted from the Urgeiriça mine, with about 91 thousand m^3 on 1.5 ha and iii) a few tons of unprocessed high-grade uranium ore deposited near the plant (45 thousand m^3). The “Old Dam” tailings composition is highly heterogeneous due to former ore treatment and disposal practices. In particular, radium content varies between 3,000 and 67,000 Bq/kg.

Site studies and past investigations [1] showed the presence of acid water resulting from groundwater percolating into the interior of the old mine and the nearby mill tailings. This water is mainly sulfuric acid diluted and is liable to transfer significant amounts of dissolved metals and radionuclides into the environment (acid mine drainage) in particular into the "Ribeira da Pantanha" stream, a tributary to the Mondego river.

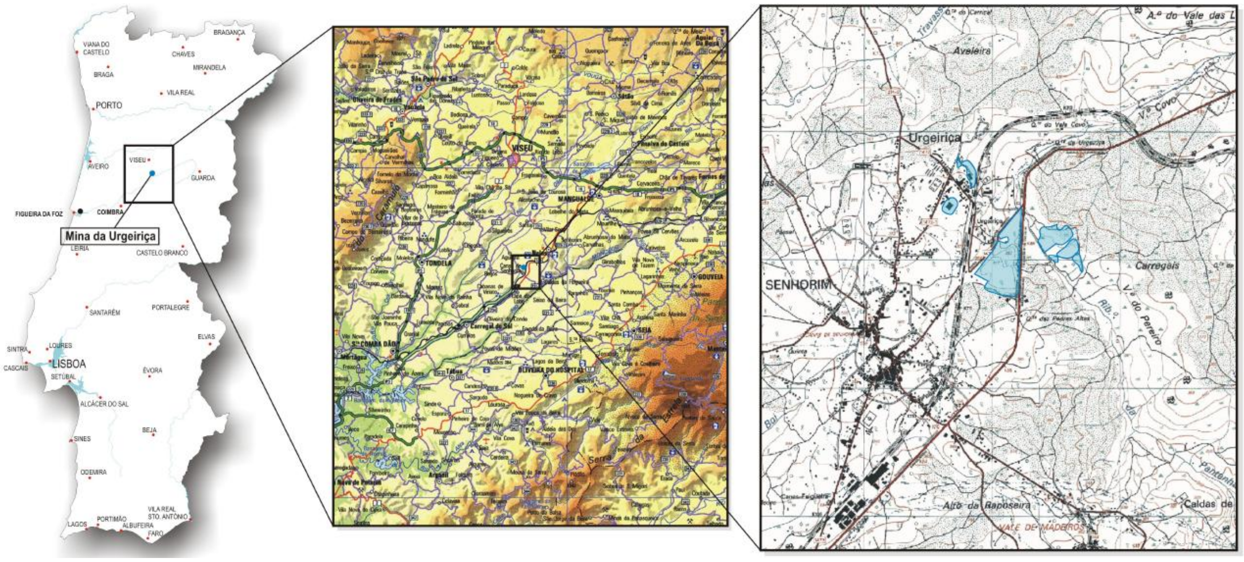

Fig. 1: Urgeiriça site location (national, regional and local), extracted from [2].

METHODOLOGY

Conceptual Approach

Radon emission occurs due to the radioactive decay of elements present within the tailings; in particular Radium-226 (Ra-226) and Thorium-230 (Th-230). Radon-222 (Rn-222) generation continues for many years due to the relatively long half-lives of these two radionuclides, both present in the uranium mill tailings. Rn-222 emanates from the radium present in bare tailings into the soil pore space followed by diffuse and advective transport in both liquid and gas phases into the atmosphere. Rn-222 attenuation to near background levels can be achieved by calculating the thickness of the cover materials that refrains the difusional transport of the radon so that it decays into a solid daughter before it reaches the atmospheric surface, becoming trapped in the cover materials [4].

A multi-layer cover design was proposed in the remediation program for the Urgeiriça site to be placed above the “Old Dam” uranium tailings. The tailings overlie uncontaminated bedrock of altered granite and are composed by crushed fine grained materials of metassedimentary granitic and some basalt composition. The surface is highly radioactive; an average value of 2.39 μGy/h was measured for external gamma radiation above the tailings [3].

