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October 11, 2016

FINAL REPORT

Dose and Risk Assessment of Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) Disposals at the Blue Ridge Landfill

Submitted to Advanced Disposal

RAC Report No. 1-BRLF TENORM-2016
3691990v2/31039-0001

RAC
RISK ASSESSMENT
CORPORATION

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Dose and Risk Assessment of Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) Disposals at the Blue Ridge Landfill

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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. 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 had been disposed of at the site[1]. In March of 2016, Advanced Disposal Services, Inc. retained Risk Assessment Corporation to conduct a radiation dose assessment to estimate doses[2] to on-site and off-site receptors associated with the disposal of these wastes. In this report, the wastes are referred to as TENORM. Risk Assessment Corporation (RAC) had no means to directly verify that TENORM waste was actually disposed of at the Blue Ridge site, and relied on disposal manifests and material analytical data provided in order to establish the radionuclide content and perform this assessment.

The material in question consisted of 92 independent shipments of assumed TENORM materials totaling approximately 1,157 U.S. tons. The 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 this 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. The different types of people likely to be exposed to these radionuclides were identified, including a landfill laborer and heavy equipment operator, an office worker at the landfill, and students and staff at the middle school and high school adjacent to the landfill site. 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 were reported on a per-disposal basis and as total dose, assuming the same worker attended all 92 disposals. For prospective doses, the only viable exposure pathway is by means of radionuclide infiltration into the groundwater. A dose assessment was performed to 100,000+ years into the future to estimate potential doses.

This assessment has demonstrated that doses received by workers on the site and to the public from the disposal of the TENORM are minimal compared to radiation exposures they receive from natural and other man-made sources. The average member of the public is exposed to about 600 mrem (6 mSv) each year from natural radiation, medical, and other sources (NCRP 2006). The highest estimated effective dose for any individual was for a hypothetical landfill worker who was assumed to be present during all the TENORM disposals. The maximum inhalation and ingestion dose calculated for the landfill worker was 1.94 mrem (1.94×10^{-2} mSv), and the external dose was 2.76 mrem (2.76×10^{-2} mSv) for a total dose of 4.7 mrem (4.7×10^{-2} mSv), which translates to an increased risk of cancer of 2 persons in a population of one million. By way of comparison, the average annual dose per person in the U.S. from exposure to natural background radiation is ~320

[1] Kentucky allows the disposal of TENORM in a solid waste landfill provided the material is generated in Kentucky or Illinois.

[2] In this report, the term dose refers to the Effective Dose as defined by International Commission on Radiation Protection Publication 60 (ICRP 1991) and 72 (ICRP 1996). The effective dose replaced the older Effective Dose Equivalent used in 10 CFR 20 and KAR 100:010.

mrem. These doses assume the same person attended all 92 disposals, and therefore represent the worst-case scenario. The maximum inhalation dose to nearby hypothetical office workers at the landfill was 2.0×10^{-3} mrem (2.0×10^{-5} mSv), and for hypothetical students and teachers at Estill County Middle and High School was 4.7×10^{-4} mrem (4.7×10^{-6} mSv). These doses translate to an increased risk of cancer of less than 5.0×10^{-5} % or 5 persons in a population of 10 million, assuming a worst case scenario. The assessment also considered times far in the future when the radioactive material could leach from the landfill into the groundwater and potentially contaminate drinking water. Assuming these circumstances, and a drinking water well located directly downstream of the facility, resulted in a maximum effective dose of 1.25 mrem (1.25×10^{-2} mSv) per year. For all potentially exposed populations considered, the increased risk of cancer is negligible when compared to the baseline cancer risk of 40% or four out of ten persons being diagnosed with cancer in their lifetime. Additionally, Ra-226/228 concentrations and uranium mass concentrations in drinking water were well below the maximum contaminant limits of 5 pCi L^{-1} and 30 μg L^{-1}, respectively, set forth in the Code of Federal Regulations (see 40 CFR 141).

This assessment has demonstrated that doses received by workers on the site and to the public from the disposal of the TENORM are extremely low, especially when compared to radiation exposures received from natural and other man-made sources. Additionally, all available environmental sampling data support the conclusion of this assessment that the estimated doses are low, and there is no evidence to suggest any measurable impact of the TENORM waste, either now or in the future.

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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
Ci	Curie, Imperial unit of radioactivity
EPA	Environmental Protection Agency
ICRU	International Commission on Radiation Units and Measurements
ICRP	International Commission on Radiological Protection
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)
TBE	Teledyne Brown Engineering, Inc.
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 7.23×10^{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.

4,231 = 4.231×10^{3}
1,230,000 = 1.23×10^{6}
0.0361 = 3.61×10^{-2}

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 7.23×10^{0} or 7.23E+00 in computer scientific notation.

Unit Conversions and Radiation Dose Terminology

Imperial unit	SI unit
Radiation activities	
1 Ci	3.7×10^{10} Bq
~27 pCi L^{-1} or pCi m^{-3} or pCi kg^{-1}	1 Bq L^{-1} or Bq m^{-3} or Bq kg^{-1}
Radiation dose quantities	
100 rad	1 Gy
100 mrem	1 mSv
100 µrem hr^{-1}	1 µSv hr^{-1}
Other	
3.9×10^3 Roentgen	1 C kg^{-1}

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

1 R ≈ 0.869 rad (8.69 mGy) in air and ≈ 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
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_T, ($\dot{H}$ for dose rates)
Units: rem or Sv
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
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.

Common Unit Prefixes

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

Scope of Work

This report documents Risk Assessment Corporation's (RAC) characterization of the type and amount of technologically enhanced naturally occurring radioactive materials (TENORM) emplaced at the Blue Ridge Landfill (BRLF) in Irvine, KY, between July 20, 2015, and February 3, 2016, and assesses the extent to which radioactive materials may be released and transported into the environment from BRLF. The dose assessment includes a characterization of the wastes, an analysis of feasible exposure pathways taking into consideration the landfill construction, local geology and hydrology, meteorology, background radiation, population distribution, and current and future land uses. The radionuclide content of these wastes is based on disposal manifests and material analytical data provided. RAC had no means to directly verify that TENORM waste was actually disposed of at the Blue Ridge site, and relied on information provided. This included waste characterization data provided by each waste generator and by Advanced Disposal, as well as environmental sampling measurements performed by Cornerstone Environmental Group LLC and Chase Environmental on behalf of Advanced Disposal, and independent sampling measurements provided by the State of Kentucky.

This analysis applies well-established methodologies and scientific principles and allows the magnitude of potential exposures and doses to be reconstructed for representative individuals based on location and specific time periods of interest. The technical approaches applied in this report are based on methods described in Till and Grogan (2008) and other risk assessment documentation found in the open literature (ANSI 2009; EPA 2000; IAEA 2003; NRC 1999).

Background

Risk Assessment Corporation (RAC) was retained by Advanced Disposal to conduct a dose assessment for the Blue Ridge Landfill located in Irvine, KY, to determine doses to on-site and off-site receptors associated with specific shipments of TENORM to the site. The waste streams were arranged and brokered by BES, LLC. The shipments were transported by Advanced TENORM Services[3] (ATS), J.R. Daniels, Mountain State Environmental and others to the Blue Ridge Landfill (BRLF) between July 20, 2015, and February 3, 2016, and consisted of 92 loads compromising 1,157.25 U.S. tons of material. The TENORM 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).

Risk Assessment Corporation

Risk Assessment Corporation (RAC) was founded by Dr. John Till in 1977 (www.racteam.com). Dr. Till has concentrated his 40-year career on radiological and chemical environmental risk assessment, while leading a team of independent scientists (see Appendix A for *curriculum vitae*). Radiological risk assessment is a multidisciplinary science, requiring individuals with a number of different skills to work together as an integrated team. RAC team members bring

[3] No relation to the owner of the BRLF, Advanced Disposal Services, Inc.

together technical skills and problem-solving experiences from a wide variety of disciplines, including dose and risk assessment, on-site and off-site monitoring, data evaluation, process engineering, environmental transport modeling, database development and use, geographic information systems integrated with databases and assessment models, radiation biology, and interactive public involvement.

RAC team members have been integral members of and advisors to nationally and internationally recognized organizations including the National Academy of Sciences, the National Council on Radiation Protection and Measurements, the International Commission on Radiological Protection, the Atomic Energy Agency, the Environmental Protection Agency Science Advisory Board, and the United Nations Scientific Committee on the Effects of Atomic Radiation among others.

RAC has extensive experience in developing and applying methods to determine how people may be exposed to contaminants in the environment and in assessing the health effects associated with such exposures. Depending on the situation, this may involve piecing together evidence to evaluate past exposures for historical dose reconstruction, evaluating the present-day situation at a facility or location and, if appropriate, the likely future impacts, or assessing the potential impact of planned or unplanned releases.

Examples of RAC's work include reconstructing doses and risks to the public from radioactive materials released from the Fernald Feed Materials Production Center during its 38 years of operation near Fernald, Ohio, and reconstructing historical public exposures from the former Rocky Flats Nuclear Weapons Plant near Denver, Colorado, that operated from 1952–1989. Later, RAC also worked with the Radionuclide Soil Action Level Oversight Panel to develop recommendations for soil cleanup at the former Rocky Flats site. The panel consisted of a mix of technical specialists and individuals with no technical experience drawn from public interest groups, local governments, and the general public.

Apart from these and other dose reconstruction projects, RAC has been involved in a wide variety of projects associated with the occurrence of radionuclides and chemicals in the environment and potential human exposures. For example, in 1997, RAC was asked by the Department of Justice to perform a series of technical audits of Los Alamos National Laboratory (LANL) for compliance with the Clean Air Act, 40 CFR 61, subpart H. The project was initiated by a lawsuit filed by Concerned Citizens for Nuclear Safety (CCNS) against the U.S. Department of Energy and the former director of Los Alamos National Laboratory. Settlement of the suit required that the audits be performed by an organization agreed to by all parties, and RAC was chosen as the independent auditor. The audit process was a success and led to significant improvements in the compliance program at LANL.

RAC has also offered scientific courses for many years, developing and presenting courses designed to enhance the general knowledge of the audience on such topics as risk assessment, pathway analysis, risk-based decisions for corrective action, risk communication, and other areas of specific or general interest. RAC is currently contracted by the U.S. Nuclear Regulatory Commission (NRC) to present up to five one-week training courses on risk assessment to NRC staff. RAC presented the first course to NRC staff in April 2015, and the contract runs through 2019.

In addition, RAC has developed the RACER© system over the last 10 years. RACER is an innovative method that converts environmental data directly to human health risk to facilitate and enhance decision-making and communication about risks from chemicals and radionuclides in the

environment. RAC developed RACER to facilitate easy access to and use of environmental measurement data for a variety of applications, ranging from basic data evaluation to more complex exposure analysis and risk calculations. RACER integrates scientific approaches with data management expertise, informed by years of experience in dose and risk assessment. The result is an approach geared toward turning data into knowledge that can be effectively communicated to a diverse audience, starting with clear objectives and using integrated processes and flexible design to make technically sound decisions. This is accomplished through the implementation of customer-specific processes and tools with a focus on stakeholder interaction and sustainability.

Curriculum vitae for RAC team members involved in this project are provided in Appendix A – *Curriculum Vitae*.

Blue Ridge Landfill (BRLF)

Disposal Facility

Blue Ridge Landfill (BRLF), located in Irvine, KY, is a municipal solid waste landfill operated by Advanced Disposal Services, Inc. (see Figure 1). The landfill began operations in 1984 and accepts 550 tons per day on average. BRLF also has a 1,600 kilowatt electrical generation plant. As landfill cells are completed, methane gas, a by-product of the decomposing material, is collected from within the waste through a system of vertical wells and pipelines and directed to a separate on-site treatment facility. The treated landfill gas is used to generate electricity at the landfill that is delivered to the electrical grid.

Figure 1. Site and Situation of Blue Ridge Landfill (BRLF).

Construction

The BRLF contains an engineered liner system consisting of four components into which solid waste is disposed to prevent wastes escaping to the groundwater below. The bottom liner, the lowest component, is comprised of re-compacted clay soil obtained on-site that has a maximum permeability of 1×10^{-7} cm/sec. The thickness of the clay is 36 inches on slopes less than 3:1 and 24 inches on slopes greater than 3:1.

The second component is a 60-millimeter high-density polyethylene (HDPE) geomembrane, which has a hydraulic conductivity less than 1×10^{-12} cm/sec and a maximum water vapor transmission rate of 0.03 grams/m^2/day.

The third component is a 12-inch granular (stone or sand) layer with a minimum permeability of 1×10^{-2} cm/sec. This layer serves the dual purpose of protecting the liner and collecting the leachate. Collected leachate flows by gravity into pipes that convey the leachate out of the landfill into storage tanks.

The top component is a geotextile laid on top of the stone or sand to help protect the integrity of the leachate collection system.

Waste Handling Procedures

As some of the waste contained up to 80% water, ADS added sawdust to absorb the excess liquid to seven of the 92 loads prior to disposal. Sawdust was added to an additional 9 of the 92 loads by L.R. Daniels prior to being transported to the BRLF (Pendergrass et al. 2015). An excavator was used to perform the mixing in a buried can (40 cubic yards) and then load the material into a dump truck for disposal in the landfill (Pendergrass et al. 2015). On arrival at BRLF, the trucks entered via the main gate and proceeded to the scale house where they were weighed and received a weight ticket. The trucks then proceeded to the working area of the landfill for disposal. The truck reversed up to the disposal area, and the driver exited the vehicle to open the back end using the turnbuckle. The driver returned to the cab and initiated the bed of the waste compartment rising and the waste was expelled by gravity. As soon as this process was completed, the truck pulled clear of the disposal area and the bed was lowered. The driver then exited the vehicle to close the back end up before driving away. The entire disposal process lasted less than 15 minutes (see Figure 2). Blue Ridge used heavy-equipment such as bulldozers and compactors to push, compact and bury waste in the landfill. The driver of the heavy-equipment was seated in an air-conditioned cab approximately 10 feet above the landfill surface. A landfill compactor unit may have been used to compact the waste into the waste mass (see Figure 3). The operator of the compactor was also seated in an air-conditioned cab approximately 15 feet above the landfill.

Figure 2. View of typical disposal of waste from a garbage truck at BRLF with a compactor unit about to push waste into waste mass.

Figure 3. Compactor unit in the process of compacting disposed waste.

Site Geology

BRLF is in Irvine, KY, within Estill County, which is located within parts of the Outer Bluegrass and the Eastern Kentucky Coal Field physiographic regions. The Blue Ridge facility is located on New Albany shale formations. The site is located on the 1976 U. S. Geological Survey Geologic Map of the Irvine Quadrangle, which defines the New Albany shale as the following:

> Shale and dolomite: Shale present at this location is olive-gray and weathers to dark brown and to dark yellowish brown where stained by limonite. It is carbonaceous, and there are abundant disseminated grains of iron sulfides and a few nodular concretions as much as 4 inches in diameter and 2 inches thick. Phosphatic nodules, 2 to 4 inches in diameter, are common in upper 15 feet. In the lower 15 feet, the soil is locally crossbedded and interbedded with dolomite. Olive-gray shale occurs in a few layers, 0.5 to 4 inches thick in the upper 40 feet, and in layers as much as 1-foot thick in the upper 10 feet. The dolomite consists of two varieties: (1) a medium-dark-gray to grayish-brown, very fine to fine-grained, carbonaceous material containing sparse grains of iron sulfides and well-rounded medium grains of quartz found in layers from less than 1 inch to more than 2 feet thick. This is locally present in the lower 15 feet, and (2) a dark-gray, mottled with variegated shades of brown, very fine to fine-grained material that at places contains fragments of dolomite, chert, and fossils which impart a breccia-like appearance. The material is carbonaceous and contains sparse well-rounded medium grains of quartz and chert, and very fine grains of iron sulfides present at its base. The Unit is commonly well exposed except on hilltops and gentle slopes. It forms broad, flat valleys, steep dissected hillsides and bluffs along streams, and flat hilltops. The contact with underlying Boyle Dolomite is conformable; the contact with the underlying Bisher Limestone and Crab Orchard Formation is unconformable. The Unit thins slightly southwestward (USGS 1976).

Natural Background Radiation in Shale

The concentration in soils of naturally occurring radionuclides in the geologic region where the landfill is situated is highly variable. Highest concentrations occur in regions where the New Albany and Nancy shale formations are exposed at the surface. Chase Environmental and the State of Kentucky Cabinet for Health and Family Services (KY CHFS) collected soil samples in areas around the landfill representative of the natural background geology and found average Ra-226 concentrations of 5.6 pCi g^{-1} and average Ra-228 concentrations of 1.3 pCi g^{-1} (Chase Environmental 2016; KY CHFS 2016a). These values are higher than the average natural background radioactivity of US soils of 1.1 pCi g^{-1} Ra-226, 1.0 pCi g^{-1} Ra-228 (PADEP 2015), and reflect outcrops of the New Albany and Nancy shale in the region.

Site Hydrology

Information provided by Cornerstone Environmental (Appendix C – Aquifer Characteristics) on behalf of Advanced Disposal regarding the underlying aquifer indicated that the potentiometric

surface lies at an elevation ranging from 710 to 740 ft (ground surface elevations range from 760 to 860 ft), and flow is to the southwest. The aquifer lies within the New Albany shale and has a saturated thickness ranging from 9.02 to 20.55 ft with an average thickness of 14.09 ft. Hydraulic gradients were estimated to be 0.0399 ft ft^{-1}, and saturated hydraulic conductivity ranged from 1.04 ft day^{-1} to 10.72 ft day^{-1}. Effective porosity of the aquifer was estimated to be 0.15.

According to the Kentucky Geological Survey (KGS 2005), the New Albany shale yields 100 to 500 gallons day^{-1} to wells in valley bottoms and on uplands, usually at depths of less than 50 ft. Water from great depths in this formation is highly mineralized.

Radiological Characterization of the Source

The radiological characterization refers to the total activity, volume, and radionuclide composition of TENORM materials that were disposed in the landfill. The source uses the inventory estimates and the geographical location of the TENORM, coupled with release mechanisms and models to estimate the quantity of TENORM materials that were released to the environment (air, soil, and water) per unit time. In this case, the inventory was based on landfill gate tickets, generator waste disposal manifests for the TENORM loads, the time frame in which it was disposed in the landfill, the estimated volume of TENORM disposed, and available site and waste characterization analyses.

RAC initially considered core sampling to quantify the amount of activity and dispersion of the source. This recommendation was not made for several reasons: (1) disturbing the waste by taking core sampling could potentially create a new risk to workers and the public; (2) the diffuse nature of the disposals (the materials were spread across multiple disposal cells); 3) the gamma scan performed by Chase Environmental showed no surface representation of the waste and therefore the TENORM waste would be difficult to locate; 4) the manifest data likely provide a better estimate of activity in the waste; and 5) data from the core samples would likely not improve the estimates of dose.

TENORM radionuclides with half-lives greater than five years are presented in Table 1. Numerous short-lived radioactive progeny would also be present if any of the parents are present in the source term. The U-238 and Th-232 decay series are the two primary TENORM decay series of concern in this situation (see Figure 4 and Figure 5).

Table 1. Relevant TENORM Radionuclides and Their Half-lives

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

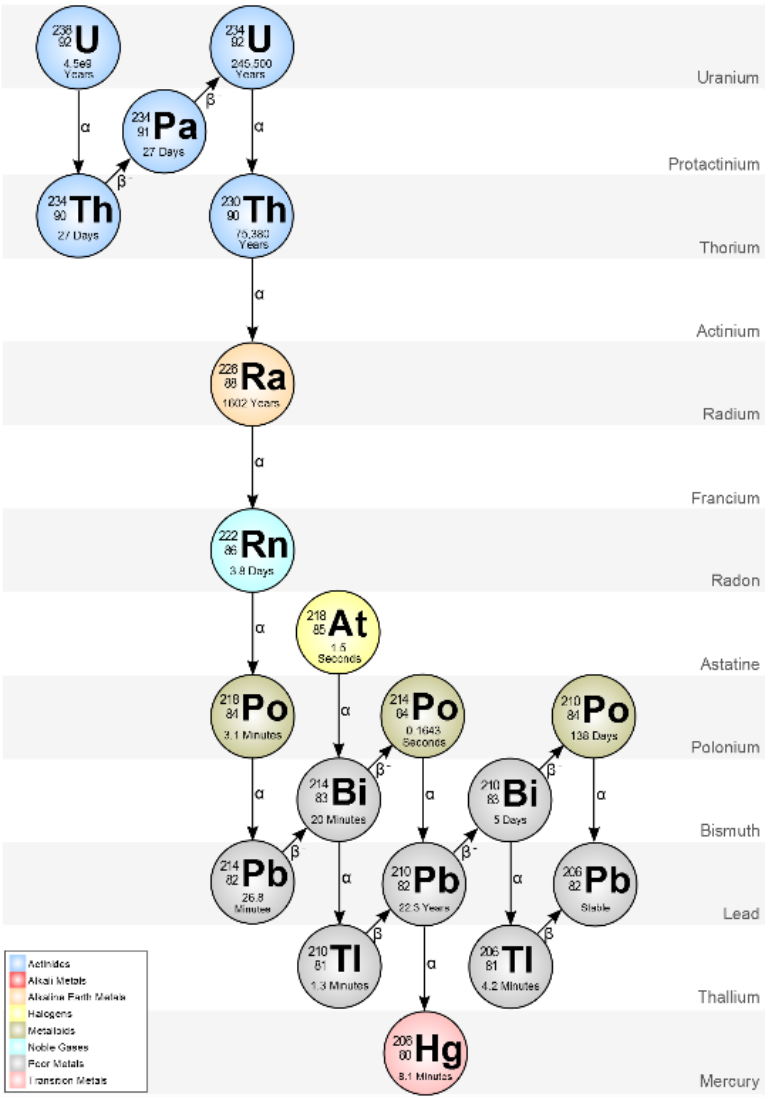

Figure 4. Uranium-238 decay scheme showing the short-lived progeny that will be present alongside the parent. Taken from http://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html.

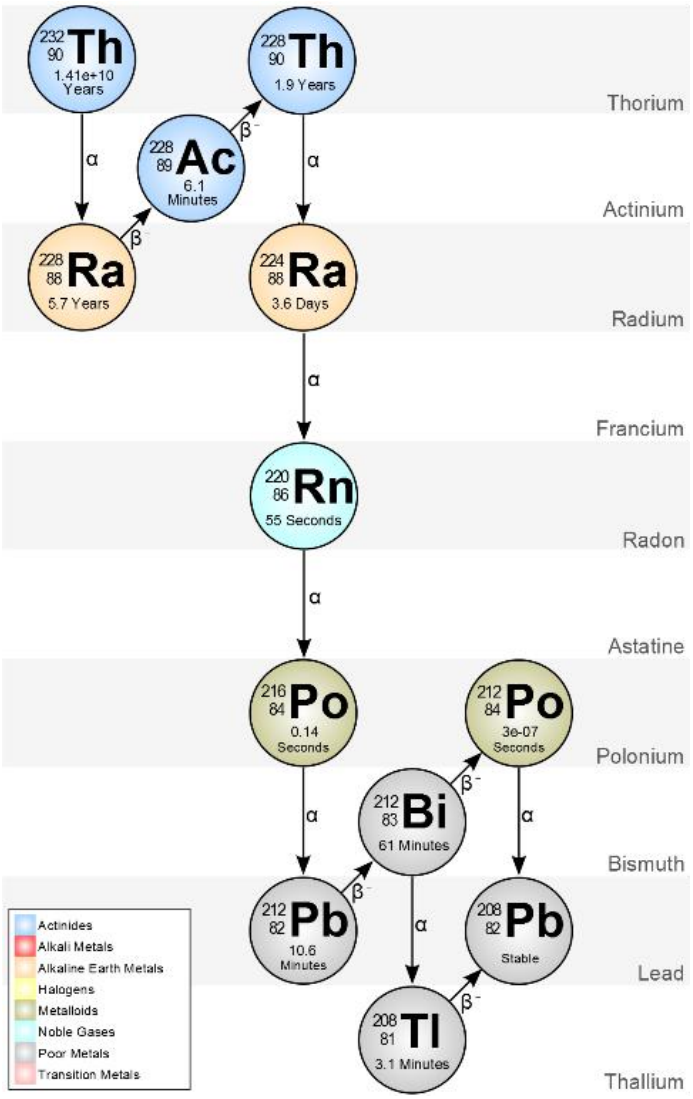

Figure 5. Thorium-232 decay series showing the short-lived progeny that will be present alongside the parent. Taken from http://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html.

Fracking Waste and Treatment

The TENORM waste in question was derived solely from oil and gas production operations in the Marcellus or Utica shale deposits in Ohio and West Virginia. According to landfill gate tickets, activity reports, and generator manifests, there are eight waste streams from four generators, described as follows:

- Cambrian
  - Four loads totaling 9.97 U.S. tons
  - Exploration and production soil and debris.
- Fairmont Brine
  - 47 loads totaling 865.33 U.S. tons
  - Exploration and production soil and debris.

- GreenHunter
  - 28 loads totaling 149.11 U.S. tons
  - Used filters and debris
  - Used filters
  - Filter sludge.
- Nuverra
  - 13 loads totaling 132.84 U.S. tons
  - Filter cake
  - Bag filters
  - Debris, soil, gravel.

According to a partial response to a request for information from ATS to the Kentucky Department for Environmental Protection dated March 25, 2016, a portion of the waste generated by Fairmont Brine was processed such that it would pass the "paint filter test" detailed in EPA 9095B (Hoskins 2016). This was accomplished by the addition of sawdust to the waste at L.R. Daniels Trucking and Salvage facility in Ashland, KY (Pendergrass et al. 2015). The sawdust solidified waste prior to transportation to BRLF is shown in Figure 6.

Figure 6. Sawdust solidified waste from Fairmont Brine Processing in semi-tractor trailer ready for hauling to ADS Blue Ridge Landfill (taken from Pendergrass et al. 2015).

Waste Material Radioanalytical Data

As noted above, 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. Table 2 below details the known radionuclide content and mass of each load or set of loads brought into the Blue Ridge Landfill. A table detailing each of the 92 individual loads considered in this analysis is provided in Appendix B – Load Information.

Table 2. Radionuclide Content +/- 2 Standard Deviations and Mass of Waste Materials Emplaced at Blue Ridge Landfill

Load number	Mass (kg)	Material	U-238 (pCi g^{-1})	Th-230 (pCi g^{-1})	Ra-226 (pCi g^{-1})	Ra-228 (pCi g^{-1})	Th-232 (pCi g^{-1})	Reference
N/A	N/A	filter sock	2.4 +/- 6.0	30.8 +/- 0.7	29.7 +/- 0.4	21.7 +/- 0.8	20.7 +/- 0.6	(Chase Environmental Group Inc. 2016)
1–4	9.04E+03	Cambrian Wells soil	Not measured	Not measured	107.3 +/- 14.5	98.1 +/- 13.6	Not measured	(Pace Analytical Services Inc. 2016)
5–40	6.95E+05	Fairmont Brine sludge pit	94.3 +/- 17.4	Not measured	1453.5 +/- 200.8	303.8 +/- 40.8	162.2 +/-	(Pace Analytical Services Inc. 2015c)
41–51	9.01E+04	Fairmont Brine sludge sample	Not measured	Not measured	13.6 +/- 2.0	3.6 +/- 0.9	Not measured	(Hoskins 2015)
52–79	1.35E+05	GreenHunter filters	Not measured	Not measured	283.0 +/- 43.3	84.5 +/- 11.5	Not measured	(Environmental Service Laboratories Inc. 2015)
52–79			7.7 +/- 3.6	Not measured	36.0 +/- 9.9	7.1 +/- 1.5	263.5 +/- 213.6	
52–79			90.0 +/- 15.6	Not measured	338.6 +/- 50.7	115.6 +/- 15.7	630.0 +/- 179.2	
52–79			42.2 +/- 8.9	Not measured	255.7 +/- 39.4	52.3 +/- 7.6	15.4 +/- 260.0	
80	7.57E+03	Nuverra sediment and pea gravel	Not measured	Not measured	7.8 +/- 3.1	2.2 +/- 0.5	Not measured	(Pace Analytical Services Inc. 2015b)
81	1.10E+04	Nuverra sediment and pea gravel	Not measured	Not measured	17.8 +/- 4.7	5.2 +/- 1.0	Not measured	(Pace Analytical Services Inc. 2015b)
82	1.14E+04	Nuverra sediment and pea gravel	Not measured	Not measured	29.1 +/- 7.2	6.7 +/- 1.2	Not measured	(Pace Analytical Services Inc. 2015b)

Load number	Mass (kg)	Material	U-238 (pCi g^{-1})	Th-230 (pCi g^{-1})	Ra-226 (pCi g^{-1})	Ra-228 (pCi g^{-1})	Th-232 (pCi g^{-1})	Reference
83	1.38E+04	Nuverra sediment and pea gravel	Not measured	Not measured	8.4 +/- 3.2	1.8 +/- 0.6	Not measured	(Pace Analytical Services Inc. 2015b)
84	1.50E+04	Nuverra sediment and pea gravel	Not measured	Not measured	10.4 +/- 3.2	3.1 +/- 0.7	Not measured	(Pace Analytical Services Inc. 2015b)
85	6.01E+03	Nuverra sediment and pea gravel	Not measured	Not measured	12.0 +/- 3.8	3.5 +/- 0.7	Not measured	(Pace Analytical Services Inc. 2015b)
86	1.40E+04	Nuverra sediment and pea gravel	Not measured	Not measured	3.3 +/- 2.1	1.8 +/- 0.5	Not measured	(Pace Analytical Services Inc. 2015b)
87	8.94E+03	Nuverra filter cake	Not measured	Not measured	106.7 +/- 17.2	34.1 +/- 4.8	Not measured	(Nuverra Environmental Resources 2015)
88–91	3.67E+03	Nuverra bag filters	Not measured	Not measured	529.3 +/- 76.5	268.2 +/- 35.7	Not measured	(Pace Analytical Services Inc. 2015a)
92	1.15E+04	Nuverra pander well soil	Not measured	Not measured	5.6 +/- 2.1	1.6 +/- 0.4	Not measured	(Nuverra Environmental Solutions 2015)

External Exposure Measurements of TENORM Shipments

External dose rates on contact from Fairmont Brine shipping containers were measured for some of the shipments. These dose rates were converted to a total radium concentration using a conversion factor developed by the Pennsylvania Department of Environmental Protection (PADEP 2015). The PADEP used the MicroShield Software Package (Grove Engineering 2013) to determine the dose rate of a 0.274-cm thick steel container with a volume of 20 yd^3 (15.3 m^3) containing the solidified TENORM brine. Based on typical Ra-226 and Ra-228 concentrations of 480 pCi g^{-1} and 183 pCi g^{-1}, respectively, the PADEP estimated a dose rate to total radium conversion factor of 2.02 µrem-g $(pCi\text{-}hr)^{-1}$ for measurements taken on contact with the container surface. This conversion factor was used to estimate total radium concentrations in Fairmont Brine shipments (loads 5–40) that had dose rate measurements (Table 3, reproduced from p11 of Hoskins 2015).

Table 3. Dose Rate Measurements and Estimated Total Radium Concentration in Fairmont Brine TENORM Shipments, Loads 5–40 (Hoskins 2015)

Box number	Location	Survey date	Box type	Reading[a] (µrem hr^{-1})	Total radium (pCi g^{-1})
VB1024	Front	6/3/15	Vac	315.4	156.14
VB1024	Left	6/3/15	Vac	249.8	123.66
VB1024	Back	6/3/15	Vac	489.8	242.48
VB1024	Right	6/3/15	Vac	433.1	214.41
VB1286	Front	6/3/15	Vac	535.3	265.00
VB1286	Left	6/3/15	Vac	499	247.03
VB1286	Back	6/3/15	Vac	503.8	249.41
VB1286	Right	6/3/15	Vac	500.7	247.87
VB1447	Front	6/3/15	Vac	471.8	233.56
VB1447	Left	6/3/15	Vac	488.2	241.68
VB1447	Back	6/3/15	Vac	471.6	233.47
VB1447	Right	6/3/15	Vac	625.3	309.55
VB1083	Front	6/3/15	Vac	510.9	252.92
VB1083	Left	6/3/15	Vac	671	332.18
VB1083	Back	6/3/15	Vac	611.2	302.57
VB1083	Right	6/3/15	Vac	n/a	[b]
VB1456	Front	6/3/15	Vac	444.8	220.20
VB1456	Left	6/3/15	Vac	n/a	[b]
VB1456	Back	6/3/15	Vac	530.5	262.62
VB1456	Right	6/3/15	Vac	765.9	379.16
V382	Front	6/3/15	Vac	291.1	144.11
V382	Left	6/3/15	Vac	704.6	348.81
V382	Back	6/3/15	Vac	422.6	209.21
V382	Right	6/3/15	Vac	598	296.04

Box number	Location	Survey date	Box type	Reading[a] (µrem hr^{-1})	Total radium (pCi g^{-1})
VB1375	Front	6/3/15	Vac	329.2	162.97
VB1375	Left	6/3/15	Vac	471.9	233.61
VB1375	Back	6/3/15	Vac	326.2	161.49
VB1375	Right	6/3/15	Vac	354.5	175.50
VB1430	Front	6/3/15	Vac	151.3	74.90
VB1430	Left	6/3/15	Vac	229.8	113.76
VB1430	Back	6/3/15	Vac	233.9	115.79
VB1430	Right	6/3/15	Vac	374.5	185.40
VB1320	Front	6/3/15	Vac	693	343.07
VB1320	Left	6/3/15	Vac	649.6	321.58
VB1320	Back	6/3/15	Vac	481.5	238.37
VB1320	Right	6/3/15	Vac	708.1	350.54
V246	Front	6/3/15	Vac	331.1	163.91
V246	Left	6/3/15	Vac	406.8	201.39
V246	Back	6/3/15	Vac	396.3	196.19
V246	Right	6/3/15	Vac	688.5	340.84
V336	Front	6/3/15	Vac	475.3	235.30
V336	Left	6/3/15	Vac	644	318.81
V336	Back	6/3/15	Vac	660.1	326.78
V336	Right	6/3/15	Vac	735.2	363.96
VB1115	Front	6/3/15	Vac	456.6	226.04
VB1115	Left	6/3/15	Vac	832.5	412.13
VB1115	Back	6/3/15	Vac	631	312.38
VB1115	Right	6/3/15	Vac	653.7	323.61
			Average	**501**	**248**
			Standard deviation	**159**	**78.9**

[a] Dose rate is taken to be the same as effective dose.
[b] Data point omitted because no measurement was reported.

