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Radioactivity of coal and ashes from Figueira coal power plant in Brazil

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The Figueira coal-fired power plant (CFPP) is among the Brazilian CFPP which presents higher uranium concentration. Gamma-ray spectrometry was used to determine ^{238}U, ^{226}Ra, ^{210}Pb, ^{232}Th and ^{40}K contents in pulverized coal, furnace bottom ash and fly ash samples. The natural radionuclide concentrations in pulverized coal ranged from 813 to 2609 Bq·kg^{-1} for U series and from 22 to 40 Bq·kg^{-1} for ^{232}Th. The fly ash fraction gave concentrations ranging from 1442 to 14641 Bq·kg^{-1}, for uranium series. The same enrichment factor was observed for ^{238}U, ^{226}Ra and ^{232}Th. Only ^{210}Pb and stable Pb presented a high enrichment factor for the last stage filter fly ash. The concentration of the uranium series found in the ashes is close to the limit adopted by the Brazilian guideline (CNEN-NN-4.01).[22] Therefore, it is advisable to evaluate the environmental impact of the installation.

Introduction

All fossil fuels contain low levels of naturally occurring radioactive elements. All types of coal contain around 12–24 Bq·kg^{-1} of ^{238}U and 12–17 Bq·kg^{-1}of ^{232}Th. However, some types of coal contain considerably higher amounts of natural radionuclides. The combustion of this coal in a coal-fired power plant leads to an increase of the natural radionuclides, and non-combustible elements with enrichments factor in the ashes of 5–10 times. According to UNSCEAR[1] the average concentrations of ^{40}K, ^{238}U and ^{232}Th in coal is estimated to be 50, 20 and 20 Bq·kg^{-1}, respectively, based on the analysis of coal samples from 15 countries, with a variation of more than two orders of magnitude. In the combustion process, there is approximately an order of magnitude enhancement of the concentration from coal to ash. Arithmetic averages of the reported concentrations in the escaping fly ash are 265 Bq·kg^{-1} for ^{40}K, 200 Bq·kg^{-1} for ^{238}U, 240 Bq·kg^{-1} for ^{226}Ra, 930 Bq·kg^{-1} for ^{210}Pb and 70 Bq·kg^{-1} for ^{232}Th. The concentrations of the radionuclides in US coals have been well documented by BECK et al.,[2] and EISENBUD and GESELL.[3] Few data has been published so far about the radioactivity of coal and ashes in Brazil. FLUES et al.[4] investigated the content of natural radionuclides in the Brazilian coal from various locations. In this study, higher concentrations were observed for ^{238}U, from 18 to 874 Bq·kg^{-1} and for ^{40}K, from 181 to 584 Bq·kg^{-1}, in the coal of Figueira – Paraná State (PR). These values are above the coal world range for ^{238}U, 10–600 Bq·kg^{-1}, and for ^{40}K, 30–100 Bq·kg^{-1}.[2] ^{232}Th radionuclide, on the other hand, is present in low concentrations (15–32 Bq·kg^{-1}) compared to the world range of 10–200 Bq·kg^{-1}. Coal of Figueira – PR presents concentration for the uranium series (range of 159–1745 Bq·kg^{-1}) at least three times higher than the other coals in Brazil.[4] Coal plays an increasingly important role to cover the energy needs of Brazil.

The coal used in power plants is pulverized and burned inside the boiler, producing bottom-ash (15–20%), which falls inside the boiler, and fly-ash (80–85%) that is suspended in the flue-gas together with vapors of volatile elements. The natural radionuclides are distributed among these fractions. The most important nuclides of the uranium series, ^{238}U, ^{226}Ra and ^{210}Pb and ^{232}Th have different physicochemical properties, resulting in a different behavior and enrichment at the different stages of the combustion process. For example, according to COLES et al.,[5] the enrichment of ^{238}U in the ashes depends upon the chemical and physical characteristics of the input fuel, as well as the conditions inside the furnace, since uranium may exist in the fuel both as uraninite as well as coffinite. Volatile and nonvolatile ^{238}U species may be formed during combustion. Since ^{232}Th and ^{226}Ra are essentially refractory elements they should remain in ash matrix and show slight preference for small fly ash particles. ^{210}Pb which is more volatile leaves the boiler in gaseous form with the flue-gas and condenses as the temperature of the flue-gas drops. The difference in the enrichment of ^{238}U, ^{226}Ra and ^{210}Pb in the ashes results in secular radioactive disequilibrium in the ashes.[5]

