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Modeling Radionuclides Dispersion and Deposition Downwind of a Coal-Fired Power Plant

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Abstract

In this study the inhalation doses and respective risk are calculated for the population living within a 20 km radius of a coal-fired power plant. The dispersion and deposition of natural radionuclides were simulated by a Gaussian dispersion model estimating the ground level activity concentration. The annual effective dose and total risk were 0.03205 mSv/y and 1.25 x 10^{-8}, respectively. The effective dose is lower than the limit established by the ICRP and the risk is lower than the limit proposed by the U.S. EPA, which means that the considered exposure does not pose any risk for the public health.

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Keywords: Coal-fired power plants; simulation models; atmospheric dispersion; deposition; inhalation dose and risk

1. Introduction

Coal contains trace quantities of the naturally occurring radionuclides like uranium, thorium and potassium 40. When coal is burned, minerals, including most of the radionuclides as well as their radioactive decay products, do not burn and concentrate in the ash. Fly and bottom ashes make up the majority of the coal combustion by-products (74% and 20%, respectively) and although they have the same origin they are physical and chemically different. Fly ash is the finest portion of coal ash particles while bottom ash consists of larger (and therefore heavier) particles collected at the bottom of the furnace. A smaller fraction is attributed to boiler slag (6%).

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Depending on the emission control system of the stacks, most of the fly ash is recovered by collection devices. However, a small proportion is discharged into the atmosphere and later deposited on the soil. Therefore, fly ashes are released by continuous emissions containing radionuclides that are concentrated a few times in comparison with their content in coal or surface soil, causing exposure to the population living in the vicinity of coal power plants.

The population living in the vicinity of a coal-fired power plant is exposed to natural radionuclides through pathways that create both internal and external exposure (ingestion and inhalation). Doses by ingestion are mainly due to ^{40}K, the ^{238}U and to ^{232}Th radionuclides series present in drinking water and foods. Doses by inhalation result from the presence in air of fly ash particles containing mainly radionuclides of the ^{238}U and ^{232}Th decay chains[1-3].

In recent years, many studies on the impact of environmental radioactivity from coal-fired power plant have been carried out in several countries[4] but no data is available for Portuguese coal-fired power plants. In this study, the inhalation doses and respective risk are calculated for the population living up to a distance of 20 km from a Portuguese coal-fired power plant by using the average of measured specific isotopes ^{40}K, ^{226}Ra and ^{238}U in fly ashes and in the environment. The annual effective dose (mSv/y) resulting from the inhalation of these radionuclides is also assessed and compared with the legal limit for the public.

2. Methods and materials

2.1 Study area

A coal-fired power plant located in the southwest coastline of Portugal was selected for this study. The coal plant is located near the city of Sines (6 km to SE) and it is part of an extensive industrial area (heavy and light industry). The region is characterized by Mediterranean climate with influence from the Atlantic Ocean. The wind velocity is relatively constant during all year with a range of 5-6 m/s and the prevailing wind direction is from N-NW to S-SE[5]. This coal-fired power plant has been operational since 1981et al, 2007. It has two operational stacks and is fueled by bituminous coal. In what concerns to particulate matter (PM_{10}), the atmospheric discharges from this coal plant have been decreased over the last few years: 1740 tons (2001); 812 tons (2004); 587 tons (2007); 394 tons (2008); 99.7 tons (2009); 100 tons (2010) and 286 tons (2011)[6].

2.2 Natural radionuclides content in fly ash

The literature related to the activity concentrations of the considered radionuclides (^{40}K, ^{226}Ra and ^{232}Th) in fly ash samples originated from different coal sources presents a wide range of concentration activities. In those studies the concentrations of ^{40}K, ^{226}Ra and ^{232}Th have been measured with high-resolution gamma spectrometry: 148-204 Bq/kg for ^{40}K, 151-248 Bq/kg for ^{226}Ra and 125-204 Bq/kg for ^{232}Th in South Africa samples; 175-489 Bq/kg for ^{40}K, 94-142 Bq/kg for ^{226}Ra and 175-489 for ^{232}Th in Colombia samples.

