Attachment C

TENORM Dose and Radiological Risk Assessment

science › environment › community

September 1, 2020

FINAL REPORT

CWMNW Arlington, OR

Chemical Waste Management of the Northwest, Inc., Landfill Radiological Dose and Risk Assessment for Bakken Oilfield Waste Disposals in Arlington, OR

Submitted to Waste Management

RAC Report No. 06-CWMNW Arlington-2020-FINAL

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Chemical Waste Management of the Northwest, Inc., Landfill Radiological Dose and Risk Assessment for Bakken Oilfield Waste Disposals in Arlington, OR

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Executive Summary

This radiological dose and risk assessment was conducted by Risk Assessment Corporation (RAC) on behalf of Chemical Waste Management of the Northwest, Inc. (CWMNW) in response to the Oregon Department of Energy (ODOE) Notice of Violation (DOE-NOV) dated February 13, 2020. This report addresses the dose and health risks from the disposal of specific technologically enhanced naturally occurring radioactive materials (TENORM, referred to as Bakken oilfield waste in this report) and for two hypothetical remediation alternatives: a leave-in-place option and an excavate- and-remove option.

The Bakken oilfield waste originated in the Bakken oilfields of North Dakota and is a byproduct of oil and natural gas production. In total, an estimated 1,285 tons of waste were received between May 2, 2016, and September 16, 2019, delivered in a total of 64 loads. The majority of the waste, roughly 80%, was filter socks. Maximum, or worst-case and weighted-average source terms were calculated. This was done to ensure potential doses and associated risks were not underestimated for the relevant exposure scenarios discussed herein.

The assessment was conducted using widely accepted computational methods and models coupled with available and generated site-specific data, where possible. For atmospheric pathways, EPA's AP-42 Compilation of Air Emissions Factors and Air Dispersion Modeling Software AERMOD were used. The Mixing Cell Model (MCM) code was used to evaluate the groundwater pathway. This code has been implemented at both the Idaho National Laboratory and at the U.S. Ecology Site on the Hanford Reservation.

To assess the risk associated with the past disposal activities, individuals who could have been or were potentially exposed (referred to as receptors) were identified for each exposure scenario. During waste disposal, the maximally exposed receptor was the waste handler—i.e., the person who drove the truck at the landfill and operated the trailer controls during disposals. Natural background dose, on average, for persons in the United States is 311 mrem per year. The maximum one-time dose during the disposals was 3.3 mrem total to the waste handler, or 94 times lower than the continuous annual exposure from natural background. The only viable exposure pathway to members of the public during disposals was potential inhalation of the subject material that may have become airborne and potentially blown off-site. The estimated maximum dose to the off-site resident was determined to be negligible at 0.00000076 (7.6×10^{-7}) mrem per year, which is essentially zero.

As part of this risk assessment, two possible remediation alternatives were identified and quantified to determine their viability and future risk potential. These are described fully in the Corrective Action Plan (Gradient 2020). Alternative 1 assumes the waste is left in place and normal landfill operations continue until closure per the CWMNW permit. Alternative 2 assumes the waste is excavated and trucked to an off-site disposal location.

For Alternative 1, the maximally exposed receptor is a hypothetical on-site resident who lives on top of the landfill after it closes sometime in the distant future. This scenario is extremely unlikely and assumes the failure of the long-term land use restrictions that are required to be in place following closure of the landfill. The on-site resident is assumed to draw groundwater from the immediate downgradient edge of the disposals, despite the fact that this water is not potable and not sufficient to support a family; thus, this represents an extremely pessimistic scenario. To assess the most conservative, or upper-bound, exposure scenario, a hypothetical future intruder is assumed to live on the site and drill a water well through the waste. The intruder is assumed to use the drill

cuttings in the foundation for a home. Further, an ecological assessment was conducted to ensure that the environment is adequately protected.

For the leave-in-place alternative, the maximum dose in a given year post closure to the hypothetical future on-site resident assuming the maximum source term was very low at 0.12 mrem. This does not occur until 260,000 years into the future. This dose assumes that the person is utilizing a water well located at the immediate downgradient edge of the disposals, which is an extreme worst-case scenario. The dose to the inadvertent intruder was predictably higher than that calculated for the hypothetical future on-site resident, but still very low at a maximum of 1.02 mrem. The ecological assessment demonstrates that doses to ecological receptors were well below the threshold where deleterious effects are likely to occur.

For Alternative 2, the excavate-and-remove option, the maximally exposed receptor is the remediation project supervisor, assumed to be on the ground during removal operations to ensure they are conducted safely. The total dose to the supervisor during hypothetical removal operations is estimated at approximately 46 mrem.

Doses for the excavate-and-remove alternative were substantially higher than those during disposals or for the leave-in-place alternative. This report does not address the risks associated with potentially disturbing the chemical and hazardous wastes that are safely disposed in the landfill. Disturbing these wastes during the excavation of the Bakken oilfield waste is ill-advised since comingling of previously disposed and properly sequestered chemical and hazardous wastes could reasonably be expected to create unplanned mixtures of unidentifiable chemicals, which would lead to unknown management challenges and unknown risks to the local community.

This assessment has demonstrated that maximum doses that may have been received by workers on the site and to the public from the disposal of the Bakken oilfield wastes were minimal and negligible when compared to radiation exposures received from natural and other man-made sources. Radiological doses were higher for the excavate-and-remove alternative. A full comparison of the potential risks for each remediation alternative is presented in the corrective action plan (CAP) (Gradient 2020).