The installation of ash collectors like cyclone and bag filters reduced significantly the emission of radionuclides into the atmosphere. In contrast, treatment and disposal of power plant ashes continues to be a serious problem, mainly in Brazil where the coal have a high ash content (20–60%)[6] and the coal combustion residues are stored at the plant sites or on disposal site, only a small part of them have commercial use (30%).[7,8] Consequently, the ash piles increases continuously, and this uncontrolled waste disposal site may lead to radiological environmental contamination.

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The aim of the present study is to determine the radionuclide concentrations in coal and ashes, to evaluate the disequilibrium and the enrichment factor of the radionuclides in all stages of the combustion process.

Experimental

Site

The CFPP which has been considered is the "Usina Termoelétrica de Figueira". This CFPP, with a capacity of 10 MWe, has been operating since 1963 and cyclone and bag filters only in 1998 had been installed. The power plant is located in Figueira County, in the north part of Paraná State, 315 km far from the city of Curitiba. The county, with a population of 9,612 inhabitants and an extension of 115 km^2 has as main activity the extraction and exploitation of coal.

Available data from the Figueira power plant showed that the amount of coal burned in the power plant between 1986 and 1997 (before the installation of filters) was 25,440 $t \cdot year^{-1}$. No data are available concerning the amount of ash generated. However, it is known that the coal from this region has 26% ash content, and also a high quantity of pyrite (7%).[9] So this information indicates a production of 6,614 $t \cdot year^{-1}$ ash. Only a small part of this ash is considered as bottom ash and the remainder is fly ash, with different particles sizes. The ashes in the bag filters are composed of the smallest particles. Recent data showed an increased of coal consumption for the Figueira coal plant of 60,000 $t \cdot year^{-1}$.[6]

Sampling

Samples of pulverized coal, furnace bottom and corresponding captured fly ashes (cyclone and bag filter) were supplied by the CFPP during the year of 2001–2002, every two months, totalizing one year of sampling. In each sampling, 1 kg of bottom ash, fly-ash (cyclone and bag filter) and pulverized coal, which is the raw material for the CFPP, a total of 24 samples were collected. All sampling was performed on the same day. All samples analyzed were ground to 200 mesh, homogenized, air dried and hermetically sealed in a cylindrical polyethylene vessel of 5 cm diameter and 5.5 cm height.

Gamma-ray spectrometry

^{238}U, ^{226}Ra, ^{210}Pb, ^{232}Th and ^{40}K contents were measured by gamma-spectrometry, with a coaxial germanium detector, EGNC 15-190-R, from Eurisys, with a relative efficiency of 15% for the photopeak of ^{60}Co at 1332 keV. The detector was calibrated using standard solutions with radionuclide activities certified by Amersham. The samples were sealed for about four weeks prior to the measurement in order to ensure the equilibrium between ^{226}Ra and its decay products of short half-life. The ^{226}Ra activities were determined by taking the mean activity of three separate photopeaks of its daughter nuclides: ^{214}Pb at 295.2 keV and 351.9 keV, and ^{214}Bi at 609.3 keV. The ^{232}Th content of the samples was determined by measuring the intensities of the 911.07 keV and 968.9 keV gamma-ray peaks from ^{228}Ac, the intensity of the 238.6 keV gamma-ray peaks from ^{212}Pb and the intensity of the 583 keV gamma-ray peak from ^{208}Tl. The ^{40}K content was measured the 1460 keV gamma-ray peak. The concentration of ^{210}Pb was determined by measuring the activity of its low energy peak (46.5 keV) and ^{238}U by measuring the ^{234}Th photopeak at 63.3 keV. Self-absorption correction was applied to the low energy peaks (^{210}Pb and ^{234}Th), since the attenuation for low energy gamma-rays is highly dependent upon sample composition. The self-absorption factor was calculated by the method suggested by CUTSHALL et al.[10]

The total metal content of uranium and lead in pulverized coal, furnace bottom ash and fly ash was determined by a wavelength dispersive X-ray fluorescence (XRF) spectrometer RIX 3000 (Rigaku Co., Osaka, Japan). Around 0.9 g of coal samples were mixed with boric acid (9:1) and ground carefully to 200 mesh. The powder was pressed with a hydraulic press to obtain double-layer pressed pellets.

