Using Monte-Carlo Simulation for Risk Assessment: Application to Occupational Exposure during Remediation Works

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Abstract. The aim of this study was to apply the Monte-Carlo techniques to develop a probabilistic risk assessment. The risk resulting from the occupational exposure during the remediation activities of a uranium tailings disposal, in an abandoned uranium mining site, was assessed. A hypothetical exposure scenario was developed and two different pathways were compared: internal exposure through radon inhalation and external through gamma irradiation from the contaminated tailings material. The input variables, such as the inhalation rate and the external exposure parameters, were considered as specific probabilistic distributions, each one characterized by its central tendency and dispersion parameters. Using the cumulative distribution function, a probabilistic value for each variable can be generated using a single random number. Thus, this methodology allows performing a probabilistic risk assessment generating a risk distribution.

Keywords: Risk and dose assessment, uranium tailings disposal, Monte-Carlo simulation, occupational exposure.

1 Introduction

The uranium mining in Portugal took place at 62 different sites, mostly in small open pit exploitations although the larger ones were underground mines or a combination of both. Most of the mining sites are located in the districts of Guarda and Viseu (central-east Portugal). One of these sites was the Urgeiriça uranium mine which was considered to be the country's most important uranium exploitation. The Urgeiriça mine was active from 1913 to 2000 and the total uranium concentrate production reached about 4730 tons.

The uranium mining and processing operations in Portugal have left a legacy of considerable environmental contamination. The extensive treatment of uranium ores at the Urgeiriça processing plant led to the production of large amounts of solid wastes (tailings) that were deposited into open-air dams. The most voluminous tailing, with an estimated volume of 1 390 000±40 000 m^3 and an area of 13.3 hectares, consists of the sludge produced in the milling facility [1].

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This tailings pile, known as the "Old Dam", includes most of the radioisotopes of the uranium decay chains as well as other hazardous chemical elements resulting from the treatment process (acid leaching). Radium is of specific concern in the uranium tailings as it decays into radon, a radioactive gas which may cause lung cancer.

Since 1996 the Portuguese government had to deal with the decommissioning of the mines, mills and other facilities and the rehabilitation of the mining sites. In 2005, the Environmental Monitoring Programme became mandatory and legally enforced. The overall environmental remediation programme at the Urgeiriça mine was planned for completion before the end of 2007. However, the tailings pile "Old Dam" rehabilitation was only concluded in April 2008.

This work focuses on the potential occupational exposure during the "Old Dam" remediation works that occurred mainly in 2008. The "Old Dam" was one of the many sites with radioactive material to be rehabilitated. The others sites in the same region are scheduled to be intervened between 2010 and 2013.

The tailings are a source of external radiation and furthermore a powerful source of radon and dust that disperses in the atmosphere. During the remediation stage, radon inhalation may lead to significant occupational radiation exposure. Since site remediation was carried out at places with enhanced dose rates and high concentrations of airborne radioactivity (long-lived alpha particles, radon progenies), a large part of the workers were exposed to radiation mainly from three main exposure pathways: i) inhalation of radon decay products, ii) inhalation of dust-borne long-lived alpha emitters and iii) external radiation. The research described in this paper focuses, in particular, on radon inhalation and external (gamma) radiation.

2 Methods and Materials

2.1 Risk Assessment and Monte-Carlo Simulations

Risk assessment tools have been widely used to evaluate environmental contaminations and the effects on humans and ecosystems. Taken as an example radon exhalation from uranium tailings, the hazards of the exposure through the inhalation of radon come from its radioactive decay daughters. When radon is inhaled it decays into other radioactive products. These will dissipate their energy (alpha radiation) in the lung cells becoming a potential cause of lung cancer.

The probability of lung cancer occurrence depends on the amount of energy dissipated per unit mass. The amount of radon inhaled, and consequently, the amount of radon daughters inside the body, depends on the breathing rate. This factor will contribute to the estimative of the intake dose which is then combined with established factors (toxicity values or cancer slope factors) to determine the human health risk for that particular exposure.

The estimate of the intake dose requires data on the type and concentration of the contaminant together with many exposure input parameters. Generally some fixed values obtained from statistical analysis of the observed concentrations for a given contaminant are combined with fixed standard values for exposure input parameters such as intake rates. The fixed input parameters are often chosen as the maximum value over a range of possible values to ensure that the estimative is on the "safe side". This is known as a based deterministic approach. The level of contamination (either measured or modeled) as well as exposure input parameters and toxicity values will always have inherent variability and uncertainty and these are not considered in a deterministic approach, which may result in an overestimate of the intake dose.