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Acronyms and Abbreviations

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

Scientific Notation (E-format)

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

$$\begin{aligned} 4{,}231 &= 4.231\times10^{3} \\ 1{,}230{,}000 &= 1.23\times10^{6} \\ 0.0361 &= 3.61\times10^{-2} \end{aligned}$$

Computers print scientific notation in a slightly different format 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 activity	
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 x 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}
μ	micro	10^{-6}
m	milli	10^{-3}
k	kilo	10
M	mega	10^{6}

1. Introduction

This Dose and Risk Assessment report has been prepared by Risk Assessment Corporation (RAC) on behalf of Chemical Waste Management of the Northwest, Inc. (CWMNW) in response to the Oregon Department of Energy (ODOE), Notice of Violation (DOE-NOV) dated February 13, 2020. Pursuant to the DOE-NOV and subsequent discussions with the Department, this report provides a quantitative evaluation of past, present, and future potential health risk to reasonably anticipated human receptors resulting from potential exposure to Bakken oilfield waste materials disposed at the CWMNW facility in Arlington, OR, between 2016 and 2019.

1.1. Scope and Background

This report addresses the dose and health risks from both the disposal and hypothetical remediation alternatives for the estimated 1,285 tons of waste received from Bakken oilfield sites. The waste was transported by third parties and disposed of in Landfill Unit L-14 at the CWMNW facility located in Arlington, OR, between May 2, 2016, and September 16, 2019.

The Bakken oilfield wastes originated from a contractor performing liquid management and water recycling services for oil and gas industry customers in North Dakota. The DOE-NOV described these wastes as technologically enhanced naturally occurring radioactive material (TENORM) subject to the disposal prohibition in ORS 469.525 and OAR 345-050.

This report uses the waste characteristics, radionuclide composition, details of the disposal facility design and operations, and the types of persons likely to be exposed to these radionuclides to quantify the doses and risks to humans during and following the disposal process. To quantify the potential doses and risks in the distant future (i.e., centuries), the potential for radionuclide transport to the subsurface from groundwater is also evaluated.

This report also quantifies potential radiological health risks for two corrective action scenarios identified by ODOE:

1) In-situ closure ("closure-in-place")
2) Hypothetical exhumation, transportation, and redisposal of all Bakken and comingled wastes ("excavate and redispose").

For the closure-in-place alternative, an ecological assessment is also provided to evaluate the potential for radiological impacts to non-human receptors and the environment. The results are compared to acceptable risk levels at which no deleterious health effects are likely to occur.

These risk assessment results provide important input information to the corrective action plan (CAP) prepared by Gradient (2020) on behalf of CWMNW to propose a preferred alternative to ODOE for final corrective action.

2. CWMNW Arlington Facility Environmental Setting

The CWMNW facility is located in Gilliam County, about 11 km (7 miles) south-southwest of the City of Arlington, OR, and south of the Columbia River (Figure 2-1). The CWMNW facility property occupies about 270 acres and is surrounded by approximately 14,000 acres of buffer land owned by Waste Management within the south-central portion of the Columbia physiographic province (Deschutes-Umatilla Plateau). The Deschutes-Umatilla Plateau is incised by Alkali

Canyon to the south. Most of the site's activities, including operations in Landfill Unit L-14, are located on the plateau above the canyon. Only a small portion of the site, including the main office, is in Alkali Canyon.

