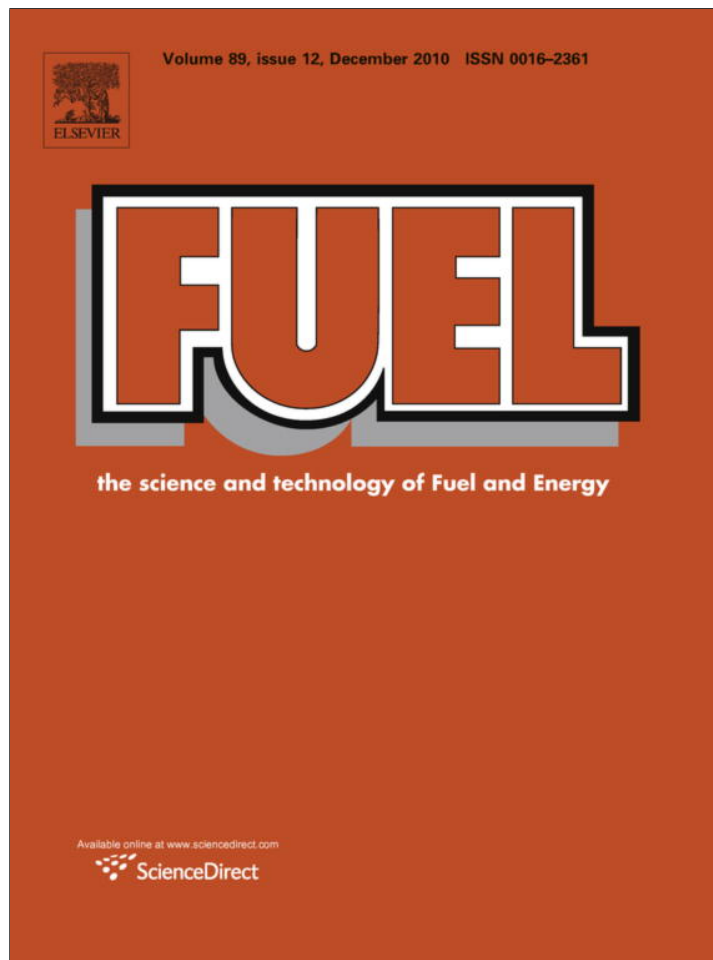


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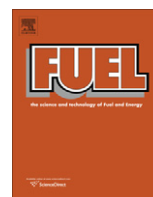


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Radiological characteristics of pulverized fly ashes produced in Turkish coal-burning thermal power plants

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ABSTRACT

The objective of this study is to determine radiological characteristics of pulverized fly ash (PFA) collected from the 15 coal-burning thermal power plants (TPPs) in operation by means of gamma spectrometric technique and to assess the radiological impacts from the utilization of PFA samples examined as filling and cover material in earthwork applications. Also, the annual effective doses received by workers handling PFA and members of the public living in a house near the PFA pile/landfill were estimated using methods specified in the Radiation Protection 122. The activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K measured in PFA samples were tabulated for each TPP. The activity results show that Turkish PFA may have relatively high natural radioactivity content, depending on its origin reaching in the case of Kangal PFA 2720 Bq kg⁻¹ of ²²⁶Ra. The values of external exposure indexes (radium equivalent activity index and gamma index) calculated for PFA samples are within the recommended safety limits. As well, the highest mean total annual effective doses estimated as 7.3 × 10⁻⁵ Sv y⁻¹ for workers and 1.5 × 10⁻⁴ Sv y⁻¹ for members of the public are significantly lower than the annual limit of 1.0 × 10⁻³ Sv y⁻¹.

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1. Introduction

Turkey is greatly dependent on fossil fuel (natural gas, coal, petroleum, fuel oil) to meet the electric power requirement. About 83% of the total electricity in Turkey is generated thermal power plants (66% of the total installed electricity generation capacity) [1]. Coal plays an important role in electric generation in Turkey because it is an essential domestic source. Lignite coal recoverable reserves are estimated to be about 8300 million tons (Mt) while hard coal reserves are about 1330 Mt [2]. Turkish lignite coal has a very low calorific value and high sulphur, dust and ash content. The ash content of the Turkish coal ranges from 16% to 50% [3]. Therefore, majority of the lignite coal is consumed by the electricity sector. Coal (lignite, hard and imported coal) accounted for about 24% (of which 81% is from lignite and 19% is from hard coal and imported coal) of the total installed electricity generation capacity of 42,000 megawatt (MW) in 2008 [1]. Coal-burning thermal power plants (TPPs) consumed 72.6 Mt of pulverized coal in 2008 [1].

Coal contains trace quantities of the naturally occurring primordial radionuclides including uranium–radium (²³⁸U–²²⁶Ra) and thorium (²³²Th) and their decay products and the radioactive isotope of

potassium (⁴⁰K). Earlier work by MTA (General Directorate of Mineral Research and Exploration) indicates that Turkish coals contain on average 12.5 mg kg⁻¹ of ²³⁸U and 6.6 mg kg⁻¹ of ²³²Th [4]. These values are higher than the worldwide mean values of elemental concentration of ²³⁸U (2 mg kg⁻¹) and ²³²Th (4 mg kg⁻¹) measured in worldwide coal [4]. Besides, pulverized fly ash (PFA) which is a combustion residue of pulverized coal blown into a fire furnace at a coal-burning TPP becomes up to 3–5 times more enriched in radionuclides mentioned above than the pulverized coals.

The 15 coal-burning TPPs listed in Table 1 produce a total of over 15 Mt of PFA annually [5]. Depending on the emission control systems the largest fraction of PFA is collected and usually stored in piles, or dumped or deposited on the land in the vicinity of the TPP. The growing production of PFA has long caused on environmental problem with technological and economic effects in the world. Also, the amount of PFAs accumulated at power stations or stored in piles or ponds can contribute to environmental radiological problems through its dispersal into atmosphere and its handling or disposal [6]. PFA contains enhanced concentration of the natural radionuclides ²²⁶Ra, ²³²Th, and their decay products and ⁴⁰K. These radionuclides emit alpha particles, beta particles, and gamma rays. Therefore PFA piles or ponds considered an ionizing radiation source can lead to the exposure of workers and members of the general public to ionizing radiation via three pathways: (i) external exposure of local workers and people living in a house

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Table 1
Parameters of Turkish coal-burning thermal power plants in operation.

Power plant	Location	Unit number	Total power (MW)	Gross generation (GW h)	Coal type	Fuel (ton/y)	Ash (%)
Afşin-Elbistan A	K. Maraş	4	1360	4198	Lignite	10,970,167	36–42
Afşin-Elbistan B	K. Maraş	4	1440	7241	Lignite	–	20–51
Çan	Çanakkale	2	320	2192	Lignite	1800,000	32
Çatalağzı	Zonguldak	2	300	1882	Hard	1658,630	41–48
Çayırhan	Ankara	4	620	3100	Lignite	3696,266	36–42
Çolakoğlu-2	Kocaeli	1	190	950	Hard	–	–
Kangal	Sivas	3	457	1811	Lignite	5194,456	19–24
Kemerköy	Muğla	3	630	3411	Lignite	4563,781	31–36
Orhaneli	Bursa	1	210	1332	Lignite	1413,436	25–31
Seyitömer	Kütahya	4	600	4051	Lignite	5384,720	32–37
Soma (A + B)	Manisa	6	1034	5482	Lignite	8948,501	25–50
Sugözü	Adana	2	1320	6050	Hard (imported)	3300,000	–
Tunçbilek (A + B)	Kütahya	5	429	1607	Lignite	1907,753	16–51
Yatağan	Muğla	3	630	3981	Lignite	5538,297	26–36
Yeniköy	Muğla	2	420	1929	Lignite	3412,505	32–40

near a piles/landfill to gamma radiation emitted from the members of the ^{226}Ra and ^{232}Th series along with ^{40}K ; (ii) internal exposure of the respiratory tract to alpha and beta particles due to inhalation of the radioactive inert gas radon (^{222}Rn , a daughter product of ^{226}Ra) and its short-lived decay products; (iii) internal exposure due to inhalation and/or ingestion of PFA particles.