Environmental Samples

Several different organizations have collected environmental samples on and around the landfill to characterize the area and determine if there is any evidence that the disposed waste has had any measurable short-term impact on the local environment. In addition, Chase Environmental Group, Inc., conducted a gamma scan survey of an extensive area within the landfill to characterize surface exposure rates (Chase Environmental Group Inc. 2016). Table 4 provides a summary of the number of samples collected by each organization and the laboratories used for the associated analyses.

Table 4. Summary of Environmental Samples Collected in the Vicinity of the Landfill

Data Provider	Laboratory	Sample type	Number of samples
Ameriphysics	Ameriphysics	Air	15
Ameriphysics	Eberline	Surface water	3
Chase	NA	Surface gamma scan	328,306[a]
Chase	TBE[b]	Air	5
Chase	TBE	Soil	16
Chase	TBE	Surface water	2
National Guard	State	Air	10
State of Kentucky	State	Groundwater	5
State of Kentucky	State	Leachate	3
State of Kentucky	State	Sediment	9
State of Kentucky	State	Soil	11
State of Kentucky	State	Solid	2
State of Kentucky	State	Surface water	18
State of Kentucky	State	Dried leachate	1
State of Kentucky	TBE	Groundwater	5
State of Kentucky	TBE	Leachate	2
State of Kentucky	TBE	Sediment	7
State of Kentucky	TBE	Sludge	1
State of Kentucky	TBE	Solid	1
State of Kentucky	TBE	Surface water	14
State of Kentucky	TestAmerica	Groundwater	5
State of Kentucky	TestAmerica	Leachate	2
State of Kentucky	TestAmerica	Sediment	11
State of Kentucky	TestAmerica	Surface water	16

[a] Number of discrete count rate measurements made.
[b] Teledyne Brown Engineering, Inc.

Figure 7 and Figure 8 show the locations where air, soil, sediment, surface water, and groundwater samples have been collected.

Figure 7. Soil (dark brown), sediment (light brown), and groundwater (blue) sampling locations. The waste in question was deposited in the area covered by the square grid cells.

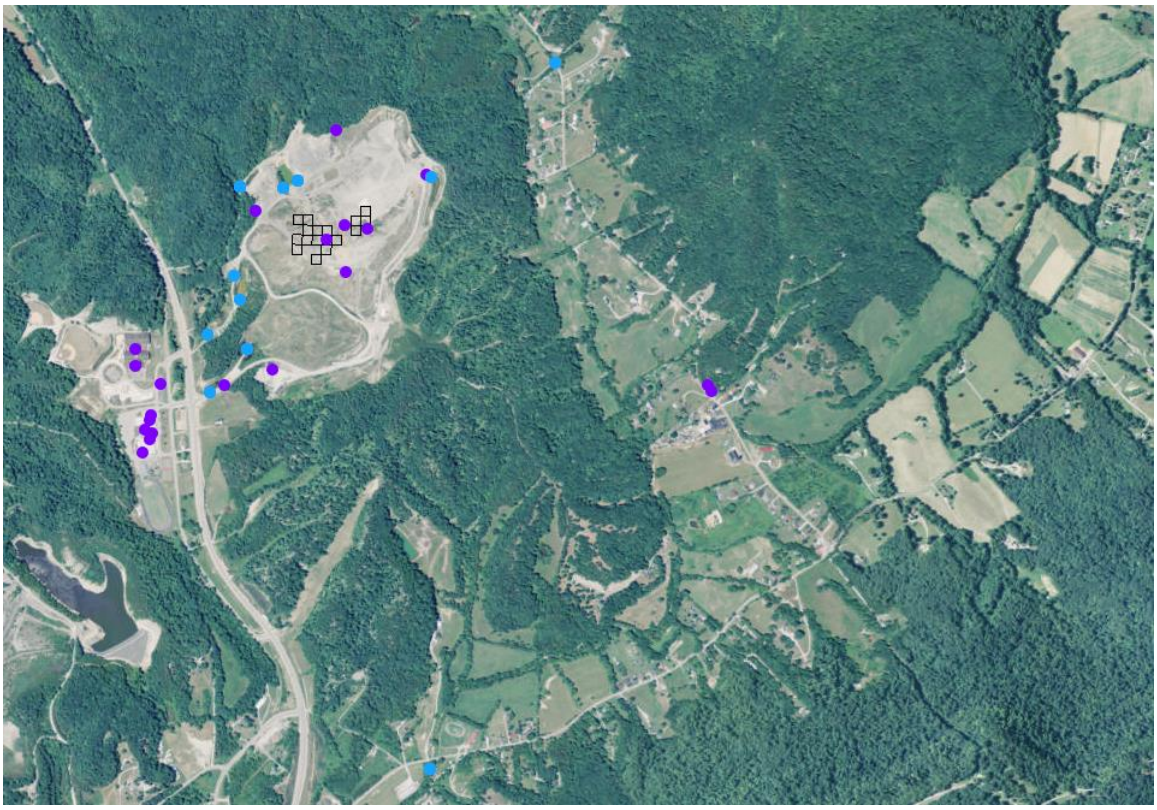

Figure 8. Air (purple) and surface water (blue) sampling locations. The waste in question was deposited in the area covered by the square grid cells.

The following sections evaluate the various environmental measurements that have been made with regard to their utility for quantifying impacts related to the TENORM waste in question, or for identifying any deviations from natural background levels that would be expected in the area. The focus of analyses of the collected samples has been on Ra-226 and Ra-228, which are important components of TENORM from a radiological dose standpoint (PADEP 2015). Consequently, the evaluation presented here focuses on these radionuclides, along with relevant measurements of gross alpha and beta activity.

Gamma Scan Measurements

Extensive surface gamma scan surveys were conducted in early March 2016 and early May 2016 and covered a significant portion of the landfill. A Ludlum 44-10 survey meter with a 2-inch-by-2-inch sodium iodide (NaI) crystal was used for the survey. Calibration records for the detector used for the survey are provided in Appendix C of the Chase Environmental report (2016). Figure 9 shows the area covered by the scan, as well as the relative count rates measured in the scanned area. There is a relatively large range of count rates related to naturally occurring radionuclides (i.e., background) in the surface soils in the area, ranging from 10,000 to 20,000 cpm in the central area of the landfill to 40,000 to 80,000 cpm in the area of exposed New Albany shale. The gamma scan did not reveal any surface activity above background in the areas where the waste in question was deposited. The results of the gamma scan are consistent with analyses of soil samples, which show higher Ra-226 concentrations in the same areas having higher gamma survey count rates.

Extensive gamma surveys were also conducted at the nearby middle and high schools. There was no evidence of elevated radiation or contamination readings above background at either school (Fowler, 2016).

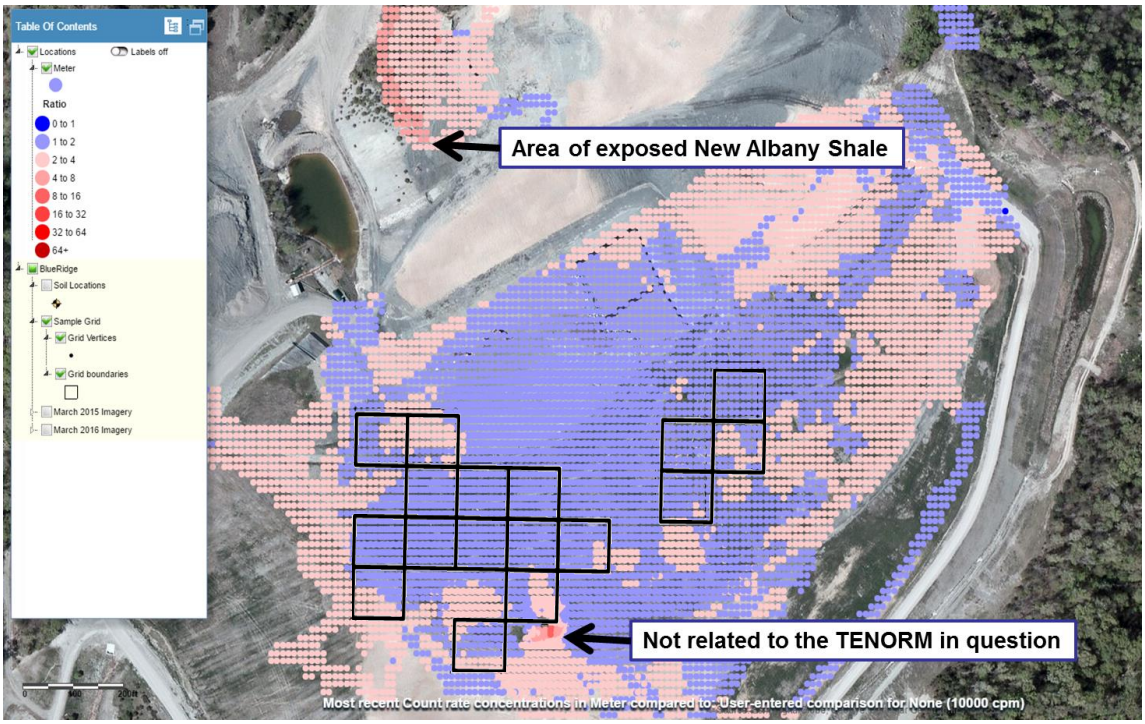

Figure 9. Area covered by the surface gamma scan. The light blue areas correspond to a count rate of 10,000 to 20,000 cpm, the light pink areas correspond to a count rate of 20,000 to 40,000 cpm, and the darker pink area near the exposed New Albany shale corresponds to a count rate of 40,000 to 80,000 cpm. The waste in question was deposited in the areas covered by the square grid cells.

Air Measurements

Air samples were collected by Ameriphysics, LLC., on February 28, 2016; by the National Guard on March 12, 2016; and by Chase on May 5, 2016, at the locations shown in Figure 8. Table 5 gives basic statistics related to the air measurements made for gross alpha and beta, Ra-226, and Ra-228, which would be of concern for identifying any measurable impact from the TENORM waste. The reported concentrations for Ra-226 and Ra-228 are all less than the analytical method detection limit, and also less than the airborne effluent criteria specified in 10 CFR 20, Appendix B, Table 2 column 1 and 902 KAR 100. There was one instance of gross beta above detection limits in a sample collected by the National Guard at the Estill County High School. There are no other gross beta detections, and there is no indication that this measurement above the gross beta detection limit relates to disposal of the TENORM waste in any way.

Table 5. Summary of Measured Concentrations in Air Samples

Parameter	Symbol[a]	Avg	Min	Max	Standard[b]	Units	Number of results
Gross alpha	<	0.336	0.0785	0.574		pCi/m^3	25
Gross beta	<	3.34	0.316	6.05		pCi/m^3	24
Gross beta	=	2.42	2.42	2.42		pCi/m^3	1
Ra-226	<	0.0291	0.0241	0.0375	0.9	pCi/m^3	5
Ra-228	<	0.0882	0.0717	0.116	2	pCi/m^3	5

[a] A symbol of "<" indicates a non-detect and "=" indicates a detection.
[b] Airborne effluent criteria specified in 10 CFR 20, Appendix B, Table 2 column 1.

Soil and Sediment Measurements

The State of Kentucky and Chase collected soil and sediment samples at the locations shown in Figure 7. Table 6 provides basic statistics related to the soil and sediment measurements made for Ra-226 and Ra-228. Several soil samples collected from the elevated area not associated with the 92 loads considered here are not included in this analysis.

Table 6. Summary of Measured Concentrations in Soil and Sediment Samples

Sample	Area[a]	Parameter	Symbol[b]	Avg	Min	Max	Units	# of results
Soil	Grid	Ra-226	=	2.25	0.661	7.27	pCi g^{-1} (dry)	10
Soil	NA	Ra-226	=	5.12	0.889	10.3	pCi g^{-1} (dry)	18
Sediment	NA	Ra-226	<	0	0	0	pCi g^{-1} (dry)	1
Sediment	NA	Ra-226	=	4	0.885	8.67	pCi g^{-1} (dry)	27
Soil	Grid	Ra-228	<	0.943	0.943	0.943	pCi g^{-1} (dry)	1
Soil	NA	Ra-228	<	0.524	0.524	0.524	pCi g^{-1} (dry)	1
Soil	Grid	Ra-228	=	1.51	1.11	2.19	pCi g^{-1} (dry)	9
Soil	NA	Ra-228	=	1.4	0.968	1.93	pCi g^{-1} (dry)	17
Sediment	NA	Ra-228	<	0.716	0.585	0.865	pCi g^{-1} (dry)	3
Sediment	NA	Ra-228	=	1.59	0.936	3.07	pCi g^{-1} (dry)	25

[a] Grid = within the areas where the BES waste was disposed and NA = outside the areas where the BES waste was disposed. The rows for "NA" illustrate the background concentrations occurring in the vicinity of the landfill.
[b] A symbol of "<" indicates a non-detect and "=" indicates a detection.

Soil samples from within the grid cells (Area = Grid) where the waste was disposed (see Figure 7) are evaluated separately from samples outside the grid cells (Area = NA). There is no indication of higher concentrations in soil within the grid cells, and the highest concentrations are from areas outside the grid cells in areas with naturally elevated concentrations (e.g., the area of exposed New Albany shale). The highest concentration of 10.3 pCi g^{-1} Ra-226 was from outside the grid cells in

the area called background area 1 (BRA1) identified by Chase (2016), which is described as an area representative of a fill site from previous operations, and is not related to any TENORM disposals.

Surface Water

The State of Kentucky and Chase collected surface water samples at the locations shown in Figure 8. Several of the samples were split and analyzed by three different laboratories: TBE, TestAmerica, and the State of Kentucky laboratory. Ameriphysics also collected 3 surface water samples in February 2016, which were analyzed by Eberline Analytical.

Samples were collected from Dry Branch Creek at both up-gradient (north of landfill) and downgradient (south of landfill) locations. Based on the results from all three laboratories, there is no apparent difference between the concentrations measured up-gradient (background) and downgradient and, likewise, no evidence of any impact of the landfill on the downgradient location.

The highest gross alpha and gross beta concentrations are for Judge Sample B (unknown location); samples from the WWTF and Sewer Plant influent locations; and influent, overflow, and effluent locations at Pond 3, which collects runoff from the area of exposed New Albany shale. There is no apparent association of the elevated gross alpha and gross beta concentrations within the area where the TENORM waste was disposed.

There are a number of significantly elevated (i.e., greater than 50 pCi L^{-1}) Ra-226 concentrations reported by TBE and one by the State of Kentucky laboratory. As Ra-226 is an alpha emitting radionuclide, if the concentration of Ra-226 is elevated in a sample, the corresponding gross alpha measurement should also be elevated. The State of Kentucky laboratory reports a Ra-226 concentration of 142 pCi L^{-1} for the sample from the up-gradient (background) stream locations, which appears to be a false positive since the corresponding gross alpha measurement is a non-detect at less than 1 pCi L^{-1}. TestAmerica and TBE both report non-detect values (<0.0618 and <10.54, respectively) for the same sample. The elevated Ra-226 concentrations reported by TBE all appear to be false positives since they are not supported by the corresponding gross alpha measurements by TBE in the same samples or the corresponding Ra-226 concentrations reported by TestAmerica and the State of Kentucky laboratory.

There are also several samples where TBE reports significantly elevated (i.e., greater than 50 pCi L^{-1}) concentrations of isotopes in the uranium decay series in addition to Ra-226, namely Bi-214, Pb-214, and Th-230. For all of these samples, the high concentrations for these isotopes are not supported by the gross alpha or gross beta measurements in the same sample.

Although there are questions about the validity of some of the reported results for surface water samples, there is no evidence to suggest that any of the samples contained quantities of radioactive material above background or were otherwise impacted by the waste in question.

Groundwater

The State of Kentucky collected groundwater samples at the locations shown in Figure 7. Table 7 provides basic statistics related to the groundwater measurements. There is a significant amount of variability in the detected gross alpha and beta and Ra-226 concentrations, which is consistent with the variability seen in the soil samples.

Table 7. Summary of Measured Concentrations in Groundwater Samples

Parameter	Symbol[a]	Avg	Min	Max	Units	Number of Results
Gross alpha	<	-0.569[b]	-74.1	29.6	pCi/L	10
Gross alpha	=	26.1	6.67	88.6	pCi/L	5
Gross beta	<	39.7	8.48	70.9	pCi/L	2
Gross beta	=	17.6	5.97	59.8	pCi/L	13
Ra-226	<	41	-1.44	161	pCi/L	10
Ra-226	=	2.65	0.562	5.37	pCi/L	10
Ra-228	<	44.2	0.114	415	pCi/L	13
Ra-228	=	0.48	0.446	0.513	pCi/L	2

[a] A symbol of "<" indicates a non-detect (below MDA) and "=" indicates a detection.
[b] Negative values can occur for radiological analyses when the sample concentration is low and/or near the counter background level.

Leachate

The leachate samples consistently have significantly elevated (i.e., greater than 100 pCi L^{-1}) gross beta concentrations as measured by all three laboratories. One sample collected from the "Leachate Tank" and analyzed by the State of Kentucky laboratory also has significantly elevated concentrations of gross alpha, Ra-226, and Ra-228. The high gross beta concentrations are not supported by any of the isotopic analyses available. The Sr-90 concentrations reported for the "Leachate Tank" sample and a few other samples are false positive results caused by interference in the sample matrix (KY CHFS 2016b).

Split Samples

As discussed above, several samples were collected and split for analysis by the State of Kentucky laboratory, TestAmerica, and TBE. The availability of results by different analytical laboratories has enabled a more complete analysis of the data. Basic statistics for the ratio of the concentrations measured by different laboratories for samples with positive detections by both laboratories are reported in Table 8.

Because of the different techniques used for analysis of liquid and solid samples, the statistics are calculated separately for each sample type. In general, the analyses by the different laboratories are in good agreement, but there are some exceptions as noted in the preceding sections. For both solid and liquid samples, there is an overall bias of the State of Kentucky results being higher than both TestAmerica and TBE, and TBE is somewhat higher on average than TestAmerica.

Table 8. Statistics Related to the Ratio of Concentrations Reported by Different Laboratories for the Same Sample[a]

Sample type	Statistic	Ratio of State to TestAmerica	Ratio of State to TBE	Ratio of Test America to TBE
Solid	Average	1.23	2.14	0.93
	SD	0.47	3.48	0.23
	Count	26	26	24
	Std error	0.092	0.682	0.0472
	CV	0.075	0.32	0.051
Liquid	Average	1.78	1.46	0.91
	SD	1.73	0.87	1.00
	Count	40	26	23
	Std error	0.27	0.17	0.21
	CV	0.15	0.12	0.23

[a] Excludes TBE results considered to be false positives (see discussion in Surface Water section above).

Exposure Scenarios and Parameters

This section presents the exposure scenarios and parameters for persons who may have been exposed to TENORM waste during disposal operations at Blue Ridge, and for persons who may be exposed to potential future TENORM waste remaining in the landfill. Exposure scenarios were constructed for landfill workers who were involved in the waste disposal operations and to other persons who were not directly involved in the disposal operations, but who were present in office buildings and schools near the landfill. Landfill workers are not considered radiation workers, and thus, public dose limits would apply to these persons.

Exposure Scenarios for Landfill Workers

Landfill workers include landfill laborers and heavy machinery operators. The landfill laborer is a person who directly assists in disposal operations in tasks such as directing a truck to the disposal cell, assuring the truck has completely emptied its load, and any other activity that may have brought them in close proximity to the TENORM waste. Landfill workers were potentially exposed to radioactive materials via ingestion or inhalation of suspended particles and external exposure. A second landfill worker was identified as a heavy-equipment operator who is responsible for mixing and compacting the TENORM waste with other municipal garbage. This individual sits in an enclosed air-conditioned cab, and is not exposed to un-filtered outside air. Therefore, inhalation doses would be minimal and bounded by the laborer standing near the truck during disposal. The heavy-equipment operator may spend more time near the TENORM disposal during mixing, compaction, and covering operations. Thus, external exposure to this person was considered separately.

Exposure Scenarios for Nearby Members of the Public

Exposure and resultant doses from the TENORM disposals to persons not directly involved in the disposal operations were calculated for office personnel who work at the landfill administrative buildings, students and teachers who attend/work at the nearby middle school and high school, and a hypothetical future resident who lives near the entrance to the disposal facility (see Figure 10). Exposure pathways for office workers, students, and teachers are limited to inhalation of particulates suspended during disposal and radon inhalation after disposal and compaction. The hypothetical future resident living off-site is assumed to be exposed to radon and contaminated groundwater. The future resident is not assumed to live on the landfill but adjacent to it. For radon exposure, the hypothetical resident is assumed to live at the present location of the middle school and high school. For groundwater ingestion, the hypothetical resident is assumed to be located on the downgradient edge of the modeled source. Note that for radon exposure, the hypothetical future resident is assumed to be present in the 100- to 200-year time frame, whereas the simulation for groundwater ingestion for a future resident is assumed to take place over 1,000 years in the future when radionuclides leaching from the TENORM waste arrive in the aquifer.

Figure 10. Locations where office worker, student, and teacher exposures were assumed to have occurred.

Exposure Parameters for Landfill Workers

Landfill laborers are assumed to be similar to construction workers in that their daily activities are similar to construction activities related to excavation and earth moving. For purposes of determining inhalation and soil ingestion rates for a laborer at the landfill, information related to construction and outdoor workers was reviewed.

Soil and Dust Ingestion

The U.S. EPA in its 1991 Risk Assessment Guidance for Superfund (RAGS) Supplemental Guidance recommends using soil ingestion rates of 50 mg day^{-1} for commercial/industrial workers and 100 mg day^{-1} for agricultural workers (EPA 1991). The U.S. EPA in its Regional Screening Level (RSL) User Guide recommends a soil ingestion rate for a construction worker of 330 mg day^{-1} (EPA 2016a). This value was adjusted from an earlier soil ingestion rate of 480 mg kg^{-1} used by

the Superfund program (EPA 1991)[4] and is presented in EPA's 2002 Supplemental Soil Screening Guidance (Exhibit 5-1 and Section 5.3.2, EPA 2002). This same value is the recommended default construction worker soil ingestion rate used by the EPA in the calculation of the construction worker radionuclide preliminary remediation goals (PRGs) (EPA 2016b).

States have adopted soil ingestion rates for the calculation of risk-based screening values ranging from 100 mg day^{-1} to 480 mg day^{-1}. The Kentucky Risk Assessment Guidance (KEEC 2002) provides a soil ingestion rate for baseline risk assessments for an outdoor worker of 480 mg day^{-1} based on USEPA 1991. Ohio EPA (OEPA 2016) recommends a soil ingestion rate of 200 mg day^{-1}, which appears to be based on the child ingestion rate from the U.S. EPA's 1991 RAGS Supplemental Guidance (EPA 1991).

The 2011 U.S. EPA Exposure Factors Handbook (EPA 2011) recommends a central tendency soil ingestion for the adult general population of 50 mg day^{-1} (Table 5-1). This document notes that studies estimating adult soil ingestion are extremely limited. One study cited estimated soil ingestion rates ranging from 23 to 92 mg day^{-1} (mean), 0 to 23 mg day^{-1} (median), and 138 to 814 mg day^{-1} (maximum), with an overall mean value of 52 mg day^{-1}. It also notes that occupational contribution to soil ingestion in some adults can be important.

This assessment uses a soil ingestion rate of 330 mg day^{-1}. This value is used in both the EPA radionuclide PRG and the EPA RSL.

A landfill laborer will only have contact with the TENORM waste for a fraction of the workday. For soil ingestion calculations, it was assumed that contact, either directly or with material suspended during disposal, was 15 minutes or 0.25 hours per disposal.

Inhalation Rate

EPA radionuclide preliminary remediation goals use a value of 60 m^3 day^{-1} for inhalation rate based on heavy activities for an outdoor worker at 2.5 m^3 $hour^{-1}$ over 24 hours. This value was based on data in Exhibit 5-23 of the 1997 Exposure Factors Handbook (EPA 1997).

The Kentucky Risk Assessment Guidance (KEEC 2002) recommends an inhalation rate for an outdoor worker of 12.5 m^3 day^{-1}. This value is based on 2.5 m^3 $hour^{-1}$ for 5 hours.

The 2011 U.S. EPA Exposure Factors Handbook (EPA 2011) provides some data on construction worker inhalation rates. Mean inhalation rates range from 1.20 m^{-3} $hour^{-1}$ to 1.50 m^{-3} $hour^{-1}$, and upper percentile (99%) inhalation rates range from 4.14 m^3 $hour^{-1}$ to 4.26 m^3 $hour^{-1}$. Recommended long-term and short-term inhalation rates are provided by age group (Table ES-1 Chapter 6). Using the short-term inhalation rates and calculating a weighted average for an adult age 21 to 61 assuming two hours light intensity, four hours moderate intensity, and two hours heavy intensity, results in a weighted average mean of 1.8 m^3 $hour^{-1}$ and 95% of 2.5 m^3 $hour^{-1}$. Using the

[4] USEPA 1991 notes that "a soil ingestion rate of 480 mg/day may be used; however, this type of work is usually short-term and is often dictated by the weather. Thus, exposure frequency would generally be less than one year and exposure duration would vary according to site-specific construction/maintenance plans." This ingestion rate is adjusted in USEPA 2002 where it is noted that the "default value of 330 mg/day (Stanek et al., 1997) listed in Equations 5-1 and 5-2 replaces the previous default ingestion rate of 480 mg/day (Hawley, 1985). While the Hawley value was based on a theoretical calculation for adults engaged in outdoor physical activity, the revised default ingestion rate is based on the 95th percentile value for adult soil intake rates reported in a soil ingestion mass-balance study."

long-term inhalation rates and calculating a weighted average for an adult age 21 to 61 results in a weighted average mean of 15.85 m^3 day^{-1} and 95% of 21.3 m^3 day^{-1}.

Based on the data above, an inhalation rate of 1.8 m^3 $hour^{-1}$, or 14.4 m^3 day^{-1}, for the worker was assumed. This value assumes various levels of activities during the day. Exposure frequency (i.e., hours per day) is irrelevant as workers are assumed exposed to the entire suspended particulate plume until it dissipates in the air.

A heavy-equipment (e.g. bulldozer) operator would have a substantially lower inhalation rate as they are sedentary. Additionally, as the worker sits in an enclosed cab where material suspended during operations will be filtered, they are less likely to be exposed via inhalation. Thus, the laborer inhalation exposure represents a worst-case estimate of possible inhalation dose

Exposure Time for External Exposure

External exposure is an important pathway for those workers in close proximity to the waste. This might include a laborer who spends time next to a loaded truck before and after dumping, and the heavy-equipment operator during compaction and burial operations. For external exposure calculations, the following exposure times for laborers and heavy-equipment operators were assumed:

- Landfill worker is assumed to spend 0.25 hours per disposal 1 meter from a truck containing TENORM waste.
- Landfill worker is assumed to spend an additional 0.083 hours per disposal (5 minutes) 1 meter from a truckload of unshielded TENORM waste before being moved by the heavy equipment.
- Heavy-equipment operator is assumed to spend 0.5 hours per disposal in the cab 3 meters from unshielded TENORM disposal.

These exposure times were assumed for each of the 92 TENORM disposals.

Exposure Parameters for Nearby Members of the Public

An adult inhalation rate of 20 m^3 day^{-1} was assumed for particulates suspended during disposal for office workers, teachers, and hypothetical future residents. This value is the default exposure factor provided in U.S. EPA's 1991 RAGS Supplemental Guidance for estimating the reasonable maximum exposure for a resident (USEPA 1991). Exposure frequency (i.e., hours per day) is irrelevant as the office workers, teachers, and future residents are assumed exposed to the entire suspended particulate plume until it dissipates in the air. For students, the 2011 U.S. EPA Exposure Factor Handbook (EPA 2011) provides a recommended long-range mean inhalation factor for various age groups. A student's age in Estill County Middle School (grades 6^{th} through 8^{th}) and Estill County High School (grades 9^{th} through 12^{th}) would typically range from age 11 through 17 years. U.S. EPA 2011 Exposure Factor Handbook (EPA 2011), Table 6-1 provides a mean inhalation rate for a child ages 11 to <16 years of 15.2 m^3 day^{-1} and a rate of 16.3 m^3 day^{-1} for a child ages 16 to <21 years. Using these values, an age-weighted inhalation rate of 15.5 m^3 day^{-1} for a student ages 11 through 17 was estimated for a student while attending middle school and high school.

For radon exposure, office workers are assumed exposed for 2,000 hours per year (8 hours per day, 5 days per week for 50 weeks a year). Student and teachers are assumed to spend 8 hours per day for 175 days per year at the school. The hypothetical future resident is assumed present 24 hours per day for 350 days per year (8,400 hours per year).

For ingestion of groundwater, a 2 L per day ingestion rate for 365 days per year was assumed for the hypothetical receptor. These values are consistent with the standard exposure scenario for calculating radionuclide MCLs for mixed beta-gamma emitters.

Methods for Estimating Exposure Concentrations and Dose

This section presents the methods and modeling parameters used to estimate air and groundwater concentrations, along with external dose rates. Environmental concentrations combined with the exposure scenario and dose coefficients are used to estimate annual doses. Appropriate documentation to support this dose assessment is provided as an electronic supplement to this report (see Appendix D – Dose Calculation Documentation for details).

Representative Concentrations in TENORM Waste

As described in the previous section, BRFL received TENORM waste from four different generators. Ninety-two separate shipments (or loads) were delivered. The largest quantity of TENORM was received from Fairmont Brine, which comprised about 75% of the total waste mass. In deriving the representative concentration, the following principles and assumptions were applied.

- For generators that only measured Ra-226 or Ra-228 concentrations, the remaining radionuclides were calculated based on activity ratios derived from the filter sock found at the landfill, as this was the only sample that was analyzed for all relevant radionuclides. The derived activity ratio for Th-230/Ra-226 was 1.0370; for Th-232/Ra-228, 0.9539; and for U-238/Ra-226, 0.0818.
- When available, container dose rate measurements combined with the PADEP conversion factor of 2.02 μrem-g $(pCi\text{-}hr)^{-1}$ were used to estimate total radium concentrations in the shipment (2015). This calculation method was used for Fairmont Brine loads 5–40. The remaining radionuclides were calculated with the ratios listed above.
- Measured Pb-210 and Th-228 concentrations were not available for all generators. Pb-210 and Th-228 concentrations were estimated by calculating the activity based on their controlling parent nuclide (i.e., Ra-226 and Ra-228, respectively) assuming a three-year ingrowth period. The ratio of Pb-210/Ra-226 after three years was 0.0891, and the ratio of Th-228/Ra-228 after three years was 0.774. Three years represented the assumed time the TENORM remained at the treatment facility before shipment to Blue Ridge Landfill. This length of time is considered worst-case because the treatment facility would likely ship TENORM waste off-site immediately after treatment.

For Fairmont Brine shipments with external dose rate measurements, Ra-226 and Ra-228 concentrations were estimated from the total radium concentration by multiplying the total radium concentration by the Ra-226/Ra-total ratio for Ra-226 and the Ra-228/Ra-total ratio for Ra-228. These ratios were derived from PADEP data for solidified brine concentrations of 480 pCi g^{-1} for Ra-226 and 183 pCi g^{-1} for Ra-228. Thus, the Ra-226/Ra-total ratio is (480 pCi g^{-1})/(480 pCi g^{-1} + 183 pCi g^{-1}) = 0.724, and the Ra-228/Ra-total is (183 pCi g^{-1})/(480 pCi g^{-1} + 183 pCi g^{-1}) = 0.276.

Radionuclide concentrations and disposal mass for each TENORM generator are presented in Table 9.