Results and discussion

The results obtained for the activity concentration of ^{238}U, ^{226}Ra, ^{210}Pb, ^{232}Th and ^{40}K in the pulverized coal, furnace bottom ash and fly ash are listed in Table 1. The range obtained for the pulverized coal samples showed higher concentrations for the natural uranium series (from 813 to 2609 $Bq \cdot kg^{-1}$) and for ^{40}K (from 200 to 450 $Bq \cdot kg^{-1}$), much higher than the world range mentioned by UNSCEAR.[1] The radioactive concentration measured in coal and ashes showed a variability of 25% in the samples during one year. Radioactive data, obtained by KARANGELOS et al.[11] in coal and ashes of a power plant in Greece, showed also high level of radioactivity in coal and ashes for uranium series. The uranium series concentration in coal reached values up to 361 $Bq \cdot kg^{-1}$, 19 $Bq \cdot kg^{-1}$ for ^{232}Th and 173 $Bq \cdot kg^{-1}$ for ^{40}K. The concentration of fly ashes for the uranium series exceeded 1 $kBq \cdot kg^{-1}$ in some cases.

Table 1. Average and range concentration of ^{238}U, ^{226}Ra, ^{210}Pb, ^{232}Th and ^{40}K in coal, bottom ash, fly-ash of Figueira (PR-Brazil) and ash average

	Coal pulverized, Bq·kg^{-1}	Bottom ash furnace, Bq·kg^{-1}	Fly-ash cyclone filter, Bq·kg^{-1}	Fly-ash bag filter, Bq·kg^{-1}	Ash average, Bq·kg^{-1}
^{238}U					
Average±sd	1078 ± 195	1945 ± 290	1858 ± 326	3097 ± 919	2300
Range	882–1325	1635–2352	1459–2988	1995–5198	
^{226}Ra					
Average±sd	1001 ± 200	2411 ± 851	1909 ± 441	3024 ± 924	2448
Range	813–1251	1387–3621	1442–2718	1875–3773	
^{210}Pb					
Average±sd	2176 ± 287	2644 ± 724	4665 ± 1060	10379 ± 3556	5896
Range	1859–2609	1649–3463	3292–6154	6353–14641	
^{232}Th					
Average±sd	30 ± 8	62 ± 20	58 ± 12	73 ± 12	64
Range	22–40	45–92	43–95	65–124	
^{40}K					
Average±sd	310 ± 104	486 ± 42	650 ± 181	621 ± 33	
Range	200–450	422–525	471–1144	577–968	
U-FRX					
Average±sd	1016 ± 230	2298 ± 327	2531 ± 490	3840 ± 1095	
Range	883–1318	1952–3271	1828–3432	2388–4900	
Stable Pb, mg·kg^{-1}					
Average±sd	80 ± 20	81 ± 11	173 ± 31	409 ± 161	
Range	51–107	66–92	95–217	258–627	

sd: Standard deviation.

High concentrations in uranium series observed in the furnace bottom ash and fly-ash showed a similar pattern than in coal. The fly ash of cyclone and bag filter showed concentrations ranging from 1459 to 5198 Bq·kg^{-1} for ^{238}U; from 1442 to 3773 Bq·kg^{-1} for ^{226} Ra; from 3292 to 14641 Bq·kg^{-1} for ^{210}Pb; from 43 to 124 Bq·kg^{-1} for ^{232}Th series and from 471 to 1144 Bq·kg^{-1} for ^{40}K. According to UNSCEAR,[1] in the combustion process, there is approximately one order of magnitude enhancement of the concentration from coal to ash. Arithmetic averages of the reported concentrations in escaping fly-ash are 200 Bq·kg^{-1} for ^{238}U, 240 Bq·kg^{-1} for ^{226}Ra, 930 Bq·kg^{-1} for ^{210}Pb, 70 Bq·kg^{-1} for ^{232}Th and 265 Bq·kg^{-1} for ^{40}K. These average data are 10 times higher for the uranium series and 2 times higher for ^{40}K when compared to UNSCEAR[1] values. For ^{232}Th series the results are similar.

