EPRI | ELECTRIC POWER RESEARCH INSTITUTE

# Radioactivity in Coal Combustion Products

**Technical Brief — *Coal Combustion Products – Environmental Issues Program***

This technical brief provides an overview of the presence of radioactive elements in coal combustion products (CCPs) and their potential impact to human health. This overview summarizes information that can be found in the full technical report *Assessment of Radioactive Elements in Coal Combustion Products* (EPRI, 2014). Readers can refer to that report for more details on the topics presented herein, and for a complete list of references. Definitions for some key terms are provided at the end of this document.

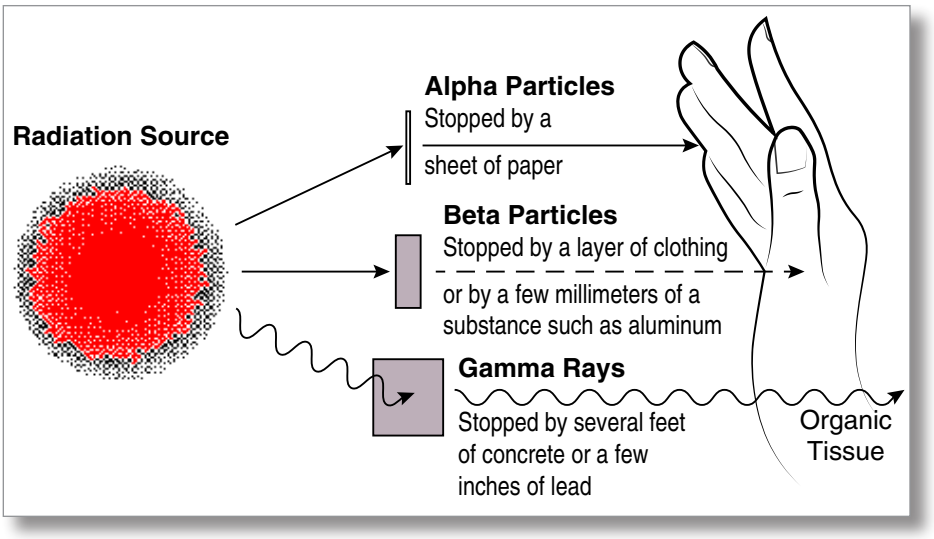


*Figure 1. Relative depth of penetration of alpha, beta, and gamma radiation. Source: US EPA (2012a, as cited by EPRI, 2014)*

## Radioactive Decay

When an element undergoes natural radioactive decay, charged and uncharged particles are emitted from the nucleus of the element, often in combination with energetic photons called gamma rays. The radiation generated from natural radioactive decay can be broadly divided into three types. *Alpha (α) radiation* consists of positively charged helium nuclei: two protons and two neutrons bound together constitute one alpha particle. *Beta (β) radiation* consists of high-velocity electrons or positrons that are ejected from the nucleus when one isotope is transforming into another. Alpha and beta particles are commonly emitted during the decay of radioactive isotopes. *Gamma (γ) radiation* is a type of short-wavelength electromagnetic radiation that is sometimes emitted by the nucleus during radioactive decay.

Alpha and beta radiation have limited penetration ability; gamma radiation is the most penetrating form of radiation generated from natural radioactive decay (see Figure 1). All of the emissions from nuclear decay are considered *ionizing radiation*, because their energy is sufficient to break chemical bonds (i.e., to disrupt the forces that hold molecules together). The primary health concern posed by ionizing radiation is that it can damage DNA, resulting in a wide array of biological effects, including cancer. Radiation can also interact with molecules other than DNA (such as lipids, proteins, and water) to produce free radicals, which can adversely react with DNA and lead to a more diverse set of adverse health effects. Exposure to ionizing radiation may be internal (e.g., inhaled or ingested) or external (e.g., dust deposited on the skin).

Radioactivity can be measured in terms of its activity in an environmental medium (curies or becquerels per kilogram of soil or liter of water), absorbed dose (energy imparted to a gram of tissue measured in rad or grays), or equivalent dose (cumulative total dose of different forms of radiation on a total body basis, measured in rem or sieverts).

## Sources of Background Radioactivity

Radioactivity occurs naturally in the atmosphere and in drinking water, soil, and foods. People are routinely exposed to natural radiation and ingest radionuclides as part of everyday life. Anthropogenic sources are primarily associated with medical procedures.

The National Council on Radiation Protection and Measurements (NCRP) has determined that the average total effective dose of background radioactivity for an individual is about 624 mrem/year (NCRP, 2009). Natural sources (rocks, soil, water, cosmic) account for 50% of background radiation, and medical applications account for approximately 48% (see Figure 2). Natural background radiation can vary significantly based on geographic location and elevation. For example, cosmic radiation is approximately 27 mrem/year at sea level and increases 1 mrem/year with every 250 feet of elevation (e.g., 47 mrem/yr at 5,000 feet above sea level). Medical procedures such as x-rays or CT scans may impart doses of <1 to 1,000 mrem. Any food or drink that contains potassium will contain about 0.012% of the isotope $^{40}$K, a beta particle emitter. Milk, for example, contains about 2,000 pCi/L of $^{40}$K.

Due to their very long half-lives, the primary naturally occurring radionuclides are Thorium-232 (14 billion-year half-life) and Uranium-238 (4.5 billion-year half-life). Thorium (100% as $^{232}$Th) and uranium (99.3% as $^{238}$U) decay into a series of daughter products that are also present in the environment (see Figures 3 and 4). The largest source of natural background radiation is from gaseous radon (Rn). The most stable radon isotope, $^{222}$Rn, is a source of alpha particles and is a decay product from background levels of radium ($^{226}$Ra), which in turn is a decay product from $^{238}$U (see Figure 3). Another isotope of radon, $^{220}$Rn, which is also known as thoron and has a very short half-life (55.6 seconds), is a decay product from $^{232}$Th (Figure 4).