Table 9. TENORM Disposal Mass and Representative Radionuclide Concentrations (pCi g^{-1}) by Waste Generator

Generator	Mass (kg)	Loads	U-238	U-234	Th-230	Ra-226	Pb-210	Th-232	Ra-228	Th-228
Cambrian[a]	9.045E+03	1-4	8.78E+00	8.78E+00	1.11E+02	1.07E+02	9.56E+00	9.36E+01	9.81E+01	7.59E+01
GreenHunter[b]	1.353E+05	52-79	1.87E+01	1.87E+01	2.37E+02	2.28E+02	2.03E+01	3.03E+02	6.49E+01	5.02E+01
Nuverra[c]	7.566E+03	80	6.34E-01	6.34E-01	8.04E+00	7.75E+00	6.91E-01	2.08E+00	2.18E+00	1.68E+00
Nuverra[c]	1.104E+04	81	1.45E+00	1.45E+00	1.84E+01	1.78E+01	1.58E+00	4.95E+00	5.19E+00	4.02E+00
Nuverra[c]	1.137E+04	82	2.38E+00	2.38E+00	3.02E+01	2.91E+01	2.60E+00	6.39E+00	6.70E+00	5.18E+00
Nuverra[c]	1.382E+04	83	6.90E-01	6.90E-01	8.75E+00	8.43E+00	7.51E-01	1.73E+00	1.82E+00	1.41E+00
Nuverra[c]	1.498E+04	84	8.49E-01	8.49E-01	1.08E+01	1.04E+01	9.25E-01	2.92E+00	3.06E+00	2.37E+00
Nuverra[c]	6.006E+03	85	9.84E-01	9.84E-01	1.25E+01	1.20E+01	1.07E+00	3.33E+00	3.49E+00	2.70E+00
Nuverra[c]	1.403E+04	86	2.70E-01	2.70E-01	3.43E+00	3.30E+00	2.94E-01	1.76E+00	1.85E+00	1.43E+00
Nuverra[d]	8.936E+03	87	8.73E+00	8.73E+00	1.11E+02	1.07E+02	9.50E+00	3.26E+01	3.41E+01	2.64E+01
Nuverra[e]	2.132E+04	88-91	4.33E+01	4.33E+01	5.49E+02	5.29E+02	4.72E+01	2.56E+02	2.68E+02	2.07E+02
Nuverra[f]	1.146E+04	92	4.58E-01	4.58E-01	5.80E+00	5.60E+00	4.98E-01	1.51E+00	1.58E+00	1.22E+00
Fairmont[g]	6.950E+05	5-40	1.47E+01	1.47E+01	1.86E+02	1.80E+02	1.60E+01	6.53E+01	6.85E+01	5.30E+01
Fairmont[h]	9.006E+04	41-51	1.12E+00	1.12E+00	1.41E+01	1.36E+01	1.21E+00	3.40E+00	3.56E+00	2.75E+00

[a.] Ra-226 and Ra-228 concentrations based on information in "Pace Analytical Report for Cambrian Well Services, LLC: Project Kemble 1-D" (Pace Analytical Services Inc. 2016). Remaining radionuclides based on ratios.

[b.] Ra-226 and Ra-228 concentrations based on file "GreenHunter Filter Report of Analysis" (Environmental Service Laboratories Inc. 2015). Remaining radionuclides based on ratios.

[c.] Ra-226 and Ra-228 concentrations based on "Pace Analytical Report for Hull & Associates, Inc.: Project HWR001 Nuverra Injection Well" (Pace Analytical Services Inc. 2015b). Remaining radionuclides based on ratios.

[d.] Ra-226 and Ra-228 concentrations based on "Nuverra Environmental Resources Production Documents NV0000043-55" (Nuverra Environmental Resources 2015). Remaining radionuclides based on ratios.

[e.] Ra-226 and Ra-228 concentrations based on "Pace Analytical Report for Appalachian Water Services: Project Goff Bag Filters 11-30-15" (Pace Analytical Services Inc. 2015a). Remaining radionuclides based on ratios.

[f.] Ra-226 and Ra-228 concentrations based on "Nuverra Environmental Solutions Waste Manifests" (Nuverra Environmental Solutions 2015). Remaining radionuclides based on ratios.

[g.] Ra-226 and Ra-228 concentrations based on average exposure readings of each surveyed container and a conversion factor of 2.02 μrem-g (pCi-hr)$^{-1}$. Ra-228 to Ra-226 ratio based on PADEP values (Table 4.3 in PADEP 2015) of typical brine material of 480 pCi g^{-1} for Ra-226 and 183 pCi g^{-1} for Ra-228. Ra-226/Ra total = 0.724, Ra-228/Ra total =0.276. Remaining radionuclides based on ratios.

[h.] Ra-226 and Ra-228 concentrations based on a single sample reported in "Fairmont Brine Data" (Hoskins 2015). Remaining radionuclides based on ratios.

The representative concentration of each TENORM radionuclide is characterized by the weighted average concentration of all the generators. The weighted average concentration is given by

$$CA_j = \sum_{i=1}^{n} \frac{C_{i,j} \cdot M_i}{M_T} \quad (1)$$

where

CA_j = weighted average concentration for radionuclide j (pCi g^{-1})
$C_{i,j}$ = concentration of radionuclide j for waste generator i (pCi g^{-1})
M_i = mass of TENORM from waste generator i (g)
M_T = total mass of TENORM from all generators (g).

Representative radionuclide inventories were calculated by multiplying the weighted-average concentration by the total TENORM mass. The weighted-average concentration (see Table 10) was used to estimate doses during TENORM disposals. The inventory was used in the groundwater and radon evaluation.

Table 10. Representative Weighted-Average Radionuclide Concentrations and Estimated Total Inventories from all TENORM Generators

Radionuclide	Weighted average concentration (pCi g^{-1})	Inventory (Ci)
U-238	13.3	0.0140
U-234	13.3	0.0140
Th-230	169	0.1775
Ra-226	163	0.1712
Pb-210	14.5	0.0152
Th-232	89.1	0.0935
Ra-228	60.8	0.0639
Th-228	47.1	0.0494

Particulate Emissions and Inhalation and Ingestion Doses during Disposal

Radionuclide emissions during disposal 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 TENORM material disposed in the Blue Ridge facility. Modeling using aggregate material results in the worst-case inhalation scenario. The exposure scenario is illustrated in Figure 11.

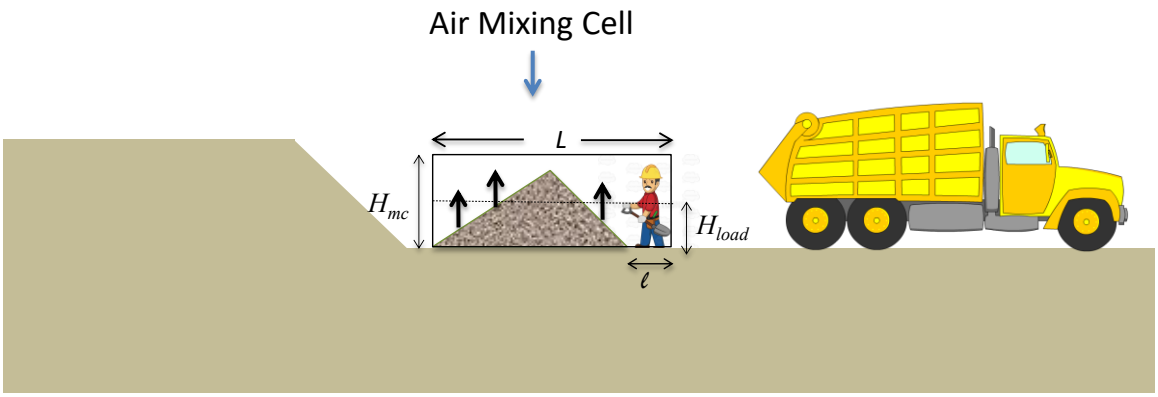

Figure 11. Conceptual model of exposure for a worker during disposal of TENORM.

The emission factor is given by

$$E = k(0.0016)\frac{\left(\frac{U}{2.2}\right)^{1.3}}{\left(\frac{MC}{2}\right)^{1.4}} \quad (2)$$

where

E = emission factor (kg released to air per Mg of material handled)
U = wind speed (m s^{-1})
MC = % moisture content
k = particle size multiplier.

Thus the product of the mass of TENORM material in a load × the emission factor provides the mass of TENORM material available for suspension in air. The amount of radionuclide release to the air is the product of the mass released to air and the representative radionuclide concentration. Thus,

$$Q = E \times M \times C \times \frac{1000\ \text{g}}{\text{kg}} \quad (3)$$

where

Q = activity released to air (pCi)
M = mass of one TENORM disposal (Mg)
C = representative radionuclide concentration in TENORM waste (pCi g^{-1}).

The total mass of TENORM waste disposed was estimated to be 1.05×10^6 kg (1.05×10^3 Mg), and the estimated bulk density of TENORM waste was 890 kg m^{-3}, yielding an estimated volume of 1,180 m^3. Thus, the volume and mass of TENORM waste per load (92 loads) was 11,413 kg and 12.83 m^3, respectively.

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

$$K = \frac{U}{L} \tag{4}$$

where

K = the removal rate constant (s^{-1})
U = wind speed ($m\ s^{-1}$)
L = the length of the mixing cell that lies parallel to the direction of wind (m).

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

$$\frac{dQ}{dt} = -KQ$$
$$Q(t) = Q_o e^{-Kt} \tag{5}$$

where Q_o is the initial activity in the mixing cell defined by Equation (2). The time-integrated air concentration that the worker is exposed to is calculated by

$$TIC = \frac{Q_o}{V}\int_0^{\infty} e^{-kt}\,dt = \left(\frac{Q_o}{V}\right)\left(\frac{1}{K}\right)e^{-kt}\Big|_0^{\infty} = -\frac{Q_o}{VK}(0-1) = \frac{Q_o}{VK} \tag{6}$$

where

TIC = the time-integrated concentration (pCi-s m^{-3})
V = volume of the mixing cell (m^3).

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

$$L = \sqrt{\frac{V_{load}}{H_{load}}} + l$$
$$V = L^2\left(H_{mc} - H_{load}\right) \tag{7}$$

where

V_{load} = the volume of the load (12.83 m^3)
H_{load} = height of the load after disposal (m)
l = buffer distance (m)
H_{mc} = height of mixing cell (m).

The assumed average pile height after dumping was 1.5 m (5.5 ft). The assumed height of the mixing cell was 2 m (6.56 ft), which allows suspended particles to be mixed with air on the side and on top of the pile. The buffer distance was assumed to be 0.5 m. We note that for external dose calculations, the person is assumed on average to be 1 m from the waste pile. Thus, the person can be closer or farther away during the exposure time, but on average is 1 m away. For the inhalation calculations, the 0.5 m buffer distance assumes that while dumping and suspending TENORM material into the air, the person is 0.5 m from the edge of the pile. This assumption results in a worst-case estimate of the mixing volume.

The inhalation dose from this exposure is given by

$$DINH = IR \times \sum_{j=1}^{n} TIC_j \times DCINH_j \quad (8)$$

where

$DINH$	=	the inhalation effective dose for a TENORM disposal (mrem)
IR	=	inhalation rate ($m^3\ s^{-1}$)
TIC_j	=	time-integrated concentration for radionuclide j (pCi-s m^{-3})
$DCINH_j$	=	inhalation effective dose coefficient for radionuclide j (mrem pCi^{-1})
n	=	number of radionuclides.

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 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 µm 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.

Ingestion effective doses during the disposal operation assume a given amount of the TENORM material is ingested via adherence to skin and hand during a disposal, and later transferred to mouth. The nominal value for soil ingestion per day for a worker is adjusted for the worker's exposure time during disposal of the TENORM waste, which was assumed to be 15 minutes. The ingestion effective dose is simply the product of the effective dose coefficient (in mrem pCi^{-1}) and the amount of activity ingested. The amount of activity ingested is the soil ingestion rate adjusted for exposure time (0.25 hours) multiplied by the activity concentration of the TENORM waste. When the heavy equipment operator begins compacting and covering waste, the laborer is assumed to vacate the area. The amount of TENORM material ingested is calculated by

$$D_{ing} = \frac{330\ \text{mg}}{\text{day}} \times \frac{1\,\text{g}}{1000\ \text{mg}} \times \frac{1\,\text{day}}{8\,\text{hours}} \times 0.25\ \text{hours} \times \sum_{j=1}^{n} \text{CA}_j DCING_j \quad (9)$$

where

D_{ing} = effective dose from ingestion (mrem)
CA_j = weighted average concentration in TENORM for radionuclide j (pCi g^{-1})
$DCING_j$ = ingestion effective dose coefficient (mrem pCi^{-1}).

Inhalation doses to off-site individuals are calculated using the amount of activity suspended into the air and a dispersion factor determined from the Gaussian plume air dispersion model. The classic Gaussian plume model as described in the second edition of *Workbook of Atmospheric Diffusion Estimates* (Turner 1994, Equation [2.1]) is given by

$$\chi(x,y,z,u,z_h,Q) = \frac{Q}{2\pi U \sigma_y \sigma_z} \exp\left[-\frac{y^2}{2\sigma_y^2}\right] \left\{ \exp\left[-\frac{1}{2}\left(\frac{z_h - z}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z_h + z}{\sigma_z}\right)^2\right] \right\} \quad (10)$$

where

x = downwind distance (m)
y = crosswind distance (m, assumed to be zero for worst-case condition)
z = height above ground (m)
U = wind speed (m s^{-1})
z_h = release height (m, assumed to be zero for worst-case condition)
σ_y, σ_z = diffusion coefficients in the y and z direction, respectively
Q = release rate (Ci s^{-1})
χ = concentration (Ci m^{-3}).

Equation (10) is the equation for a puff release that is integrated with respect to time from zero to infinity yielding a time-integrated concentration (*TIC*, pCi-s m^{-3}). The integrated puff equation is identical to the Gaussian plume equation for a constant release. When Equation (10) is used to calculate a *TIC* from a puff of material released to the air, the total mass released in the puff is substituted for Q. For this exercise, diffusion coefficients were calculated from the Pasquill-Gifford formulations as given in Table 2.4 of Turner (1994). Dispersion factors were calculated for a typical meteorology that would be present during daylight hours (stability class D and 4 m s^{-1}). The wind speed for typical meteorological conditions is the annual average wind speed for the nearest city with annual wind speed data, which was Lexington, KY. For a worst-case assessment, the wind is always assumed to blow in the direction of the receptor.

Model parameters and calculated values are presented in Table 11. Inhalation and ingestion dose coefficients are presented in Table 12.

Table 11. Parameters for Emission Model during Disposal and Transport in Air

Parameter	Symbol	Value	Notes
Average wind speed (m s^{-1})	U	4.07	LexingtonKYClimateData.xlsx (http://www.climate-zone.com/climate/united-states/kentucky/lexington/)
Moisture %	MC	10	AP 42 (EPA 1995) Table 13.2.4-1 in Section 13.2.4, value for Clay in Municipal Landfills
Wind speed multiplier	K	0.48	AP-42 (EPA 1995) – assumes particles ≤15 µm are respirable
Volume of TENORM waste/disposal (m^3)	V_{load}	12.83	Calculated based on mass of TENORM per shipment and bulk density
Bulk density (kg m^{-3})	ρ_b	890	Calculated from total volume/mass of TENORM shipments
Buffer distance (m)	l	0.5	Assumed distance from edge of disposal pile to a laborer
Disposal pile height	H_{load}	1.5	Assumed average height of disposed load before compaction
Mixing cell height	H_{mc}	2.0	Assumed height of air mixing cell
Length of air mixing cell (m)	L	3.42	Calculated from Equation (7)
Volume of mixing cell (m^3)	V	10.6	Calculated from Equation (7)
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^{-1})	K	1.19	Calculated using Equation (4)
Emission rate (kg release to air per load)	E	2.01×10^{-3}	Calculated using Equation 2 from AP-42 (EPA 1995)

Table 12. Inhalation and Ingestion Effective Dose Coefficients[a]

	Representative person		10-year-old child	
Radionuclide[b]	Inhalation (mrem pCi^{-1})	Ingestion (mrem pCi^{-1})	Inhalation (mrem pCi^{-1})	Ingestion (mrem pCi^{-1})
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

[a] Dose coefficients from DOE-Std 1196 (DOE 2011) as presented in the RESRAD code.
[b] The "+D" designation includes contributions of radioactive progeny that are assumed to be in secular equilibrium with their parent in the environment. These summations are performed within the RESRAD code.

External Dose During Waste Receipt and Disposal

Fairmont Brine reports dose rates for the sludge it shipped that range from 0 to 832 µrem hr^{-1} above background with a mean value of 480 µrem hr^{-1} (Hoskins 2015). Using the representative inventory and the MicroShield code (Grove Engineering, Inc. 2013), we calculated a dose rate of 382 µrem hr^{-1} on contact from unshielded waste. These values can be used to estimate dose to laborers and heavy-equipment operators near the waste during disposal. The general equation for estimating dose from external exposure is

$$D = DR \times ET \times DF \quad (11)$$

where

DR = the dose rate on contact with the material (382 µrem hr^{-1})
ET = the exposure time (hours)
DF = distance factor (unitless).

The Fairmont Brine data sheet calculates the distance attenuation factor as the ratio of the contact distance squared to the actual distance squared. This correction is applicable for a point source, but not for the volume source that is addressed in this assessment. A distance attenuation factor for a volume source was calculated using MicroShield, the representative concentration, and the source geometry provided in Appendix J in the Pennsylvanian Department of Environmental Protection TENORM Study (PADEP 2015). The source geometry was a rectangular block measuring 2.44 m × 4.88 m × 1.22 m. Attenuation factors were calculated at the center point of the long side of the block for the following scenarios:

- Laborer stands 1 meter from containerized truck containing TENORM waste; Attenuation factor = 0.32.

- Laborer stands 1 meter from TENORM waste after disposal (i.e., no shielding); Attenuation factor = 0.29.
- Heavy-equipment operator sits 3 meters from unshielded waste in the heavy-equipment cab. Attenuation factor = 0.056.

The thickness of the TENORM shipment container of 0.274 cm was taken from the PADEP study. The heavy-equipment cab was assumed to be 20-gauge steel (0.095 cm), and the driver was assumed to be 13 cm (5 inches) from the side of the cab.

Radon Exposure and Dose

Emission of radon from the disposal facility presents a continuous exposure situation, and therefore, the assessment focuses on emissions after waste compaction and covering. Radon-222 emissions from the landfill resulting from TENORM disposals were calculated using Nuclear Regulatory Commission models and methods for assessment of uranium mill tailings (Rogers et al. 1984). A diffusion model is used to first calculate radon flux from the surface of uncovered compacted waste containing TENORM and municipal waste. The flux from the bare surface is given by

$$J_t = 10^4 C \rho_b E \sqrt{\lambda D_t}\, \tanh\left(\sqrt{\frac{\lambda}{D_t}} x_t\right) \tag{12}$$

where

J_t = flux from the surface of TENORM layer in the disposal cell (pCi m^{-2} s^{-1})
C = Ra-226 concentration in TENORM and municipal waste (pCi g^{-1})
D_t = radon diffusion coefficient in TENORM and municipal waste (m^2 s^{-1})
λ = radon decay constant (2.1×10^{-6} s^{-1})
ρ_b = bulk density TENORM (g cm^3)
E = Rn-222 emanation coefficient
x_t = thickness of compacted municipal and TENORM waste (cm).

The Ra-226 concentration in this case represents the average concentration in the compacted municipal waste and TENORM waste. This waste is then covered with soil and other municipal waste, and ultimately an infiltration-reducing cover is installed. The radon flux after burying and covering the waste is given by

$$\begin{aligned} J_c &= \frac{2 J_t e^{-b_c x_c}}{\left(1+\sqrt{a_t/a_c}\,\tanh\left(b_t x_t\right)\right)+\left(1-\sqrt{a_t/a_c}\,\tanh\left(b_t x_t\right)\right)e^{-2b_c x_c}} \\ b_i &= \sqrt{\lambda/D_i}\,, i = c \text{ or } t \\ a_i &= \phi D_i \left(1-\left(1-k\right)m_i\right)^2 \\ m_i &= 10^{-2} MP\left(\frac{1}{\rho_b}-\frac{1}{\rho_s}\right) \end{aligned} \tag{13}$$

where

J_c = radon flux from the disposal cell surface (pCi m^{-2} s^{-1})
ρ_s = particle density (g cm^{-3})
ϕ = porosity
MP = dry weight percent moisture (g of water g^{-1} of dry soil × 100)
k = 0.26 pCi cm^{-3} in water per pCi cm^{-3} in air
m_i = moisture saturation fraction for waste (i=t) or cover (i=c).

The radon diffusion coefficient is given by

$$D_i = 0.07 \exp\left[-4\left(m - m\phi^2 - m^5\right)\right] \tag{14}$$

The flux at the surface can be compared to the limit applied to uranium mill tailings disposal cells of 20 pCi m^{-2} s^{-1}.

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 International Commission on Radiation Protections (ICRP Publication No. 126, 2014) derived values for underground mines and indoor residential structures of 1,100 mrem WLM^{-1} and 1,300 mrem WLM^{-1}, respectively. However, these conditions reflect confined conditions where radon is either generated in the walls, ceiling[5], 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 WL is defined as any combination of short-lived radon progeny in one liter of air that will result in the emission of 1.3×10^5 MeV of potential alpha energy. One WL equals 100 pCi L^{-1} of radon in air with all short-lived progeny in equilibrium. The WL is related to the equilibrium equivalent concentration (EEC) and given by NCRP (1988)

$$EEC = 0.105A + 0.516B + 0.379C \tag{15}$$

where A, B, and C are the concentrations of Po-218, Pb-214, and Bi-214, respectively. For these calculations, we assume worst-case conditions where radon progeny are in equilibrium with radon. If A, B, and C are measured in pCi L^{-1}, then 1 WL = EEC/100. Assuming progeny are in equilibrium with radon (a worst-case assumption) and 1 pCi L^{-1} radon concentration, then the EEC is 1 EEC per pCi L^{-1}. The working level month (WLM) and dose from radon is given by

$$\begin{aligned} WLM &= WL\,\frac{\text{hours exposed}}{170\ \text{hours}} \\ D &= 760\,\frac{\text{mrem}}{\text{WLM}} \times WLM \end{aligned} \tag{16}$$

Radon model parameters are presented in Table 13. Discussion of some of the parameters follows.

[5] In mining, the walls and ceiling of a drift are referred to as the ribs and back of the drift, respectively.

Table 13. Radon Model Parameters

Parameter	Symbol	Value	Notes
Waste thickness (m)	*xt*	4.57	Maximum compacted waste thickness (15 ft) as provided in Daily Cell Construction.pdf (see text)
Cover thickness (m)	*xc*	3	Minimum compacted waste thickness above TENORM (10 ft) as provided in Daily Cell Construction.pdf (see text)
Dry weight percent moisture, waste	*MP*	5	Assumed to be minimal for worst-case conditions (see text)
Dry weight percent moisture, cover	*MP*	5	Assumed to be minimal for worst-case conditions (see text)
Bulk density, waste (g cm^{-3})	ρ_b	1.5	Assumed bulk density of compacted waste
Bulk density, cover (g cm^{-3})	ρ_b	1.5	Assumed bulk density of compacted waste
Porosity, waste	ϕ	0.4	Assumed to contain 40% void space for worst-case
Porosity, cover	ϕ	0.4	Assumed to contain 40% void space for worst-case
Particle density, waste	ρ_s	2.57	Calculated using $\rho s = \rho b/(1-\phi)$
Particle density, cover	ρ_s	2.57	Calculated using $\rho s = \rho b/(1-\phi)$
Radon emanation coefficient	*E*	0.2	Typical value for uranium mill tailings (see text)
Ra-226 concentration (pCi g^{-1})	*C*	26	Calculated based on the total Ra-226 inventory placed in one disposal block.
Surface area of TENORM disposals (m^2)	*A*	15,794	The sum of the area of 17, 30.48m × 30.48m disposal blocks (see text)

Waste thickness and cover thickness were based on a schematic provided by BRLF of the daily working area construction (Daily Cell Construction.pdf). Compacted waste was between 10 ft and 15 ft thick. For the waste containing TENORM, 15 ft (4.57 m) was assumed. Radium-226 (the radon source) was assumed to be uniformly distributed within this thickness. The worst-case Ra-226 concentration was estimated by placing the entire Ra-226 inventory (0.166 Ci) in one 30.48 m × 30.48 m (100 ft × 100 ft) × 4.57 m disposal block and applying an assumed bulk density of compacted waste of 1,500 kg m^{-3}.

Radon flux generally increases with waste thickness until the radon diffusion time is sufficient to result in decay of radon generated in the lower levels before exiting the top. For the waste over the TENORM, the minimum thickness (10 ft) was used. Thicker covers will attenuate radon flux allowing for decay of radon within the cover before emission to the surface.

The waste was assumed to be relatively dry with a dry weight percent moisture of 5%. Rogers et al. (1984) showed that radon diffusion coefficients decrease with moisture saturation. A doubling of the moisture saturation results in a decrease in the radon diffusion coefficient by a factor of 2 or more (see Figure 12 in Rogers et al. [1984]). Typical mill tailings covers have moisture contents ranging from 6% to 11%. Thus, a dry weight percent moisture of 5% is considered worst-case because it maximizes fluxes. The TENORM waste in question had a maximum solids content of 20% (e.g. the material was 80% water) by weight, which would inhibit radon emanation and transport (Kalt 2016).

The radon emanation coefficient was assumed similar to uranium mill tailings, and a value of 0.2 was selected based on Figure 15 in Rogers et al. (1984). This value was considered worst-case because Rood et al. (1998) noted that measured radon emanation from barite scale ($BaSO_4$) that accumulates in oil production tubing is substantially lower (0.02–0.06) compared to uranium mill tailings (0.1–0.3). The Fairmont Brine sludge that makes up most of the TENORM waste consists of barium sulfate where, like the barite scale, radium replaces barium in the crystal lattice.

Radon concentrations at office buildings and the school were calculated using the Gaussian plume model described earlier in this report. Because radon flux occurs over a region representing the disposal blocks where the TENORM was disposed, a virtual area source was used instead of the point source as described in Turner (1994). The initial lateral dispersion coefficient (σy_o) is determined first by dividing the length of the area source (assumed a square) by 4.3. The TENORM disposals were reported in seventeen 30.48 m (100 ft) square blocks (929 m^2 per block) for a total area of 15,794 m^2. Assuming a square area source, the length of one side is $(15{,}794\ m^2)^{1/2}$ = 126 m. Thus σy_o = 126/4.3 =29.22 m. A distance Δx is added to the downwind distance to compensate for the initial dispersion from the source. Using the equations for Stability Class D and setting σ_y equal to σy_o, yields a Δx value of 400 m. Thus σ_y values were determined for distance of $x + \Delta x$ for each of the receptors (nearest office of landfill, main office of landfill, and nearby school).

Groundwater Exposure and Dose

The groundwater evaluation begins with evaluating the dose potential of the inventory of TENORM disposed in the landfill. This evaluation is done using the groundwater screening factors provided by the National Council on Radiation Protection (NCRP) report 123 (NCRP 1996) and the representative inventory (see Table 10). The product of the NCRP groundwater screening factor and the radionuclide inventory yields a screening dose that can be evaluated against a dose criterion. U.S. Department of Energy low-level radioactive waste facilities are limited to a dose of 25 mrem yr^{-1} for times up to 1,000 years from the present. Using the 25 mrem yr^{-1} screening criteria, the TENORM inventories disposed in the landfill will require additional assessment based on the NCRP screening assessment (see Table 14).

Table 14. Results of NRCP Groundwater Screening Assessment

Radionuclide	Representative inventory (Ci)	NCRP SF[a] (rem Ci^{-1})	Representative screening effective dose (mrem)
U-238	1.40E-02	5.18E+02	7.25E+03
U-234	1.40E-02	1.55E+01	2.18E+02
Th-230	1.78E-01	1.92E+00	3.42E+02
Ra-226	1.71E-01	1.70E+01	2.91E+03
Pb-210	1.52E-02	2.00E+01	3.05E+02
Th-232	9.35E-02	1.78E+00	1.66E+02
Ra-228	6.39E-02	2.00E+00	1.28E+02
Th-228	4.94E-02	7.77E-03	3.84E-01

[a] The NCRP screening factor (SF) converted from Sv Bq^{-1} to rem Ci^{-1}. The screening factor represents doses from the direct ingestion of groundwater.

A more detailed assessment of the groundwater pathway considers the site-specific features of the disposal facility and the site-specific climate and hydrology of the site. The conceptual model is illustrated in Figure 12. The TENORM waste is represented by a rectangular area source. Infiltration through the 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.

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.

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 hydrologically failed. These assumptions are worst-case because they maximize water fluxes through the disposal facility and minimize radionuclide transit times to the aquifer.

The conceptual model is quantitatively represented by two established models used in low-level radioactive waste performance assessment. The mixing cell model (MCM) (Rood 2004; Rood 2005) was used to compute water fluxes and solute transport in the vadose zone. MCM is a one-dimensional unsaturated flow and transport model. The vadose zone is discretized into a series of mixing cells, and the model then calculates water and solute balance in mixing cells. The model addresses transient water infiltration and is thus well suited for assessments involving landfills with infiltration reducing covers. For the aquifer, the GWSCREEN code was used (Rood 1994; Rood 2002). The GWSCREEN model is an application of the U.S. NRC semi-analytical groundwater

models for time variable solute fluxes (Codell et al. 1981). The semi-analytical model assumes one-dimensional flow and three-dimensional dispersion in an aquifer of infinite lateral extent and finite thickness. Because the well is located on the downgradient edge of the source, the infinite aquifer is an acceptable assumption because edge or boundary effects are minimal or non-existent. 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.

Groundwater model parameters are presented in Table 15. Parameters are discussed in the following subsections.

Infiltration

Natural infiltration was calculated using the annual average precipitation for Irvine, KY, and the equations for calculating net infiltration in the RESRAD code (Yu et al. 2001). Data for the evapotranspiration rate was taken from the RESRAD data collection manual (Yu et al. 1993). Infiltration was assumed at the calculated natural background rate (0.32 m yr^{-1}) for 40 years while the disposal facility remained in operation. The engineered cover was assumed to reduce infiltration to 10 cm yr^{-1} and to remain hydrologically intact for 200 years. Over the next 100 years, infiltration is assumed to increase linearly up to the natural infiltration rate and continue at this rate for all times in the future.

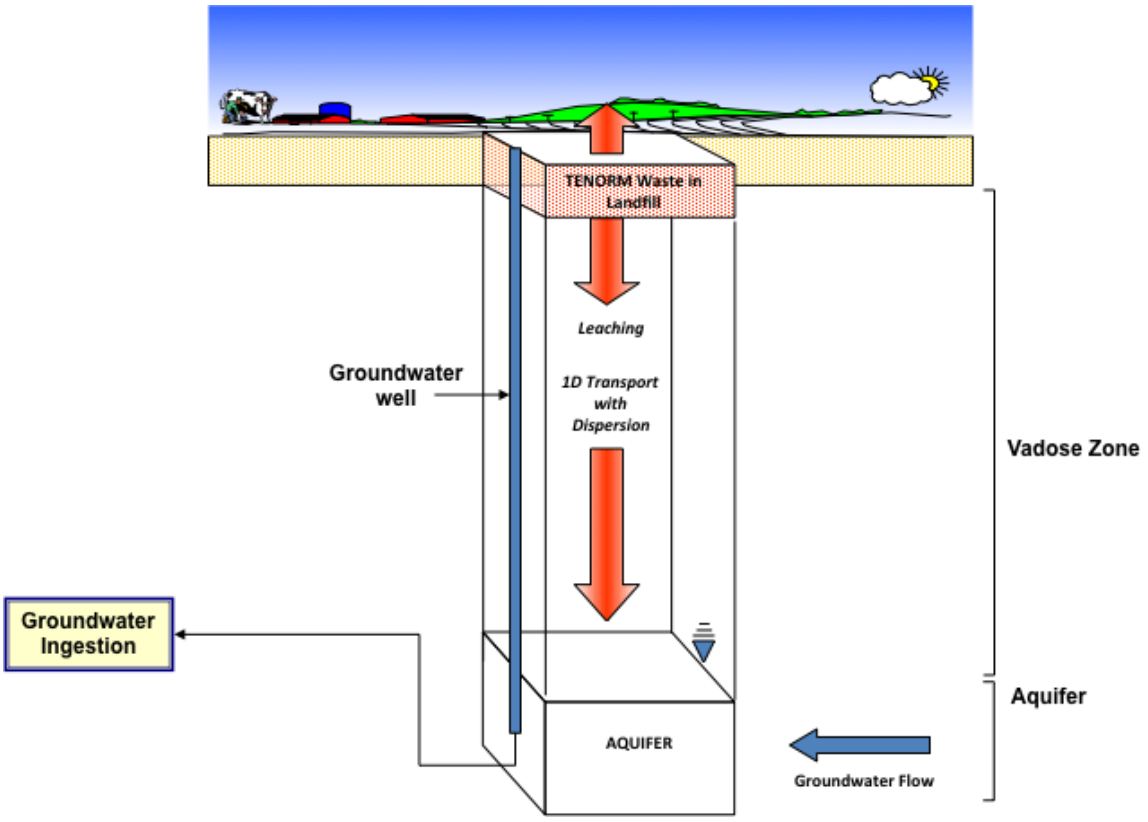

Figure 12. Conceptual model for groundwater transport and dose (Rood 2002).

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 13) and the region over which the TENORM 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 waste containing the TENORM was assumed placed in the first 3 m of the unsaturated zone; thus, the unsaturated transit distance was 9 m.

