

# **Attachment A2**

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## **RAC 2017 Radiological Risk Assessment**

~~May-August 128~~, 2017

# FINAL REPORT

## Corrective Action Plan for Blue Ridge Landfill: Radiological Risk Assessment

*Submitted to Advanced Disposal Services*

~~May 1~~August 28, 2017

# FINAL REPORT

## Corrective Action Plan for Blue Ridge Landfill: Radiological Risk Assessment

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## Executive Summary

The Blue Ridge Landfill (BRLF), located in Irvine, KY, is a municipal solid waste landfill operated by Advanced Disposal Services (ADS). The landfill began operations in 1984 and accepts 550 tons of waste per day on average. In February 2016, it was claimed that technologically enhanced naturally occurring materials (TENORM) derived from oil and gas exploration and production activities in Ohio and West Virginia were disposed of at the site. In March of 2016, Advanced Disposal Services, Inc. retained Risk Assessment Corporation (RAC) to conduct a radiation dose assessment to estimate doses to on-site and off-site receptors associated with the disposal of these wastes and a report was completed in October of 2016. The waste streams were arranged and brokered by BES, LLC and consisted of 92 independent shipments totaling approximately 1,157 U.S. tons, and are referred to as BES Wastes in this report. As described in RAC's 2016 report, RAC had no means to directly verify that TENORM waste was actually disposed of at the Blue Ridge site. For the radiological analysis of the corrective action plan, the BES Wastes are assumed to contain TENORM, and thus provides a conservative analysis.

Pursuant to the corrective action plan (CAP) agreed upon by the landfill and the State of Kentucky, ADS retained RAC to conduct a radiation dose and risk assessment for the two remediation alternatives identified. The radiological dose and risk calculations performed for each alternative represent bounding scenarios whereby the results are expected to overestimate actual doses and risks. Exposure parameters are generally representative of reasonable maximum exposures (RMEs). Underlying transport calculations used to determine the air and groundwater concentrations were deliberately high-sided, resulting in higher estimates of risk than would actually be incurred. Alternative 1 is closure-in-place with routine monitoring and alternative 2 is to excavate and redispense. The closure-in-place alternative assumes that the BES Waste disposed at BRLF remains in place in its current location (mixed with municipal solid waste (MSW)), and is topped with a minimum of 30 feet of MSW. The assumption is that the landfill continues to operate for 40 years at which point it is closed and the landfill is capped as part of the final cover system. This scenario is consistent with BRLF operating and closure permit (033-00004), approved by Kentucky Energy and Environment Cabinet. The excavate and redispense alternative assumes heavy equipment is used to remove the BES Waste disposed at BRLF and is loaded into trucks for haulage to an alternate disposal location via the public road system.

Based on additional information from the KY Department of Public Health (DPH), dose estimates for the disposal operations (provided in RAC 2016) were revised and cancer morbidity and mortality risk estimates calculated. Results from the re-analysis are provided as Appendix A.

The BES waste was characterized using landfill gate tickets, shipping manifests, and radioanalytical data of individual shipments or groups of shipments provided to RAC by Advanced Disposal. Based on the above information, weighted average radionuclide concentrations and total radionuclide inventories were calculated for the following radiologically relevant nuclides found in TENORM: uranium-238, uranium-234, thorium-230, radium-226, lead-210, thorium-232, radium-228, and thorium-228. For the remediation alternatives, the radionuclide concentrations computed above for the disposal operations were diluted based on a ratio of BES waste volume to total volume of mixed MSW and BES waste. The different types of people likely to be exposed to these radionuclides were identified: a landfill worker, an office worker at the landfill, another customer coming to the landfill, and students and staff at the middle school and high school adjacent to the landfill site. For the excavate and redispense alternative, an on-site supervisor was also

considered. Exposure scenarios for these groups were determined based on videos of landfill operations provided by Advanced Disposal and discussions regarding landfill activities with Advanced Disposal management. Exposure parameters (e.g., inhalation and soil ingestion rates) were selected to ensure doses were not underestimated.

Doses are reported on a per-load (disposed or removed) basis and as total dose, assuming the same worker is present for all removal operations. For prospective doses, viable exposure pathways are by means of radionuclide infiltration into the groundwater and inhalation of radon. A dose assessment was performed to 100,000+ years into the future to estimate potential doses. Radiological risks represent both the increased likelihood of being diagnosed with cancer (morbidity) and the increased likelihood of death from cancer (mortality) associated with exposure to radionuclides in the TENORM that was assumed to be disposed of at the landfill. Risks from radon inhalation are given on an annual and a lifetime (30-year) basis. Risks from groundwater ingestion assumed 30 years of exposure. Risks for disposal and removal operations are assumed to be incurred during each respective activity.

For Alternative 1, closure-in-place, inhalation doses from radon ranged from 0.025 mrem ( $2.5 \times 10^{-4}$  mSv) for the landfill worker to 0.0095 mrem ( $9.5 \times 10^{-5}$  mSv) for office workers at the south office. Lifetime (30-year) mortality risks were very low at  $5.3 \times 10^{-7}$  for the landfill worker and  $2.0 \times 10^{-7}$  for office workers at the south office (i.e., less than one in one million for any worker). For the future resident, maximum groundwater ingestion dose was 6.7 mrem ( $6.7 \times 10^{-2}$  mSv) and lifetime mortality risk was  $3.5 \times 10^{-5}$  (3.5 in 100,000) at 2700 years into the future assuming the groundwater is used as the drinking water source.

For Alternative 2, excavate and redispense, the total inhalation and ingestion effective dose to the landfill worker would be 3.7 mrem ( $3.7 \times 10^{-2}$  mSv); external doses would be 34.8 mrem (0.348 mSv). Total mortality risk incurred to the landfill worker in the excavate and redispense alternative would be  $1.2 \times 10^{-5}$  (1 in 100,000). For workers at the south office, the total dose would be  $2.9 \times 10^{-3}$  mrem ( $2.9 \times 10^{-5}$  mSv) from inhalation of particulates. Total mortality risk incurred to the south office worker in the excavate and redispense alternative would be  $4.6 \times 10^{-10}$  (~5 in 10,000,000,000).

These calculations indicate that Alternative 2 (excavate and redispense) results in the highest risks to the landfill worker. In addition, the radiological risks associated with redispersing these materials at a separate landfill would be comparable to the ~~excavation~~-risk incurred during the original disposals, and the subsequent long-term risks would be comparable to the closure-in-place risks calculated for Alternative 1 at the Blue Ridge Landfill.

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## Acronyms and Abbreviations

ADS	Advanced Disposal Services
BRLF	Blue Ridge Landfill
Bq	Becquerel, SI unit of radioactivity
C	Coulomb, SI unit of electric charge
CAP	Corrective Action Plan
Ci	Curie, Imperial unit of radioactivity
EPA	Environmental Protection Agency
ICRU	International Commission on Radiation Units and Measurements
ICRP	International Commission on Radiological Protection
KY	Kentucky
MSW	Municipal Solid Waste
NCRP	National Council on Radiological Protection
NORM	Naturally occurring radioactive materials
NRC	Nuclear Regulatory Commission
R	Roentgen, Imperial unit of exposure
RAC	Risk Assessment Corporation
SI	Système international d'unités (International System of Units)
TENORM	Technologically enhanced naturally occurring radioactive materials

## Scientific Notation (E-format)

Some of the numbers in this report are presented in scientific notation. Scientific notation is useful for presenting very large or very small numbers, or numbers that are different by many orders of magnitude. In scientific notation, numbers are expressed as the product of two terms; a digit term and an exponential term. For example, the number 723 expressed in scientific notation would be  $7.23 \times 10^2$  where 7.23 is the digit term and  $10^2$  (10 raised to the power of 2 or 100) is the exponential term. The power is the number of places to shift the decimal point to present the number in long format. If the power is positive, then shift the decimal point to the right. If the power is negative, then shift the decimal point to the left. Here are some examples.

$$\begin{aligned} 4,231 &= 4.231 \times 10^3 \\ 1,230,000 &= 1.23 \times 10^6 \\ 0.0361 &= 3.61 \times 10^{-2} \end{aligned}$$

Computers print scientific notation slightly different where the exponential term is reported as “E” followed by the power term. Thus, in the preceding example, 723 in computer scientific notation is 7.23E+02. Both forms of scientific notation are used in this report. Finally, for numbers between 1 and 10, the power term is zero because any number raised to the zero power is 1. Thus 7.23 expressed in scientific notation is  $7.23 \times 10^0$  or 7.23E+00 in computer scientific notation.

## Unit Conversions and Radiation Dose Terminology

Imperial unit	SI unit
Radiation Activity	
1 Ci	$3.7 \times 10^{10}$ Bq
$\sim 27$ pCi L <sup>-1</sup> or pCi m <sup>-3</sup> or pCi kg <sup>-1</sup>	1 Bq L <sup>-1</sup> or Bq m <sup>-3</sup> or Bq kg <sup>-1</sup>
Radiation Dose Quantities	
100 rad	1 Gy
100 mrem	1 mSv
100 $\mu$ rem hr <sup>-1</sup>	1 $\mu$ Sv hr <sup>-1</sup>
Other	
$3.9 \times 10^3$ Roentgen	1 C kg <sup>-1</sup>

**Exposure, R**, is a quantity that is defined only for photons in air. Ion chambers directly measure exposure (Roentgen, R or C kg<sup>-1</sup>), which can be converted to dose as follows:

1 R  $\approx$  0.869 rad (8.69 mGy) in air and  $\approx$  0.87 rem (8.7 mSv). The exact conversion is found in ICRU (1962), and includes temperature as well as absorption coefficients of tissue and air for the appropriate photon energy. For safety purposes only, an approximation of 1 R = 1 rad = 1 rem is frequently utilized.

### Absorbed Dose or Dose, *D*

Units: rad or Gy

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

Absorbed dose is a measure of energy absorbed per unit mass in a material or tissue.

### Dose Equivalent, *H<sub>T</sub>*, (*H* for dose rates)

Units: rem or Sv

$$\text{Equation: } H_T = D \times w_R$$

The product of the absorbed dose in tissue and the radiation-specific quality factor,  $w_R$ , that considers radiation type and its biological effect ( $w_{R\alpha}=20$ ;  $w_{R\beta}=1$ ;  $w_{R\gamma}=1$ ).

### Effective Dose, *E*

Units: rem or Sv

$$\text{Equation: } E = \sum_T w_T \times H_T$$

*E* is the sum of the product of the dose equivalent to the organ or tissue ( $H_T$ ) and the tissue-weighting factor ( $w_T$ ) applicable to each of the body organs or tissues that are irradiated. The tissue weighting factors,  $w_T$ , reflect the relative radiosensitivities of the various organs and tissues of the body from stochastic effects (cancer and heritable effects). The weighting factors are normalized to unity and thus the effective dose is equivalent to a hypothetical uniform irradiation of the body called whole body dose. The Effective Dose is a convenient quantity for regulating radiation exposure and is not appropriate for epidemiological studies where organ-specific dose is required.

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**Common Unit Prefixes**

p	pico	$10^{-12}$	k	kilo	$10^3$
$\mu$	micro	$10^{-6}$	M	mega	$10^6$
m	mili	$10^{-3}$			



## Scope of Work

This report documents Risk Assessment Corporation’s (RAC) evaluation of the radiological risks associated with the remediation alternatives identified in the Corrective Action Plan (CAP) concerning specific shipments of assumed technologically enhanced naturally occurring radioactive materials (TENORM) to Blue Ridge Landfill (BRLF) located in Irvine, KY between July 20, 2015, and February 3, 2016. The waste streams were arranged and brokered by BES, LLC. The shipments were transported by Advanced TENORM Services<sup>1</sup> (ATS), J.R. Daniels, Mountain State Environmental, and others to BRLF, and consisted of 92 loads comprising 1,157.25 U.S. tons of material. The waste material was generated by Cambrian Well Services (hereafter Cambrian), Fairmont Brine Processing (hereafter Fairmont Brine), GreenHunter Resources (hereafter GreenHunter), and Nuverra Environmental Services or Nuverra Environmental Resources (hereafter Nuverra).

## Introduction

In an earlier report (RAC 2016) RAC characterized the type and amount of BES waste emplaced at BRLF between July 20, 2015, and February 3, 2016, and conducted a dose assessment for the BES Waste assuming it is TENORM. The dose assessment considered the extent to which radioactive materials may be released and transported into the environment, the potential exposure pathways and the types of individuals who may have been exposed. Consideration was given to exposures at the time of disposal, and exposures following disposal, including exposures in the future recognizing the long half-life of some radionuclides in TENORM.

The risk assessment described in this report builds upon the assumptions, data and analyses presented in the previous report. The reader is referred to the earlier report for detailed information on the waste inventory and characteristics, environmental sampling measurements provided by the State and by Advanced Disposal Services (ADS), and site characterization information including the landfill design, local geology and hydrology, meteorology, and land use (RAC 2016). Dose and risks associated with the original disposal of the material into the landfill were revised based additional information and comments received from the Kentucky Department of Public Health. These estimates can be found in Appendix A. This report focuses on the radiological risks

Glossary-1

[Project Name]

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“Report title”  
“Chapter title”

Glossary-1

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<sup>1</sup> No relation to the owner of the BRLF, Advanced Disposal Services, Inc.

associated with each remediation alternative identified in the CAP. The full CAP report then evaluates these risks together with the other sources of risk associated with each remediation alternative. In order to allow the different sources of risk to be compared, risk is presented in terms of increased risk of death. For radiological risks, this is the increased likelihood of death from cancer associated with exposure to radionuclides in the BES Waste disposed at the BRLF. Cancer morbidity risk is also provided in this report.

