Ionizing Radiation Doses from Coal Combustion Products

2022 TECHNICAL REPORT

Ionizing Radiation Doses from Coal Combustion Products

3002024222

Final Report, October 2022

EPRI Project Manager
B. Hensel

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Risk Assessment Corporation

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Together…Shaping the Future of Energy®

ACKNOWLEDGMENTS

The following organizations, under contract to EPRI, prepared this report:

Risk Assessment Corporation
417 Till Rd
Neeses, SC 29107

Principal Investigator
C. Mangini

Contributing Authors
E. Caffrey
H. Grogan
J. Mohler
A. Rood
J. Till

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Ionizing Radiation Doses from Coal Combustion Products. EPRI, Palo Alto, CA: 2022. 3002024222.

ABSTRACT

Coal combustion product (CCP) worker radiation exposures have been identified as a potential factor contributing to various health issues because uranium decay series radionuclides are present in the respirable fraction of fly ash. Although limited government reports and regulations are available with established limits on effective radiation exposure to certain classes of workers and the general public, there are no published case studies in the peer-reviewed scientific literature or applicable regulations pertaining to effective doses of ionizing radiation from CCPs to site workers at CCP management units. The objective of this research is to use analytical measurements of radionuclides in CCPs to advance the understanding of the potential ionizing radiation doses to workers at CCP management facilities using an independent assessment that is transparent, timely, and scientifically defensible.

This analysis uses measurements of specific radionuclides in CCPs along with modeling to estimate air concentrations that could occur from activities related to managing CCPs. Hypothetical exposure scenarios that could lead to worker doses are developed and characterized based on readily available values in the literature. The dose calculations represent the bounding doses that could be received by hypothetical outdoor site workers at CCP management units and put them into perspective based on published dose thresholds for technologically enhanced naturally occurring radioactive material (TENORM) disposal facilities.

Keywords

Coal combustion products (CCPs)
Ionizing radiation
Radium
Worker dose

Deliverable Number: 3002024222

Product Type: Technical Report

Product Title: Ionizing Radiation Doses from Coal Combustion Products

PRIMARY AUDIENCE: Electric utility occupational health and safety (OHS) managers and environmental managers.

SECONDARY AUDIENCE: Electric utility policy staff; other entities that own sites where CCPs are managed.

KEY RESEARCH QUESTION

Coal combustion product (CCP) worker radiation exposures have been identified as a potential factor contributing to various health issues because uranium decay series radionuclides are present in the respirable fraction of fly ash. Although limited government reports and regulations are available with established limits on effective radiation exposure to certain classes of workers and the general public, there are no published case studies in the peer-reviewed scientific literature or applicable regulations pertaining to effective doses of ionizing radiation from CCPs to site workers at CCP management units. The objective of this research was to use analytical measurements of radionuclides in CCPs to advance the understanding of the potential ionizing radiation doses to workers at CCP management facilities using an independent assessment that is transparent, timely, and scientifically defensible.

RESEARCH OVERVIEW

The research objectives were achieved via a collaborative effort between EPRI and the Tennessee Valley Authority (TVA). TVA provided radionuclide measurements from CCPs and background soils at its power plants, and EPRI independently performed the analysis. This analysis uses measurements of specific radionuclides in CCPs along with modeling to estimate air concentrations that could occur from activities related to managing CCPs. Hypothetical exposure scenarios that could lead to worker doses are developed and characterized based on readily available values in the literature. The dose calculations represent the bounding doses that could be received by hypothetical outdoor site workers at CCP management units and put them into perspective based on published dose thresholds for technologically enhanced naturally occurring radioactive material (TENORM) disposal facilities.

KEY FINDINGS

- Using the measured CCP concentrations, the bounding exposure scenario for periods of no placement yielded a worst-case annual effective dose of 10.2 mrem above background.
- When placement was considered, an additional effective dose from inhalation of 3.42×10^{-3} mrem per CCP load was estimated.
- Under the implausible scenario in which a worker is continuously exposed to placement activities over the course of a 1,680-hour work year, the additional annual dose was estimated to be 43.1 mrem above background.
- The worst-case effective doses estimated in this report were all less than the 100 mrem yr^{-1} dose limit recommended by the American National Standards Institute for workers at TENORM landfills.
- Doses presented here are all well below the level at which potential health effects may be observed, according to Health Physics Society's 2004 Positional Statement on Radiation Risk in Perspective.

WHY THIS MATTERS

This research helps utilities and other entities that work with CCPs to understand maximum doses likely to be received by site workers.

HOW TO APPLY RESULTS

Readers interested in general information on dose assessment are referred to Section 2. Section 4 describes assumptions based on protective CCP management unit worker safety measures at one electric utility. Section 8 explains how the conservative doses calculated during this research compare to reference values.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Readers interested in the general occurrence of radionuclides in CCPs can refer to the following previously published EPRI research:

- 1024742, *Health Effects of Inhalation of Coal Combustion Products*, 2011
- 3002003774, *Assessment of Radioactive Elements in Coal Combustion Products*, 2014
- 3002008481, *Radioactivity in Coal Combustion Products*, 2016
- 3002016496, *Chemical Constituents in Coal Combustion Products: Radium*, 2019

EPRI CONTACTS: Bruce Hensel, Technical Executive, bhensel@epri.com; Benjamin Gallagher, Principal Technical Leader, bgallagher@epri.com

PROGRAM: CCP Land and Groundwater Management, P242; Coal Combustion Products Management, P241

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

ACRONYMS AND ABBREVIATIONS

AMAD	Activity Median Aerodynamic Diameter
ANSI	American National Standards Institute
Ci	Curie, imperial unit of radioactivity
CCP	Coal Combustion Products
CCR	Coal Combustion Residual
CED	Committed Effective Dose
DL	Detection Limit
DOE	U.S. Department of Energy
EEC	Equilibrium Equivalent Concentration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FGR	Federal Guidance Report
HPS	Health Physics Society
ICRP	International Commission on Radiological Protection
IAEA	International Atomic Energy Agency
MDC	Minimum Detectable Concentration
NCRP	National Council on Radiation Protection and Measurements
NORM	Naturally Occurring Radioactive Materials
NRC	U.S. Nuclear Regulatory Commission
PEF	Particle Emission Factor
PM	Particulate Matter
PRG	Preliminary Remediation Goals
RAGS	Risk Assessment Guidance for Superfund (RAGS) Supplemental Guidance
RSL	Regional Screening Levels
TENORM	Technologically Enhanced Naturally Occurring Radioactive Materials
WHO	World Health Organization
WLM	Working Level Month

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Coal combustion product (CCP) worker radiation exposures have been identified as a potential factor contributing to various health issues, in part based on findings such as those of Mustonen and Jantunen (1985), who showed nearly 40 years ago that uranium decay series radionuclides are present in the respirable fraction of fly ash. Although limited government reports and regulations are available with established limits on effective radiation exposure to certain classes of workers and the general public, there are no published case studies in the peer-reviewed scientific literature on effective doses of ionizing radiation from CCPs to site workers at CCP management units. The objective of this research is to use analytical measurements of radionuclides in CCPs to advance the understanding of the potential ionizing radiation doses to workers at CCP management facilities using an independent assessment that is transparent, timely, and scientifically defensible.

This analysis uses measurements of specific radionuclides in CCPs along with modeling to estimate air concentrations that could occur from activities related to managing CCPs. Hypothetical exposure scenarios that could lead to worker doses are developed and characterized based on readily available values in the literature. The dose calculations represent the bounding doses that could be received by hypothetical outdoor site workers at CCP management units and put them into perspective based on published dose thresholds recommended by the American National Standards Institute for workers at TENORM landfills. In addition, doses presented here are compared to the level at which potential health effects may be observed, according to Health Physics Society's 2004 Positional Statement on Radiation Risk in Perspective.

2
DOSE ASSESSMENT METHODOLOGY

In the profession of health physics, *radiological dose assessment* is defined as the process of estimating dose to humans from exposure to radiation. Radiation originates from a source that may be either man-made or natural. Exposure occurs through direct irradiation from the source or through radioactive materials released to air or water in the environment that results in a flux or concentration in environmental media at the point of exposure. These concentrations can be converted to dose by assuming a scenario of exposure for individuals present.

Dose assessments may be carried out using deterministic or probabilistic methods. In either approach, valid measurement data or mathematical modeling or a combination of the two is typically required. Valid measurement data should always be used to the fullest extent possible because they represent the most direct method for characterizing concentrations in the environment.

The process of assessing radiological dose to humans from exposure to radiation requires the merging of several scientific disciplines. The components that make up radiological dose assessment evolved from individual sciences that have been merged to form the computational methods now used to estimate dose to humans. In explaining the process of dose assessment, the following illustrative equation (Till and Grogan, 2008) can be used to express the interdisciplinary nature of this research:

$$Dose = (S \cdot T \cdot E \cdot D)_u \quad \textbf{Eq. 2-1}$$

where

S = source term (characterization of the quantity and type of material released to the environment)

T = environmental transport and fate of the material released

E = exposure factors (characteristics and behavior of individuals exposed)

D = conversion to dose

u = uncertainty

The source (S) and transport (T) terms are used to calculate radionuclide concentrations in the environment to which people are exposed. In some cases, analytical measurements are available and can be used directly without requiring separate calculations of S and T.

Source Term

The source (S) term is the characterization and quantification of the material released to the environment that ultimately causes exposure; it is the heart of a dose assessment in the absence of concentrations measured directly in environmental media. Therefore, it is important that development of the source term be given high priority from the outset of a dose assessment. It is often based on historical records or prior release measurement data for a facility; facility throughput; notebooks or logs of materials released; and any other data that help establish the amounts and types of material being received, processed, and released to the environment.

A source emitting direct radiation is characterized by intensity, energy, type of radiation, and half-life of the material. The radiation dose at the point of exposure is affected by time spent in the vicinity, distance from the source, and shielding. For radionuclides released to air or water or present in environmental media, such as CCP materials, the source is characterized by type of radionuclide, concentration, temporal duration of release, and chemical and physical form.

Uncertainties should be included with the estimates of releases. This aspect of the source term has frequently been overlooked in the past, with release estimates being reported as single values when, in reality, a range of possible values exists. The uncertainty estimates account for sources of uncertainty in the calculation of the release estimates.

Environmental Transport

Once characteristics of the source have been estimated, the next step is to determine the concentration of radionuclides in environmental media at the point of exposure. For exposure to radionuclides released from a source, relevant exposure pathways need to be determined and transport (T) of radionuclides through these pathways must be addressed. Once key pathways and specific types of radioactive materials (radionuclides) are identified, more comprehensive transport models are applied.

Transport of radioactive materials in the environment can be evaluated in several ways. If there are measurement data in the environment that are sufficiently thorough, these measurements may be used directly to determine concentrations in media. The more data available to characterize the environment, the more defensible the estimates of dose will be. Measurements of environmental concentrations are preferable to modeling because they mitigate the uncertainty in transport models and their inputs. In some cases, measurement data are not available. An example is dose assessments that are being undertaken for new facilities where releases of materials may occur at some point in the future. In most cases, environmental transport is determined using a combination of both modeling and measurement data.

One important aspect of estimating environmental transport is to use data (for example, wind speed, moisture contents, and bulk densities) that are representative of the site. However, site-specific data required to fully characterize and evaluate transport through the environment are often lacking. In most cases, some surrogate information must be applied. These data may come from several different sources; however, the resulting dose calculation will be most relevant if site-specific transport information is used when available or collected if possible.

For fly ash storage and disposal activities at a coal-fired power plant, the two principal mechanisms for airborne emissions are 1) wind-driven suspension from in-place CCPs and 2) placement (that is, unloading and grading) of new CCPs.

Exposure Factors

The radiological dose to a person depends on several characteristics, called *exposure factors* (E), such as exposure frequency, exposure duration, and the traits of the individual. These traits include physiological parameters (e.g., breathing rate), dietary information (e.g., consumption rate of various foods or inadvertent soil ingestion), residence data (e.g., type of dwelling), use of local resources (e.g., agricultural resources), recreational activities (e.g., swimming), and any other individual-specific information that is necessary to estimate dose. Default values for many exposure factors have been widely researched and are available in the scientific literature. In radiological assessment, a specific set of these characteristics is referred to as an *exposure scenario*.

The target of a radiological assessment may be real individuals or representative individuals. Real individuals are those who are or were actually exposed. Their characteristics should be defined as closely as possible to those that existed during their exposure period. Representative, or hypothetical, individuals are not characterized by specific persons but have characteristics similar to people in the area who are or were exposed in the past or who may be exposed in the future.

There is no prescribed approach for defining and presenting scenarios of exposure in radiological assessment. This decision must fit the particular assessment being undertaken, the type of individual (real or representative) being evaluated, and the goals of the assessment. For this study, this individual will be limited to a general worker working outdoors at an active CCP management unit.

Conversion to Dose

The conversion of radionuclide intake or external exposure to dose (D) is well established because of advancements made in deriving and publishing dose coefficients using metabolic models. Dose coefficients for radiological dose assessments are those published by the International Commission on Radiological Protection (ICRP), U.S. Department of Energy (DOE), or the Environmental Protection Agency (EPA). These coefficients continue to be updated (ICRP 1993, 1995a, 1995b, 1996, 2002) to cover a large number of radionuclides and age groups. For this project, the most up-to-date dose coefficients for external exposure published by EPA were used (EPA, 2019). Likewise, the most recent dose coefficients for radionuclide intakes published by DOE were used (DOE, 2021).

Uncertainty

Radiological dose assessments may be conducted deterministically or probabilistically, or a combination of these may be applied. The goal is to use the simplest approach that meets the objective of the dose assessment. In some cases, a deterministic approach using simple screening models may be used that incorporates high-sided values for parameters that maximize the resulting dose (NCRP, 1996). If screening yields a result in compliance with a regulatory limit, no further action is typically needed. If the screening result indicates potential for a dose higher than a regulatory limit or otherwise raises questions that require further analysis, a more realistic approach for estimating parameters is typically undertaken. If a probabilistic approach is applied, uncertainty (u) is considered for pertinent aspects and elements of the calculation.

Uncertainty analysis evaluates the precision of the calculated doses. This is achieved by investigating the uncertainty of variables used in calculations that rely on measurements and models. Uncertainty analysis and the methods for quantification of uncertainty have been well established. The most widely accepted method for uncertainty analysis uses Monte Carlo statistical techniques that incorporate a random sampling of distributions of the various model input parameters. Typically, when a dose assessment is done, the mean estimate of dose from numerous computer runs (termed *model realizations*) is reported. For one model realization, the Monte Carlo statistical method randomly selects one value from a distribution assigned to each parameter. These values are then run in the model to produce an output value that is stored, and the process is repeated hundreds to thousands of times, resulting in a distribution of output values. The mean value from the output distribution is typically reported.

Dose Terminology

There are several ways that radiation dose is quantified. At its most basic level, radiation dose is simply the amount of energy absorbed per unit mass of biological tissue—this is called the *absorbed dose*. However, there are several different types of radiation, for example, alpha particles, beta particles, and gamma rays. Each type of radiation causes a different amount of damage to biological tissue for the same amount of energy absorbed per unit mass. To account for this, an adjustment factor—called the *radiation weighting factor (w_R)*—is applied to the absorbed dose, and a new dose quantity—the *equivalent dose*—is the result. In addition, each organ in the body has a different sensitivity to radiation. To account for these differences, another adjustment factor—the tissue weighting factor (w_T)—is applied to the equivalent dose, and a third dose quantity, the *effective dose*, is the result. The relationship between these three types of radiation doses is summarized here:

Absorbed Dose, *D*

Units: rad

Equation: $D = \frac{\text{energy}}{\text{mass}}$

Equivalent Dose, *H*$_T$

Units: rem

Equation: $H_T = D \times w_R$

Effective Dose, *E*

Units: rem

Equation: $E = \sum_T w_T \times H_T$

Once a radionuclide has entered the body—e.g., via inhalation or ingestion of material—its radioactivity will decrease over time based on its radiological and biological half-life. The radiological half-life is a physical property of the radionuclide that was inhaled or ingested and represents the amount of time for half of the original amount of material to decay. The biological half-life is the amount of time it takes the body to excrete half of the original amount of intake and is dependent on both the radionuclide and body chemistry. The combination of the radiological and biological half-life is often referred to as the *effective half-life*. Some radionuclides have such long radiological and biological half-lives that they essentially remain in the body indefinitely. To account for this ongoing radiation in the body, the equivalent and effective doses can also be expressed as *committed equivalent dose* or *committed effective dose (CED)*. A committed dose integrates the dose over a specified time period, usually to age 70. This accounts for the dose received by a person from a single intake over their lifetime.