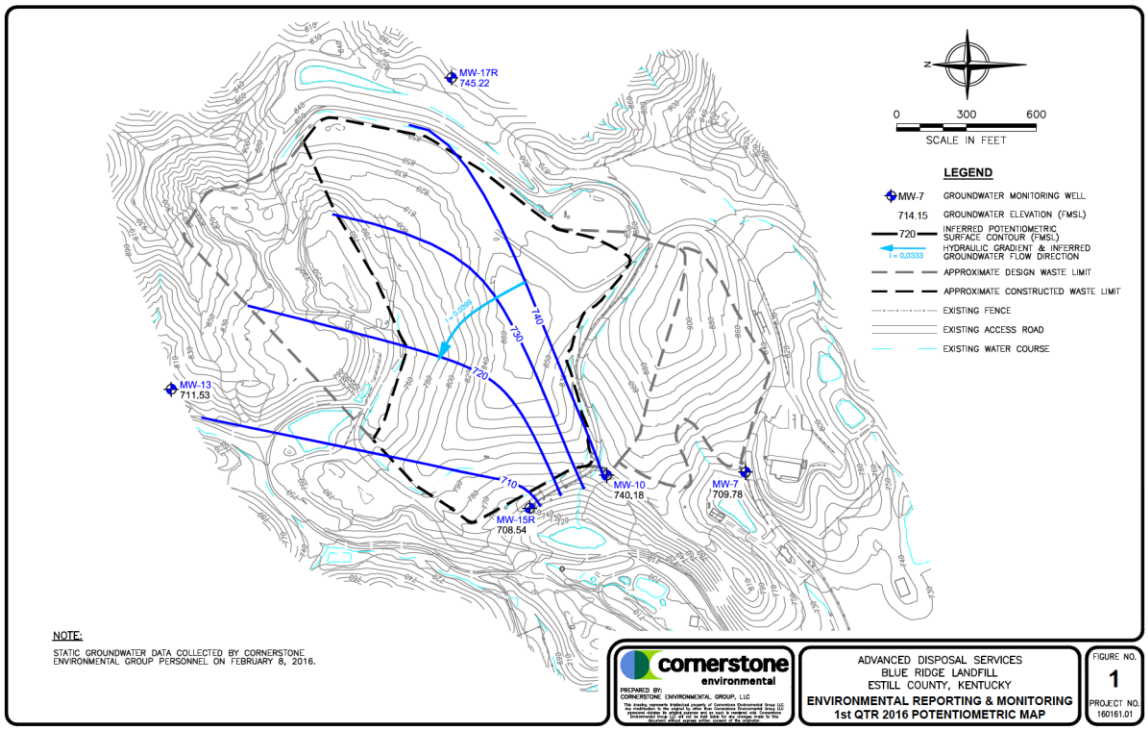

Figure 13. Groundwater potentiometric surface as provided by Cornerstone Environmental Group LLC (2016).

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 m]^2 × 17 = 15,794 m^2) by 152.4 m.

Table 15. Groundwater Model Parameters

Parameter	Value	Notes
Infiltration parameters		
Precipitation (m yr^{-1})	1.24	48.7 inches yr^{-1} for Irvine, KY (where landfill is) from http://www.usclimatedata.com/climate/irvine/kentucky/united-states/usky1783
Evapotranspiration (m yr^{-1})	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^{-1}
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^{-1})	0.32	Calculated using RESRAD methodology
Source parameters		
Area (m^2)	15,793	BES waste placement areas were 17, 100-ft × 100-ft blocks
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^{-2})	1.5	Assumed for compacted waste
Mass of source volume	7.11E+07	Calculated
Saturated hydraulic conductivity (m yr^{-1})	387	Assumed to be similar to sandy loam in Carsel and Parrish (1988)
Total porosity	0.41	Sandy loam parameters
Residual moisture content	0.065	Sandy loam parameters
van Genuchten *n* parameter	1.89	Sandy loam parameters
van Genuchten α parameter	7.5	Sandy loam parameters

Parameter	Value	Notes
Vadose zone parameters		
Thickness (depth to aquifer, m)	9	Estimated (see discussion)
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^{-1})	556.2	Assumed to be the same as the aquifer material
Aquifer parameters		
Effective porosity	0.15	Aquifer characteristics.pdf
Hydraulic gradient	0.0399	Aquifer characteristics.pdf
Saturated hydraulic conductivity (m yr^{-1})	556.2	Midpoint between low (1.04 ft/d) and high (10.72 ft/d) values
Darcy velocity (m yr^{-1})	83.4	Calculated
Pore velocity (m yr^{-1})	148	Calculated
Thickness (m)	4.54	Aquifer characteristics.pdf, average value

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. Unsaturated hydrologic properties of these materials were lacking, except for the hydraulic conductivity and total porosity reported for the aquifer. Material properties were thus chosen from properties reported in Carsel and Parrish (1998) that had similar saturated hydraulic conductivity to the shale. The material selected was sandy loam. For the waste, the parameters from Carsel and Parrish were used without modification. The total porosity for sandy loam was higher than reported for shale, but this is justified because municipal waste mixed with shale would have a higher void volume than undisturbed shale. Moisture retention curves use the van Genuchten formulations (van Genuchten 1980) that are described by the parameters α 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 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 (Appendix C – Aquifer Characteristics). 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 screening 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 valance 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 16).

Table 16. Sorption Coefficient (K_d) Values Used in Groundwater Modeling

Element	RESRAD default (mL g^{-1})	Sheppard and Thibault sand (mL g^{-1})	Value used in model (mL g^{-1})
Pb	100	270	100
Ra	70	500	70
Th	60000	3200	3200
U	50	35	35

Groundwater Ingestion Dose Calculations

Groundwater ingestion doses were calculated with GWSCREEN (Rood 2002) using the exposure scenario described in the exposure parameters section (2 L of water per day for 365 days per year) and ingestion dose coefficients provided in Table 12.

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. Conservatisms incorporated into the different components of the calculations are summarized below.

Source Term

The bulk of TENORM activity received was from Fairmont Brine. Based on mean exposure readings taken on the shipments and the conversion factor developed by PADEP, the Ra-226/228 concentrations were estimated. 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 TENORM material 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.

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 laborer was assumed to stand next to the TENORM 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 the disposal, 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 laborer 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 Estimates

Inhalation, Ingestion, and External Doses for a Landfill Worker

The landfill laborer represents a bounding dose estimate for a worker in close contact with the TENORM 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 disposal. Time-integrated concentrations (TIC) and effective doses (ED) are presented in Table 17 on a per disposal basis. The total dose of 1.94 mrem (1.94×10^{-2} mSv) assumes that the *same* person attended all 92 disposals.

Table 17. Inhalation and Ingestion Effective Dose (ED) to a Landfill Laborer

Radionuclide	*Q* (pCi)	TIC (pCi-m^3 hr^{-1})	Inhalation ED (mrem per disposal)	Ingestion ED (mrem per disposal)	Total ED (mrem per disposal)	Total ED for 92 disposals (mrem)
U-238	2.73E+01	6.01E-04	3.48E-05	2.94E-05	6.41E-05	5.90E-03
U-234	2.73E+01	6.01E-04	4.05E-05	2.96E-05	7.00E-05	6.44E-03
Th-230	3.46E+02	7.62E-03	5.28E-03	1.63E-03	6.91E-03	6.36E-01
Ra-226	3.34E+02	7.35E-03	5.05E-04	2.83E-03	3.33E-03	3.07E-01
Pb-210	2.97E+01	6.55E-04	4.73E-05	1.54E-03	1.58E-03	1.46E-01
Th-232	1.82E+02	4.01E-03	3.08E-03	9.46E-04	4.03E-03	3.70E-01
Ra-228	1.25E+02	2.74E-03	3.13E-04	3.72E-03	4.03E-03	3.71E-01
Th-228	9.63E+01	2.12E-03	6.70E-04	4.54E-04	1.12E-03	1.03E-01
Total		**mrem (mSv)**	**9.97E-03 (1.0E-04)**	**1.12E-02 (1.1E-04)**	**2.11E-02 (2.1E-04)**	**1.94E+00 (1.9E-02)**

The external dose per disposal was 3.00×10^{-2} mrem (3.00×10^{-4} mSv) and 2.76 mrem (2.76×10^{-2} mSv) assuming the *same* person was attending all 92 disposals (Table 18). This was calculated assuming a laborer spends 0.25 hours per disposal at a distance of 1.0 m from the TENORM container, and 0.083 hours 1 meter from the deposited waste pile. The external dose for the heavy equipment operator who spends 0.5 hour exposed to the deposited waste pile was 1.24×10^{-2} mrem (1.24×10^{-4} mSv) per disposal and 1.14 mrem (1.14×10^{-2} mSv) assuming the *same* person attended all 92 disposals. Thus, the laborer exposure provides a worst-case estimate of external doses.

Table 18. Summary of Parameters and External Effective Dose to a Landfill Laborer

External dose parameter	Parameter value
Landfill laborer	
Exposure time in front of truck with shielded waste (hr)	0.25
Exposure rate 1 m from truck (mrem hr^{-1})	0.0815
Exposure time in front of unshielded waste (hr)	0.083
Exposure rate 1 m from unshielded waste (mrem hr^{-1})	0.116
Total per disposal in mrem (mSv)	0.03 (0.0003)
Total for 92 disposals in mrem (mSv)	**2.76 (0.028)**
Heavy-equipment operator	
Exposure time (hr)	0.5
Exposure rate inside cab (mrem hr^{-1})	0.0247
Total dose per shipment in mrem (mSv)	0.0124 (0.000124)
Total dose for 92 shipments in mrem (mSv)	**1.14 (0.0114)**

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 χ/Q in s m^{-3}) calculated with the Gaussian plume model using stability class D and an average wind speed of 4 m s^{-1} was 3.81×10^{-4}, 2.31×10^{-4}, and 8.81×10^{-5} for the south office (300 m), main office (400 m), and school (700 m), respectively. The product of the χ/Q and the activity emitted from the source (Q value, see Table 17) yields the time-integrated concentration. The breathing rate for adults and students was lower than what was assumed for the landfill laborer.

The effective doses (Table 19) 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 19. Inhalation Effective Dose (ED) to an Office Worker and Student/Teacher

	South office	Main office	School	South office	Main office	School[a]
Radionuclide	TIC (pCi-s m^{-3})	TIC (pCi-s m^{-3})	TIC (pCi-s m^{-3})	ED (mrem per disposal)	ED (mrem per disposal)	ED (mrem per disposal)
U-238	1.04E-02	6.32E-03	2.40E-03	7.73E-08	4.70E-08	1.60E-08
U-234	1.04E-02	6.32E-03	2.40E-03	9.00E-08	5.47E-08	1.92E-08
Th-230	1.32E-01	8.01E-02	3.05E-02	1.17E-05	7.14E-06	2.23E-06
Ra-226	1.27E-01	7.73E-02	2.94E-02	1.12E-06	6.84E-07	2.35E-07
Pb-210	1.13E-02	6.88E-03	2.62E-03	1.05E-07	6.40E-08	2.30E-08
Th-232	6.94E-02	4.22E-02	1.61E-02	6.85E-06	4.16E-06	1.39E-06
Ra-228	4.74E-02	2.88E-02	1.10E-02	6.96E-07	4.23E-07	1.46E-07
Th-228	3.67E-02	2.23E-02	8.48E-03	1.49E-06	9.06E-07	3.36E-07
Total per disposal			mrem (mSv)	2.22E-05 (2.2E-07)	1.35E-05 (1.4E-07)	4.39E-06 (4.4E-08)
Total for 92 disposals			**mrem (mSv)**	**2.04E-03 (2.0E-05)**	**1.24E-03 (1.2E-05)**	**4.04E-04 (4.0E-06)**

a. Doses in this column are for a school-age child. The total dose for an adult teacher was 5.13E-06 mrem (5.13E-08 mSv) per disposal and 4.72E-04 mrem (4.72E-06 mSv) for 92 disposals.

Radon Flux and Doses

Radon flux at the surface of the disposal cell was calculated based on a 4.47-m-thick waste zone having an average Ra-226 concentration of 26.9 pCi g^{-1} and assuming 3 m of clean waste (i.e., municipal waste containing no TENORM) on top of the TENORM-bearing waste. The radon flux was 2.37 pCi m^{-2} s^{-1}, which is substantially less than the limit for uranium mill tailings disposal cells of 20 pCi m^{-2} s^{-1}. Calculations showed that the 20 pCi m^2 s^{-1} limit could be achieved with as little as 1/10 of a meter of cover (4 inches) or a decrease of the radon emanation fraction to 0.18 with no cover. 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 may be an extreme worst case, as it is outside the range of emanation coefficients for this material and more typical of uranium mill tailings.

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 conversion from WLM to dose was 760 mrem per WLM (see Table 20). The integrated flux over the disposal area was 37,400 pCi s^{-1}. The scenario also assumes that the indoor-outdoor air concentrations are the same. Annual radon doses were less than one mrem (< 0.01 mSv) at all locations.

Table 20. Radon Doses to an Office Worker, Student or Teacher, and Future Resident

Receptor	Distance (m)	*X/Q* (s m^{-3})	Radon concentration (pCi L^{-1})	WLM	Effective dose in mrem yr^{-1} (mSv yr^{-1})
South office	300	8.81E-05	3.29E-03	3.95E-04	0.300 (3.0E-03)
Main office	400	6.99E-05	2.62E-03	3.14E-04	0.239 (2.4E-03)
School	700	3.59E-05	1.34E-03	1.21E-04	0.0918 (9.2E-04)
Future resident	700	3.59E-05	1.34E-03	6.63E-04	0.504 (5.0E-03)

Groundwater Ingestion Dose

The groundwater ingestion effective dose as a function of time at the downgradient receptor well (see Figure 14) showed a maximum of 1.25 mrem (1.25×10^{-2} mSv) at 2,900 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^{-1} (0.25 mSv yr^{-1}) dose limit for low-level radioactive disposal sites. The maximum Ra-226/228 concentration in groundwater was estimated to be 0.86 pCi L^{-1}, less than the 40 CFR 141 MCL for Ra-226/228 of 5 pCi L^{-1}. Maximum U-238 activity concentration was 0.26 pCi L^{-1}, and the mass concentration was 0.8 µg L^{-1}. Uranium is not regulated based on it radiological properties, but instead its chemical toxicity. The MCL for uranium in 40 CFR 141 is 30 µg L^{-1} and the predicted concentration is well below this value.

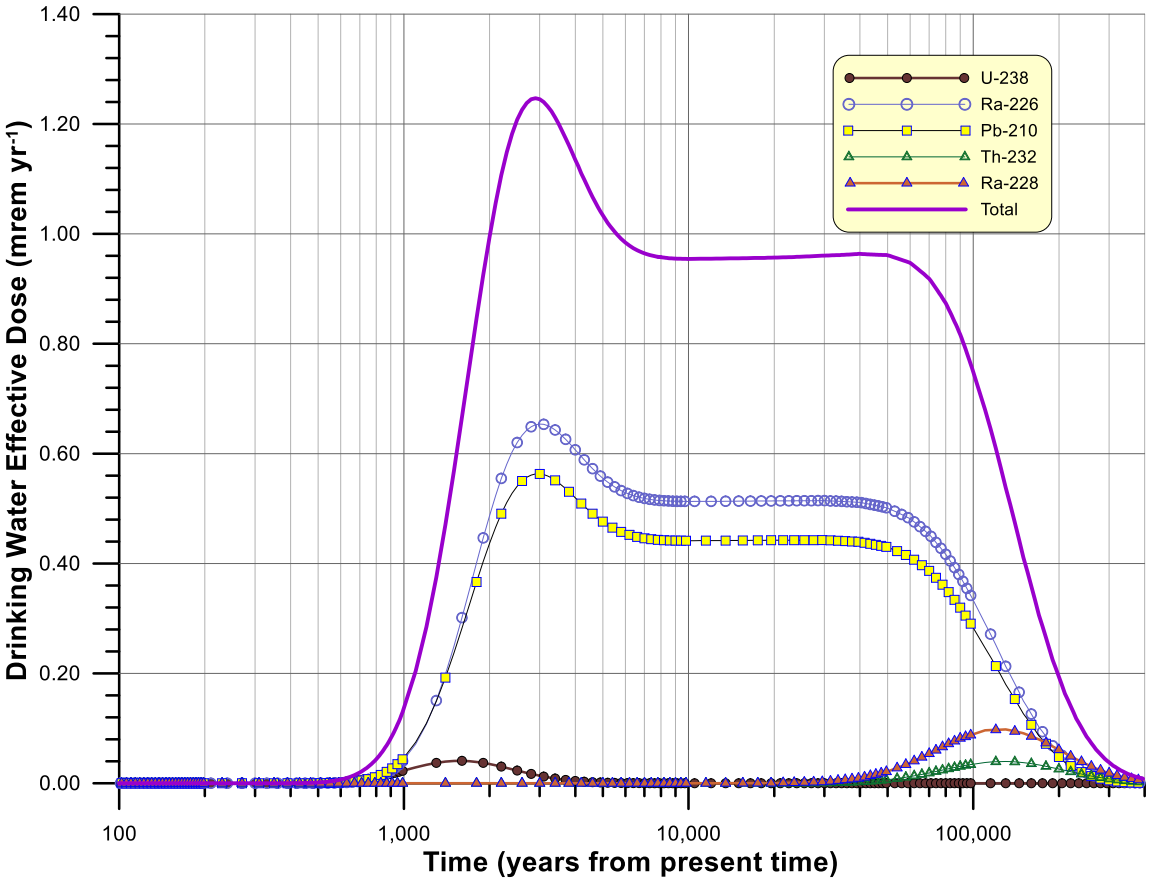

Figure 14. Groundwater ingestion effective dose as a function of time for key radionuclides.

TENORM Regulations and Guidance

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

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

The NRC regulates TENORM when concentrations of uranium and thorium are greater than or equal to 0.05% of the chemical mixture, compound, solution, or alloy. TENORM waste byproducts (e.g., sludges from water and wastewater) are not regulated by the NRC.

Fewer than half of all states have regulations covering TENORM materials. Prior to these disposals, the only specific guidance for the disposal of TENROM within the state of Kentucky were set out in the Central Midwest Interstate Low-Level Radioactive Waste Commission Regional Management Plan adopted May of 1999 (Retrieved from: https://www.illinois.gov/iema/Info/Documents/cmccplan.pdf; hereafter referred to as the CMIC Plan) (Kentucky General Assembly 1999). The CMIC Plan is a legal agreement between the State of Illinois and the Commonwealth of Kentucky. According to the CMIC Plan, it is the policy of the Commission to bar the import of TENORM waste with concentrations equal to or greater than 5 pCi g^{-1}. Additionally, the Regional Management Plan also states as "policy" that TENORM waste with concentrations less than 2,000 pCi g^{-1} should be "disposed in accordance with the method approved by the appropriate party state regulatory agency." Kentucky recently introduced HB563, which would "clarify that solid wastes from oil and gas drilling operations that contain low-level radioactive wastes are included in prohibited imports" and would "amend KRS 224.50-760 to prohibit importation of certain solid wastes resulting from oil and gas drilling operations" (http://www.lrc.ky.gov/record/16rs/HB563.htm). KRS 224.50-760 does not currently contain any language referring to NORM, TENORM, or radioactive materials in general.

The American National Standards Institute (ANSI) and the Heath Physics Society developed a standard for the control and release of TENORM (ANSI 2009). The standard adopts an overall dose limit of 100 mrem yr^{-1} (1 mSv y^{-1}) above background from all sources (including TENORM and other manmade sources) and pathways of exposure to radionuclides, excluding radon and short-lived decay products, consistent with current IAEA safety standards (IAEA Safety Standards Series No. GSR Part 3 2014). This dose limit applies to all facility operations and practices that release radionuclides to the environment. For the unrestricted use of TENORM-contaminated land that has been remediated, a dose limit of 25 mrem yr^{-1} (0.25 mSv yr^{-1}) from all pathways excluding radon and short-lived decay products was established. The recommended annual average outdoor radon concentration limit was 0.5 pCi L^{-1} (20 Bq m^{-3}) at the fence line or any downwind location. For indoor radon concentration, ANSI adopted the EPA recommended value of 4 pCi L^{-1} (150 Bq m^{-3}). Indoor radon is generally an issue when radon present in soils diffuses through the building foundation and into the structure. Unless a structure is built on top of the landfill, indoor radon is

not considered a viable pathway for these TENORM disposals. Radon surface flux from uranium mill tailings piles is limited in 40 CFR 192 to 20 pCi m^{-2} s^{-1} (540 Bq m^{-2} s^{-1}).

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

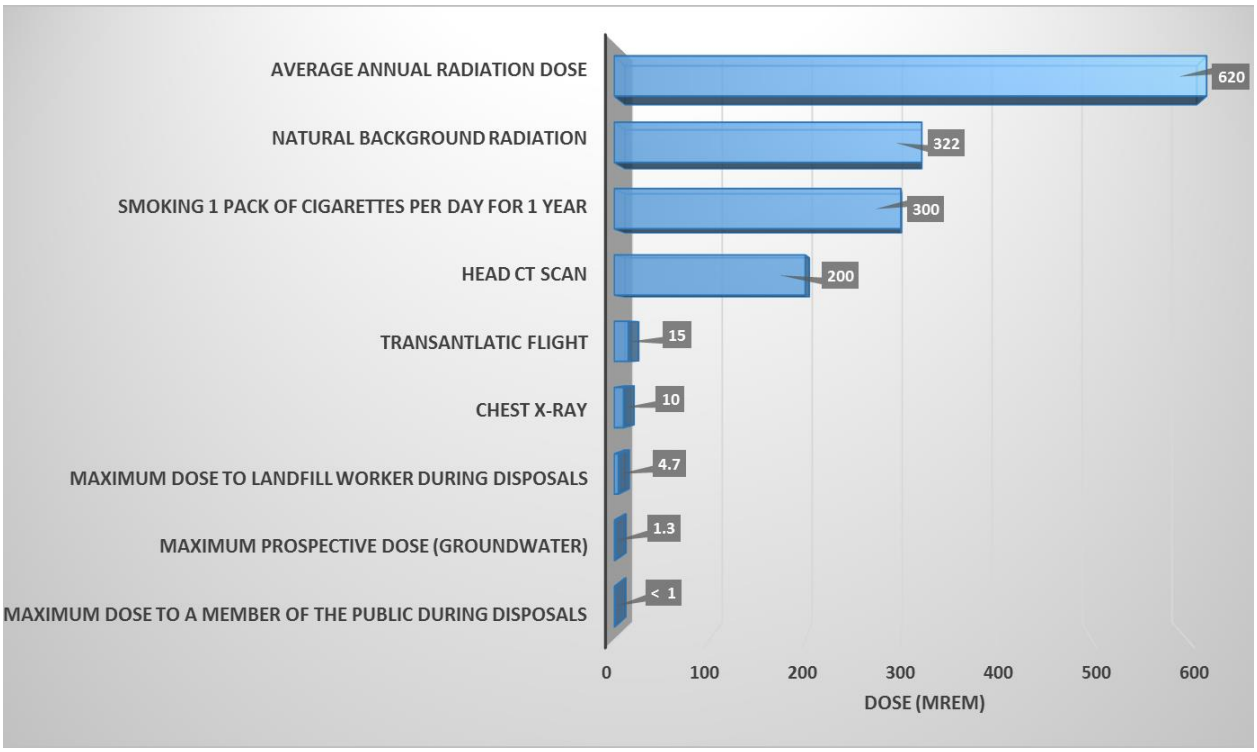

Figure 15. Radiation dose in perspective.

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 Position Statement 2004). The highest dose calculated for

potentially exposed individuals from the TENORM disposals is 4.7 mrem (4.7×10^{-2} mSv), well below the level at which potential health effects may be observed.

According to the National Cancer Institute (NCI), the background incidence of cancer from all sources in the United States is about 40%, that is, 4 out of every 10 people will be diagnosed with cancer at some point in their lives (NCI 2016). Based on numerous epidemiological studies performed over several decades, the International Commission on Radiological Protection (ICRP) recommends a dose to risk conversion factor of 0.00005% per mrem (0.005% per mSv) of exposure (ICRP 2007) or 5 persons in a population of 10 million for a dose of one millirem. The increased risk of cancer for each exposure group considered above is shown in Table 21.

Table 21. Cancer Risk for Each Exposure Group

Exposure scenario	Dose in **mrem** (mSv)	Risk above baseline value of 40% (%)
Landfill worker during disposals	**4.7** (4.7×10^{-2})	2.4×10^{-4}
Member of the public during disposals	**< 1** ($< 1.0 \times 10^{-2}$)	$< 5.0 \times 10^{-5}$
Maximum prospective dose	**1.25** (1.25×10^{-2})	6.3×10^{-5}

Summary and Conclusions

A total of 92 loads of TENORM waste materials from oil and gas production and exploration totaling approximately 1,157 U.S. tons were brought into the Blue Ridge Landfill between July 20, 2015, and February 3, 2016. From a radiological health perspective, key radionuclides considered included U-238, Ra-226, Ra-228, Th-230, and Th-232. The waste materials had average concentrations of these radionuclides as follows: U-238: 13.3 pCi g^{-1}, Ra-226: 163 pCi g^{-1}, Ra-228: 60.8 pCi g^{-1}, Th-230: 169 pCi g^{-1}, and Th-232: 89.1 pCi g^{-1}. A weighted-average radionuclide concentration value was computed for each load or set of loads based on provided material analytical data, and these values were used to compute doses.

During the disposals, landfill workers may have been exposed to these materials internally via inhalation or ingestion of suspended materials, and externally by standing near or working in close proximity to the wastes. The highest estimated effective dose for any individual was a landfill worker who was present during the TENORM disposals. The calculated inhalation and ingestion dose for the landfill worker was 1.9 mrem (1.9×10^{-2} mSv), and the external dose was 2.8 mrem (2.8×10^{-2} mSv) for a total of 4.7 mrem (4.7×10^{-2} mSv). These doses assume the same person attended all 92 disposals, and therefore, represent a worst-case dose estimate.

Other members of the public (e.g., on-site office workers, or teachers and students at the nearby schools) may have been exposed internally via inhalation of materials that may have been suspended in air and transported downwind. Ingestion and external exposure to these individuals from the TENORM wastes were not viable pathways of exposure. Worst-case inhalation dose estimates from particulates suspended during disposal were 2.0×10^{-3} mrem (2.0×10^{-5} mSv) to nearby office workers at the landfill, and 4.7×10^{-4} mrem (4.7×10^{-6} mSv) to students and teachers at Estill County Middle School and High School. These doses assume the wind always blows in the direction of the receptor during the disposals, and therefore, represent worst-case scenarios.

Worst-case dose estimates from radon after disposal were 3.0×10^{-1} mrem yr^{-1} (3.0×10^{-3} mSv yr^{-1}) for the office worker, and 9.2×10^{-2} mrem yr^{-1} (9.2×10^{-4} mSv yr^{-1}) for the student and teacher. Again, the wind was assumed blowing in the direction of the receptor 100% of the time. A future resident living on the current school property had a maximum dose estimate from radon of 5.0×10^{-1} mrem yr^{-1} (5.0×10^{-3} mSv yr^{-1}). Maximum radon concentrations in outdoor air were less than 0.0035 pCi L^{-1}.

The assessment also considered times far in the future when the radioactivity could be leached from the landfill into the groundwater and potentially used for drinking water. Assuming these circumstances and a drinking water well directly downgradient of the facility resulted in a maximum effective dose of 1.25 mrem yr^{-1} (1.25×10^{-2} mSv yr^{-1}). This dose was less than the 25 mrem yr^{-1} (0.25 mSv yr^{-1}) dose standard for low-level radioactive disposal sites. Additionally, Ra-226/228 concentrations and uranium mass concentrations in drinking water were well below the maximum contaminant limits of 5 pCi L^{-1} and 30 µg L^{-1}, respectively, set forth in 40 CFR 141.

All predicted effective doses were substantially less than the 25 mrem yr^{-1} dose limit (0.25 mSv yr^{-1}) recommended by the American National Standards Institute (ANSI 2009) for unrestricted release of TENORM-contaminated land. Predicted annual average radon concentration in outdoor air was less than the ANSI recommended value of 0.5 pCi L^{-1}.

The maximum dose was 4.7 mrem (4.7×10^{-2} mSv) to a landfill worker present during all 92 disposals, which translates to an increased risk of cancer of 2.4×10^{-4} % or slightly more than 2 persons in a population of one million. For a member of the general public, the maximum dose was

less than 1 mrem (0.01 mSv), translating to an increase in cancer risk of less than 5.0×10^{-5} % or 5 persons in a population of 10 million. These exposure levels are significantly less than one dental (or chest) x-ray and a fraction of the natural background radiation. The increased risk of cancer is insignificant when compared to the baseline cancer risk of 40% or four out of ten persons being diagnosed with cancer in their lifetime.

The geologic region where the landfill is situated has a relatively high degree of variability in naturally occurring background radionuclide concentrations, with the highest concentrations occurring in areas of exposed shale. The soil and surface water samples and surface gamma exposure rates reflect the range of natural background in the area except in the area outside where the TENORM waste in question was disposed (see Figure 9). The gamma scans and soil measurements confirm that the TENORM waste that was mixed with municipal waste in the landfill resulted in overall low radionuclide concentrations in the landfill such that there is no surface representation of the disposals above background external exposure rates or Ra-226/228 concentrations.

In the areas identified as taking waste brokered by BES, there is no evidence that the TENORM waste disposal resulted in any measurable short- or long-term impacts to air concentrations in the area where members of the public may have been, including the Estill County middle and high schools that are adjacent to the landfill.

All available environmental sampling data support the assessment that the estimated doses are low, and there is no evidence to suggest any measurable impact of the TENORM waste, either now or in the future.

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NRC (National Research Council). 1999. *Evaluation of Guidelines for Exposures to Technologically Enhanced Naturally Occurring Radioactive Materials*. Washington, D.C.: National Academy Press.

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Nuverra Environmental Solutions. 2015. Nuverra Environmental Solutions Waste Manifests. Norwich, OH. [Blue Ridge Disposals Back-up Documents].

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Pace Analytical Services Inc. 2015c. Pace Analytical Report for Waste Management: Project Fairmont Brine - Sludge Pit Cl. Greensburg, PA. [Pace Fairmont Brine Sludge].

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Rood, A.S., G.J. White, and D.T. Kendrick. 1998. "Measurement of ^{222}Rn Flux, ^{222}Rn Emanation, and ^{226,228}Ra Concentration from Injection Well Pipe Scale." *Health Physics* 75 (2): 187–192.

Rood, A.S. 2004. "A Mixing-Cell Model for Assessment of Contaminant Transport in the Unsaturated Zone under Steady-State and Transient Flow Conditions." *Environmental Engineering Science* 21 (6): 661–677.

Rood, A.S. 2005. *Mixing Cell Model: A One-Dimensional Numerical Model for Assessment of Water Flow and Contaminant Transport in the Unsaturated Zone*. ICP/EXT-05-00748, Idaho National Laboratory, Idaho Falls, ID. March.

Rood, A.S. 2002. GWSCREEN: *A Semi-Analytical Model for Assessment of the Groundwater Pathway from Surface or Buried Contamination: Theory and User's Manual Version 2.5 Rev 1b*. INEEL/EXT-98-00750. Idaho National Laboratory, Idaho Falls, ID. July.

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Turner, D.B. 1994. *Workbook of Atmospheric Diffusion Estimates, Second Edition*. Boca Raton, Florida: Lewis Publishers (imprint of CRC press).

USGS (U.S. Geological Survey). 1976. Geologic map of the Irvine quadrangle, Estill County, Kentucky. Retrieved from http://ngmdb.usgs.gov/Prodesc/proddesc_10820.htm.

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

Yu, C., C. Loueiro, J-J Cheng, L.G. Jones, Y.Y. Wang, Y.P. Chia, and E. Faillace. 1993. *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil*. ANL/EAIS-8, Environmental Assessment Division, Argonne National Laboratory, April.

Appendix A – *Curriculum Vitae*

John E. Till, Ph.D.

President, Risk Assessment Corporation

Education

Ph.D., Nuclear Engineering, Georgia Institute of Technology, Atlanta, Georgia, 1976
M.S., Health Physics, Colorado State University, Fort Collins, Colorado, 1972
U.S. Naval Nuclear Propulsion Program, Submarine Force. Three schools consisting of Nuclear Power School, Mare Island, California; S5G Prototype NPTU, Idaho Falls, Idaho; Submarine School, Groton, Connecticut
B.S., Engineering (with distinction), U.S. Naval Academy, Annapolis, Maryland, 1967

Professional Experience

Risk Assessment Corporation (formerly ***Radiological Assessments Corporation***)
President/Owner, Neeses, South Carolina (1977–present)

Owner and president of Risk Assessment Corporation, Inc. (formerly *Radiological Assessments Corporation*), which focuses on the analysis of exposure and dose from radionuclides and chemicals released to the environment. Conducting research contracts for the Environmental Protection Agency, Vanderbilt University, Colorado State University, National Cancer Institute, Centers for Disease Control and Prevention, Chem-Nuclear Corporation, Oak Ridge National Laboratory, Battelle Pacific Northwest Laboratory, Du Pont Company, University of Utah, Colorado Department of Public Health and Environment, Department of Justice, Battelle Pacific Northwest Laboratories, the New Mexico Department of Environment, Pueblo de San Ildefonso, among others.

Embeford Farm

President/Owner (1000-acre family farm), Neeses, South Carolina (1977–present), producing corn and soybeans.

Oak Ridge National Laboratory

Research Associate, Oak Ridge Tennessee (1974–1977)

Conducted assessments of radiological impacts around nuclear facilities, performed studies to evaluate environmental impact of advanced fast reactor fuels, and developed and improved models to evaluate radionuclide releases to the environment.

Consultant, Allied-General Nuclear Services

Consultant, Barnwell, South Carolina (1973–1974)

Developed an in-plant health physics training program and wrote the *Safety and Environmental Control Department Policy Manual* for a nuclear fuel reprocessing plant being constructed by Allied-General Nuclear Services.

Georgia Institute of Technology

Research Assistant, Atlanta, Georgia (1973–1974)

Provided research and teaching support in the School of Nuclear Engineering.

Colorado State University

Research Assistant, Fort Collins, Colorado (1971–1972)

Developed and tested an instrument that rapidly measures working level exposure of radon daughters.