The selected coal-fired power plant burns coal imported from many different countries (Australia, Colombia, Poland, South Africa, USA, etc.). The radionuclides content of fly ash discharged through the stacks of the coal plant were measured with a Canberra high purity coaxial detector (HPGe) gamma spectrometer. The Canberra software Genie 2000 and ISOCS (In Situ Object Counting Systems) were used to identify and quantify the radionuclides detected in the fly ash: 901.44 Bq/kg for ^{40}K, 53.97 Bq/kg for ^{226}Ra and 40.13 Bq/kg for ^{232}Th.

2.3 Atmospheric transport

In order to estimate the average atmospheric transport, dispersion and deposition of the discharged radionuclides from the coal plant stacks, a Gaussian plume dispersion model is used in the calculations. Pasquill atmospheric stability classes A (extremely unstable) and C (slightly stable) with site-specific average meteorological conditions, were used in the modified dispersion model. The annual radioactivity release rates available for the dispersion are calculated from the ash emission rate from the stacks and the measured radionuclides activity in fly ash. The stacks height is 225 m, the inside stacks diameter is 7 m and the flow rate of each one is 115 kg/h. The radionuclides concentration dispersion is calculated from the stacks location, at the mixing height, up to a distance of 20 km in each wind direction.

Ground level radionuclides concentrations along each direction are evaluated taking into account the respective average wind velocity and the frequency of the occurrence.

2.4 Dose and risk assessment

The critical group for which individual doses are to be assessed is representative of the members of the population living in the vicinity of the coal fired power plant up to a distance of 20 km from the stacks, considering the impact from exposure to the airborne effluents of the coal plant through the submersion in the contaminated plume and resuspension of the deposited activity. In particular, the members of the population are considered to be constituted of self-sustaining farmers. The annual doses are derived from the inhalation exposure pathway which is considered to be the most significant exposure pathway in the scenario adopted.

The individual inhalation dose through submersion in the contaminated plume (Eq. 1) is derived from the average concentration of the radionuclides in the plume at ground level ($C_{air,i}$) and the individual inhalation dose from the resuspension (Eq. 2) is calculated from the radionuclides concentration in soil ($C_{soil,i}$), combined with a soil resuspension factor[7] (R_f), ranging from 10^{-5} to 10^{-10} m^{-1} with typical values[8] being on the order of 10^{-8} m^{-1}, and the depth of active soil surface layer[1,7] (D_{as}). The individual inhalation doses are calculated by the following equations:

$$D_{sub,inh,i} = C_{air,i}.F_{dinh}.E_f.B_r \quad (1)$$

$$D_{res,inh,i} = C_{soil,i}.\rho_s.R_f.D_{as}.F_{dinh}.E_f.B_r \quad (2)$$

where $D_{sub,inh,i}$ (Bq/y) is the inhalation dose resulting from the submersion in the plume; $C_{air,i}$ is the radionuclides concentration in air at ground level, given by the dispersion model outputs (Table 1); F_{dinh} is the inhalable fraction of the aerosol in the plume[1] (assumed to be 1); E_f is the outdoor exposure frequency (2922 h/y resulting from the exposure of 8-h per day during 365.25 days per year); B_r is the inhalation rate (0.8 m^3/h)[9]; $D_{res,inh,i}$ (Bq/y) is the inhalation dose resulting from the radionuclides ressuspended from the soil; $C_{soil,i}$ is the radionuclides concentration in soil measured by gamma spectrometry in Bq/kg (Table 1), converted to Bq/m^3 assuming an average soil density (ρ_s) of 1600 kg/m^3; R_f (m^{-1}) is the soil resuspension factor (10^{-8} m^{-1})[8]; D_{as} is the depth of active soil layer (assumed to be 0.3 m)[1,7] and the subscript *i* corresponds to each one of the radionuclide considered. The annual effective dose (Sv/y) is estimated by including in the previous equations the inhalation dose factor, $DC_{inh,i}$ (Sv/Bq) from the International Commission on Radiological Protection (1995)[10]. The total inhalation doses are obtained by summation over the radionuclides considered in this study: ^{40}K, ^{226}Ra and ^{232}Th.