A computer based algorithm was developed to evaluate the performance of the engineered cover design proposed. The efficiency was investigated mainly in what concerns to Rn-222 exhalation to the atmosphere. The conceptual model adopted includes contaminant source and release information, a description of transport mechanisms and pathways. The model was simulated for the multilayer cover proposed in the remediation program, for an alternative optimized multilayer cover, and another simulation was done to accomplish a defined threshold.

Mathematical Approach

The developed algorithm is based on the diffusion equation applied to the Rn-222 diffusion in the air space and in the water space of a multiphase system as proposed by Rogers and Nielsen [4], [5]. Rn-222 diffusion through a two-phase medium in the pore spaces of earthen materials can be characterized by the following diffusion equations [4], [5]:

$$D_a \frac{\partial^2 C_a}{\partial x^2} - \lambda C_a + \frac{R\rho\lambda E_a}{\varepsilon - \theta} + \frac{T_w}{\varepsilon - \theta} = 0 \qquad \text{(Eq. 1)}$$

$$D_w \frac{\partial^2 C_{wa}}{\partial x^2} - \lambda C_{wa} + \frac{R\rho\lambda E_w}{\theta} - \frac{T_w}{\theta} = 0 \qquad \text{(Eq. 2)}$$

The necessary parameters for solving these equations are: Rn-222 diffusion coefficient D ($m^2.s^{-1}$), Rn-222 decay constant λ (s^{-1}), radium concentration in the pores space C ($Bq.m^{-3}$), radium concentration in the tailings R ($Bq.kg^{-1}$), bulk density of the dry material ρ ($kg.m^{-3}$), Rn-222 emanation coefficient E (dimensionless), total porosity ε (dimensionless), moisture θ (dimensionless) and Rn-222 transfer rate from water to air T_w ($Bq.m^{-3}.s^{-1}$). The subscript *a* refers to air-filled pore space and *w* refers to water filled pore space.

Rn-222 concentration in air filled pore space (C_a) and water filled pore space (C_w) are related by this expression [4], [5]:

$$C = \frac{C_a(\varepsilon - \theta) + C_w \theta}{\varepsilon} \qquad \text{(Eq. 3)}$$

and combining equations 1, 2 and 3 yields:

$$D \frac{\partial^2 C}{\partial x^2} - \lambda C + \frac{R\rho\lambda E}{\varepsilon} = 0 \qquad \text{(Eq. 4)}$$

where D is the Rn-222 diffusion coefficient in the total pore space and E is the total emanation coefficient ($E_a + E_w$) of the material.

The generic solution of the diffusion equation (Eq. 4) gives the Rn-222 flux released considering either no cover system, J_t, either the Rn-222 flux through a designed cover system, J_{ci} [6]. The following equation was used to calculate the Rn-222 flux, J_t ($Bq.m^{-2}.s^{-1}$) from bare tailings with a thickness of x_t (m) [4], [5]:

$$J_t = R\rho E \sqrt{\lambda D_t}\, \mathrm{tgh}\left(\sqrt{\frac{\lambda}{D_t}} x_t \right) \qquad \text{(Eq. 5)}$$

For thick tailings sources inferior to 2 m, the hyperbolic tangent term (tgh) is equal to unity and may be ignored [4], [5].

The surface Rn-222 flux exhalation through a homogeneous cover material (J_c, Bq m^{-2} s^{-1}) placed over the tailings pile, was calculated with the following equation [4], [5]:

$$J_c(x_c) = \frac{2 \cdot J_t e^{-b_c x_c}}{\left[1 + \sqrt{a_t / a_c}\, \mathrm{tgh}(b_t x_t)\right] + \left[1 - \sqrt{a_t / a_c}\, \mathrm{tgh}(b_t x_t)\right] e^{-2 \cdot b_c x_c}} \qquad \text{(Eq. 6)}$$

where b_i, a_i and m may be calculated with equations 7, 8 and 9, respectively [4], [5]:

$$b_i = \sqrt{\lambda / D_i}\,(i = c \text{ ou } t),\ \left(m^{-1}\right) \qquad \text{(Eq. 7)}$$

$$a_i = \varepsilon_i^2 D_i \left[1-(1-k)m\right]^2,\ \left(m^2 \cdot s^{-1}\right) \qquad \text{(Eq. 8)}$$

$$m = 10^{-2}\,\frac{\rho M}{\varepsilon} \qquad \text{(Eq. 9)}$$

and x_c (m) is the cover thickness; M (dry weight percent) is the moisture content; m (dimensionless) is the fraction of saturation and k represents 0,26 Bq/m^3 in water per Bq/m^3 in air. The fraction of saturation can be estimated by the empirical correlation proposed by Rogers and Nielsen [4]:

$$D_t = 7\,x10^{-6}\,e^{\left[-4\left(m - m\varepsilon^2 + m^5\right)\right]} \qquad \text{(Eq. 10)}$$