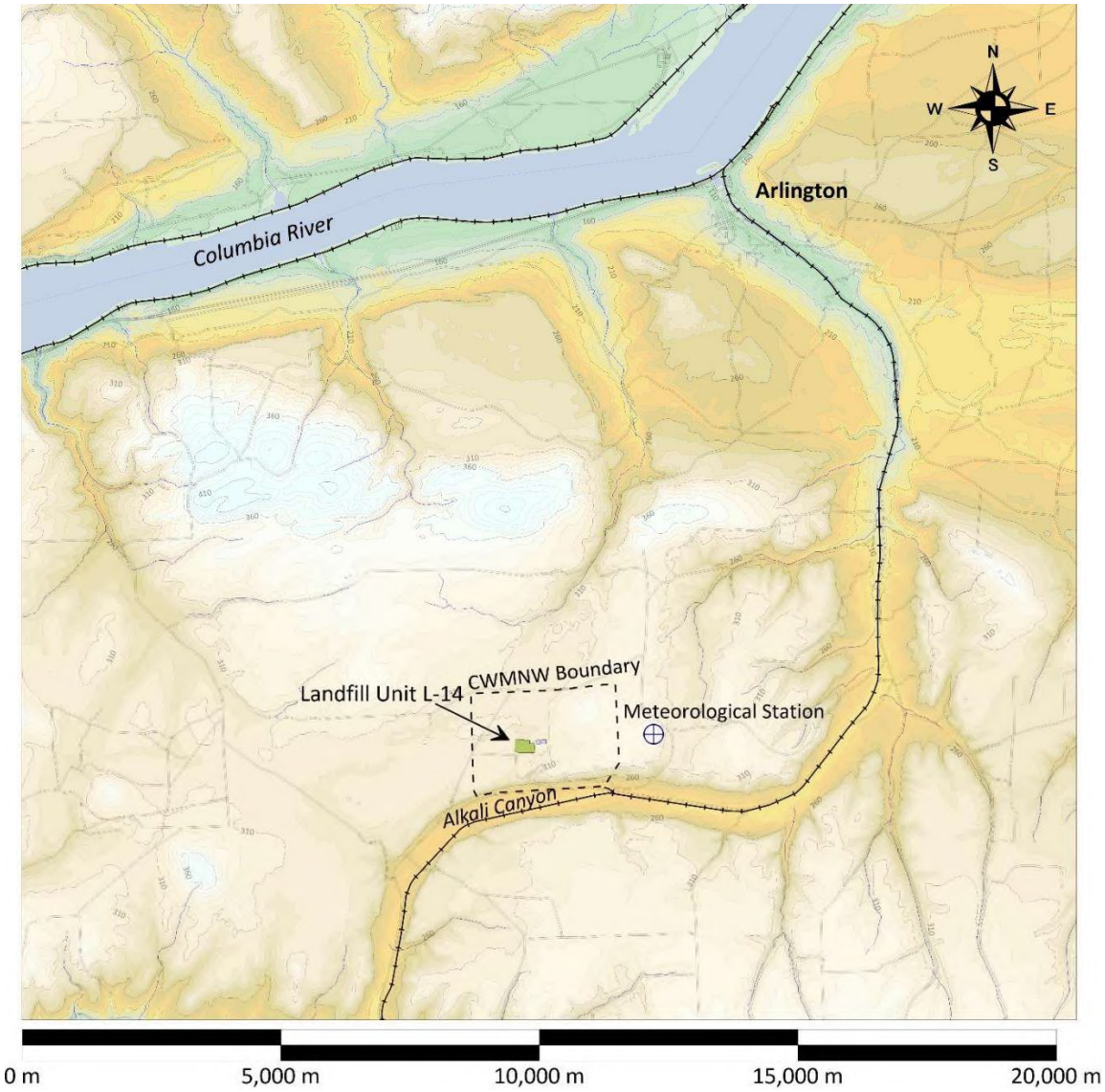

Figure 2-1. Location of CWMNW relative to the City of Arlington and the Columbia River. Also shown is the meteorological station.

2.1. Disposal Facility

Landfill Unit L-14 is located on the west side of the CWMNW facility. Figure 2-2 shows the location of Landfill Unit L-14, the evaporation ponds (Pond-A, Pond-B), the wastewater treatment plant-1 (WWT-1), the CWMNW Laboratory, and the facility entrance.

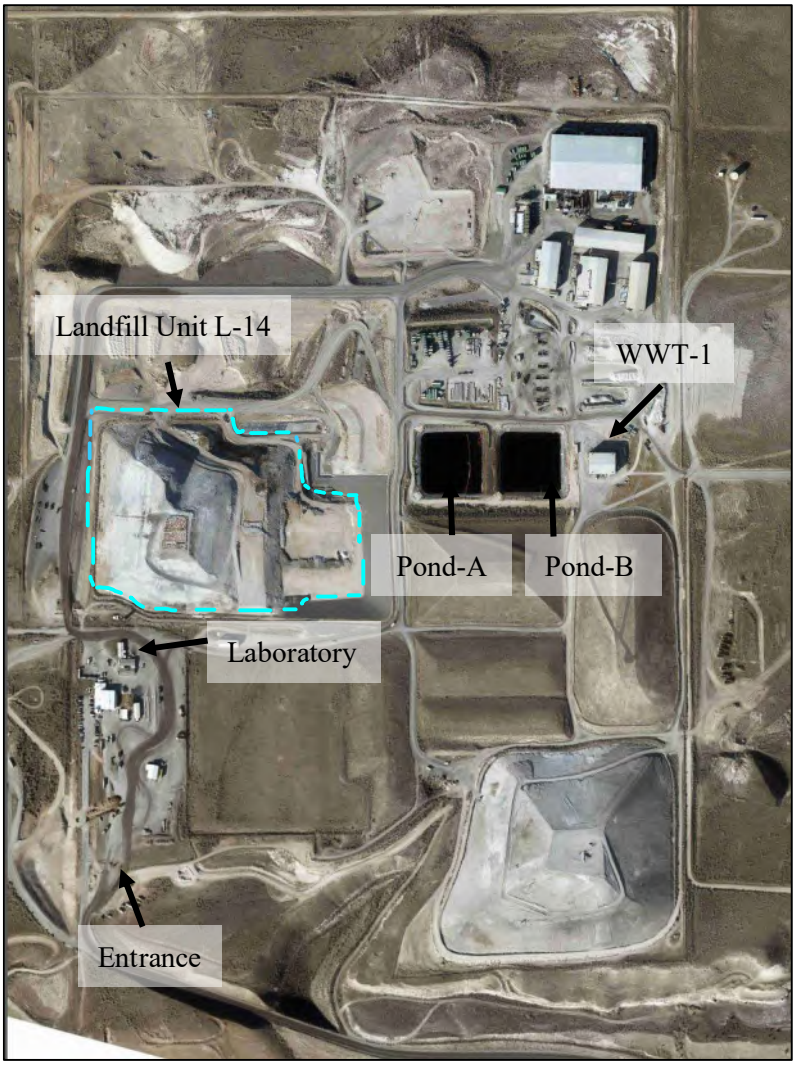

Figure 2-2. Layout of CWMNW Arlington landfill. The rough edge of Landfill Unit L-14 is outlined with a dotted blue line. Other salient features of the landfill are indicated.