This report also includes an ecological screening assessment performed using the Environmental Risk from Ionizing Contaminants Assessment (ERICA) tool. The ERICA tool combines data on environmental transfer of radionuclides and dosimetry to obtain a measure of exposure. This is subsequently compared to exposure levels defined by regulators or those at which deleterious effects are known to occur.

## Remediation Alternatives

The CAP identifies the following primary remediation alternatives for the BES Waste disposed at the Blue Ridge Landfill.

1. Closure-in-Place and Monitoring: This option assumes that the BES Waste disposed at BRLF remains in place in its current location (mixed with municipal solid waste (MSW)), and is topped with a minimum of 30 feet of MSW. The landfill continues to operate for 40 years at which point it is closed and the landfill is capped as part of the final cover system. This scenario is consistent with BRLF operating and closure permit (033-00004), approved by Kentucky Energy and Environment Cabinet. It is assumed that the cap starts to fail after 200 years of operation and that infiltration increases linearly to the natural infiltration rate over the next 100 years. Monitoring procedures for the landfill continue as specified in the permit.
2. Excavate and Redispose BES Waste: This option assumes heavy equipment is used to remove the TENORM disposed at BRLF and is loaded into trucks for haulage to an alternate disposal location via the public road system.

The radiological risks associated with each alternative are evaluated using a consistent methodology when appropriate. Thus, the assumed volume and characteristics of the BES Waste and associated materials located in the BRLF and considered in the CAP are identical for each alternative and are summarized in Excavate and Redispose Parameters below. Similarly, the same starting conditions are assumed with regard to characterization of the landfill, local geology, hydrology, meteorology, land use and surrounding population. For each alternative, the potential exposure pathways and receptors (potentially exposed individuals) are identified. Radiological risk is expressed in terms of the increased chance of cancer morbidity or mortality on a population basis for each remediation alternative. For the Closure-in-Place option, the ecological risks associated with the BES Waste in the BRLF were also evaluated.

### Alternative 1: Closure-in-Place

The closure-in-place alternative was evaluated previously in RAC's dose assessment report where the doses that would result in the future from the BES Waste disposed in BRLF were

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calculated (e.g. from radon inhalation and groundwater ingestion). However, based on comments received from the Kentucky Department of Public Health (KY DPH) regarding the characterization of the BES Wastes from Fairmont Brine, refinements are made to the original analysis (see RAC 2016) to account for additional information. Furthermore, the previous assessment calculated radiation doses only and did not present the results in terms of cancer mortality risk. Additionally, MSW placed over the BES Waste disposals was originally assumed to be 3 m (9.8 ft), whereas at least 30 ft of MSW are actually to be placed over the BES Waste disposal. For these reasons the October 2016 assessment is updated, revised doses are provided, and cancer morbidity and mortality risks are calculated. Appendix A provides the updated doses and associated cancer morbidity and mortality risks for the disposal operations. Revised prospective dose and risk calculations are included in the closure-in-place scenario (e.g. for radon inhalation and groundwater ingestion).

## **Alternative 2: Excavate and Redispose BES Waste**

The excavate and redispose alternative requires that all disposal cells containing the BES Waste are identified, and that all the BES Waste is excavated from the landfill and placed in trucks before hauling offsite to an alternate approved disposal location. This alternative was not evaluated in the earlier dose assessment report and is presented here in full. For alternative 2, the soil cover and MSW overlying the BES Waste must first be excavated and relocated to another part of the BRLF Site before the BES Waste materials mixed with MSW can be excavated and transported by truck to a separate landfill approved for its receipt. The volume of waste material that must be excavated for transport offsite is significantly greater than the original waste volume transported to BRLF for disposal. This is because the original waste is mixed with MSW and daily cover materials, the spatial distribution of disposals is recorded on a 100 ft × 100 ft grid and the depth to BES Waste varies by grid cell. Once the total excavation volume of waste was calculated (see Attachment B of CAP report), the time required to complete removal of the waste was determined (see Excavate and Redispose Parameters below).

## **BES Waste Characteristics**

The BES material was described as exploration and production soil and debris, sludge, debris, soil, and gravel on waste manifests (see RAC 2016, Attachment A1 to the CAP). The material was a chemical precipitate that was likely to be more uniform in nature than soil with regard to particle size. RAC assumed the characteristics of soil and debris with a variety of particle sizes in the respirable range so that potential exposures were not underestimated. Further, the material was very wet, and some loads had sawdust added to help absorb excess moisture and solidify the material.

RAC relied upon information regarding the radionuclide content of the waste materials from each generator in the form of analytical laboratory reports coupled with disposal manifests. In some cases, each box or container of material was individually sampled and could be matched directly to an individual load. In other cases, batch sampling was performed, and the results were subsequently applied to several loads. This process is described in detail in the earlier dose assessment report (RAC 2016).

Representative radionuclide activity concentrations for each load or set of loads is the same as previously reported with one exception. A composite radioanalytical sample describing Fairmont

Brine Loads 5-40 was used in place of the exposure rate measurements (Quinn 2015). Assuming the composite sample accurately represents the material sent from Fairmont Brine to the Blue Ridge Landfill in loads 5-40, revised activity concentrations were determined by converting sample weights from a dry-weight to wet-weight basis as the material received at the landfill was wet weight. The sample was analyzed for percent moisture with an average value of 22%. Ra-226 concentration in wet weight was 1191 pCi g<sup>-1</sup> (based on conversion equation 6.2 in ASTM D 2974-87) compared to the dry weight concentration of 1453.5 pCi g<sup>-1</sup> reported by Pace Analytical (Quinn 2015). Total wet weight radium concentration (Ra-226 and Ra-228) was 1440 pCi g<sup>-1</sup>. Coupling this with the average exposure rate on the containers sampled (543 μR hr<sup>-1</sup>), an exposure rate to total radium wet-weight concentration conversion was determined to be 0.377 μR hr<sup>-1</sup> per pCi g<sup>-1</sup> total radium. Using this conversion factor, total radium from the other surveyed containers was computed. Using the average container exposure rate and the revised conversion factor yields a total radium concentration for Fairmont Brine loads 5-40 of 1273 pCi g<sup>-1</sup>. Th-230 and U-238 concentrations in the Fairmont Brine material were computed based on the Th-232/Ra-228 ratio (0.533) and U-238/Ra-226 ratio (0.0649) in the sample.

Radionuclide activity concentrations for all other loads remained as previously reported (RAC 2016). Table 1 below provides the updated weighted average activity concentration assumed for the material as it entered the landfill. The doses and cancer mortality risks associated with exposures during the disposal operations are presented in Appendix A. As noted previously, these values update and replace the values reported by RAC (2016).

**Table 1. Representative Weighted-Average Radionuclide Concentrations and Estimated Total Inventories from all Generators as Disposed**

Radionuclide	Weighted Average Concentration (pCi g <sup>-1</sup> )	Inventory (Ci)
U-238	6.06E+01	6.37E-02
U-234	6.06E+01	6.37E-02
Th-230	4.18E+02	4.39E-01
Ra-226	7.41E+02	7.78E-01
Pb-210	6.60E+01	6.93E-02
Th-232	1.24E+02	1.30E-01
Ra-228	1.61E+02	1.69E-01
Th-228	1.25E+02	1.31E-01

### ***Excavate and Redispose Parameters***

The 92 loads of BES Wastes were disposed at BRLF in combination with MSW (e.g. mixed waste) in a total of 17 grid cells (100 ft × 100 ft). A soil cover layer (approximately 6 in depth) was applied over the waste at end of each day and a minimum of 30 feet of additional MSW will be placed on top of the TENORM waste. Table 2 details the mixed waste removal parameters provided by ADS that were used in determining dose and risk for the excavate and redispose alternative.

**Table 2. Mixed Waste Removal Parameters (provided by ADS)**

Parameter	Value (unit)
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Expected total tons of waste removed per day	480 (tons day <sup>-1</sup> )
Expected total number of 8-hour working days	76 (days)
Expected total amount of time to remove all waste	608 (hours)
Total number of truck loads to remove mixed material offsite	1,823 (loads)
In-place bulk waste density	1,600 (lbs yd <sup>-3</sup> )
Total excavation volume	55,926 (yd <sup>3</sup> )
Total mixed waste volume to be trucked offsite (includes 15% “fluff” factor) (AFCEE 2010)	45,575 (yd <sup>3</sup> )
BES Waste volume as disposed	1,446.6 (yd <sup>3</sup> )
Municipal volume covering mixed waste (to remain onsite; <u>includes 15% “fluff” factor</u> )	<u>18,745</u> <del>16,296</del> (yd <sup>3</sup> )

To account for the dilution of the BES Waste with MSW, a volume dilution factor was computed as:

$$\text{Dilution Factor} = \frac{\text{BES Waste volume}}{\text{Total Waste Volume}} = \frac{1450}{45600} = 0.0317$$

Applying the dilution factor, the weighted average activity concentration used for computing dose and risk for the excavate and redispense alternative is provided in Table 3 below.

**Table 3. Weighted-Average Radionuclide Concentrations within the Affected Disposal Cells**

Radionuclide	Weighted Average Concentration (pCi g <sup>-1</sup> )
U-238	1.92E+00
U-234	1.92E+00
Th-230	1.33E+01
Ra-226	2.35E+01
Pb-210	2.10E+00
Th-232	3.93E+00
Ra-228	5.12E+00
Th-228	3.96E+00

## Exposure Scenarios and Parameters

The Blue Ridge Landfill is located in eastern Kentucky, near the town of Irvine in Estill County. The population of Estill County on July 1, 2016 was reported as 14,307 ([www.census.gov](http://www.census.gov)) and the population of Irvine, 2,432 in 2014 (<http://population.us/ky/irvine/>). The population has shown a small decreasing trend since 2000. About 70% of Estill County is forested land (upland areas), with the remaining areas consisting of farms and urban development (see Section 2.2.5 and Figure 2.1 of the main report). Land use to the east of the landfill includes residential, rural, and agricultural uses. Directly southwest of the landfill are Estill County High School and Middle

School (Figure 2.1). Southwest of the middle and high schools is an industrial park that includes mining operations and warehouses.

There is no potable waste use at the Blue Ridge Landfill site. A private water well survey in 1992 (Rust Environment & Infrastructure, Inc. 1992) identified wells within one mile of the downgradient (northwest) site boundary (Figure 2.2a). A review of the Kentucky Geological Data Repository was conducted in 2017 (Figure 2.2b). In addition, an update of the 1992 survey is underway to determine if water supply conditions in the vicinity of the landfill have changed significantly.

~~This section provides~~ The exposure scenarios and parameters evaluated in the radiological risk assessment are provided in this section. The approach has been to identify those people most likely to receive the highest exposures so that exposures to other groups or categories can be assumed to be smaller. Consideration was given to the different types of workers at the BRLF for landfill workers, members of the public, and hypothetical future residents. To address releases to the atmosphere, potential public receptors located closest to the disposal area were identified, characterized and the doses calculated. Any member of the public at more distant locations would receive lower doses or no dose at all. Similarly, evaluation of the groundwater exposure pathway was designed to be bounding. A hypothetical well was assumed to be located directly downgradient from the source and the water extracted for human consumption directly. Any potential impacts to groundwater wells located at greater distances would result in lower doses. Details for each selected value can be found in the previous report (RAC 2016).

## Pathways and Parameters for the Landfill Worker and Supervisor

Potential onsite receptors include landfill laborers, heavy machinery operators, and a supervisor (excavate and redispense alternative only).

### *Alternative 1: Closure-in-Place*

The only potentially viable exposure pathway for the landfill worker is the inhalation of radon daughters that result from the decay of radium-226. Radon (Rn-222) has a short half-life (3.8 days) which means that the longer the travel time from the buried TENORM in the BES Waste to the surface, the lower the release rate from the surface to the air. The landfill worker is assumed to be exposed for 170 hours per month for 12 months per year for 30 years. To ensure exposures are not underestimated, it is assumed that the landfill worker is outside and in close proximity to the waste and that the wind is blowing towards the worker at all times. Heavy equipment operators work in enclosed cabs that are air-conditioned and will receive lower exposures than the laborer. They are and are therefore not ~~explicitly~~ considered explicitly.

### *Alternative 2: Excavate and Redispense*

Exposure pathways associated with the excavation and redispense alternative are associated with the TENORM waste being released into the environment during the excavation process and include inhalation of TENORM particulates, incidental ingestion of TENORM waste, and external exposures from TENORM brought to the surface. Moreover, there will be additional exposures created from the transportation and re-disposal of the material that are not explicitly considered

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here. Further, the exposure pathways associated with the closure-in-place alternative would apply in this scenario as well to the landfill in which this material would be placed.

An inhalation rate of  $1.8 \text{ m}^3 \text{ hour}^{-1}$  was assumed. This value assumes various levels of activities during the day.

This assessment uses a soil ingestion rate of  $330 \text{ mg day}^{-1}$ . This value is used in both the EPA radionuclide preliminary remediation goals (PRGs) and the EPA Regional Screening Level (RSL) (EPA 1991; EPA 2002; EPA 2011; EPA 2016a; EPA 2016b). The value represents the amount of soil ingested during an 8-hour working day.

A landfill laborer will only have contact with the BES Waste for a fraction of the workday. For soil ingestion calculations, it was assumed that contact, either directly or with material suspended during removal, was 20 minutes or 0.33 hours per truck-load. These exposure times were assumed for each of the truck-loads removed, and it is assumed that the same worker is present during all removal operations.