The cover thickness required to accomplish a Rn-222 flux inferior to a specified value, can be deduced from equation 6, resulting in [4], [5]:

$$x_c = \sqrt{\frac{D_c}{\lambda}}\,\ln\left[\frac{2 \cdot J_t / J_c}{\left(1+\sqrt{a_t / a_c}\,\mathrm{tgh}\left(b_t x_t\right)\right) + \left(1-\sqrt{a_t / a_c}\,\mathrm{tgh}\left(b_t x_t\right)\right)\left(Jc / Jt\right)^2}\right] \qquad \text{(Eq. 11)}$$

To calculate the Rn-222 flux for a multilayer cover system it was used a sequential application of equation 6 and equation 11 to each layer. The process treats each layer as a single cover system with an updated source considering the tailings and all the cover layers beneath the layer in question [4], [5].

To perform these calculations, an algorithm was developed and implemented in Matlab code. It simulates the Rn-222 flux exhalation from the tailings and from the cover, using the mathematical formulation given by equations 5 and 6 and then optimizes the cover thickness (Eq. 11) to satisfy a given flux constraint. The code simulates not only Rn-222 flux but also the Rn-222 concentration at 1 m above the ground and the dispersion with the wind in several directions and in the dominant wind direction [7], [8].

Cover Systems Studied

In what concerns the geotechnical stabilization, three different cover systems were studied to quantify the Rn-222 exhalation: i) a multilayer cover proposed in the remediation program for Urgeiriça site composed by six different layers, ii) an optimized multilayer cover considering the regional natural background levels, and iii) a multilayer cover designed to accomplish a defined threshold.

The multilayer cover system proposed in the remediation plan to be placed over the surface of the tailings, from bottom to top, was composed by [2] [3]:

- A compacted layer of geological materials from other mine tailings (2-5 m);
- A clay layer (0.60 m);
- An HDPE liner in conjunction with a geo-textile membrane (2 mm);
- A layer of well sorted gravel (0.30 m);
- A fine sand layer (0.25 m);
- And a layer of a composite soil (0.5 m).

The area and the thickness of the tailings were estimated in 133,000 m^2 and 14 m, respectively [3]. Different ^{226}Ra concentrations were considered based on samples collected in drill-holes perforated in the tailings [9]. The total area was individualized into seven smaller areas according to the radium concentration. These areas and the respective Ra-226 concentration are presented in Table I.

Table I: Ra-226 Concentration for Each Considered Area.

Area	A (m^2)	Ra-226 ($Bg.kg^{-1}$)
A_1	110,575	4,898
B_1	1,575	9,764
B_2	1,575	9,764
B_3	2,750	28,275
B_4	6,825	21,500
B_5	4,075	27,200
B_6	5,625	63,313

The model parameters for the tailings material are the Rn-222 emanation coefficient (0.24), the total porosity (0.37) and the bulk density (1.67 g/cm^3). For the total cover, an average thickness of 5.15 m was used, as proposed in the site rehabilitation project [3]. Considering the cover composition of clay, sand and gravel, an average value of 1.67 g/cm^3 and 0.30 were adopted for the cover bulk density and total porosity, respectively. As the flux of Rn-222 through the tailings and cover material depends on Rn-222 diffusion coefficient, the following average values were calculated for the tailings and for the cover: 5×10^{-7} m^2/s and 9.2×10^{-7} m^2/s, respectively [3].

The cover thickness was optimized in a second stage, to reduce Rn-222 flux to near natural background levels. For the Urgeiriça region this value varies between 20 and 30 Bq/m^3. This may be generated by an average Rn-222 flux of 1.36 $Bq.m^{-2}.s^{-1}$, considering previous studies in this site [6], [7], [8]. Same materials with the same characteristics but with different thickness (2 and 3 meters for total thickness) were investigated, by adjusting the bottom layer composed of geological materials from other mine tailings.