# Radionuclides in Coal and Coal Combustion Products

## Coal

Like all rocks and soils, raw coal contains naturally occurring radionuclides (Table 1 and Figure 5). Average concentrations of uranium and thorium in raw coals are 0.3–2.0 pCi/g $^{238}$U and 0.35 pCi/g $^{232}$Th, respectively. [1] Concentrations of these radionuclides in raw coal are comparable to those in the earth's crust (USGS, 1997). The average amount of uranium and thorium in the earth's crust is estimated to be 0.76 pCi/g $^{238}$U and 1.1 pCi/g $^{232}$Th, respectively.

Coal also contains radioactive $^{40}$K associated with potassium in sediments and clay minerals. Finkelman (1993) calculated that the average amount of potassium in U.S. coals is 0.18%, based on 7,830 samples. Thus, a kilogram of coal would contain about 0.22 mg/kg of $^{40}$K, or 1.6 pCi/g, again similar to what is found in soil, which is estimated as 2.7 to 19 pCi/g (UNSCEAR, 2000).

## Coal Ash

Through the process of combustion, some naturally occurring radionuclides in coal become

[1] *To convert pCi/g to mg/kg:*
*$^{238}$U: 1.0 pCi/g = 3.03 mg/kg*
*$^{232}$Th: 1.0 pCi/g = 9.09 mg/kg*
*$^{40}$K: 1.0 pCi/g = 0.14 mg/kg*
*$^{226}$Ra: 1.0 pCi/g = $10^{-6}$ mg/kg (1 ng/kg)*

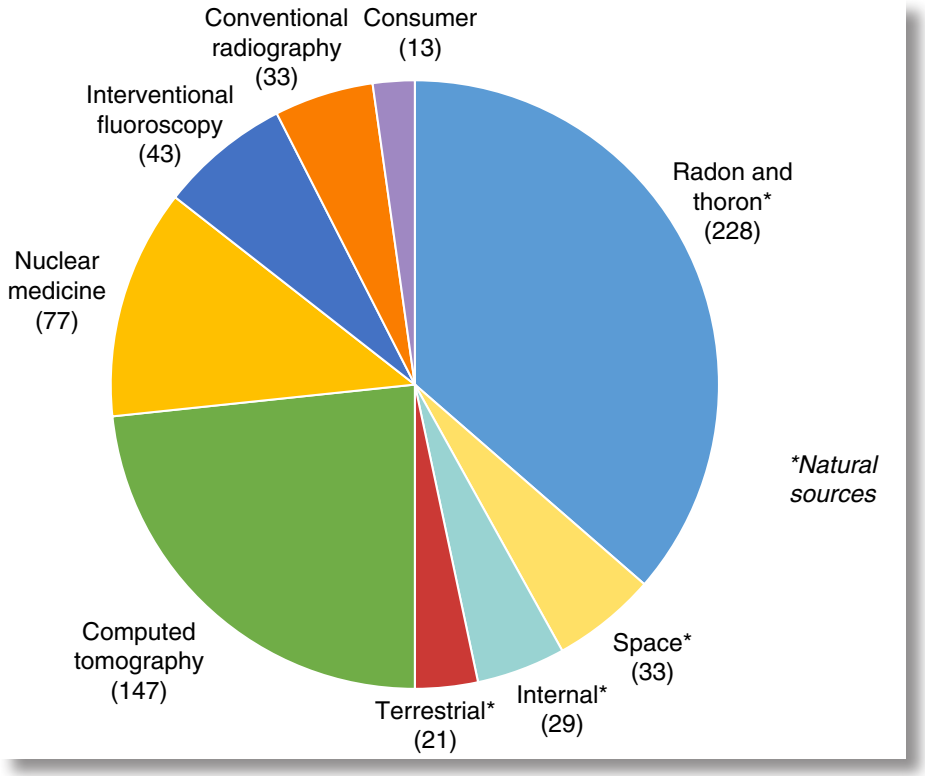


*Figure 2. Distribution of the various background radiation sources (mrem/year)*
*Source: from NCRP, 2009. (Note: Industrial exposure [0.3 mrem/year] and occupational exposure [0.5 mrem/year] were not included in this figure.)*

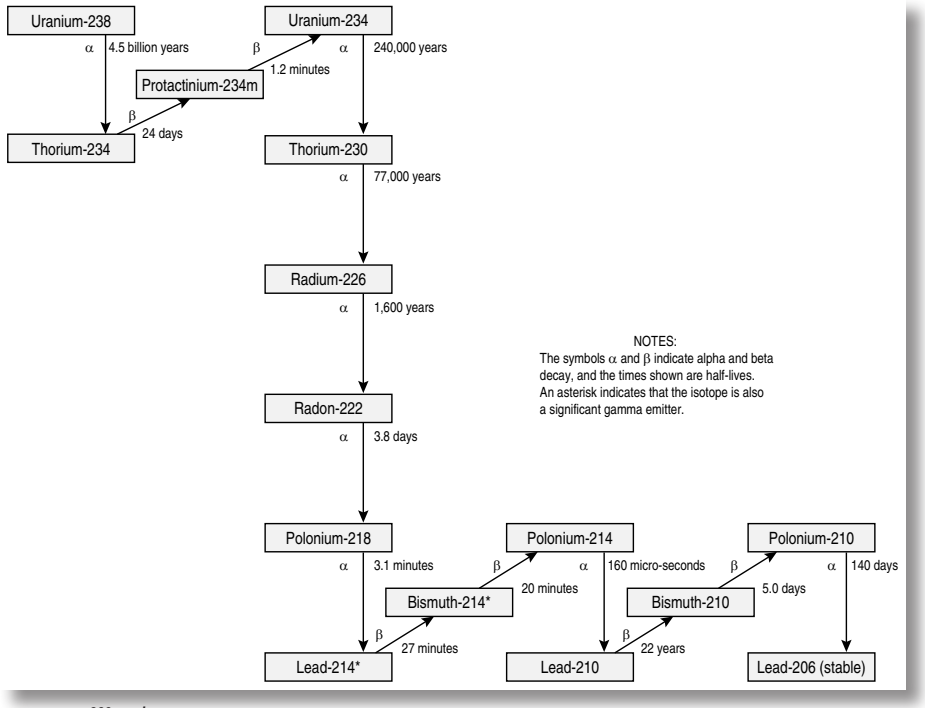


*Figure 3. $^{238}$U decay series*
*Source: Peterson et al. (2007, as cited in EPRI, 2014)*