U.S. Navy, Nuclear Submarine Force (active duty)

Officer (1967–1971)

Became qualified to operate an S5W nuclear reactor and qualified in submarines. Other responsibilities included reactor control officer, electrical division officer, and operations officer.

Special Awards/Positions

37th Taylor lecture presented on March 11, 2013 at the annual meeting of the National Council on Radiation Protection and Measurements, Bethesda, MD.

Recipient of the E.O. Lawrence Award in the field of environmental science and technology. Award is presented to several outstanding scientists each year following nominations sought from over 2000 organizations, 1995

Recipient of Elda E. Anderson Award presented annually to a member of the Health Physics Society less than 40 years of age for excellence in contributions to the profession of health physics and the Society, 1983

Technical Advisor to Board of Directors, Exelon Corporation, (Current)

Member, International Commission on Radiological Protection (ICRP), Committee 4, 1997–2006

Chairman, Radiation Advisory Committee, Science Advisory Board, U.S. Environmental Protection Agency, member Executive Committee Science Advisory Board, U.S. Environmental Protection Agency, 1986–1987

Chairman, South Carolina Governor's Nuclear Advisory Council, 1987–1989

Advisor to Dean, University of Utah School of Medicine, "Assessment of Leukemia and Thyroid Disease in Relation to Fallout in Utah," 1986–1994

Adjunct Professor of Physics, Emory University, Atlanta, Georgia, 1985–1995

Chairman, Technical Steering Panel, Hanford Dose Reconstruction Project, 1988–1994

Professional Activities

National Council on Radiation Protection and Measurements (NCRP)

Distinguished Emeritus Member, NCRP, 2003–present

Member, National Council on Radiation Protection and Measurements (NCRP), 1984–2003.

Chairman NCRP Scientific Committee 6-8 Operation TOMODACHI Radiation Dose Assessment, 2012–2014

Member, NCRP Committee 6–9, Dosimetry on the One-mIllion Worker Study, 2012–current.

NCRP 2013 Annual Meeting Committee, 2012–2013

MemberAdvisor, NCRP Scientific Committee 6–22, "Design of Effective Radiological Effluent Monitoring and Environmental Surveillance Programs" NCRP Publication 169, 2009–2012

Chairman, NCRP Committee 64, Umbrella Committee on Environmental Issues, 1996–2003

Strategic Planning Committee, 1999–2000

President Selection Committee for successor to Dr. Warren Sinclair, 1992–1993

Member, NCRP Board of Directors, 1989–1994

Member, NCRP Nominating Committee, 1988–1993

Chairman, NCRP Program Committee for Year 2003 Annual Meeting of the NCRP, "Radiation Protection at the Beginning of the 21st Century–A Look Forward"

Member, Program Committee for Year 2000 Annual Meeting of the NCRP, "Past and Future Bases for Setting Radiation Protection Standards"

Member, National Council on Radiation Protection and Measurements Scientific Committee 64 on Environmental Radioactivity, 1985–2002

Chairman, NCRP Scientific Committee 64–19, "Dose Reconstruction," 1994–2000

Chairman, NCRP Program Committee for 1995 Annual Meeting, "Environmental Dose Reconstruction and Risk Implications," April 12–13, 1995, Crystal City, Virginia

Chairman, NCRP Task Group on Disposal of Low-Level Radioactive Waste in Oceans, National Council on Radiation Protection and Measurements, 1985–1990

Chairman, NCRP Committee 64–6, "Screening Models," NCRP Publication 123 1982–1994

Chairman, NCRP Committee 64–2 and 3, "Radiological Assessment," NCRP Publication 76, 1978–1982

Chairman, NCRP Committee for Comentary No. 3, "Screening Techniques for Determining Compliance with Environmental Standards," 1986 (Rev. 1989)

Member NCRP Task Group on "Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to Public Health Significance of the Proposed Release of Tritiated Waters from Three Mile Island," NCRP Commentary No. 4, 1987

National Academy of Sciences

Chairman, National Academy of Sciences Committee, "A Review of the Dose Reconstruction Program of the Defense Threat Reduction Agency," 2001–2003

Member, National Academy of Sciences "Advisory Committee to Study the Mortality of Military Personnel Present at Atmospheric Tests of Nuclear Weapons," 1994–2000

Member, National Academy of Sciences Committee to Provide Interim Oversight of the Department of Energy Nuclear Weapons Complex, 1988–1989

Member, "Mortality of Military Personnel Present at Atmospheric Tests of Nuclear Weapons," National Academy of Sciences, 1993–1995

Chairman, Dosimetry Working Group, "Mortality of Military Personnel Present at Atmospheric Tests of Nuclear weapons," National Academy of Sciences, 1993–1995

International Commission on Radiological Protection (ICRP) and International Atomic Energy Agency (IAEA)

Member, Committee Four of the International Commission on Radiological Protection (ICRP) 1997–2005.

Chairman, ICRP Task Group on "Defining the Individual," 2002–2005.

Member, International Commission on Radiological Protection Committee on Prolonged Exposures, 1997–2000.

Member, International Commission on Radiological Protection Working Party on Controllable Doses, 1997–2000

Chairman, International Commission on Radiological Protection Working Party on Environmental Doses, 1997–2000.

Special Appointments

Appointment by the Secretary of Energy to the Department of Energy Commission on Fire Safety and Preparedness, November 2000–2001

Scientific Review Group, U.S. Department of Energy, Joint Coordinating Committee for Radiation Effects Research, 1995–1997.

Consultant to U.S. Nuclear Regulatory Commission, Advisory Committee on Reactor Safeguards, 1986–1990.

Chairman, Advisory Panel, "Managing Nuclear Materials from Warheads: Weapons Dismantlement and Its Aftermath," Office of Technology Assessment, Congress of the United States, June 1992–1993

Illinois Department of Nuclear Safety Technical Advisory Panel on Low-Level Waste Disposal Systems, 1986–1989.

Member, U.S. Department of Energy Committee on Research on the Validation of Predictive Models Resulting from the Chernobyl Nuclear Accident, 1986–1988

Member, Department of Energy "Joint Coordinating Committee on Radiation Effects Research," 1995–1997

Professional Society Memberships and Activities

Health Physics Society

Chairman, Education and Training Committee, Health Physics Society, 1975–1979.

Councilman, East Tennessee Chapter, Health Physics Society, 1975–1977.

Program Chairman, "Pathway Analysis and Risk Assessment," 1989 Health Physics Society Summer School, St. John's College, Santa Fe, New Mexico, June 18–23, 1989.

Program Chairman, "Assessment of Releases of Radioactivity to the Environment," 1980 Health Physics Society Summer School, University of Washington, Seattle, Washington, July 14–18, 1980.

Program Chairman, "A Seminar on Solid Radioactive Waste Storage in the United States," sponsored by the East Tennessee and Bluegrass Chapters of the Health Physics Society at Mammoth Cave, Kentucky, September 18, 1976.

Member, Committee on Scientific and Public Issues, Health Physics Society, 1979–1981.

Society for Risk Analysis

Society of Exposure Analysis

American Nuclear Society

American Association for the Advancement of Science

Journal Editorship

Editor, *International Radiation Protection Association* ***BULLETIN****,* 1988–1992.

Editor for Environmental Consequences Section of *Nuclear Safety,* 1975–1977.

Health Physics Advisory Board, 1988–1992.

Editor, "Radiation Protection at the Beginning of the 21st Century-A Look Forward," *Health Physics*.

Military

Rear Admiral, U.S. Naval Reserve, 1991–1999, retired

Mobilization Assistant to U.S. Strategic Command, 1998–1999

Deputy Commander, Submarine Operations, N87R, Washington, D.C., 1994–1997.

Deputy Commander, Submarine Force U.S. Atlantic Fleet, Norfolk, Virginia, 1991–1994

Commander Naval Reserve Readiness Command, Region Ten, New Orleans, Louisiana, 1992–1994.

Commanding Officer, Naval Weapons Station, HQ107, Charleston, South Carolina, 1988–1990.

Member, National Naval Reserve Policy Board, 1989–1992.

Commanding Officer, Naval Electronic Systems Engineering Command DET 407, 1985–1987.

Management Information Officer, Naval Reserve Readiness Command Region Seven, Charleston, South Carolina, 1983–1985.

Commanding Officer, AS–40 FRANK CABLE, DET 107, Charleston, South Carolina, 1981–1983.

Commanding Officer, Nuclear Weapon Training Group, DET 107, Charleston, South Carolina, 1979–1981.

Qualified in submarines.

Military Awards

National Defense Medal, 1999; Legion of Merit, 1994; Meritorious Service Medal, second award 1994; Meritorious Service Medal, 1990; Navy Commendation Medal, second award 1987; Navy Commendation Medal, 1984; Naval Reserve Service Medal, 1979; Navy Achievement Medal, 1971; National Defense Service Medal, 1964

Special Training and Certifications

Naval Nuclear Submarine Program including the following:

Six months (625 classroom hours) of instruction in the principles of science and engineering fundamental to design, construct, and operate a nuclear propulsion plant, July 1967–January 1968.

Six-month prototype training designed to provide on-the-job experience at starting up, operating, shutting down, and handling emergencies associated with nuclear propulsion plants, January 1968–August 1968.

Six months submarine school consisting of 675 hours of intensified instruction and 10 days of underway training aboard an operating submarine, August 1968–February 1969.

Certification to supervise the operation of a Naval Nuclear Reactor.

Training and certification to conduct experiments with highly toxic radioactive materials in a glove box, Oak Ridge National Laboratory, January 1968–April 1975.

Courses Taught and Offered

"Environmental Risk Assessment and Analysis," April 27–May 1, 2015, 15 Presented to staff of the U.S. Nuclear Regulatory Commission, White Flint, Maryland, 15 attendees

"Radiological Risk Assessment for Decision-Making, Compliance, and Emergency Response," March 4–8, 2013, Washington, D.C., 40 attendees

"Radiological Risk Assessment for Decision-Making, Compliance, and Emergency Response," March 5–9, 2012, Washington, D.C., 40 attendees

"Environmental Risk Assessment Analysis," January 26–30, 2009, U.S. Nuclear Regulatory Commission, Washington, D.C. 25 attendees

"Three Short Courses for Regulators and Radiation Health Specialists: Emerging Topics in Radiation Protection and Risk Assessment," March 16 – 18, 2004, Kiawah Island, South Carolina, 25 attendees

"Calculating and Understanding Risk from Radionuclides Released to the Environment," November 15–19, 1999, Seattle, Washington, 40 attendees

"Calculating and Understanding Risk from Chemicals Released to the Environment," April 12–15, 1999, San Antonio, Texas, 30 attendees

"Chemical Risk Assessment—A Practical Approach for Making Risk-Based Decisions," April 27 – May 1, 1998, Santa Fe, New Mexico, 75 attendees

"Pathway Analysis and Risk Assessment for Environmental Compliance and Dose Reconstruction," November 6–10, 1995, Kiawah Island, South Carolina, 75 attendees

"Chemical Risk Assessment for Environmental Compliance and Dose Reconstruction," February 27–March 3, 1995, Kiawah Island, South Carolina, 85 attendees

"Pathway Analysis and Risk Assessment for Environmental Compliance and Dose Reconstruction," February 28–March 4, 1994, Kiawah Island, South Carolina, 150 attendees

"Risk Assessment and Public Communication," March 1–5, 1993, Kiawah Island, South Carolina, 85 attendees

"Pathway Analysis and Risk Assessment for Environmental Compliance and Dose Reconstruction," March 2–6, 1992, Kiawah Island, South Carolina, 150 attendees

"Pathway Analysis and Risk Assessment for Environmental Compliance and Dose Reconstruction," February 25–March 1, 1991, Kiawah Island, South Carolina, 90 attendees

"Calculating and Understanding Risk from Radionuclides Released to the Environment," April 28–May 2, 1997, Santa Fe, New Mexico, 150 attendees

"Chemical Risk Management–A Practical Approach for Implementing Risk-Based Corrective Action," April 27–May 1, 1998, Santa Fe, New Mexico, 75 attendees

"Calculating and Understanding Risk from Chemicals released to the Environment," April12–15, 1999, San Antonio, TX, 40 attendees

Peer Reviewed Publications and Technical Reports

Till, J.E. 1975. "A Comparison of the Potential Radiological Impact of Recycle ^{233}U Fuel and LMFBR Plutonium Fuel Released to the Environment." ORNL/TM-4768. January.

Parzyck, D.C., J.P. Witherspoon, and **J.E. Till**. 1976. "Validation of Environmental Transport Models in the CUEX Methodology." Chapter in *Radioecology and Energy Resources.* Edited by C.E. Cushing, Jr. New York: Dowden, Hutchinson & Ross, Inc.

Tennery, V.J., E.S. Bomar, W.D. Bond, S.V. Kaye, L.E. Morse, and **J.E. Till**. 1976. "Potential Generation and Radiological Impacts of Gaseous ^{14}C Released During Reprocessing of Advanced LMFBR Fuels." ORNL/TM-5538. June.

Tennery, V.J., E.S. Bomar, W.D. Bond, G.S. Hill, L.E. Morse, R.D. Seagren, L.B. Shappert, and **J.E. Till**. 1976. "Environmental Assessment of LMFBR Advanced Fuels—A Radiological Analysis of Fuel Reprocessing, Refabrication, and Transportation." ORNL-5230. November.

Till, J.E. 1976. "A Comparison of Environmentally Released Recycle ^{233}U Fuel and LMFBR Plutonium Fuel." Chapter in *Radioecology and Energy Resources.* Edited by C.E. Cushing, Jr. New York: Dowden, Hutchinson & Ross, Inc.

Till, J.E. 1976. "Assessment of the Radiological Impact of ^{232}U and Daughters in Recycled ^{233}U HTGR Fuel." ORNL/TM-5409. February.

Till, J.E. 1976. "The Toxicity of Uranium and Plutonium to the Developing Embryos of Fish." ORNL-5610. July.

Till, J.E. 1976. "Potential Radiation Doses from ^{14}C Produced in Advanced FBR Fuels." *Transcripts American Nuclear Society,* November 14–19.

Till, J.E. 1976. "Education and Training Opportunities in Health Physics." A brochure on education and training for the Health Physics Society. December.

Till, J.E. and Dennis C. Parzyck. 1976. "An Evaluation of Operational Exposures which could Result from Potential Environmental Releases of ^{232}U and Daughters." *Proceedings Ninth Midyear Topical Symposium on Operational Health Physics.* Denver, Colorado, February.

Emery, R.M., M.L. Warner, H.R. Meyer, C.A. Little, and **J.E. Till**. 1977. "Environmental Assessment Strategies in Support of the Nonproliferation Alternative Systems Assessment Program (NASAP)." PNL-2415. October.

Tennery, V.J., E.S. Bomar, **J.E. Till**, L.E. Morse, M. Pobereskin, and W.J. Madia. 1977. "Radiological Environmental Assessment of the Recycle of LMFBR Advanced Fuels" *Proceedings Advanced LMFBR Fuels.* Tucson, Arizona, October.

Till, J.E. 1977. "A Laboratory Technique for Obtaining Fathead Minnow Eggs for Use in Toxicity Experiments." *Prog. Fish. Cult.* **39**: pp. 24–27. April.

Till, J.E. 1977. "A Uniform Approach for On-Site Training and Qualification of Health Physics Technicians." *Health Physics* **32**: pp. 423–428. May.

Till, J.E. and M.L. Frank. 1977. "Bioaccumulation, Distribution, and Dose of ^{241}Am, ^{244}Cm, and ^{238}Pu in Developing Fish Embryos." *Proc. IVth International IRPA Congress.* Paris, France, April 24–30. pp. 645–648.

Till, J.E. and G.G. Killough. 1977. "Scenarios of ^{14}C Release from the World Nuclear Power Industry 1975–2020 and Estimated Radiological Insult to the Population." *Airborne Radioactivity*. Selected papers from 1977 ANS Winter Meeting. Edited by David Shaw. LaGrange, Illinois: American Nuclear Society Press.

Till, J.E., C.J. Barton, G.W. Parker. 1977. "Nuclear Energy: A Viable Alternative." *Aviation Medical Bulletin.* February.

Killough, G.G. and **J.E. Till**. 1978. "Scenarios of ^{14}C Release from the World Nuclear Power Industry 1975–2020 and Estimated Radiological Impact." *Nuclear Safety* **19** (5).

Tennery, V.J., E.S. Bomar, W.D. Bond, L.E. Morse, H.R. Meyer, **J.E. Till**, and M.G. Yalcintas. 1978. "Environmental Assessment of Alternate FBR Fuels: Radiological Assessment of Airborne Releases from Thorium Mining and Milling." ORNL/TM-6474. October.

Tennery, V.J., E.S. Boamr, W.D. Bond, H.R. Meyer, L.E. Morse, and **J.E. Till**. 1978. "Environmental Assessment of Alternate FBR Fuels: Radiological Assessment of Reprocessing and Refabrication of Thorium/Uranium Carbide Fuel." ORNL/TM-6493. August.

Meyer, H.R., **J.E. Till** et al. 1978. "Nonproliferation Alternative Systems Assessment Program (NASAP)—Preliminary Environmental Assessment of Thorium/Uranium Fuel Cycle Systems." ORNL/TM-6069. June.

Meyer, H.R. and **J.E. Till**. 1978. "Radiological Hazards of Denatured Fuel Isotopes," Section 3.3 in *Interim Assessment of the Denatured Uranium Fuel Cycle.* Edited by L.S. Abbott, D.E. Bartine, and T.J. Burns. ORNL-5388. December.

Till, J.E. 1978. "The Effect of Chronic Exposure to ^{238}Pu(IV) Citrate on the Embryonic Development of Carp and Fathead Minnow Eggs." *Health Physics* **34** (4).

Till, J.E., E.S. Bomar, L.E. Morse, and V.J. Tennery. 1978. "A Radiological Assessment of Reprocessing Advanced Liquid-Metal Fast Breeder Reactor Fuels." *Nuclear Technology* **37** (3). March.

Till, J.E., F.O. Hoffman, and D.E. Dunning. 1978. "Assessment of Technetium-99 Releases to the Atmosphere—A Plea for Applied Research." ORNL/TM-6260. June.

Etnier, E.L. and **J.E. Till**. 1979. "Significance of Incorporating Age-Dependent Data into Population Dose Estimates." *Health Physics* **37** (6).

Kocher, D.C. and **J.E. Till**. 1979. "Iodine-129 Dose to the World Population from the Nuclear Power Industry." *Trans. Am. Nuc. Soc.*, November 12–16.

Meyer, H.R. and **J.E. Till**. 1979. "Anticipated Radiological Impacts from the Mining and Milling of Thorium for the Nonproliferative Fuels." Invited paper, *Proceedings of the Symposium—Radioactivity and Environment.* Norderney, Federal Republic of Germany, October 2–6, 1978, IRPA.

Meyer, H.R., **J.E. Till**, E.S. Bomar, W.D. Bond, L.E. Morse, V.J. Tennery, and M.G. Yalcintas. 1979. "Radiological Impact of Thorium Mining and Milling." *Nuclear Safety* 20 (3).

Meyer, H.R., C.A. Little, J.P. Witherspoon, and **J.E. Till**. 1979. "A Comparison of Potential Radiological Impacts of ^{233}U and ^{239}Pu Fuel Cycles." *Trans. Am. Nuc. Soc.*, November 12–16.

Till, J.E. and G.G. Killough. 1979. "Scenarios for ^{14}C Release to the Atmosphere by the World Nuclear Industry and Estimated Radiological Impacts." Invited paper *Proceedings of the Symposium—Radioactivity and Environment,* Norderney, Federal Republic of Germany, October 2–6, 1978, IRPA.

Till, J.E., F.O. Hoffman, and D.E. Dunning. 1979. "A New Look at ^{99}Tc Releases to the Atmosphere." *Health Physics* **36** (1).

Tennery, V.J., E.S. Bomar, W.D. Bond, H.R. Meyer, L.E. Morse, **J.E. Till**, and M.G. Yalcintas. 1980. "Summary of Radiological Assessment of the Fuel Cycle for a Thorium/Uranium Carbide Fueled Fast Breeder Reactor." ORNL/TM-6953. May.

Till, J.E., H.R. Meyer, V.J. Tennery, E.S. Bomar, M.G. Yalcintas, L.E. Morse, and W.D. Bond. 1980. "Reprocessing Nuclear Fuels of the Future: A Radiological Assessment of Advanced (Th, U)C Fuels." *Nuclear Technology* **48** (1).

Till, J.E. , H.R. Meyer, E.L. Etnier, E.S. Bomar, R.D. Gentry, G.G. Killough, P.S. Rohwer, V.J. Tennery, and C.C. Travis. 1980. "Tritium—An Analysis of Key Environmental and Dosimetric Questions." ORNL/TM-6990. May.

Till, J.E., E.L. Etnier, and H.R. Meyer. 1980. "Updating the Tritium Quality Factor—The Argument for Conservatism." *Proc. Tritium Technology in Fission, Fusion, and Isotopic Applications.* American Nuclear Society National Topical Meeting, U.S. Department of Energy Document No. CONF-800427.

Till, J.E., 1981. "Radiological Assessment for Submerged Demineralizer System for Three Mile Island." *RAC* Report 1/81. *Radiological Assessments Corporation*, Neeses, South Carolina.

Till, J.E., E.L. Etnier, and H.R. Meyer. 1981. "A Review of Methodologies for Calculating Dose from Environmental Releases of Tritium." *Nuclear Safety* **22** (2).

Till, J.E. 1983. "Special Case Radionuclides." Chapter 9 in *Radiological Assessment,* U.S. Nuclear Regulatory Commission. NUREG/CR-3332.

Till, J.E. 1983. "Long-Lived Radionuclides," *Proc. 19th Annual Meeting of National Council on Radiation Protection and Measurements.* NCRP, Washington, D.C.

Till, J.E. 1983. "Tritium—An Executive Summary of Environmental and Dosimetric Properties." Report for Chem-Nuclear Corporation. RAC/R/1. *Radiological Assessments Corporation*, Neeses, South Carolina. March.

Till, J.E. 1983. "Long-Lived Global Cycling Radionuclides." *Proc. 1983 American Nuclear Society Annual Meeting.* **41**. June.

Till, J.E. and H.R. Meyer, eds. 1983. *Radiological Assessment: A Textbook on Environmental Dose Analysis.* NUREG/CR-3332, ORNL-5968. U.S. Nuclear Regulatory Commission.

Killough, G.G., **J.E. Till**, E.L. Etnier, B.D. Murphy, and R.J. Raridon. 1984. "Dose Equivalent due to Atmospheric Releases of Carbon-14." Chapter 11 in *Models and Parameters for Environmental Radiological Assessments*. Edited by C.W. Miller. DOE/TIC-11468, U.S. Department of Energy, Washington, D.C.

Till, J.E. and W.L. Templeton (technical editors and task group leaders). 1984. *Radiological Assessment: Predicting the Transport, Bioaccumulation, and Intake by Man of Radionuclides Released to the Environment.* NCRP Report No. 76.

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Till, J.E. 2007. "Reconstruction of Historical Doses from Radionuclides Released to the Environment by the Uravan Mining and Milling Site." In re: June et al. v. Union Carbide Corporation et al., No.1: 04-CV-00123-MSK-MJW, January 15, 2007.

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J.E. Till and H.A Grogan. 2009. "It's the Dose — Strategies for Environmental Dose Reconstruction and Risk Assessment." Proceedings of Toxic Torts and Environmental Law Seminar, March 19-20, 2009, Phoenix Arizona. Defense Research Institute, Chicago, IL 60678-7252.

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J.E. Till. 2014. "When Does Risk Assessment Get Fuzzy?" 37th Taylor Lecture presented at the annual Meeting of the National Council on Radiation Protection and Measurements, March 11, 2013. *Health Physics,* **106** (2). February.

J.E. Till, H.L. Beck, J.W. Aanenson, H.A. Grogan, J.J. Mohler, S. S. Mohler, and P.G. Voillequé. 2014. "Military Participants at U.S. Atmospheric Nuclear Weapons Testing—Methodology for Estimating Dose and Uncertainty. *Radiation Research*, **181**, 471-484.

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A. Bouville, R. E. Toohey, J.D. Boice, H.L. Beck, L.T. Dauer, K.F. Eckerman, D. Hagemeyer, R.W. Leggett, D.L. Miller, B. Napier, K.H. Pryor, M. Rosenstein, D.A. Schauer, S. Sherbini, D.O. Stram, J. L. Thompson, **J.E. Till**, C. Yoder, C. Zeitlin. "Dose Reconstruction for the Million-WorkerMillion Worker Epidemiologic Study: Status and Guidelines." *Health Physics*, **108**, 206-220.

G. G. Caldwell, MD; M. M. Zack, MD; M.T. Mumma, MS; H. Falk, MD, MPH; C. W. Heath, Jr., MD; **J. E. Till, PhD**; H. Chen, PhD; J. D. Boice, Jr., ScD. "Mortality of Military Nuclear Test Participants at SMOKY and PLUMBBOB, 1957–2010." Submitted for publication, *JAMA.*

Helen A. Grogan, Ph.D.

President/Owner, Cascade Scientific, Inc.

Profile

Trained as a radioecologist, with three decades of experience evaluating exposure and health risk to the public from radionuclides and chemicals in the environment. Served on committees for the International Atomic Energy Agency, United Nations, National Academy of Sciences, the Environmental Protection Agency, and the National Council on Radiation Protection. Presently works closely with Risk Assessment Corporation (www.racteam.com) assuming responsibilities for the technical aspects of projects and undertakes independent projects as time permits. Career highlights include:

- Contribution to reconstruction of public exposures and risks from historical releases of radionuclides and chemicals from nuclear weapon production facilities in the USA including Rocky Flats in Colorado, the Savannah River Site in South Carolina, and the Hanford Nuclear Facility in Washington, and from former uranium processing facilities at Uravan, Colorado and Apollo, Pennsylvannia.
- Quantifying organ-specific cancer incidence risk and its uncertainty following exposure to plutonium from inhalation and ingestion
- Development of data management applications that facilitate access to and use of environmental measurement data for a variety of applications, ranging from basic data evaluation to more complex analyses including dose/risk assessment and decision making.
- Development of scientific methods and decision support tools to guide efforts to reduce public exposures and environmental impacts from existing exposures.
- Participation in BIOMOVS, the first international cooperative effort to test computer models developed to predict the fate and transport of radionuclides in the environment, and chairing one of the test scenarios.
- Assisting in developing an International Features, Events and Processes (FEP) Database for the Nuclear Energy Agency, Organization for Economic Cooperation and Development, France used in the performance assessment of radioactive waste disposal systems.
- Co-editor of Radiological Risk Assessment and Environmental Analysis (Oxford University Press, 2008) and author/co-author of more than 70 open technical publications (papers, reports, articles and book chapters - appended).

Experience

Risk Assessment Corporation, Neeses, South Carolina, USA (2002–present)
Technical Coordinator

Cascade Scientific, Bend, Oregon, USA
President/Owner (1999–present)

Senior Consultant

Consultant in all areas of environmental risk assessment with emphasis on public exposures to radionuclides and chemicals released to the environment. Work has been carried out for EPRI, US EPA, NCRP, NAS/NRC, Waste Control Specialists, Colorado Department of Public Health and Environment, Centers for Disease Control and Prevention, State of New Jersey Department of Environmental Protection, New Mexico Environment Department, Department of Justice, and State of Washington Office of Attorney General. Many projects have been performed in collaboration with Risk Assessment Corporation.

- Dose reconstruction of public exposures and risks from historical releases of radionuclides and chemicals from Rocky Flats in Colorado, the Savannah River Site in South Carolina and the Hanford Nuclear Facility in Washington.
- Audits of Los Alamos National Laboratory for compliance with the Clean Air Act, and Oak Ridge National Laboratory Rad NESHAPs Program and Dose Assessment Methodologies Required for DOE Order 5400.5
- Review and Development of Soil Action Levels for Clean Up of Rocky Flats
- Exposure and Risks from the Cerro Grande Fire at Los Alamos
- Development of scientific methods and tools to guide long term recovery decisions with stakeholder involvement following a radiological emergency.
- RACER - Development of web-based data management application that facilitates access to and use of environmental measurement data for a variety of applications, ranging from basic data evaluation to more complex analyses.

Teaching

- Environmental Risk Assessment Training Course H-420. Source Term Evaluation; Terrestrial Transport and Pathway Analysis; Exposure Scenarios, Dose and Risk Coefficients; Screening Approach Case Studies; Validation and Confirmatory Analysis; Case Study – The Fernald Historical Dose Reconstruction Project. Training Course H-420 prepared and presented by Risk Assessment Corporation for the U.S. Nuclear Regulatory Commission at the NRC Professional Development Center, Three White Flint North, Maryland. April 27–May 1, 2015. 9 Attendees
- Radiological Risk Assessment for Decision Making, Compliance, and Emergency Response. Exposure Scenarios; Model Validation and Testing. Crystal City Marriott, Arlington, VA. Risk Assessment Corporation. March 4–8, 2013. 52 Attendees.
- Radiological Risk Assessment for Decision Making, Compliance, and Emergency Response. Scenarios of Exposure, Defining the Representative Individual; Model Validation and Testing. Crystal City Marriott, Arlington, VA. Risk Assessment Corporation. March 5–9, 2012. 37 Attendees.

- Radiological Risk Assessment and Environmental Analysis Course. Uncertainty in Assessment Models and Validation; Case Studies: Pulling it all Together; RACER: A Process and Tools for an Integrated Approach to Risk Assessment. ITC School of Underground Waste Storage and Disposal. University of Bristol Risk Centre, Bristol, United Kingdom. June 22–26, 2009. 17 Attendees.
- Environmental Risk Assessment Analysis Training Course H-401. Source Term Evaluation; Exposure, Dose and Risk Assessment; Practical Application of Models to Risk Assessment; Validation and Confirmatory Analysis; Continuing the Environmental Risk Assessment Process. Training Course H-401 prepared and presented by Risk Assessment Corporation for the U.S. Nuclear Regulatory Commission at the NRC's Professional Development Center, Bethesda, Maryland. January 26–30, 2009. 23 Attendees.
- Risk Assessment for Radioactively Contaminated Sites: Los Alamos Case Study. Geologic Disposal of High-Level Waste. ITC School of Underground Waste Storage and Disposal. September 2–5, 2008. Las Vagas, Nevada. 25 Attendees.
- Risk Assessment for Radioactively Contaminated Sites: Los Alamos Case Study. Geologic Disposal of High-Level Waste. ITC School of Underground Waste Storage and Disposal. June 25–28, 2007. Las Vagas, Nevada. 24 Attendees.
- Conversion to Dose and Risk. Part of Three Short Courses for Regulators and Radiation Health Specialists: Emerging Topics in Radiation Protection and Risk Assessment. March 16–18, 2004. Kiawah Island, South Carolina. 25 Attendees.
- Model Testing and Uncertainty. Part of Three Short Courses for Regulators and Radiation Health Specialists: Emerging Topics in Radiation Protection and Risk Assessment. March 16–18, 2004. Kiawah Island, South Carolina. 25 Attendees.
- Testing Models Used for Risk Assessment. Part of a five-day course developed and presented by Risk Assessment Corporation. Calculating and Understanding Risks from Radionuclides Released to the Environment. November 15–19, 1999. Seattle, Washington. 40 Attendees.
- Testing Models Used for Risk Assessment. Part of a five-day course developed and presented by Radiological Assessment Corporation. Calculating and Understanding Risks from Radionuclides Released to the Environment. April 28–May 2, 1997. Santa Fe, New Mexico. 150 Attendees.

Intera Information Technologies (1989–1992)
Environmental Systems Assessment Group

Senior Consultant

Involved in a wide range of projects concerned with the assessment of radioactive and nonradioactive hazardous wastes. Provided technical assistance to Nagra to coordinate and execute the Kristallin I and Wellenberg '92 safety assessments for high-level waste and low-/intermediate-level waste disposal. Responsible for technical coordination of Intera contracts with Nagra. Key projects included the following:

- Technical secretariat to BIOMOVS (BIospheric MOdel Validation Study) – an international cooperative effort to test models designed to quantify the transfer and accumulation of radionuclides and other trace substances in the environment.

- Developed an outline methodology for the comparative assessment of environmental impacts from landfilled wastes generated by prescribed processes for Her Majesty's Inspectorate of Pollution, Department of the Environment.
- Conducted a project for the Commission of the European Communities (CEC) in collaboration with IMA (Spain) to compare the approaches used to justify land based disposal of toxic wastes and solid radioactive wastes, to identify where technical improvements to these approaches could be made, and to develop methods for their implementation.
- Conducted scenario analyses for the Nagra Kristallin I and Wellenberg projects and developed the supporting databases to provide a structured and consistent framework for identifying important phenomena (features, events, and processes)
- that need to be accounted for in repository performance assessment.
- Investigated the post-disposal implications of gas generated from a low- /intermediate-level waste repository for Nagra.

Eidg. Institut für Reaktorforschung (EIR) (1984–1989)
Repository Performance Assessment Group

EIR (now the Paul Scherrer Institute [PSI]) was the Swiss Federal Institute for Reactor Research.