3

RADIOLOGICAL CHARACTERIZATION OF THE SOURCE TERM AND OTHER DATA

For this analysis, the *source term* refers to the total activity, volume, and radionuclide composition of CCP materials that are processed at a CCP management unit. Radionuclides contributing to worker doses are those associated with technologically enhanced naturally occurring radioactive material (TENORM), because CCPs typically contain higher concentrations of these radionuclides than those that occur naturally in the environment (Karamdoust and Durrani, 1991). These radionuclides consist of those in the uranium and thorium decay series, including Ra-226, Th-230, U-238, U-235, and radon progeny. The full decay schemes for U-238 and Th-232 are shown in Figure 3-1 and Figure 3-2. Karamdoust and Durrani (1991) also noted that there is a significant disturbance of radioactive equilibrium within the uranium series.

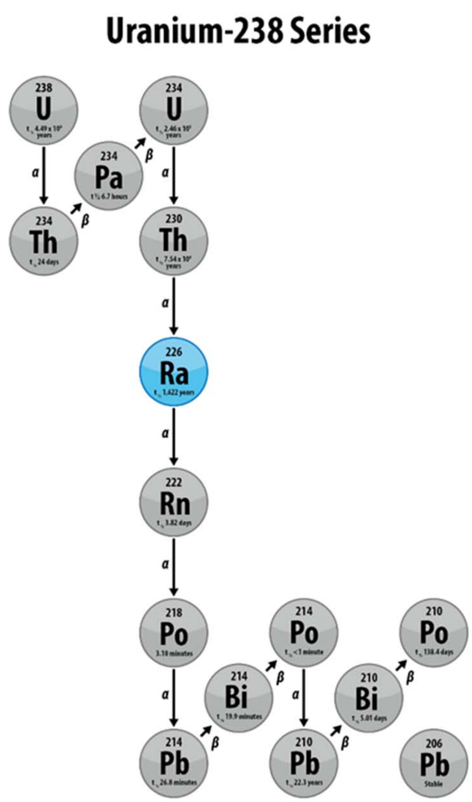

Figure 3-1
Uranium-238 decay scheme showing the short-lived progeny that will be present alongside the parent (modified from EPRI, 2019)

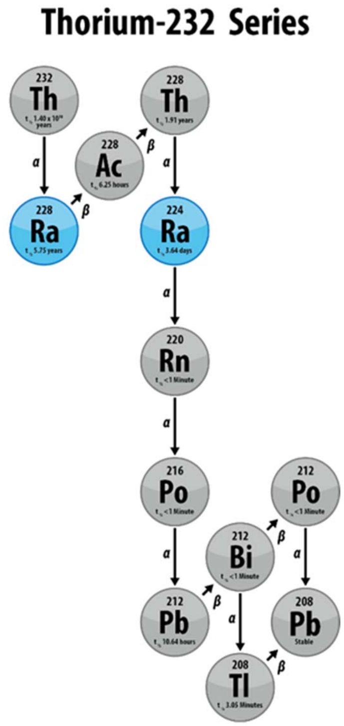

Figure 3-2
Thorium-232 decay series showing the short-lived progeny that will be present alongside the parent (modified from EPRI, 2019)

When coal is burned, the resulting CCPs will have differing levels of TENORM that are directly related to the amount of radioactive material that was in the coal before it was burned, the physical and chemical properties of the radionuclides, and the characteristics of the coal-burning processes. Karangelos et al. (2004) found that due to the different enrichments in U-238, there was a significant disturbance of radioactive equilibrium within the uranium series. More specifically, the volatile Pb-210 condenses out preferentially on the finer fly ash particles, which are cooled first. These finer fly ash particles have a higher surface-to-volume ratio, resulting in higher specific activity of the condensed Pb-210. This is supported by Mustonen and Jantunen (1985) who found that Pb-210 in emitted fly ash had an output-to-input activity ratio of 1.4. Similarly, Lauer et al. (2015) found that Pb-210 was at elevated concentrations compared to U-238 and Ra-226, attributing the increase to the volatilization of lead during the combustion process. However, they concluded that U-238 and Ra-226 appeared to be in secular equilibrium as well as Th-232 and Ra-228. Their study focused on three different CCP deposits in the United States.

As will be discussed later, measurement data for this report were limited to Ra-226 and Ra-228. The assumption of secular equilibrium is made for each respective decay chain. TENORM radionuclides with half-lives greater than five years are presented in Table 3-1. Numerous short-lived radioactive progeny would also be present. This assumption is considered high-sided because Pb-210 is the only decay progeny found to be at consistently higher levels than other progeny measured in CCP materials. As will be shown later in this report, Pb-210 is not a prominent contributor to the calculated radiological doses.

Table 3-1
Relevant TENORM radionuclides and their half-lives

Radionuclide	Half-Life (years)
U-238	4.47×10^9
U-234	2.46×10^5
Th-230	7.54×10^4
Ra-226	1.6×10^3
Pb-210	22.2
Th-232	1.4×10^{10}
Ra-228	5.75
Th-228	1.91

Data Assembly and Evaluation

This research was a collaborative effort between EPRI and the Tennessee Valley Authority (TVA) in which TVA provided radionuclide measurements and EPRI performed independent analysis on the data. TVA provided EPRI with analytical measurements of Ra-226 and Ra-228 levels in CCP and background soils at many of its CCP management units. The background data enabled characterization of both gross and net concentrations.

The CCP samples were composed of mostly fly ash but also contained some bottom ash, FGD gypsum, and possibly lesser amounts of slag, dry scrubber material, and mixtures. Other data—including meteorological, industrial hygiene respirable dust concentrations, and CCP physical property information—are also used to evaluate the concentrations to which outdoor workers could be exposed from the CCP piles directly and from CCP material suspended in the air due to management and movement of the CCP by site workers.

Analysis of Coal Combustion Product Analytical Data

The TVA data were compiled into a database to facilitate efficient analysis. Samples were categorized as either CCP material from the facility or soil representing background in the vicinity of the facility. The endpoint of interest for this study was to evaluate on-site worker exposures above background. Therefore, the net excess CCP concentration (CCP concentration minus background concentration) was selected as the appropriate exposure concentration.

The data were initially examined to evaluate the distribution of concentrations (e.g., normal or log-normal) and to confirm the assumption that the CCP pile content can be considered homogeneous. For these analyses, only detected concentrations were used, although it is important to consider the non-detect results as part of establishing the assumed exposure concentrations. Non-detect measurements were removed because of the large range of detection limit values. Treatment of non-detect measurements for establishing exposure levels is discussed further in the Methodology for Establishing Exposure Levels section.

Figures 3-3 and 3-4 show the distribution of detected CCP concentrations at all plants for Ra-226 and Ra-228, respectively. In general, the data exhibit a relatively normal distribution with a slight skew toward higher concentrations for Ra-226, which is suggestive of a log-normal distribution. A normal distribution would be consistent with the similarity observed between the mean and median concentrations, where Ra-226 has a mean concentration of 4.3 pCi g^{-1} and a median concentration of 4.1 pCi g^{-1} and Ra-228 has a mean concentration of 2.6 pCi g^{-1} and a median concentration of 2.7 pCi g^{-1}. As such, using either the mean or median concentration will not have a significant effect on the assumed exposure concentrations.

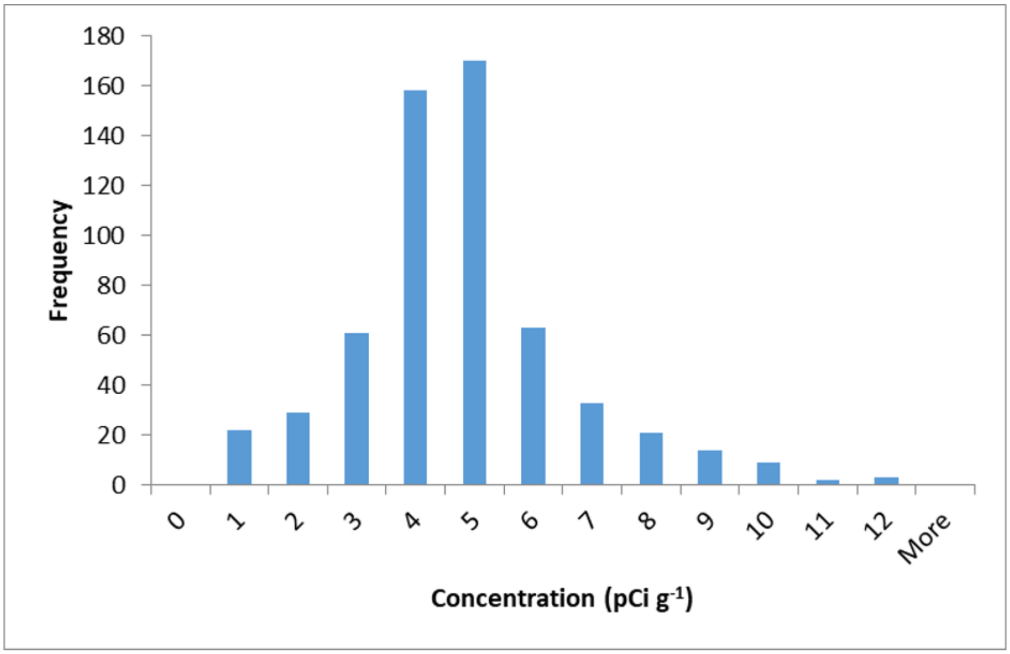

Figure 3-3
Frequency distribution of Ra-226 concentrations in CCP materials

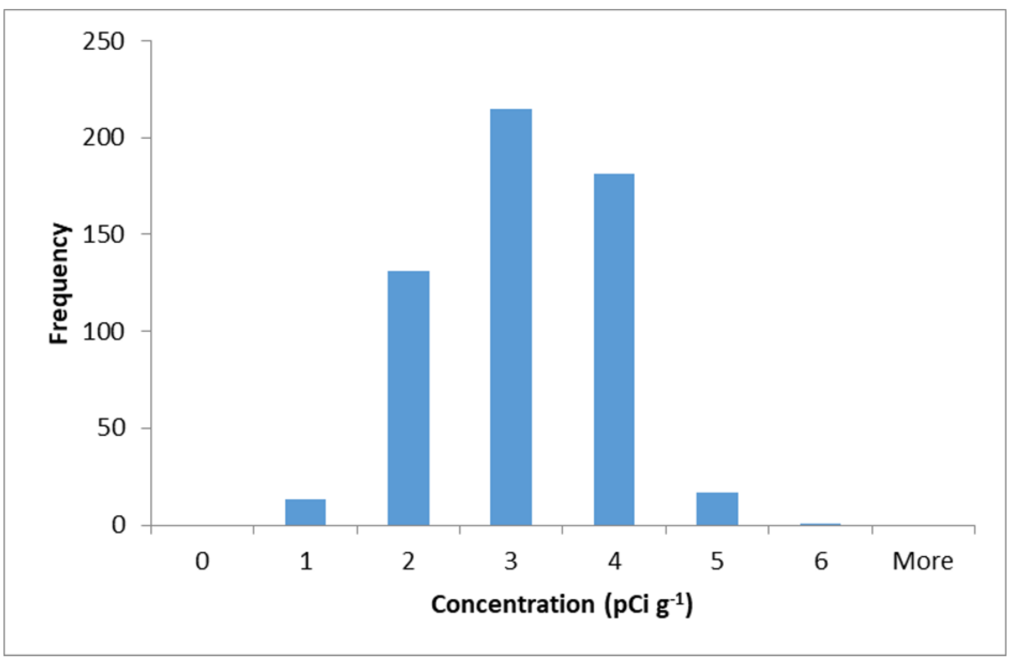

Figure 3-4
Frequency distribution of Ra-228 concentrations in CCP materials

Figures 3-5 and 3-6 show the Ra-226 detected concentrations in CCP samples as a function of depth from the surface within the CCP piles compared to the Ra-226 concentrations as a function of depth for background samples for the Bull Run Fossil Plant and Kingston Fossil Plant, respectively. The pattern is generally similar for the other sites (see Appendix A), and there is no clear indication of increasing or decreasing concentration with depth—which supports the assumption that the CCP piles are homogeneous with respect to Ra-226 and Ra-228 concentrations.

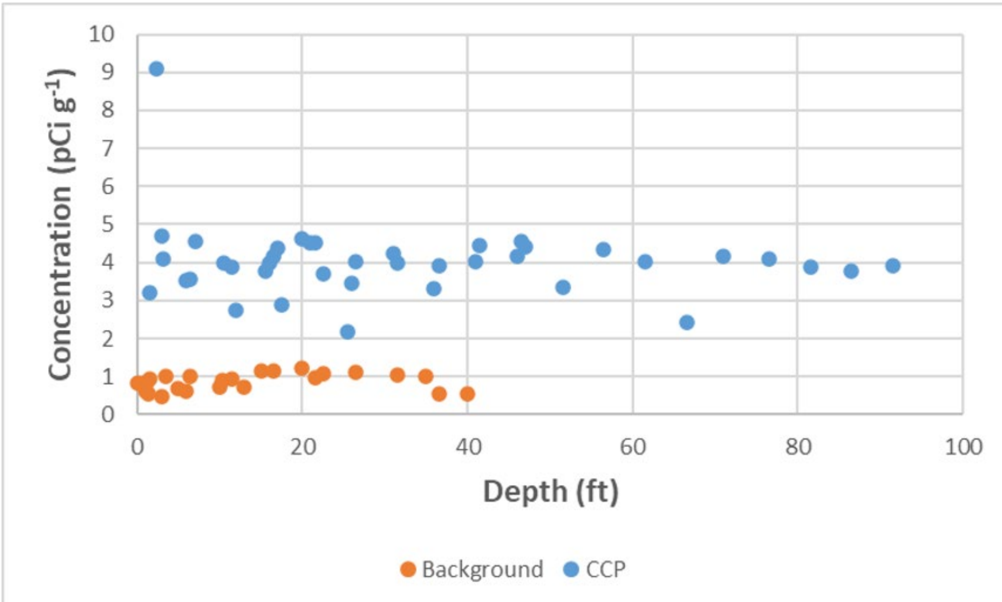

Figure 3-5
Ra-226 concentrations as a function of depth at the Bull Run Fossil Plant

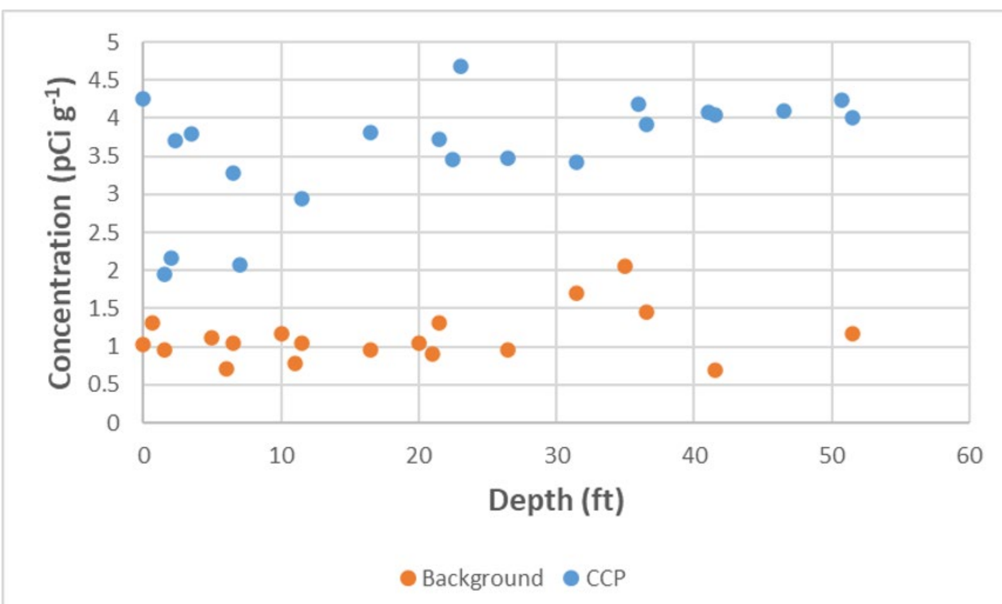

Figure 3-6
Ra-226 concentrations as a function of depth at the Kingston Fossil Plant

Analysis of Other Data

Meteorological Data

Meteorological data were obtained for several TVA sites and analyzed to determine an appropriate wind speed for estimating particle suspension during management and movement of the CCP material by on-site workers. Table 3-2 shows the average wind speed measured at 10 m for several plants. The data are summarized for all hours, working hours only, and non-working hours only. It is evident that the wind speed is consistently greater during working hours than during non-working hours.