These problems have led to the implementation of various alternative utilizations, in which PFA is considered as a value-added product. Approximately 33% of the total PFA produced in Europe is used as cement raw materials, as constituent in blended cements and as an addition for the production of concrete [7], while an estimated 1% of the total PFA produced in Turkey is used for cement, concrete and brick production, and earthwork applications (highway backfill, road stabilization, road pavement, embankments, etc.) [8].

From a radiological point of view, it is very important to study in detail the radiological characteristics of PFAs for accurately assessing the radiation exposure of the occupational and members of the public and developing standards and guidelines for the use and management of these materials. By this time a few studies concerning to the radioactivity of Turkish PFA collected some TPPs were published in the literature [8–13]. However the detailed information on the radiometric characterization of PFAs obtained from all coal-burning TPPs in operation in Turkey and the radiological impacts of the utilization of PFAs as filling and cover material in earthwork applications is not available in literature. In the present study, the radiological characteristics of PFA samples collected from the 15 coal-burning TPPs were determined using gamma ray spectrometer connected with HPGe detector. Elemental concentra-

tions of ^{238}U , ^{232}Th and ^{40}K were calculated using the results of the activity concentrations of these radionuclides measured in the PFA samples. Radium equivalent activity (Ra_{eq}) and gamma index (I_1 and I_2) was calculated to assess radiological impacts of the utilization of PFA in earthwork applications (road construction, roadbeds, road pavement, landfill, landscaping, embankments, etc.). In addition, the total annual effective doses, which are the sum of the effective doses of external gamma radiation, inhalation and ingestion received by for workers and members of the public (adults) were estimated using methods given in the Radiation Protection 122 in various exposure scenarios (outdoor storage, transportation and road construction for workers and residence in a house near the PFA pile/landfill for adults) [14].

2. Material and methods

2.1. PFA sampling

A total of 317 PFA samples analyzed in this study were collected from the 15 coal-burning TPPs widely distributed, with the majority in the West region of Turkey as shown in Fig. 1. The samples were dried in a temperature-controlled furnace at 110 °C for 4 h to remove moisture. After moisture removal, these samples were cooled in moisture-free atmosphere. The samples were transferred to containers and weighed. Each container was hermetically sealed to prevent escape of radon gas. Before counting each sample was stored for more than 4 weeks to allow ^{226}Ra and its short-lived decay products to reach the secular equilibrium because of the

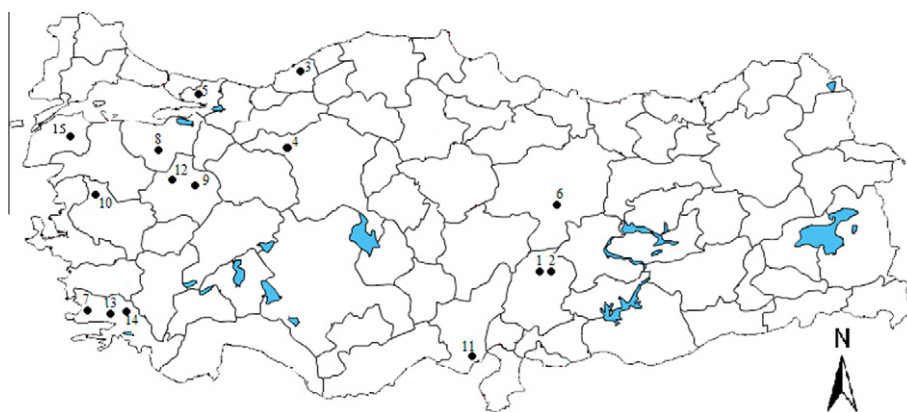


Fig. 1. Locations of the coal-burning TPPs [(1) Afşin-Elbistan A, (2) Afşin-Elbistan B, (3) Çatalağzı, (4) Çayırhan, (5) Çolakoğlu-2, (6) Kangal, (7) Kemerköy, (8) Orhaneli, (9) Seyitömer, (10) Soma, (11) Sugözü, (12) Tunçbilek, (13) Yatağan, (14) Yeniköy, (15) Çan] sampled in the study.

Table 2
The range (maximum and minimum) and mean values of the activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K measured in the PFA samples.

Power plant	N	Activity concentration (Bq kg ⁻¹ ± 1σ)			
		²²⁶ Ra	²³² Th	⁴⁰ K	
Afşin-Elbistan A	16	Range	234.0 ± 11.2–1245.0 ± 54.8	11.0 ± 0.5–127.0 ± 6.9	61.0 ± 5.7–1613.0 ± 155.5
		Mean ± SE*	541.1 ± 73.1	59.3 ± 10.9	280.9 ± 91.5
Afşin-Elbistan B	12	Range	117.0 ± 5.6–431.1 ± 19.0	10.0 ± 0.5–77.0 ± 4.2	65.7 ± 6.2–371.5 ± 35.8
		Mean ± SE	221.3 ± 31.7	47.1 ± 6.4	234.3 ± 31.1
Çan	6	Range	103.4 ± 5.0–248.0 ± 13.1	55.3 ± 3.6–113.0 ± 5.0	84.7 ± 8.6–342.6 ± 12.7
		Mean ± SE	186.0 ± 26.2	87.1 ± 10.4	173.3 ± 39.2
Çatalağzı	19	Range	20.0 ± 0.7–229.0 ± 12.4	50.0 ± 2.0–217.0 ± 7.4	90.0 ± 7.6–2532.3 ± 218.8
		Mean ± SE	117.9 ± 12.4	117.0 ± 9.7	1105.9 ± 137.2
Çayırhan	11	Range	17.0 ± 0.8–476.0 ± 20.0	10.1 ± 0.3–155.5 ± 4.8	17.0 ± 1.3–850.0 ± 55.6
		Mean ± SE	210.9 ± 42.8	66.6 ± 11.3	445.5 ± 67.7
Çolakoğlu-2	15	Range	47.2 ± 1.9–186.0 ± 6.0	10.4 ± 0.3–138.6 ± 4.6	123.0 ± 9.1–815.0 ± 55.7
		Mean ± SE	105.9 ± 10.1	77.6 ± 8.3	321.3 ± 42.6
Kangal	14	Range	156.0 ± 6.9–2720 ± 139.3	16.0 ± 0.8–158.0 ± 7.2	98.0 ± 8.1–1978.0 ± 135.3
		Mean ± SE	1013.9 ± 153.2	42.5 ± 9.3	355.9 ± 127.7
Kemerköy	11	Range	341.0 ± 11.0–1142. ± 43.5	9.0 ± 0.3–141.0 ± 5.1	75.0 ± 6.1–484.0 ± 35.3
		Mean ± SE	569.9 ± 76.6	55.3 ± 12.6	300.4 ± 37.5
Orhaneli	19	Range	87.0 ± 2.5–575.9 ± 15.8	75.0 ± 2.2–212.0 ± 5.6	28.0 ± 2.2–2057.0 ± 148.7
		Mean ± SE	322.9 ± 29.6	119.4 ± 8.3	591.7 ± 93.7
Seyitömer	44	Range	99.0 ± 3.4–493.0 ± 17.1	69.0 ± 2.8–172.0 ± 5.6	23.8 ± 2.0–1387.0 ± 114.2
		Mean ± SE	160.9 ± 10.8	97.2 ± 2.9	611.6 ± 34.5
Soma	30	Range	23.0 ± 0.9–2398.0 ± 94.6	38.0 ± 1.7–279.0 ± 11.8	13.4 ± 1.2–2974.0 ± 259.4
		Mean ± SE	571.2 ± 94.9	113.1 ± 8.7	543.7 ± 106.0
Sugözü	13	Range	70.0 ± 3.1–166.0 ± 6.2	48.0 ± 2.1–204.0 ± 9.6	195.0 ± 10.3–695.0 ± 35.0
		Mean ± SE	103.6 ± 8.3	96.1 ± 11.7	445.5 ± 36.2
Tunçbilek	36	Range	117.0 ± 6.1–790.0 ± 38.3	105.5 ± 4.2–274.0 ± 8.9	25.3 ± 2.3–2349.0 ± 193.4
		Mean ± SE	405.7 ± 30.7	160.8 ± 6.2	505.4 ± 68.5
Yatağan	58	Range	63.0 ± 2.2–992.0 ± 34.6	40.5 ± 1.3–696.0 ± 21.0	12.0 ± 1.0–2062.0 ± 155.9
		Mean ± SE	400.7 ± 19.3	128.5 ± 11.1	600.3 ± 39.7
Yeniköy	13	Range	182.1 ± 6.6–906.2 ± 35.1	9.0 ± 0.4–96.0 ± 3.0	112.0 ± 9.3–1244.0 ± 92.8
		Mean ± SE	433.7 ± 60.5	34.2 ± 6.0	316.5 ± 81.5