Probabilistic-based methods provide more realistic estimates using probability density functions for the input data instead of using fixed single values; for each parameter a probability density function is assigned. These distributions can take several forms (e.g. normal, lognormal, uniform, triangular, etc.).

A probabilistic methodology, such as Monte Carlo simulations, may be used to generate the cumulative intake dose, and then an intake dose value of the 90th to 99,9th percentiles of this distribution may be used for further risk assessment. The result will be a cumulative distribution of the intake dose that would, in a more realistic way, account for variability and uncertainty.

2.2 Occupational Exposure in Remediation/Rehabilitation Activities

The International Commission on Radiological Protection (ICRP) has established for occupational exposure an effective dose limit of 20 mSv per year, averaged over 5 years (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year [2]. European legislation follows these limit values legislated in the Directive 96/29 EURATOM. This directive is designed to establish uniform safety standards to protect the health of workers and the general public against the dangers of ionizing radiation.

Although this directive came into force for European member states in 2000, Portugal was an exception. Portugal has notified transposition measures which were distributed in various legislative texts, instead of a coherent and consolidated legal framework. The European Commission considered that this made Portuguese legislation on radiation protection too complex and caused uncertainty for the citizens regarding the relevant transposition provisions [3]. In this way, Portugal was considered to have failed in fulfilling its obligations on basic safety standards for the health protection of workers and the general public from ionizing radiation.

After these events, EURATOM Directive was completely transposed to national law, in November 2008. Regarding these circumstances, in the previous context (before November 2008), the great majority of the rehabilitation works were done by workers that were officially non-radiologically exposed and consequently, their dose limit was the same as for the public, 1 mSv/year.

The U. S. Environmental Protection Agency (EPA) evaluates the risk due to radiation exposure as the carcinogenic slope factor, representing the lifetime excess total cancer risk per unit intake or exposure. The product of the cancer slope factor by the dose received estimates the risk for a member of the critical

Table 1. Gamma radiation emitters and dose coefficients

Radionuclide	Average soil concentration ($C_{soil,i}$) (Bq/kg)[7]	Dose coefficients ($DC_{ext,i}$) (Sv s^{-1})/(Bq m^{-2})[8]
^{235}U	483	1.48×10^{-16}
^{234}Th	6506	8.32×10^{-18}
^{226}Ra	3004	6.44×10^{-18}
^{210}Pb	3046	2.48×10^{-18}
^{137}Cs	9.90	2.85×10^{-19}
^{40}K	1738	1.46×10^{-16}

group due to their activity. This risk represents the probability of cancer inducing by this particular exposure, in excess relative to the background risk.

The acceptable risk is generally defined as 10^{-6} for the general public and 10^{-5} for occupational works. This means that an additional one case of cancer is accepted for population of 1 million or 100 000, being the general background risk around 20% for most of the industrialized countries. A risk level of 1 in a million, or 1 in one hundred thousand, also implies a likelihood that up to one person, out of one million (or 100 000) equally exposed people would contract cancer if they are exposed continuously (24 hours per day) to a specific radiation dose over 70 years (an assumed average lifetime).

The exposure scenario adopted in this study considers both internal and external exposure for estimating the exposure of the workers involved in the remediation activities of the tailings pile "Old Dam" and evaluates the health risks by means of a Monte-Carlo simulation. The estimative includes the dose and the associated risk from the activities. The dose assessment was done exclusively in a deterministic way while the risk assessment was done in a probabilistic based methodology. The critical receptor is represented by an average adult worker, involved in the remediation of the tailings, assuming an exposure during an 8-hour work day, 5 days per week, 48 weeks/year (accounting for the receptor being away on vacation for 4 weeks per year), during 3 years. It was also assumed that all the working time is spent outdoor [4]. The relevant pathways considered for the workers exposure are radon inhalation and gamma radiation from the tailings.

2.3 Sampling Methods

A radon survey over an area of 13.3 ha in the tailings pile and in its vicinity was carried out during two field campaigns in 2001. The first one was done in spring using 45 sampling points and the second one was done in summer using 22 sampling points. The sampling campaigns comprised various types of measurements, including radon exhalation rates (Bq m^{-2} s^{-1}) and radon concentration (Bq/m^3).

The radon concentrations in the atmospheric air, measured at 1 m above the soil, ranged from 195 to 1205 Bq/m^3, with an average value of 557 Bq/m^3. In the vicinity of the tailings pile the measured radon concentration varied from 50 to 930 Bq/m^3 with an average value of 251 Bq/m^3 [6].