Table 3-2
Average wind speed measured at 10 m for different plants

Site	Time Period	Average Wind Speed (mph)
Colbert	All hours	5.1
Johnsonville		4.6
Kingston (valley)		3.1
Paradise		6.0
Shawnee		5.5
Widows Creek (valley)		4.1
Average[a]		4.5
Colbert	Non-Working	4.2
Johnsonville		3.9
Kingston Valley		2.5
Paradise		5.6
Shawnee		4.7
Widows Creek (valley)		3.4
Average		3.8
Colbert	Working[b]	6.4
Johnsonville		5.7
Kingston Valley		4.0
Paradise		6.6
Shawnee		7.0
Widows Creek (valley)		5.3
Average		5.7

a. Weighted average of site averages based on number of measurements at each site.
b. Defined as 9 am to 5 pm.

Industrial Hygiene Data

Industrial hygiene data were obtained from TVA for employees while performing work activities, primarily as part of remediation work at the Kingston Fossil Plant in 2009. Among other parameters, these data included respirable dust concentrations obtained through personnel air monitoring. The monitoring data were separated into two categories: those that likely involved movement of CCP material (e.g., grader operator, dozer operator, trackhoe operator, excavator, dump truck operator) and those that did not likely involve movement of CCP material (e.g., boat operator, shoreline operator, flagger, vacuum truck technician). Table 3-3 shows statistics related to the respirable dust concentrations that were measured. The data suggest that activities involving digging and movement of CCP materials may lead to an increase of approximately 0.03 mg m^{-3} above ambient air concentrations of respirable dust.

Table 3-3
Respirable dust measured for placement and non-placement activities types at Kingston Fossil Plant

Parameter Measured	Units	Placement	Average	Median	Min	Max
Respirable dust	mg m^{-3}	no	0.067	0.051	0.033	0.14
Respirable dust	mg m^{-3}	yes	0.095	0.0725	0.042	0.26

Physical Properties of Coal Combustion Products

Important physical properties of CCP include density, particle size, and moisture content. Given that the majority of CCP material present in the analyzed samples was fly ash, physical properties of fly ash were used to characterize the CCP material in this report. The specific physical property parameters required as inputs for the outdoor worker exposure analysis depend on the approach selected for estimating particulate emissions (see Section 5). Table 3-4 shows density and particle diameters for which 10, 50, and 90% of the material is smaller (e.g., 10% of particles at Bull Run are smaller than 5.7 µm in diameter) for fly ash at several plants (EPRI, 1993). Based on these data, a fraction (more than 10% and less than 50%) of the CCPs would be at or below the assumed respirable activity median aerodynamic diameter (AMAD) of 10 µm.

Table 3-4
Physical properties of fly ash

Site	Particle Density (g cm^{-3})	Bulk Density (g cm^{-3})	Physical Diameter for Which the Noted Percentage of Particles Are Smaller (µm)		
			10%	50%	90%
Bull Run	2.11	1.26	5.7	19	150
Cobert	2.34	1.26	4.8	19	80
Kingston	2.41	1.35	2.7	9	70
Shawnee	2.23	1.17	3.8	17	100
Johnsonville	2.42	1.48	4.5	34	70
John Sevier	2.35	1.33	3.8	27	130
Average	2.31	1.31	4.2	21	100

There are several references that report moisture content values for CCP material. Values between 20% and 25% are reported for fly ash in CCP management units at several TVA plants by EPRI (1993).

Methodology for Establishing Exposure Levels

The mean concentration was selected as an appropriate representation of potential exposure levels due to the similarity between the mean and median Ra-226 and Ra-228 concentrations, as noted previously. Because consideration and inclusion of non-detect values can be important for establishing exposure levels, several options for handling non-detect values were evaluated—including replacing non-detects with 0, using the detection limit (DL) divided by 2, using the DL directly, Cohen's Method, Aitchison's Method, using the trimmed mean, using the Winsorized mean and standard deviation, and tests for proportions (EPA, 2006). No general procedures are applicable in all cases, and the recommended procedure depends on the amount of data below the detection limit and the purpose of the analysis. In addition, many of the methods require that the detection limit always be the same, which is typically not the case with radionuclide analytical data. When a small proportion of the observations are non-detects, one of the simplest and most straightforward recommended approaches is to replace the non-detects with a small number, usually DL/2 (EPA, 2006).

Because the percentage of non-detects for the CCP analytical data is relatively small (i.e., 3% for Ra-226 and 7% for Ra-228), an approach was developed in consultation with EPRI for including non-detect observations. For this analysis, if the non-detect value was greater than the mean concentration, the detection limit was deemed to be too high to provide useful information, and the result was excluded from the analysis. If the non-detect value was less than or equal to the mean concentration and the non-detect value was not equal to the minimum detectable concentration (MDC), the non-detect result value was used as reported. If the non-detect value was less than or equal to the mean concentration and the non-detect value was equal to the MDC, the non-detect value divided by 2 was used. Other similar iterations were investigated but ultimately, because of the relatively small percentage of non-detect observations, the overall impact of using alternative methods did not change the estimated mean concentration by more than a few percentage points. Table 3-5 shows the mean CCP, background, and net concentrations computed using the approach described previously.

Table 3-5
Statistics for nuclide concentrations measured in CCP and soil from background locations at selected TVA plants

			Gross Concentration (pCi g^{-1})					Net Excess in CCP	
Nuclide	**Site**	**Sample Type**	**Avg**	**SD**	**n**	**Min**	**Max**	**Mean**	**SD**
Ra-226	All	Bkg	1.14	1.41	646	-0.0218	18.3		
	All	CCP	4.18	1.94	603	-0.185	11.8	3.04[a]	2.40
	Allen Fossil Plant	Bkg	0.90	0.59	93	0.0512	3.71		
	Bull Run Fossil Plant	Bkg	0.87	0.31	81	-0.0218	1.58		
		CCP	3.75	1.46	126	0.0306	9.09	2.88	1.50
	Cumberland Fossil Plant	Bkg	1.95	2.43	78	0.201	13.2		
		CCP	5.40	3.35	111	-0.185	11.8	3.46	4.14
	Gallatin Fossil Plant	Bkg	0.81	0.78	99	0.1865	4.41		
		CCP	3.11	1.16	42	1.75	6.54	2.30	1.39
	John Sevier Fossil Plant	Bkg	0.84	0.31	78	0.124	1.63		
		CCP	4.32	1.45	102	1.09	7.82	3.48	1.49
	Johnsonville Fossil Plant	Bkg	1.71	2.99	67	0.363	18.3		
		CCP	4.19	1.00	141	1.35	6.24	2.47	3.15
	Kingston Fossil Plant	Bkg	1.06	0.41	78	0.288	2.27		
		CCP	3.63	0.81	58	1.57	5	2.57	0.90
	Watts Bar Fossil Plant	Bkg	1.17	0.38	74	0.12	2.12		
		CCP	3.21	1.44	23	0.634	6.69	2.04	1.49
Ra-228	All	Bkg	1.22	0.56	627	-0.011	3.3		
		CCP	2.45	1.01	599	-0.317	5.49	1.23[a]	1.15
	Allen Fossil Plant	Bkg	0.84	0.49	93	0.0466	1.99		
	Bull Run Fossil Plant	Bkg	1.40	0.43	81	0.287	2.29		
		CCP	3.06	1.12	126	0.00181	5.49	1.66	1.20
	Cumberland Fossil Plant	Bkg	1.29	0.42	78	0.181	2.5		
		CCP	1.50	0.93	111	-0.317	3.21	0.20	1.02
	Gallatin Fossil Plant	Bkg	0.94	0.46	78	0.253	2.16		
		CCP	2.04	0.47	35	1.1	2.91	1.11	0.66
	John Sevier Fossil Plant	Bkg	1.28	0.43	78	-0.011	2.37		
		CCP	2.96	0.62	102	0.795	4.21	1.69	0.75
	Johnsonville Fossil Plant	Bkg	1.01	0.55	67	0.0485	3.04		
		CCP	2.43	0.77	141	0.863	3.96	1.42	0.95
	Kingston Fossil Plant	Bkg	1.49	0.63	78	0.28	2.85		
		CCP	2.56	0.68	58	0.0729	3.97	1.06	0.93
	Watts Bar Fossil Plant	Bkg	1.60	0.54	74	0.169	3.3		
		CCP	2.08	0.61	23	0.311	3.29	0.48	0.81

a. Highlighted cells show the concentrations used for the dose calculations.

Two-sided t-tests were performed to determine if mean CCP concentrations at the individual sites were significantly different from the mean concentrations using the entire data set. Although most of the sites showed a statistically significant difference between the site mean and the entire data set mean, the range of concentrations was relatively small (i.e., 3.11 to 5.4 pCi g^{-1} for Ra-226 and 1.5 to 3.06 pCi g^{-1} for Ra-228). Based on these observations, the mean net excess concentrations using the entire data set were selected for the baseline analysis. As noted previously, the net excess concentrations (i.e., 3.04 pCi g^{-1} for Ra-226 and 1.23 pCi g^{-1} for Ra-228) were used to represent the total dose that could be received by an on-site worker. The results can easily be scaled to represent the concentrations at a specific site or to represent the gross concentrations.

4
EXPOSURE SCENARIOS AND PARAMETERS

This section presents the exposure scenarios and parameters for workers who may be exposed to CCPs during material management operations at coal-fired power plants. Exposure scenarios are constructed for CCP management unit workers who are working outside of heavy equipment because they are the individuals who would experience the most exposure to CCPs. Heavy equipment operators who are responsible for loading, unloading, and grading CCP material were assumed to work from enclosed air-conditioned cabs and are not exposed to unfiltered outside air. In addition, the operator is sitting further from the CCP surface (roughly 3 meters high) than a worker on the ground and will be afforded radiation shielding from the steel cab floor and other components of the heavy equipment. Workers operating ancillary equipment, such as water tankers, would also receive these added layers of protection and are therefore not considered in this assessment. Two disposal scenarios are considered: a baseline scenario that applies at all times the worker is on-site and a placement scenario that calculates additional dose during periods of active CCP placement.

Exposure Scenarios for CCP Management Unit Workers

CCP management unit workers are individuals who directly assist in materials management operations in tasks such as directing a truck to the placement area, ensuring that the truck has completely emptied its load, taking CCP samples, providing fuel, and any other activity that may have brought them in close proximity to the CCP. CCP management unit workers are potentially exposed to radioactive materials via incidental ingestion, inhalation of suspended particles and radon/radon progeny, and external exposure.

Exposure Parameters for CCP Management Workers

CCP management unit workers are assumed to be engaged in general construction activities such as excavation and earth moving. To determine inhalation and soil ingestion rates for a worker at the CCP management unit, information related to construction and outdoor workers was reviewed.

Soil and Dust Ingestion

The 2011 U.S. EPA Exposure Factors Handbook (EPA, 2011) recommends a central tendency soil ingestion for the adult general population of 50 mg day^{-1} and 100 mg day^{-1} for soil + dust ingestion. This document notes that an additional occupational contribution to soil and dust ingestion in some adults can be important.

U.S. EPA in its 1991 Risk Assessment Guidance for Superfund (RAGS) Supplemental Guidance recommends using soil ingestion rates of 50 mg day^{-1} for commercial/industrial workers and 100 mg day^{-1} for agricultural workers (EPA, 1991). U.S. EPA in its Regional Screening Level (RSL) User Guide recommends a soil ingestion rate for a construction worker of 330 mg/day^{-1} (EPA, 2016a). This same value is the recommended default construction worker soil ingestion rate used by EPA in the calculation of the construction worker radionuclide preliminary remediation goals (PRGs) (EPA, 2016b).

To be conservative and in agreement with the occupational setting assumed for this analysis, a soil ingestion rate of 330 mg day^{-1} was used for an outdoor worker.

Inhalation Rate

EPA radionuclide PRGs use a value of 60 m^3 day^{-1} for inhalation rate based on heavy activities for an outdoor worker at 2.5 m^3 hour^{-1} over 24 hours. This value was based on data in Exhibit 5-23 of the 1997 Exposure Factors Handbook (EPA, 1997). The 2011 U.S. EPA Exposure Factors Handbook (EPA, 2011) provides some data on construction worker inhalation rates. Mean inhalation rates range from 1.20 m^{-3} hour^{-1} to 1.50 m^{-3} hour^{-1}, and upper percentile (99%) inhalation rates range from 4.14 m^3 hour^{-1} to 4.26 m^3 hour^{-1}. Recommended long-term and short-term inhalation rates are provided by age group (EPA, 2011; Table ES-1 Chapter 6). Using the short-term inhalation rates and calculating a weighted average for an adult age 21 to 61 assuming 2 hours light intensity, 4 hours moderate intensity, and 4 hours heavy intensity results in a weighted average mean of 1.8 m^3 hour^{-1} and 95th percentile value of 2.5 m^3 hour^{-1}.

Based on these data, an inhalation rate of 1.8 m^3 hour^{-1}, or 14.4 m^3 day^{-1}, for the outdoor worker was assumed and reflects various levels of activities during the day. A heavy equipment operator would have a substantially lower inhalation rate because they are sedentary. In addition, because a heavy equipment operator sits in an enclosed cab where material suspended during operations will be filtered, they are less likely to be exposed via inhalation. Therefore, the outdoor worker inhalation exposure represents a worst-case estimate of possible inhalation dose.

Exposure Frequency and Outdoor Exposure Time

Exposure frequency and outdoor exposure time are important parameters for outdoor workers in close proximity to CCPs because their dose will be linearly proportional to these variables. Dose calculations for workers during periods when there is no placement of CCPs assume the following:

- Worker is assumed to work 48 weeks per year, or 240 days per year.
- Worker is assumed to work 7 hours per day for a total of 1,680 hours per year.
- Worker is assumed to spend 100% of that time on the CCP management unit with no shielding or personal protective equipment (PPE).

During periods of active placement, it is assumed that each unloading and grading event takes approximately 8 minutes (EPRI, 2012). The number of loads in a given hour, day, or year is highly variable and subject to many unknowns. However, as a highly conservative and implausible[1] scenario, it is assumed that an outdoor worker is continuously exposed to an

[1] This scenario is implausible because it assumes that the plant is operating and generating CCPs all 240 days that the worker is on-site, when in reality outages for maintenance and during periods of low electric demand result in periods when there is no activity at the CCP management unit.

unloading and grading process during their 1,680-hour work year. This yields 12,600 loads per year. See Table 4-1.

Table 4-1
Exposure parameters for outdoor worker

Parameter	Value	Units	Reference
Hourly inhalation rate	1.8	m^3	EPA (2011)[a]
Daily soil ingestion rate	330	mg per day	EPA (2016)[a]
Hours exposed, outdoor worker	1,680	hours	TVA (2021)
Outdoor exposure time	7	hours day^{-1}	TVA (2021)
Exposure frequency	240	days $year^{-1}$	TVA (2021)
Maximum CCP loads per year	12,600	loads	Calculation[b]
Minutes per disposal	8	minutes	EPRI (2012)

a. Represents a weighted-average calculated using short-term inhalation rates for construction workers assuming 2 hours light intensity, 4 hours moderate intensity, and 2 hours heavy intensity.

b. Based on implausible assumption that worker is continuously exposed over entire exposure time (240 days/$year^{-1}$ at 7 hours/day^{-1}) to 8-minute load processing events.

5
DOSE CALCULATIONS

This section presents the methodology used in calculating doses from the exposure pathways outlined in Section 4. Environmental concentrations combined with the exposure scenario and dose coefficients are used to estimate annual doses. The modeling tool used to estimate doses during periods when there is no placement of CCP is discussed. In addition, the methods and modeling parameters used to estimate the concentrations in air and consequent doses resulting from placement (unloading and grading) of CCPs are detailed.

The pathways of exposure during the periods with no placement are independent of placement activities. It is assumed that these baseline pathways are valid at all times and the subsequent doses are received by the worker regardless of the activities taking place at a CCP management unit. When placement is considered, the inhalation of suspended CCPs during placement and corresponding dose is assumed to be an additional dose received by the worker beyond the baseline doses.

Inhalation, Ingestion, and External Doses for CCP Management Units During Periods with No Placement

Exposure to radionuclides in CCP material during periods of no placement is assumed to occur through external radiation, inhalation of suspended particulates containing radionuclides, and incidental ingestion of soil/CCPs. The suspension of particulates during periods when placement is not occurring is assumed to occur through windborne processes, as opposed to mechanical processes. The parameter values used to characterize this exposure scenario for an outdoor worker are provided in Section 4.

Doses are computed independently for each exposure pathway contributing to the outdoor worker exposure scenario. The following equations illustrate how the calculations are performed, using the committed effective dose (CED) for ingestion and inhalation pathways and the effective dose for external pathways as an example. Doses are computed on an annual basis using RESRAD-ONSITE (Kamboj, 2018).