In the third stage, the US EPA (1983) value for the standard Rn-222 flux exhalation from the surface of an inactive uranium mill tailings pile was set at the maximum permissible limit to accomplish; 20 $pCi.m^{-2}.s^{-1}$ or 0.74 $Bq.m^{-2}.s^{-1}$ [10]. As a starting point for the optimization of the cover thickness, a clay layer of 0.5 m was considered in the simulation. In addition, an overburden layer with unknown thickness was also considered.

RESULTS AND DISCUSSION

A simulation was performed to calculate the Rn-222 flux through the bared tailings; initially it was used a single average value for Ra-226 concentration in the tailings (12,900 Bq/kg). The resulting Rn-222 flux was 7.19 $Bq.m^{-2}.s^{-1}$. In an alternative approach, a simulation was done considering the individualized areas according to radium content in the tailings. The resulting average flux, weighted by the respective area, was 5.31 $Bq.m^{-2}.s^{-1}$. The Rn-222 flux exhalation through the multilayer cover system defined in the remediation project was also simulated for each one of these areas. The results are presented in Table II.

Table II: Rn-222 Flux from the Tailings (J_t) and from Each One of the Layers (J_C) Bq.m^{-2}.s^{-1}. Thickness x_c = 5.15 m.

Area	J_t	J_{C1}	J_{C2}	J_{C3}	J_{C4}	J_{C5}	J_{C6}
A_1	2.74	1.41×10^{-3}	5.05×10^{-4}	4.81×10^{-4}	2.47×10^{-4}	1.79×10^{-4}	4.97×10^{-5}
B_1	5.46	2.81×10^{-3}	1.00×10^{-3}	9.67×10^{-4}	4.92×10^{-4}	3.58×10^{-4}	9.90×10^{-5}
B_2	5.46	2.81×10^{-3}	1.00×10^{-3}	9.67×10^{-4}	4.92×10^{-4}	3.58×10^{-4}	9.90×10^{-5}
B_3	15.81	8.15×10^{-3}	2.91×10^{-3}	2.8×10^{-3}	1.42×10^{-3}	1.03×10^{-3}	2.87×10^{-4}
B_4	12.02	6.20×10^{-3}	2.22×10^{-3}	2.13×10^{-3}	1.08×10^{-3}	7.87×10^{-4}	2.18×10^{-4}
B_5	15.21	7.84×10^{-3}	2.80×10^{-3}	2.69×10^{-3}	1.37×10^{-3}	9.96×10^{-4}	2.76×10^{-4}
B_6	35.40	1.82×10^{-2}	6.53×10^{-3}	6.27×10^{-3}	3.19×10^{-3}	2.32×10^{-3}	6.42×10^{-4}

The average Rn-222 exhalation rate through the tailings (J_t) is 5.31 Bq.m^{-2}.s^{-1}. On the top of the sixth cover layer, the average Rn-222 exhalation is approximately equal to 9.64 x 10^{-5} Bq.m^{-2}.s^{-1}. The multilayer cover design with the thickness of 5.15 m reduced almost all the Rn-222 exhalation; 99.82% from 5.31 to an average value of 9.64 x 10^{-4} Bq.m^{-2}.s^{-1}(Rn-222 flux from J_{C6} averaged with the respective area). This means that the Rn-222 exhalation is much lower than the regional natural background level.

Figure 2 shows the Rn-222 exhalation decrease through the different cover layers for each one of the 7 individualized areas.