Research Scientist

- Responsible for the biosphere modelling aspects of the performance assessment of high-level waste and low-/intermediate-level waste repositories.
- Contributed to Projekt Gewähr 1985 (demonstration of radwaste disposal feasibility in Switzerland)
- Spent summer of 1987, working with Robert Gardner, Ph.D and F. Owen Hoffman at Oak Ridge National Laboratory to gain experience in probabilistic modelling techniques.
- Development of quantitative geomicrobiological models. Appointed technical coordinator of the new Nagra microbiology program, in April 1988, which was designed to quantitatively consider microbial effects in a radioactive waste repository for use in subsequent performance assessments. This effort involved coordinating research groups within Switzerland and other European countries.
- January 1988, appointed sub-program leader for the geosphere and biosphere transport modelling. This work encompassed performance assessment in general, including scenario evaluation and consequence analysis.
- Actively participated in BIOMOVS. As chairperson for test scenario B2 (Irrigation with Contaminated Groundwater), was responsible for producing and editing the technical report presenting the study results.

Committee Memberships

Member, U.S. Delegation, 62st Session of United Nations Scientific Committee on the Effects of Atomic Radiation. Vienna, Austria. 1–5 June, 2015.

Member, U.S. Delegation, 61st Session of United Nations Scientific Committee on the Effects of Atomic Radiation. Vienna, Austria. 21–25 July, 2014.

Member, National Council on Radiation Protection and Measurements Scientific Committee 3-1 "Guidance for Emergency Responder Dosimetry," 2014–present.

Chair, IAEA consultancy to develop guidance on management of large amounts of radioactive waste after an emergency situation, 2013–present.

Member, Institute of Medicine of the National Academies "Research Directions in Human Biological Effects of Low Level Ionizing Radiation," 2013–2014.

Advisor, National Council on Radiation Protection and Measurements Scientific Committee 5-1 "Decision Making for Late-Phase Recovery from Nuclear or Radiological Incidents," 2011–2013.

Member, National Council on Radiation Protection and Measurements Scientific Committee 1-19 "Health Protection Issues Associated with Use of Active Detection Technology Security Systems for Detection of Radioactive Threat Materials," 2009–2011.

Member, National Academy of Sciences Committee to Review the "Worker and Public Health Activities Program Administered by the Department of Energy and the Department of Health and Human Services," 2005–2006.

Member, Merit Panel, "Review of the Preliminary Performance Assessment for Waste Management Area C at the Hanford Site, Washington." Convened by CH2M-Hill Hanford Group Inc. with concurrence of the Department of Energy and the State of Washington Department of Ecology, 2004.

Member, Radiation Advisory Committee, Science Advisory Board, U.S. Environmental Protection Agency, 2001–2007.

Consultant, Environmental Models Subcommittee, Executive Committee, U.S. Environmental Protection Agency, 1999–2000.

Member, Scientific Committee on Dose Reconstruction, National Council on Radiation Protection and Measurements, 1994–2000.

Professional Society Memberships

American Association for the Advancement of Science

Member, National Council on Radiation Protection and Measurements (NCRP), 2014

Health Physics Society

Education / Professional Qualifications

Ph.D. in Radioecology, Imperial College of Science and Technology, University of London, 1984

"Pathways of Radionuclides from Soils into Crops Under British Field Conditions."

B.Sc 2(1) in Botany, Imperial College of Science and Technology, University of London, 1980

Diploma of Imperial College, University of London, 1980

Associate of the Royal College of Science, University of London, 1980

Nationality: American / British

Languages: English, German, intermediate French

List of Open Publications: January 2015

Book Publications

Institute of Medicine and National Research Council of the National Academies. 2014. *Research on Health Effects of Low-Level Ionizing Radiation Exposure – Opportunities for the Armed Forces Radiobiology Research Institute.* Review Committee Members– Hricak, H. (Chair), D.J. Brenner, L.T. Dauer, G.X. Ding, F. Dominici, **H.A. Grogan**, D. Hoel, E.F. Maher, W.F. Morgan, G. Pion, D. Richardson, R. Wilkins. The National Academies Press, Washington, DC.

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

National Research Council of the National Academies. 2006. *Review of the Worker and Public Health Activities Program Administered by the Department of Energy and the Department of Health and Human Services.* Review Committee Members–Przybylowicz, E.P (Chair), E.H. Clark II, I. Feller, P. Fenner-Crisp, R.W. Field, S.M. Friedman, **H.A. Grogan**, J. Mandel, G. Paulson, R.K. Sokas, D.O. Stram, T. Zheng. The National Academies Press, Washington, DC.

Referred Publications / Book Chapters

Till, J.E., H.L. Beck, J.W. Aanenson, **H.A. Grogan**, H.J. Mohler, S.S. Mohler, P.G. Voillequé. 2014. Military Participants at U.S. Atmospheric Nuclear Weapons Testing-Methodology for Estimating Dose and Uncertainty. *Radiat Res.* 181, 471 – 484.

J.E. Till, **H.A. Grogan**, H.J. Mohler, J.R. Rocco, S.S. Mohler. 2012. "An Integrated Approach to Data Management, Risk Assessment, and Decision Making." *Health Physics*, 102 (4), April.

Mohler, H.J., **H.A. Grogan**, J.R. Rocco, R.F. Kiefer, and J.E. Till. 2012. RACER: Dynamic Use of Environmental Measurement Data for Decision Making and Communication. *Operational Radiation Safety*, Vol. 102, Suppl 1. February.

McKinley, I.G., **H.A. Grogan** and L.E. McKinley. 2011. Fukushima: Overview of Relevant International Experience. *Journal of Nuclear Fuel Cycle and Environment* 18 (2): 89–100.

National Council on Radiation Protection and Measurement (NCRP). 2011. Radiological Health Protection Issues Associated With Use of Active Detection Technology Systems for Detection

of Radioactive Threat Materials. NCRP Commentary No. 22. NCRP, Bethesda, MD. September.

Grogan, H.A. 2008. "Model Validation." Chapter 14 in *Radiological Risk Assessment and Environmental Analysis.* Oxford University Press, New York. pp. 589-612.

Rood, A.S., P.G. Voillequé, S.K. Rope, **H.A. Grogan**, and J.E. Till. 2008. Reconstruction of atmospheric concentrations and deposition of uranium and decay products released from the former uranium mill at Uravan, Colorado. *J. Env. Radioactivity* 99:1258–1278.

Mohler, H.J., K.R. Meyer, **H.A. Grogan**, J.W. Aanenson, and J.E. Till. 2004. Application of NCRP Air Screening Factors for Evaluating Both Routine and Episodic Radionuclide Releases to the Atmosphere. *Health Physics* 86(2): 135–144.

Till, J.E., A.S. Rood, P.G. Voillequé, P.D. McGavran, K.R. Meyer, **H.A. Grogan**, W.K. Sinclair, J.W. Aanenson, H.R. Meyer, H.J. Mohler, S.K. Rope, and M.J. Case. 2002. Risks to the Pubic from Historical Releases of Radionuclides and Chemicals at the Rocky Flats Nuclear Weapons Plant. *J. Exp. Analysis and Env. Epidemiology* 12: 355–372.

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Professional Certification

Certified Laser Safety Officer, 2002

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National Registry of Radiation Protection Technologists, 1998

Fellow, American College of Forensic Examiners, 1996

Academic Positions

(2012–2015) Elected Head, Radiation Protection & Measurements Section, Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, CO

(2011–present) Associate Professor, Health Physics, Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, CO

(2005–2011) Assistant Professor, Health Physics, Department of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, CO

(1998–2005) Assistant Professor, Health Physics, Department of Preventive Medicine and Biometrics, Uniformed Services University of the Health Sciences, Bethesda, MD

(1994–1997) Teaching Assistant, Department of Health Sciences, Industrial Hygiene and Health Physics, Purdue University, West Lafayette, IN

(1993–1994) Teaching Assistant, Department of Environmental Engineering, Industrial Hygiene and Health Physics, Northwestern University, Evanston, IL

Other Positions

(2011–2012) Appointed to the U.S. EPA Radiation Advisory Committee augmented In- Situ Recovery Panel

(2015) Chair, State of Colorado Radiation Advisory Committee

(2010–2018) Appointed by Governors Ritter (2010) and Hickenlooper (2013, 2016) to represent higher education on the Colorado Radiation Advisory Committee

(1997–1999) Consulting Health Physicist, CSI - Radiation Safety Training and Consulting, Kensington, MD

(1995) Health Physicist, Commonwealth Edison, Braidwood, IL

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(1993) Industrial Hygienist and Health Physicist, The Dow Chemical Company, Midland, MI

(1992–1993) Safety and Quality Control Engineer, Northern Indiana Public Service Co., Merrillville, IN

(1990–1992) Pressure Vessel Inspector and Risk Assessment Analyst, The Chubb Group, Chicago, IL

Military

(2005–2009) Senior Health Physicist, (reservist) Air Force Radiation Assistant Team, Brooks Air Force Base, TX (AFRAT)

(2000–2005) Program Reviewer, (reservist) Air Force Office of Scientific Research (NE), Ballston, VA

(1997–2000) Technical Advisor, (reservist), USAF Surgeon General's Radioisotope Committee, Air Force Medical Operations Agency, SGOR Bolling AFB, DC

(1994–1997) Medical Physicist, (reservist), Radiation Safety Office, Air Force Reserves, Wright Patterson Medical Center, SGORP WPAFB, OH

(1986–1990) Engineering Laboratory Technician, USS Cavalla (SSN 684), F.P.O. San Francisco, CA

Honors and Awards

(2014) Fellow, Health Physics Society

(2012) CVMBS Graduate Advisor Award, Colorado State University

(2010) N. Preston Davis Award, Colorado State University

(2010) CVMBS Innovative Instructional Methodology Award in Graduate Education, Colorado State University

(2007) CVMBS Innovative Teaching Award, Colorado State University

(2007) Honorable Mention Award, Great Plains University Continuing Education Association

(2005) Meritorious Service Medal, USAF Reserve

(2003) Air Force Commendation Medal, USAF Reserve

(2001) Air Force Organizational Excellence Award, USAF Reserve

(2000) Air Force Achievement Medal, USAF Reserve

(1997) Air Force Longevity Service Award, USAF Reserve

(1996) Air Force Outstanding Unit Award, USAF Reserve

(1995) Air Force Training Ribbon, USAF Reserve

(1996) Health Physics Society Scholarship Recipient

(1995) Rho Chi Honor Society for Health Sciences, Purdue University

(1994) National Defense Service Medal, USAF Reserve

(1994, 1995) Health Physics Society Summer School Scholarship Recipient

(1988, 1989) Dean's List, Southern Illinois University

(1988) Navy Good Conduct Medal, USN

(1987) Qualified Submarines, USN

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Textbooks

H. Cember, T.E. Johnson, 2009 The Health Physics Solutions Manual, 2nd Edition, P.S. & E. Press, Silver Spring, MD (ISBN 0-9625963-8-8), 518 pages. Completely responsible for all revisions after passing of Herman Cember in March 2009.

H. Cember, T.E. Johnson, 2008, Introduction to Health Physics, 4th Edition, McGraw-Hill, NY, (ISBN 0071423087) 806 pages. Responsible for editing/updates of all chapters and complete revision of Chapter 14. Sales as of August 2010, Domestic: 2117, International: 735.

H. Cember, T.E. Johnson, 1999, The Health Physics Solutions Manual, P.S. & E. Press, Silver Spring, MD (ISBN 0-9625963-6-1), 442 pages. Performed majority of work in preparing manuscript.

Refereed Chapters in Books

H. Cember, T.E. Johnson, 2010. Physical Agents, Ionizing Radiation, Volume 4, Chapter 29, In: Patty's Toxicology 6th edition, edited by Vernon Rose, John Wiley & Sons. Completely revised and updated chapter upon Herman Cember's passing in March 2009.

J.A. Johnson, T.E. Johnson, S. Brown, 2009, Uranium Recovery Operations, Chapter 4 In: NORM/TENORM Health Physics Society Professional Development School Textbook, Edited by P. Andrew Karam and Brian J. Vetter, (ISBN 978-1-930524-47-7) Medical Physics Publishing, Madison WI. pp. 50-109. Prepared all numerical examples and sections on dose, approximately 33% of the text.

Refereed Proceedings/Transactions

Long term stability of sensation thresholds from 10 ms pulses of 2.01μm laser light Ernest L. Scott, Thomas E. Johnson* SPIE, Photonics West, January, 2013.

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T.E. Johnson, N. Keeler, J.E. Dennis, C.L. Figueroa, H.A. Press, R. J. Rockwell Jr., B.E. Stuck, W.P. Roach, A.L. Wartick, 2003 "Investigation of Laser Injuries" In: Laser and Noncoherent

Light Ocular Effects: Epidemiology, Prevention, and Treatment III, Bruce E. Stuck; Michael Belkin M.D., Vol. 4953, pp.61-69. *#

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T.E. Eurell, T.E. Johnson, W.P. Roach, 2002 "Morphometric Comparison of the Acute Rabbit Corneal Response to 1540 nm Laser Light Following In Vitro Exposure to Millisecond or Nanosecond Pulse Widths" In: Laser Tissue Interaction XIII: Photochemical, Photothermal, and Photomechanical, Steven L. Jacques; Donald D. Duncan; Sean J. Kirkpatrick; Andres Kriete, Vol. 4617, pp.26-29.

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W.P. Roach, B. K. Ketzenberger, T.E. Johnson, 2002 "Corneal Injury from 1318-nm Single Laser Pulses" In: Laser Tissue Interaction XIII: Photochemical, Photothermal, and Photomechanical, Steven L. Jacques; Donald D. Duncan; Sean J. Kirkpatrick; Andres Kriete, Vol. 4617, pp. 30-39 .*#

T.E. Eurell, T.E. Johnson, W.P. Roach, 2001 "A morphometric comparison of the acute rabbit and pig corneal response to 1540 nm laser light following ex vivo exposure" In: Laser and Noncoherent Light Ocular Effects: Epidemiology, Prevention, and Treatment, Bruce E. Stuck; Michael Belkin M.D., Vol 4246; pp. 180-184.

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W. P. Roach, T.E. Eurell, T.E. Johnson, 2001 "A morphometric comparison of the acute rabbit and pig corneal response to 1540 nm laser light following ex vivo exposure," In: Vol. 4246: Laser

and Noncoherent Light Ocular Effects: Epidemiology, Prevention, and Treatment, Bruce E. Stuck; Michael Belkin M.D., Vol. 4246, pp. 89-96.

B. Ketzenberger, T.E. Johnson, Stephen P. Wild, Kenneth B. Pletcher, and W. P. Roach, 2001 "ED50 Determination and Histological Characterization of Epithelial Layers in Animal Models: Lesions Produced by 1318 nm Laser Radiation Pulses" In: Lasers in Surgery: Advanced Characterization, Therapeutics, and Systems XI, R. Rox Anderson M.D.; Kenneth E. Bartels D.V.M.; Lawrence S. Bass M.D.; C. Gaelyn Garrett M.D.; Kenton W. Gregory M.D.; Abraham Katzir; Nikiforos Kollias; Michael D. Lucroy D.V.M.; Reza S. Malek M.D.; J. Stuart Nelson M.D.; George M. Peavy D.V.M.; Hans-Dieter Reidenbach; Lou Reinisch; David S. Robinson M.D.; Lloyd P. Tate V.D.M.; Eugene A. Trowers M.D.; Timothy A. Woodward M.D. Vol. 4244, pp. 544-551. *#

T.E. Johnson, M.A. Mitchell, P.J. Rico, D. J. Fletcher, T.E. Eurell, W.P. Roach, 2000 "Corneal and Skin Laser Exposures from 1540 nm Laser Pulses" In: Laser-Tissue Interaction XI: Photochemical, Photothermal, and Photomechanical, Donald D. Duncan; Jeffrey O. Hollinger D.D.S.; Steven L. Jacques, Vol. 3914, pp. 222-229. *#

D.J. Fletcher, T.E. Johnson, M.A. Mitchell, T.E. Eurell, P.J. Rico, W. P. Roach, 2000 "Corneal Equivalents: a Replacement Model for In-vivo 1540 nm Laser Exposure Studies" In: Lasers in Surgery: Advanced Characterization, Therapeutics, and Systems X, R. Rox Anderson M.D.; Kenneth E. Bartels D.V.M.; Lawrence S. Bass M.D.; C. Gaelyn Garrett M.D.; Kenton W. Gregory M.D.; Nikiforos Kollias; Harvey Lui M.D.; Reza S. Malek M.D.; George M. Peavy D.V.M.; Hans-Dieter Reidenbach; Lou Reinisch; David S. Robinson M.D.; Lloyd P. Tate V.D.M.; Eugene A. Trowers M.D.; Timothy A. Woodward M.D. Vol. 3907, p. 468-475. *#

P.J. Rico, M.A. Mitchell, T.E. Johnson, W. P. Roach, 2000 "ED50 determination and histologic characterization of porcine dermal lesions produced by 1540 nm laser radiation pulses" In: Lasers in Surgery: Advanced Characterization, Therapeutics, and Systems X, R. Rox Anderson M.D.; Kenneth E. Bartels D.V.M.; Lawrence S. Bass M.D.; C. Gaelyn Garrett M.D.; Kenton W. Gregory M.D.; Nikiforos Kollias; Harvey Lui M.D.; Reza S. Malek M.D.; George M. Peavy D.V.M.; Hans-Dieter Reidenbach; Lou Reinisch; David S. Robinson M.D.; Lloyd P. Tate V.D.M.; Eugene A. Trowers M.D.; Timothy A. Woodward M.D., Vol. 3907, p. 476-483. *#

T. E. Johnson, T. A. Eggleston, D. Fletcher, K. Lopez, P.J. Rico, M.A. Mitchell, W.P. Roach, 1999 "Determination of Single-Pulse Exposure Threshold (ED50) for 1400 – 2000 nm Lasers" In: Laser-Tissue Interaction X: Photochemical, Photothermal, and Photomechanical, Steven L. Jacques; Gerhard J. Mueller; Andre Roggan; David H. Sliney, Vol. 3601, pp.55-58. *#

T.A. Eggleston, M. Mitchell, T.E. Johnson, W.P. Roach, 1999 "Comparison of In Vivo Skin Models for Near Infrared Laser Exposure" In: Lasers in Surgery: Advanced Characterization, Therapeutics, and Systems IX, R. Rox Anderson M.D.; Kenneth E. Bartels D.V.M.; Lawrence S. Bass M.D.; Darryl J. Bornhop; C. Gaelyn Garrett M.D.; Kenton W. Gregory M.D.; Nikiforos Kollias; Harvey Lui M.D.; Reza S. Malek M.D.; Aaron P. Perlmutter M.D.; Hans-Dieter Reidenbach; Lou Reinisch; David S. Robinson M.D.; Lloyd P. Tate V.D.M.; Eugene A. Trowers M.D, Vol. 3590, pp. 356-360. *#

Non-Refereed Journal Articles/Chapters/Proceedings/Transactions

T.E. Johnson, 2013, Central Rocky Mountain Chapter Update, in: Health Physics Society Newsletter, Vol. XLI p.11.

T.E. Johnson, 2012, Getting to know the HPS, in: Health Physics Society Newsletter, Vol. XL p.29.
T.E. Johnson and A. Brandl, 2011, Central Rocky Mountain Chapter Update, in: Health Physics Society Newsletter, Vol. XXXIX p.11.
T.E. Johnson, 2010, Colorado State University Student Branch Activities, In: Health Physics Society Newsletter, Vol. 38, No. 7, pp. 9.
T.E. Johnson, 2010, ANSI Z136 Annual Meeting Updates, In: Laser Institute of America Newsletter, No. 2 pp. 20.
T.E. Johnson, 2009, Central Rocky Mountain Chapter of the Health Physics Society sponsors two CSU students, In: Health Physics Society Newsletter, Vol. 37, No. 12, pp. 8.
J. Sorcic, T.E. Johnson, 2009, Colorado State University Student Branch Activities, In: Health Physics Society Newsletter, Vol. 37, No. 8, pp. 7.
T.E. Johnson, 2009, CRMCHPS Annual Technical Meeting at CSU, In: Health Physics Society Newsletter, Vol. 37, No. 6, pp. 18-19.
A.E. Draine, J. Sorcic, T.E. Johnson, 2009, Colorado State University Student Branch Activities, In: Health Physics Society Newsletter, Vol. 37, No. 1, pp. 8.
T.E. Johnson, 2008, ANSI Z136 Annual Meeting Updates, In: Laser Institute of America Newsletter, pp.10.
T.E. Johnson, 2008, Annual ANSI Z136 Laser Safety Meeting, In: Health Physics Society Newsletter, Vol. 36, No. 4, p. 14.
T.E. Johnson, 2007, "American National Standards Institute Standards for Nonionizing Radiation," In: Health Physics Society Newsletter, Vol. 35, No. 12, p. 16-17.
T.E. Johnson, 2006, "Annual Meeting Focuses on Updates," In: Vol. 14, No. 3, p. 1 and 8.
T.E. Johnson, 2006 "Annual ANSI Z136 Laser Safety Meeting," In: Health Physics Society Newsletter, Vol. 34, No. 5, p. 23-24.
T.E. Johnson, W.P. Roach, 2002 "Solution to question 9 from the American Board of Health Physics Exam," In: Health Physics Society Newsletter, p. 10.
T.E. Johnson, 1997, "The Problem With Tritium in Beer," In: Baltimore-Washington Chapter of the Health Physics Society Chapter Newsletter, pp.3-4.

Performances, Exhibits, Productions (Visual/Performing Arts)

Clinics/Adjudications/Workshops

2008. "Uranium Technical Symposium." Colorado State University (worldwide distribution). Videotaping, editing, and producing a four-DVD set for distribution to the public. Almost eight hours of video were produced. Approximately 50 copies were produced and distributed.

Non-Juried Activities

2009. "Seminar Series in Health Physics." Colorado State University (worldwide distribution). Videotaping, editing, and producing seminars in health physics for the MAP ERC website for continuing education. Five videos have been posted to date.

2006, 2007, 2008, 2009. "Health Physics Exam Review." Colorado State University (worldwide distribution). Videotaping, editing, and producing and annual updating of EDLL 2005. Approximately 50 hours of video were produced for both streaming and use on an iPod. Over 100 copies of the entire production distributed.

2009. "Radioecology." Colorado State University (worldwide distribution). Videotaping, editing, and producing of ERHS 570. Approximately 30 hours of video are in the process of being produced for both streaming and use on an iPod. This video is capturing Dr. Ward Whicker, as he is retiring, and will make his lecture material available for future classes for reference.

Papers Presented/Symposia/Invited Lectures/Professional Meetings/Workshops

Invited Lectures and Presentations

2013. "Laser User's Perspective on Laser Safety" with Benjamin Rockwell, ILSC, Orlando, FL.

2012. "Livestock Decontamination Considerations" Webinar, CSU Extension.

2012. "Livestock Decontamination." Dr Herman Cember memorial presentation, AIHA annual meeting, Indianapolis, IN.

2011. "Decontamination of Livestock." EFCOG SOMD, at NREL, Golden, CO.

2011. "Uranium Mining, Milling and Enrichment." University of Ontario Institute of Technology, Ontario, Canada.

2010. "In Situ Uranium Mining." Fort Collins Rotary Club, presenter, Fort Collins, CO.

2009. "In-situ Uranium Mining." Weld County Commissioners, presenter, Greeley, CO.

2009. "Uranium Fuel Cycle Impacts." Global Uranium Symposium, U2009, presenter, Keystone, CO.

2009. "Advanced Health Physics Problem Solving." Navy and Marine Corps Occupational Health and Preventive Medicine Conference, presenter, Portsmouth, Virginia.

2006. "Workshop on Solving Advanced Health Physics Problems." U.S. Army Center for Health Promotion and Preventive Medicine, presenter, Aberdeen Proving Ground, MD.

2006. "Power Lines, Politics and Pulses." University of Michigan, presenter, Ann Arbor, MI.

2003. "Trends in Laser Injury Reporting." Keynote speaker, Joint International Laser Conference, prepared materials for student to present (K. Clark), Edinburgh, Scotland.

2001. "Airborne Radioactive Materials Transport." Baltimore-Washington Chapter of the Health Physics Society, presenter, Bethesda, MD.

2000. August 2000 'Radiation Bioeffects.' presenter, USAF School of Aerospace Medicine, Brooks AFB, TX.
2000. "Radioactive Decay." presenter, Baltimore-Washington Chapter of the Health Physics Society Review Class, White Flint, MD.
1999. "C.H.P. Certification Review Class." instructor and coordinator, Air Force Office of Scientific Research, Bethesda, MD.
1998. "Statistics Review for Health Physicists." presenter, Baltimore-Washington Chapter of the Health Physics Society, White Flint, MD.

Professional Meetings

2014. Shatila, O., Johnson, T., "A Review of Radiation Doses at Oil Extraction Sites" 59th Annual HPS meeting, Baltimore, MD, July, 2014.
2014. Ruedig, E., Borch, T., Bhattacharyya, A., Johnson, T. "Model-Model Intercomparison of Risk Assessment at an In Situ Recovery Uranium Mine Located in Wyoming, USA", 59th Annual HPS meeting, Baltimore, MD, July, 2014.
2014. Johnson, T., Daxon, E., Ruedig, E. "A Brief History of Emergency Responder Dose Recommendations" 59th Annual HPS meeting, Baltimore, MD, July, 2014.
2014. Daxon, E., Johnson, T., Ruedig, E. "An Argument for Using Health Risk in Place of Dose Guidance in Operational Decision Making in Radiological Emergencies" 59th Annual HPS meeting, Baltimore, MD, July, 2014.
2014. Martinez, N.E., T.E. Johnson, E. Ruedig, J.E. Pinder III, "Comparison of rainbow trout phantoms for estimation of whole body and organ radiation dose rates from uptake of iodine-131 in freshwater systems," International Conference on Radioecology and Environmental Radioactivity, 2014.
2013. Transitioning from Radiation Safety to Health Risk for Emergency Response: Complete the Separation.
2013. Daxon, E., Johnson, T. 58th Annual HPS Meeting, Madison, Wisconsin, July 11, 2013.
2013. The Development of a Livestock Decontamination Protocol. Sprenger, P., Brandl, A., Johnson, T. 58th Annual HPS Meeting, Madison, Wisconsin, July 11, 2013.
2013. Areal Radiological Surveys - A Comparison of Radiation Detection Technologies. Bailey, D., Cardarelli, J., Johnson, T. 58th Annual HPS Meeting, Madison, Wisconsin, July 11, 2013.
2013. Perceptions of Product Irradiation in a College Population Condon, C., Johnson, T., Peel, J. 58th Annual HPS Meeting, Madison, Wisconsin, July 11, 2013.
2013. Aerosol Size Distribution in the Schwartzwalder Uranium Mine Liu, X., Doerges, J., Volckens, J., Johnson, T. 58th Annual HPS Meeting, Madison, Wisconsin, July 11, 2013.
2013. A Health Physics Student's Experience at the AECL ZED-2 Reactor Physics Winter School Edquist, B., Parson, J., Johnson, T. 58th Annual HPS Meeting, Madison, Wisconsin, July 11, 2013.
2013. Martinez, N.E. and T.E. Johnson, "Community involvement of the Colorado State University Health Physics Program: Ideas for boosting interest in and understanding of radiation and radiation protection," 58th Annual HPS Meeting, Madison, Wisconsin, July 11, 2013.
2013. Martinez, N.E., J.E. Pinder III, T.E. Johnson, "The Influence of Lake Trophic Structure on 131-I Accumulation and Subsequent Cumulative Radiation Dose to Trout Thyroids," 12th International Conference of the Biogeochemistry of Trace Elements. Athens, Georgia, June 17, 2013 (Invited).

2013. Martinez, N.E., S.L. Kraft, and T.E. Johnson, "A Proposed Simple Model for Occupational Radiation Dose to Staff From Veterinary 18F-FDG PET Procedures," 5th Annual NIOSH Mountain & Plains Education and Research Center Research Day, Denver, Colorado, April 4, 2013.

2013. J.R. Schilz, K.J. Reddy, S. Nair, T.E. Johnson, R.B. Tjalkens, K.P. Krueger, S. Clark, Adsorption of Arsenic by Cupric Oxide Nanoparticles* from Uranium In Situ Recovery Bleed Water and Effects on Cell Viability, 12th International Conference on the Biogeochemistry of Trace Elements - ICOBTE 2013, Athens, GA.

2012. Martinez, N.E., T.E. Johnson, T.G. Hinton, F.W. Whicker, J.E. Pinder, "The Transfer of Cesium Through Aquatic Trophic Levels Following Releases into Experimental Ponds," Poster presentation, Workshop on Radioecology in the 21st Century hosted by the National Center for Radioecology, Aiken, South Carolina, August 15, 2012.

2012. Dayton McMilian, A. Brandl, T.E. Johnson, Livestock Decontamination. Washington DC, IND forum.

2012. Martinez, NE; Kraft, SL; Ryan, SD; Johnson, TE, Occupational External Radiation Dose to Personnel Involved in Veterinary Positron Emission Tomography Procedures, IRPA 13, Glasgow, Scotland.

2011. Empirical Comparison of Neutron Activation Sample Analysis Methods - Gillenwalters, E., Johnson, T., Pinder, J., Kearney, P. HPS meeting, Palm Beach Florida.

2011. A Comparison of MCNP Modeling against Empirical Data for the Measurement of the Effectiveness of Lead Apron Shielding - Adams, D., Lee, M., George, G., Brandl, A., Johnson, T. HPS meeting, Palm Beach Florida.

2011. Laser Damage Thresholds of Ex-Vivo Pig and Rabbit Corneas at 2500 and 2700 nm with 8 ns Laser Pulse Duration - Guo, Y., Johnson, T. HPS meeting, Palm Beach Florida.

2011. Occupational Radiation Exposure to Personnel in Veterinary Positron Emission Tomography - Martinez, N.E., Kraft, S.L., Ryan, S.D., Johnson, T.E HPS meeting, Palm Beach Florida.

2011. Efficacy of Coffee Makers at Removing Contaminants - Nguyen, V., Johnson, T., Brattin, B., Dooley, G., Ramsdell, H. HPS meeting, Palm Beach Florida.

2011. The Transfer of Cs Trhough Aquatic Trophic Levels Following Releases into Experimental Ponds - Martinez, N., Johnson, T., Hinton, T., Whicker, W., Pinder, J. HPS meeting, Palm Beach Florida.

2011. Involvement of Different Mechanisms in Heavy Ion and Gamma Ray Induced Hepatocellular Carcinoma of Mice - Liu, X., Bedford, J., Ray, F., Genik, P., Fallgren, C., Battaglia, C., Ullrich, R., Johnson, T., Weil, M. HPS meeting, Palm Beach Florida.

2011. "Temperature increase of ex-vivo Corneas from multiple 2.01 micron incident laser pulses", E. Kelly, T.E. Johnson. Thirteenth Annual Directed Energy Symposium, 15-19 November 2010, Bethesda, Maryland Abstract ID 10-Symp-124.

2010. "A Comparison of the Stated Performance of Various Radon Measurement Instruments and Techniques" A. Riccardi, T.E. Johnson, presenter, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Characterizing Biomass Accumulation Dynamics in Uranium Bioremediation by Principal Component Analysis" H. Dong, T.E. Johnson, presenter, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Trends in Groundwater Chemistry Pre- and Post-Remediation at Irigaray and Grover In-Situ Uranium Mines" N. Roche, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Dosimetry and Partial Body Irradiation of Mice" C. Pedersen, F.R. Ray, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Determining Canine Organ Radiation Doses from PET-CT Procedures" N. Martinez, T.E. Johnson, S. Kraft, J.F. Harmon, D. Gibbons, student presented, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Determining the Activity in a Shipping Container Using a High Purity Germanium Detector" E.D. Gillenwalters, T.M. Debey, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Characterizing Canine Organ Radiation Doses from CT Procedures" C. Hall, J.F. Harmon, E. Randall, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Intentional Poisonings with Radioactive Materials" J. Sorcic, T.J. Johnson, student presented, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "The contribution of U-238 and Th-232 to Radiation Dose and Risk from Fly Ash Effluent of Coal Fired Power Plants." F. Beckfield, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Salt Lake City, UT.

2010. "Characterization of Canine Organ Radiation Doses from PET & CT Procedures" S.L. Kraft, N. E. Martinez, C. Hall, T.E. Johnson, D.S. Gibbons, E. Randall, J. F. Harmon, student presented, World Molecular Imaging, Montreal, Canada.

2009. "Monte Carlo Spectral Simulations as Microcalorimeter Gamma-Spectrometer Design Tool" E. Sassi, T.E. Johnson, M. Rabin, J. Ullom, student presented, Annual Meeting of the Health Physics Society, Minneapolis, MN.

2009. "The Medical X-ray Technologist: A potential Source of Health Physicists or Radiation Safety Officers?" F. Beckfield, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Minneapolis, Minnesota.

2009. "Radiofrequency Field Strength Fluctuation Due to Digital Conversion of Television Signals: a Pilot Study" P.B. Lane, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Minneapolis, MN.

2009. "Radioactive and Non-radioactive Contaminants in Aquifers Post In-situ Recovery Uranium Mining" A. Coler, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Minneapolis, MN.

2009. "Decommissioning a Major Medical Research Institution" A. Morton, T.E. Johnson, D. Elder, R. Safadi, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Minneapolis, MN.

2009. "Public Reaction to Uranium In-situ Recovery in Northern Colorado" T.E. Johnson, A.E. Draine, student presented, Annual Meeting of the Health Physics Society, Minneapolis, MN.

2008. "Groundwater Chemistry of the Grover Uranium In-Situ Recovery Pilot Test Site, Weld County" Hall, Susan M, Johnson, T.E., prepared part of presentation, Geological Society of America 2008 Joint Annual Meeting, Houston, TX.

2008. "Decontamination of Medical Radioisotopes from Hard Surfaces Using Peelable Polymer Based Decontamination Agents: Update" A.E. Draine, K.J. Walter, M.P. O'Neil, G.J.