2.1.1. Construction and Environmental Protection Features

Landfill Unit L-14 at CWMNW is a double-lined Subtitle C hazardous waste landfill. The disposal cells are designed to meet stringent U.S. Environmental Protection Agency (EPA) and state requirements. The disposal cells are monitored by a leachate collection system, groundwater monitoring network, and leak detection systems (Figure 2-3).

Upon the closure of Landfill Unit L-14, an engineered evapotranspiration final cover system will cap the landfill to restrict infiltration of rainwater and thereby reduce or eliminate leachate production. Post-closure maintenance activities will last for at least 30 years after landfill closure. These activities include semi-annual and/or annual inspection of the cap and its vegetative cover, checking the security fencing, and monitoring and maintenance of the leachate collection system. The post-closure activities also include groundwater monitoring for at least 30 years after the landfill closure.

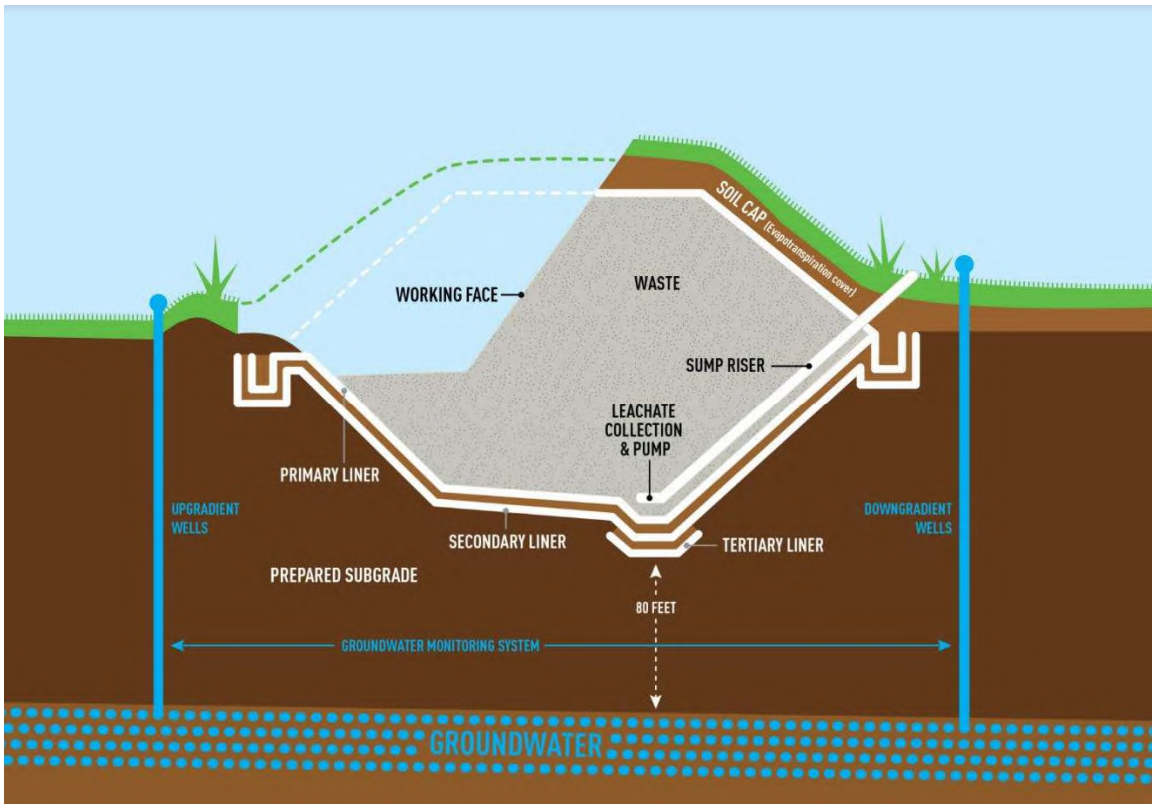

Figure 2-3. This figure shows a stylized cross section of the landfill and identifies key environmental protection features.

2.1.2. Waste Handling Procedures

Waste is transported to the CWMNW facility by public roads or by rail to the rail yard east of the facility. All wastes transported by rail are loaded onto trucks and enter the CWMNW facility over a private road between the rail yard and the facility entrance. The Bakken oilfield wastes were transported by rail initially and later over the road by third-party transporters. Upon entry to the site, the vehicles were cleared through the receiving department, and the truck driver was escorted by a landfill inspector in a separate vehicle to the designated disposal location within Landfill Unit L-14. The truck drivers for the Bakken oilfield wastes, referred to as waste handlers, donned the required personal protective equipment (PPE) prior to entering Landfill Unit L-14 disposal area. While in the active area of the landfill, respiratory protection is required. Waste handlers are not Waste Management employees. On reaching the designated disposal location, the waste handler exited the cab of the truck and walked to the space between the cab and bed of the truck where the controls for the trailer were located. The load was deposited on to the landfill surface in the designated disposal area, and once the offload was complete and the rear door was secured, the driver reentered the cab of the truck and departed the landfill. The waste handler spent approximately seven minutes outside of the cab of the truck per disposal load. The landfill inspector (escort) remained inside their truck at least 15 ft away from the transport vehicle in full PPE the entire time and never exited the truck. Following the offloading, landfill operators in full PPE, enclosed in heavy equipment cabs, pushed the waste into the disposal location where it may have been comingled with other non-reactive wastes before finally being covered with clean soil from

on-site cover borrow areas. The wastes may have remained uncovered for up to a week prior to being covered by a landfill operator. Landfill operators are required to wear designated PPE, including a respirator as a protective measure to mitigate the risks associated with disposal of hazardous wastes.