The uranium and lead determination in coal and fly ash (bag filter) by X-ray fluorescence spectrometry presented average concentrations of 1016±230 Bq·kg^{-1} and 80±20 mg·kg^{-1}, 3840±1095 Bq·kg^{-1} and 409±161 mg·kg^{-1}, respectively. The ^{238}U concentration in the pulverized coal and ashes obtained by gamma-spectrometry was compared with the uranium concentration obtained by XRF for the same samples. The ratio $U_{\gamma spec}/U_{XRF}$ was around 1.2, with good correlation ($r = 0.87$). These values confirm that both techniques are suitable for U determination. The correlation between ^{210}Pb and stable Pb gave interesting information. The correlation between ^{210}Pb and stable Pb in coal presented a very poor correlation ($r = 0.12$), suggesting that ^{210}Pb and stable Pb occurrence in coal have different origin from minerals. The correlation between Pb in bottom ashes and cyclone filter increased from 0.3 to 0.5, respectively. On the other hand, the correlation between ^{210}Pb and stable Pb in the bag filter ashes showed very high correlation ($r = 0.90$) suggesting a similar behavior. According to COLES at al.[5] some of the more volatile trace elements are preferentially recondensed on smaller particles. Lead-210 appears to be the most volatile radionuclide. It is quite depleted in bottom ash probably because volatilization and later condensation onto fly-ash matrix occurs, as the temperature of the flue-gas drops. Since heterogeneous condensation is a surface area phenomenon, the lead should be enriched on the finer fly-ash particles. The same behavior is expected for stable lead what is confirmed by the good correlation between lead in the bag filter ashes and the finest fly-ash particles.

Enrichment factor

Box plot was used to evaluate the distribution of the experimental results of the coal and ash samples (Fig. 1), which allows determining the mean, the median and the

dispersion of the results. It can be seen that all radionuclide concentration increases from the coal to ash. The highest concentrations were observed by the bag filter ash.

Considering the concentration of all elements in the six samplings, the ratios of coal/bottom ash, coal/cyclone ash and coal/ bag ash were determined. The same enrichment factor was observed for the uranium series (^{238}U and ^{226}Ra) and for the ^{232}Th, with ratios around 2, 2, 3, respectively. Only ^{210}Pb and stable Pb presented no enrichment factor in the first stage coal/bottom ash (ratio ~1) and a very high enrichment factor for the last stage coal/bag filter fly-ash (ratio ~5). These results agree with the enrichment patterns observed in the literature.[1,5,11,12]

According to COLES at al.,[5] the behavior of uranium during the combustion process is determined by the conditions of the furnace as well as the chemical and physical form of the coal input. Coal-fired power plants operate their furnaces with about 10% stoichiometric excess of oxygen**.** This should result in an oxidizing combustion environment with a temperature range of 1500–1600 °C. Under these conditions the volatile species UO_3 should be formed. Uranium might be incorporated into a silica melt during combustion if it were originally associated with a silicate (i.e., coffinite ($U(SiO_4)_{1-x}$–$(OH)_{4x}$)). If sufficient silica is present in the solution, mineral coffinite can be formed instead of uraninite (UO_2). A bimodal existence of uranium in the coal can, therefore, give rise simultaneously to both a volatile and nonvolatile species, since both uraninite and coffinite can coexist in the pulverized and semi homogenized coal.

In the combustion of coal, most part of the alumino-silicate minerals (mostly clay) form a melt and drop out as slag. Most part of Th and Ra isotopes follow this slag. ^{210} Pb remains volatile and passes along with the gases and fly-ash to the emission control system. Much of the U that is associated with the clays, or was mineralized as coffinite, also remains with the bottom ash. On the other hand the U that is dispersed in the coal as uraninite becomes volatile as UO_3 species and goes along with the gases, ^{210}Pb, and the fly ash. Fly ash is rich in ^{210}Pb, moderate in U and poor in Ra isotopes.