Edgington, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Pittsburgh, PA.

2008. "The Long Path of Tc-99m Production in North America" M. Cervera, E. Waller, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Pittsburgh, PA.

2008. "Adventures in Public Information: A Uranium Case Study" J.A. Johnson, S.H. Brown, T.E. Johnson, prepared part of presentation, Annual Meeting of the Health Physics Society, Pittsburgh, PA.

2008. "Decontamination of Medical Radioisotopes from Hard Surfaces using Peelable Polymer-Based Decontamination Agents," A. E. Draine, K. J. Walter, M. P. O'Neill, T.E. Johnson, student presented, Health Physics Society Mid-Year Meeting, Oakland, CA.

2007. "Uranium Mining and Uranium Toxicity," T.E. Johnson, presenter, Rocky Mountain Chapter, American Society of Safety Engineers, Denver, CO.

2007. "NIOSH Training Programs in Health Physics" T. B. Borak, T.E. Johnson, presenter, Annual Meeting of the Health Physics Society, Portland, OR.

2007. "Variation in Gamma Emitter Concentration in Urine in a High Background Region R. Zhang, E. Crawford, T.E. Johnson," student presented, Annual Meeting of the Health Physics Society, Portland, OR.

2007. "Developing a Rapid Screening Method for ^{90}Sr Contamination in Urine" E. Crawford, J. LaRosa, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Portland, OR.

2007. "Distance Continuing Education On-line: Experiences of the Colorado State University Student Chapter of Health Physics Society." D. Elder, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Portland, OR.

2007. "Decontamination of a Fume Hood Contaminated with Tritiated Thymidine" K.J. Walter, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Portland, OR.

2007. "Decontamination of Nuclear Medicine Isotopes from Hard Surfaces using a Peelable Polymer-based Hydrogel" G.J. Edgington, M.P. O'Neill, T.E. Johnson, W.C. Gaul, M.S. Davidson, K.M. Lee, prepared part of presentation, Annual Meeting of the Health Physics Society, Portland, OR.

2007. "A method of measuring cutaneous laser injury thickness" C. Walker, T. Eurell, T. Johnson, student poster, Annual Meeting of the Health Physics Society, Portland, OR.

2006. "Gross Skin Response to 3.8 Micron Laser Pulses" T.E. Johnson, A. Wood, presenter, Annual Meeting of the Health Physics Society, Providence, RI.

2006. "Comparision of ESR Dosimetry in Human vs. Sus Scrofa Domestica Tooth Enamel" C. Heiserman, T. Johnson and J. Zimbrick, student poster, Annual Meeting of the Health Physics Society, Providence, RI.

2006. "Characterization of a Low Dose Rate Facility Using Radiochromic Film" T. Sirisalee Magers, R. Ullrich, T.E. Johnson, student presented, Annual Meeting of the Health Physics Society, Providence, RI.

2006. "Re-vitalizing a Radiation Dosimetry Laboratory Class" T.E. Johnson, J.D. Zimbrick, presenter, Health Physics Society Mid-Year meeting, Phoenix, Arizona.

2003. "Prediction of Bioeffects of Human Exposure to 3.8 micron Lasers" P. Williams, T.E. Johnson, student presented, The Non-lethal Technology and Academic Research Symposium V, Baltimore, MD.

2003. "Correlating In-vivo and In-vitro Models to Predict the Bioeffects of Human Exposure to 3.8 micron Lasers," P. Williams, T.E. Johnson, student presented, Directed Energy Weapons Symposium, Albuquerque NM.
2002. "Trends in Laser Injury Reporting," T.E. Johnson, Health Physics Society Annual Meeting, Tampa, FL .
2001. "Trends in Laser Injury" J. C. Dunn, T.E. Johnson, W.P. Roach, student presented, Baltimore Washington Chapter of the Health Physics Society Annual Meeting, Gaithersburg, MD.
2000. "Hazards Associated with 1540 nm Lasers" T.E. Johnson, W.P. Roach, presenter, Health Physics Society Annual Meeting, Denver, CO.
2000. "Effects of 1540 nm Laser Pulses on the Skin and Cornea" T.E. Johnson, W.P. Roach, presenter, Baltimore Washington Chapter of the Health Physics Society Annual Meeting, Gaithersburg, MD.
2000. "Misconceptions and Portable Radiation Detection Instrument Training" T.E. Johnson, Health Physics Society Midyear Meeting, Virginia Beach, VA.
1999. "Probability of Biological Effects from High Energy Infrared Lasers" T.E. Johnson, W.P. Roach, presenter, First High Energy Laser Probabilistic Risk Assessment Conference, San Antonio, TX.
1998. "Recent Experiences in Radiation Safety Officer Training" T.E. Johnson, presenter, Health Physics Society Mid-Year Meeting, Mobile, AL.
1997. "External Radiation Dosimetry" T.E. Johnson, USAF School of Aerospace Medicine, Health Physics Symposium, Brooks Air Force Base, TX.
1995. "Current Implications of the Chelyabinsk Nuclear Incident," T.E. Johnson, Purdue University Department of Health Sciences, West Lafayette, IN.
1994. "Evaluation of the Concentrations of 14C and 3H in Stack Gas, Water, and Ash Effluents Following Incineration of Radioactive Wastes Containing 14C and 3H," E.A. Crim, T.E. Johnson, prepared materials, Health Physics Society Annual Meeting, San Francisco, CA.

Workshops

2012. "CHP Review class" T.E. Johnson, presenter, Rio Grande Chapter Health Physics Society Annual Meeting, Santa Fe, NM.
2010. "Cloud Chamber Theory and Construction" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Salt Lake City, UT.
2009. "Uranium Mining and Milling" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Minneapolis, MN.
2008. "Uranium Mining and Milling" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Pittsburgh, PA.
2008. "Solving Complex Health Physics Problems Workshop" T.E. Johnson, presenter and organizer, U.S. Army Center for Health Promotion and Preventive Medicine, Aberdeen Proving Grounds, MD.
2008. "Overview of Part One of the CHP Exam" T.E. Johnson, presenter, Navy Occupational Health and Preventive Medicine Conference, Portsmouth, Virginia.
2008. "Overview of the Uranium Fuel Cycle" T.E. Johnson, presenter and organizer, Uranium Technical Symposium, Fort Collins, CO.

2007. "Non-ionizing radiation: An Overview of Incoherent Non-ionizing Radiation Hazards" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Portland, OR.

2007. "Identification and Control of Electromagnetic Fields (0-300 GHz)" B. Edwards, T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Portland, OR.

2007. "Non-ionizing Radiation: An Overview of Incoherent Non-ionizing Radiation Hazards" T.E. Johnson, presenter, Professional Enrichment Program, Annual Meeting of the Health Physics Society, Portland, OR.

2006. "Power Lines and Politics" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Providence, RI.

2005. "Laser Safety Audits" T.E. Johnson, presenter, Professional Enrichment Program, Annual Meeting of the Health Physics Society, Spokane, WA.

2004. "Radiological Detection Equipment" T.E. Johnson, presenter, AIHce Professional Development Course, Atlanta, GA.

2002. "Laser Safety Calculations Using the 2000 ANSI Z136.1 Standard" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Tampa, FL.

2001. "Laser Safety Calculations Using the 2000 ANSI Z136.1 Standard" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Cleveland, OH.

2000. "Laser Safety Calculations," T.E. Johnson and W.P. Roach, "presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, Denver, CO.

1997. "Problem Solving for Health Physicists" T.E. Johnson, presenter, Professional Enrichment Program, Health Physics Society Annual Meeting, San Antonio, TX.

Other Evidence

Nicole Martinez awarded F. Ward Whicker Scholarship by HPS (2012).

Nikolas Roche (Robert Gardner Fellowship) and Nicole Martinez (Burton J. Moyer Fellowship) awarded Health Physics Society Fellowships in Summer 2010.

Elizabeth Gillenwalters awarded a Health Physics Society Fellowship in Summer 2009.

Amanda Drain was awarded best poster at the MAP ERC First Annual Research Day held in conjunction with the Rocky Mountain Academy of Occupational and Environmental Medicine on January 16th, 2009.

Margaret Cervera was selected to receive the Richard J. Burke Jr. award from the Health Physics Society ($5000 cash award) based on her scholarship.

Jeffery Hibbert (Lone Star High School) was selected for best science fair project in his region in Colorado for 2008, and was judged number 2 at the state science fair. He won a $250 cash award from the Health Physics Society for his poster presentation. In 2009 he won the medallion award from both the Army and Air Force at the Colorado State Regional Science Fair, chosen to present at the International Science Fair, and will be competing at the State Science Fair in April 2009.

The following students received scholarships for travel to the Annual Health Physics Society meetings during their time at CSU based on their presentations at that meeting:

Ken Walter, Rui Zhang, Amanda Draine, Angela Coler, Clint Walker, Chris Heiserman, Margaret Cervera, Felicity Cunningham-Beckfield (two awards), Haitao Dong, Cheri Hall, Nicole Martinez, Alan Morton, Chris Pedersen, Nikolas Roche.

Advising

Graduate Students

Current Graduate Advisees

Omar Shatila Master of Science in Health Physics, Chair (2015)

Peter Sprenger Doctorate in Health Physics, Committee Member (2014)

Albert Riccardi Master of Science in Health Physics, Chair (2012)

Jonathan Elden, Doctorate in Electrical Engineering, Committee Member (2014)

Graduate Degrees Completed Under My Supervision *(past 5 years)*

Jonathan Elden, Master of Science in Electrical Engineering, Committee Member (2014)

John Klumpp, PhD, Committee member (2014)

Lisa Scallan, committee member (2014)

Sarah Sublett, committee member (2014)

Britt Mueller Master of Science in Health Physics, Chair (2014)

Lucas Hetrick Master of Science in Health Physics, Chair (2014)

Derek Bailey Master of Science in Health Physics, committee member (2014)

Nicole Martinez Doctorate in Health Physics, Chair (2014)

Ernie Scott Master of Science in Health Physics, Chair (2013)

Daniel Mannis Master of Science in Health Physics, committee member (2013)

David Dolan Master of Science in Health Physics, Chair (2013)

Ahamad Hussin Doctorate in Education, committee member (2013)

Alan Morton Master of Science in Health Physics, Chair (2012)

David Adams Master of Science in Health Physics, committee member (2012)

Aaron Miaullis Master of Science in Health Physics, Chair (2012)

Xianan Liu, Master of Science in Health Physics, Chair (2012)

Chris Pederson Master of Science in Health Physics, Chair (2012)

Yuanqing Guo Master of Science in Health Physics, Chair (2011)

Elizabeth Gillenwalters Master of Science in Health Physics, Chair (2011)

Cheri Hall Master of Science in Health Physics, committee member (2011)

Edward Kelly Master of Science in Health Physics, Chair (2011)

Nicole Martinez Master of Science in Health Physics, Chair (2011)

Nikolas Roche Master of Science in Health Physics, Chair (2011)

Jessica Nieset Doctorate in Health Physics, committee member (2010)

Felicity Cunningham Master of Science in Health Physics, Chair (2010)

Haitao Dong Master of Science in Health Physics, Chair (2010)

P. Brian Lane Master of Science in Health Physics, Chair (2010)

Joseph Sorcic Master of Science in Health Physics, Chair (2010)

D.N. Schaaf Doctorate in Health Physics, Chair (2010)

Margaret Cervera Master of Science in Health Physics, Chair (2009)

Amanda Draine Master of Science in Health Physics, Chair (2009)

Dan Dugan Master of Science in Health Physics, Chair (2009)

Matt Rosenbaum D.V.M. Master of Science in Microbiology Immunology Pathology, Chair (2009). First and only Laboratory Animal Medicine Resident to successfully defend a thesis, complete all requirements and graduate as scheduled.

Eric Sassi Master of Science in Health Physics, Chair (2009)

Deirdre Elder Master of Science in Health Physics, Committee member (2008)

Ken Walters Master of Science in Health Physics, Chair (2008)

Nichole McPherson Doctorate in Public Health, Uniformed Services University of the Health Sciences, Chair (2007)

Jim Fyffe Master of Science in Public Health, Uniformed Services University of the Health Sciences, Chair (2005)

Postdoctoral Students/Research Associates

Elizabeth Ruedig, PhD, CHP (August 2013–February 2015)

Past 5 years: Valarie Adams PhD (2007–2008)

Descriptions of Mentoring Activities

Jeffery Hibbert, High School Student at Lone Star High School: Mentored Jeff for two years. His first year (2007–2008), Jeff was awarded regional and state prizes for his poster, and presented his poster at the Annual Health Physics Society meeting in Pittsburg PA, and was awarded $250 for his efforts.

Undergraduate Mentoring

Jessica Gills (2010–2013)

Dayton McMillian (2010–2013)

Vi Nguyen (2010–2011) Presented at the Annual Health Physics Society meeting.

Jennifer Hartman (2008–2009)

Angela Coler (2007–2009) Presented a poster at the Annual Health Physics Society meeting.

Clint Walker (2007–2008) Presented a poster at the Annual Health Physics Society meeting.

Chris Heiserman (2006–2007) Presented a poster at the Annual Health Physics Society meeting.

Sarah Yoder (2006–2007)

Luci Nelson (2005–2006)

Research Advisor for Laboratory Animal Residents

Matthew Rosenbaum (2009)

Christine Ege (2007)

Anthony Bostick (2006)

Gregory Langham (2005)

Two HP students, Haitao Dong and Daniel Dugan, have been funded, at least partially, in their education using funds generated from Continuing Education classes. Both students might have otherwise been forced to drop out to be able to afford completing their education.

Six HP graduate students were funded (from EDLL 2005 funds) to travel to Keystone Colorado in August 2008 to attend the NEI Health Physics conference. This resulted in multiple contacts for both the students and the HP program, increasing the status of the program, since no other graduate students from any other programs in the country attended.

Annually since 2006 presentations on basics of radiation and health physics have been made at the University of Northern Colorado in the Physics Department. This has resulted in two outstanding students (Ken Walter, graduated May 2008) and Nicholas Roche (Fall 2009) attending CSU. We are also negotiating a potential track III collaboration with UNC.

As faculty advisor for the CSU Branch of the Health Physics Society, we have established a strong local presence and collaboration with the local Chapter of the Health Physics Society. We have also been using the student branch of the HPS to work with alumni. In 2007 we prepared polo shirts with the CSU logo, in 2008 we had both vests and water bottles with the CSU logo that were offered to alumni and friends of the program. This has resulted in a great increase in goodwill from our alumni, and several donations to the student branch. These donations have allowed us to entertain prospective students, taking them to lunch and dinner, and assisting with our recruiting activities. This has engaged the alumni with the current students, resulting in increased opportunities for our students.

Committees

CRC College Committee, 2013–present

EPA Science Advisory Board ISR Uranium mining advisory Committee, 2011–2012

State of Colorado Radiation Advisory Committee, 2010–2016

American Board of Health Physics Professional Development Committee, 2009–2012

University Radiation Safety Committee, 2007 –present

Department Health Physics ABET Accreditation Committee Chair, 2005–present

CSU achieved accreditation 18 months after starting at CSU. The Health Physics program not only was accredited in the shortest amount of time possible, it was accredited for seven years, and the maximum that is typically allowed for any program is 6 years. This was in recognition of the outstanding health physics program and the accreditation cycle of the IH program. The Health Physics section had proposed pursuing accreditation in 2003, but no action. Under my leadership, a 200-page accreditation document, complete with the associated monitoring programs, were created and implemented. There are only five accredited master's programs in health physics in the USA. It should be noted that I also spearheaded the accreditation process of one of the other four ABET programs. Responsible for re-accreditation in 2013, only 2 concerns found.

Professional Affiliations and Activities

Chair, ANSI Z136 Editorial Working Group, 2010

JAALAS Reviewer, 2010

Member, ANSI Z136 Editorial Working Group, (2008–present)

Health Physics Society, Continuing Education Committee, (2008–present)

American Academy of Health Physics, Professional Development Committee (2008–present)

NCRP Reviewer, 2007

Editorial Reviewer: Toxicology for the Industrial Hygienist, Chapter 19 (2007)

Vice Chair, ANSI Z136.1 revision (2007–present)

Member, Editorial Working Group, ANSI Z136 Committee (2007–present)

Reviewer, Health Physics Society Journal (2006–present)

Reviewer, IEEE Transactions on Plasma Science (2005–present)

Chair, Baltimore Washington Chapter of the Health Physics Society CHP review class, (2003–2004)

Executive Committee, Baltimore-Washington Chapter, Health Physics Society (2001–2004)

President, Baltimore-Washington Chapter of the Health Physics Society (2000–2001)

Certification Review Course Instructor, Potomac Chapter AIHA (2000–2002)

Chair, Science Teacher's Workshop, Baltimore-Washington Chapter of the Health Physics Society (1998–2000)

Teacher's Workshop Committee Baltimore Washington Chapter (1997)

Health Physics Society History Committee Secretariat (1999–2004)

BWC Health Physics Society CHP review committee and class instructor (1998–2004)

ANSI Z136.1 Health Physics Society Representative (1999–present)

Laser Institute of America (1998–present)

International Society for Optical Engineering (1999–2005)

American Academy of Health Physics, Member (1996–present)

Fellow, American College of Forensic Examiners (1996–present)

Radiation Research Society (1995–present)

Health Physics Society (1994–present)

American Nuclear Society (1988–present)

Graduate Representative, Grade Appeals Committee, Purdue University (1996)

Lindgren Science and Engineering Residence Advisor, Northwestern University (1993–1994)

Licensed by the National Board of Boiler and Pressure Vessel Inspectors (1990)

Other Activities/Accomplishments – Service/Outreach

Selected to be an ABET program evaluator 2013.

Virginia Uranium Mining Symposium, November, 2011. Public information forum on uranium and uranium mining. Over 100 attendees from across the USA.

Lone Star High School – Invited to lecture to entire school on basics of radiation. October, 2010

Uranium Technical Symposium, February 2008 – Public information forum on uranium and uranium mining. Over 270 attendees from across the USA.

Poudre High School Chemistry Class - Invited lecture on radiation basics. Taught to 2 chemistry classes at the high school. 2009.

Invited lecture for four 6th grade classes at Mountain School in Los Alamos NM. Supervised students during the annual practicum teaching these classes, May, 2009, May 2010.

Fossil Ridge High School Chemistry Class – Invited lecture on radiation basics. Taught to every chemistry class (six) at the high school. November 16, 2007.

Central Rocky Mountain Chapter of the Health Physics Society – Responsible for organizing annual technical meeting for 2007, 2008, 2009, 2010, 2011, including speakers and all other arrangements.

Mentor for Jeff Hibbert, High School Student at Lone Star High School, Colorado. Winner of local and state science fair awards in 2008 and 2009.

Arthur S. Rood

Owner/President, K-Spar, Inc.

Education

M.S. Health Physics, Radioecology, Colorado State University, 1987
B.S. Geology, Mesa State College, 1982
A.A. Mathematics, Santa Monica College**,** 1978

Summary

Twenty-seven years of experience in multimedia contaminant fate and transport modeling, dose and risk assessment. Developed and implemented mathematical models for contaminant fate and transport in environment systems, conducted numerical uncertainty analysis, and designed and implemented environmental sampling and monitoring programs.

Employment History

Private Consultant (7/1994–Present)
K-Spar Inc. Idaho Falls, Idaho

Develop and implement mathematical and computer models for assessment of multimedia transport of contaminants (radionuclides and other) in the environment. Quantify uncertainty and sensitivity of model predictions using Monte Carlo sampling techniques. Validate models using environmental monitoring data and compute health risk associated with predicted environmental media concentrations. Specific projects include evaluation of environmental air monitoring network at the Idaho National Laboratory, atmospheric transport of radionuclide and chemicals from the former Rocky Flats Plant for the Historical Public Exposures Studies at Rocky Flats, establishment of plutonium clean up levels at the former Rocky Flats Plant, fluvial transport of radionuclides at the Hanford Reservation, performance assessment of the U.S. Ecology low-level waste site in Richland Washington, analysis of air quality impacts from the Cerro Grande Fire in Los Alamos, New Mexico, reconstruction of atmospheric concentrations and doses from the former Uravan uranium mill, development contaminant transport models for contaminated soils at Los Alamos National Laboratory, and development of radionuclide limits in waste water and sediments for Waste Control Specialists low-level waste site.

Instructor for Risk Assessments Corporation courses on radiological risk assessment held in Washington DC (2009, 2012, 2013), Bristol UK (2009), and Nuclear Regulatory Commission (2015). Member of Task Group 98 of the International Commission on Radiation Protection.

Advisory Scientist (Retired) (5/1994–1/2013)
Modeling and Measurements Group, Idaho National Laboratory, Idaho Falls, Idaho

Research, develop, and apply state-of-the-art techniques for assessment of environmental transport and impacts associated with release of radioactive material and hazardous chemicals. Specific modeling expertise includes chronic and accident air dispersion, food-chain transport, groundwater

flow and transport, dose and risk assessment, thermodynamic chemical vapor models, shielding and external exposure calculations, and first order kinetic models. Major efforts were directed toward low-level waste performance assessment at the three Idaho National Laboratory low-level waste disposal sites and long-range atmospheric dispersion calculations for evaluation of toxic pollutants emitted to the air from INL facilities using the CALPUFF dispersion model.

Provide lead technical guidance for INL and Department of Energy-wide programs requiring complex environmental assessments and safety analyses. Provide technical guidance for an international study on uncertainty estimates in reactor consequence code evaluation. Assist the National Low-Level Waste program in providing technical assistance to waste compact states and foreign countries. Instructor for the University of Idaho graduate-level course, **Environmental Modeling** (INTER 504) from 1991 to 1999.

Principal Investigator for a national survey of naturally occurring radioactive material (NORM) in oil and gas production equipment. Member of the Health Physics Society/ANSI working group on NORM.

Senior Scientist (5/1990–5/1994)
Integrated Earth Science/Geotechnologies, Idaho National Laboratory

Provide lead technical guidance and funding management for Idaho National Engineering Laboratory (INEL) and DOE-wide programs requiring complex environmental assessments and safety analyses. Developed groundwater transport models and computer codes (GWSCREEN) for assessment of CERCLA sites and performance assessment of low-level waste disposal facilities at the INEL. Performed the groundwater modeling and dose assessment section for the Radioactive Waste Management Complex Performance Assessment at the Idaho National Engineering Laboratory. Co-author of the food-chain model (COMIDA) for the MAACS reactor consequence code, an internationally-recognized reactor accident assessment code.
Participated in four "AIRDOS/CAP-88" radiological assessment courses for another DOE laboratory, INEL contractor, and state personnel. Conducted Performance Assessment Workshops and provided technical assistance to the low level waste compact states for the National Low-Level Waste Management Program.

Staff Scientist (8/1989–4/1990)
UNC Geotech, Grand Junction, Colorado

Radon Laboratory - Performed indoor radon assessments and developed instrumentation for measurement of radon progeny using alpha and beta spectroscopy. Conducted quality control experiments of radon measuring devices and wrote software for data acquisition systems and computer controlled instrumentation.

Environmental Scientist (9/1987–7/1989)
Environmental Sciences and Engineering Unit, Idaho National Laboratory, Idaho Falls, Idaho

Environmental Sciences and Engineering - Research, develop, and apply state-of-the-art techniques assessing the environmental transport and impacts associated with release of radioactive material and hazardous chemicals. Specific modeling experience includes chronic and accident air dispersion, food-chain transport, groundwater contaminant transport, and dose and risk assessment.

Senior Health Physics Technician (11/1984–9/1986)
Oak Ridge National Laboratory, Grand Junction, Colorado

Coordinated gamma spectroscopy laboratory for gamma spectral analysis of soil samples contaminated with uranium mill tailings. Wrote and implemented spectral analysis algorithms, multichannel analyzer control programs and data base software. Designed, constructed, and calibrated an activated charcoal radon measurement device. Developed and implemented laboratory quality control procedures.

Associate Mine Geologist (8/1982–12/1983)
Plateau Resources LTD, Grand Junction, Colorado

Supervised uranium mine longhole drilling program for ore body fringe development and preparation for full scale production. Evaluated drilling results for ore trend production and ore reserve calculations.

Geoscientist I (1/1981–7/1982)
Bendix Field Engineering, Grand Junction, Colorado

Assisted in researching uranium ore body development and exploration indicators and writing results published in Department of Energy reports. Tasks included interpretation of electric drill hole logs and generation of isopleth maps and cross sections from the data.

Physical Science Aide (5/1980–9/1980)
U.S. Department of Energy, Grand Junction, Colorado

Assisted staff geologist in reviewing resource maps and assessment data for the 1980 National Uranium Resource Evaluation Report.

Affiliations

Member of the Health Physics Society Working Group on Naturally Occurring Radioactive Material
Member of the Health Physics Society
Member of the International Commission on Radiation Protection (ICRP) Task Group 98.

Honors, Awards, and Leadership Positions

- Licensed Invention, GWSCREEN Software System, Lockheed Martin 1996
- President and Executive Board Member, Desert Eagles Model Airplane Club, 2008–2010

Courses Taught

Environmental Risk Assessment for the Nuclear Regulatory Commission, Bethesda Maryland, April 2015.

Radiological Risk Assessment and Environmental Assessment. Crystal City Marriott, Arlington, VA. Risk Assessment Corporation. March 4-8, 2013. 51 Attendees.

Radiological Risk Assessment for Decision Making, Compliance, and Emergency Response. Crystal City Marriott, Arlington, VA. Risk Assessment Corporation. March 5-9, 2012. 37 Attendees.

Radiological Risk Assessment and Environmental Analysis Course. ITC School of Underground Waste Storage and Disposal. University of Bristol Risk Centre, Bristol, United Kingdom. June 22–26, 2009. 17 Attendees.

Environmental Risk Assessment Analysis Training Course H-401. Training Course H-401 prepared and presented by Risk Assessment Corporation for the U.S. Nuclear Regulatory Commission at the NRC's Professional Development Center, Bethesda, Maryland. January 26–30, 2009. 23 Attendees.

Expert Testimony

"Reconstruction of Historical Doses from Radionuclides Released to the Environment by the Uravan Mining and Milling Site." In re: June et al. v. Union Carbide Corporation et al., No.1: 04-CV-00123-MSK-MJW. January 15, 2007.

"Assessment of Thyroid Doses Received by Specified Individuals from Releases of Iodine-131 from Hanford." In re: Hanford Nuclear Reservation Litigation Master File No. CY-91-3015-WFN. August 13, 2004.

"Historical Public Exposures Studies on Rocky Flats." August 6, 2004, In re: Cook et al. v. Rockwell et al., U.S. District Court for the District of Colorado, No. 90-K-181. August 6, 2004.

Selected Publications and Reports

Text Book Chapters

Whicker, F.W. and **A.S. Rood**, 2008. "Terrestrial Food Chain Pathways: Concepts and Models" In: *Radiological Risk Assessment and Environmental Analysis*", J.E. Till and H.A. Grogan Editors. CRC Press, Boca Raton FL.

Grogan, H.A., J.W. Aanenson,, P.D. McGavran, K.R. Meyer, H.J. Mohler, S.S. Mohler, J.R. Rocco, **A.S. Rood**, J.E. Till, and L.H. Wilson, 2006. "Modeling of the Cerro Grande Fire at Los Alamos: An Independent Analysis of Exposure, Heath Risk, and Communication with the Public" In: *Applied Modeling and Computations in Nuclear Science*. ACS Symposium Series 945. American Chemical Society, Washington DC.

Peer-Reviewed Publications

Rood, A.S., A.J. Sondrup, and P.D. Ritter, 2016. "Quantitative Evaluation of an Air Monitoring Network using Atmospheric Dispersion Modeling and Frequency of Detection Methods" Health Physics 110(4).

Till, J.E., **A.S. Rood**, C.D. Garzon, and R.H. Lagdon, 2014. "Comparison of the MACCS2 Atmospheric Transport Model with Lagrangian Puff Models as Applied to Deterministic and Probabilistic Safety Analysis." *Health Physics,* 107(2): 213-230.

Rood, A.S., 2014. "Performance Evaluation of AERMOD, CALPUFF, and Legacy Air Dispersion Models using the Winter Validation Tracer Study Dataset." *Atmospheric Environment,* 89: 707-720.

Till, J.E., H.A. Grogan, J.H. Mohler, J.R. Rocco, **A.S. Rood**, and S.S. Mohler, 2011. "An Integrated Approach to Data Management, Risk Assessment, and Decision Making." *Health Physics,* 102(4): 367-377.

Rood, A.S., P.G. Voillequé, S.K. Rope, H.A. Grogan, and J.E. Till, 2008. "Reconstruction of Atmospheric Concentrations and Deposition of Uranium and Decay Products Released from the Former Uranium Mill at Uravan Colorado USA." *Journal of Environmental Radioactivity,* 99: 1258–1278.

Rood, A.S., 2004. "A Mixing-Cell Model for Assessment of Contaminant Transport in the Unsaturated Zone Under Steady-State and Transient Flow Conditions." *Environmental Engineering Science*, 21(6): 661–677.

Abbott, M.L., D.D. Susong, D.P. Krabbenhoft, **A.S. Rood**, 2002. "Mercury Deposition in Snow near an Industrial Emission Source in Southeastern Idaho and the Teton Range, Wyoming," *Water, Air, and Soil Pollution*, 139: 95–114.

Rood, A.S., H.A. Grogan, J.E. Till, 2002. "A Model for a Comprehensive Evaluation of Plutonium Released to the Air from the Rocky Flats Plant, 1953–1989." *Health Physics,* 82(2).

Till, J.E., **A.S. Rood**, P.G. Voilleque, P.D. McGavran, K.R. Meyer, H.A. Grogan, W.K. Sinclair, J.W. Aanenson, H.R. Meyer, H.J. Mohler, S.K. Rope, and M.J. Case, 2002. "Risks to the Public from Historical Releases of Radionuclides and Chemicals at the Rocky Flats Environmental Technology Site." *Journal of Exposure Analysis and Environmental Epidemiology,* 12 (5): 355-372

White, G.J., and **A.S. Rood**, 2001. "Radon Emanation from NORM-Contaminated Pipe Scale and Soil at Petroleum Industry Sites." *Journal of Environmental Radioactivity,* 54: 401–413.

Rood, A.S., P.D. McGavran, J. Aanennson, 2000. "Stochastic Estimates of Carcinogenic Risk with Uncertainty from Carbon Tetrachloride Released from the Rocky Flats Plant." *Risk Analysis,* 21(4): 675-696.

Rood, A. S., G. G. Killough, J. E. Till, 1999 "Evaluation of Atmospheric Transport Models for use in Phase II of the Historical Public Exposure Studies at the Rocky Flats Plant." *Risk Analysis,* 19(4): 559-576.

McGavran, P. D., **A. S. Rood**, J. E. Till, 1999. "Chronic Beryllium Disease and Cancer Risk Estimates with Uncertainty for Beryllium Released to the Air from the Rocky Flats Plant." *Environmental Health Perspectives,* 107(8): 731-744.

Rood, A. S., G. J. White, and D. T. Kendrick, 1998. "Measurement of ^{222}Rn Flux, ^{222}Rn Emanation, and ^{226}Ra Concentration from Injection Well Pipe Scale" *Health Physics,* 75(2): 187-192.

Rood, A. S., 1994, "GWSCREEN: A Model for Assessment of the Groundwater Pathway from Surface or Buried Contamination", *The Environmental Professional,* 16(3):196-210.

Nguyen, H. D., S. Paik, **A. S. Rood**, 1994, "Effects of Thermally Generated Convection on the Migration of Radionuclides in Saturated Geologic Formations" *International Journal Engineering Science,* 32(10): 1605-1614.

Abbott, M. L. and **A. S. Rood**, 1994 "COMIDA: A Radionuclide Food-Chain Model for Acute Fallout Deposition", *Health Physics*, 66(1):17-29.

Martz, D. E., **A. S. Rood**, J. L. George, M. D. Pearson, G. H. Langner, 1991, "Year-to-Year Variations in Annual Average Indoor ^{222}Rn Concentrations". *Health Physics*, 61(3): 409-413.

Walton, J. C., **A. S. Rood**, R. G. Baca and M. D. Otis, 1989, "Model for Estimation of Chlorinated Solvent Releases from Waste Disposal Sites", *Journal of Hazardous Materials*, 21, 15-34.

Company Technical Publications

Rood, A.S., and A.J. Sondrup, 2015. Application of Frequency of Detection Methods in Design and Optimization of the INL Site Ambient Air Monitoring Network. INL/EXT-15-36544. Idaho National Laboratory, Idaho Falls, Idaho.

Rood, A.S., and A.J. Sondrup, 2014. Development and Demonstration of a Methodology to Quantitatively Assess the INL Site Ambient Air Monitoring Network. INL/EXT-14-33194. Idaho National Laboratory, Idaho Falls, Idaho.

Rood, A.S., H.J. Mohler, H.A. Grogan, and J.E. Till, 2014. Methodology and Example Calculations for Effluent Discharge Limits and Sediment Concentration Limits for the LLRW Federal Waste Facility Discharge Evaporation Pond. 1-WCS-TO2-2014. Risk Assessment Corporation, Neeses, SC.

Electric Power Research Institute, 2014. EPRI Recommendations for the National Academies' Pilot Study of Cancer Risks in Populations around Nuclear Facilities. Technical Report 3002003163. Electric Power Research Institute, Palo Alto, CA.

U.S. Department of Energy, 2012. Performance Assessment for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility. DOE/ID-11421. Idaho National Laboratory, Idaho Falls, ID.