RESRAD-ONSITE (hereafter RESRAD) is a computer code developed at Argonne National Laboratory for estimating radiation doses and cancer risks to an individual located on top of radioactively contaminated soils. The calculation of dose by the RESRAD code is scenario driven with nine exposure pathways that can be selected or suppressed to reflect the land use and receptor scenario under consideration. The four RESRAD exposure pathways examined[2] are 1) direct external radiation from radionuclides in soil, 2) inhalation of airborne radionuclides suspended from soil, 3) incidental ingestion of soil, and 4) outdoor inhalation of radon and radon progeny. Input information needed for the calculation from these pathways includes

[2] RESRAD pathways not considered in this study are ingestion of meat and ingestion of milk produced by livestock fed with contaminated fodder and water, ingestion of drinking water from a well or pond adjacent to a contaminated area, ingestion of aquatic foods from the pond, and ingestion of produce grown on the contaminated area.

characteristics of the radioactive material, properties of the material surface, and exposure parameters for the individual. These parameters are provided throughout this section as well as Section 4. As described in Section 3, the CCP materials are physically characterized using fly ash parameters.

RESRAD modeling considers radiological decay and ingrowth and environmental transport, partitioning, and dilution, governed by the principle of mass conservation over time. Input parameters used for the calculation can be specified by the user to control the level of conservatism assumed for each calculation. In a case in which only external exposure, particulate inhalation, and soil ingestion doses are being examined, the modeling can be further simplified by conservatively setting the RESRAD sorption coefficients, or K_d, at very large values, such as 1.0×10^6 cm^3 g^{-1}.

The sorption coefficient value describes the partitioning of a radionuclide between its sorbed and aqueous phase. For radionuclides with a K_d value of zero, all the mass is in the aqueous phase, and the radionuclide travels at the same rate as the water. Therefore, a relatively high K_d has the effect of both reducing the aqueous-phase concentration and retarding (i.e., slowing) the movement of the radionuclide in groundwater. Setting the K_d values to 1.0×10^6 cm^3 g^{-1} effectively eliminates the aqueous-phase concentration and associated movement, keeping all CCP radionuclides in the solid phase within the area of interest.

The conceptual dose calculations implemented in RESRAD are described in the preceding sections. These calculations can be performed manually outside of RESRAD given the simplified model described previously. However, RESRAD allows for the simple inclusion of radioactive progeny that are assumed to be in secular equilibrium with their parent in the environment.

External Dose

The general equation for estimating annual effective dose from external radiation sources in CCPs is

$$Dext = \sum_{i=1}^{n} C_i \, ET_{outdoor} \, EF \, DCext_i, \qquad \textbf{Eq. 5-1}$$

where

C_i = measured CCP concentration of radionuclide i (pCi g^{-1})

$ET_{outdoor}$ = exposure time outdoor (hr day^{-1})

EF = exposure frequency (days yr^{-1})

$DCext_i$ = soil/CCP external effective dose coefficient for an infinite volume source for radionuclide i (mrem-g pCi^{-1} hr^{-1})

n = number of radionuclides

External dose coefficients for a reference individual were taken from Federal Guidance Report 15 (FGR 15) (EPA, 2019) and added as a new dose coefficient library in the RESRAD code. They are shown in Table 5-1. RESRAD contains external dose coefficients from FGR 12, published in 1993. Compared to FGR 12, FGR 15 incorporates six different age groups (whereas FGR 12 had one), updated tissue weighting factors (from ICRP 2007) and radionuclide decay data (from ICRP 2008), and improved computing power to provide more precise calculations.

Table 5-1
Effective dose coefficients for external exposure to soil/CCP of infinite depth[a]

Radionuclide	Reference Individual External Exposure (mrem pCi^{-1}g)
Ac-228	5.16E+00
At-218	5.27E-04
Bi-210	1.29E-01
Bi-212	8.16E-01
Bi-214	9.38E+00
Hg-206	7.30E-01
Pa-234	8.29E+00
Pa-234m	4.46E-01
Pb-210	2.35E-03
Pb-212	6.50E-01
Pb-214	1.30E+00
Po-210	5.60E-05
Po-212	0.00E+00
Po-214	4.78E-04
Po-216	8.82E-05
Po-218	2.26E-06
Ra-224	4.91E-02
Ra-226	3.21E-02
Ra-228	1.37E-04
Rn-218	4.20E-03
Rn-220	3.44E-03
Rn-222	2.11E-03
Th-228	7.43E-03
Th-230	1.16E-03
Th-232	5.12E-04
Th-234	2.99E-02
Tl-206	2.00E-01
Tl-208	2.20E+01
Tl-210	1.73E+01
U-234	9.21E-04
U-238	1.72E-04

a. Dose coefficients from FGR 15 (EPA, 2019) as presented in the RESRAD code.

Inhalation Dose

The annual CED from inhalation of CCP particulates is estimated using

$$Dinh = \sum_{i=1}^{n} C_i \; MF \; AF \; BR \; ET \; EF \; DCinh_{i,} \qquad \textbf{Eq. 5-2}$$

where

C_i = measured CCP concentration of radionuclide i (pCi g^{-1})

MF = mass loading factor (g m^{-3})

AF = area factor (dimensionless)

BR = breathing rate (m^3 hr^{-1})

$ET_{outdoor}$ = exposure time (hr day^{-1})

EF = exposure frequency (days yr^{-1})

$DCinh_i$ = inhalation committed effective dose coefficient for radionuclide i (mrem pCi^{-1})

n = number of radionuclides

Inhalation dose coefficients for a reference individual were taken from the DOE Standard 1196 (DOEStd-1196) (DOE, 2021), which were also added as a new dose coefficient library in the RESRAD code. The libraries in RESRAD are updated only to the DOEStd-1196 values published in 2011 (DOE, 2011). The new DOEStd provides age-specific committed effective dose coefficients for inhalation and ingestion of radionuclides based on updated biokinetic and dosimetric models of the International Commission on Radiological Protection (ICRP) and tissue weighting factors recommended in ICRP Publication 103 (ICRP, 2007).

RESRAD has a simplified approach to particulate suspension where the radionuclide air concentration C_a (Bq m^{-3}) is estimated as the product of a mass loading factor ML (g m^{-3}), an area factor AF (dimensionless), and the concentration C_s of activity in surface soil (Bq kg^{-1}):

$$C_a \equiv C_s \cdot ML \cdot AF \qquad \textbf{Eq. 5-3}$$

The mass loading factor may be estimated as the steady-state mass concentration of suspended soil particles. If the source area of the suspended particles is effectively infinite and uniformly contaminated, the air concentration is given by the product $C_s \cdot$ ML, so that AF = 1.0. Otherwise, the area factor is intended to adjust for the effect of dilution of the air concentration by uncontaminated soil particles that are transported from beyond the contaminated source region. Conservatively, the AF can be set to 1.0 in RESRAD by defining a contaminated area of sufficient size. The mass loading factor used for these calculations is based on the worst-case respirable dust value of 0.095 mg m^{-3} presented in Table 3-3.

Ingestion Dose

The annual CCP ingestion committed effective dose is estimated using

$$Ding = \sum_{i=1}^{n} C_i \; IR \; ET \; EF \; FC \; DCing_i \qquad \textbf{Eq. 5-4}$$

where

C_i = measured CCP concentration of radionuclide i (pCi g^{-1})

IR = soil/CCP ingestion rate (kg hr^{-1})

$ET_{outdoor}$ = exposure time (hr day^{-1})

EF = exposure frequency (days yr^{-1})

FC = fraction of ingested material that is contaminated (assumed to be 1.0)

$DCing_i$ = ingestion committed effective dose coefficient for radionuclide i (mrem pCi^{-1})

n = number of radionuclides

As with the inhalation dose coefficients, the ingestion dose coefficients for a reference adult were taken from DOEStd-1196 (DOE, 2021) and entered into the RESRAD code as a new library. DOEStd-1196 inhalation and ingestion dose coefficients used for these calculations are shown in Table 5-2.

Table 5-2
Inhalation and ingestion effective dose coefficients[a]

Radionuclide[b]	Reference Individual	
	Inhalation (mrem pCi^{-1})	Ingestion (mrem pCi^{-1})
Pb-210+D	7.22E-02	5.80E-03
Ra-226+D	9.00E-02	4.71E-04
Ra-228+D	1.47E-01	1.26E-03
Th-228+D	1.45E-01	2.43E-04
Th-230	1.05E-01	2.22E-04
Th-232	4.40E-08	2.61E-04
U-234	8.95E-02	1.28E-04
U-238	7.92E-02	1.14E-04
U-238+D	7.92E-02	1.16E-04

a. Dose coefficients from DOEStd-1196 (DOE, 2021) as presented in the RESRAD code.
b. The “+D” designation includes contributions of radioactive progeny that are assumed to be in secular equilibrium with their parent in the environment. These summations are performed within the RESRAD code.

Outdoor Radon Exposure and Dose

Radon (Rn-220 and Rn-222) is formed continually in the ground and migrates through the soil from radium within CCP materials. Emission of radon from the CCP management unit presents a continuous exposure situation that is dependent on the radon flux emanating from the bare surface of the CCP (i.e., no cover). The movement of radon atoms through the pores of CCP materials may be caused by diffusion or convection processes. The size distribution and configuration of the pore spaces in the materials as well as their moisture content and spatial distribution are key parameters in determining the radon diffusion rate and resulting radon surface fluxes (Yu, 2001).

The radon concentration in the outdoor air above a CCP management unit with radium isotopes is influenced by the radon flux from the ground surface, environmental factors (wind speed) and the size of the source, location, and time. RESRAD uses a simplified model along with conservative assumptions to estimate both radon and radon progeny concentration (see Figure 3-1 and Figure 3-2 in Section 3). The derivations of radon surface flux, radon, and radon progeny concentrations are not detailed here but are available in the literature (Yu, 2001).

Doses from outdoor radon are dependent on the radon progeny concentrations in outdoor air that exist in various levels of equilibrium with radon. Doses are estimated using the working level (WL) and a conversion of 760 mrem per working-level month (Yu, 2001). The WL is defined as any combination of short-lived radon progeny in one liter of air that will result in the emission of 1.3×10^5 MeV of potential alpha energy. One WL equals 100 pCi L^{-1} of radon in air with all short-lived progeny in equilibrium. The WL is related to the equilibrium equivalent concentration (EEC) given by NCRP (1988):

$$EEC = 0.105A + 0.516B + 0.379C \qquad \textbf{Eq. 5-5}$$

where A, B, and C are the concentrations of Po-218, Pb-214, and Bi-214, respectively. Assuming that progeny are in equilibrium with radon (a worst-case assumption) and 1 pCi L^{-1} radon concentration, the EEC is 1 EEC per pCi L^{-1}. The working level month (WLM) and dose from radon is given by

$$WLM = WL\frac{hours\ exposed}{170\ hours}$$

$$D = 760\frac{mrem}{WLM}xWLM \qquad \textbf{Eq. 5-6}$$

Radon Model Parameters

For outdoor exposure to radon, the primary RESRAD model parameters of concern are the radon emanation and diffusion coefficients in the contaminated zone. The default radon-222 and radon-220 emanation coefficients for soil in RESRAD are 0.25 and 0.15, respectively. Emanation coefficients for fly ash have been studied extensively in the literature and have shown a large dependency on percent moisture of the fly ash. Barton and Ziemer (1986) showed an increasing trend in emanation for stoker-fired fly ash as percent moisture increased up to roughly 20% at which point emanation decreased as percent moisture increased. The reported emanation coefficients varied between 0.001 and 0.04, depending on particle size. These data are consistent with Kalkwarf et al. (1985) who measured emanation coefficients ranging from 0.098 down to 0.007 for radon-222 in dry fly ash from three common types of coal and with aerodynamic equivalent diameters less than 15 µm. The radon emanation coefficient used for this project was conservatively chosen as 0.1 for both radon-222 and radon-220.

The default radon diffusion coefficient for soil in RESRAD is $2.0 \times 10^{-6}\ m^2\ s^{-1}$. This value is consistent with the less permeable materials examined by Narula et al. (2010) who reported a diffusion coefficient of $1.65 \times 10^{-6}\ m^2\ s^{-1}$ for soil and $2.06 \times 10^{-6}\ m^2\ s^{-1}$ for fly ash. The diffusion coefficient used for this project was conservatively chosen as 2.06 x 10^{-6} m^2 s^{-1}. Model parameters are summarized in Table 5-3.

Table 5-3
RESRAD transport parameters modified from default values

Parameter (RESRAD Input Names)	Value	Notes
Area of contaminated zone (m^2)	3.6×10^5	Hypothetical CCP landfill area (EPRI, 1997, 2014)
Thickness of contaminated zone (m)	8.0	TVA (2021)
Density of contaminated zone (g cm^{-3})	1.31	Based on fly ash average from Table 3-4 of this report
Contaminated zone total porosity	0.47	Based on range of fly ash porosities determined by EPRI (1993)
Contaminated zone hydraulic conductivity (m yr^{-1})	15.8	Based on range of fly ash hydraulic conductivities determined by EPRI (1993)
Mass loading for inhalation (g m^{-3})	9.5×10^{-5}	Worst-case value from Table 3-3 of this report
Shielding factor, outdoor gamma	0.0	No shielding assumed (TVA, 2021)
All sorption coefficients (Kd) (cm^3 g^{-1})	1.0×10^6	Selected to eliminate aqueous-phase concentrations/transport
Radon-222 emanation power	0.1	Based on highest value reported by Kalkwarf et al. (1985)
Radon-220 emanation power	0.1	Based on highest value reported by Kalkwarf et al. (1985)
Radon diffusion coefficient (m^2 s^{-1})	2.06×10^{-6}	Based on Narula et al. (2010)
Pb-210 CCP concentration (pCi g^{-1})[a]	3.04	Net excess concentration calculated using Table 3-5 of this report
Ra-226 CCP concentration (pCi g^{-1})	3.04	Net excess concentration calculated using Table 3-5 of this report
Ra-228 CCP concentration (pCi g^{-1})	1.23	Net excess concentration calculated using Table 3-5 of this report
Th-228 CCP concentration (pCi g^{-1})	1.23	Net excess concentration calculated using Table 3-5 of this report
Th-230 CCP concentration (pCi g^{-1})	3.04	Net excess concentration calculated using Table 3-5 of this report
Th-232 CCP concentration (pCi g^{-1})	1.23	Net excess concentration calculated using Table 3-5 of this report.
U-234 CCP concentration (pCi g^{-1})	3.04	Net excess concentration calculated using Table 3-5 of this report
U-238 CCP concentration (pCi g^{-1})	3.04	Net excess concentration calculated using Table 3-5 of this report

a. These radionuclides were entered explicitly into RESRAD. All decay progeny with half-lives less than 180 days were automatically assumed to be in equilibrium with their respective parent radionuclide.

Particulate Emissions and Inhalation Doses During CCP Placement

Inhalation doses are calculated for the outdoor worker scenario as a function of loads handled. The calculations are performed outside of the RESRAD code using the methodology outlined here. The inhalation dose coefficients were taken from the new DOEStd-1196 library described previously (DOE, 2021).

Radionuclide emissions during placement operations of dry CCPs (i.e., dry fly ash) are based on CCP-specific particulate emission factors (PEF) developed using ash handling information, detailed data on conditions in the atmospheric boundary layer, and a transport model to link source activity with measured downwind concentrations (EPRI, 2012). The PEF is expressed as grams of PM_c emitted per Mg of ash processed where PM_c is the mass of particles between 2.5 µm and 10 µm in effective diameter.