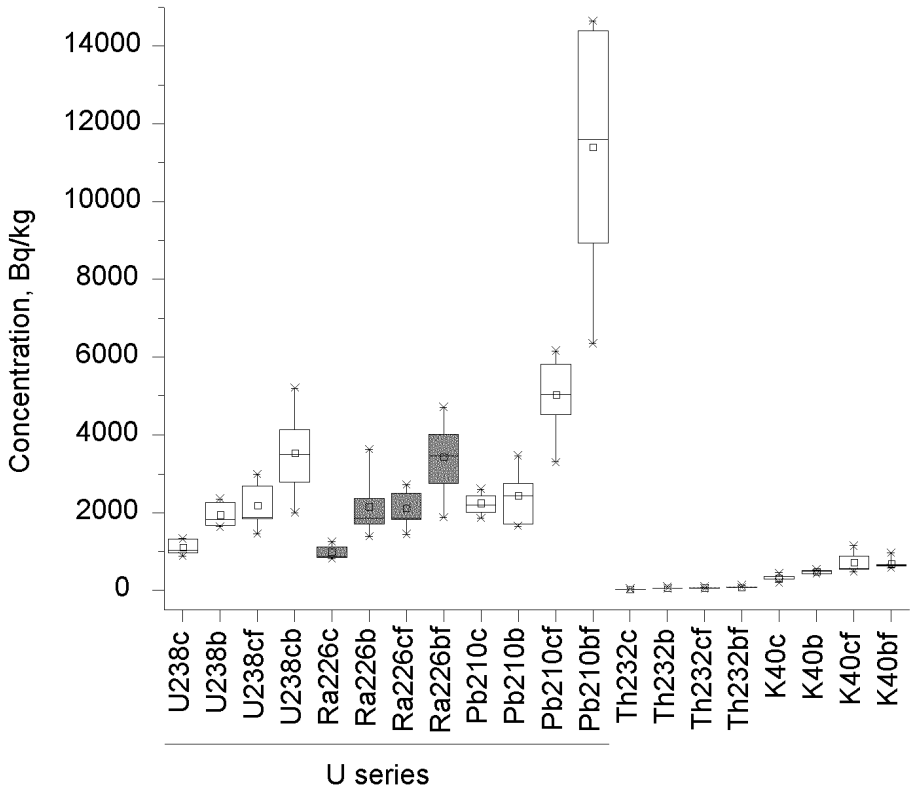

Fig. 1. Concentration of the natural radionuclides (^{238}U, ^{226}Ra, ^{210}Pb, ^{232}Th and ^{40}K) in coal (c), bottom ash (b), cyclone filter ash (cf) and bag filter ash (bf)

According to BECK[12] the maximum enrichment occurs on the smallest fly-ash particles, apparently due to volatilized compounds recondensing onto particle surfaces. Since smallest particles have the largest surface to volume ratio, they exhibit the highest enrichment. The radionuclides ^{238}U, ^{226}Ra and ^{210}Pb are radionuclides from the same decay series, therefore, their concentration should follow the same pattern. However, since ^{210}Pb is formed by direct decay from radon, it can be adsorbed more easily by dust particles and ^{210}Pb is considered more volatile than ^{238}U and ^{226}Ra. This behavior explains why ^{210}Pb presents higher activities in the fine grain ash particles. The maximum enrichment has been found in particles with diameters of about 1 μm. ^{210}Pb and ^{210}Po exhibit the greatest enrichment, as much as a factor of 5, while maximum enrichment for uranium isotopes is about a factor of 2, and for radium a factor of around 1.5. Thorium isotopes are not enriched in fly-ash. The differences in enrichment for radium and uranium isotopes appear to be related to the fact that uranium and radium probably exist in various chemical forms in coal, each with different volatilities. The enrichment does not appear to increase as particles sizes become smaller than 1 μm, suggesting that processes other than just condensation are also taking place.[13–15]

COLES et al.[5] also observed that ^{210}Pb appears to be the most volatile radionuclide and it is depleted in the bottom ash. The ^{210}Pb depletion in bottom ash probably occurs as volatilization and later condensation onto the fly-ash matrix. Since heterogeneous condensation is a surface area phenomenon, the lead should be enriched on the finer fly-ash particles. The ^{210}Pb depletion in bottom ash is observed by many authors.[5,12,16,17]

Secular equilibrium

There is a significant disturbance of radioactive equilibrium within the uranium series due to the different enrichment factors for ^{238}U, ^{226}Ra and ^{210}Pb in the fly-ash samples.