2.1.3. Leachate Management System

Landfill Unit L-14 at CWMNW has four lined leachate collection sumps that consist of a primary sump, secondary leak detection sump, and tertiary leak detection sump collecting leachate from the current 86,490 m^2 (21 acre) landfill. The landfill is divided into four cells, with each cell designed to drain into a sump (Figure 2-4). For a detailed review of the CWMNW leachate management methods please refer to "Analysis of CWMNW Leachate Management Practices" Technical Memorandum (Rood et al. 2020)[1].

As described in the memorandum referenced above, water infiltrates the landfill surface due to precipitation and to a lesser extent from using leachate for dust control by applying it to the top surface of the landfill. Liquids that filter down through the waste mass are conveyed by the primary liner to the leachate collection sumps at the base of the landfill. Leachate pumped from the sumps is generally applied as dust control on the surface of the landfill and has been demonstrated not to result in a large amount of water infiltration as the facility is situated in an arid climate and the leachate is readily evaporated from the surface of the landfill. CWMNW employs an alternate leachate management practice during periods when leachate cannot be applied as dust control. Filtered leachate is placed in one of two on-site evaporation ponds as described in Section 2.1.3.2. An overview of the leachate management practices is given in Figure 2-5.

2.1.3.1. Leachate Applied as Dust Control

When leachate is used for dust control, the leachate is pumped from the sumps via a hose and sprayed over the surface of the landfill where it evaporates. CWMNW is located in an arid climate that has 109 inches of dry pan evaporation per year. The spraying process continues until the area is adequately wetted. Once the area is adequately wetted to control dust, the sprayer is repositioned to a new location and the process is repeated. Spraying is performed in areas of no disposal activity, mainly across L-14 cell 1, L-14 cell 2, and L-14 cell 3. Annually, the use of leachate for dust control will be distributed over all three cells. Any runoff from the spray operations is collected using the landfill internal stormwater collection system and sent to a separate lined stormwater pond at the north end of the current landfill. The approximate area of a single spray is 337 m^2 (Rood et al. 2020).

[1] Available here: https://www.oregon.gov/energy/safety-resiliency/Documents/2020-05-29-CWM-Prelim-Leachate-Analysis.pdf.

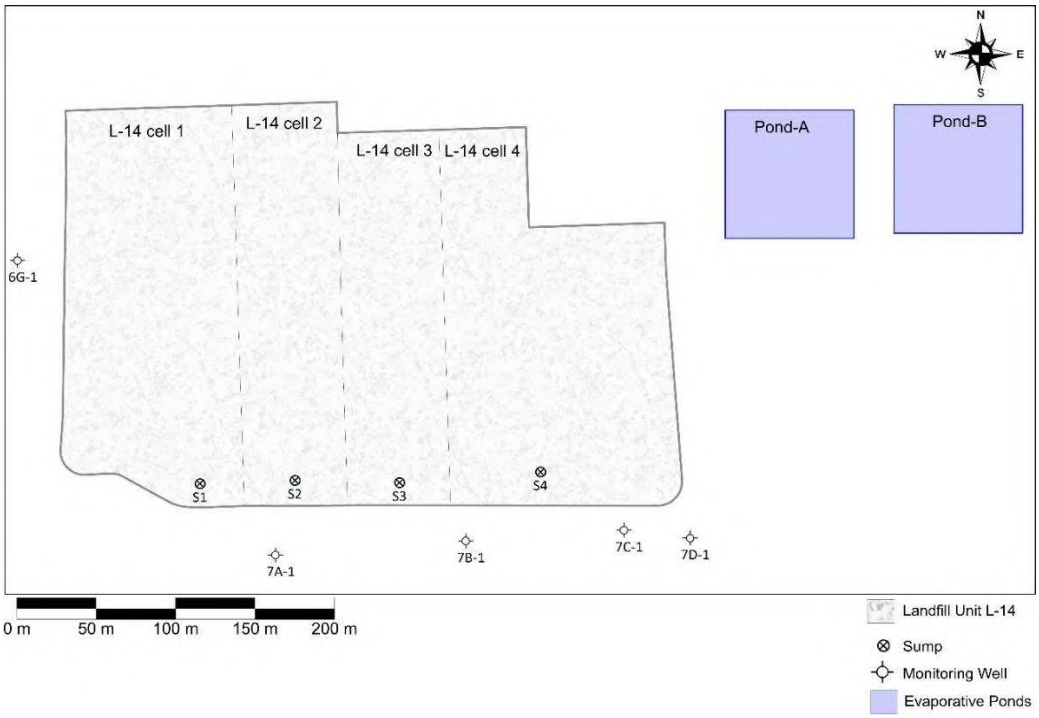

Figure 2-4. Landfill Unit L-14 showing the four cells (L-14 cell 1, L-14 cell 2, L-14 cell 3, and L-14 cell 4), the sumps (S1, S2, S3, and S4), evaporations ponds (Pond-A and Pond-B), and nearby monitoring wells.