The CCP particle size data presented in Table 3-4 show that on average, 50% of CCP particles have diameters less than 21 µm and 10% have diameters less than 4.2 µm. Absent more refined data, it is difficult to determine what fraction of the CCP particles would fall in the 2.5 to 10 µm range. However, the fraction of particles less than 2.5 µm would be less than 10% and the fraction less than 10 µm would be less than 50%. Conservatively, it is assumed that the 2.5–10 µm fraction is 40%. Therefore, the product of the mass of CCP material in a load × 40% × the PEF provides the mass of respirable CCP material available for suspension in air per load. The amount of respirable radioactivity released to the air is the product of the mass released to air and the representative radionuclide concentration. Therefore,

$$Q = 0.4\, PEF\, M\, C_i \frac{1E{+}06\ \mathrm{g}}{\mathrm{Mg}} \qquad \textbf{Eq. 5-7}$$

where

Q = activity released to air (pCi)

M = mass of one CCP load (Mg)

C_i = measured CCP concentration of radionuclide i (pCi g^{-1})

The air concentration is calculated by assuming the entire mass that is suspended into a mixing volume of air (defined later). The radionuclide concentration in air is then Q/V, where V is the volume of the mixing cell. The exposure scenario assumes that the worker is exposed continuously until the material in air dissipates. The rate of removal from the mixing cell is described by the removal rate constant defined by

$$K = \frac{U}{L} \qquad \textbf{Eq. 5-8}$$

where

K = the removal rate constant (s^{-1})

U = wind speed (m s^{-1})

L = the length of the mixing cell that lies parallel to the direction of wind (m)

Assuming a square area source, the value of L is given by $(A)^{1/2}$, where A is the surface area of the mixing cell. The change in concentration over time is described by the differential equation and solution.

$$\frac{dQ}{dt} = -KQ$$

$$Q(t) = Q_o e^{-Kt} \qquad \textbf{Eq. 5-9}$$

where Q_o is the initial activity in the mixing cell defined by Equation 5-7. The time-integrated air concentration (TIC) that the worker is exposed to is calculated by

$$TIC = \frac{Q_o}{V}\int_0^{\infty} e^{-Kt} = \left(\frac{Q_o}{V}\right)\left(-\frac{1}{K}\right) = -\frac{Q_o}{V\,K}(0-1) = \frac{Q_o}{V\,K} \qquad \textbf{Eq. 5-10}$$

where

TIC = the time-integrated concentration (pCi-s m^{-3})

V = volume of the mixing cell (m^3)

The area of the mixing cell is assumed to be the surface area of the graded area plus a buffer distance around the grader that allows a worker to stand at the edge of the source area. The surface area of the disposal is the disposal volume divided by the assumed average height of the pile. The mixing cell volume is the surface area (including buffer) × the difference between the height of the mixing cell and the average height of the pile:

$$L = \sqrt{\frac{V_{load}}{H_{load}}} + l$$

$$V = L^2(H_{mc} - H_{load}) \qquad \textbf{Eq. 5-11}$$

where

V_{load} = the volume of the load (m^3)

H_{load} = height of the load after disposal (m)

l = buffer distance (m)

H_{mc} = height of mixing cell (m)

Based on previous work done by EPRI related to the hauling, unloading, and grading of CCPs at a coal-fired power plant, the grading process requires the equipment operator to drive from off the pile across the pile and back again, creating an effective area that is driven over (composed of all CCP) of about 22.15 m in length (or 25 m in diameter) (EPRI, 2012). Each dumped load is graded to a height of 0.46–0.61 m, with a midpoint of 0.53 m. Using a bulk density of 1.31×10^3 kg m^{-3} (Table 3-4) and an assumed truck capacity of 15 cubic yards (EPRI, 2016), the volume per load is 11.4 m^3. The grading process creates a pile length of 4.64 m. An individual working outside would need to be standing outside of this effective source area by a safe distance. Conservatively, this distance is assumed to be 1 m, resulting in a total safety buffer distance of 18.51 m (22.15 m + 1 m – 4.64 m) and mixing cell length of 25.15 m. The height of the mixing cell is assumed to be 2 m, which encompasses the complete breathing zone of a 6-foot-tall worker. See Figure 5-1.

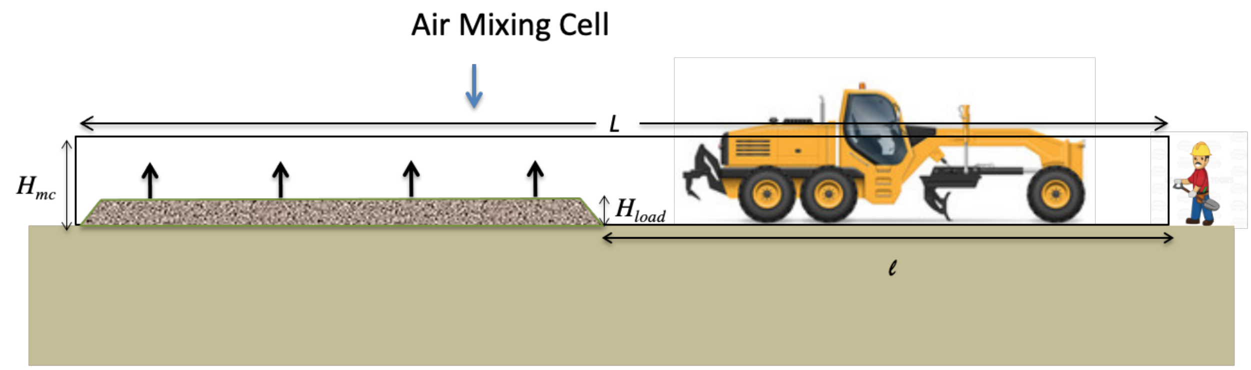

Figure 5-1
Conceptual model of exposure for an outdoor worker during unloading and spreading of CCP load

The inhalation committed effective dose per load from this exposure is given by

$$Dinh = IR \times \sum_{i=1}^{n} TIC_i \times DCinh_i \qquad \textbf{Eq. 5-12}$$

where

Dinh = the inhalation effective dose for a CCP load (mrem)

IR = inhalation rate (m^3 hr^{-1})

TIC_j = time-integrated concentration for radionuclide *i* (pCi-hr m^{-3})

$DCinh_j$ = inhalation effective dose coefficient for radionuclide *i* (mrem pCi^{-1})

n = number of radionuclides

Ingestion committed effective doses during the placement operations assume that a given amount of the CCP material is ingested via adherence to skin and hand during unloading and grading and later transferred to mouth. The ingestion committed effective dose is simply the product of the effective dose coefficient (in mrem pCi^{-1}) and the amount of activity ingested. The amount of activity ingested is the soil ingestion rate adjusted for exposure time × the activity concentration of the CCP material (on the surface, not the CCP material suspended in the air). Given the conservative ingestion rates assumed in Section 4 for a construction worker, the ingestion doses outlined previously are assumed to account for additional ingestion that would occur during the unloading and grading processes. Therefore, no additional ingestion doses are calculated for this scenario. Model parameters and calculated values are presented in Table 5-4.

Table 5-4
Parameters for emission model during placement operations

Parameter	Symbol	Value	Notes
Average wind speed (m s^{-1})	U	2.55	Average wind speed during hours of 9 am to 5 pm from Table 3-2
Volume of CCP material per load (m^3)	V_{load}	11.40	Calculated based on assumed 15 cubic yard truck capacity
Bulk density (kg m^{-3})	ρ_b	1.31×10^3	Based on fly ash average value from Table 3-4
Buffer distance (m)	l	18.51	Assumed distance from edge of graded CCP pile to a worker
Disposal pile height	H_{load}	0.53	Assumed average height of graded pile (EPRI, 2012)
Mixing cell height	H_{mc}	2.0	Assumed height of air mixing cell
Length of air mixing cell (m)	L	23.15	Calculated from Equation 5-11
Volume of mixing cell (m^3)	V	7.88×10^2	Calculated from Equation 5-11
Removal rate constant (s^{-1})	K	0.10	Calculated using Equation 5-8
Particle mission factor (g release to air per Mg CCP processed)	E	59.0	Mean value in Table 4-2 (EPRI, 2012)

6
DOSE ESTIMATES

This section provides effective dose estimates for the hypothetical outdoor worker at a CCP management unit. The doses are presented as an annual effective dose for the assumption of a management unit with no active movement of CCP materials and as an additional effective dose per CCP load during placement. The additional effective dose resulting from CCP placement is presented on a per load basis so that one may make their own assumptions about the level of activity at a CCP management unit over the course of year as well as the likelihood of having an outdoor worker in the vicinity during the heavy equipment operations.

Baseline Annual Effective Dose Estimates for CCP Management Unit Worker

This annual effective dose is based on the assumptions and parameters discussed in previous sections of this report and were estimated using RESRAD. All doses are reported in mrem per year and represent the peak dose calculated in RESRAD over a 1,000-year period (user selected). The peak dose in all exposure pathways occurred at the beginning of the first year of the model simulations. The dose estimates in Table 6-1 are the net excess effective dose (excluding radon) that the hypothetical outdoor worker would receive as a result of working on the CCP management unit. The effective doses in Table 6-2 represent the natural background dose (excluding radon) the individual would receive if the CCP materials did not contain enhanced concentrations of naturally occurring radionuclides but rather concentrations consistent with native background soil concentrations. The doses in Table 6-2 were obtained by running the RESRAD model with the background soil activity concentration values provided in Table 3-5. All other model parameters remained unchanged. Outdoor radon inhalation doses are provided in Table 6-3. The radon dose is not included in the RESRAD All Pathway doses provided in this report and is not included in the Radiation Dose and Risk in Perspective section because the threshold dose used for comparison does not include radon contributions.

The CCP management unit outdoor worker represents a bounding dose estimate for a worker in close contact with the CCP material. Other workers, such as heavy equipment operators, would have lower doses because they are enclosed and shielded in a cab and are farther away than a person standing next to the surface of the CCP source term.

Table 6-1
Peak annual doses for representative outdoor worker at a hypothetical CCP management unit using net excess radionuclide concentrations

	Effective Dose (mrem yr^{-1})			
Radionuclide[a]	External	Inhalation[b]	CCP Ingestion	All Pathways
Pb-210+D	4.31E-03	6.39E-03	4.83E-01	4.94E-01
Ra-226+D	5.95E+00	6.27E-03	7.97E-02	6.04E+00
Ra-228+D	1.42E+00	5.71E-03	7.06E-02	1.50E+00
Th-228+D	1.76E+00	9.50E-03	1.25E-02	1.79E+00
Th-230	1.93E-03	6.58E-02	5.51E-02	1.23E-01
Th-232	8.12E-02	2.91E-02	2.84E-02	1.39E-01
U-234	2.00E-04	6.08E-03	1.27E-02	1.90E-02
U-238+D	9.28E-02	5.20E-03	1.24E-02	1.10E-01
Total	9.32E+00	1.34E-01	7.55E-01	1.02E+01

a. The “+D” designation includes contributions of radioactive progeny that are assumed to be in secular equilibrium with their parent in the environment. These summations are performed within the RESRAD code.
b. Excluding radon.

Table 6-2
Peak annual doses for representative outdoor worker at a hypothetical CCP management unit using native soil activity concentrations

	Effective Dose (mrem yr^{-1})			
Radionuclide[a]	External	Inhalation[b]	CCP Ingestion	All Pathways
Pb-210+D	1.62E-03	2.39E-03	1.81E-01	1.85E-01
Ra-226+D	2.23E+00	2.35E-03	2.99E-02	2.26E+00
Ra-228+D	1.41E+00	5.67E-03	7.00E-02	1.49E+00
Th-228+D	1.75E+00	9.42E-03	1.24E-02	1.77E+00
Th-230	7.22E-04	2.47E-02	2.07E-02	4.60E-02
Th-232	8.05E-02	2.89E-02	2.81E-02	1.38E-01
U-234	7.48E-05	2.28E-03	4.78E-03	7.13E-03
U-238+D	3.48E-02	1.95E-03	4.63E-03	4.14E-02
Total	5.51E+00	7.76E-02	3.52E-01	5.94E+00

a. The “+D” designation includes contributions of radioactive progeny that are assumed to be in secular equilibrium with their parent in the environment. These summations are performed within the RESRAD code.
b. Excluding radon.

Table 6-3
Peak annual doses due to outdoor radon inhalation for representative outdoor worker at a hypothetical CCP management unit

	Effective Dose (mrem yr^{-1})	
Radionuclide[a]	Outdoor Radon – Net Excess CCP	Outdoor Radon – Native Soils
Pb-210+D	0.00E+00	0.00E+00
Ra-226+D	6.62E-02	2.48E-02
Ra-228+D	1.65E-02	1.63E-02
Th-228+D	8.92E-02	8.84E-02
Th-230	1.44E-05	5.38E-06
Th-232	6.88E-04	6.82E-04
U-234	4.40E-11	1.65E-11
U-238+D	3.10E-17	1.16E-17
Total	1.73E-01	1.30E-01

a. The “+D” designation includes contributions of radioactive progeny that are assumed to be in secular equilibrium with their parent in the environment. These summations are performed within the RESRAD code.

Additional Inhalation Dose Estimate During CCP Placement Events

The additional effective dose due to particle emissions and inhalation during the unloading and grading of CCP materials is based on the models, model parameters, and assumptions discussed previously in this report. This additional dose, provided in Table 6-4, could be interpreted as a dose conversion factor for a worst-case scenario in which an individual is standing within 3 ft of the placement and grading operations. An implausible scenario is assumed to have the outdoor worker standing 3 ft from the placement area continuously during the 1,680-hour work year. This equates to 12,600 CCP loads per year based on the load capacity assumptions made previously and adds an additional annual effective dose of 43.1 mrem above background.

As before, the CCP management unit outdoor worker in this scenario represents a bounding dose estimate for the movement of CCP materials. Other workers, such as heavy equipment operators (i.e., land grader), would have lower doses because they are enclosed and shielded in a cab and are farther away than a person standing next to the grading activity. Ignoring the effects of cabin filtration and lower breathing rates (less active worker), Equation 5-11 can be used to show that if the mixing cell height is increased to account for the height of the grader cabin (e.g., 4 m), the 12,600 loads per year dose drops to 18.3 mrem, which still represents an overestimate of the effective dose.

Table 6-4
Effective dose per load due to inhalation of suspended CCP particles during unloading and grading processes

Radionuclide[a]	Effective Dose per Load from Inhalation[b] (mrem $load^{-1}$)
Pb-210+D	6.48E-04
Ra-226+D	3.61E-04
Ra-228+D	5.53E-04
Th-228+D	4.89E-04
Th-230	3.67E-04
Th-232	1.10E-10
U-234	5.56E-04
U-238+D	4.45E-04
Total	3.42E-03

a. The “+D” designation includes contributions of radioactive progeny that are assumed to be in secular equilibrium with their parent in the environment. These summations are performed within the RESRAD code.

b. Excluding radon.

7 UNCERTAINTY ANALYSIS

Uncertainty is attributed to both lack of knowledge and natural variability in the various inputs of the dose calculation. In general, uncertainty due to lack of knowledge can include such things as estimates of source concentrations and volumes as well as parameter values for release and transport models (parametric uncertainty). Uncertainty due to natural variability includes variability in meteorological conditions and receptor behavior patterns. ICRP guidance states that uncertainty may be addressed in two ways (ICRP, 2006). The first method involves simple deterministic calculations (termed *screening calculations*) that employ simple models and parameter values to reflect the worst case that when combined are not likely to underestimate the dose. The second method is a detailed uncertainty analysis using models and parameter values designed to provide an unbiased estimate of dose coupled with methods to propagate the uncertainty in the models and parameter values into the output, resulting in a distribution of possible doses. Detailed uncertainty analysis requires substantially more effort than deterministic methods and is important when the most realistic possible (i.e., unbiased and not intentionally conservative or high-sided) dose estimates are desired (as in epidemiological studies).

This study falls into the simple deterministic class of assessments. This approach is generally sufficient if it can be demonstrated that the magnitude of the dose estimated using simple deterministic models is small relative to regulatory dose standards and that it is unlikely that the dose will be underestimated. And although there is inherent uncertainty in all dose assessments, models, assumptions, and parameters, values in this assessment were chosen to maximize impacts—that is, to overestimate the dose to any real person. This was accomplished by using a hypothetical person as a surrogate for a real person that behaves in such a way as to maximize their dose. Conservatisms incorporated into the different components of the calculations are summarized next.

Source Term

Measurement data for the source activities were limited to Ra-226 and Ra-228. The assumption of secular equilibrium was made for each respective decay chain. However, Pb-210 is the only decay progeny that is typically found to be at consistently higher levels than other progeny measured in CCP materials. Other radionuclides tend to show a decreasing deviation from secular equilibrium.

The particle emission factor used to account for the suspension of particles into the air during the grading process is valid for particles between 2.5 μm and 10 μm. Based on available CCP particulate data, it was conservatively assumed that 40% of the particles fell within this range.

Transport

The selection of the mass loading factor for the RESRAD model is based on respirable dust suspension during placement activities. RESRAD was used to calculate the outdoor worker doses excluding the effects of placement (e.g., no digging). The selected value of 95 µg m^{-3} is conservative compared to the 67 µg m^{-3} measured when no placement was occurring. Both of these values are higher than the 48 µg m^{-3} published by EPA for PM_{10} particulate concentrations in the Southeast from 2001 to 2022.[3]

The safety buffer transport parameter affects the air mixing volume calculated in Equation 5-11, which in turn affects the respirable air concentration. The assumption of an additional 1 m from the edge of the grading area was made to maximize the dose to the individual by getting as close to the grading operation as possible (without risking serious injury). Unlike most parameters, such as particle emission factors or mass loading factors, the worker dose has a nonlinear sensitivity to the buffer distance. As the buffer distance is increased from 1 to 100 m, the worker dose drops off in a nonlinear fashion, as shown in Figure 7-1.