To evaluate the secular equilibrium in coal and ashes of the Figueira of power plant, a column graphic was plotted (Fig. 2). The ratios ^{238}U/^{226}Ra and ^{210}Pb/^{226}Ra, for uranium series in pulverized coal and ashes was calculated considering the average data of Table 1. The average ratios for ^{238}U/^{226}Ra in pulverized coal and ashes were 1.1±0.7 and 1.0±0.2, respectively. These values suggest an approximate equilibrium between the parents and the Ra isotopes in the uranium series, in the coal samples. If the results of the ratios ^{210}Pb/^{226}Ra average values of 2.3±0.2 in pulverized coal and (1.3±0.5 in bottom ash; 2.4±0.2 in cyclone filter fly-ash and 3.3±0.2 in bag filter fly-ash) are taken into account, it is seen that the secular equilibrium in the decay series is disturbed, probably due to ^{222}Rn that migrates into or out of the coal seam, the half-life of ^{222}Rn is short ($T_{1/2}$ = 3.8 d) and decays to ^{210}Pb. These appear to represent on atypical situation for the pulverized coal samples. Similar behavior was also described in some papers for coal.[18–20] The major studies[11,12,17] with ashes, even the results of his work showed that the secular equilibrium in the decay series of uranium is disturbed.

TADMOR[14] and HEDVALL and ERLANDSSON[21] observed variations in radionuclide enrichment in different fractions of ash. These variations may reflect the difference in composition and origin of the coal, the use of different firing systems and furnace temperature.

Disposal pattern

By taking into account the ash average concentration of ^{238}U, ^{226}Ra, ^{210}Pb and ^{232}Th (Table 1), the total ash produced by the Figueira coal power plants (PR-Brazil) is 10,700 Bq·kg^{-1}. This value showed a good agreement with the estimated value of 8,776 Bq·kg^{-1} published recently by FLUES et al.[4] The Brazilian regulatory agency published recently a Guideline concerned with the radiological protection of activities which may lead to enhanced concentrations of radionuclides, such as coal burning (CNEN-NN-4.01).[22] The Figueira power plant presents 10,700 Bq·kg^{-1} ash activity concentration which classifies the installation in Category III of the Guideline. To comply with the regulation, this installation should perform a more detailed study of the environmental impact.

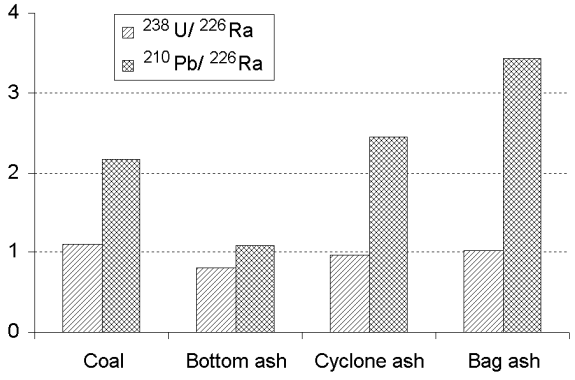

Fig. 2. ^{238}U/^{226}Ra and ^{210}Pb/^{226}Ra ratios for uranium series in pulverized coal and ashes

Conclusions

Coal of Figueira power plant (PR-Brazil) presents high uranium concentration when compared with other coals in Brazil. The radioactive evaluation of the pulverized coal and ashes of the Figueira plant showed concentrations above the world average for the uranium series, mainly for ^{210}Pb. The same enrichment factors were observed for ^{238}U, ^{226}Ra and ^{232}Th. Stable Pb and ^{210}Pb presented no enrichment factor in the first stage coal/bottom ash and a very high enrichment factor for the last stage coal/bag filter fly-ash.