* SE: standard error.

equilibrium in the coal being disturbed due to burning process and release of the radon.

2.2. Measurement systems

Two high-resolution gamma ray spectrometers with p-type coaxial HPGe detectors were used to determine the radiological characteristics of the PFA samples. One of the HPGe detectors has

a relative efficiency of 50% and an energy resolution of 1.8 keV at 1332.5 keV of ⁶⁰Co while the other detector has a relative efficiency of 110% and an energy resolution of 2.1 keV. The detectors were shielded to reduce background radiation. The absolute efficiency calibration of the gamma spectrometers were determined using a solid nuclide mixture of gamma reference materials sealed in a standard Marinelli beakers with an active volume of 1000 ml, and average density of 1 g cm⁻³, and IAEA reference materials

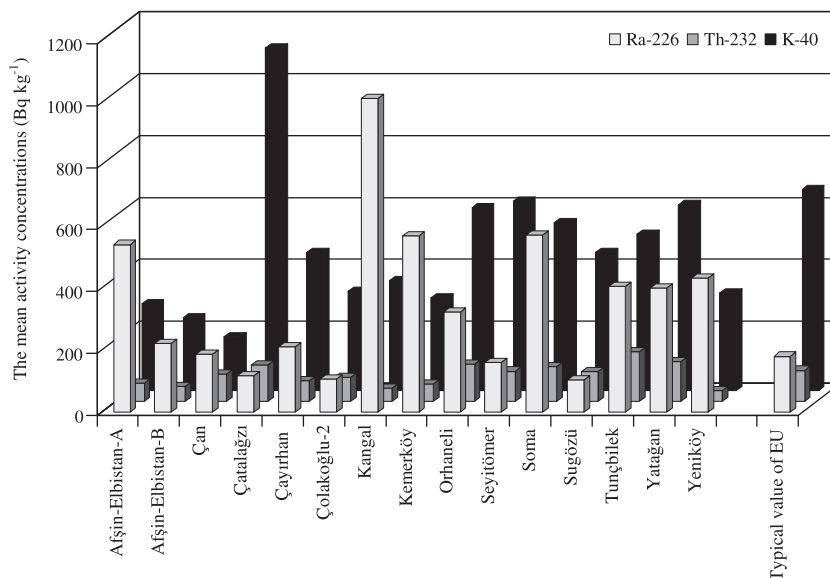


Fig. 2. Comparison of the mean activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K of the Turkish PFA samples with the typical values measured in PFA samples from the European Union.

Table 3
Statistical data for the activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K (Bq kg⁻¹) measured in the Turkish PFA samples.

	²²⁶ Ra	²³² Th	⁴⁰ K
Range	17.0–2720.0	9.0–696.0	12.0–2974.0
Mean	360.3	101.7	517.1
Standard deviation (SD)	317.8	59.5	406.2
Standard error (SE)	17.9	3.3	23.3
Median	287.0	100.0	455.0
Mode	115	110	315
Skewness	3.1	3.4	2.6
Kurtosis	15.7	30.6	10.1
Number of sample	317	317	317
Frequency distribution	Log-normal	Log-normal	Log-normal

RGU-1 (U-ore), RGTh-1 (Th-ore) and RGK-1 (K₂SO₄). Each sample was measured for an accumulating time between 10 and 24 h. Background measurements were taken under the same conditions of sample measurements and subtracted in order to get net counts for the sample.

The activity concentrations were averaged from gamma ray peaks at several energies assuming secular equilibrium in the ²³⁸U and ²³²Th decay series. The gamma-ray peak of the 351.9 keV from ²¹⁴Pb and the 609.3 keV from ²¹⁴Bi were used to determine the activity concentration of ²³⁸U while the gamma-ray with energy of 186 keV was used for ²²⁶Ra. The gamma-ray peak of the 911.2 keV from ²²⁸Ac and the 583.2 keV from ²⁰⁸Tl were used to determine the activity concentration of ²³²Th. The activity concentration of ⁴⁰K was measured directly by its own gamma-ray peak at 1460.8 keV.

3. Results and discussion

3.1. Radiological characteristics of the PFA samples

The activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K measured in the PFA samples together with the statistical uncertainty (1σ) are given in Table 2. As can be observed from Table 2 that the lowest mean activity concentration of ²²⁶Ra, ²³²Th and ⁴⁰K was measured in the PFA samples of collected from Sugözü, Yeniköy and Çan, respectively, while the highest mean activity concentration of ²²⁶Ra, ²³²Th and ⁴⁰K was measured in the PFA samples of collected from Kangal, Tunçbilek and Çatalağzı, respectively. The mean activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K are compared with typical values measured in PFA samples from the European Union (EU) countries, which are 180, 100 and 650 Bq kg⁻¹ for ²²⁶Ra, ²³²Th and ⁴⁰K, respectively [15] in Fig. 2. It can be seen from Fig. 2 that the mean activity concentrations of ²²⁶Ra measured in PFA samples from Çatalağzı, Çolakoğlu-2, Seyitömer and Sugözü TPP are lower than that of the typical value of EU, whereas the mean activity concentrations of ²³²Th measured in PFA samples from Çatalağzı, Orhaneli, Soma, Tunçbilek and Yatağan TPP are higher than that of the typical value of EU. However, the mean activity concentrations of ⁴⁰K measured in PFA samples from all TPPs, except for Çatalağzı, are lower than that of the typical value of EU. Statistical data (range, mean, standard deviation, standard error, median, mode, skewness and kurtosis) for the activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K in Turkish PFA samples is given in Table 3. As can be seen from Table 3 that the values of skewness and kurtosis for these radionuclides are significantly higher than the null value. This situation signifies the non-existence of normal situation for the radionuclides. This is also verifies from log-normal distribution shown in Fig. 3a–c. The activity concentrations of ²²⁶Ra, ²³²Th and ⁴⁰K in the PFA samples ranged from 17.0 to 2720.0 Bq kg⁻¹ with a mean of 360.3 ± 17.9 Bq kg⁻¹, 9.0 to 696.0 Bq kg⁻¹ with a mean of 101.7 ± 3.3 Bq kg⁻¹ and 12.0 to 2974.0 Bq kg⁻¹ with a

mean of 517.1 ± 23.2 Bq kg⁻¹, respectively. The mean values are given with standard error. The mean activity concentration of ²²⁶Ra measured in the Turkish PFA samples is two times higher than that of the typical value of EU, while the mean activity concentration of ²³²Th is slightly higher than that of the typical value of EU. Whereas the mean activity concentration of ⁴⁰K is lower than that of the typical value of EU.