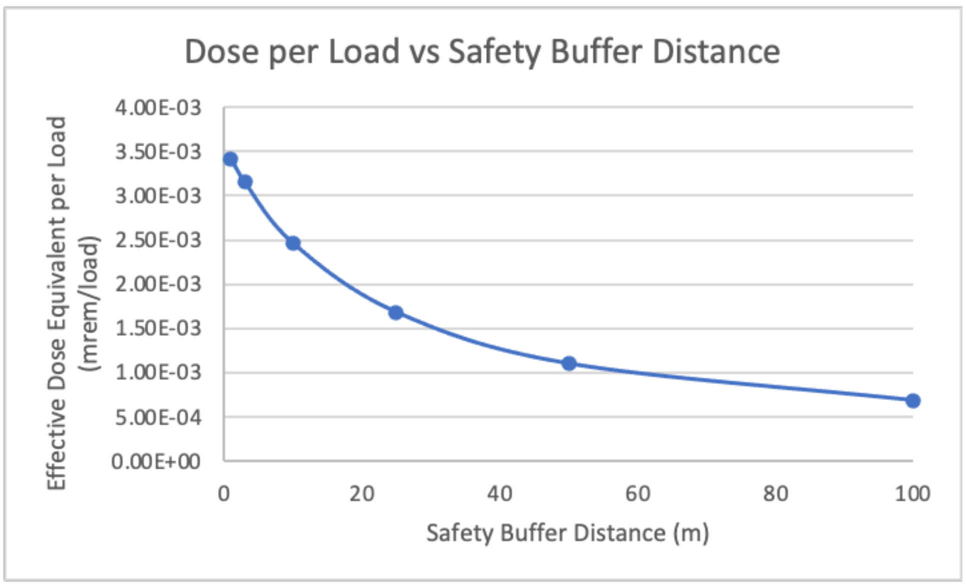

Figure 7-1
Outdoor worker dose per CCP load processed as a function of added safety buffer distance

[3] https://www.epa.gov/air-trends/particulate-matter-pm10-trends.

Exposure Assessment

A CCP management unit worker was assumed to stand next to or on the CCP material rather than sit in the cab of the equipment, exposing the worker to suspended particles for the entire duration of the workday and maximizing their inhalation and ingestion doses. In addition, inhalation and ingestion rates were selected to be conservative for this continuously exposed individual, ensuring that inhalation and ingestion doses were representative of a worst-case scenario. The dose from external exposure to the outdoor worker was maximized by assuming that the person spends 100% of their work year outdoors and in contact with the CCP materials.

These exposure factors all have a linear relationship with the calculated dose, simplifying any model sensitivities associated with them.

8
RADIATION DOSE AND RISK IN PERSPECTIVE

Because uranium, thorium, and radium are naturally occurring elements (WHO, 2012), humans are exposed to them through normal daily activities such as eating, drinking, and breathing. Numerous studies have compiled concentrations of uranium, radium, and thorium in environmental media. These concentrations may vary widely by location and can also be impacted by local anthropogenic activities.

Risk in the context of radiation exposure is the increased chance of getting cancer above the rate normally expected in the population at large. Risk estimates that are used to predict public health effects are based on detailed epidemiological studies of well-defined populations. Such studies have not demonstrated health effects to individuals exposed to less than 10,000 mrem (100 mSv), though there is scientific evidence for health risks following high-dose exposures (e.g., above 10,000 mrem or 100 mSv). At doses below 5,000 mrem (50 mSv), the risks of health effects are either too small to be observed or nonexistent (HPS, 2004). The highest annual dose (excluding radon) calculated for potentially exposed workers from the CCPs at a management unit is 53.3 mrem (43.1 mrem from 12,600 CCP loads + 10.2 mrem from baseline exposure), well below the level at which potential health effects may be observed. These doses were the result of implausible exposure parameters and placement assumptions. As demonstrated in Section 7, actual doses to workers will be lower.

Regulatory Analysis

There are no uniform national regulations or guidelines for the management of TENORM waste. Management of these materials falls under a variety of regulatory authorities, including EPA, the Nuclear Regulatory Commission (NRC), and the authority of individual states.

EPA regulates releases of TENORM to air from the phosphate industry and uranium mines under the confines of the Clean Air Act. Through the Clean Water Act, the EPA regulates liquid discharges of TENORM into surface waters from uranium mines and mills. Abandoned hazardous waste sites fall under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA, e.g., Superfund). TENORM waste byproducts (e.g., sludges from water and wastewater) are not regulated by EPA.

The American National Standards Institute (ANSI) and the Heath Physics Society (HPS) developed a standard for the control and release of TENORM (ANSI, 2009). The standard adopts an overall dose limit of 100 mrem yr^{-1} (1 mSv y^{-1}) above background from all sources (including TENORM and other manmade sources) and pathways of exposure to radionuclides, excluding radon and short-lived decay products, consistent with current IAEA safety standards (IAEA Safety Standards Series No. GSR Part 3 2014). This dose limit applies to all facility operations and practices that release radionuclides to the environment. A dose comparison is shown in Figure 8-1 demonstrating that with even the most conservative and unrealistic assumptions, the outdoor worker doses estimated in this assessment do not exceed this limit.

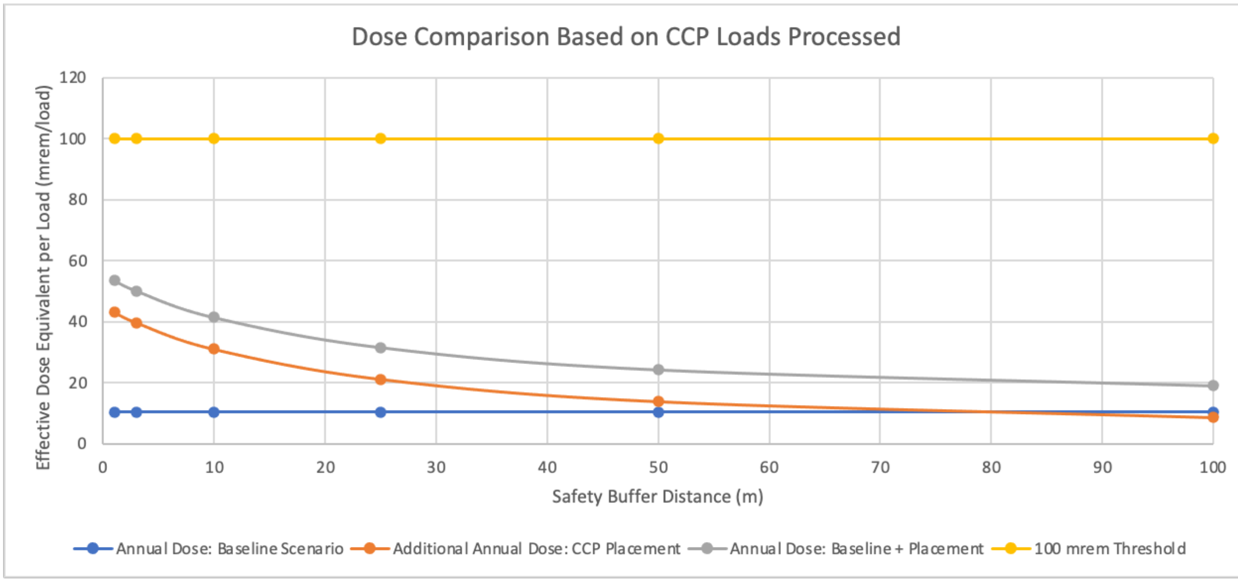

Figure 8-1
Outdoor worker dose (excluding radon) comparison as a function of added safety buffer distance

Radon Exposure

Radon exposures are unique among internal exposures in that the relationship between exposure to short-lived decay products of radon in air and the risk of lung cancer can be estimated, with some uncertainty, from epidemiologic studies in various groups of underground miners and people in their homes. As a result, control of radon exposures is typically based directly on measurements of air concentrations and the setting of reference levels for workplaces and homes rather than estimating the dose per intake and comparing to a dose threshold (ICRP, 2007, 2014).

The radon dose calculated in Section 5 is provided in this report to allow for a direct comparison of radon exposure to other exposure pathways at a CCP management unit. The net excess outdoor radon-222 concentration provided in the RESRAD model that contributed to the reported radon dose is 0.065 pCi L-1. The ANSI and HPS standard recommends an outdoor radon-222 concentration threshold downwind or at the site boundary of a TENORM disposal facility of 0.5 pCi L-1 above background (ANSI, 2009). Therefore, the radon emissions that a hypothetical outdoor worker is exposed to, as calculated based on the large data set used in this study, is well below the ANSI standard reference value.

9 SUMMARY AND CONCLUSIONS

This research is a collaborative effort between EPRI and TVA. TVA provided radionuclide measurements from CCPs and background soils at its power plants, and EPRI independently performed the analysis. This analysis used measurements of specific radionuclides in CCPs from eight CCP management units along with modeling to estimate air concentrations that could occur from activities related to managing CCPs. Hypothetical exposure scenarios that could lead to worker doses were developed and characterized based on readily available values in the literature. The exposure scenarios were based on a CCP management unit with no placement activities (baseline scenario) and a placement scenario that accounts for periods of active CCP management.

The average net excess Ra-226 and Ra-228 concentrations detected at all sites were 3.04 pCi g^{-1} and 1.23 pCi g^{-1}, respectively. Although most sites showed a statistically significant difference between the site mean and the entire data set mean, the range of mean concentrations was relatively small (i.e., 3.11 to 5.4 pCi g^{-1} for Ra-226 and 1.5 to 3.06 pCi g^{-1} for Ra-228). Based on these observations, the mean net excess concentrations using the entire data set were selected for the baseline analysis. All radionuclides in the Ra-226 and Ra-228 decay chains were assumed to be in secular equilibrium within their respective decay chains. Radium-226 is part of the U-238 decay chain, and Ra-228 is part of the Th-232 decay chain.

During periods with no placement activities, it was assumed that a hypothetical CCP management unit worker may be exposed to these materials internally via inhalation or ingestion of suspended materials and externally by standing near or working in close proximity to the CCPs. An implausible exposure scenario was assumed in which the worker was exposed during the entire work year, or 1,680 hours. This resulted in a worst-case annual total effective dose of 10.2 mrem, excluding radon. The calculated inhalation and ingestion dose for the CCP management unit worker was 0.134 mrem and 0.755 mrem, respectively, and the external dose was 9.32 mrem. The effective dose from radon inhalation was 0.173 mrem.

During periods of CCP placement, the worker—who is assumed to be within 3 ft of the placement operations—is estimated to receive an additional effective dose from inhalation of 3.42×10^{-3} mrem per load above background. In the implausible scenario in which the worker is continuously exposed to placement activities during the 1,680-hour work year (i.e., 12,600 loads), the additional annual effective dose was 43.1 mrem above background.

The worst-case effective doses in this report were less than the 100 mrem yr^{-1} dose limit recommended by the American National Standards Institute (ANSI, 2009) for workers at TENORM landfills. In addition, the doses estimated here are well below the level at which potential health effects may be observed (HPS, 2004).

10 REFERENCES

ANSI/HPS (American National Standards Institute/Health Physics Society). 2009. Control and Release of Technologically Enhanced Naturally Occurring Radioactive Material (TENORM). ANSI/HPS N13.53-2009. McLean, VA: Health Physics Society.

Barton, T. P. and Ziemer, P. L. 1986. The effects of particle size and moisture content on the emanation of Rn from coal ash. *Health physics*, *50*(5), 581–588.

DOE (U.S. Department of Energy). 2011. *Derived Concentration Technical Standard*. DOE-STD-1196-2011. U.S. Department of Energy, Washington, D.C.

DOE. 2021. *Derived Concentration Technical Standard*. DOE-STD-1196-2021. U.S. Department of Energy, Washington, D.C.

EPA (U.S. Environmental Protection Agency). 1991. Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual Supplemental Guidance Standard Default Exposure Factors. Interim Final. OSWER Directive 9285.6-03.

EPA. 1997. Exposure Factors Handbook. (Final Report). U.S. Environmental Protection Agency, Washington, D.C., EPA/600/P-95/002F a-c.

EPA. 2006. Data Quality Assessment: Statistical Methods for Practitioners. Office of Environmental Information, Washington, D.C., EPA/240/B-06/003. February.

EPA. 2011. Exposure Factors Handbook: 2011 Edition. National Center for Environmental Assessment, Office of Research and Development, U.S. Environmental Protection Agency, Washington, D.C., EPA/600/R-090/052F. September.

EPA. 2016a. Regional Screening Levels (RSLs) – Users Guide (May 2016). U.S. Environmental Protection Agency. Retrieved from: https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide-may-2016. May.

EPA. 2016b. Preliminary Remediation Goals for Radionuclides (PRG), PRG User Guide, U.S. Environmental Protection Agency, Waste and Cleanup Risk Assessment. Retrieved from: https://epa-prgs.ornl.gov/radionuclides/prg_guide.html.

EPA. 2019. Federal Guidance Report 15, External Exposure to Radionuclides in Air, Water and Soil. EPA-402/R/99-002, Rev 1. U.S. Environmental Protection Agency, Washington, D.C.

EPRI. 1993. *Physical and Hydraulic Properties of Fly Ash and Other By-Products from Coal Combustion*. Palo Alto, CA. TR-101999. February.

EPRI. 1997. *Coal Combustion By-Products and Low-Volume Wastes Comanagement Survey*. Palo Alto, CA. TR-108369. December.

EPRI. 2012. *Fugitive Particulate Emissions from Fly Ash Disposal and Unpaved Roads at a Coal-Fired Power Plant*. Palo Alto, CA. 1025050. June.

EPRI. 2014. *Hydrogeologic Environments at Coal Combustion Residuals Management Facilities*. Palo Alto, CA. 3002003765. December.

EPRI. 2016. *Relative Impact Framework Application for a Hypothetical Coal Combustion Residual Surface Impoundment*. Palo Alto, CA. 3002007544. May.

EPRI. 2019. *Chemical Constituents in Coal Combustion Products: Radium*. Palo Alto, CA. 3002016496.

European Commission, Food and Agricultural Organization of the United Nations, International Atomic Energy Agency, International Labor Organization, OECD Nuclear Energy Agency, Pan American Health Organization, United Nations Environment Program, World Health Organization 2014. Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3. Vienna, Austria. Retrieved from: http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1578_web-57265295.pdf.

HPS (Health Physics Society). 2004. Radiation Risk in Perspective: Position Statement of the Health Physics Society. Retrieved from: https://hps.org/documents/radiationrisk.pdf.

ICRP (International Commission on Radiological Protection). 1993. Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 2, Ingestion Dose Coefficients. ICRP Publication 67. Oxford: Pergamon Press.

ICRP. 1995a. Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 3, Ingestion Dose Coefficients. ICRP Publication 69. Oxford: Pergamon Press.

ICRP. 1995b. Age-Dependent Doses to Members of the Public from Intake of Radionuclides: Part 4, Inhalation Dose Coefficients. ICRP Publication 71. Oxford: Pergamon Press.

ICRP. 1996. Age Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5: Compilation of Ingestion and Inhalation Coefficients. ICRP Publication 72. Oxford: Pergamon Press.

ICRP. 2002. Doses to the Embryo and Fetus from Intakes of Radionuclides by the Mother. ICRP Publication 88. Corrected Version. Oxford: Pergamon Press.

ICRP 2006. *The Optimization of Radiological Protection – Broadening the Process.* ICRP Publication 101b. Ann. ICRP 36 (3). International Commission on Radiation Protection, Oxford.

ICRP. 2007. *The 2007 Recommendations of the International Commission on Radiological Protection*. ICRP Publication 103. Ann. ICRP 37 (2–4). International Commission on Radiation Protection, Oxford.

ICRP. 2008. *Nuclear Decay Data for Dosimetric Calculations*. ICRP Publication 107, Pergamon Press.

ICRP. 2014. *Radiological protection against radon exposure*. ICRP Publication 126. Ann. ICRP 43 (3). International Commission on Radiation Protection, Oxford.

Kalkwarf, D. R., Jackson, P. O., and Kutt, J. C. 1985. Emanation coefficients for Rn in sized coal fly ash. *Health physics*, *48*(4), 429–436.

Kamboj, S., Gnanapragasam, E., and Yu, C. 2018. *User's Manual for RESRAD Version 7.2*. ANL/EVS/TM-18/1. Environmental Science Division, Argonne National Laboratory, March.

Karamdoust, N.A. and Durrani, S. A. 1991. Determination of radon emanation power of fly ash produced in coal-combustion power stations. Nuclear Tracks and Radiation Measurements, 19(1-4), 339–342.

Karangelos, D. J., Petropoulos, N. P., Anagnostakis, M. J., Hinis, E. P., and Simopoulos, S. E. 2004. Radiological characteristics and investigation of the radioactive equilibrium in the ashes produced in lignite-fired power plants. *Journal of environmental radioactivity*, *77*(3), 233–246.

Lauer, N. E., Hower, J. C., Hsu-Kim, H., Taggart, R. K., and Vengosh, A. 2015. Naturally Occurring Radioactive Materials in Coals and Coal Combustion Residuals in the United States. *Environmental science & technology*, *49*(18), 11227–11233.

Mustonen, R. and M. Jantunen, 1985. "Radioactivity of Size Fractionated Fly-Ash Emissions from a Peat- and Oil-Fired Power Plant." *Health Physics* 49(6), 1251–1260.