In addition to landfill worker there is also assumed to be a supervisor present. The same inhalation and soil ingestion rates are assumed. The supervisor is assumed to be present onsite for one hour per day for the entire 76 days.

The cancer risk coefficients for external exposure to soil from FGR-13 assume a person stands upon soil contaminated to an infinite depth and infinite area (EPA 1999). Thus, risks from this exposure pathway are expected to be overestimates because the TENORM constituents of the BES Waste do not represent contamination infinite in depth and area, and the landfill worker is not likely to stand on top of the waste for an extended period of time.

## Pathways and Parameters for the Public

Public receptors include office workers located at the south office (300 m) and main office (400 m) of the disposal facility, students and teachers located offsite at the nearby middle and high schools (~700 m), and another customer (100 m) delivering trash to the landfill. A hypothetical future resident is also assumed to be located 700 m from the landfill at the location of the current schools.

[This assessment does not directly address the possibility of exposure to residents driving up to the working face to dump their loads using their personal vehicles during the time span for receipt of the BES waste. However, exposure to any resident that may have been at the landfill during the disposals would be bounded by that of the landfill laborer, who spent more time in closer proximity to the waste than a resident.](#)

### *Alternative 1: Closure-in-Place*

The potential exposure pathway for the closure-in-place alternative is inhalation of radon daughters released to the air from the surface of the landfill. In the far future (~2700 years from now) there is potential exposure to radionuclides that are assumed to be leached from the landfill in groundwater that is assumed to be potable and ingested.

For the inhalation exposure pathway, the office worker is assumed to be exposed for 170 hours per month for 12 months per year, the student/teacher is assumed to be exposed for 170 hours per month for 9 months per year, the other customer is assumed to be exposed for 20 minutes per day,

six days per week for 50 weeks of the year. A future resident is assumed to be exposed for 24 hours per day for 365 days per year. All risks were computed assuming 30 years of exposure.

For groundwater, a hypothetical future resident is assumed to drink 2 L per day, 365 days per year for 30 years. The groundwater well is assumed to be on the downgradient edge of the BES Waste disposal. This provides a bounding exposure scenario for the groundwater pathway because groundwater concentrations are maximized on the downgradient edge of the source, and any potential impacts to groundwater wells located at greater distances or in geological formations that supply drinking water would result in lower doses. Exposure to radon from an individual who builds a house on top of the impacted disposal area was not considered a viable exposure pathway because residential construction on top of landfills is typically restricted.

### ***Alternative 2: Excavate and Redisperse***

For office workers, students, and teachers, the only potential exposure pathway is inhalation of TENORM particulates released during the excavation and redispersion process. For the other customer, potential exposure pathways include inhalation of TENORM particulates, and incidental ingestion of TENORM waste material, and external exposure from TENORM brought to the surface during the excavation and redispersion process. The other customer is assumed to have the same inhalation ( $1.8 \text{ m}^3 \text{ hr}^{-1}$ ) and soil ingestion rates ( $330 \text{ mg day}^{-1}$ ) as the landfill worker; they are assumed to come twice per day for 10 minutes each time for a total of 20 minutes per day for each of the 76 days. Office workers and teachers are assumed to have an adult inhalation rate of  $20 \text{ m}^3 \text{ day}^{-1}$ .

Exposure to radon daughters during removal was not calculated because radon primarily represents a long-term exposure issue and the integrated exposure time during removal is small compared to annual exposure from individuals who live and work near or at the facility.

## **Methods for Estimating Exposure Concentrations, Dose, and Risk**

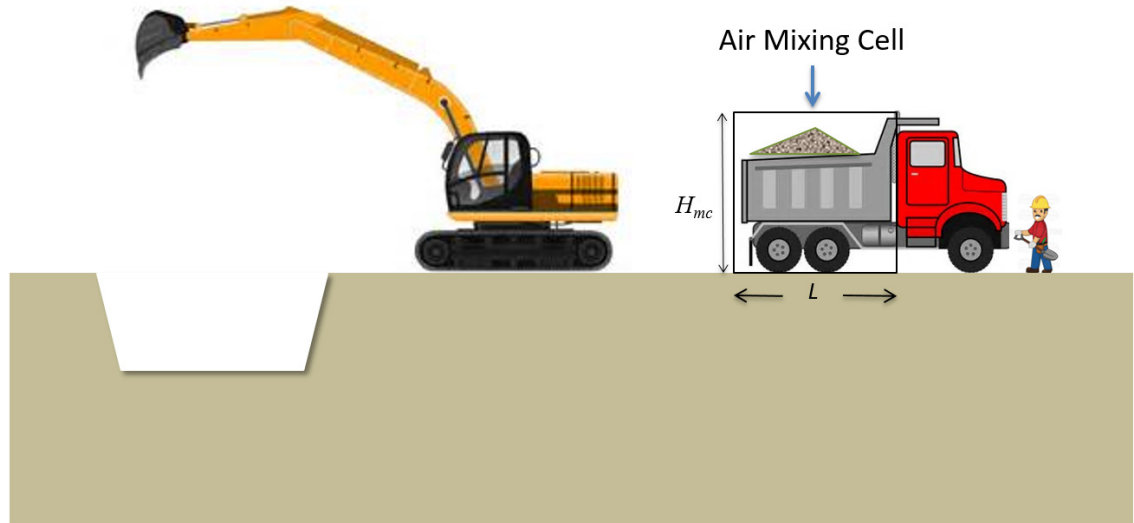
Methods for estimating exposure concentrations and dose are detailed in the previous report (RAC 2016). In summary, radionuclide emissions during excavation (consistent with those utilized for the original disposals) are based on the EPA emission model for aggregate handling and storage piles during drop loading operations as described in AP-42 Compilation of Air Pollutant Emission Factors (EPA 1995). Aggregate material is typically much drier and particulate aggregate is more easily dispersed in air than the solidified brines that comprise most of the BES material disposed in the Blue Ridge facility. Modeling using aggregate material provides a bounding inhalation scenario.

Waste characteristics, removal parameters, a revised weighted average concentration for the closure-in-place alternative, and a diluted weighted average concentration for the excavate and redisperse alternative are provided above. Model parameters and calculated values for particulate emissions, dispersion of particulates and radon in air, and inhalation and ingestion doses during removal operations are presented in Table 4, and a conceptual diagram is shown in Figure 1.

The dose coefficients for a reference individual were taken from the U.S. Department of Energy Standard 1196 (hereafter DOESTd-1196) (DOE 2011), which are provided in the RESRAD

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code. Ingestion and inhalation dose coefficients are based on the default values provided in the RESRAD code for a given solubility class and gut absorption factor, and a 1- $\mu\text{m}$  particle size for inhalation. Dose coefficients in DOESTd-1196 use the methodology described in Federal Guidance Report 13 (EPA 1999) and International Commission on Radiation Protection (ICRP) Reports 68 and 72 (ICRP 1994, 1996). Inhalation dose coefficients for a 10-year-old child were also obtained from RESRAD and based on ICRP 72. These dose coefficients were used for dose calculations involving students at the Estill County middle and high schools. The 70-year integrated inhalation and ingestion dose coefficients used in this assessment are presented in Table 5.



**Figure 1.** Conceptual model of exposure for a worker during removal operations.

**Table 4. Parameters for Emission Model during Disposal and Transport in Air for Excavation and Redisposal Alternative**

Parameter	Symbol	Value	Notes
Average wind speed ( $\text{m s}^{-1}$ )	$U$	4.07	LexingtonKYClimateData.xlsx ( <a href="http://www.climate-zone.com/climate/united-states/kentucky/lexington/">http://www.climate-zone.com/climate/united-states/kentucky/lexington/</a> )
Moisture %	$MC$	10	AP 42 (EPA 1995) Table 13.2.4-1 in Section 13.2.4, value for Clay in Municipal Landfills
<del>Wind-Particle speed-size multiplier</del>	<del><math>kK</math></del>	0.48	AP-42 (EPA 1995) – assumes particles $\leq 15 \mu\text{m}$ are respirable
Volume of BES Waste per truck load ( $\text{m}^3$ )	$V_{load}$	19.13	Calculated based on total removal volume and bulk density
Bulk density ( $\text{kg m}^{-3}$ )	$\rho_b$	949.2	Provided by ADS

Parameter	Symbol	Value	Notes
Height of air mixing cell	$H_{mc}$	2.9	Based on dimensions of Mack CL703 Dump Truck
Length of air mixing cell (m)	$L$	4.0	Based on dimensions of Mack CL703 Dump Truck
Width of air mixing cell (m)	$W$	2.44	Based on dimensions of Mack CL703 Dump Truck
Volume of mixing cell (m <sup>3</sup> )	$V$	28.30	Calculated as Length*Width*Height
Distance to closet office (m)	$x$	300	Minimum distance estimate from Google Earth
Distance to main office (m)	$x$	400	Minimum distance estimate from Google Earth
Distance to school (m)	$x$	700	Minimum distance estimate from Google Earth
Release height (m)	$z$	0	Worst-case condition for a ground-level release
Removal rate constant (s <sup>-1</sup> )	$K$	1.02	Calculated as $U/\text{length of mixing cell}$ (worst case scenario)
Emission rate (kg released to air per load)	$E$	$3.26 \times 10^{-3}$	Calculated using Equation 2 from AP-42 (EPA 1995)

**Table 5. Inhalation and Ingestion Effective Dose Coefficients<sup>a</sup>**

Radionuclide <sup>b</sup>	Representative person		10-year-old child	
	Inhalation (mrem pCi <sup>-1</sup> )	Ingestion (mrem pCi <sup>-1</sup> )	Inhalation (mrem pCi <sup>-1</sup> )	Ingestion (mrem pCi <sup>-1</sup> )
U-238+D	3.21E-02	2.13E-04	3.70E-02	2.83E-04
U-234	3.74E-02	2.15E-04	4.44E-02	2.74E-04
Th-230	3.85E-01	9.36E-04	4.07E-01	8.88E-04
Ra-226+D	3.82E-02	1.68E-03	4.46E-02	2.96E-03
Pb-210+D	4.01E-02	1.03E-02	4.90E-02	1.67E-02
Th-232	4.26E-01	1.03E-03	4.81E-01	1.07E-03
Ra-228+D	6.34E-02	5.92E-03	7.42E-02	1.44E-02
Th-228+D	1.75E-01	9.34E-04	2.21E-01	1.56E-03

<sup>a</sup> Dose coefficients from DOE-Std 1196 (DOE 2011) as presented in the RESRAD code.

<sup>b</sup> 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.

Cancer morbidity and mortality risks were calculated using Federal Guidance Report 13 (FGR13) methods and coefficients (EPA 1999). Default absorption classes were assumed where applicable.

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When a default absorption class was not provided, it was assumed to be type S (slow) to ensure doses were not underestimated. External coefficients for soil contaminated to an infinite depth were used. Inhalation, ingestion, groundwater ingestion, and external mortality risk coefficients are presented in Table 6; morbidity risk coefficients are presented in Table 7. Where applicable daughter radionuclides were assumed to be in equilibrium with parent radionuclides (“+D” designation in Table 6 and 7).

Table 6. FGR13 Cancer Mortality Risk Coefficients (EPA 1999)

Radionuclide	Inhalation [risk Bq <sup>-1</sup> ]	Ingestion [risk Bq <sup>-1</sup> ]	Groundwater Ingestion [risk Bq <sup>-1</sup> ]	External [risk-kg Bq <sup>-1</sup> -s]
U-238	2.38E-07	1.51E-09	1.13E-09	2.70E-20
Th-234	7.11E-10	5.07E-10	3.46E-10	9.52E-18
Pa-234	3.02E-11	5.77E-11	4.00E-11	5.08E-15
<b>U-238+D</b>	<b>2.39E-07</b>	<b>2.07E-09</b>	<b>1.516E-09</b>	<b>5.09E-15</b>
Ra-226	2.93E-07	9.56E-09	7.17E-09	1.33E-17
Pb-214	9.31E-10	9.51E-12	6.82E-12	5.72E-16
Bi-214	7.96E-10	5.98E-12	4.34E-12	4.37E-15
<b>Ra-226+D</b>	<b>2.95E-07</b>	<b>9.58E-09</b>	<b>7.18E-09</b>	<b>4.96E-15</b>
Pb-210	6.84E-08	2.31E-08	1.75E-08	8.06E-19
Bi-210	1.16E-08	1.95E-10	1.34E-10	1.66E-18
Po-210	2.76E-07	4.44E-08	3.53E-08	2.30E-20
<b>Pb-210+D</b>	<b>3.56E-07</b>	<b>6.77E-08</b>	<b>5.29E-08</b>	<b>2.49E-18</b>
Ra-228	1.26E-07	2.74E-08	2.00E-08	0.00E+00
Ac-228	1.25E-09	4.49E-11	3.10E-11	2.64E-15
<b>Ra-228+D</b>	<b>1.27E-07</b>	<b>2.74E-08</b>	<b>2.00E-08</b>	<b>2.64E-15</b>
Th-228	3.40E-06	2.46E-09	1.82E-09	3.25E-18
Ra-224	2.56E-07	3.88E-09	2.74E-09	2.17E-17
Pb-212	1.48E-08	5.95E-10	1.82E-09	2.97E-16
Bi-212	2.17E-09	1.88E-11	1.35E-11	5.18E-16
<b>Th-228+D</b>	<b>3.67E-06</b>	<b>6.95E-09</b>	<b>6.39E-09</b>	<b>8.40E-16</b>
<b>U-234</b>	<b>2.90E-07</b>	<b>1.66E-09</b>	<b>1.24E-09</b>	<b>1.44E-19</b>
<b>Th-230</b>	<b>7.23E-07</b>	<b>2.16E-09</b>	<b>1.67E-09</b>	<b>4.74E-19</b>
<b>Th-232</b>	<b>1.10E-06</b>	<b>2.45E-09</b>	<b>1.87E-09</b>	<b>1.97E-19</b>