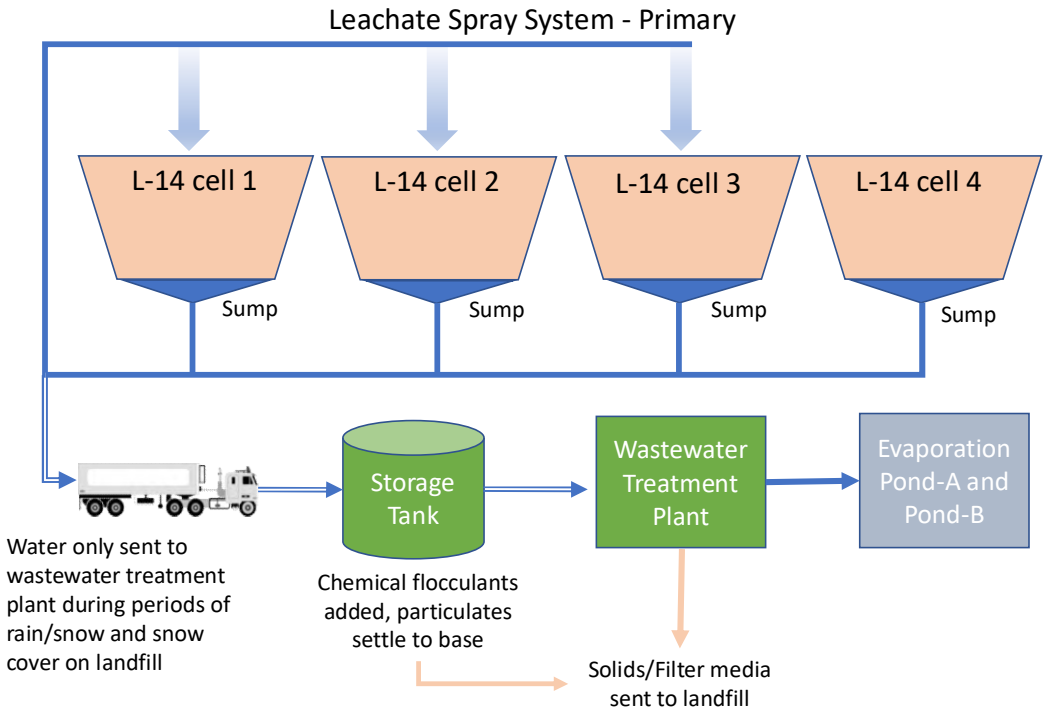

Figure 2-5. Overview of leachate management at CWMNW.

2.1.3.2. Alternative Leachate Management Methods

An alternative leachate management practice is used when evapotranspiration is poor and leachate removal from sumps is required. Leachate is pumped into a tanker truck and transported to the wastewater treatment plant-1 (WWT-1) where it is offloaded into a storage tank. Chemical flocculants are added to the leachate so that flocked solids precipitate to the base of the tank. The remaining liquid is passed through carbon filters and stored in a separate tank that is later pumped into one of two lined ponds (Pond-A, Pond-B) east of L-14 following compatibility and land disposal restriction (LDR) clearance testing. Periodically, the flocked solids and carbon filter media from the WWT-1 are removed and disposed in the landfill. This happens approximately six times per year.

2.2. Site Geology and Hydrogeology

Geologic units (from shallowest to deepest) beneath Landfill Unit L-14 at CWMNW are:

- Sedimentary deposits of the Dalles Group (Alkali Canyon Formation)
- Selah Member and associated sedimentary deposits of the Ellensburg Formation
- Priest Rapids Member of the Wanapum Basalt (PRB) of the Columbia River Basalt Group (CRBG).

Older Members of the Wanapum Basalt and the Grande Ronde Basalt of the CRBG are also present beneath the site but are not discussed here. Detailed descriptions of each of the geologic units are presented below.

The Alkali Canyon Formation of the Dalles Group outcrops at the surface and overlies the Selah. As seen in Figure 2-6, Landfill Unit L-14 penetrates the Alkali Canyon Formation and its base is in the Selah Member. The Alkali Canyon Formation is unsaturated at the site. It consists of three distinct sedimentary deposits (or facies): the basal portion, which consists of a conglomerate facies; a tuffaceous siltstone facies; and a channel gravel facies that incises down to the top of the Selah Member in the vicinity of Landfill Unit L-14 (Dames and Moore 1987; RUST 1998a; RUST 1998b).