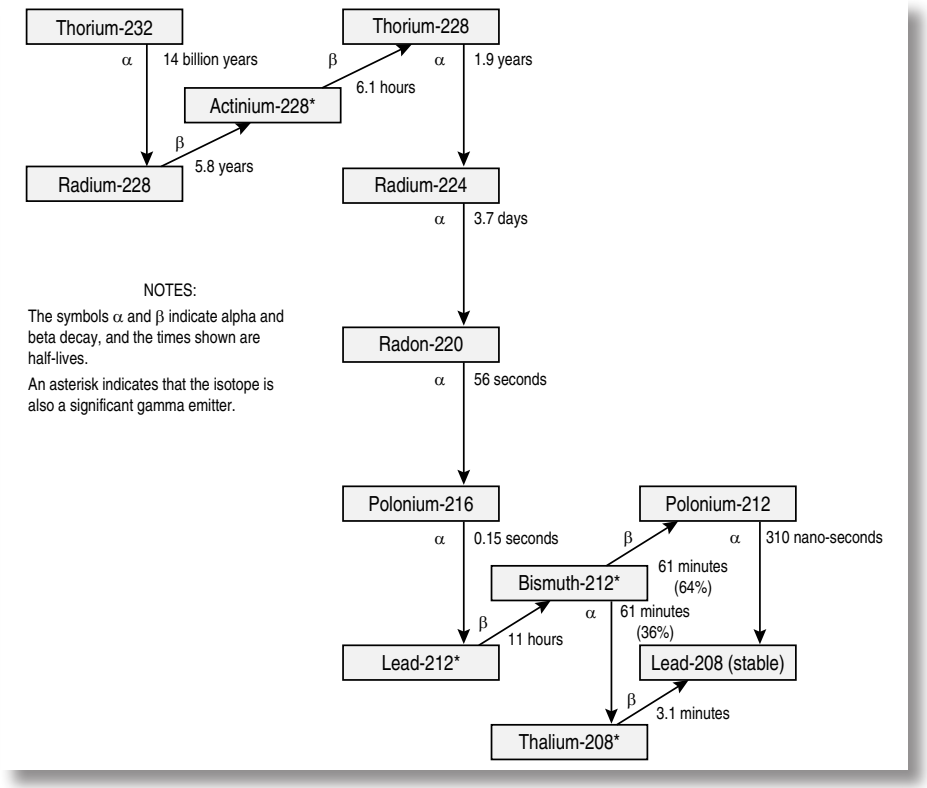


*Figure 4. $^{232}$Th decay series*
*Source: Peterson et al. (2007, as cited in EPRI, 2014)*

concentrated in the remaining coal ash material. For this reason, coal ash is known as a naturally occurring radioactive material (NORM), or sometimes as a technologically enhanced NORM (TENORM). As the ash content of the coal increases, the enrichment factor decreases. For bituminous and subbituminous coals with 10–15% ash, Lauer et al. (2015) reported that total radium activities in the ash were 7–10 times greater than in the original feed coal.

Using the average concentrations of thorium, uranium, and potassium in several U.S. coal types and an enrichment factor of 10-fold, a typical coal ash would contain about 7 pCi $^{238}$U/g, 4 pCi $^{232}$Th/g, and 15 pCi $^{40}$K/g. Based on the information available in the 1970s, the United States Environmental Protection Agency (US EPA, 1984) calculated average estimates of 9 pCi/g for $^{238}$U and 4 pCi/g for $^{232}$Th in coal ash. These estimates are in agreement with measured concentrations reported in the scientific literature (Table 2). Recently, Lauer et al. (2015) reported radionuclide concentrations for several raw coal and CCP materials, similar to those that have been reported previously (Tables 1 and 2).

## Flue Gas Desulfurization Solids

Wet flue gas desulfurization (FGD) solids are the residue generated by removing sulfur diox-

*Table 1. Concentrations of thorium and uranium in raw U.S. coals*

| Source | Thorium (mg/kg) | $^{232}$Th (pCi/g) | Uranium (mg/kg) | $^{238}$U (pCi/g) |
|---|---|---|---|---|
| U.S. Natural Soils (UNSCEAR, 2000) | — | Mean = 0.95[a] Range = 0.1-3.5 | — | Mean = 0.95[a] Range = 0.1-3.8 |
| U.S. Raw Coal[b] (Kolker and Finkelman, 1998) | Mean = 3.2 (n = 6,866) | Mean = 0.35 (n = 6,866) | Mean = 2.1 (n = 6,923) | Mean = 0.69 (n = 6,923) |
| U.S. Raw Coal[b] (Zielinski et al., 1999) | — | — | Range = <1-4.0 (n = 2,300)[c] | Range = 0.33-1.32 (n = 2,300)[c] |
| U.S. Raw Lignite Coal[b] (EPRI, 2014) | Mean = 3.3 (n = 2,503) | Mean = 0.36 (n = 2,503) | Mean = 6.06 (n = 2,503) | Mean = 2.00 (n = 2,503) |
| KY Bituminous Coal (Zielinski and Budahn, 1998) | — | — | Mean = 1.94 (n = 6) | Mean = 0.64 (n = 6) |
| U.S. Raw Coals[d] (Lauer et al., 2015) | — | — | — | Range = 0.16-1.16 (n = 11)[a,d] |

Notes:
Bq = Becquerel; pCi = Picocurie.
(a) Data reported in Bq/kg and converted to pCi/g (1 Bq = 27.03 pCi).
(b) U.S. coal data from the United States Geological Survey (USGS) National Coal Resources Data System (NCRDS) Database (USGS, 2006).
(c) Coal measurements included 2,000 samples from the western United States and 300 samples from the Illinois Basin.
(d) Raw coal samples collected from Appalachian (bituminous), Illinois (bituminous), and Powder River (subbituminous) Basins.