3.2. Elemental concentrations of ²³⁸U, ²³²Th and ⁴⁰K in PFA samples

The activity concentrations of the radionuclides can be converted into the elemental concentrations of U (in ppm), Th (in ppm) and K (in%) using the following formula:

$$E_C = \frac{C_E \cdot A_{M,E} \cdot F}{\lambda_E \cdot N_{Av} \cdot h_E} \quad (1)$$

where E_C is the elemental concentration of element E . C_E , $A_{M,E}$, λ_E , N_{Av} and h_E are the measured activity concentration (Bq kg⁻¹), the

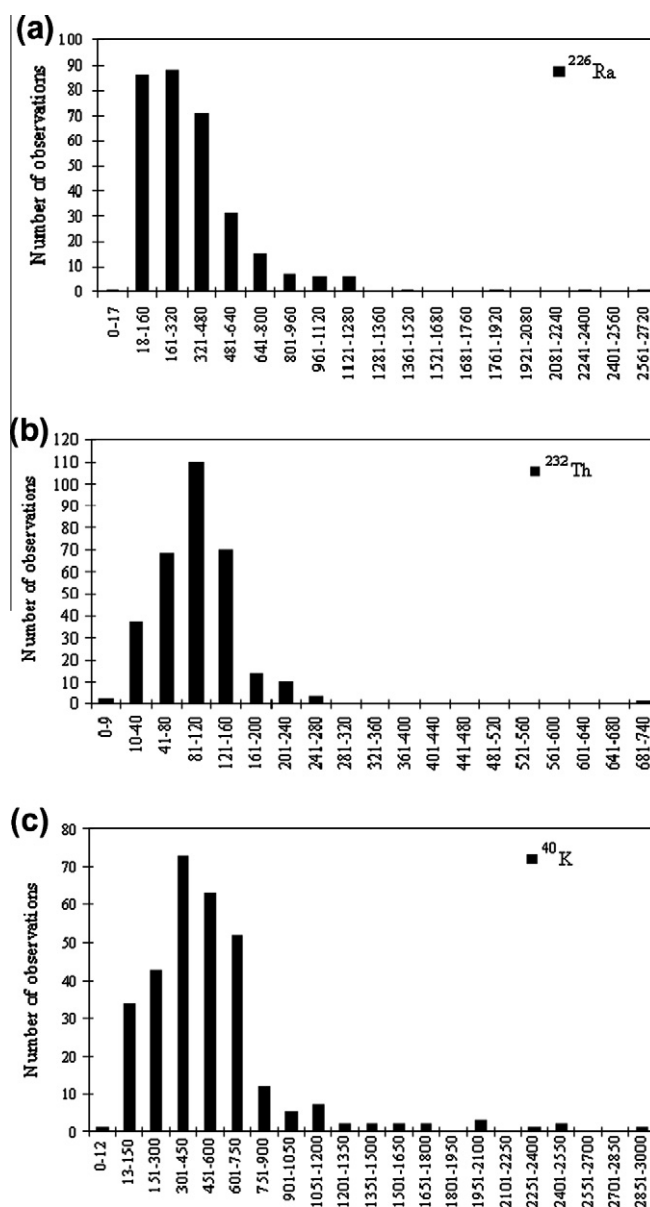


Fig. 3. Frequency (number of observation) distribution of the activity concentration of ²²⁶Ra (a), ²³²Th (b) and ⁴⁰K (c) in the PFA samples.

atomic mass (kg mol^{-1}), the decay constant (s^{-1}), Avogadro's number ($6.023 \times 10^{23} \text{ atoms mol}^{-1}$) and the atomic abundance in nature. F is a factor with a value of 1,000,000 for ^{238}U and ^{232}Th in unit mg kg^{-1} and 100 for ^{40}K in unit percentage (%). The elemental concentration of ^{238}U was calculated assuming the secular equilibrium between ^{238}U and ^{226}Ra and ^{226}Ra and ^{222}Rn . However ^{226}Ra cannot be equilibrium with ^{222}Rn because of exhalation of ^{222}Rn from the PFA. ^{226}Ra : ^{214}Pb and ^{226}Ra : ^{214}Bi ratios in the PFA samples analyzed are in the range 1.10–1.18, suggesting that the actual activity concentrations of ^{238}U in the PFA samples could be approximately 10–20% higher than the activity concentrations of ^{214}Pb and ^{214}Bi in the PFA samples.

The elemental concentration calculated for the Turkish PFA samples from coal-burning TPPs range from 1.4 to 220.3 mg kg^{-1} with a mean of $29.2 \pm 1.4 \text{ mg kg}^{-1}$ for ^{238}U , from 2.2 to 171.6 mg kg^{-1} with a mean of $25.1 \pm 0.8 \text{ mg kg}^{-1}$ for ^{232}Th and from 0.04% to 9.59% with a mean of $1.67 \pm 0.07\%$ for ^{40}K . It is concluded from these values that the ^{238}U and ^{232}Th content of Turkish PFA has become approximately 2 and 4 times richer than that of the feed Turkish coal, respectively.

3.3. Assessment of radiological impacts from the utilization of PFA in earthwork applications

3.3.1. Radium equivalent activity index

Radium equivalent activity (Ra_{eq}) index has been used to compare the activity concentrations of materials containing different amounts of ^{226}Ra , ^{232}Th and ^{40}K and assess the radiation hazards associated with these radionuclides. This index is defined based on the fact that 10 Bq kg^{-1} of ^{226}Ra , 7 Bq kg^{-1} of ^{232}Th and 130 Bq kg^{-1} of ^{40}K produce the same gamma dose rate and calculated from the following equation [16]:

$$\text{Ra}_{\text{eq}} = C_{\text{Ra}} + \frac{10}{7} \cdot C_{\text{Th}} + \frac{10}{130} \cdot C_{\text{K}} \quad (2)$$

where C_{Ra} , C_{Th} and C_{K} are the activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K , respectively in Bq kg^{-1} . The recommended limits of the Ra_{eq} index for earthwork applications as follows: Ra_{eq} must be less than 2220 for Bq kg^{-1} for highway, road, railway and bridge constructions (roadbeds, road pavement, road stabilization, etc.) and

Table 4
The range (maximum and minimum) and mean values of the external exposure indexes (the radium equivalent activity (Ra_{eq}) index and the gamma index (I_1 and I_2)) calculated for the PFA samples.