Narula, A., Chauhan, R. P., and Chakarvarti, S. K. 2010. Testing permeability of building materials for radon diffusion. Indian Journal of Pure and Applied Physics. 48.

NCRP (National Council on Radiation Protection). 1988. *Measurements of Radon Daughters in Air*. NCRP Report 97. NCRP, Bethesda, MD.

NCRP. 1996. *Screening Models for Release of Radionuclides to Atmosphere, Surface Water, and Ground.* NRCP Report 123. NCRP, Bethesda, MD.

Till, J. E. and H. A. Grogan, eds. 2008. *Radiological Risk Assessment and Environmental Analysis*. New York: Oxford University Press.

TVA. 2021. Personal communication, N. Carriker to B. Hensel (EPRI), May 4, 2021.

WHO (World Health Organization). 2012. Uranium in Drinking-water: Background document for development of WHO Guidelines for Drinking-Water Quality. WHO/SDE/WSH/03.04/118/Rev1.

Yu, C., A. J. Zielen, J. J. Cheng, D. J. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo III, W. A. Williams, and H. Peterson. 2001. *User's Manual for RESRAD Version 6*. ANL/EAD-4. Environmental Assessment Division, Argonne National Laboratory, July.

A

CONCENTRATION VS. DEPTH PROFILES

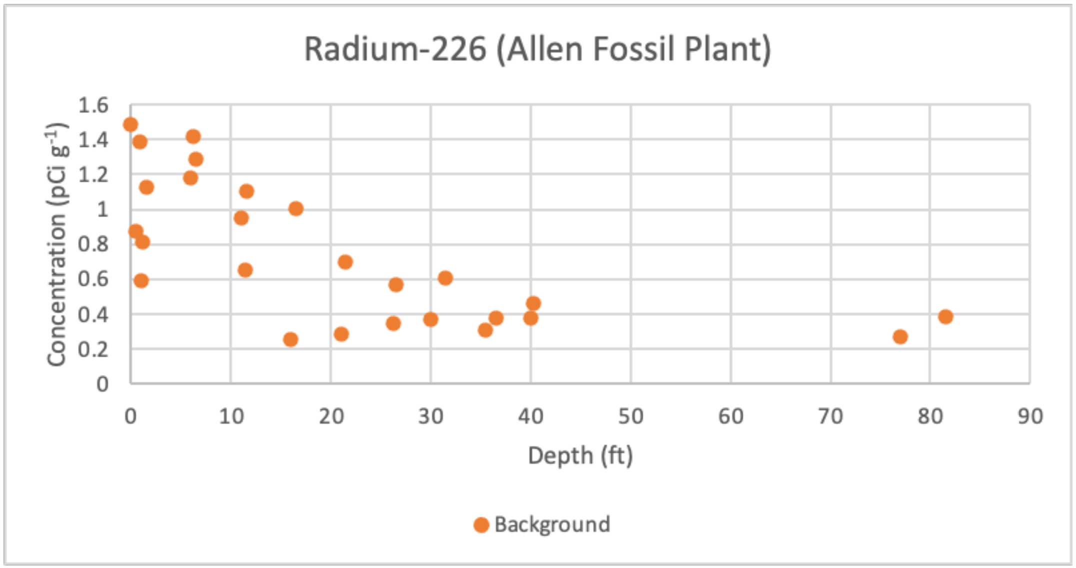

Figure A-1
Ra-226 concentrations as a function of depth at the Allen Fossil Plant (no data available for CCP material)

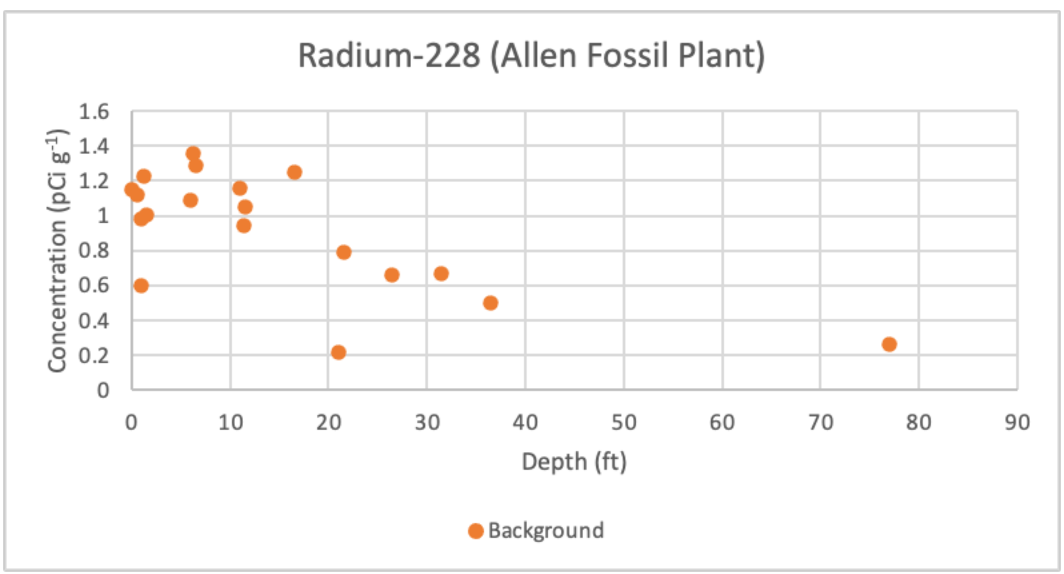

Figure A-2
Ra-228 concentrations as a function of depth at the Allen Fossil Plant (no data available for CCP material)

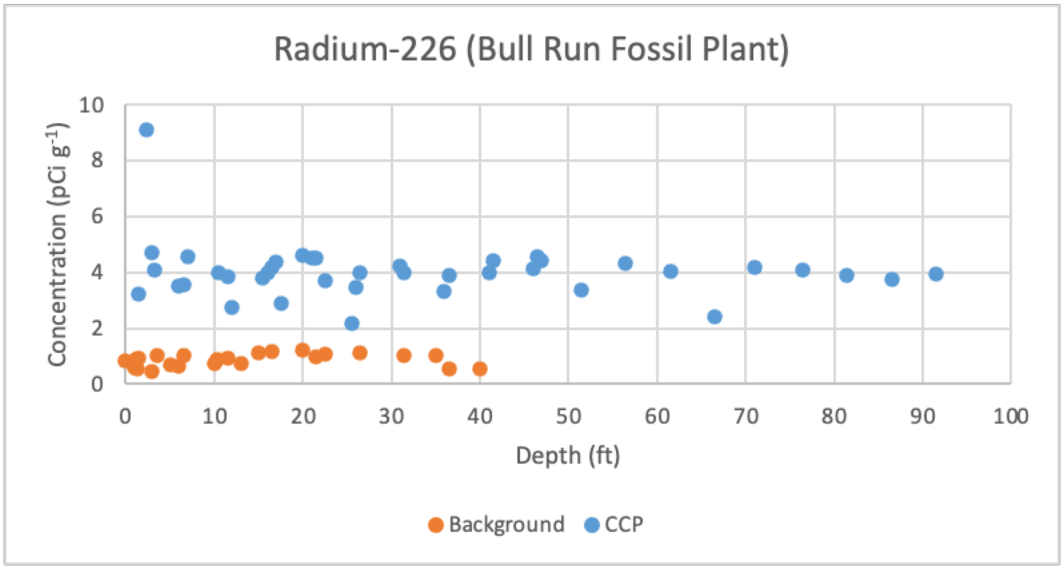

Figure A-3
Ra-226 concentrations as a function of depth at the Bull Run Fossil Plant

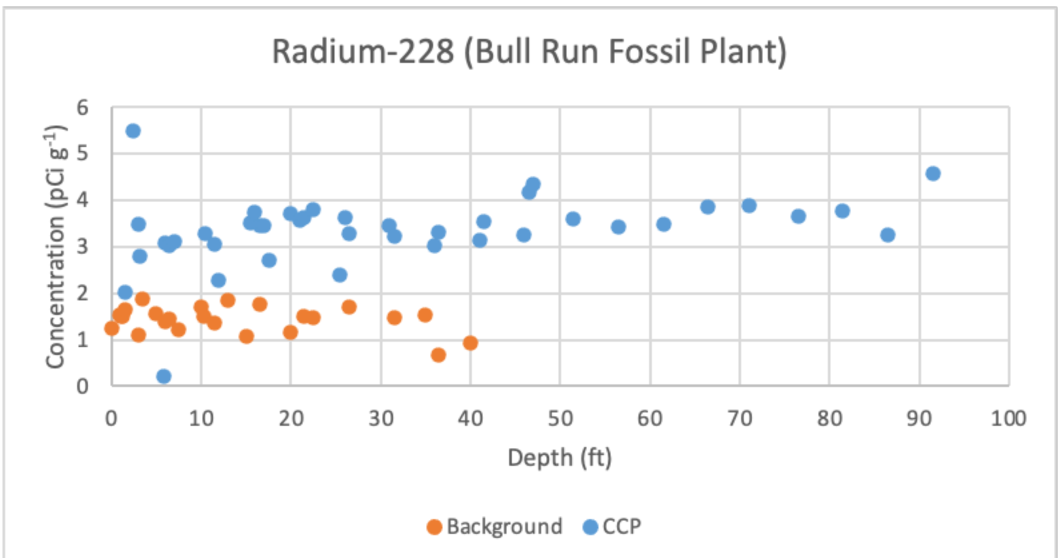

Figure A-4
Ra-228 concentrations as a function of depth at the Bull Run Fossil Plant

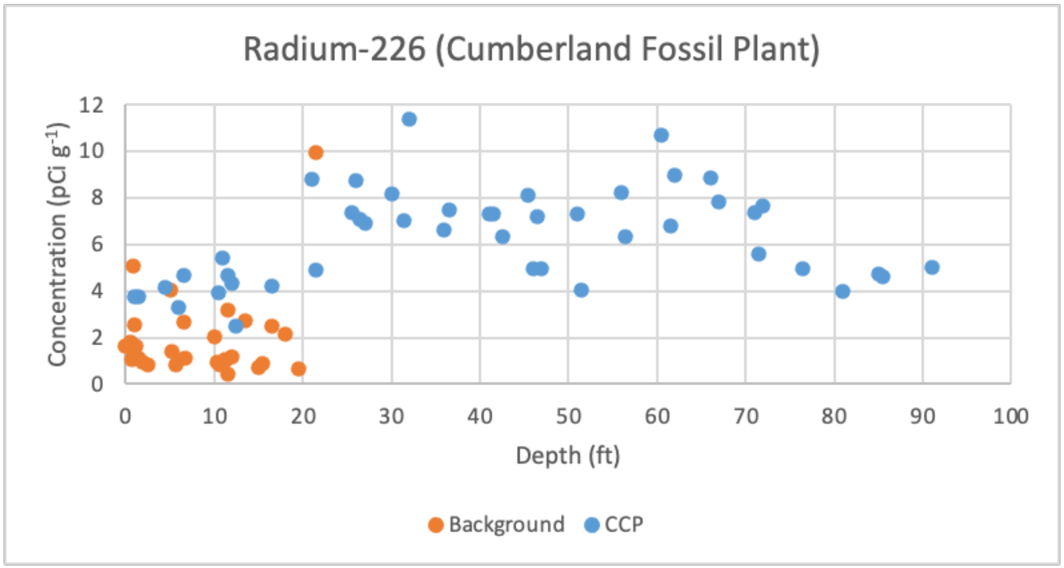

Figure A-5
Ra-226 concentrations as a function of depth at the Cumberland Fossil Plant

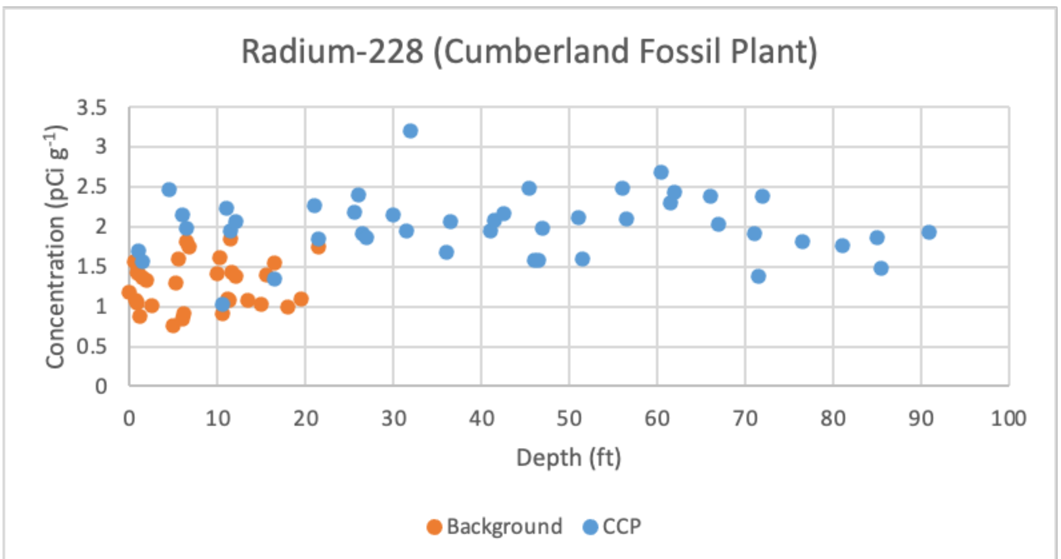

Figure A-6
Ra-228 concentrations as a function of depth at the Cumberland Fossil Plant

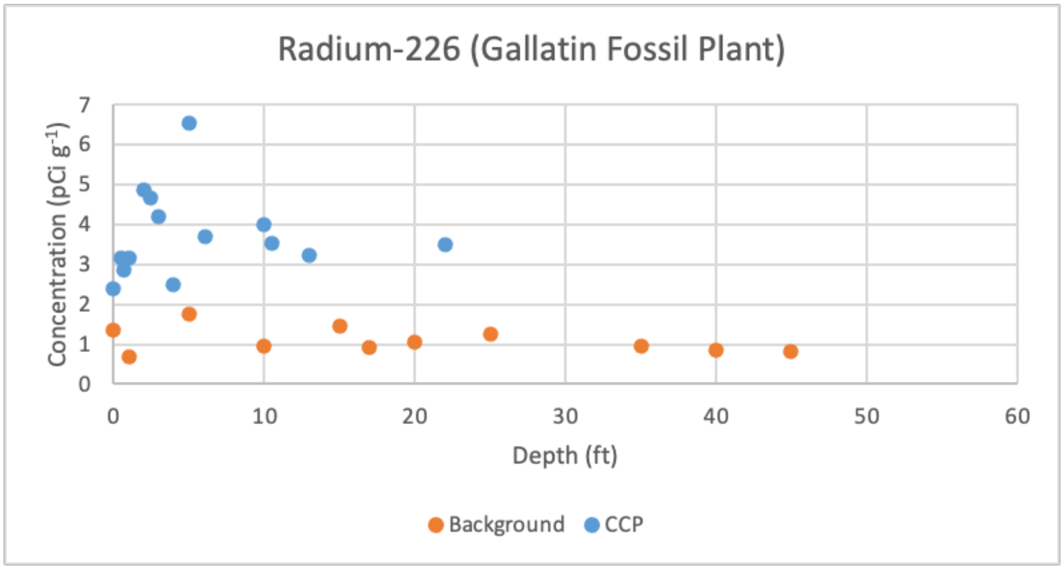

Figure A-7
Ra-226 concentrations as a function of depth at the Gallatin Fossil Plant

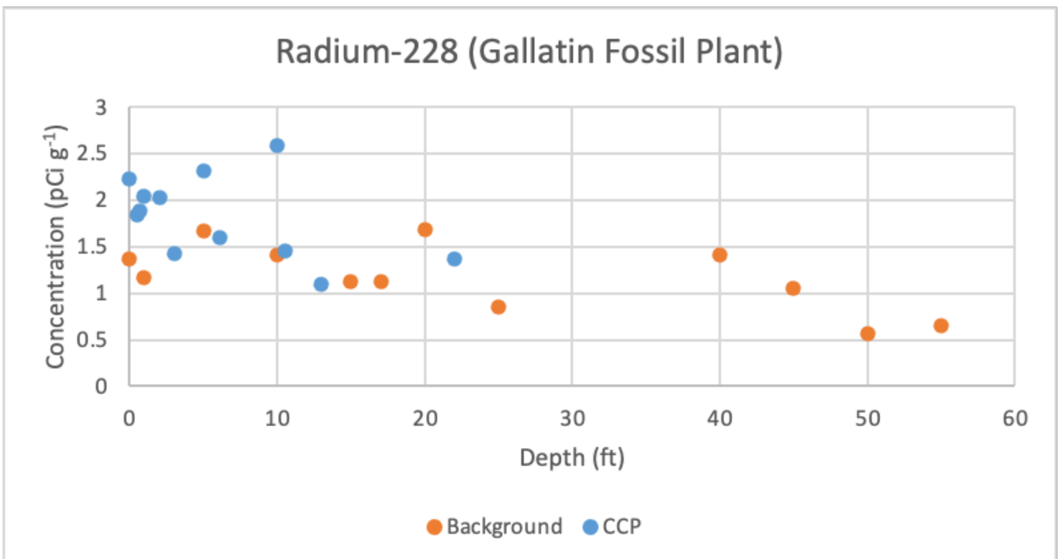

Figure A-8
Ra-228 concentrations as a function of depth at the Gallatin Fossil Plant