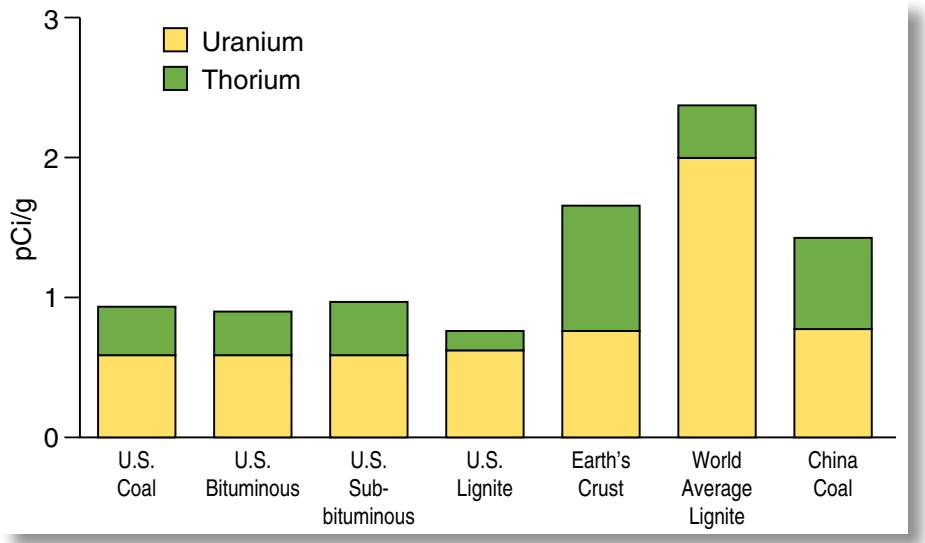


*Figure 5. Mean concentration of uranium and thorium in coal and the earth's crust*
*Source: EPRI, 2014. (Note: The averages for all U.S. coal, and for bituminous, subbituminous, and lignite coal were calculated using the COALQUAL database.)*

ide ($SO_2$) from the exhaust gases of a coal-fired power plant. The solids consist primarily of calcium sulfite/sulfate. Nearly all wet FGD systems in the United States collect fly ash before the FGD absorber, so the FGD solids contain little or no fly ash. The sources of radionuclides in FGD solids will primarily be the radionuclides initially present in the limestone or lime as well as those associated with any small amount of fly ash carryover.

Roper et al. (2013), measured activities of $^{238}$U, $^{232}$Th, and $^{40}$K in 20 FGD gypsum samples from eastern bituminous and western subbituminous coals. The mean activities of each radionuclide were less than 0.40 pCi/g. The activity of uranium ranged from 0.03 to 0.65 pCi/g, which suggests that these FGD samples contained very little fly ash. Data from other studies suggest that $^{238}$U content can vary from 1.8 to 3.2 pCi/g in FGD solids, and that $^{226}$Ra is in secular equilibrium with the uranium, as evidenced by the similar (activity) concentrations (Wagner et al. 1980; Wagner and Greiner, 1982). Dry FGD system (e.g., spray dryer absorber) solids are collected with varying amounts of fly ash, and as a result can have slightly higher concentrations than wet FGD solids.

# Radiological Exposure and Risk from Coal Combustion Products

## Occupational Exposure and Risk

EPRI (2014) identified studies that assessed exposure to and potential risks posed by radionuclides present in CCPs. Several studies evaluated occupational risks at CCP disposal sites and highway embankments made with CCPs. The results of these assessments indicate that the radiological doses that result from exposure to CCPs are typically well below regulatory limits and therefore do not pose a health concern (Table 3).

Corbett (1983) estimated that coal ash in a landfill in the United Kingdom that contained typical concentrations of $^{40}$K, $^{232}$Th, $^{238}$U, and $^{235}$U would yield 9 mrem/year of gamma radiation to an exposed worker. In another United Kingdom landfill scenario, Smith et al. (2001) estimated the occupational dose from direct

*Table 2. Concentrations of radionuclides in U.S. coal ash samples (pCi/g)*

| Source | $^{232}$Th | $^{228}$Ra | $^{238}$U | $^{226}$Ra | $^{210}$Pb |
|---|---|---|---|---|---|
| KY Bituminous Coal Fly Ash (Zielinski and Budahn, 1998) | — | Mean = 3.39 (n = 17) | Mean = 4.67 (n = 17) | Mean = 4.60 (n = 17) | Mean = 6.52 (n = 17) |
| KY Bituminous Coal Bottom Ash (Zielinski and Budahn, 1998) | — | Mean = 2.85 (n = 6) | Mean = 3.73 (n = 6) | Mean = 4.26 (n = 6) | Mean = 2.17 (n = 6) |
| TVA Kingston Coal Ash (Ruhl et al., 2009) | — | Mean = 3.04 (n = 15) | — | Mean = 4.35 (n = 15) | Mean = 4.04 (n = 3) |
| Eastern Bituminous Coal Ash (Roper et al., 2013) | Mean = 1.97 (n = 30) | — | Mean = 3.21 (n = 30) | — | — |
| Western Subbituminous Coal Ash (Roper et al., 2013) | Mean = 2.19 (n = 9) | — | Mean = 3.11 (n = 9) | — | — |
| U.S. Coal Ash[a] (Lauer et al., 2015) | Mean = 2.28 (n = 39) | Mean = 2.30 (n = 54) | Mean = 5.08 (n = 54) | Mean = 5.13 (n = 54) | Mean = 6.15 (n = 54) |

Notes:
Bq = Becquerel; pCi = Picocurie; TVA = Tennessee Valley Authority.
(a) Mean of coal ash samples collected from Appalachian (bituminous), Illinois (bituminous), and Powder River (subbituminous) Basins. Data reported in Bq/kg and converted to pCi/g (1 Bq = 27.03 pCi).