U.S. Department of Energy, 2011. Performance Assessment for the Idaho CERCLA Disposal Facility Landfill. DOE/ID-10978. Idaho National Laboratory, Idaho Falls, ID.

Grogan, H.A., B. Jacobs, and **A.S. Rood**, 2010. Source Term and Transport Modeling for Single-Shell Tanks at the Hanford Site. RAC Report No. 1-WA-2009-FINAL. Risk Assessments Corporation, Neeses, South Carolina.

Rood, A.S., and B.L. Jacobs, 2008. Response Surface Model User Documentation. 32-RACER LANL 2008 FINAL. Risk Assessment Corporation, Neeses, South Carolina.

U.S. Department of Energy, 2008. Composite Analysis for the RWMC Active Low-Level Waste Disposal Facility at the Idaho National Laboratory Site. DOE/NE-ID-11244. Idaho National Laboratory, Idaho Falls, ID.

U.S. Department of Energy, 2007. Performance Assessment for the RWMC Active Low-Level Waste Disposal Facility at the Idaho National Laboratory Site. DOE/NE-ID-11243. Idaho National Laboratory, Idaho Falls, ID.

Rood, **A.S**. 2005. Mixing Cell Model: A One-Dimensional Numerical Model for Assessment of Water Flow and Contaminant Transport in the Unsaturated Zone. ICP/EXT-05-00748, Idaho National Laboratory, Idaho Falls, ID. March.

Grogan, H.A., **A.S. Rood**, J.W. Aanenson, and E.B. Liebow, 2002. A Risk-based Screening Analysis for Radionuclides Released to the Columbia River from Past Activities at the U.S. Department of Energy Nuclear Weapons Site in Hanford, Washington. RAC Report No. 3-CDC Task Order 7-2000 FINAL. Risk Assessments Corporation, Neeses, South Carolina.

Case, M.J., **A.S. Rood**, J.M. McCarthy, S.O. Magnuson, B.H. Becker, T.K. Honeycutt, 2000. Technical Revision of the Radioactive Waste Management Complex Low-Level Waste Radiological Performance Assessment for Calendar Year 2000. INEEL/EXT-2000-01089. Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho.

White, G.J. and **A.S. Rood**, 1999. Radon Emanation from NORM-Contaminated Pipe Scale, Soil, and Sediment at Petroleum Industry Sites. DOE/ID/13223-2. National Petroleum Technology Office, U.S. Department of Energy, Tulsa Oklahoma.

Rood, A. S., H. A. Grogan, 1999. Estimated Exposure and Lifetime Cancer Incidence Risk from Plutonium Released from the 1969 Fire at the Rocky Flats Plant. 07-CDPHE-RFP-1999, Radiological Assessments Corporation, Neeses, South Carolina. August.

Rood, A. S., H. A. Grogan, 1999. Comprehensive Assessment of Exposure and Lifetime Cancer Incidence Risk from Plutonium Released from the Rocky Flats Plant. 13-CDPHE-RFP-1999, Radiological Assessments Corporation, Neeses, South Carolina. September.

Rood, A. S., H. A. Grogan, 1999. Estimated Exposure and Lifetime Cancer Incidence Risk from Plutonium Released from the 1957 Fire at the Rocky Flats Plant. 02-CDPHE-RFP-1999, Radiological Assessments Corporation, Neeses, South Carolina. August.

Rood, A. S., H. A. Grogan, 1999. Estimated Exposure and Lifetime Cancer Incidence Risk from 903 Area Plutonium Releases at the Rocky Flats Plant. 01-CDPHE-RFP-1999, Radiological Assessments Corporation, Neeses, South Carolina. August.

Rood, A. S., 1999. Performance Evaluation of Atmospheric Transport Models. 3-CDPHE-RFP-1996 (Rev. 1), Radiological Assessments Corporation, Neeses, South Carolina. August.

Rood, A. S., 1999. Estimated Exposure and Lifetime Cancer Incidence Risk from Routine Plutonium Releases at the Rocky Flats Plant. 08-CDPHE-RFP-1997 (Rev. 1), Radiological Assessments Corporation, Neeses, South Carolina. August.

Grogan, H. A., P. D. McGavran, K. R. Meyer, H. R. Meyer, J. Moler, **A. S. Rood**, W. K. Sinclair, P. G. Voillequé, J. M. Weber, 1999. Technical Summary Report of the Historical Public Exposures Studies for Rocky Flats Phase II. 14-CDPHE-RFP-1999-DRAFT, Radiological Assessments Corporation, Neeses, South Carolina. August.

McGavran, P. D., **A. S. Rood**, 1999. Estimated Exposure and Cancer Risk from Beryllium Released to the Air from the Rocky Flats Plant. 02-CDPHE-RFP-1997 (Rev. 1), Radiological Assessments Corporation, Neeses, South Carolina. August.

McGavran, P. D., **A. S. Rood**, 1999. Estimated Exposure and Cancer Risk from Carbon Tetrachloride Released to the Air from the Rocky Flats Plant. 04-CDPHE-RFP-1997 (Rev. 1), Radiological Assessments Corporation, Neeses, South Carolina. August.

Weber, J.M., **A. S. Rood**, H. R. Meyer, 1999. Development of the Rocky Flats Plant 903 Area Plutonium Source Term. 08-CDPHE-RFP-1998 (Rev. 1), Radiological Assessments Corporation, Neeses, South Carolina. August.

White, G.J. and **A.S. Rood**, 1998.Characterization of the National Petroleum Reserve NO. 3 (NPR-3) Site for Naturally Occurring Radioactive Material (NORM). DOE/5AC304. National Petroleum Technology Office, U.S. Department of Energy, Tulsa Oklahoma.

Brown, J., M. L. H. J. Goossens, B. C. P. Kraan, R. M. Cooke, J. A. Jones, F. T. Harper, F. E. Haskin, M. L. Abbott, M. L. Young, S. C. Hora, **A. S. Rood**, 1997. Probabilistic Accident Consequence Uncertainty Analysis: Food Chain Uncertainty Assessment. NUREG/CR-6523 U.S. Nuclear Regulatory Commission, Washington D.C.

Abbott, M. L. and **A. S. Rood**, 1996. Source Group Optimization Program (SGOP): A Program the Groups Emission Sources for Input into Air Dispersion Models INEL-96/0376 Idaho National Engineering Laboratory, Idaho Falls, Idaho.

Maheras, S.J. **A. S. Rood**, S. O. Magnuson, M. E. Sussman, R. N. Bhatt, 1994. Radioactive Waste Management Complex Low-Level Waste Radiological Performance Assessment. EGG-WM-8773, Idaho National Engineering Laboratory, May.

Rood, A.S., 1994. GWSCREEN: A Semi-Analytical Model for Assessment of the Groundwater Pathway from Surface or Buried Contamination: Theory and Users Manual Version 2.0, EGG-GEO-10797, Revision 2, Idaho National Engineering Laboratory, June.

Abbott M. L. and **A. S. Rood**, 1993. COMIDA: A Radionuclide Food-Chain Model for Acute Fallout Deposition, EGG-GEO-10367, Idaho National Engineering Laboratory, November.

Abbott, M. L. S. L. Harms, **A. S. Rood**, 1993. Dose Calculations for Accidental Airborne Releases of ITER Activation Products, EGG-EEL-10994, Idaho National Engineering Laboratory, December.

Rood, A. S. and M. L. Abbott, 1991. Comparison of Dose and Dose-rate Conversion Factors from the Soviet Union, United Kingdom, U.S. Department of Energy and the Idaho National Engineering Laboratory Fusion Safety Program, EGG-FSP-9865, Idaho National Engineering Laboratory, December.

Seitz, R. R. **A. S. Rood**, G. A. Harris, S. J. Maheras, M. Kotecki, 1991. Sample Application of Sensitivity/Uncertainty Analysis Techniques to a Groundwater Problem, DOE/LLW-108, U. S. Department of Energy, National Low Level Waste Program, June.

Rood, A. S. Assessment of Impacts at the Advanced Test Reactor as a Result of Chemical Releases at the Idaho Chemical Processing Plant, EGG-EST-9523, Idaho National Engineering Laboratory, February, 1991.

Abbott, M. L. and **A. S. Rood**, 1990. Concentration Factors for Fusion-Related Radionuclides Calculated Using the Food-Chain Model FUSEMOD, EGG-EST-9223, Idaho National Engineering Laboratory, September.

Rood, A. S., J. L. George, G. H. Langner, 1990. Variation in the Annual Average Radon Concentration Measured in Homes in Mesa County, Colorado, DOE/ID/12584-57 UNC/GJ-50(TMC), U. S. Department of Energy, Grand Junction, Colorado, April.

Rood, A. S., R. C. Arnett, J. Barraclough, 1989. Contaminant Transport in the Snake River Plain Aquifer: Phase 1, Part 1: Simple Analytical Model of Individual Plumes, EGG-ER-8623, Idaho National Engineering Laboratory, May.

Rood, A. S., 1988. *Environmental Transport Concentration Factors for the FUSECRAC Fusion Reactor Safety Code*, EGG-ESE-8033, Idaho National Engineering Laboratory, May.

Presentations and Symposium Proceedings

Rood, A.S., 2016. "Exposure Pathways from TENORM in Unconventional Oil and Gas Production", Health Physics Society 49th Midyear Meeting, NCRP TENORM in Unconventional Oil and Gas Production Workshop, Austin, Texas February 1–3, 2016.

Rood, A.S., A.J. Sondrup, and A.L. Schafer, 2011. "An Evaluation of Long-Term Performance of Liner Systems for Low-Level Waste Disposal Facilities." Waste Management 2011, Phoenix, AZ February 28 – March 4, 2011.

Rood, A.S, B.L. Jacobs, P. Shanahan, H.J. Mohler, J.W. Aannenson, J.R. Rocco, L.Hay-Wilson, H.A. Grogan, and J.E. Till, 2009. "Overview of Environmental Transport Models Contained in the Risk Analysis Communication, Evaluation, and Reduction (RACER) Software Tools at Los Alamos National Laboratory", Waste Management 2009, Phoenix Arizona, March, 1–5, 2009.

Rood, A.S, "Sensitivity and Uncertainty Analysis for Low-Level Waste Performance Assessment" Probabilistic Workshop on Performance Assessment, Augusta Georgia, March 10–11, 2008.

Rood, A.S, "Distilling Complex Models into Simpler Models for Assessment of Performance of Waste Facilities" Waste Management 2007, Tucson, Arizona, February 2007.

Rood, A.S, "Response Surface Modeling Activities to Simulate Transport in the Snake River Plain Aquifer at the Idaho National Laboratory" Great Rift Symposium, Idaho State University, Pocatello, Idaho, October 6, 2005.

Rood, A.S, "A Mixing-Cell Model for Assessment of Water Flow and Solute Transport in the Unsaturated Zone" INRA 2003 Subsurface Science Symposium, Salt Lake City, Utah, October 7, 2003.

Rood, A.S., "Spatial and Temporal Variations in Exposure and Risk at the Rocky Flats Plant: 1953–1989." Society for Risk Analysis Annual Meeting, Seattle WA, December 5, 2001.

Rood, A.S., "Estimating Uncertainty in Groundwater Modeling for a Performance Assessment of the Radioactive Waste Management Complex" John Horan Memorial Symposium on Radioactive Waste Management Issues. Greater Salt Lake Chapter of the Health Physics Society, Salt Lake City, Utah, April 28, 2001.

Rood, A.S, "Measurement of ^{222}Rn Flux, ^{222}Rn Emanation, and ^{226}Ra Concentration from Injection Well Pipe Scale". 29th Midyear Topical Meeting of the Health Physics Society, Scottsdale, Arizona, January 7-9, 1996.

Rood, A.S, "GWSCREEN, A Model for Assessment of the Groundwater Pathway from Surface or Buried Contamination". American Nuclear Society, 1993 Winter Meeting, San Francisco, CA., November 14-18, 1993,

Rood, A.S, "A Performance Assessment of Radioactive Waste Encapsulated in Iron-Enriched Basalt and Disposed at the Idaho National Engineering Laboratory's, Radioactive Waste Management Complex", Spectrum 92, International Topical Meeting for Nuclear and Hazardous Waste Management, Boise, Idaho, August 23 - 27, 1992.

D. J. Thorne and **A. S. Rood**, "Contaminant Fate and Effects in Ground and Surface Water at a Remediated Dioxin Site", Hazardous Material Control, January, 1990.

R. G. Baca, J. C. Walton, **A. S. Rood**, M. D. Otis, "Organic Contaminant Release from a Mixed Waste Disposal Site: A Computer Simulation Study of Transport Through the Vadose Zone and Site Remediation", 10th Annual DOE Low Level Waste Conference, Denver Colorado, August, 1987.

Rood, A.S, M. J. Case, "The Role of Performance Assessment in the Evaluation of Remedial Action Alternatives for the Radioactive Waste Management Complex (RWMC) at the Idaho National Engineering Laboratory", 10th Annual DOE Low Level Waste Conference, Denver Colorado, August, 1987.

H. Justin Mohler

Bridger Scientific, Inc.

Education

M.S., Environmental Health Physics, Colorado State University, Fort Collins, Colorado, 1997
B.S., Biology, Southwest Missouri State, Springfield, Missouri, 1993

Professional Experience

Bridger Scientific, Inc.
President/Owner, Belgrade, Montana (2002–present)

President and owner of Bridger Scientific, Inc., which specializes in various aspects of environmental health physics, including environmental sampling and measurement, tabular and spatial data management and interpretation, environmental transport, exposure and risk assessment, database design and management, and communication and presentation of technical information.

Currently supporting Risk Assessment Corporation (RAC) to evaluate exposure and dose related to radionuclides and chemicals released to the environment for a variety of projects. Specific involvement in these projects includes:

- Managing existing information and implementing dose calculation methodology to estimate doses for veterans involved with nuclear weapons tests at the Nevada Test Site and Pacific Proving Grounds
- Analyzing and interpreting monitoring data to characterize the extent and magnitude of site impact on the surrounding environment
- Evaluating potential human exposures to facility radionuclide releases and assessing and comparing predicted concentrations related to historical releases with observed environmental measurements
- Developing an independent and comprehensive data access and risk assessment process called RACER© to guide understandable, consistent, and transparent management and communication of risk from both chemical and radionuclide in the environment
- Implementing different aspects of the RACER process for various clients
- Presenting technical material to various panels and committees and interested members of the public and working with the public and Site personnel to obtain data and understand issues of concern.

Past projects with RAC have included studies for the Centers for Disease Control and Prevention and the Colorado Department of Public Health and Environment, which focused on reconstructing historical releases of radioactive and nonradioactive materials and estimating potential exposure and risk to surrounding populations.

For the Savannah River Site Dose Reconstruction Project, summarized environmental monitoring data and evaluated their usefulness for direct exposure assessment and source term model validation. For Task Order 5, reconstructed, screened, and prioritized historical radionuclide releases from the Idaho National Laboratory. For Task Order 6, managed and coordinated the

review of historical documents to identify information useful for completing a future detailed dose reconstruction at the Idaho National Laboratory.

Participated in three technical audits focused on assessing the Los Alamos National Laboratory's compliance with the Clean Air Act. Evaluated the accuracy and completeness of radionuclide usage at Site facilities and reviewed various other components of the compliance program.

Assessed the appropriateness of soil action levels or cleanup criteria for the Rocky Flats Environmental Technology Site. Evaluated distributions and assessed uncertainty and sensitivity for the parameters used in a dose calculation model.

Evaluated exposure and risk through both the air and surface water pathways as a result of the Cerro Grande Fire at the Los Alamos National Laboratory. Managed the collection and compilation of all relevant environmental monitoring data, as well as data available for source term characterization of contaminated sites impacted by the fire. Documented observations and recommendations resulting from the process of completing this risk assessment.

Provided assistance to the San Ildefonso Pueblo in New Mexico with their Tribal Risk Assessment process and communicating human health impacts to the Pueblo community.

Independent Consultant
Belgrade, Montana (1997–2001)

Worked with RAC on several projects related to exposures and potential risks from both historical and contemporary releases of radionuclides and chemicals to the environment.

Colorado State University

Research Associate, Fort Collins, Colorado (September 1996–January 1997)
Performed gamma spectra analyses of Rocky Flats Plant soil samples. Operated and calibrated HPGe and Ge(Li) detector and conducted spectral analysis and interpretation.

Laboratory Technician (September 1993–May 1994)
Collected and prepared soil samples for actinide analysis.

Additional Experience

Courses Taught
Environmental Risk Assessment for the Nuclear Regulatory Commission, Bethesda Maryland, April 2015.

Courses Attended
Microsoft Access advanced programming course for application developers (summer 1999).

Enhanced understanding of the data modeling requirements for developing a relational database. Focused on the programming necessary for custom database design as well as the fundamental structural elements of a relational database.

Research
U.S. Department of Energy's Par Pond Radioecology Laboratory
Savannah River Site, Aiken, South Carolina (summer 1994)

Conducted M.S. thesis research, which focussed on evaluating temporal trends of ^{137}Cs in an aquatic system. Also involved the development of a multi-compartment model to predict the distribution of ^{137}Cs in various ecosystem compartments.

U.S. Department of Energy Health Physics Fellow
Idaho National Engineering Laboratory, Idaho Falls, Idaho (summer 1996)

Analyzed the effects of building downwash for facility regulatory compliance using current air dispersion codes (ISC3) and software (Surfer® and GIS ARC/INFO®).

Honors

U.S. Department of Energy Applied Health Physics Fellowship, 1994–1996
Burton J. Moyer Memorial Fellowship, 1994–1995
Colorado Graduate Fellowship, 1994–1995
Soutwest Missouri State University Scholar (undergraduate academic scholarship)
Graduated Magna Cum Laude in the Honors College
Member of Phi Eta Sigma (honor society)

Peer-Reviewed Publications

J.E. Till, H.L. Beck, J.W. Aanenson, H.A. Grogan, **H.J. Mohler**, S.S. Mohler, and P.G. Voillequé. 2014. "Military Participants at U.S. Atmospheric Nuclear Weapons Testing—Methodology for Estimating Dose and Uncertainty. *Radiation Research*, 181, 471-484.

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Mohler, H.J., H.A. Grogan, J.R. Rocco, R.F. Kiefer, and J.E. Till. 2012. "RACER: Dynamic Use of Environmental Measurement Data for Decision Making and Communication." *Operational Radiation Safety* 102, Suppl 1. February.

Mohler, H.J., K.R. Meyer, H.A. Grogan, J.W. Aanenson, and J.E. Till. 2004. "Application of NCRP Air Screening Factors for Evaluating both Routine and Episodic Radionuclide Releases to the Atmosphere." *Health Physics* 86 (2): 135–144.

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Mohler, H.J., F.W. Whicker, and T.G. Hinton. 1997. "Temporal Trends of ^{137}Cs in an Abandoned Reactor Cooling Reservoir." *Journal of Environmental Radioactivity* 37 (3): 251–268.

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Education

Ph.D. Radiation Health Physics with minor in Statistics, Oregon State University, 2016
M.S. Radiation Health Physics with minor in Statistics, Oregon State University, 2012
B.S. Nuclear Engineering, Oregon State University, 2010

Professional Experience

Radian Scientific, LLC
President and Owner (2016–present)

Health physics consulting with Risk Assessment Corporation (RAC), specializing in radiation dose reconstructions, source term development, atmospheric modeling, environmental assessments, and data management for a wide variety of governmental and industry clients.

University of Alabama at Birmingham
Adjunct Faculty (2016–present)

Currently assisting in the development of a new health physics master's program by writing course syllabi, assisting in the creation of a health physics website, and writing funding grants. Teaching MHP 601 Principles of Health Physics course Fall Semester 2016.

Oregon State University School of Nuclear Science and Engineering
Graduate Research Assistant (2010–2016)

Performed original research in environmental protection and risk assessment. Completed two projects for the Electrical Power Research Institute, one in examining dose calculation methodologies for Carbon-14 emissions from nuclear power plants and the second in investigating tritium separation technologies for groundwater. Developed substantial analytical and technical skills in statistical analysis and data interpretation through minor degree coursework. Created and taught graduate level course in Liquid Scintillation Counting. Taught introductory course in Nuclear Engineering and Radiation Health Physics. Served as a teaching assistant and lecturer for Radioecology and Radiobiology. Led a multicultural research group of 10 graduate students for over two years.

Australian Nuclear Science and Technology Organization
Endeavor Research Fellow (2015)

Provided innovative computational modeling capabilities to support several research projects. Collected and prepared soil samples for plutonium particle analysis. Performed fieldwork at nuclear waste site near Sydney by obtaining tree cores for radionuclide analysis. Selected to present Ph.D. research to the Australian Radiation Protection and Nuclear Safety Agency.

Oregon State University
Radiation Safety Student Technician (2008–2010)

Monitored personnel and laboratories for radiation exposure. Authored operating procedures for the Liquid Scintillation Counter. Managed acquisition, storage, handling, and disposal of radioactive materials. Assisted in performing annual inspections of on-campus radiation use laboratories. Assisted in verifying that veterinary radiography facilities were in compliance with regulatory requirements.

Mathematics Tutor (2008)

Tutored small groups of students in advanced algebra and integral calculus.

Honors

Australian Endeavor Research Fellowship Recipient in 2015
Inducted into Alpha Nu Sigma Honor Society in 2013
Selected as an ARCS Scholar in 2012

Affiliations

Alumna of Phi Sigma Rho National Engineering Sorority
Health Physics Society Member since 2010
American Nuclear Society Member since 2006

Presentations and Publications

Caffrey, E.A., 2016. Development and Application of Voxelized Dosimetric Models for Biota: Characterization of the Uncertainty in the International Commission on Radiological Protection's Wildlife Dosimetry System. *Oregon State University Doctoral Dissertation.* Oregon State University. Available at: http://hdl.handle.net/1957/58187.

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Appendix B – Load Information

Table B-1. Load Summary by Generator

Generator	Location	Tons	Loads
Cambrian	Norwich, OH	9.97	4
Fairmont Brine	Fairmont, WV	766.06	36
Fairmont Brine	Fairmont, WV	99.27	11
GreenHunter	Dexter City, OH	32.84	7
GreenHunter	Ellenboro, WV	12.07	4
GreenHunter	Portland, OH	45.53	9
GreenHunter	Reno, OH	19.98	4
GreenHunter	New Matamoras, OH	38.69	4
Nuverra	Norwich OH	86.86	7
Nuverra	Norwich OH	9.85	1
Nuverra	Norwich OH	36.13	5
TOTALS		**1,157.25**	**92**
Reference: Advanced Disposal 2016			

Table B-2. Material Data by Individual Load

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
1	7/20/2015 9:49 a.m.	Cambrian Well Services	SW-C-SOIL (EX) – EXT	0.56	508.02	0.57	(Pace Analytical Services Inc. 2016)
2	7/24/2015 11:19 a.m.	Cambrian Well Services	SW-C-SOIL (EX) – EXT	0.74	671.32	0.75	
3	8/7/2015 4:04 p.m.	Cambrian Well Services	SW-C-SOIL (EX) – EXT	0.50	453.59	0.51	
4	1/4/2016 11:08 a.m.	Cambrian Well Services	SW-C-SOIL (EX) – EXT	8.17	7,411.70	8.33	
5	7/24/2015 1:50 p.m.	Fairmont Brine	SW-SOLIDIFICATION - EXT	10.52	9,543.59	10.72	(Hoskins 2015; Pace Analytical Services Inc. 2015c)
6	7/27/2015 1:52 p.m.	Fairmont Brine	No data	24.14	21,899.45	24.61	
7	7/27/2015 1:50 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	22.56	20,466.09	23.00	
8	7/28/2015 2:47 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	16.04	14,551.25	16.35	
9	7/28/2015 2:50 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	16.00	14,514.96	16.31	
10	7/31/2015 11:52 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	17.83	16,175.11	18.18	
11	7/31/2015 11:55 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	16.46	14,932.27	16.78	
12	8/3/2015 11:22 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	22.12	20,066.93	22.55	

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
13	8/4/2015 2:24 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	19.34	17,544.96	19.72	
14	8/4/2015 2:26 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	21.71	19,694.99	22.13	
15	8/6/2015 12:33 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	21.72	19,704.06	22.14	
16	8/6/2015 12:31 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	22.16	20,103.22	22.59	
17	8/7/2015 3:06 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	17.92	16,256.76	18.27	
18	8/7/2015 3:08 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	13.86	12,573.58	14.13	
19	8/11/2015 8:15 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	23.01	20,874.33	23.46	
20	8/11/2015 8:18 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	19.51	17,699.18	19.89	
21	8/11/2015 2:08 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	21.86	19,831.06	22.28	
22	8/11/2015 2:12 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	20.49	18,588.22	20.89	
23	8/12/2015 2:25 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	23.11	20,965.05	23.56	
24	8/12/2015 2:28 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	26.08	23,659.38	26.59	
25	8/13/2015 11:04 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	22.46	20,375.38	22.90	

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
26	8/13/2015 1:02 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	19.22	17,436.10	19.59	
27	8/14/2015 7:32 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	24.05	21,817.80	24.52	
28	8/14/2015 3:01 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	21.15	19,186.96	21.56	
29	8/14/2015 3:19 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	25.53	23,160.43	26.03	
30	8/17/2015 8:01 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	15.17	13,762.00	15.46	
31	8/18/2015 7:49 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	26.73	24,249.06	27.25	
32	8/18/2015 10:52 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	20.70	18,778.73	21.10	
33	8/21/2015 8:32 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	30.47	27,641.93	31.06	
34	8/21/2015 8:33 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	21.45	19,459.12	21.87	
35	8/24/2015 8:16 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	20.36	18,470.29	20.76	
36	8/24/2015 8:18 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	28.35	25,718.69	28.90	
37	8/24/2015 1:54 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	21.16	19,196.03	21.57	
38	8/27/2015 8:50 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	23.41	21,237.20	23.86	

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
39	8/27/2015 8:52 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	18.99	17,227.44	19.36	
40	8/31/2015 11:07 a.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	30.42	27,596.57	31.01	
41	11/4/2015 1:48 p.m.	Fairmont Brine	SW-SOLIDIFICATION -EXT	15.46	14,025.08	15.76	
42	11/6/2015 2:24 p.m.	Fairmont Brine	SW-SOLIDIFICATION - EXT	15.32	13,898.07	15.62	
43	11/9/2015 12:25 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	10.04	9,108.14	10.23	
44	11/11/2015 1:22 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	7.15	6,486.37	7.29	
45	11/11/2015 1:25 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	5.58	5,062.09	5.69	
46	11/12/2015 1:07 p.m.	Fairmont Brine	SW-SOLIDIFICATION - EXT	5.14	4,662.93	5.24	(Hoskins 2015)
47	11/12/2015 1:11 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	6.06	5,497.54	6.18	
48	11/13/2015 1:19 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	10.19	9,244.22	10.39	
49	11/13/2015 1:50 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	8.61	7,810.86	8.78	
50	11/16/2015 1:23 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	7.76	7,039.76	7.91	
51	11/16/2015 1:25 p.m.	Fairmont Brine	SW-C-SOIL (EX) – EXT	7.96	7,221.19	8.11	

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
52	8/11/2015 8:16 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.70	4,263.77	4.79	(Environmental Service Laboratories Inc. 2015)
53	8/11/2015 8:17 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.52	5,007.66	5.63	
54	8/11/2015 10:49 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.44	4,935.09	5.55	
55	9/2/2015 10:12 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.32	3,919.04	4.40	
56	11/6/2015 2:46 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.35	3,946.25	4.43	
57	1/26/2016 2:13 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	3.27	2,966.49	3.33	
58	1/26/2016 3:13 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.24	4,753.65	5.34	
59	8/11/2015 10:51 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	3.30	2,993.71	3.36	
60	8/12/2015 12:13 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	3.51	3,184.22	3.58	
61	9/23/2015 12:25 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	2.35	2,131.88	2.40	
62	11/13/2015 1:18 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	2.91	2,639.91	2.97	
63	8/11/2015 10:48 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	7.40	6,713.17	7.54	
64	9/2/2015 11:44 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.13	3,746.67	4.21	

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
65	10/1/2015 12:40 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.55	4,127.69	4.64	
66	11/4/2015 1:50 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.25	3,855.54	4.33	
67	11/5/2015 12:49 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.91	4,454.28	5.01	
68	1/25/2016 1:58 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.10	4,626.64	5.20	
69	1/25/2016 2:00 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.24	4,753.65	5.34	
70	1/26/2016 2:05 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.54	4,118.62	4.63	
71	1/27/2016 1:14 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.41	4,907.87	5.52	
72	8/12/2015 11:57 a.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.39	4,889.73	5.49	
73	8/12/2015 12:06 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.59	5,071.16	5.70	
74	11/10/2015 2:07 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.31	3,909.97	4.39	
75	11/11/2015 1:20 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	4.69	4,254.70	4.78	
76	8/19/2015 10:45 a.m.	GreenHunter	SW-SOLIDIFICATION - EXT	12.35	11,203.73	12.59	
77	8/19/2015 1:48 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	3.86	3,501.73	3.93	

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
78	11/20/2015 12:56 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	5.66	5,134.67	5.77	
79	11/20/2015 12:58 p.m.	GreenHunter	SW-C-SOIL (EX) – EXT	16.82	15,258.85	17.15	
80	9/23/2015 9:26 a.m.	Nuverra	SW-SOLIDIFICATION - EXT	8.34	7,565.92	8.50	(Heckmann Water Resources (CVR) Inc. 2015; Pace Analytical Services Inc. 2015b)
81	9/23/2015 9:29 a.m.	Nuverra	SW-SOLIDIFICATION - EXT	12.17	11,040.44	12.41	
82	9/24/2015 8:33 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	12.53	11,367.03	12.77	
83	9/24/2015 8:32 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	15.23	13,816.43	15.53	
84	9/25/2015 8:09 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	16.51	14,977.62	16.83	
85	9/25/2015 8:11 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	6.62	6,005.56	6.75	
86	9/29/2015 8:30 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	15.46	14,025.08	15.76	
87	10/23/2015 8:22 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	9.85	8,935.77	10.04	(Hoskins 2016; Nuverra Environmental Resources 2015)
88	12/17/2015 8:53 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	4.05	3,674.10	4.13	(Nuverra Environmental Solutions 2015; Pace Analytical
89	12/18/2015 8:27 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	4.26	3,864.61	4.34	

Load #	Ticket date	Generator	Material (as described in BRLF activity reports)	Billing quantity (US tons)	Billing quantity (kg)	Billing quantity (m^3)*	Radioanalytical data reference
90	1/15/2016 9:15 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	10.31	9,353.08	10.51	Services Inc. 2015a)
91	1/21/2016 12:25 p.m.	Nuverra	SW-C-SOIL (EX) – EXT	4.88	4,427.06	4.97	
92	2/3/2016 8:58 a.m.	Nuverra	SW-C-SOIL (EX) – EXT	12.63	11,457.75	12.88	(Nuverra Environmental Solutions 2015)
			TOTALS	**1,157.25**	**1,049,839.84**	**1,179.71**	
				U.S. tons	**kg**	**m^3**	
*1500 lbs/cy = 889.91 kg/m^3							
Reference: Advanced Disposal 2016							

Appendix C – Aquifer Characteristics

The following information was provided to RAC by Cornerstone Environmental Inc. on May 31, 2016.

Groundwater Flow Velocity Calculations
Blue Ridge Landfill, Kentucky First Quarter 2016 Event

FLOW VELOCITY OF NEW ALBANY SHALE

Parameters:

Saturated Thickness (b) = average saturated thickness is approximately 14.09 ft.

Well	Well Depth (ft)	Depth to Water (ft)	Saturated Thickness (ft)
MW-10	70.00	60.98	9.02
MW-13	64.50	54.61	9.89
MW-15R	76.00	55.45	20.55
MW-17R	93.49	76.60	16.89
Average Saturated Thickness =			14.09

Transmissivity (T) = Transmissivity values for the New Albany Shale are listed as ranging from 110 to 1,130 gpd/ft as noted in Table 4 of "Ground-Water Resources in the White and West Fork White River Basin, Indiana," State of Indiana Department of Natural Resources-Division of Water, Water Resource Assessment 2002-6.

Hydraulic Conductivity (k) = transmissivity (T) x saturated thickness (b)
Minimum k = (110 gpd/ft)/ 14.94 ft = 14.7 ft^2/d / 14.09 ft = 1.04 ft/d
Maximum k = (1,130 gpd/ft) / 14.94 ft = 151 ft^2/d / 13.39 ft = 10.72 ft/d

Conversion factor = ft^2/day = gpd/ft / 7.481

Effective Porosity (n_e) = assumed to be approximately 0.15 for shale bedrock according to the USEPA "Interim Final RCRA Facility Investigation Guidance Document", May 1989, EPA 530/SW-89-031, p 10-51.

Gradient (*i*) = calculated from the gradient at the site using the First Quarter 2016 potentiometric map.

- Gradient (*i*) = Change in groundwater elevation along flow path *i*: From 740 contour to 720 contour = 20ft / 501ft = 0.0399

Calculations:

Minimum Velocity
$V = [(k)(i)] / n_e$
$V = [(1.04 \text{ ft/d})(0.0399)] / 0.15$
V = 0.28 ft/d

Maximum Velocity
$V = [(k)(i)] / n_e$
$V = [(10.72 \text{ ft/d})(0.0399)] / 0.15$
V = 2.85 ft/d

Appendix D – Dose Calculation Documentation

Computer code information, input and output files, run scripts, and appropriate explanation files are provided separately as an electronic attachment in *BlueRidgeArchive_(10-11-16).zip*.

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