To assess the external dose, measurements on the radionuclides gamma emitters were carried out [7]. The radionuclides gamma emitter concentrations in the soil were assessed by gamma-spectrometry and are presented in Table 1.

3 Applied Methodology

3.1 Effective Dose Assessment

The critical group for which individual doses are to be assessed is representative of the adult workers involved in the remediation activities. The effective dose due to radon inhalation may be calculated through the following equation:

$$D_{Rn} = C_{Rn} \times DC_{inh} \times E_f \times f_{eq}, \tag{1}$$

where D_{Rn} is the annual dose resulting from radon inhalation (mSv/year); C_{Rn} is the average radon concentration in breathing air at the tailings pile (Bq/m^3); DC_{ing} is the radon effective dose equivalent factor (mSv/(Bq h m^{-3})); E_f is the outdoor exposure frequency (hour/year) and f_{eq} is the equilibrium factor for radon decay products (unitless).

We have adopted the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommendation for the conversion of potential alpha energy exposure (Bq h m^{-3}) to effective dose equivalent (mSv) [5]. A value of 9×10^{-6} mSv per Bq h m^{-3} was adopted for the radon effective dose equivalent factor. This conversion factor has implicit an adult average breathing rate of 19.2 m^3/d [5]. It was assumed an outdoor exposure frequency of 1920 hours per year and an equilibrium factor for radon decay products of 0.4 [5].

For the external exposure dose due to the contaminated ground surface ($D_{ext,i}$), the U.S. EPA dose coefficients (Table 1) were converted into the appropriated units by assuming a soil density of 1600 kg/m^3 (ρ) and a soil depth contamination of 1 m (T_s) [8], in the following equation:

$$D_{ext,i} = C_{soil,i} \times DC_{ext,i} \times E_f \times 3600 \times \rho \times T_s, \tag{2}$$

where $C_{soil,i}$ is the radionuclide concentration in soil (Bq/kg), $DC_{ext,i}$ is the dose coefficient and the subscript "i" corresponds to each radionuclide (Table 1). In practice, doses obtained from the assessment of exposure from external radiation and from intake of radon are combined for the assessment of the value of total effective dose for demonstrating compliance with dose limits and constraints.

3.2 Risk Assessment

In a simplified approach, the annual risk incurred to a receptor by internal exposure due to radon inhalation may be estimated combining the radon concentration, the individual breathing rate, the exposure frequency and the radon cancer slope factor as given by equation (3):

$$R_{Rn} = C_{Rn} \times B_R \times RC_{inh} \times E_f \times f_{eq}, \tag{3}$$

where R_{Rn} is the annual risk resulting from radon inhalation; B_R is the breathing rate (log-normally distributed) at the exposure location (m^3/d) and RC_{inh} is the radon slope factor for inhalation (Risk/Bq); a value of 2.04×10^{-10} was adopted for this parameter [4].

A log-normal distribution of the daily breathing rate, normalized to the average body weight, was adopted based on values published for this log-normal distribution. We adopted the mean and the standard deviation designated by the ICRP [2]. For this distribution the mean, standard deviation, median and 95th percentile are respectively 16.45, 4.69, 16.32, 20.25 m^3/d.

The Monte Carlo methodology was used to generate an output cumulative distribution of the exposure risk: the Monte-Carlo, as a probabilistic method, performs the combination of probability distributions by numerical simulation and calculates the risk several thousand of times by generating random values for the input variables from the distribution function. This process was implemented using Matlab for programming an algorithm with different probability distribution for some of the variables involved in the risk calculations and performing about 30000 random generations.

In the algorithm the risk equation is expressed as a function of carcinogenicity (radon slope factor) and radon concentration, both as point values, and two exposure variables (breathing rate and exposure frequency) that are characterized by probability distributions functions (PDFs). The computer selects a value for each exposure variable from a specified PDF (log-normal for breathing rate and triangular for exposure frequency) and calculates the corresponding risk. This process is repeated many times (30000), each time saving the set of input values and corresponding estimate of risk. The results from each simulation are displayed in a graph, in the form of a probability density function or the corresponding cumulative distribution function.