*Table 3. Regulatory annual radiation dose limits*

| Population | Type of Exposure | Limit | Source |
|---|---|---|---|
| Occupational/radiological worker | Whole body (including internal and external sources of radiation) | 5,000 mrem/year (50 mSv/year) | US NRC (2012) |
| Occupational/radiological worker | Lens of the eye | 15,000 mrem/year (150 mSv/year) | US NRC (2012) |
| Occupational/radiological worker | Extremities (hands and arms below the elbow, feet and legs below the knees) | 50,000 mrem/year (500 mSv/year) | US NRC (2012) |
| General public and minors | Whole body (including internal and external sources of radiation) | 100 mrem/year (1 mSv/year) greater than background levels | US NRC (2012) |
| General public | Drinking water (National Primary Drinking Water Standard) | 5 pCi/L for $^{226}Ra/^{228}Ra$ 30 µg/L for uranium | US EPA (2014b) |

Notes:
mrem = Millirem, or One Thousandth of a Roentgen Equivalent in Man; mSv = Millisievert; pCi = Picocurie; US EPA = United States Environmental Protection Agency; US NRC = United States Nuclear Regulatory Commission.

radiation from a model ash placed in a landfill. The authors predicted that the maximum dose of direct radiation to landfill workers would be about 0.5 mrem/year. Of that dose, $^{238}U$, $^{235}U$, and the daughter products of both contributed 0.28 mrem/year, and $^{232}Th$ and its daughter products accounted for 0.19 mrem/year. Both of these studies yielded estimated doses that are well below the occupational limit of 5,000 mrem/year (Table 3).

Alleman et al. (1998) conducted a study to determine whether gamma radiation from coal ash would pose a significant radiological risk to Indiana highway workers if the material was used as fill in highway embankments. Coal, fly ash, and bottom ash samples were collected from 16 power plants throughout the state of Indiana. The authors estimated the equivalent dose of gamma radiation that a highway worker would be exposed to during a 2,000-hour work year from an embankment of uncompacted coal ash without any soil or asphalt cover. The calculated equivalent dose rates for bottom ash and fly ash ranged from 8.09 to 37.5 mrem/year and from 7.90 to 59.1 mrem/year, respectively, both of which are well below regulatory limits of 5,000 mrem/year for occupational exposure (Table 3). These results are also in agreement with those of Smith et al. (2001) when normalized from 2,000 hours to 50 hours per year.

EPRI (2014) conducted a detailed modeling assessment of potential radiological risk to workers (see Table 4). The exposure assessment included incidental ingestion of soil (with ash) particles, inhalation of ash particles, and external exposure to radiation from the ash. In this

*Table 4. Summary of a typical fly ash model and the calculated dose in an "outdoor worker soil" scenario*

| Isotope | Concentration (pCi/g) | Half-Life | Mode of Decay and Specific Activity (Ci/g) | Calculated Dose (mrem/year) |
|---|---|---|---|---|
| $^{238}U$ | 7 | $4.468 \times 10^{9}$ years | α, $3.4 \times 10^{-7}$ | 0.027 |
| $^{230}Th$ | 7 | 80,000 years | α, 0.020 | 0.125 |
| $^{226}Ra$ | 7 | 1,602 years | α, 1.00 | 0.201 |
| $^{222}Rn$ | 7 | 3.823 days | α, 160,000 | <0.001 |
| $^{214}Pb$ | 7 | 27 minutes | β, $3.3 \times 10^{7}$ | <0.001 |
| $^{214}Bi$ | 7 | 20 minutes | β, $4.5 \times 10^{7}$ | <0.001 |
| $^{210}Pb$ | 7 | 21 years | β, 77 | 0.281 |
| $^{210}Po$ | 7 | 138.4 days | α, 4,500 | 0.015 |
| $^{232}Th$ | 4 | $1.4 \times 10^{10}$ years | α, $1.1 \times 10^{-7}$ | 0.078 |
| $^{228}Ra$ | 4 | 5.8 years | β, 280 | 0.077 |
| $^{40}K$ | 15 | $1.3 \times 10^{9}$ years | β, $7.1 \times 10^{-6}$ | 2.510 |
| **TOTAL** | | | | **3.32** |

Notes:
α = Alpha; β = Beta; Ci = Curie; mrem = Millirem, or One Thousandth of a Roentgen Equivalent in Man; pCi = Picocurie.

analysis, the following common isotopes and decay products were assessed: $^{238}$U, $^{232}$Th, $^{230}$Th, $^{222}$Rn, $^{228}$Ra, $^{226}$Ra, $^{210}$Po, $^{214}$Pb, $^{210}$Pb, $^{40}$K, and $^{214}$Bi. Exposures from ingestion, inhalation, and external radiation were considered for all isotopes, except radon exposure, which was considered as only that emanating from the ash particles inhaled by the outdoor worker (radon is primarily a heavy gas, and solid products of radon decay quickly).

Conservative values were used for model inputs. US EPA default exposure factors used include an outdoor worker who is exposed for 225 days for 8 hours per day, ingests 100 mg of soil with ash per day, and inhales particulates at a rate of 60 $m^3$/day. Concentrations were upper-bound estimates for each of the radionuclides and assumed secular equilibrium with long-lived daughter products plus radon. When all calculated doses were added together, the total dose from the model fly ash was 3.3 mrem/year, with $^{40}$K contributing about 76% of the calculated dose (Table 4). This total dose is again well below the occupational limit of 5,000 mrem/year.

## General Public Exposure and Risk

The primary pathways whereby the general public may potentially be exposed to radionuclides in CCPs include living near CCP disposal sites and fills, surface water and groundwater that have been impacted by CCP leachates, and fugitive dust.

The assessments summarized in the previous section indicated that calculated occupational doses to workers at CCP disposal sites and fills were less than 60 mrem/year. In addition to being well below the occupational dose limit of 5,000 mrem/year, this value is also below the limit specified for the general public of 100 mrem/year above background (Table 3). Alleman et al. (1998) concluded that radiological exposures would be much less for the general public than they were for the CCP workers, because of significantly less exposure time and greater distance for the general public.