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**Table 7. FGR13 Cancer Morbidity Risk Coefficients (EPA 1999)**

<b>Radionuclide</b>	<b>Inhalation [risk Bq<sup>-1</sup>]</b>	<b>Ingestion [risk Bq<sup>-1</sup>]</b>	<b>Groundwater Ingestion [risk Bq<sup>-1</sup>]</b>	<b>External [risk-kg Bq<sup>-1</sup>-s]</b>
U-238	2.52E-07	2.34E-09	1.73E-09	4.27E-20
Th-234	8.31E-10	9.18E-10	6.25E-10	1.40E-17
Pa-234	3.94E-11	1.00E-10	6.93E-11	7.46E-15
<b>U-238+D</b>	<b>2.53E-07</b>	<b>3.36E-09</b>	<b>2.42E-09</b>	<b>7.47E-15</b>
Ra-226	3.10E-07	1.39E-08	1.04E-08	1.96E-17
Pb-214	9.81E-10	1.31E-11	9.31E-12	8.41E-16
Bi-214	8.38E-10	7.17E-12	5.19E-12	6.41E-15
<b>Ra-226+D</b>	<b>3.12E-07</b>	<b>1.39E-08</b>	<b>1.04E-08</b>	<b>7.27E-15</b>
Pb-210	7.48E-08	3.18E-08	2.38E-08	1.21E-18
Bi-210	1.23E-08	3.52E-10	2.41E-10	2.36E-18
Po-210	2.93E-07	6.09E-08	4.79E-08	3.38E-20
<b>Pb-210+D</b>	<b>3.80E-07</b>	<b>9.31E-08</b>	<b>7.19E-08</b>	<b>3.60E-18</b>
Ra-228	1.40E-07	3.86E-08	2.81E-08	0.00E+00
Ac-228	1.33E-09	7.82E-11	5.38E-11	3.88E-15
<b>Ra-228+D</b>	<b>1.41E-07</b>	<b>3.87E-08</b>	<b>2.82E-08</b>	<b>3.88E-15</b>
Th-228	3.58E-06	3.99E-09	2.90E-09	4.79E-18
Ra-224	2.70E-07	6.42E-09	4.50E-09	3.19E-17
Pb-212	1.56E-08	9.58E-10	6.76E-10	4.36E-16
Bi-212	2.28E-09	2.70E-11	1.92E-11	7.60E-16
<b>Th-228+D</b>	<b>3.87E-06</b>	<b>1.14E-08</b>	<b>8.10E-09</b>	<b>1.23E-15</b>
<b>U-234</b>	<b>3.08E-07</b>	<b>2.58E-09</b>	<b>1.91E-09</b>	<b>2.16E-19</b>
<b>Th-230</b>	<b>7.70E-07</b>	<b>3.22E-09</b>	<b>2.46E-09</b>	<b>7.01E-19</b>
<b>Th-232</b>	<b>1.17E-06</b>	<b>3.60E-09</b>	<b>2.73E-09</b>	<b>2.93E-19</b>

## External Dose During Excavation and Redisposal

The Pennsylvania Department of Environmental Protection conversion factor of 2.02  $\mu\text{rem hour}^{-1}$  per  $\text{pCi g}^{-1}$  was used to estimate the exposure rate from the exhumed waste (PADEP 2015). Although this value underestimates the radium concentration in waste when provided with an exposure rate, it will overestimate the exposure rate when provided with a radium concentration in TENORM. For this reason, using this value ensures that doses are not underestimated.

## Radon Exposure and Dose

A detailed discussion of exposure and dose calculations for radon is provided in the previous report (RAC 2016). Radon model parameters are presented in Table 8. Doses from radon are dependent on the radon progeny concentrations in air that exist in various levels of equilibrium with radon. Doses were estimated using the working level (WL) and a conversion of 760 mrem per working-level month (Yu et al. 2001). The ICRP (2014b) derived values for underground mines and indoor residential structures of 1,100 mrem  $\text{WLM}^{-1}$  and 1,300 mrem  $\text{WLM}^{-1}$ , respectively.

However, these conditions reflect confined conditions where radon is either generated in the walls, ceiling, and floor of the underground mine, or from residential soils. In this assessment, the radon derived from disposed TENORM is present in outdoor air. Therefore, the value used in RESRAD was deemed appropriate for this assessment. The risk coefficient for radon inhalation is  $5.4 \times 10^{-4}$  for the average U.S. population, taken from the EPA's *Assessment of Risks from Radon in Homes* (2003). Radon calculations assume there is 30 ft (9.14 m) of MSW placed on top of the BES Waste (Gradient 2017) and no credit is taken for an engineered cover.

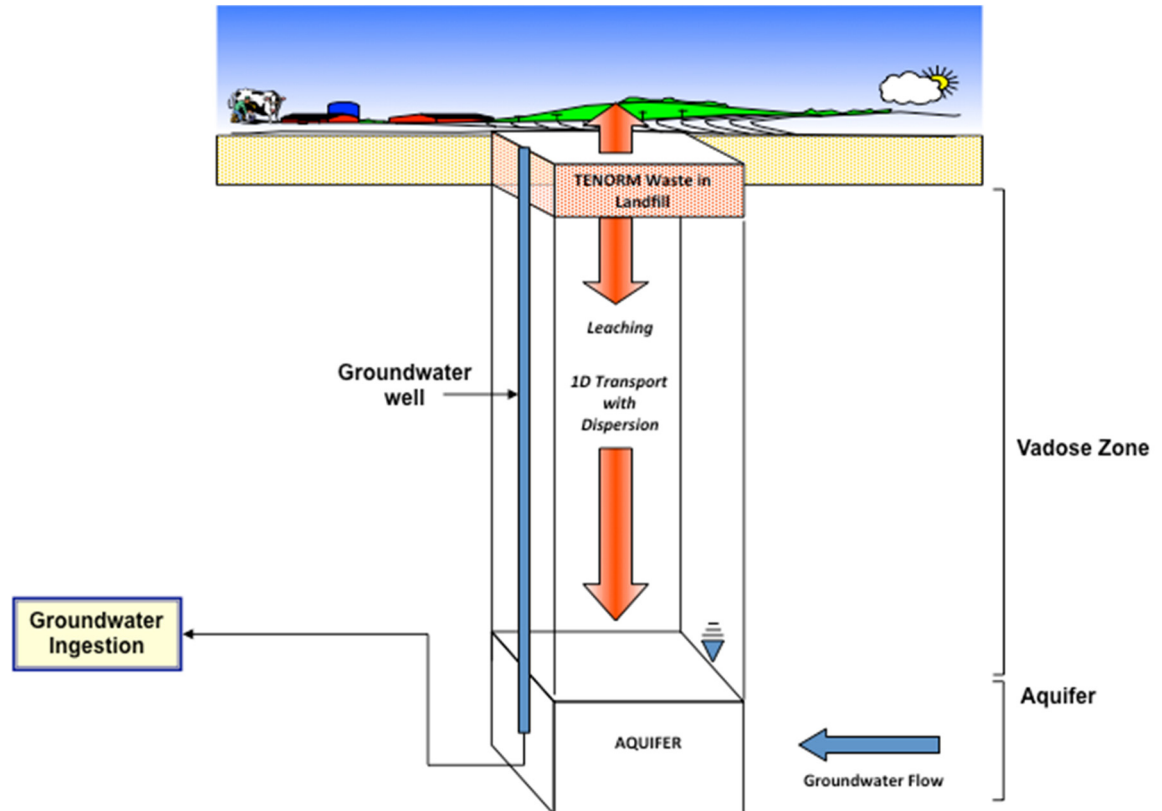
**Table 8. Radon Model Parameters**

Parameter	Symbol	Value	Notes
BES Waste thickness (m)	$x_t$	4.57	Maximum compacted waste thickness (15 ft) (Waste Management of KY 1994)
Cover thickness (m)	$x_c$	9.14	MSW thickness above BES Waste (30 ft) (Gradient 2017)
Dry weight percent moisture, waste	$MP$	21	Blue Ridge 1994
Dry weight percent moisture, cover	$MP$	21	Blue Ridge 1994
Bulk density, waste ( $\text{g cm}^{-3}$ )	$\rho_b$	0.9492	Bulk density of compacted waste provided by ADS
Bulk density, cover ( $\text{g cm}^{-3}$ )	$\rho_b$	0.9492	Bulk density of compacted waste provided by ADS
Porosity, waste	$\phi$	0.65	Blue Ridge 1994
Porosity, cover	$\phi$	0.65	Blue Ridge 1994
Particle density, waste	$\rho_s$	2.712	Calculated using $\rho_s = \rho_b / (1 - \phi)$
Particle density, cover	$\rho_s$	2.711	Calculated using $\rho_s = \rho_b / (1 - \phi)$
Radon emanation coefficient	$E$	0.2	Typical value for uranium mill tailings
Ra-226 concentration ( $\text{pCi g}^{-1}$ )	$C$	1.93E+02	Calculated based on the total Ra-226 inventory placed in one disposal block.
Surface area of BES Waste disposals ( $\text{m}^2$ )	$A$	15,794	The sum of the area of 17 $30.48 \text{ m} \times 30.48 \text{ m}$ disposal blocks

## Groundwater Exposure and Dose

The conceptual model is illustrated in Figure 2. The TENORM is represented by a rectangular area source. Infiltration through the landfill facility leaches radionuclides from the disposal cell and into the vadose zone. One-dimensional vertical transport was assumed. Leachate entering the groundwater mixes in a volume equal to the area of source footprint projected into the aquifer and the well screen thickness. A hypothetical well is placed directly downgradient from the source and water is extracted from that point for human consumption.

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**Figure 2.** Conceptual model for groundwater transport and dose (Rood 2002).

The facility's liner and leachate collection system were not considered in the groundwater model. The leachate collection system will have ceased operation after landfill closure, and the liner is assumed to have failed hydrologically. These assumptions are worst-case as they maximize water fluxes through the disposal facility and minimize radionuclide transit times to the aquifer. The model does not account for water withdrawn from the well, which maximizes the impact because it does not account for additional dilution from clean water drawn downgradient from the source. Additional details on the conceptual model can be found in the previous report (RAC 2016) and these references: Codell et al. (1981), Rood (1994), and Rood (2002).

Groundwater model parameters are presented in Table 9. Some parameters are discussed in the following subsections.

**Table 9. Groundwater Model Parameters**

Parameter	Value	Notes
<i>Infiltration parameters</i>		
Precipitation (m yr <sup>-1</sup> )	1.24	48.7 inches yr <sup>-1</sup> for Irvine, KY (where landfill is) from <a href="http://www.usclimatedata.com/climate/irvine/kentucky/united-states/usky1783">http://www.usclimatedata.com/climate/irvine/kentucky/united-states/usky1783</a>
Evapotranspiration (m yr <sup>-1</sup> )	0.61	Figure 12.1 in Yu et al. (1993), "Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil." Converted from 24 in yr <sup>-1</sup>
Runoff coefficient	0.25	Table E.1 in Yu et al. (1993). Based on rolling land with average slopes
Evapotranspiration coefficient	0.657	Calculated using RESRAD methodology
Net natural infiltration (m yr <sup>-1</sup> )	0.32	Calculated using RESRAD methodology
Infiltration through engineered barrier (m yr <sup>-1</sup> )	2.0E-05	HELP model runs provided by BRLF (Blue Ridge 1994)
<i>Source parameters</i>		
Area (m <sup>2</sup> )	15,793	BES waste placement areas: 17 blocks, 100-ft × 100-ft each
Thickness of waste (m)	3	Minimum compaction thickness
Number of cells parallel to flow	5	Number of 100-ft blocks parallel to flow
Cross flow length (m)	103.6	Calculated
Length parallel to flow (m)	152.4	Calculated
Bulk density (g cm <sup>-3</sup> )	0.9492	Provided by ADS
Mass of source volume	4.50E+07	Calculated
Saturated hydraulic conductivity (m yr <sup>-1</sup> )	62.76	HELP model runs provided by BRLF (Blue Ridge 1994)
Total porosity	0.65	HELP model runs provided by BRLF (Blue Ridge 1994)
Residual moisture content	0.12	HELP model runs provided by BRLF (Blue Ridge 1994)
van Genuchten <i>n</i> parameter	1.35	Calibrated so moisture content of 0.25 for 2.0E-05 m yr <sup>-1</sup> infiltration through intact cap
van Genuchten <i>α</i> parameter	7.5	Sandy loam from Carsel and Parrish in MCM manual
<i>Vadose zone parameters</i>		
Thickness (depth to aquifer, m)	9	Estimated (see discussion)