Power plant	N	Ra_{eq} (Bq kg^{-1})		I_1		I_2	
		Range	Mean \pm SE [†]	Range	Mean \pm SE	Range	Mean \pm SE
Afşin-Elbistan A	16	254.4–1382.5	647.5 \pm 77.9	0.36–1.98	0.93 \pm 0.11	0.13–0.69	0.32 \pm 0.04
Afşin-Elbistan B	12	143.3–518.9	306.6 \pm 33.0	0.21–0.74	0.44 \pm 0.05	0.07–0.26	0.15 \pm 0.02
Çan	6	208.8–414.9	323.8 \pm 39.2	0.30–0.59	0.46 \pm 0.06	0.11–0.20	0.16 \pm 0.02
Çatalağzı	19	158.4–665.4	370.1 \pm 28.6	0.23–0.98	0.54 \pm 0.04	0.08–0.35	0.19 \pm 0.07
Çayırhan	11	51.9–684.2	340.3 \pm 57.2	0.08–0.99	0.49 \pm 0.08	0.03–0.35	0.17 \pm 0.03
Çolakoğlu-2	15	72.5–400.6	241.5 \pm 21.4	0.11–0.58	0.35 \pm 0.03	0.04–0.20	0.12 \pm 0.01
Kangal	14	259.8–2760.9	1102.1 \pm 148.1	0.37–3.95	1.58 \pm 0.21	0.13–1.38	0.55 \pm 0.07
Kemerköy	11	376.1–1201.0	672.0 \pm 74.3	0.54–1.72	0.96 \pm 0.11	0.19–0.60	0.34 \pm 0.04
Orhaneli	19	269.1–812.1	539.0 \pm 36.4	0.38–1.18	0.77 \pm 0.05	0.13–0.42	0.27 \pm 0.02
Seyitömer	44	224.5–675.8	346.9 \pm 13.2	0.32–0.97	0.50 \pm 0.02	0.11–0.34	0.18 \pm 0.01
Soma	30	187.6–2630.1	774.7 \pm 95.5	0.27–3.75	1.11 \pm 0.14	0.10–1.31	0.39 \pm 0.05
Sugözü	13	174.9–402.7	275.1 \pm 21.8	0.25–0.57	0.40 \pm 0.03	0.09–0.20	0.14 \pm 0.01
Tunçbilek	36	374.4–1090.0	674.3 \pm 35.8	0.54–1.56	0.96 \pm 0.05	0.19–0.54	0.34 \pm 0.02
Yatağan	58	255.0–1710.5	622.4 \pm 26.5	0.37–2.42	0.89 \pm 0.04	0.13–0.83	0.31 \pm 0.01
Yeniköy	13	212.0–968.3	506.9 \pm 60.7	0.30–1.39	0.73 \pm 0.09	0.11–0.49	0.26 \pm 0.03
EU [*]		–1644.0	373	–2.36	0.54	–0.83	0.19
India ^{**}		179.3–439.7	263.8	0.25–0.63	0.37	0.09–0.22	0.13
Baoji, (China) ^{***}		265.8–485.2	352.6	0.38–0.69	0.50	0.13–0.24	0.17

^{*} Taken from Ref. [15].

^{**} Taken from Ref. [18].

^{***} Taken from Ref. [19].

Table 5
Parameters (exposure time, dilution factor, breathing rate, dust concentration, ingestion rate and dose coefficient) and exposure pathways in each scenario for workers.

Parameters	Scenarios for workers								
	Outdoor storage (large quantities)			Transport (long distances)			Road construction (earthwork application)		
	Exposure pathways			Exposure pathways			Exposure pathways		
	External	Inhalation	Ingestion	External	Inhalation	Ingestion	External	Inhalation	Ingestion
t_e (h y^{-1})	1800	1800	1800	850	100	100	1800	1800	1800
f_d	1	1	1				0.1	0.1	0.1
B_f ($\text{m}^3 \text{ h}^{-1}$)		1.2			1.2			1.2	
C_{dust} (kg m^{-3})		5×10^{-7}			1×10^{-6}			2×10^{-6}	
R_{ing} (kg h^{-1})			1×10^{-5}			1×10^{-5}			1×10^{-5}
D_{ext} ($\mu\text{Sv h}^{-1}/\text{Bq kg}^{-1}$), D_{inh} ($\mu\text{Sv Bq}^{-1}$) and D_{ing} ($\mu\text{Sv Bq}^{-1}$) for ^{226}Ra	3.14×10^{-5}	2.23	0.28	7.61×10^{-5}	2.23	0.28	3.01×10^{-4}	2.23	0.28
D_{ext} ($\mu\text{Sv h}^{-1}/\text{Bq kg}^{-1}$), D_{inh} ($\mu\text{Sv Bq}^{-1}$) and D_{ing} ($\mu\text{Sv Bq}^{-1}$) for ^{232}Th	4.77×10^{-5}	48.2	1.06	1.18×10^{-4}	48.2	1.06	4.59×10^{-4}	48.2	1.06
D_{ext} ($\mu\text{Sv h}^{-1}/\text{Bq kg}^{-1}$), D_{inh} ($\mu\text{Sv Bq}^{-1}$) and D_{ing} ($\mu\text{Sv Bq}^{-1}$) for ^{40}K	2.86×10^{-6}	0	0	7.61×10^{-6}	0	0	2.89×10^{-5}	0	0

Table 6

Parameters (exposure time, dilution factor, breathing rate, dust concentration, ingestion rate and dose coefficient) and exposure pathways in each scenario for members of public (adults).

Parameters	Scenario for members of the public											
	Residence in the house (indoors, pile-25 m)			Staying in the garden (outdoor, pile-20 m)			Staying on the pile (outdoor, on pile 1 m)					
	Exposure pathways			Exposure pathways			Exposure pathways					
	External	Inhalation	Ingestion	External	Inhalation	Ingestion	External	Inhalation	Ingestion			
t_e (h y ⁻¹)	6000	6000	6000	1000	1000	1000	100	100	100			
f_d	1	1	1	1	1	1	1	1	1			
B_r (m ³ h ⁻¹)		0.9			0.9			0.9				
C_{dust} (kg m ⁻³)		5×10^{-8}				1×10^{-7}				5×10^{-7}		
R_{ing} (kg h ⁻¹)			5×10^{-6}			5×10^{-6}			5×10^{-6}			
D_{ext} (µSv h ⁻¹ /Bq kg ⁻¹), D_{inh} (µSv Bq ⁻¹) and D_{ing} (µSv Bq ⁻¹) for ²²⁶ Ra	4.43×10^{-6}	9.53	0.28	4.37×10^{-5}	9.53	0.28	4.20×10^{-4}	9.53	0.28			
D_{ext} (µSv h ⁻¹ /Bq kg ⁻¹), D_{inh} (µSv Bq ⁻¹) and D_{ing} (µSv Bq ⁻¹) for ²³² Th	8.85×10^{-6}	84.6	1.06	8.19×10^{-5}	84.6	1.06	6.21×10^{-4}	84.6	1.06			
D_{ext} (µSv h ⁻¹ /Bq kg ⁻¹), D_{inh} (µSv Bq ⁻¹) and D_{ing} (µSv Bq ⁻¹) for ⁴⁰ K	4.90×10^{-7}	0	0	4.95×10^{-6}	0	0	3.77×10^{-5}	0	0			

Table 7

The mean values of the annual effective doses of the total (E_{total}), external gamma radiation (E_{ext}), inhalation (E_{inh}) and ingestion (E_{ing}) estimated for workers.