In a review of fly ash produced by the combustion of U.S. coal, the United States Geological Survey (USGS, 1997) concluded that the uranium was uniformly distributed throughout the glassy particles, which is the dominant form of fly ash particles. Consequently, the leaching of uranium and release to surface and groundwater would be limited by the glassy-host particles' relatively slow rate of dissolution. USGS (1997) also proposed that, because fly ash leachate typically contains relatively large concentrations of sulfate, the concentration of radium released by fly ash particles would be limited by the solubility of radium sulfate.

In EPRI (2008), 18 leachate samples were collected from a total of three CCP management facilities in the midwestern United States. The samples were collected from surface impoundments and landfills and were analyzed for a comprehensive list of alpha and beta radiation sources. All of the samples contained less than 1 pCi/L of $^{238}$U (2.9 µg/L $^{238}$U). $^{226}$Ra was detected in 20% of the samples, but at concentrations that were also less than 1 pCi/L. $^{228}$Th was detected in only one sample (0.55 ± 0.26 pCi/L). Based on 50 coal ash leachate samples collected from 18 facilities (either landfills or surface impoundments) in the EPRI CPInfo database, the median concentration of $^{238}$U was 0.43 pCi/L (1.3 µg/L $^{238}$U), and two-thirds of the samples were below 1 pCi/L. Similarly, for 10 FGD leachate samples, the median concentration of $^{238}$U was 0.27 pCi/L (0.79 µg/L $^{238}$U), and most were again below 1 pCi/L. These values in leachate are well below the national drinking water limits for uranium of 30 µg/L and radium of 5 pCi/L (Table 3). Given the low concentrations present in CCP leachates, there is little potential for public exposure to radionuclides above drinking water limits from CCP-contaminated groundwater.

The Tennessee Department of Health, in cooperation with the federal Agency for Toxic Substances and Disease Registry, completed a public health assessment following the December 2008 coal ash spill from the Tennessee Valley Authority Fossil Plant in Kingston, Tennessee. The Kingston spill was by far the largest accidental release of ash in the United States, and therefore represents an extreme case of potential public exposure to radionuclides in ash. Average radionuclide concentrations in the ash were similar to CCP concentrations reported in the literature. With respect to radionuclides, the report states:

> The Tennessee Department of Health concludes that the small amount of radiation from the coal ash is not expected to harm people's health. Any exposure to radiation from the small amount of naturally occurring radionuclides present in coal ash, even in the more concentrated forms in coal ash, would be too small to give a radiation dose to people that would be substantially greater than the normal, everyday background radiation dose to which all people are exposed.
> *(Tennessee Dept. of Health, 2010, page xxxiv)*

## Building Material Exposure and Risk

Fly ash is used as a cement replacement in concrete and related products; in 2014, this use accounted for 13.1 million tons of fly ash. In 1983, US EPA reported that $^{226}$Ra in fly ash exceeds that in cement by "a few pCi/g," and the use of fly ash as a cement replacement will result in a slight [less than 1.0 mrem/year] increase in gamma radiation (U.S. Federal Register, 1983). Further, US EPA noted that the use of typical fly ash in concrete does not constitute a significantly different radiation risk than the risk from the cement it replaces (Table 5).

Similarly, the largest use of FGD gypsum is in commercial wallboard. By specification, wallboard-grade FGD gypsum contains very little fly ash (<1%). Assuming that all of the radium initially present in the limestone sorbent remained in the FGD solids, and assuming a 1% fly ash content, the total amount of $^{226}$Ra in the FGD gypsum would be 0.53 pCi/g, which is close to background levels. Of that amount, 84% of the radium would be derived from the natural limestone product. This calculation is in good agreement with the measurements by Roper et al. (2013) presented earlier.

*Table 5. Summary of $^{226}Ra$, $^{232}Th$, and $^{40}K$ concentrations in building materials[a]*

| Material | $^{226}Ra$ | $^{232}Th$ | $^{40}K$ |
|---|---|---|---|
| Concrete | 0.03-6.75 pCi/g (0.03-6.75 ηg/kg) | 0.03-5.13 pCi/g (0.25-46.6 mg/kg) | 0.14-42.4 pCi/g (0.02-5.97 mg/kg) |
| Cement | 0.19-4.86 pCi/g (0.19-4.86 ηg/kg) | 0.19-6.48 pCi/g (1.72-58.9 mg/kg) | 0.65-23.0 pCi/g (0.09-3.23 mg/kg) |
| Clay (Red) Bricks | 0.03-5.40 pCi/g (0.03-5.50 ηg/kg) | 0.03-5.40 pCi/g (0.25-49.1 mg/kg) | 1.62-54.0 pCi/g (0.23-7.61 mg/kg) |
| Limestone | 0.16-1.35 pCi/g (0.16-1.35 ηg/kg) | 0.03-0.81 pCi/g (0.25-7.36 mg/kg) | 0.14-18.9 pCi/g (0.02-2.66 mg/kg) |
| Tiles (Glazed and Unglazed) | 0.81-5.40 pCi/g (0.81-5.40 ηg/kg) | 0.54-5.40 pCi/g (4.91-49.1 mg/kg) | 4.32-38.1 pCi/g (0.61-5.36 mg/kg) |
| Natural Gypsum | <0.03-1.89 pCi/g (<0.03-1.89 ηg/kg) | <0.03-2.70 pCi/g (<0.25-24.6 mg/kg) | 0.19-7.56 pCi/g (0.03-1.06 mg/kg) |
| Roof Tile | 1.10-1.44 pCi/g (1.10-1.44 ηg/kg) | 1.58-2.10 pCi/g (14.3-19.1 mg/kg | 18.4-21.0 pCi/g (2.59-3.01 mg/kg) |
| Hollow Brick | 1.18-1.39 pCi/g (1.18-1.39 ηg/kg) | 1.50-1.74 pCi/g (13.7-15.8 mg/kg) | 17.5-20.5 pCi/g (2.46-2.88 mg/kg) |

Notes:
ηg = Nanogram; pCi = Picocurie.
(a) Sources: International Atomic Energy Agency (IAEA, 2003) and Lu et al. (2012).