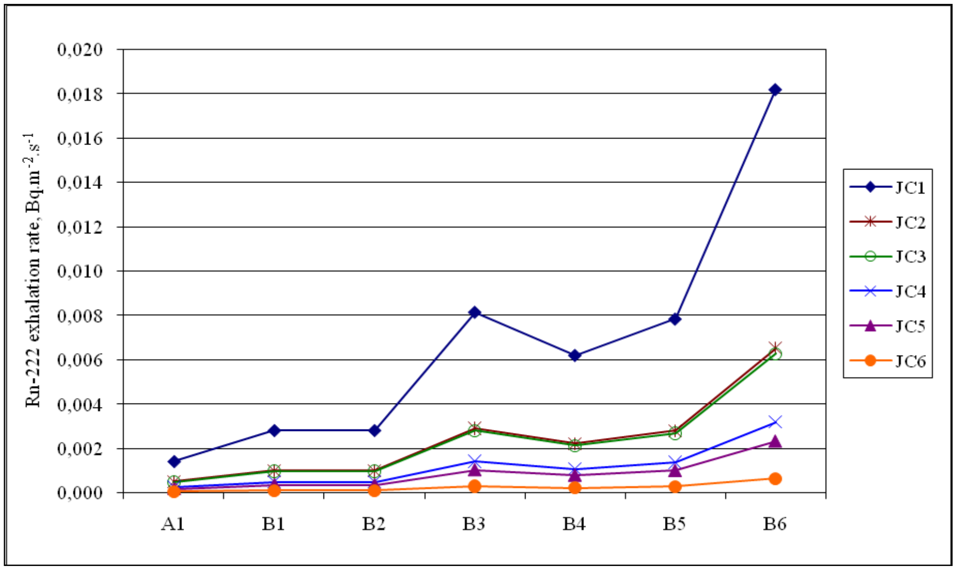

Fig. 2: Rn-222 exhalation rate through the multilayer cover system proposed to be placed over the “Old Dam”.

The area identified as B_6 has the highest Rn-222 exhalation rate as expected, due to the higher Ra-226 concentration present. It is also clear that the variation of Rn-222 exhalation rate between the seven areas is much less significant in the upper layer (J_{C6}) and it seems to be more or less homogenous along its thickness.

In the second stage, the purpose of the simulation was to optimize the cover thickness in order to reduce Rn-222 flux to near the natural background level. The same materials with the same characteristics were investigated; at first it was considered a total cover thickness of 3 meters and after, a value of 2 meters. This was done by adjusting the bottom layer composed of mining wastes from other mines with different geological characteristics. The results are presented in Table III and Table IV, respectively.

Table III: Rn-222 Flux from the Tailings (J_t) and from Each One of the Layers (J_C) $Bq.m^{-2}.s^{-1}$. Thickness x_c = 3 m.

Area	J_t	J_{C1}	J_{C2}	J_{C3}	J_{C4}	J_{C5}	J_{C6}
A_1	2.74	4.10×10^{-3}	9.60×10^{-4}	9.19×10^{-4}	5.94×10^{-4}	4.34×10^{-4}	1.21×10^{-4}
B_1	5.46	8.10×10^{-3}	1.90×10^{-3}	1.80×10^{-3}	1.20×10^{-3}	8.66×10^{-4}	2.42×10^{-4}
B_2	5.46	8.10×10^{-3}	1.90×10^{-3}	1.80×10^{-3}	1.20×10^{-3}	8.66×10^{-4}	2.42×10^{-4}
B_3	15.81	2.34×10^{-2}	5.50×10^{-3}	5.30×10^{-3}	3.40×10^{-3}	2.50×10^{-3}	7.00×10^{-4}
B_4	12.02	1.78×10^{-2}	4.20×10^{-3}	4.10×10^{-3}	2.60×10^{-3}	1.90×10^{-3}	5.32×10^{-4}
B_5	15.21	2.25×10^{-2}	5.30×10^{-3}	5.10×10^{-3}	3.33×10^{-3}	2.40×10^{-3}	6.73×10^{-4}
B_6	35.40	5.24×10^{-2}	1.24×10^{-2}	1.19×10^{-2}	7.70×10^{-3}	5.60×10^{-3}	1.60×10^{-3}

The results showed that the multilayer cover design with 3 m reduced the averaged Rn-222 exhalation in 99.55%; it decreased from 5.31 $Bq.m^{-2}.s^{-1}$ to 2.36×10^{-4} $Bq.m^{-2}.s^{-1}$ (Rn-222 flux from J_{C6} averaged with the respective area). The results are similar with those obtained in the previous simulation. These results are presented in Fig. 3.