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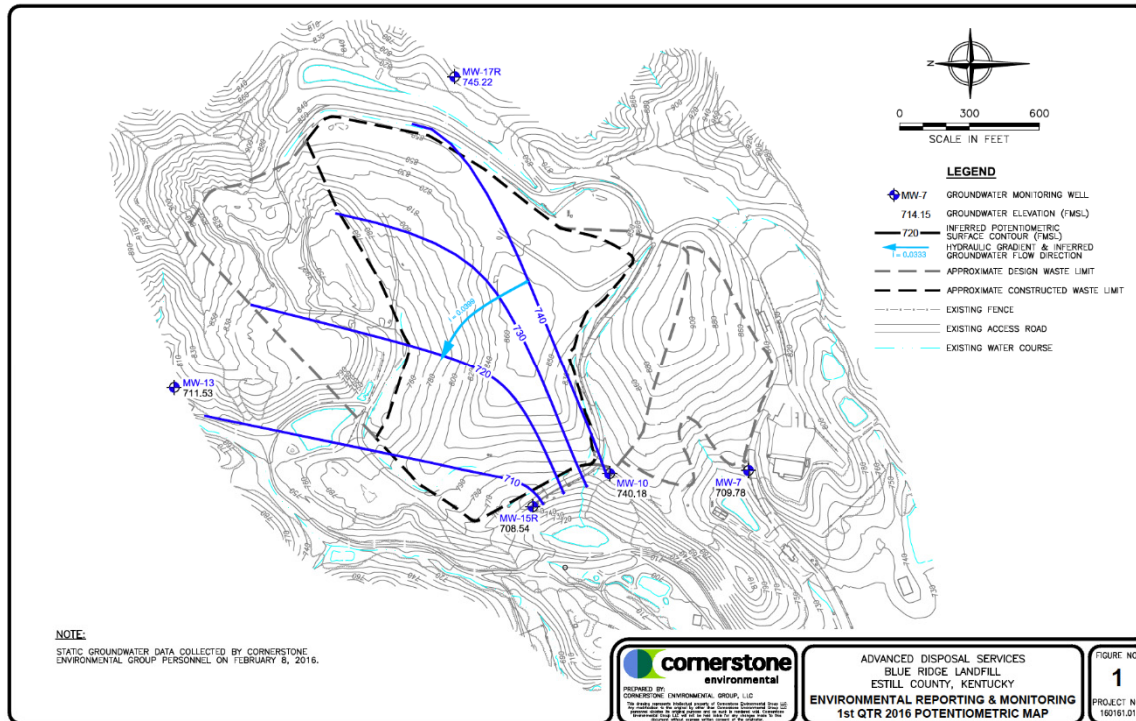
Parameter	Value	Notes
Hydraulic parameters	---	Assumed to be the same as the source zone except total porosity and saturated hydraulic conductivity
Total porosity	0.15	Assumed to be the same as the aquifer
Saturated hydraulic conductivity (m yr <sup>-1</sup> )	556.2	Assumed to be the same as the aquifer material
<i>Aquifer parameters</i>		
Effective porosity	0.15	Cornerstone Environmental 2016a
Hydraulic gradient	0.0399	Cornerstone Environmental 2016a
Saturated hydraulic conductivity (m yr <sup>-1</sup> )	556.2	Midpoint between low (1.04 ft/d) and high (10.72 ft/d) values
Darcy velocity (m yr <sup>-1</sup> )	83.4	Calculated
Pore velocity (m yr <sup>-1</sup> )	148	Calculated
Thickness (m)	4.54	(Cornerstone Environmental 2016a), average value

### ***Infiltration***

Infiltration through the disposal cover is assumed equal to natural infiltration during operation of the facility and is assumed to continue for 40 years while the facility remains in operation. An infiltration reducing-cover is placed over the disposal cell and is assumed to last 200 years. Over the next 100 years, the cover degrades and infiltration returns to its natural level. No credit is taken for the disposal cell liner. Recent studies of geosynthetic covers and liners in low-level waste facilities (Benson 2016) suggest minimum cover service life is in the range of 730–1,400 years. Thus, assuming a 200-year service life is worst-case. Natural infiltration is assumed to be 0.32 m yr<sup>-1</sup>. Infiltration through the cap is 0.002 cm yr<sup>-1</sup> based on the percolation from Layer 2 in the HELP model runs provided by BRLF (Blue Ridge 1994).

### ***Depth to Aquifer***

The depth to aquifer or the unsaturated thickness (or vadose zone) was estimated from the potentiometric surface map provided by Cornerstone Environmental (see Figure 3) and the region over which the BES Waste was disposed. The depth to the aquifer was estimated from the difference between the land surface elevation and the elevation of the potentiometric surface. Depths ranged from 40 ft to 120 ft, primarily in response to land surface elevations differences. For the assessment, 40 ft (~12 m) was assumed for a worst-case situation. The BES Waste containing the TENORM was assumed to be placed in the first 3 m of the unsaturated zone; thus, the unsaturated transit distance was 9 m. This assumption represents a worst-case scenario as there is likely more distance between the TENORM and the water table surface (Gradient 2017).



**Figure 3.** Groundwater potentiometric surface as provided by Cornerstone Environmental Group LLC (2016).

### *Source Dimensions*

The source dimensions include the length of the source parallel to groundwater flow, width of the source perpendicular to flow, and the thickness of the source. Leaching rates are inversely proportional to the thickness of the waste, and therefore, the minimum waste compaction thickness (3 m) was assumed. The 17 disposal blocks where TENORM was disposed were consolidated into a single region elongated in the direction parallel to the groundwater flow. Sources elongated in the direction of groundwater flow provide higher concentrations than source elongated in the direction perpendicular to groundwater flow. The number of 30.48-meter blocks parallel to the flow was estimated to be five. Thus, the length parallel to flow was 152.4 m. The width perpendicular to flow was 103.6 m and was calculated by dividing the total area ( $[30.48 \text{ m}]^2 \times 17 = 15,794 \text{ m}^2$ ) by 152.4 m.

### *Material Properties*

Material properties include saturated hydraulic conductivity, total porosity, bulk density, residual moisture content, and moisture retention parameters. Materials comprising the vadose zone and aquifer are reported to be shale. The waste zone is a combination of shale and municipal waste. Where noted, material properties were taken from properties reported in Carsel and Parrish (1998) that had similar saturated hydraulic conductivity to the shale. The material selected was sandy loam. Moisture retention curves use the van Genuchten formulations (van Genuchten 1980) that are described by the parameters  $\alpha$  and  $n$ . For the vadose zone, the moisture retention properties for sandy loam were retained, but the total porosity and saturated hydraulic conductivity for shale were

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used instead. The lower porosity and higher hydraulic conductivity in the vadose zone will result in more rapid transport of radionuclides to the aquifer and, thus, are worst-case assumptions. Aquifer properties were provided by Cornerstone Environmental Group. Where ranges of values were present, the midpoint value was used.

### ***Sorption Coefficients***

The sorption coefficient, or  $K_d$ , 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. Thus, the sorption coefficient has the effect of both reducing the aqueous-phase concentration and retarding (i.e., slowing) the movement of the radionuclide in groundwater. Thus, lower  $K_d$  values represent the worst-case because travel time is minimized and aquifer concentrations are maximized. Sorption coefficients are known to vary by orders of magnitude and are dependent on the stable element of the radionuclide, material comprising the groundwater media, and local geochemistry.

For this assessment, the default  $K_d$  values from RESRAD along with those summarized by Sheppard and Thibault (1990) were reviewed and the lowest of the values were used in the simulation. Low  $K_d$  values result in higher pore water concentrations and more rapid transport in the vadose zone and aquifer. Typically, shales contain clay minerals and clay minerals tend to sorb radionuclides with positive valence states such as Ra, U, and Th. The  $K_d$  values for sand are typically lower. Out of an abundance of caution, the median sand  $K_d$  values given in Sheppard and Thibault were compared to the RESRAD defaults, and the minimum (e.g., worst-case) value was used (see Table 10).

**Table 10. Sorption Coefficient ( $K_d$ ) Values Used in Groundwater Modeling**

<b>Element</b>	<b>RESRAD default (mL g<sup>-1</sup>)</b>	<b>Sheppard and Thibault sand (mL g<sup>-1</sup>)</b>	<b>Value used in model (mL g<sup>-1</sup>)</b>
<b>Pb</b>	100	270	100
<b>Ra</b>	70	500	70
<b>Th</b>	60000	3200	3200
<b>U</b>	50	35	35

### ***Groundwater Ingestion Dose and Risk Calculations***

Groundwater ingestion doses and risks were calculated with GWSCREEN (Rood 2002) using the exposure scenario described in the exposure parameters section (2 L of water per day, 365 days per year, 30 years), ingestion dose coefficients provided in Table 5, and ingestion risk coefficients for tap water in Table 6.

### **Uncertainty in Dose Estimates**

Uncertainty is attributed to both lack of knowledge and natural variability in the various inputs of the dose calculation. Uncertainty due to lack of knowledge includes such things as estimates of source concentrations and volumes, and parameter values for release and transport models (parametric uncertainty). Uncertainty due to natural variability includes variability in

meteorological conditions and receptor behavior patterns. The International Commission on Radiation Protection (ICRP) guidance states that uncertainty may be addressed 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 are important when an accurate (i.e., unbiased) dose estimates are required (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.

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 his or her dose. Conservatism incorporated into the different components of the calculations are summarized below.

### ***Source Term***

The bulk of the TENORM activity in the BES Waste received was from Fairmont Brine. All Fairmont Brine material was assumed to be represented by a single composite radioanalytical sample in place of the exposure rate measurements, thus ensuring concentrations were maximized. Concentrations of the remaining radionuclides were estimated based on activity ratios from a single filter sock sample that maximized thorium isotope concentrations. Thorium isotopes have the highest inhalation dose coefficients, and thus, inhalation doses would be maximized.

Suspension of particles into the air from the waste disposal facility was assumed similar to dry aggregate, thus maximizing suspension rates. The BES Waste was reported to be wet (80% water by weight), and therefore, little suspension would be expected (Kalt 2016).

For the Rn-222 assessment, the entire Ra-226 source term was assumed to be placed in a single disposal block (30.48 m × 30.48 m [100 ft × 100 ft]) resulting in maximum Rn-222 fluxes.

The predicted radionuclide concentrations in groundwater were maximized by consolidating all the disposal blocks (17 × [30.48 m × 30.48 m [100 ft × 100 ft]]) into a single block elongated in the direction of groundwater flow.

The engineered cover over the landfill was only assumed to last 200 years. After that, infiltration returns to natural conditions and thereby maximizes leach rates from the source.

A minimum waste cell thickness was used to estimate leach rates from the waste, thereby maximizing leach rates.

### ***Transport***

The wind was always assumed to blow in the direction of the receptor (e.g., a person), and thus, exposure concentrations are maximized. Furthermore, the atmospheric stability class and wind speed was selected to represent daytime conditions and mean average wind speed.

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For the groundwater transport calculations, the Blue Ridge Landfill liner, which is specifically designed to prevent infiltration of leachate into the subsurface, was intentionally ignored, allowing any radionuclides to leach out the bottom of the landfill immediately. In addition, it was assumed that a groundwater well existed at the downgradient edge of the source where maximum groundwater concentrations are observed.

### ***Exposure Assessment***

A landfill worker was assumed to stand on top of soil contaminated to an infinite depth and infinite area waste as it was being deposited, rather than sitting in the cab of the equipment, thus exposing him to suspended particles for the entire duration of each removal load, and maximizing his inhalation and ingestion doses. Additionally, inhalation rates were selected to overestimate reality, thus assuring that inhalation doses were representative of a worst-case scenario. The dose from external exposure to a landfill worker was maximized by assuming that the person was standing within about a meter from a truck containing TENORM or the disposed pile.

Inhalation rates for office workers, teachers, and students were also selected to overestimate reality and thus maximize doses. In addition, while indoor air will have lower concentrations of contaminants than the corresponding outdoor air, this reduction in concentration was intentionally ignored, resulting in maximized downwind radionuclide concentrations and subsequently maximized inhalation doses.

Lastly, to ensure future doses were maximized, it was assumed that a person's drinking water was derived entirely from a groundwater well located directly downstream of the location where the maximum radionuclide concentration would be found.

## **Dose and Risk Estimates**

This section provides both radiation doses and cancer morbidity and mortality risk estimates for landfill workers and members of the public for both the closure-in-place alternative and the excavation and redisposal alternative. Reported cancer risks for inhalation and ingestion represent the lifetime increase in cancer morbidity or mortality above the baseline value for cumulative exposure during the exposure period (i.e. risks are incurred during disposal or removal operations). For radon, cancer morbidity and mortality risks are presented on both an annual and a 30-year basis. Cancer morbidity and mortality risks from groundwater ingestion assume an exposure time of 30-years. All calculations assume the same person is present during all removal operations.

### **Dose and Risk Estimates for the Landfill Worker and Supervisor**

#### ***Closure-in-Place Alternative – Radon***

Inhalation of radon gas is the only viable exposure pathway for the landfill worker if the material remains buried in place.

Radon flux at the surface of the disposal cell was calculated based on a 4.57-m-thick waste zone having an average Ra-226 concentration of 27.8 pCi g<sup>-1</sup> and assuming 9.14 m (30 ft) of clean waste (i.e., municipal waste containing no TENORM) on top of the TENORM-bearing waste. The radon flux was 7.49×10<sup>-2</sup> pCi m<sup>-2</sup> s<sup>-1</sup>, which is substantially less than the limit for uranium mill

tailings disposal cells of  $20 \text{ pCi m}^{-2} \text{ s}^{-1}$ . Rood et al. (1999) showed that emanation fractions in barite scale did not exceed 0.06. Thus, the assumed emanation fraction value of 0.2 likely represents an extreme worst case, as it is outside the range of emanation coefficients for this material and more typical of uranium mill tailings.