The most significant concern that has been raised relates to the inhalation of radon, formed by the radioactive decay of $^{226}Ra$. US EPA (2014a) examined radon exposure as part of its recent beneficial-use evaluation of fly ash concrete and FGD gypsum wallboard. Based on an extensive review of the literature, US EPA concluded that:

> The cumulative body of evidence provided by these evaluations is considered sufficient to demonstrate that radiation from fly ash concrete is either comparable to that from analogous products made without CCRs [coal combustion residuals], or is at or below relevant benchmarks established by national and international standard-setting and regulatory bodies. Therefore, the current evaluation eliminated radionuclides from further consideration.
> *(US EPA, 2014a, page 1-7)*

## Summary

Coal and coal ash contain naturally occurring radionuclides. The radiation emitted from these materials is similar to the radiation from other terrestrial sources, and represents a very small level relative to total background radiation from natural and anthropogenic (mostly medically related) sources. Studies over the last several decades have consistently concluded that there is little or no incremental risk to workers and the general public attributable to radionuclide exposure from CCP disposal facilities and beneficial use applications, or from accidental releases to the environment. As summarized by the USGS:

> Radioactive elements in coal and fly ash should not be sources of alarm. The vast majority of coal and the majority of fly ash are not significantly enriched in radioactive elements, or in associated radioactivity, compared to common soils and rocks.
> *(USGS, 1997, page 4)*

# References


Alleman, JE; Clikeman, FM; Skronski, T. 1998. "Identification and Quantification of Radionuclides in Coal Ash." Report FHWA/IN/JTRP 98/1. Indiana Department of Transportation. 77p. Accessed at http://docs.lib.purdue.edu/jtrp/113.

Corbett, JO. 1983. "The radiation dose from coal burning: a review of pathways and data." *Radiation Protection Dosimetry* 4(1):5-19.

Electric Power Research Institute (EPRI). 2008. *Gross Alpha and Gross Beta Measurements in Coal Combustion Product Leachate*. EPRI, Palo Alto, CA. 1015546.

Electric Power Research Institute (EPRI). 2014. *Assessment of Radioactive Elements in Coal Combustion Products*. EPRI, Palo Alto, CA. 3002003774.

Finkelman, RB. 1993. "Trace and Minor Elements in Coal." In *Organic Geochemistry: Principles and Applications*. (Eds.: Engel, MH; Macko, SA), Plenum Publishing Corp., New York, NY, p.593-607.

International Atomic Energy Agency (IAEA). 2003. "Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation." Technical Reports Series Number 419.

Kolker, A; Finkelman, RB. 1998. "Potentially hazardous elements in coal: modes of occurrence and summary of concentration data for coal components." *Coal Preparation* 19(3-4):133-157.

Lauer, NE; Hower, JC; Hsu-Kim, H; Taggart, RK; Vengosh, A. 2015. "Naturally occurring radioactive materials in coals and coal combustion residuals in the United States." *Environmental Science & Technology*. doi: 10.1021/acs.est.5b01978.

Lu, X; Yang, G; Ren, C. 2012. "Natural radioactivity and radiological hazards of building materials in Xianyang, China." *Radiation Physics and Chemistry* 81(7):780-784.

National Council on Radiation Protection and Measurements (NCRP). 2009. "Ionizing Radiation Exposure of the Population of the United States." NCRP Report No. 160. 387p.

Roper, AR; Stabin, MG; Delapp, RC; Kosson, DS. 2013. "Analysis of naturally-occurring radionuclides in coal combustion fly ash, gypsum, and scrubber residues samples." *Health Physics* 104(3):264-269.

Ruhl, L; Vengosh, A; Dwyer, GS; Hsu-Kim, H; Deonarine, A; Bergin, M; Kravchenko, J. 2009. "Survey of the potential environmental and health impacts in the immediate aftermath of the coal ash spill in Kingston, Tennessee." *Environmental Science & Technology* 43(16):6326-6333.

Ryan, JL; Rai, D. 1987. "Thorium (IV) hydrous oxide solubility." *Inorganic Chemistry* 26(24):4140-4142.

Smith, KR; Crockette, GM; Oatway, WB; Harvey, MP; Penfold, JSS; Mobbs, SF. 2001. "Radiological Impact of the UK Population of Industries Which Use or Produce Materials Containing Enhanced Levels of Naturally Occurring Radionuclides: Part 1: Coal-fired Electricity Generation." National Radiological Protection Board (UK), OX11 ORQ, Report NRPB-R327.

Tennessee Dept. of Health. 2010. "Public Health Assessment, Tennessee Valley Authority (TVA) Kingston Fossil Plant Coal Ash Release, 714 Swan Pond Road, Harriman, Roane County, Tennessee (Final)." with Agency for Toxic Substances and Disease Registry (ATSDR), 317p., September 7.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2000. "Sources and Effects of Ionizing Radiation: Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, with Scientific Annexes. Volume I: Sources." Submitted to the United Nations General Assembly. UNSCEAR 2000 Report, Vol. I. Accessed at http://www.unscear.org/unscear/en/publications/2000_1.html.

US EPA. 1984. "Radionuclides: Background Information Document for Final Rules, Volume 2." Office of Radiation Programs. National Technical Information Service (NTIS). EPA-520/1-84-022-2; NTIS PB85-165769. 474p., October 22.

US EPA. 2014a. "Coal Combustion Residual Beneficial Use Evaluation: Fly Ash Concrete and FGD Gypsum Wallboard." Office of Solid Waste and Emergency Response, Office of Resource Conservation and Recovery. 91p., February. Accessed at http://www2.epa.gov/sites/production/files/2014-12/documents/ccr_bu_eval.pdf.

US EPA. 2014b. "National Primary Drinking Water Regulations." 40 CFR 141. Accessed at http://www.gpo.gov/fdsys/pkg/CFR-2014-title40-vol23/pdf/CFR-2014-title40-vol23-part141.pdf.

US Geological Survey (USGS). 1997. "Radioactive Elements in Coal and Fly Ash: Abundance, Forms, and Environmental Significance." USGS Fact Sheet FS-163-97. 4p., October.