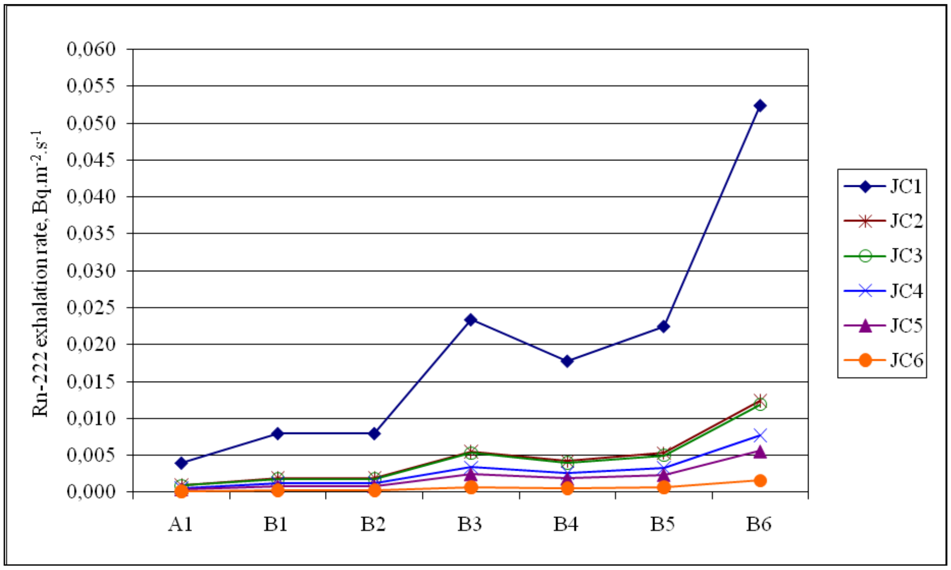

Fig. 3: Rn-222 exhalation rate through the alternative multilayer cover system, x_c = 3m.

As the results for Rn-222 exhalation are of the same magnitude in both simulations, another reduction in the cover thickness may be optimized. For this alternative the efficiency of the multilayer cover with the two meters thickness was tested.

Table IV: Rn-222 Flux from the Tailings (J_t) and from Each One of the Layers (J_C) $Bq.m^{-2}.s^{-1}$. Thickness x_c = 2 m.

Area	J_t	J_{C1}	J_{C2}	J_{C3}	J_{C4}	J_{C5}	J_{C6}
A_1	2.74	3.35×10^{-2}	7.9×10^{-3}	7.50×10^{-3}	4.90×10^{-3}	3.5×10^{-3}	9.89×10^{-4}
B_1	5.46	6.67×10^{-2}	1.57×10^{-2}	1.50×10^{-2}	9.70×10^{-3}	7.10×10^{-3}	2.00×10^{-3}
B_2	5.46	6.67×10^{-2}	1.57×10^{-2}	1.50×10^{-2}	9.70×10^{-3}	7.10×10^{-3}	2.00×10^{-3}
B_3	15.81	1.93×10^{-1}	4.54×10^{-2}	4.34×10^{-2}	2.81×10^{-2}	2.05×10^{-2}	5.70×10^{-3}
B_4	12.02	1.47×10^{-1}	3.45×10^{-2}	3.30×10^{-2}	2.13×10^{-2}	1.56×10^{-2}	4.30×10^{-3}
B_5	15.21	1.86×10^{-1}	4.37×10^{-2}	4.17×10^{-2}	2.70×10^{-2}	1.97×10^{-2}	5.55×10^{-3}
B_6	35.40	4.32×10^{-1}	1.016×10^{-1}	9.71×10^{-2}	6.29×10^{-2}	4.59×10^{-2}	1.28×10^{-2}

The multilayer cover design with 2 m reduced the Rn-222 exhalation rate in 96.39%; the value decreased from 5.31 to 1.92 x 10^{-3} Bq.m^{-2}.s^{-1} (Rn-222 flux from J_{C6} averaged with the respective area). The results are presented in Fig. 4.