Based on inhalation doses calculations (Bq/y), the health effects are estimated by using the carcinogenetic slope factor[11]. The cancer slope factor represents the slope of the dose-response curve, at very low concentrations, thus quantifying the cancer inducing potential; the unit is the inverse of a dose. The product of the cancer slope factor by the dose received estimates the risk for a member of the critical group due to a specific exposure scenario[12,13]. Therefore, the annual risk (Table 1) incurred to a receptor by internal exposure due to the inhalation through submersion in the plume and soil resuspension, R_{inh}, is estimated combining the total inhalation dose (Bq/y) with the inhalation carcinogenetic slope factors ($SF_{inh,i}$) of ^{40}K, ^{226}Ra and ^{232}Th (7.46 x 10^{-12}; 2.75 x 10^{-9} and 1.93 x 10^{-8} Risk/Bq, respectively)[11,13] in Eq. 3:

$$R_{inh} = \sum_{i=1}^{n} \left(D_{inh,i}.SF_{inh,i}\right) \quad (3)$$

3. Results and discussion

Meteorological data from the years of 1986 and 2012 obtained from the coal plant's meteorological station were used in the dispersion model and different Pasquill stability classes (A and C) were considered as well. In the following figures are presented two outputs of the dispersion plume model simulated for ^{226}Ra with meteorological data from 1986 (a) and 2012 (b) and Pasquill stability class C (Fig. 1).

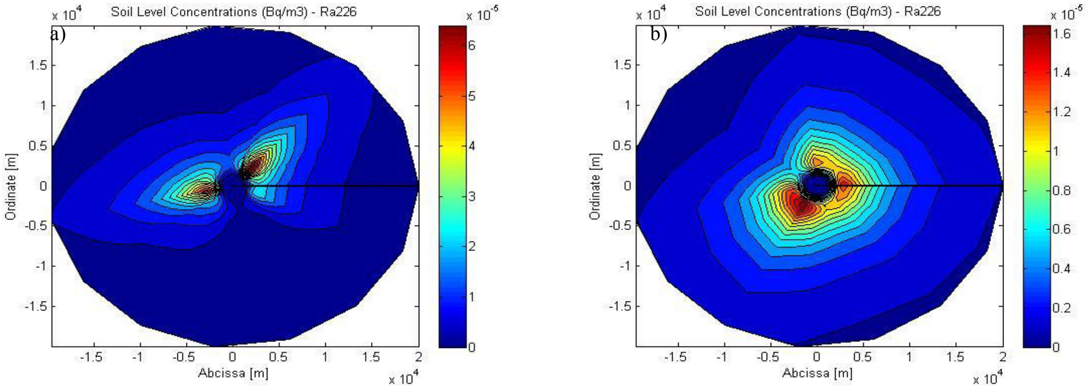

Fig. 1. ^{226}Ra dispersion with the distance to the stacks, Pasquill stability class C, (a) meteorological data of 1986; (b) meteorological data of 2012.

Ground-level concentration of ^{226}Ra was significantly higher in 1986 than in 2012 for the simulation with the same stability class. The dispersion occurred predominantly in the NE and SW wind directions in 1986, while in 2012 the dispersion occurred more or less in all wind directions except to NW. However, for both situations the dispersion reached a distance of 20 km from the stacks. A comparison between the average results from years 1986 and 2012 obtained with stability classes A (extremely unstable) and C (slightly stable) is presented in Table 1.

Table 1. Radionuclides concentration in air and in soil, individual inhalation doses, total risk and effective doses.