The cancer risk induced by external radiation was estimated using the external radionuclide slope factor for each one of the radionuclides contributing to the external gamma radiation exposure. The following equation was used to assess the resulting risk,

$$R_{ext} = \sum_{i=1}^{n} \times (C_{soil,i} \times T_e \times SF_{ext,i} \times E_f \times S_f). \tag{4}$$

The input parameters are the soil concentration for each radionuclide, $C_{soil,i}$ (Bq/kg), the gamma exposure time factor, T_e (8h/24h), the external radionuclide slope factor, $SF_{ext,i}$ (Risk/year)/(Bq/kg) [9], the external exposure frequency, E_f (1920 h/365 d) and the outdoor gamma shielding factor, S_f (1) [9].

4 Results and Discussion

For the hypothetical exposure scenario, the effective dose for one year of radon internal exposure at 557 Bq/m^3 is 3.85 mSv while for external exposure the estimated total gamma radiation emitters dose is 4.5 mSv/year. The value for total effective dose from internal and external exposure is 8.35 mSv/year.

Table 2. Risk assessment summary results

Risk	Average$\pm\sigma$	Median	95th percentile
Annual Rn inhalation	$6.00 \times 10^{-5} \pm 6.24 \times 10^{-11}$	5.95×10^{-5}	7.38×10^{-5}
Gamma radiation	4.33×10^{-5}	-	-
Total	$1.03 \times 10^{-4} \pm 6.24 \times 10^{-11}$	1.03×10^{-4}	1.17×10^{-4}
During rehabilitation	$3.52 \times 10^{-4} \pm 3.16 \times 10^{-32}$	3.52×10^{-4}	3.52×10^{-4}
Incremental lifetime risk	$0.0072 \pm 3.06 \times 10^{-7}$	0.0072	0.0082

A summary of the risk assessment values for the hypothetical scenario created is presented in Table 2. For analyzing the results, the mean and median values, as well as the 95th percentile, were extracted and presented. The estimative includes: i) the resulting annual risk; ii) the risk incurred by the exposure during the period of time necessary to complete the rehabilitation works which was considered to be 3 years and iii) the incremental lifetime cancer risk.

The total annual risk incurred by external exposure and by radon inhalation is log-normally distributed with a mean, standard deviation, median and 95th percentile as presented in Table 2, being σ the standard deviation.

For dose assessment, external exposure to gamma radiation was found to be the most significant exposure pathway, although radon inhalation contributes up to 46% to the annual effective dose. However, the higher risk in this exposure scenario is associated with radon inhalation contributing up to 52% to the total risk. As mentioned before, deterministic dose assessment may overestimate dose values as it uses single input values, which are often chosen as the maximum over the range of possible values, and consequently higher uncertainty. Risk assessment probabilistic approach generates values with lower uncertainty as it uses parameters distributions, instead of single input values. According to radon concentration measured in this site and dose measurements only for external exposure, radon inhalation was effectively the most concern for radiological exposure. In the present study only the breathing rate probability distribution was used in the risk calculation, while the other input parameters were considered as constants. It was our intention to demonstrate that the highest contribution to the dose, the external gamma irradiation, does not correspond to the highest probabilistic risk originated by radon inhalation and that an assessment based only on doses deterministic estimative may imply a non-realistic situation. Probabilistic risk calculations should also be taken into consideration when assessing human health exposure. Further work is being developed for using probabilistic distributions for all uncertain or variable input parameters.

5 Conclusions

The present study is based on a standard occupational exposure scenario for workers involved in the remediation activities in a low level radioactive waste disposal. A deterministic approach is used to perform a dose assessment. The results predict that external exposure is the highest concerning pathway. A single point estimative for the dose is obtained and is useful to compare with the legal limit values. However, the probabilistic risk estimative showed that internal exposure poses, in fact, the highest risk to the exposed workers, and this fact should be considered. In this context, the workers involved in the remediation of the "Old Dam" could have been subject to radiation exposure (through internal and external pathways) and, for the exposure scenario created, the assessed values involve a hypothetical meaningful risk. The results for incremental cancer risk during the mean lifetime (0.0072) can be expressed as a probability of seven chances in 1000 for a specific worker experiencing a cancer fatality as a result of this particular exposure. This value is added to the background risk. In addition, dust inhalation containing radionuclides was not considered and this fact may contribute significantly to a higher inhalation dose and consequently increase the risk.

Further remediation works are planned to take place from 2010 to 2013 for other uranium tailings contaminated sites. It is clear that in the previous remediation activities workers were radiologically exposed. This preliminary study shows that many safety measures must be accomplished in future works, either by implementing individual protection equipment (internal and external exposure) or by periodical monitoring and control, in order to assess the experienced working exposure.

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