Dose to a landfill worker from radon is  $2.5 \times 10^{-2}$  mrem ( $2.5 \times 10^{-4}$  mSv) per year (see Table 11). The annual increased risk of cancer morbidity for the landfill worker is  $1.9 \times 10^{-8}$ , the 30-year risk is  $5.6 \times 10^{-7}$ . The annual increased risk of cancer mortality for the landfill worker is  $1.8 \times 10^{-8}$ , the 30-year risk is  $5.3 \times 10^{-7}$ .

**Table 11. Radon Dose to a Landfill Worker for Closure-in-Place Alternative**

Receptor	Distance [m]	$\chi/Q$ [s/m <sup>3</sup> ]	Radon Concentration [pCi L <sup>-1</sup> ]	WLM	Dose [mrem]
Landfill worker (100 m)	100	2.32E-04	2.74E-04	3.29E-05	<b>2.5E-02</b>

### *Excavate and Redispose Alternative*

During retrieval and removal operations, the landfill worker and supervisor will be exposed via inhalation of particulates, ingestion of soil, and external soil exposure. Radon inhalation represents a long-term exposure concern, and is thus not considered for the excavation and redisposal alternative. A landfill laborer on the ground represents a bounding dose estimate for a worker in close contact with the BES Waste. Other workers, such as heavy equipment operators, would be expected to have lower doses because they are enclosed and shielded in a cab and thus are not explicitly considered. Supervisors will spend substantially less time onsite, and are thus exposed to less radioactive material, therefore their doses will be substantially lower than those of the landfill worker; nonetheless their doses are considered explicitly at the request of ADS.

The activity emitted from the source ( $Q$ ), calculated time-integrated concentrations (TIC), and effective doses (ED) are presented in Table 12 on a per load basis. The total dose of 3.7 mrem ( $3.7 \times 10^{-2}$  mSv) assumes that the same worker attends all 1,823 loads. For a supervisor onsite for one hour per day (the equivalent of three truckloads), the total ED is 0.46 mrem ( $4.6 \times 10^{-3}$  mSv). Cancer morbidity risks by pathway are shown in Table 13; total cancer morbidity risks for the landfill worker and supervisor incurred during removal operations are  $1.8 \times 10^{-5}$  and  $2.2 \times 10^{-6}$ , respectively. Cancer mortality risk by pathway are shown in Table 14; total mortality risks for the landfill worker and supervisor incurred during removal operations are  $1.2 \times 10^{-5}$  and  $1.5 \times 10^{-6}$ , respectively.

**Table 12. Inhalation and Ingestion Effective Dose (ED) to a Landfill Worker During Excavation and Removal**

Radionuclide	$Q$ [pCi]	TIC [pCi-hr $m^{-3}$ ]	Inhalation ED [mrem per load]	Ingestion ED [mrem per load]	Total ED [mrem per load]	Total ED for 1823 loads (mrem)
U-238	6.26E+00	6.05E-05	3.50E-06	5.59E-06	9.09E-06	1.66E-02
U-234	6.26E+00	6.05E-05	4.07E-06	5.63E-06	9.70E-06	1.77E-02
Th-230	4.32E+01	4.17E-04	2.89E-04	1.69E-04	4.58E-04	8.35E-01
Ra-226	7.66E+01	7.39E-04	5.08E-05	5.38E-04	5.89E-04	1.07E+00
Pb-210	6.82E+00	6.58E-05	4.76E-06	2.93E-04	2.97E-04	5.42E-01
Th-232	1.28E+01	1.23E-04	9.45E-05	5.50E-05	1.50E-04	2.73E-01
Ra-228	1.67E+01	1.61E-04	1.83E-05	4.13E-04	4.31E-04	7.85E-01
Th-228	1.29E+01	1.24E-04	3.93E-05	5.04E-05	8.96E-05	1.63E-01
<b>Total</b>		<b>mrem</b>	<b>5.0E-04</b>	<b>1.5E-03</b>	<b>2.0E-03</b>	<b>3.7E+00</b>
		<b>mSv</b>	<b>5.0E-06</b>	<b>1.5E-05</b>	<b>2.0E-05</b>	<b>3.7E-02</b>

**Table 13. Cancer Morbidity Risks for a Landfill Worker and Supervisor Incurred During Excavation and Removal**

Receptor	Pathway	Risk
<b>Inhalation of Particulates</b>		
Landfill worker, supervisor	inhalation per removal load	8.38E-11
Landfill worker	total inhalation (1823 loads)	1.53E-07
Supervisor	total inhalation (228 loads)	1.91E-08
<b>Incidental Soil Ingestion</b>		
Landfill worker, supervisor	ingestion per removal load	4.20E-10
Landfill worker	total ingestion (1823 loads)	7.66E-07
Supervisor	total ingestion (228 loads)	9.57E-08
<b>External exposure</b>		
Landfill worker, supervisor	external per removal load	9.33E-09
Landfill worker	total external (1823 loads)	1.70E-05
Supervisor	total external (228 loads)	2.13E-06
<b>Total Risk Incurred During Removal Operations</b>		
<b>Landfill worker (1823 loads)</b>		<b>Total Risk 1.8E-05</b>
<b>Supervisor (228 loads)</b>		<b>Total Risk 2.2E-06</b>

**Table 14. Cancer Mortality Risks for a Landfill Worker and Supervisor Incurred During Excavation and Removal**

Receptor	Pathway	Risk	
<b>Inhalation of Particulates</b>			
Landfill worker, supervisor	inhalation per removal load	7.91E-11	
Landfill worker	total inhalation (1823 loads)	1.44E-07	
Supervisor	total inhalation (228 loads)	1.80E-08	
<b>Incidental Soil Ingestion</b>			
Landfill worker, supervisor	ingestion per removal load	2.92E-10	
Landfill worker	total ingestion (1823 loads)	5.33E-07	
Supervisor	total ingestion (228 loads)	6.66E-08	
<b>External exposure</b>			
Landfill worker, supervisor	external per removal load	6.36E-09	
Landfill worker	total external (1823 loads)	1.16E-05	
Supervisor	total external (228 loads)	1.45E-06	
<b>Total Risk Incurred During Removal Operations</b>			
	<b>Landfill worker (1823 loads)</b>	<b>Total Risk</b>	<b>1.2E-05</b>
	<b>Supervisor (228 loads)</b>	<b>Total Risk</b>	<b>1.5E-06</b>

External exposure is the primary cause of dose and risk to landfill workers. The external dose per truckload is 0.02 mrem ( $2.0 \times 10^{-4}$  mSv). Total external dose to the landfill worker present for all 1,823 truckloads is 34.8 mrem (0.348 mSv). Total external dose to the supervisor is 4.4 mrem ( $4.4 \times 10^{-2}$  mSv). Cancer morbidity risk from external exposure to soil incurred during the removal operations is  $1.7 \times 10^{-5}$  for the landfill worker. Cancer morbidity risk from external exposure to soil incurred during the removal operations is  $1.2 \times 10^{-5}$  for the landfill worker.

## Dose and Risk Estimates for Members of the Public

### *Closure-in-Place Alternative – Radon*

Radon inhalation and ingestion of groundwater are the only viable exposure pathways to members of the public for the Closure-in-Place alternative. Annual radon doses at office buildings and the school were calculated using the Gaussian plume model for an area source, assuming 170 hours per month exposure for 12 months a year for the office workers and 9 months a year for students and teachers. The other customer is assumed to be exposed for one hour per day, six days per week for 50 weeks of the year; the future resident is assumed to be present 24 hours per day for 365 days per year. The conversion from WLM to dose was 760 mrem per WLM (see Table 8). The integrated flux over the disposal area was  $1.18 \times 10^3$  pCi s<sup>-1</sup>. The scenario assumes that the indoor-outdoor air concentrations are the same, thus ensuring doses are not underestimated. A summary of dose to each receptor is provided below in Table 15. A summary of annual and lifetime (30-year) morbidity and mortality risks are provided in Table 16.

**Table 15. Radon Doses to Members of the Public for Closure-in-Place Alternative**

Receptor	Distance [m]	X/Q [s/m <sup>3</sup> ]	Radon Concentration [pCi L <sup>-1</sup> ]	WLM	Dose [mrem]
Other customer	100	2.32E-04	2.74E-04	4.83E-06	<b>3.7E-03</b>
South Office	300	8.81E-05	1.04E-04	1.25E-05	<b>9.5E-03</b>
Main Office	400	6.99E-05	8.27E-05	9.93E-06	<b>7.6E-03</b>
School	700	4.11E-05	4.86E-05	4.37E-06	<b>3.3E-03</b>
Future Resident	700	4.11E-05	4.86E-05	2.50E-05	<b>1.9E-02</b>

**Table 16. Cancer Morbidity and Mortality Risks from Radon Inhalation to Members of the Public for Closure-in-Place Alternative**

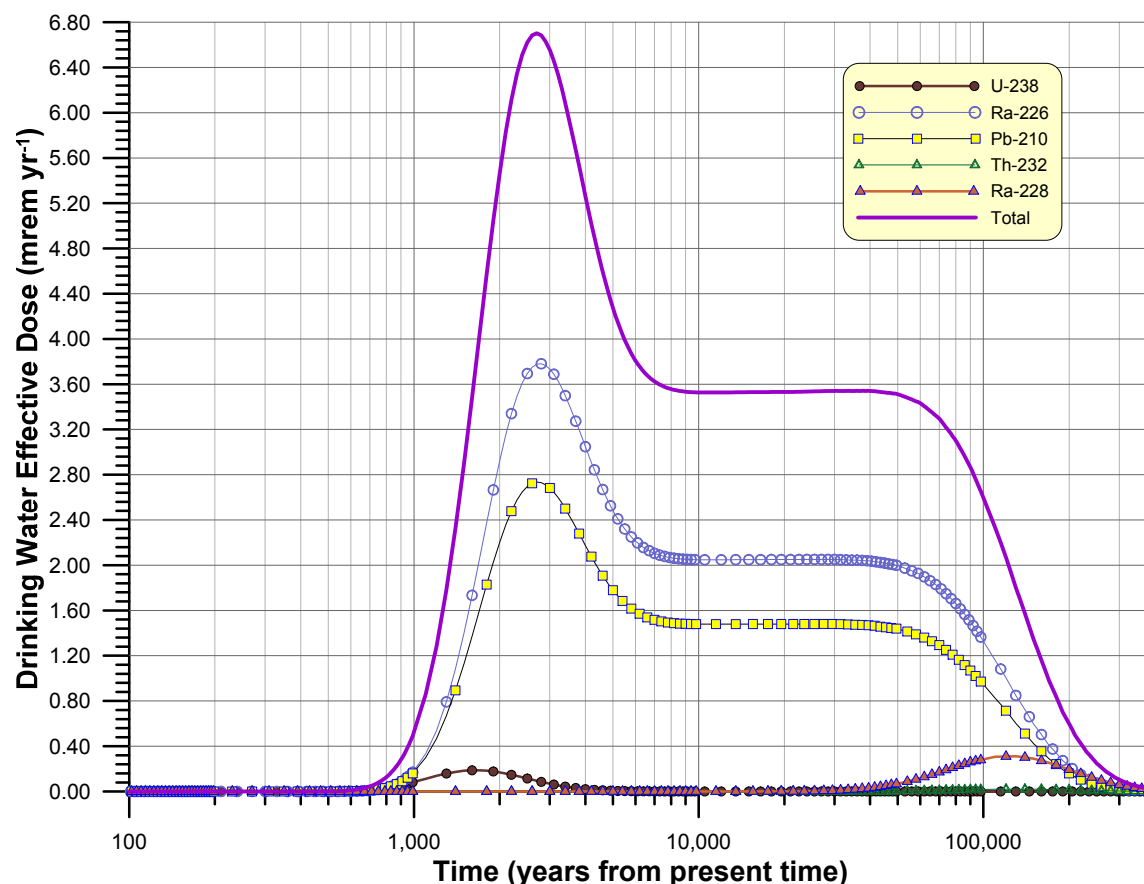
Receptor	Morbidity Risk		Mortality Risk	
	Annual	Lifetime (30 year)	Annual	Lifetime (30 year)
Other customer (100 m)	2.7E-09	8.2E-08	2.6E-09	7.8E-08
South Office (300 m)	7.1E-09	2.1E-07	6.7E-09	2.0E-07
Main Office (400 m)	5.6E-09	1.7E-07	5.3E-09	1.6E-07
School (700 m)	2.5E-09	7.4E-08	2.4E-09	7.1E-08
Future Resident (700 m)	1.4E-08	4.3E-07	1.4E-08	4.0E-07

***Closure-in-Place Alternative – Groundwater Ingestion***

The groundwater ingestion effective dose as a function of time at the downgradient receptor well (see Figure 4) showed a maximum of 6.7 mrem (0.067 mSv) at 2,700 years into the future from present time. Doses were primarily from Ra-226 and Pb-210. The shoulder of the curve to the right of the peak was from ingrowth of Ra-226 from Th-230. The relatively short half-life of Pb-210 (22 years) and its higher sorption coefficient relative to radium means that it will not move very far from Ra-226. The high sorption coefficient for thorium isotopes results in long transport times, and these isotopes arrive at the receptor well in excess of 40,000 years from the present. Maximum effective doses were well below the 25 mrem yr<sup>-1</sup> (0.25 mSv yr<sup>-1</sup>) dose limit for low-level radioactive disposal sites. The maximum total Ra (Ra-226+Ra-228) concentration in groundwater was estimated to be 3.08 pCi L<sup>-1</sup>, less than the 40 CFR 141 MCL for Ra-226/228 of 5 pCi L<sup>-1</sup>. Maximum U-238 activity concentration was 1.21 pCi L<sup>-1</sup>, and the mass concentration was 3.6 µg L<sup>-1</sup>. Uranium is not regulated based on its radiological properties, but instead its chemical toxicity. The MCL for uranium in 40 CFR 141 is 30 µg L<sup>-1</sup> and the maximum predicted concentration is well below this value.