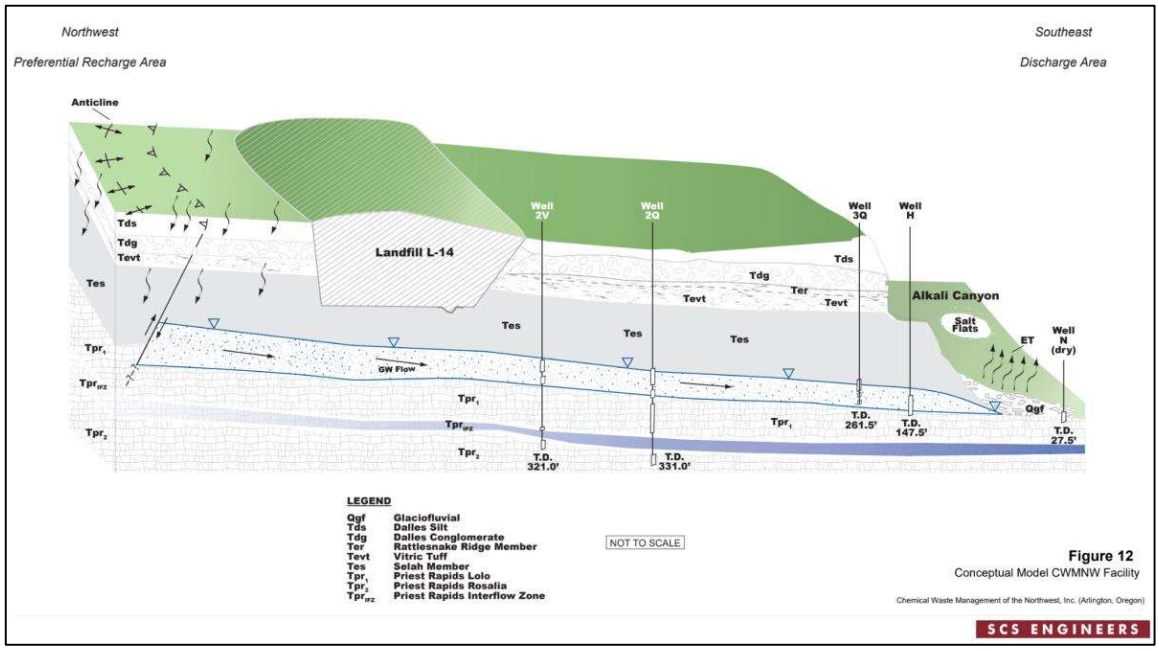

Figure 2-6. Conceptual model and geologic cross section of the CWMNW facility showing Landfill Unit L-14, aquifer in the Selah Member, and the deeper Priest Rapids basalt flow. The axis of the east-west trending anticline is shown north of Landfill Unit L-14.

Two minor units of the Ellensburg Formation are found below the Alkali Canyon Formation and above the Selah Formation. The two units have previously been classified as the Rattlesnake Ridge Member and the Vitric Tuff Member of the Ellensburg Formation based on their tuffaceous characteristics (RUST 1998b; CH2M Hill 2008). The Rattlesnake Ridge Member is a 4- to 6-ft-thick weathered tuffaceous siltstone that overlies the Vitric Tuff. The Vitric Tuff is composed of a soft-to-medium-hard, blue-grey, well-sorted, fine-grained tuffaceous siltstone/sandstone. The vitric tuff is up to 30 ft thick. Both units have been eroded and are absent in localized areas where they were eroded during deposition of the Dalles Group (RUST 1998b; CH2M Hill 2008).

Underlying these two members of the Ellensburg Formation is the Selah Member. The Selah Member ranges in thickness from 35 to 49 m (115 to 160 ft) beneath the upland plateau where the active area of the CWMNW facility is located. The upper portion of the Selah is unsaturated, with groundwater present in the lowest 6.1 to 21.3 m (20 to 70 ft) of the Selah (CH2M Hill 2008). Immediately south of the facility, the Selah Member is fully exposed in the face of the bluff in Alkali Canyon, where it was eroded away by catastrophic floods of glacial origin that inundated the Columbia Plateau during the Pleistocene Epoch. Even though the Selah is heterogeneous, the primary lithologic character of the Selah is a siltstone with varying degrees of clay and sand content.

The PRB consists of two flows at the site, a younger Lolo flow and the older Rosalia flow. The two flows have the typical characteristics of a basalt flow consisting of dense to columnar-jointed flow interior between a brecciated flow bottom and weathered flow top. The Lolo and Rosalia flows are separated by a partially lithified sedimentary interbed of the Ellensburg Formation composed of silt and clay. This interbed lies 15.2 to 22.9 m (50 to 75 ft) below the Selah/PRB contact and ranges in thickness from 6.1 to 36.6 m (2 to 12 ft) across the site (CH2M Hill 2008).

2.2.1. Geologic Structure

Tectonic activities folded and faulted the older geologic units of the Selah and PRB after they were deposited. An east-west trending anticline fold is present along the northern portion of the site based on geological borehole data and surface geophysical surveys. The fold dips to the north of the site and towards Alkali Canyon to the south. Additionally, a thrust fault that offsets beds within the Selah and PRB trends roughly parallel to the anticline in the portion of the site north of Landfill Unit L-14. The thrust fault is truncated by intact Holocene glacial flood deposit, indicating the fault pre-dated Holocene deposition (Dames and Moore 1987; RUST 1998a).

2.2.2. Groundwater Hydrology

The Selah contains the uppermost saturated zone beneath the CWMNW facility. Depth of the uppermost saturated layer is from about 40 to 60 m (130 to 200 ft) below the upland plateau where the active portion of the landfill is located. The Selah underlies the more permeable sands and gravels of the Alkali Canyon Formation of the Dalles Group and overlies the PRB of the Columbia River Basalt Group. The regional groundwater source(s) are much deeper in the older CRBG units of the Frenchman Springs Member of the Wanapum Basalt and older flows of the Grande Ronde Basalt.