Power plant	For workers											
	Outdoor storage (large quantities)				Transport (long distances)				Road construction (earthwork application)			
	E_{ext}	E_{inh}	E_{ing}	E_{total}	E_{ext}	E_{inh}	E_{ing}	E_{total}	E_{ext}	E_{inh}	E_{ing}	E_{total}
Afşin-Elbistan-A	37.1	4.4	3.9	45.4	42.8	0.5	0.2	43.5	35.7	1.8	0.4	37.8
Afşin-Elbistan-B	17.7	3.0	2.0	22.7	20.5	0.3	0.1	21.0	17.1	1.2	0.2	18.5
Çan	18.9	5.0	2.6	26.5	21.9	0.6	0.1	22.6	18.2	2.0	0.3	20.4
Çatalağzı	22.4	6.4	2.8	31.6	26.5	0.7	0.2	27.4	21.8	2.5	0.3	24.6
Çayırhan	19.9	4.0	2.3	26.2	23.2	0.4	0.1	23.8	19.2	1.6	0.2	21.1
Çolakoğlu-2	14.3	4.3	2.0	20.6	16.7	0.5	0.1	17.3	13.8	1.7	0.2	15.7
Kangal	62.8	4.7	5.9	73.4	72.1	0.5	0.3	73.0	60.3	1.9	0.6	62.7
Kemerköy	38.5	4.3	3.9	46.7	44.4	0.5	0.2	45.0	37.0	1.7	0.4	39.1
Orhaneli	31.5	7.0	3.9	42.4	36.7	0.8	0.2	37.7	30.4	2.8	0.4	33.6
Seyitömer	20.6	5.4	2.7	28.7	24.1	0.6	0.1	24.9	19.9	2.2	0.3	22.4
Soma	44.8	7.3	5.0	57.1	51.8	0.8	0.3	52.9	43.1	2.9	0.5	46.5
Sugözü	16.4	5.2	2.4	24.0	19.2	0.6	0.1	19.9	15.9	2.1	0.2	18.2
Tunçbilek	39.3	9.3	5.1	53.8	45.6	1.0	0.3	47.0	37.9	3.7	0.5	42.1
Yatağan	36.2	7.7	4.5	48.4	42.0	0.9	0.2	43.1	34.9	3.1	0.4	38.4
Yeniköy	29.1	2.8	2.8	34.7	33.5	0.3	0.2	34.0	28.0	1.1	0.3	29.4

Table 8

The mean values of the annual effective doses of the total (E_{total}), external gamma radiation (E_{ext}), inhalation (E_{inh}) and ingestion (E_{ing}) estimated for members of public (adults).

Power plant	For members of the public									
	Residence in the house (indoor, pile-25 m)			Staying in the garden (outdoor, pile-20 m)			Staying on the pile (outdoor, on pile 1 m)			E_{total}
	E_{ext}	E_{inh}	E_{ing}	E_{ext}	E_{inh}	E_{ing}	E_{ext}	E_{inh}	E_{ing}	
Afşin-Elbistan-A	18.4	2.8	6.4	33.9	0.9	1.1	27.5	0.5	0.1	91.6
Afşin-Elbistan-B	9.1	1.7	3.4	15.7	0.6	0.6	13.1	0.3	0.1	44.4
Çan	10.1	2.6	4.3	17.1	0.9	0.7	13.9	0.4	0.1	50.0
Çatalağzı	12.6	3.1	4.7	15.9	1.0	0.8	16.4	0.5	0.1	55.1
Çayırhan	10.5	2.1	3.9	16.8	0.7	0.6	14.7	0.4	0.1	49.7
Çolakoğlu-2	7.9	2.1	3.4	12.0	0.7	0.6	10.5	0.4	0.1	37.5
Kangal	30.3	3.7	9.9	57.9	1.2	1.6	46.6	0.6	0.2	152.0
Kemerköy	19.0	2.8	6.5	35.1	0.9	1.1	28.5	0.5	0.1	94.6
Orhaneli	16.7	3.7	6.5	27.1	1.2	1.1	23.2	0.6	0.1	80.2
Seyitömer	11.2	2.7	4.4	16.6	0.9	0.7	15.1	0.5	0.1	52.3
Soma	22.8	4.2	8.4	39.9	1.4	1.4	33.1	0.7	0.1	112.0
Sugözü	9.2	2.5	3.9	13.4	0.8	0.7	12.0	0.4	0.1	43.1
Tunçbilek	20.8	4.9	8.5	35.0	1.6	1.4	28.9	0.8	0.1	102.1
Yatağan	18.9	4.1	7.5	32.0	1.4	1.2	26.7	0.7	0.1	92.6
Yeniköy	14.3	2.0	4.7	26.1	0.7	0.8	21.5	0.3	0.1	70.4

less than 3700 for Bq kg⁻¹ for utilization in foundation of non-residential buildings (structural fill, landfill, embankments, etc.) [17].

The range and mean values of the calculated $R_{a_{eq}}$ for the Turkish PFA samples studied are shown in the third column of Table 4.

It can be easily seen from Table 4 that the mean values of the $R_{a_{eq}}$ activity index calculated for the all PFA samples are significantly lower than the recommended limits of 2220 Bq kg⁻¹ and 3700 for Bq kg⁻¹.

3.3.2. Gamma index

Gamma indexes (I_1 and I_2) are used only as a screening tool for identifying materials which might be of concern. The gamma index (I_1) is calculated for assessing of the radiological impacts from the utilization of the PFA samples as cover material in road, street, embankments, pavement and related construction work using the formula [20]:

$$I_1 = \frac{C_{Ra}}{700 \text{ Bq kg}^{-1}} + \frac{C_{Th}}{500 \text{ Bq kg}^{-1}} + \frac{C_K}{8000 \text{ Bq kg}^{-1}} \quad (3)$$

where C_{Ra} , C_{Th} and C_K are the activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K , respectively in Bq kg^{-1} . The gamma index (I_2) is calculated for assessing of the radiological impacts from the utilization of the PFA samples as filling material in landfill, embankment and landscaping using the formula [20]:

$$I_2 = \frac{C_{Ra}}{2000 \text{ Bq kg}^{-1}} + \frac{C_{Th}}{1500 \text{ Bq kg}^{-1}} + \frac{C_K}{20000 \text{ Bq kg}^{-1}} \quad (4)$$

where C_{Ra} , C_{Th} and C_K are the activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K , respectively in Bq kg^{-1} . The value of the I_1 and I_2 must be less than unity for materials used in earthwork applications.

The range and mean values of the calculated I_1 and I_2 for all the studied PFA samples are shown in the fifth and seventh column of Table 4, respectively. The mean values of I_1 are lower than the unity, except Kangal and Soma TPP for which the mean value of I_1 calculated is about 60% and 10% higher than the unity, respectively. However, the mean values of I_2 are lower than the unity.

3.4. Estimation of the annual effective doses

An estimate of the total annual effective dose (E_{total}) received by workers and members of the general public was performed using methods recommended in the Radiation Protection 122 [14]. In general the total annual effective dose is determined by means of the following equations:

$$E_{\text{total}} = E_{\text{ext}} + E_{\text{inh}} + E_{\text{ing}} \quad (5)$$

where E_{ext} , E_{inh} and E_{ing} are the annual effective doses (in $\mu\text{Sv y}^{-1}$) due to external gamma radiation, inhalation and ingestion exposures and calculated using the following equations:

$$E_{\text{ext}} = t_e \cdot f_d \cdot (D_{\text{extRa}} \cdot C_{Ra} + D_{\text{extTh}} \cdot C_{Th} + D_{\text{extK}} \cdot C_K) \quad (6)$$

$$E_{\text{inh}} = t_e \cdot f_d \cdot B_r \cdot C_{\text{dust}} (D_{\text{inhRa}} \cdot C_{Ra} + D_{\text{inhTh}} \cdot C_{Th} + D_{\text{inhK}} \cdot C_K) \quad (7)$$

$$E_{\text{ing}} = t_e \cdot f_d \cdot R_{\text{ing}} (D_{\text{ingRa}} \cdot C_{Ra} + D_{\text{ingTh}} \cdot C_{Th} + D_{\text{ingK}} \cdot C_K) \quad (8)$$

where D_{extRa} , D_{extTh} and D_{extK} , D_{inhRa} , D_{inhTh} and D_{inhK} and D_{ingRa} , D_{ingTh} and D_{ingK} are the dose coefficients (in $\mu\text{Sv h}^{-1}$ per Bq kg^{-1}) for external gamma radiation, inhalation and ingestion exposures for ^{226}Ra series, ^{232}Th series and ^{40}K , respectively; C_{Ra} , C_{Th} and C_K are the activity concentrations (in Bq kg^{-1}) of ^{226}Ra , ^{232}Th and ^{40}K measured in PFA samples, respectively; t_e is the exposure time h y^{-1} ; f_d is the dilution factor; B_r is the breathing rate (in $\text{m}^3 \text{h}^{-1}$); C_{dust} is the dust concentrations (in kg m^{-3}); R_{ing} is the ingestion rate (in kg h^{-1}).