Due to the various enrichment factors for ^{238}U, ^{226}Ra and ^{210}Pb in the fly-ash samples collected along the emission control system, there is a significant disturbance of radioactive equilibrium within the uranium series.

According to the Brazilian Guideline CNEN-NN-4.01,[22] the Figueira power plant is classified in Category III due to the levels of radioactivity present in the ashes (10,700 Bq·kg^{-1}). To comply with the statements of the Guideline, the installation should evaluate its environmental impact. The power plant currently operates at 10 MWe and plans to increase its energy production capacity to 140 MWe in the years to come.

Another point to be considered is the application of the waste ashes for commercial use, like bricks, road pavement, agriculture, etc. In this case, careful consideration should be given to relevant dosimetric calculations for this application.

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References

1. UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation, Sources, Effects and Risks of Ionizing Radiation, United Nation, New York, 1988.
2. H. L. BECK, C. V. GOGOLAK, K. M. MILLER, W. M. LOWDER, in: T. F. GESELL, W. M. LOWDER (Eds), The Natural Radiation Environment III, Vol. 2, U.S. Department of Energy, Washington, D.C.,CONF-89-42, 1980, p. 1521.
3. M. EISENBUD, T. GESELL, Environmental Radioactivity from Natural, Industrial and Military Sources, 4th ed., Academic Press, San Diego, CA, 1997, p. 175.
4. M. FLUES, I. M. C. CAMARGO, P. M. FIGUEIREDO, P. S. C. SILVA, B. P. MAZZILLI, International Nuclear Atlantic Conference – INAC 2005 Santos, SP, Brazil, August 28 to September 2, 2005.
5. D. G. COLES, R. C. REGAINI, J. M. ONDOV, Environ. Sci. Technol., 12 (1978) 442.
6. DNPM-Sumário Mineral, Ministério de Minas e Energia, Departamento Nacional de Produção Mineral (DNPM) V.14, 1999 (ISSN 0101 2053) 1999.
7. I. D. FERNANDES, L. S. FERRET, C. A. KHAHL, J. C. T. ENDRES, Intern. Ash Utilization Symp., Lexington, Kentucky, USA, 1999.
8. L. S. FERRET, I. D. FERNANDES, C. A. KHAHL, J. C. T. ENDRES, A. MAEGAWA, Intern. Ash Utilization Symp., Lexington, Kentucky, USA, 1999.
9. M. FLUES, V. MORAES, B. P. MAZZILLI, J. Environ. Radioact., 63 (2002) 285.
10. N. CUTSHALL, I. LARSEN, C. OLSEN, Nuclear Instr. Meth., 206 (1983) 309.
11. D. J. KARANGELOS, N. P. PETROPOULOS, M. J. ANAGNOSTAKIS, E. P. HINIS, S. E. SIMOPOULOS, J. Environ. Radioact., 77 (2004) 233.
12. H. L. BECK, Radiat. Phys. Chem., 34 (1989) 285.
13. R. D. SMITH, J. A. CAMPBELL, K. K. NIELSON, Environ. Sci. Technol., 13 (1979) 553.
14. J. TADMOR, J. Environ. Radioact., 4 (1986) 177.
15. UNSCEAR, United Scientific Committee on the Effects of Atomic Radiation, Ionizing Radiation: Sources and Biological Effects, United Nations, New York, 1982.
16. W. S. SEAMES, U. J. O. L. WENDT, Adv. Environ. Res., 4 (2000) 45.
17. R. A. ZIELINSKI, J. R. BUDAHN, Fuel, 77 (1998) 259.
18. C. PAPASTEFANON, S. CHARALAMBOUS, Health Phys., 46 (1984) 293.
19. V. DESANTIS, I. LONGO, Health Phys., 46 (1984) 73.
20. J. W. KAAKINEN, R. M. JORDEN, M. H. LAWASANI, Environ. Sci. Technol., 9 (1975) 862.
21. R. HEDVALL, B. ERLANSSON, J. Environ. Radioact., 32 (1996) 19.
22. CNEN-NN, 4.01 Requisitos de Segurança e Proteção Radiológica para Instalações Mínero-industriais, published in Diário Oficial da União (DOU), 01-2005.