Morbidity and mortality risks were calculated using FGR13 coefficients for tap water ingestion, see Table 6 and 7 above (EPA 1999). Maximum morbidity risk is  $4.9 \times 10^{-5}$  and occurs

at 2700 years from present day. Maximum mortality risk is  $3.5 \times 10^{-5}$  and occurs at 2700 years from present day.



**Figure 4.** Groundwater ingestion effective dose as a function of time for key radionuclides.

### *Excavate and Redispose Alternative*

Inhalation dose from particulates to other customers (100 m from the source), office workers, students, and teachers at office buildings 300 m and 400 m from the source, and at the school 700 m from the source was calculated using the Gaussian plume model and the AP-42 emission model (EPA 1995) described earlier (RAC 2016). This calculation assumes the wind is always blowing toward the receptor, which maximizes potential doses. The calculation also uses atmospheric stability class conditions typical of daytime conditions and an annual average wind speed. The concentration divided by the source term (or  $\chi/Q$  in  $\text{s m}^{-3}$ ) calculated with the Gaussian plume model using stability class D and an average wind speed of  $4 \text{ m s}^{-1}$  was  $2.32 \times 10^{-4}$ ,  $8.81 \times 10^{-5}$ ,  $6.99 \times 10^{-5}$ , and  $4.11 \times 10^{-5}$  for the location of the customer (100 m), south office (300 m), main office (400 m), and school (700 m), respectively. The product of the  $\chi/Q$  and the activity emitted from the source (Q value, see Table 17) yields the time-integrated concentration (TIC). The breathing rate for adults and students was lower than what was assumed for the landfill laborer ( $20 \text{ m}^3 \text{ day}^{-1}$  for the teacher and  $15.5 \text{ m}^3 \text{ day}^{-1}$  for the student).

The effective doses (Table 17) were substantially less than that for the landfill laborer. In this scenario, it is probable that the same person may be exposed to all 1,823 truckloads (except for the

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other customer, who is present during ~76 loads) because office staff, students, and teachers would likely be present during all removal operations. However, even in this case, all doses are significantly less than one mrem ( $< 0.01$  mSv). Inhalation risks are summarized in Table 18. Total morbidity risk incurred to members of the public during excavation and removal operations were very low, ranging from  $1.1 \times 10^{-10}$  to  $4.9 \times 10^{-10}$  for office workers at the south office (300 m) and students/teachers at the school, respectively. Total mortality risk incurred to members of the public during excavation and removal operations were very low, ranging from  $1.1 \times 10^{-10}$  to  $4.6 \times 10^{-10}$  for office workers at the south office (300 m) and students/teachers at the school, respectively.

The other customer is also exposed via incidental soil ingestion and from external soil exposure. Assuming the other customer is onsite near removal operations for 20 minutes each day (the equivalent of a single truckload), the total ED (inhalation and ingestion) is 0.15 mrem ( $1.5 \times 10^{-3}$  mSv). Ingestion morbidity and mortality risks for the other customer are  $3.2 \times 10^{-8}$  and  $2.2 \times 10^{-8}$ , respectively. Total external dose to the other customer is 1.5 mrem ( $1.5 \times 10^{-2}$  mSv); total morbidity and mortality risks from external soil are  $7.1 \times 10^{-7}$  and  $4.8 \times 10^{-7}$ , respectively. Total morbidity and mortality risks incurred during removal operations for the other customer are  $7.5 \times 10^{-7}$  and  $5.1 \times 10^{-7}$ , respectively.

**Table 17. Inhalation Effective Dose (ED) to an Office Worker and Student/Teacher During Excavation and Removal**

	Other customer (100 m)	South office (300 m)	Main office (400 m)	School (700 m)	Other Customer (100 m) <sup>a</sup>	South office (300 m)	Main office (400 m)	School <sup>b</sup> (700 m)
Radionuclide	TIC (pCi-s m <sup>-3</sup> )				Effective Dose (mrem per load)			
U-238	2.18E-01	1.50E-03	9.12E-04	3.47E-04	3.50E-06	1.12E-08	6.78E-09	2.31E-09
U-234	2.18E-01	1.50E-03	9.12E-04	3.47E-04	4.07E-06	1.30E-08	7.90E-09	2.76E-09
Th-230	1.50E+00	1.03E-02	6.29E-03	2.39E-03	2.89E-04	9.22E-07	5.60E-07	1.75E-07
Ra-226	2.66E+00	1.83E-02	1.11E-02	4.24E-03	5.08E-05	1.62E-07	9.86E-08	3.39E-08
Pb-210	2.37E-01	1.63E-03	9.93E-04	3.78E-04	4.76E-06	1.52E-08	9.23E-09	3.32E-09
Th-232	4.44E-01	3.06E-03	1.86E-03	7.08E-04	9.45E-05	3.02E-07	1.83E-07	6.11E-08
Ra-228	5.79E-01	3.99E-03	2.42E-03	9.23E-04	1.83E-05	5.85E-08	3.56E-08	1.23E-08
Th-228	4.48E-01	3.09E-03	1.88E-03	7.14E-04	3.93E-05	1.25E-07	7.62E-08	2.83E-08
Total per disposal				mrem (mSv)	5.0E-04 (5.0E-06)	1.6E-06 (1.6E-08)	9.8E-07 (9.8E-09)	3.2E-07 (3.2E-09)
<b>Total for 1823 loads</b>				<b>mrem (mSv)</b>	<b>3.8E-02 (3.8E-04)</b>	<b>2.9E-03 (2.9E-05)</b>	<b>1.8E-03 (1.8E-05)</b>	<b>5.8E-04 (5.8E-06)</b>
<p>a. Other customer is only present for 76 loads.</p> <p>b. Doses in this column are for a school-age child. The total dose for an adult teacher was 3.7E-07 mrem (3.7E-09 mSv) per disposal and 6.8E-04 mrem (6.8E-06 mSv) for 1823 loads.</p>								

**Table 18. Cancer Morbidity and Mortality Risks from Inhalation to Members of the Public Incurred During Excavation and Removal**

Receptor	Morbidity Risk	Mortality Risk
Other customer (100 m)	6.4E-09	6.0E-09
South Office (300 m)	4.9E-10	4.6E-10
Main Office (400 m)	3.0E-10	2.8E-10
School (700 m)	1.1E-10	1.1E-10

## Summary of Total Radiological Risk Estimates

Table 19 and Table 20 summarize the total morbidity and mortality risks for the various receptors associated with each remediation alternative. Risks for the closure-in-place alternative represent lifetime risk and assumes 30 years of exposure. Risks for the excavate and redispense alternative are those incurred during actual removal operations. It can be anticipated that the radiological risks from redispense of the material in another landfill will be comparable to those incurred during the original disposals at Blue Ridge, but they are not ~~considered~~ evaluated explicitly in this analysis. Furthermore, the risks associated with the closure-in-place alternative would apply to any landfill in which this material might be placed. These calculations indicate that Alternative 2 (excavate and redispense) results in the highest risks to the landfill worker. All values are well within the EPA's target risk range of  $10^{-4}$  to  $10^{-6}$  (EPA 1990, 1991a), though Kentucky's *de minimis* risk value of  $10^{-6}$  is exceeded for groundwater exposure for the future resident in alternative 1, and for the landfill worker and supervisor during excavation and removal operations for alternative 2.

**Table 19. Total Lifetime Cancer Morbidity and Mortality Risk for Closure-in-Place Alternative 1**

Receptor	Lifetime Morbidity Risk	Lifetime Mortality Risk	Notes
Landfill worker (100 m)	5.6E-07	5.3E-07	Radon exposure only; values are for average US population and assume 30-years of exposure
Other customer (100 m)	8.2E-08	7.8E-08	
Office worker (300 m)	2.1E-07	2.0E-07	
Office worker (400 m)	1.7E-07	1.6E-07	
Student/teacher (700 m)	7.4E-08	7.1E-08	
Future resident (700 m)	4.3E-07	4.0E-07	
Future resident (downgradient edge of BES Waste disposal)	4.9E-05	3.5E-05	Groundwater only; risks occur 2700 years from present day; value is assuming 30-years of exposure

**Table 20. Total Lifetime Cancer Morbidity and Mortality Risk for Excavate and Redispose Alternative 2<sup>a</sup>**

Receptor	Total Morbidity Risk Incurred During Excavation and Removal Operations	Total Mortality Risk Incurred During Excavation and Removal Operations	Notes
Landfill worker (100 m)	1.8E-05	1.2E-05	Inhalation of particulates; incidental soil ingestion; external exposure
Supervisor (100 m)	2.2E-06	1.5E-06	
Other customer (100 m)	7.5E-07	5.1E-07	
Office worker (300 m)	4.9E-10	4.6E-10	Inhalation of particulates only
Office worker (400 m)	3.0E-10	2.8E-10	
Student/teacher (700 m)	1.1E-10	1.1E-10	

<sup>a</sup> Radiological risk only; physical risk not included.

## Ecological Risk Assessment

An ecological risk assessment was performed using the ERICA Tool (Brown 2008; Larsson 2008). The ERICA tool combines data on environmental transfer of radionuclides and dosimetry to obtain a measure of exposure. This is subsequently compared to exposure levels defined by regulators or those at which deleterious effects are known to occur. The ERICA tool has a hierarchical structure consisting of three tiers of impact assessment. After the first 2 tiers, the user is given a “stoplight” that is either red (further assessment recommended), yellow (potential concern, further assessment warranted) or green (negligible concern). The first tier is the most general and represents a worst-case scenario. Tier 1 is media concentration based and uses pre-calculated environmental media concentration limits to estimate risk quotients. If the calculated risk quotient is less than unity at the end of the tier 1 assessment, no further calculations are necessary. Otherwise a tier 2 assessment is required. Tier 2 calculates dose rates and allows the user to examine and edit most of the parameters used in the calculation, including concentration ratios, distribution coefficients, percentage dry weight soil or sediment, dose conversion coefficients, radiation weighting factors, and occupancy factors. Tier 3 allows for a probabilistic assessment by assigning probability distribution functions to each underlying parameter value.

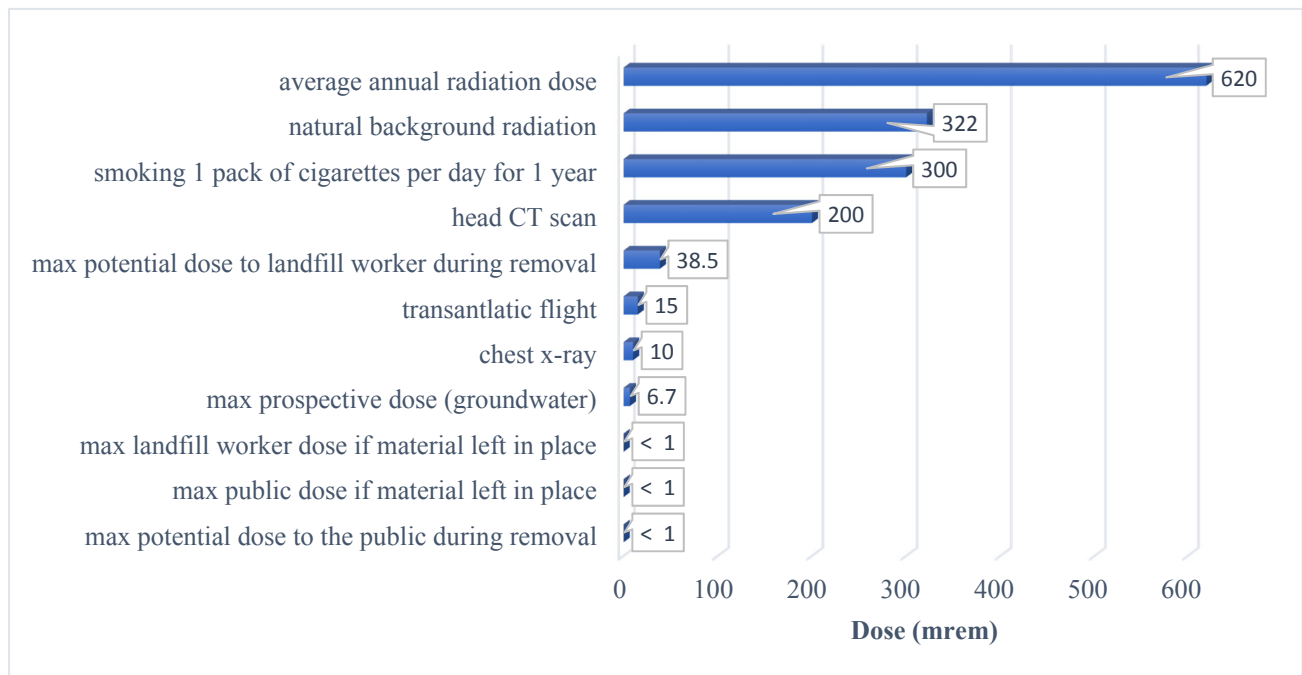
First a tier 1 assessment was performed using the activity concentrations provided in Table 3, and assigning a dose rate screening value of 40  $\mu\text{Gy hr}^{-1}$  for terrestrial mammals and 400  $\mu\text{Gy hr}^{-1}$  for birds and plants, consistent with US Department of Energy and ICRP guidance (DOE 2002; ICRP 2014a). The tier 1 assessment exceeded these screening values for generic bird and vascular plant receptors, so a tier 2 assessment was conducted.