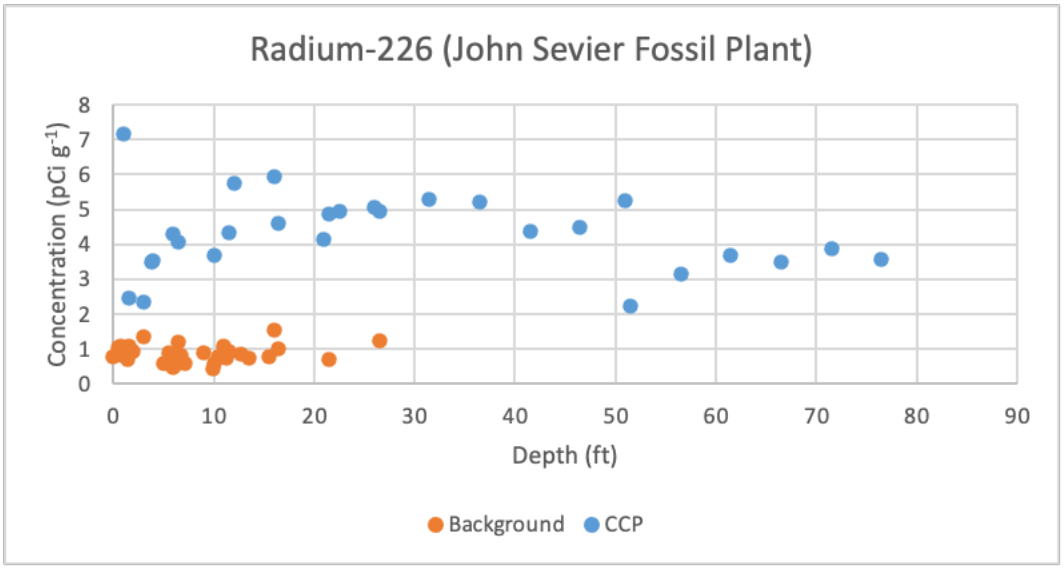

Figure A-9
Ra-226 concentrations as a function of depth at the John Sevier Fossil Plant

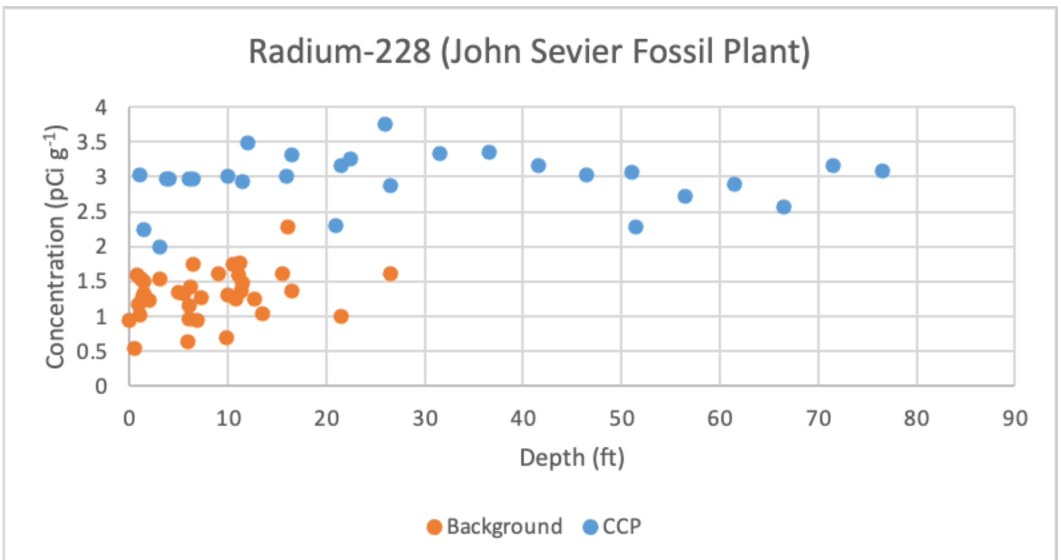

Figure A-10
Ra-228 concentrations as a function of depth at the John Sevier Fossil Plant

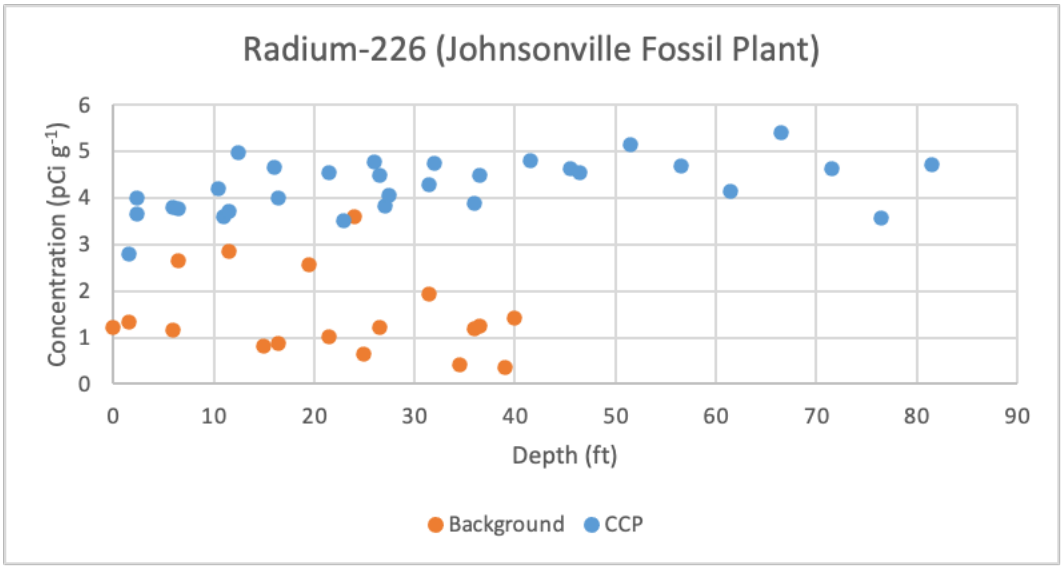

Figure A-11
Ra-226 concentrations as a function of depth at the Johnsonville Fossil Plant

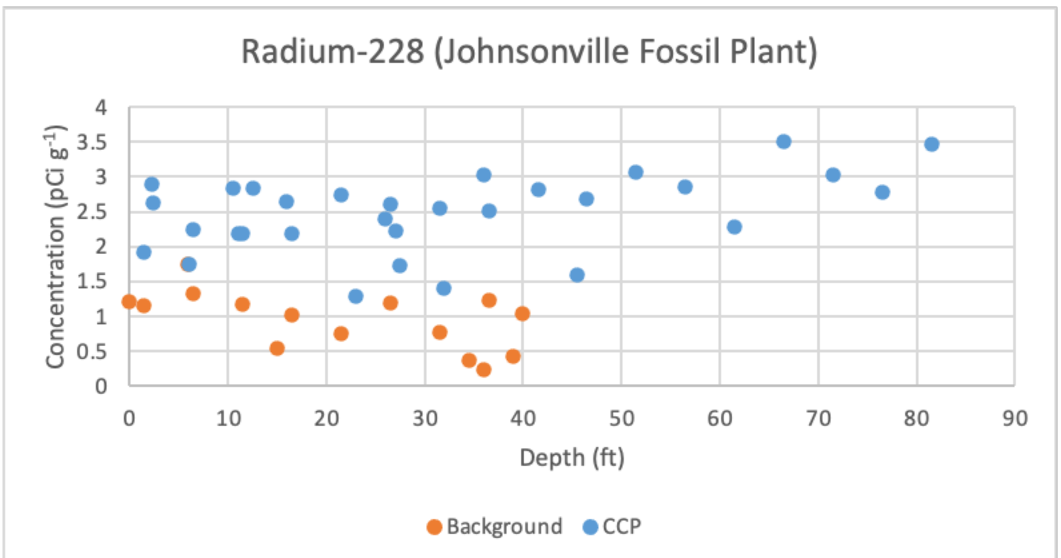

Figure A-12
Ra-228 concentrations as a function of depth at the Johnsonville Fossil Plant

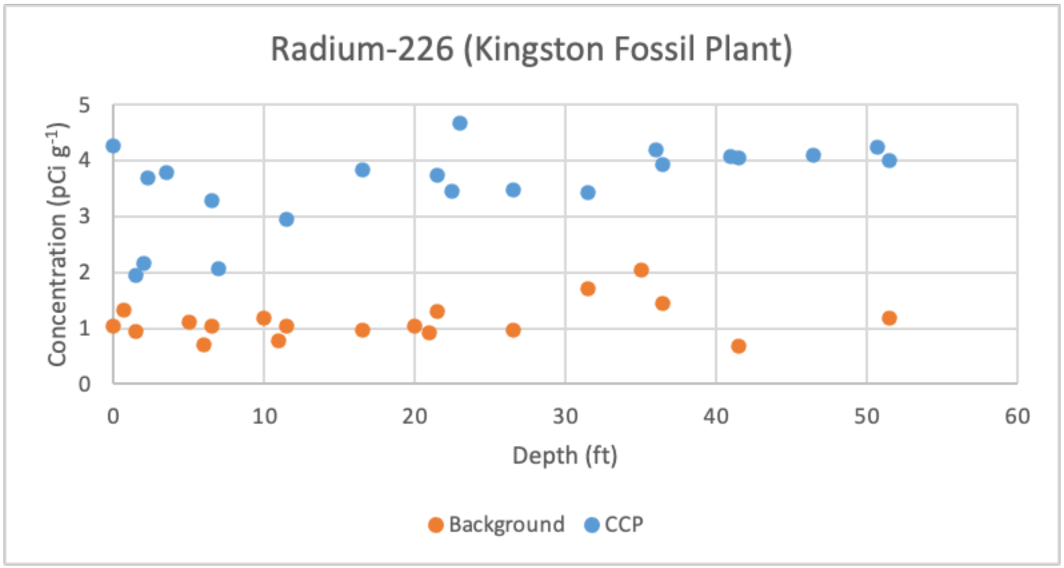

Figure A-13
Ra-226 concentrations as a function of depth at the Kingston Fossil Plant

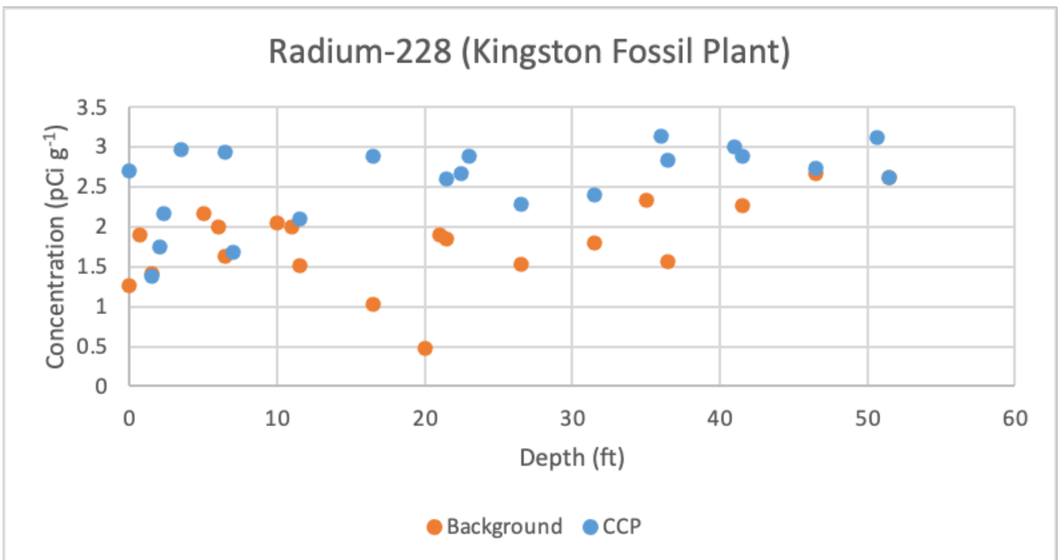

Figure A-14
Ra-228 concentrations as a function of depth at the Kingston Fossil Plant

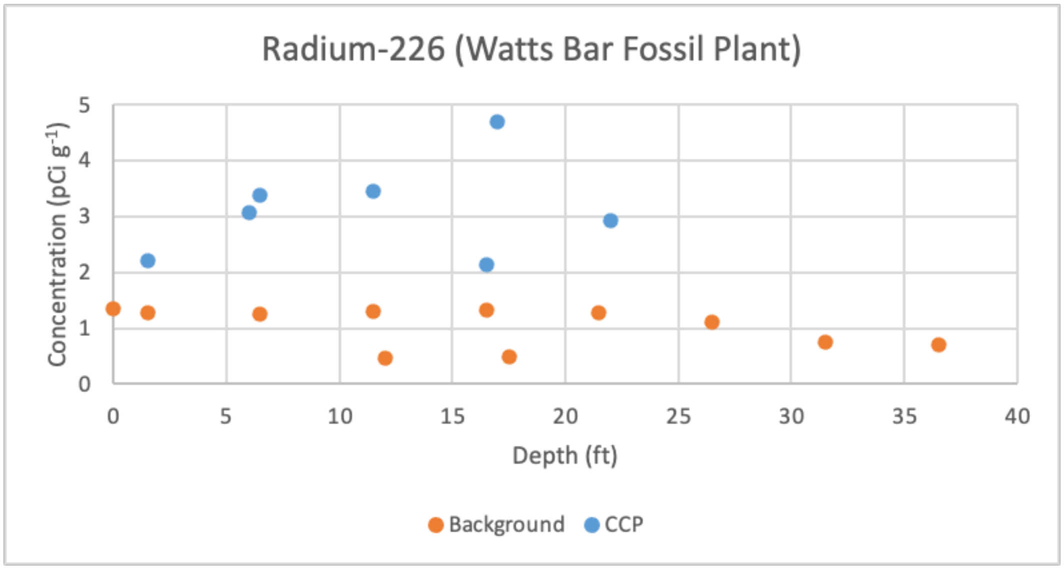

Figure A-15
Ra-226 concentrations as a function of depth at the Watts Bar Fossil Plant

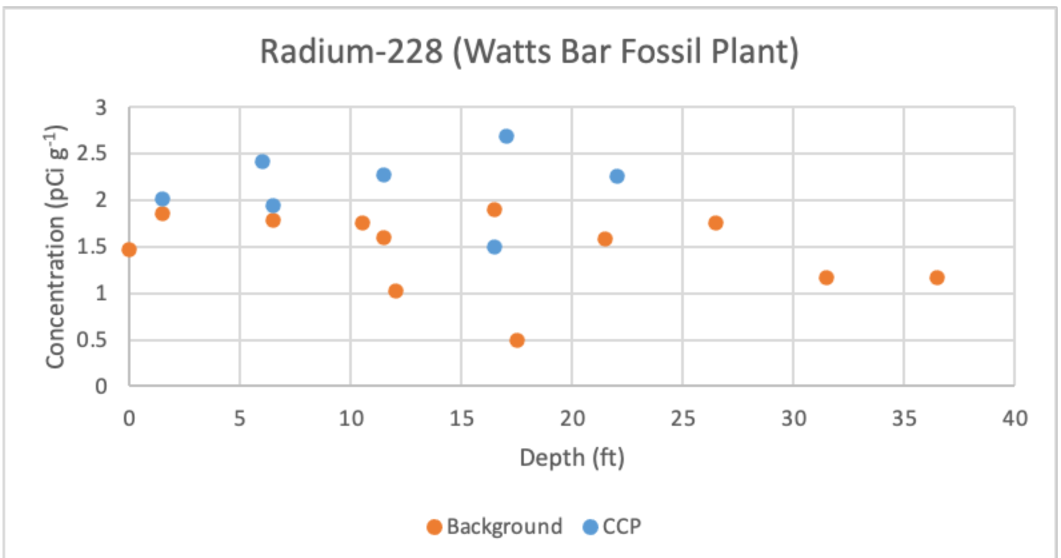

Figure A-16
Ra-228 concentrations as a function of depth at the Watts Bar Fossil Plant

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

Program:

CCP Land and Groundwater Management

3002024222

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com