Pasquill stability class (A) – meteorological data from 1986							
Nuclide	C_{air} (Bq/m^3)	C_{soil} (Bq/kg)	$D_{inh,sub,i}$ (Bq/y)	$D_{inh,res,i}$ (Bq/y)	R_{inh} (Risk/y)	D_{sub} (mSv/y)	D_{res} (mSv/y)
^{40}K	2.11×10^{-3}	361.8	1.05×10^{-1}	4.06	8.40×10^{-10}	2.19×10^{-10}	8.53×10^{-9}
^{226}Ra	7.23×10^{-5}	20.44	6.26×10^{-3}	2.29×10^{-1}	5.11×10^{-10}	2.19×10^{-8}	8.03×10^{-7}
^{232}Th	5.38×10^{-5}	23.59	4.65×10^{-3}	2.65×10^{-1}	2.48×10^{-9}	5.12×10^{-7}	2.91×10^{-5}
Pasquill stability class (A) – meteorological data from 2012							
^{40}K	6.01×10^{-4}	361.8	5.20×10^{-2}	4.06	8.29×10^{-10}	1.09×10^{-10}	8.53×10^{-9}
^{226}Ra	2.31×10^{-10}	20.44	3.11×10^{-3}	2.29×10^{-1}	2.77×10^{-10}	1.09×10^{-8}	8.03×10^{-7}
^{232}Th	1.21×10^{-9}	23.59	2.31×10^{-3}	2.65×10^{-1}	1.26×10^{-9}	2.54×10^{-7}	2.91×10^{-5}
Pasquill stability class (C) – meteorological data from 1986							
^{40}K	4.81×10^{-3}	361.8	4.16×10^{-1}	4.06	9.02×10^{-10}	8.73×10^{-10}	8.53×10^{-9}
^{226}Ra	2.88×10^{-4}	20.44	2.49×10^{-2}	2.29×10^{-1}	1.90×10^{-9}	8.71×10^{-8}	8.03×10^{-7}
^{232}Th	2.14×10^{-4}	23.59	1.85×10^{-2}	2.65×10^{-1}	9.71×10^{-9}	2.04×10^{-6}	2.91×10^{-5}
Pasquill stability class (C) – meteorological data from 2012							
^{40}K	2.39×10^{-3}	361.8	2.07×10^{-1}	4.06	8.60×10^{-10}	4.34×10^{-10}	8.53×10^{-9}
^{226}Ra	1.43×10^{-4}	20.44	1.24×10^{-2}	2.29×10^{-1}	9.66×10^{-10}	4.33×10^{-8}	8.03×10^{-7}
^{232}Th	1.06×10^{-4}	23.59	9.20×10^{-3}	2.65×10^{-1}	4.85×10^{-9}	1.01×10^{-6}	2.91×10^{-5}

The annual effective dose is similar with meteorological data from different years and different stability classes: 0.03 mSv/y, however, the total risk presents a few variations: 3.83×10^{-9} (stability A, 1986); 2.37×10^{-9} (stability A, 2012); 1.25×10^{-8} (stability C, 1986) and 6.68×10^{-9} (stability C, 2012). Stability class C generates higher values for the effective dose and risk: 0.03205 mSv/y and 1.25×10^{-8}, respectively.

4. Conclusions

In this study dose and risk calculations have been carried out with output data from a Gaussian dispersion model for the population living within 20 km radius of a Portuguese coal-fired power plant. Based on the radionuclides concentration in air given by the dispersion model, the inhalation dose and consequent health effects have been estimated through estimation of the risk. The effective dose was also calculated with the dose coefficients given by ICPR and compared with the legal limit. The results showed that the total dose equivalent rate is approximately 0.03205 mSv/y and the total annual risk is 1.25 x 10^{-8} (the worst case). These values are lower than the recommended by the ICRP for effective dose (1 mSv/y) and EPA's risk value of 10^{-6} for the general public, and it does not pose any risk for public health through the considered exposure pathway. Nevertheless, when considering the presence or ^{226}Ra both in soil and in resuspended materials, ^{222}Rn will be present as well and will contribute to a higher dose with a much more meaningful risk[9,12].

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