The tier 2 assessment was performed for a generic mammal, bird, vascular plant, amphibian, benthic and pelagic fish. The maximum dose rate in the tier 2 assessment was  $5.9 \times 10^{-1} \mu\text{Gy hr}^{-1}$  for the vascular plant. All dose rates were substantially less than the screening values, and thus the assessment was considered complete, and no deleterious ecological effects are likely to occur should the closure-in-place alternative be selected.

## Radiation Dose and Risk in Perspective

Everyone is exposed to radiation on a daily basis from both natural and man-made sources. According to the National Council on Radiological Protection (NCRP), the average annual radiation dose per person in the United States from all sources is about 620 mrem (6.2 mSv). Most (about 52% or 322 mrem [3.2 mSv]) of this dose comes from natural background radiation sources. Other contributors to annual radiation dose are medical procedures, such as x-rays or CT scans. A single chest x-ray gives about 10 mrem (0.1 mSv), a single head CT about 200 mrem (2 mSv). While not every member of the public uses tobacco products, they are a large source of radiation dose to those who do. The dose comes from the natural radioactivity in tobacco, especially Po-210 and Pb-210. These emit alpha particles that cause a significant dose to the lungs. There have been numerous studies of the levels of radioactivity in tobacco smoke and the resulting dose from smoking about one pack of cigarettes a day for a year. The estimated dose to the lungs ranges between 300 mrem (3 mSv) per year to more than 3,000 mrem (30 mSv) per year.

Figure 5 puts the radiation doses to landfill workers and the public into perspective.



**Figure 5.** Radiation dose in perspective.

Risk in this context 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 exceedingly 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 are nonexistent (HPS 2004). All calculated doses were well below this threshold.

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According to the National Cancer Institute (NCI), the background cancer mortality rate in the United States is about  $1.7 \times 10^{-3}$  (NCI 2016). Typical acceptable levels of risk are  $10^{-4}$  to  $10^{-6}$  (EPA 1990, 1991a). Kentucky's de minimis risk value is  $10^{-6}$ . All risk estimates computed here are well within or below the EPA's levels. The Kentucky target risk level is exceeded for groundwater exposure for the future resident in alternative 1, and for the landfill worker and supervisor during excavation and removal operations for alternative 2.

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## Appendix A. Dose and Risk Estimates During Disposal at BRLF

This appendix provides dose estimates for exposures associated with the disposal of the 92 loads of technologically enhanced naturally occurring radioactive materials (TENORM) at Blue Ridge Landfill (BRLF) located in Irvine, KY between July 20, 2015, and February 3, 2016. The dose estimates below replace the earlier estimates provided in RAC (2016). This appendix also provides risk estimates for these same exposures.

It can be assumed that the addition of sawdust and other materials to solidify the wastes reduced the magnitude of any fugitive dust emissions from this source significantly. For this analysis, it was assumed that the waste material could be characterized like soil that is susceptible to suspension so that particulate emissions would not be underestimated and in all likelihood overestimated. Fugitive dust emissions during transportation to the site were not evaluated explicitly.

### Inhalation, Ingestion, and External Doses and Risks for a Landfill Worker

The landfill laborer represents a bounding dose estimate for a worker in close contact with the BES Waste material. Other workers, such as heavy equipment operators, would be expected to have lower doses because they are enclosed and shielded in a cab and are farther away than a person standing next to the TENORM during disposal. Table 1 provides the updated weighted average activity concentration used for computing dose and risk during disposals. The conceptual model is shown in Figure A-1 below. Time-integrated air concentrations (TIC) and effective doses (ED) are presented Table A-1 on a per disposal basis. The total dose of 6.6 mrem ( $6.6 \times 10^{-2}$  mSv) assumes that the *same* person attended all 92 disposals.

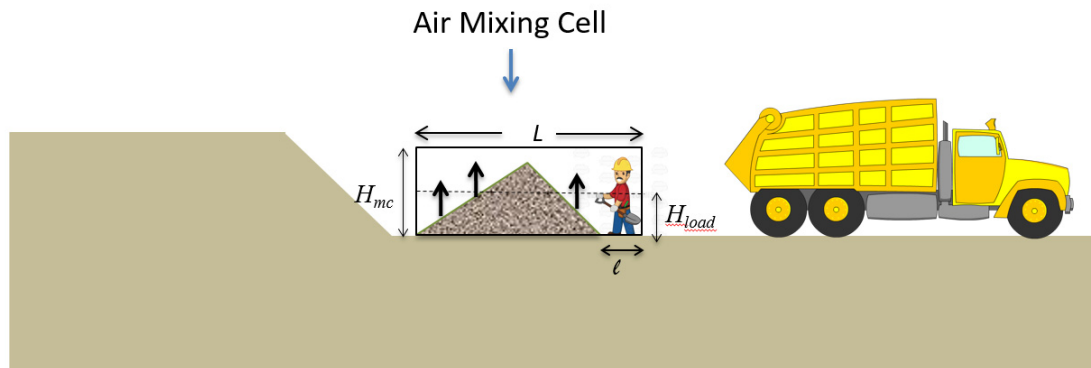


Figure A-1. Conceptual model of exposure for a worker during disposal operations.

**Table A-1. Inhalation and Ingestion Effective Dose (ED) to a Landfill Laborer During Disposal**

Radionuclide	$Q$ (pCi)	TIC (pCi-hr $m^3$ )	Inhalation ED (mrem per disposal)	Ingestion ED (mrem per disposal)	Total ED (mrem per disposal)	Total ED for 92 disposals (mrem)
U-238	1.24E+02	2.78E-03	1.61E-04	1.76E-04	3.37E-04	3.10E-02
U-234	1.24E+02	2.78E-03	1.87E-04	1.77E-04	3.64E-04	3.35E-02
Th-230	8.56E+02	1.91E-02	1.33E-02	5.33E-03	1.86E-02	1.71E+00
Ra-226	1.52E+03	3.39E-02	2.33E-03	1.70E-02	1.93E-02	1.77E+00
Pb-210	1.35E+02	3.02E-03	2.18E-04	9.22E-03	9.44E-03	8.68E-01
Th-232	2.53E+02	5.66E-03	4.34E-03	1.73E-03	6.08E-03	5.59E-01
Ra-228	3.30E+02	7.38E-03	8.42E-04	1.30E-02	1.38E-02	1.27E+00
Th-228	2.55E+02	5.71E-03	1.80E-03	1.59E-03	3.39E-03	3.12E-01
<b>Total</b>		<b>mrem (mSv)</b>	<b>2.3E-02 (2.3E-04)</b>	<b>4.8E-02 (4.8E-04)</b>	<b>7.1E-02 (7.1E-04)</b>	<b>6.6E+00 (6.6E-02)</b>

The external dose per disposal was 0.13 mrem ( $1.3 \times 10^{-3}$  mSv) and 11.8 mrem ( $11.8 \times 10^{-2}$  mSv) assuming the *same* person was attending all 92 disposals (Table A-2). This was calculated assuming a laborer spends 0.33 hours per disposal at a distance of one meter from the container, and 0.083 hours (5 min) one meter from the deposited waste pile. The external dose for the heavy equipment operator who spends 0.33 hours exposed to the deposited waste pile was  $2.9 \times 10^{-2}$  mrem ( $2.9 \times 10^{-4}$  mSv) per disposal and 2.6 mrem ( $2.6 \times 10^{-2}$  mSv) assuming the *same* person attended all 92 disposals. Thus, the laborer exposure provides a worst-case estimate of external doses.

**Table A-2. Summary of Parameters and External Effective Dose to a Landfill Laborer During Disposal**

External dose parameter	Parameter value
<b>Landfill laborer</b>	
Exposure time in front of truck with shielded waste (hr)	0.33
Exposure rate 1 m from truck (mrem hr <sup>-1</sup> )	2.77E-01
Exposure time in front of unshielded waste (hr)	0.083
Exposure rate 1 m from unshielded waste (mrem hr <sup>-1</sup> )	4.42E-01
Total per disposal in mrem (mSv)	0.13 (1.3E-03)
<b>Total for 92 disposals in mrem (mSv)</b>	<b>11.8 (11.8E-02)</b>
<b>Heavy-equipment operator</b>	
Exposure time (hr)	0.33
Exposure rate inside cab (mrem hr <sup>-1</sup> )	8.71E-02
Total dose per shipment in mrem (mSv)	2.9E-02 (2.9E-04)
<b>Total dose for 92 shipments in mrem (mSv)</b>	<b>2.6E+00 (2.6E-02)</b>

Cancer morbidity and mortality risks were calculated using FGR13 risk coefficients, shown in Table 6 and 7 (EPA 1999). Total cancer morbidity risk for landfill workers from inhalation and ingestion during all 92 disposals was  $1.6 \times 10^{-6}$ . Total risk for landfill workers from external soil exposure during all 92 disposals was  $2.7 \times 10^{-5}$ . Assuming the same landfill worker was present at all 92 disposals, their maximum total morbidity risk incurred during disposal would be  $2.9 \times 10^{-5}$ . Total cancer mortality risk for landfill workers from inhalation and ingestion during all 92 disposals was  $1.2 \times 10^{-6}$ . Total risk for landfill workers from external soil exposure during all 92 disposals was  $1.8 \times 10^{-5}$ . Assuming the same landfill worker was present at all 92 disposals, their maximum total risk incurred during disposal would be  $2.0 \times 10^{-5}$ .

## Inhalation Doses at Office Buildings and School

Inhalation dose to office workers, students, and teachers at office buildings 300 m and 400 m from the source, and at the school 700 m from the source was calculated using the Gaussian plume model and the AP-42 emission model (EPA 1995) described earlier. This calculation assumes the wind is always blowing toward the receptor and uses atmospheric stability class conditions typical of daytime conditions and an annual average wind speed. The concentration divided by the source term (or  $\chi/Q$  in  $\text{s m}^{-3}$ ) calculated with the Gaussian plume model using stability class D and an average wind speed of  $4 \text{ m s}^{-1}$  was  $3.81 \times 10^{-4}$ ,  $2.31 \times 10^{-4}$ , and  $8.81 \times 10^{-5} \text{ s m}^{-3}$  for the south office (300 m), main office (400 m), and school (700 m), respectively. The product of the  $\chi/Q$  and the activity emitted from the source ( $Q$  value) yields the TIC. The breathing rate for adults and students was lower than what was assumed for the landfill laborer.

The effective doses (Table A-3) were substantially less than that for the landfill laborer. In this scenario, it is probable that the same person may be exposed to all 92 disposals because office staff,

students, and teachers would likely be present during all disposal operations. However, even in this case, all doses are significantly less than one mrem (< 0.01 mSv).

**Table A-3. Inhalation Effective Dose (ED) to an Office Worker and Student/Teacher During Disposal**

	South office	Main office	School	South office	Main office	School <sup>a</sup>
Radionuclide	TIC (pCi-s m <sup>-3</sup> )			Effective Dose (mrem per disposal)		
U-238	4.73E-02	2.87E-02	1.09E-02	3.52E-07	2.14E-07	7.26E-08
U-234	4.73E-02	2.87E-02	1.09E-02	4.09E-07	2.49E-07	8.71E-08
Th-230	3.26E-01	1.98E-01	7.53E-02	2.90E-05	1.77E-05	5.50E-06
Ra-226	5.78E-01	3.51E-01	1.34E-01	5.11E-06	3.11E-06	1.07E-06
Pb-210	5.15E-02	3.13E-02	1.19E-02	4.78E-07	2.91E-07	1.05E-07
Th-232	9.64E-02	5.86E-02	2.23E-02	9.51E-06	5.78E-06	1.92E-06
Ra-228	1.26E-01	7.64E-02	2.91E-02	1.84E-06	1.12E-06	3.87E-07
Th-228	9.72E-02	5.91E-02	2.25E-02	3.95E-06	2.40E-06	8.91E-07
Total per disposal			mrem (mSv)	5.1E-05 (5.1E-07)	3.1E-05 (3.1E-07)	1.0E-05 (1.0E-07)
<b>Total for 92 disposals</b>			<b>mrem</b> <b>(mSv)</b>	<b>4.7E-03</b> <b>(4.7E-05)</b>	<b>2.8E-03</b> <b>(2.8E-05)</b>	<b>9.2E-04</b> <b>(9.2E-06)</b>

<sup>a</sup> Doses in this column are for a school-age child. The total dose for an adult teacher was 1.2E-05 mrem (1.2E-07 mSv) per disposal and 1.1E-03 mrem (1.1E-05 mSv) for 92 disposals.

Cancer morbidity and mortality risks were calculated using FGR13 risk coefficients, shown in Table 6 and 7 (EPA 1999). Lifetime total morbidity risk for members of the public at the south office (300 m), main office (400 m), and school (700 m) from inhalation during all 92 disposals were  $7.8 \times 10^{-10}$ ,  $4.7 \times 10^{-10}$ ,  $1.8 \times 10^{-10}$ , respectively. Lifetime total mortality risk for members of the public at the south office (300 m), main office (400 m), and school (700 m) from inhalation during all 92 disposals were  $7.3 \times 10^{-10}$ ,  $4.5 \times 10^{-10}$ ,  $1.7 \times 10^{-10}$ , respectively.

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