US Geological Survey (USGS). 2006. "National Coal Resources Data System." Accessed at http://energy.er.usgs.gov/products/databases/CoalQual/index.htm.

US Nuclear Regulatory Commission (US NRC). 2012. "Part 20. Standards for Protection Against Radiation." Accessed at http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/full-text.html.

Wagner, P; Dreesen, DR; Wewerka, EM; Greiner, NR. 1980. "Radioactive Emissions from Coal Production and Utilization." Progress Report LA-8618-PR. Los Alamos Scientific Laboratory, 28p.

Wagner, P; Greiner, NR. 1982. "Radioactive Emissions from Coal Production and Utilization." Progress Report LA-9359-PR. Los Alamos Scientific Laboratory, 21p.

Zielinski, RA; Budahn, JR. 1998. "Radionuclides in fly ash and bottom ash: improved characterization based on radiography and low energy gamma-ray spectrometry." *Fuel* 77(4):259-276.

Zielinski, RA; Affolter, RH; Budahn, JR; O'Connor, JT; Rice, CA. 1999. "Uranium in coal and fly ash: abundance, forms, and environmental significance." In *Proceedings of the 24th International Technical Conference on Coal Utilization and Fuel Systems, March 8-11, 1999, Clearwater, Florida*. Coal and Slurry Technology Association, Washington, DC, p.913-924.

# Definitions

**Absorbed Dose**: The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest in that material. For any radiation type and any medium, absorbed dose (D) is the total energy (e) absorbed per unit mass (m) of material: D = e/m. The two main metrics for absorbed dose are the gray (Gy) and the rad. 1 rad = 0.01 joule/kg material, and 1 Gy = 100 rad

**Activity**: The rate of transformation (or "disintegration" or "decay") of radioactive material. The units of activity are the curie (Ci) and the becquerel (Bq).

**Alpha ($\alpha$) Particle**: A positively charged nuclear particle identical to the nucleus of a helium atom that consists of two protons and two neutrons and is ejected spontaneously at a high speed in certain radioactive transformations. Alpha radiation is more damaging than the same dose of beta or gamma radiation but can be stopped by a sheet of paper.

**Becquerel (Bq)**: A unit of measurement of radioactivity. One becquerel is the activity of a quantity of radioactive material in which one nucleus decays per second. One Ci is equal to $3.7 \times 10^{10}$ Bq, and 1 Bq is equal to 27.03 picocurie (pCi).

**Beta ($\beta$) Particle**: A negatively charged particle that is emitted by the nucleus of certain radioactive atoms during radioactive decay. Beta radiation is less damaging than the same dose of alpha radiation but is more penetrating. Beta radiation can be stopped by a thin sheet of metal or plastic.

**Curie (Ci)**: The unit of measurement of radioactivity that equals the quantity of radioactive material that will have $3.7 \times 10^{10}$ disintegrations per second. Units commonly used in environmental measurements are smaller units, such as the picocurie (pCi), which is equal to one trillionth ($1/10^{12}$) Ci.

**Decay Chain**: A series of radionuclides, each of which disintegrates into the next until a stable nuclide is reached.

**Effective Dose**: A dose metric that is used to account for the relative susceptibility of specific tissues to radiation-induced damage. To obtain an effective dose from the equivalent dose, tissue weighting factors are applied. These factors have been officially tabulated by organizations such as the National Council on Radiation Protection (NCRP), the International Commission on Radiological Protection (ICRP), and the United States Nuclear Regulatory Commission (US NRC). Like the equivalent dose, the effective dose is expressed in either sieverts (Sv) or roentgen equivalent in man (rem).

**Equivalent Dose**: A dose metric that is based on absorbed dose but is more closely related to biological and health effects of radiation. The equivalent dose differs from the absorbed dose in that it accounts for the relative biological effectiveness of the type of radiation to cause tissue damage (e.g., $\alpha$-particles versus X-rays). The two main metrics for equivalent dose are the Sv and the rem.

**Gamma ($\gamma$) Rays**: High-energy electromagnetic photons that are similar to X-rays. Gamma rays are highly penetrating and can only be stopped by several inches of lead or several feet of concrete.

**Roentgen Equivalent in Man (Rem)**: This unit relates to adjusting absorbed dose in human tissue to the effective biological damage due to the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Here, the quality factor (q) is unique to the type of incident radiation. The equivalent dose is often expressed in terms of thousandths of rem (or mrem). The equivalent dose (rem) is equal to the absorbed dose (rad) multiplied by the quality factor (1 rem = 0.01 sievert).

**Ionizing Radiation**: Any type of radiation that, directly or indirectly, can change the electric charges of atoms or molecules. In other words, ionizing radiation is radiation with enough energy that, during its interaction with an atom, it can remove tightly bound electrons from their orbits, causing the atom to become charged or ionized. Ionizing radiation is produced when radionuclides decay. Gamma rays are an example of ionizing radiation.

**Naturally Occurring Radioactive Materials (NORM)**: Long-lived radioactive elements, such as uranium, thorium, and potassium, and any of their decay products, such as radium and radon, are examples of NORM. These elements have always been present in the earth's crust and atmosphere and are concentrated in some places, such as in bodies of uranium ore, which may be mined.

**Secular Equilibrium**: In secular equilibrium, the rate of decay of a parent is equal to that of its decay product. Secular equilibrium occurs when the half-life of the daughter isotope is much shorter than the half-life of the parent isotope.

**Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM)**: Materials in which the amount of radioactivity has been increased or concentrated as a result of industrial processes. Industries known to produce TENORM include coal mining and combustion, oil and gas production, metal mining and smelting, and construction.

**The Electric Power Research Institute, Inc.** (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together . . . Shaping the Future of Electricity

**Contact Information**
The Electric Power Research Institute (EPRI) prepared this technical update. The EPRI technical contact is Ken Ladwig, keladwig@epri.com or 262-361-8075.

3002008481 October 2016

**Electric Power Research Institute**
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com