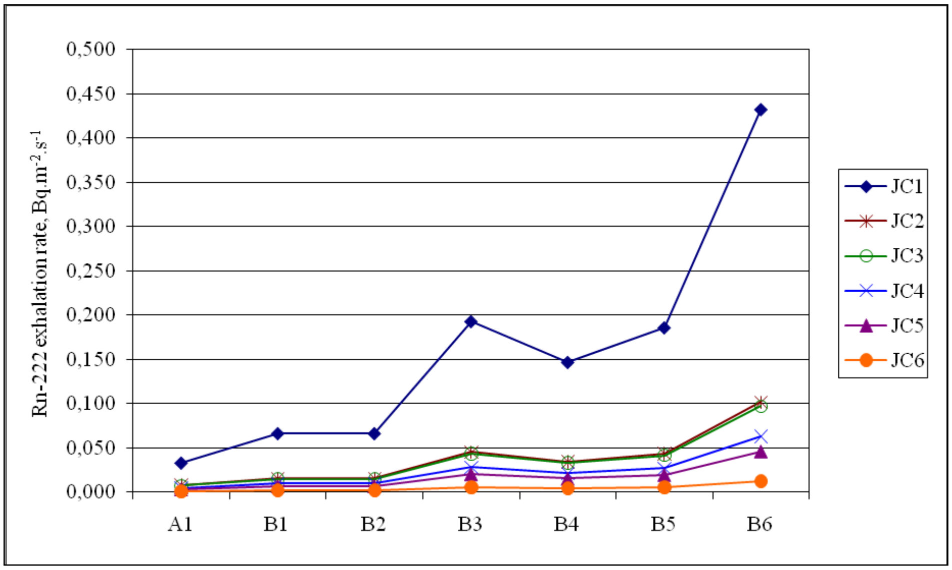

Fig. 4: Rn-222 exhalation rate through the alternative multilayer cover system, x_c = 2m.

For the third stage the purpose was limiting the surface Rn-222 exhalation to 0.74 Bq.m^{-2}.s^{-1} (20 pCi.m^{-2}.s^{-1}). As a first approach, it was considered a layer of 0.5 m of clay plus a layer of overburden to achieve an Rn-222 exhalation rate inferior to this limit. The diffusion coefficient for the clay cover layer was the same value used in the previous simulations. For the overburden layer a diffusion coefficient of 2.2 x 10^{-6} m^2.s^{-1} was calculated and a total porosity of 0.37 was used. The diffusion coefficient for the new source term (tailings plus clay layer) was calculated in the algorithm (7.17 x 10^{-7} m^2.s^{-1}) and used to estimate the second layer cover thickness.

Considering a single average value for radium content in the tailings (12,900 Bq/kg), the value obtained for the second layer is x_{c2} = 0.57 m which gives a total cover thickness of 1.07 m. On the other hand, considering the heterogeneous Ra-226 concentration in the tailings, we stipulated that the limit should be achieved for all the individualized areas and in these conditions; the second cover layer thickness was optimized to 1.49 m, which gives 1.99 m for total cover thickness. This assures that for any individualized area the Rn-222 flux is inferior to the EPA limit. The obtained average Rn-222 exhalation rate weighted by the respective area was 0.23 Bq.m^{-2}s.$^{-1}$.The Rn-222 exhalation rate was reduced in 95.67%; from 5.31 to 0.23 Bq.m^{-2}s.$^{-1}$.

CONCLUSIONS

A computer based algorithm was implemented in Matlab code to evaluate the efficiency of an engineered final cover for the remediation of a uranium tailings disposal. The developed studies were applied to a specific site, the Urgeiriça uranium mining site.

Three different situations were simulated in the algorithm based on the multilayer cover system proposed in the rehabilitation project for this site. Different criterions were established and subsequently different resulting thicknesses were obtained for final covers; 5.15 m, 3 m and 2 m.

The multilayer cover design with 5.15 m proposed in the remediation program reduced the Rn-222 flux in 99.82%. The alternative optimized cover with 3 meters reduced the Rn-222 exhalation in 99.55%. When the desired performance criterion is to achieve the Rn-222 standard emission rate from the surface of inactive uranium mill tailings piles, a cover with a thinner thickness could perfectly be used. In the simulation done, the two layers cover with a thickness of 2 meters allowed to reduce the Rn-222 exhalation to 0.23 $Bq.m^{-2}.s^{-1}$ (decreased in 95.67%) which is inferior to the defined threshold.

The cover proposed in the remediation project leads to a complete black out of Rn-222 exhalation which means that the “Old Dam” tailings pile exhalation is much lower than the natural background. In this context, a 2 or 3 meters for the total cover system could be adopted.

The results showed that for all the three simulated situations the cover system allows reducing the Rn-222 exhalation rates to negligible values, once the regional natural background is inferior to 30 $Bq.m^{-3}$. The main difference between different simulations refers to the thickness of the bottom compacted layer composed by geological materials from other mine tailings.

This may suggest that the very high efficiency of the cover system is predominantly assured by upper layers, in particular, the HDPE liner in conjunction with the geo-textile membrane liner, isolate the hydrologic situations in the drainage layer above from the clay layer. Nevertheless, other important parameters could and should have been varied in the simulations developed, in particular porosity and saturation degree, as the Rn-222 diffusion coefficient is a function of both.

Considering the costs associated with this type of rehabilitation works, not only due to variety of materials involved but also due to their movement and transportation, the simulation of the attenuation of the radon flux attenuation throughout several alternative multilayer covers allows to minimize the costs assuring, simultaneously, the environmental feasibility of the remediation.

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