3.5. Exposure of workers

In estimating the annual effective doses received by workers handling PFAs, storage scenario, transport scenario and road construction scenario given in the Radiation Protection 122 was considered [14]. The storage scenario describes the storage of the PFA in large quantities outdoors. In the transport scenario, a truck driver transports the PFAs from place of the coal-burning TPP to its destination place, which can be landfill, a road construction or a

mill where the material is processed for the preparation of concrete or other building material. The road construction scenario contains the recycling of PFAs as filling and covers material in earthwork applications [14]. The annual effective doses in each scenario were calculated using exposure pathways and parameters given in Table 5.

3.6. Exposure of members of the public

In order to estimate the radiological impact of the coal-burning TPP on members of the public the scenario of an adult person living

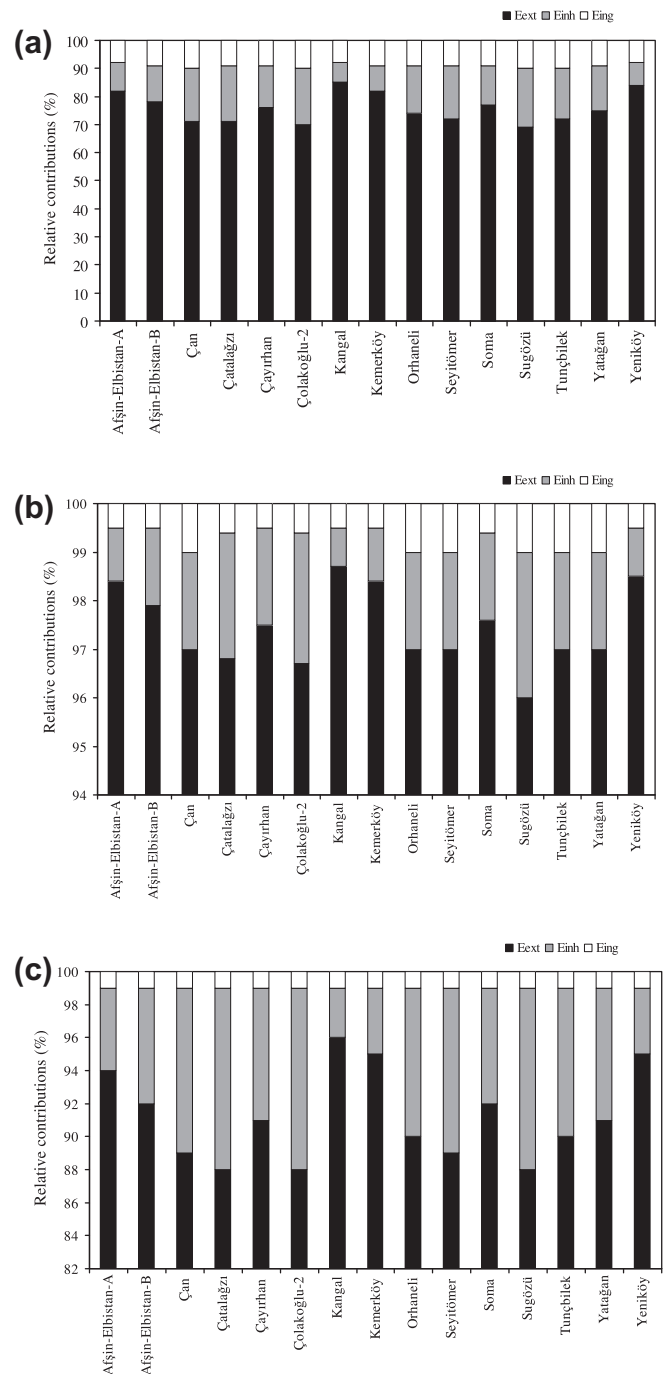


Fig. 4. Relative contributions to the total annual effective dose due to the annual effective doses of the external gamma radiation, inhalation and ingestion exposure of workers in the scenario of the outdoor storage (a), transportation (b) and road construction (c).

in a house near the PFA pile/landfill belonging to each TPP has been considered possible significant exposure route. The scenario contains three exposure situations: (i) residence in the house located at a distance of 25 m from the edge of the pile/landfill; (ii) staying in the garden which has a distance of 20 m from the edge of the pile/landfill belonging to the house; (iii) staying on the pile/landfill without presence of a covering layer [14]. The annual effective doses each exposure situation were calculated using exposure pathways and parameters given in Table 6. For the stay on the pile the dose rate is calculated at a height of 1 m [14].

The mean values of the annual effective doses of the total (E_{total}), external gamma radiation (E_{ext}), inhalation (E_{inh}) and ingestion (E_{ing}) estimated for workers and members of the public using the parameters in Tables 5 and 6 and Eqs. (5–8) are given in Tables 7 and 8, respectively. From Tables 7 and 8 the highest total annual effective dose ($152 \mu\text{Sv y}^{-1}$) estimated for the members of the public is about two times higher than the highest total annual effective dose ($73.4 \mu\text{Sv y}^{-1}$) estimated for the workers. Relative contribution of the E_{ext} , E_{inh} and E_{ing} to the E_{total} in each scenario for workers and members of the public was illustrated in Fig. 4 and Fig 5, respectively. It can be easily seen from Figs. 4 and 5 that the external gamma radiation dose is the main fraction of the total dose, followed by the inhalation dose, while the ingestion dose is the minor fraction of the total dose.

4. Conclusion

Coal-burning TPPs in operation in Turkey produces a total of over 15 million tons of PFA annually. The handling and disposal of PFA raises concerns about its human health and ecological effects. Therefore, the recycling of PFA in construction and earthwork applications (road construction, roadbeds, road pavement, landfill, landscaping, embankments, etc.) can bring economical and environmental benefits such as reducing energy costs and land disposal needs, etc. In Turkey, coal combustion PFA has been utilized as filling and covers material in earthwork applications. In this study, the activity concentrations of ^{226}Ra , ^{232}Th and ^{40}K in the PFA samples were measured to determine the radiological characteristics of the Turkish PFA. The external exposure indexes (R_{aeq} , I_1 and I_2) were calculated to assess the radiological impacts from the utilization of the PFA samples in earthwork applications. Besides, the total annual effective doses were estimated to assess the health risk to the workers and the members of the public using various exposure scenarios. It is observed that the radioactivity of the PFA samples produced in coal-burning TPPs mostly depends on the sampling location. On the average, Turkish PFA contains 3–4 times more ^{238}U and ^{232}Th than feed coal. The all mean values of the R_{aeq} , I_1 (except mean value calculated for PFA from Kangal and Soma TPP) and I_2 calculated for PFA samples are below the recommended limit value. The results indicate that the utilization of the examined PFA samples with the exception of Kangal and Soma TPP, in road, street, roadbeds, and road pavement do not pose any significant source of radiation hazard. The PFA samples from Kangal and Soma TPP can be used in landfill, landscaping and embankments. The maximum mean total annual effective doses of $7.3 \times 10^{-5} \text{ Sv y}^{-1}$ and $1.5 \times 10^{-4} \text{ Sv y}^{-1}$ estimated for the workers and the members of the public, respectively are significantly lower than the statutory limit of $1.0 \times 10^{-3} \text{ Sv y}^{-1}$. More over both values are well below the dose criterion of $3.0 \times 10^{-4} \text{ Sv y}^{-1}$ used as the radiological protection goal concerning the exposure of a reference person (worker or member of the public) by PFAs.

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References

- [1] Web site of Turkish Electricity Transmission Company. <<http://www.teias.gov.tr/istatistik2008>>.
- [2] Yılmaz AO. Renewable energy and coal use in Turkey. *Renew Energ* 2008;33–5:950–9.
- [3] Oktay Z. Investigation of coal-fired power plants in Turkey and a case study: can plant. *Appl Therm Eng* 2009;29:550–7.
- [4] Maden Tetkik ve Arama Genel Müdürlüğü (General Directorate of Mineral Research and Exploration), Türkiye tersiyer kömürlerinin kimyasal ve teknolojik özellikleri, Ankara; 2002 (in Turkish).

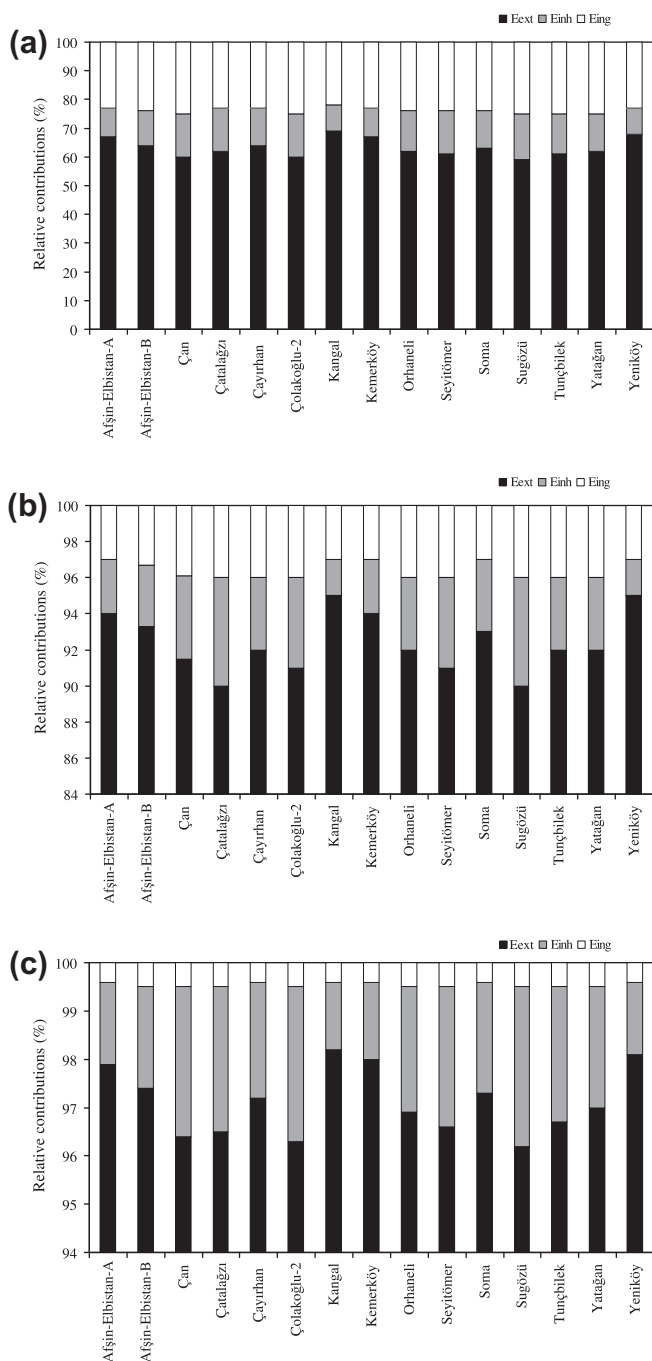


Fig. 5. Relative contributions to the total annual effective dose due to the annual effective doses of the external gamma radiation, inhalation and ingestion exposure of adults in the scenario of the residence in the house (a), staying in the garden (b) and staying on the pile (c).

- [5] Turhan Ş, Arıkan İH, Yücel B, Varinlioğlu A, Köse A. Evaluation of the radiological safety aspects of utilization of Turkish coal combustion fly ash in concrete production. *Fuel* 2010;89:2528–35.
- [6] Chauhan RP, Kant K, Sharma SK, Chakarvarti SK. Measurement of alpha radioactive air pollutants in fly ash brick dwellings. *Radiat Meas* 2003;36:533–6.
- [7] Feuerborn HJ. Coal ash utilization over the world and in Europe. Workshop on Environmental and Health Aspects of Coal Ash Utilization, Israel; 2005.
- [8] Baba A. Assessment of radioactive contaminants in by-products from Yatagan (Mugla, Turkey) coal-fired power plant. *Environ Geo* 2002;41:916–21.
- [9] Yener G, Uysal I. Low energy scintillation spectrometry for direct determinations of ^{238}U and ^{210}Pb in coal and ash samples. *Appl Radiat Isotopes* 1996;47:93–6.
- [10] Aycik GA, Ercan A. Radioactivity measurements of coals and ashes from coal-fired power plants in the southwestern part of Turkey. *J Environ Radioactiv* 1997;35(1):23–35.
- [11] Cevik U, Damla N, Koz B, Kaya S. Radiological characterization around the Afşin-Elbistan coal-fired power plant in Turkey. *Energ Fuel* 2008;22–1:428–32.
- [12] Cevik U, Damla N, Nezir S. Radiological characterization of Cayırhan coal-fired power plant in Turkey. *Fuel* 2009;86:2509–13.
- [13] Aytakin H, Baldık R. On the radiological character of a coal-fired power plant at the town of Çatalağzı, Turkey. *Turk J Eng Env Sci* 2008;32:101–5.
- [14] EC (European Commission), Radiation protection 122. Practical use of the concepts of clearance and exemption-Part II: Application of the concepts of exemption and clearance to natural radiation sources. Directorate-General Environment; 2002.
- [15] EC (European Commission), Radiation protection 112. Radiological protection principles concerning the natural radioactivity of building materials. Directorate-General Environment, Nuclear Safety and Civil Protection; 1999.
- [16] Stranden E. Some aspects on radioactivity of building materials. *Phys Norv* 1976;8:167–73.
- [17] TAEK TR 2009–11. Türkiye'deki kömür yakıtlı termik santrallerden elde edilen uçucu küllerin inşaat sektöründe kullanılabilirliğinin radyolojik açıdan değerlendirilmesi. Ankara; 2009 (in Turkish).
- [18] Mishra UC. Environmental impact of coal industry and thermal power plants in India. *J Environ Radioactiv* 2004;72(1–2):35–40.
- [19] Xinwei L, Xiaodan J, Fengling W. Natural radioactivity of coal and its by-products in the Baoji coal-fired power plant, China. *Curr Sci* 2006;91(11):1508–11.
- [20] Guide ST. 12.2: the radioactivity of building materials and ash, STUK, Finland: Helsinki; 2005.