Recharge to the Selah occurs along the northern portion of the site near the structural features and through the unsaturated zone, which varies between approximately 90 ft thick in the central area of the site to 135 ft in the northern part of site to 220 ft thick towards the western and eastern areas of the site. Recharge to groundwater is primarily from precipitation and has been previously estimated to be approximately 0.1 ft/year (RUST 1998b). Groundwater flow within the saturated portion of the Selah is generally toward the southeast and towards Alkali Canyon and away from the Columbia River to the north, consistent with the structural dip of the underlying PRB. Water balance calculations in CH2M HILL (2008) indicates groundwater does not discharge from the Selah south into Alkali Canyon but is lost through evapotranspiration. Water that may accumulate in the winter in Alkali Canyon is attributed rainfall, snowmelt, and poor drainage conditions in the bottom of the canyon.

In general, the Selah is a partially confined groundwater system at the site, although more confined conditions may exist toward the northwestern and southeastern portions of the site. In the northwestern area, a clay-rich horizon (designated the “grey clay” layer by Dames and Moore [1987]), indicated by the natural gamma geo-physical logs, likely acts as a confining to semi-confining layer below which is a zone of lower clay content (and potentially higher hydraulic conductivity). The lower portion of the Selah contains low-conductivity materials that limits the movement of water from the lower Selah to the PRB.

The Selah has horizontal hydraulic conductivity values (K_h) ranging from 1×10^{-6} to 1×10^{-4} cm s^{-1} based on pumping test data, packer testing, and core sample testing (Dames and Moore 1987; RUST 1998a; CH2M Hill 2008). Horizontal hydraulic conductivity values estimated for test intervals crossing the Selah/PRB contact and the vertical hydraulic conductivity of the Selah Member have been estimated to range from 5×10^{-9} cm s^{-1} to about 5×10^{-6} cm s^{-1} with a geometric mean of about 5×10^{-8} cm s^{-1} (CH2M Hill 2008). For comparison, the horizontal hydraulic conductivity of materials used for engineered landfill liner materials to prevent releases of leachate from a landfill to the environment is typically less than 1×10^{-6} cm s^{-1}. Using the historic average hydraulic gradient of approximately 0.015 to 0.035 m m^{-1} and the estimated hydraulic conductivity

of the Selah, groundwater flows laterally at an estimated rate of between 0.23 to 2.1 m yr^{-1} (0.77 to 6.9 ft yr^{-1}).

Isotopic age dating of groundwater at the site is consistent with the long travel times for groundwater from the surface to the saturated zone of the low permeability Selah and horizontally within the Selah. Available radiocarbon dating using carbon-14 suggests that the age of the shallow groundwater in the Selah is greater than 770 years with a probable age range of between 1,000 to 4,000 years (CH2M Hill 2008). For comparison, the maximum age range for the upper Priest Rapids is estimated to be between 9,600 and 12,900 years old, and the deeper Frenchman Springs Basalt used for water supply at the site is estimated to be between 14,000 to 16,000 years old. These much older ages of groundwater from the basalt interflows suggest limited hydraulic connection, if any, between the shallow Selah water-bearing zone and the deeper basalt aquifers.

2.2.3. Surface Water

Except for the on-site storm water management ponds, which themselves do not consistently contain water, permanent surface water is absent at the facility. During the few storm runoff events, surface water exterior to the facility generally drains from the upland plateau via overland flow into Alkali Canyon, then down into the broad canyon floor where it disperses or collects into ephemeral ponds. During winter and early spring, shallow seasonal ponds occasionally form in Alkali Canyon, south of the site. The only permanent surface water bodies are located several miles from the site and include the Columbia River, approximately 11 km (7 miles) north of the site; the John Day River, approximately 12 km (7.5 miles) west of the site; Rock Creek, approximately 5.5 km (3.5 miles) southwest of the site; and Cedar Springs, approximately 2.5 km (1.5 miles) west of the site. None of these water bodies are hydraulically connected to the surface water from the site. All stormwater from the facility is moved by on-site stormwater conveyances to on-site stormwater retention ponds that do not discharge to any of the local rivers, streams, or other water bodies.

2.3. Background Radiation Levels and Site Survey Data

A radiation survey of the CWMNW Arlington site was conducted June 15 to 19, 2010, by Environmental Restoration Group, Inc. (ERG), in collaboration with K2 Environmental, LLC (ERG and K2 2020). The survey was designed to measure gamma radiation across the site to determine the natural background gamma radiation in the area and if there were any evidence of increased gamma radiation associated with the disposal of the Bakken oilfield wastes in Landfill Unit L-14. To do this, gamma radiation was measured across Landfill Unit L-14, at off-site background locations representative of natural undisturbed geology in the area, and at on-site locations free of waste where materials were taken and later used for cover and fill in Landfill Unit L-14.

The investigation consisted of gamma radiation surveys using an unmanned aerial vehicle (UAV) equipped with radiation detection and GPS equipment to measure gamma count rates across the site, at locations with cover and fill materials, and at background areas. In addition, exposure rate measurements were taken at locations with cover and fill material and background locations using a high-pressure ionization chamber (HPIC). A correlation was developed between the HPIC and UAV-based measurements that enabled the conversion of UAV-based gamma survey data to exposure rate data.

The results of the radiological investigation showed no evidence of increased gamma radiation from waste disposals in Landfill Unit L-14. Observed differences in gamma radiation corresponded to the location and use of waste-free cover and fill materials. The radiation survey results showed that all background measurements were within the expected variability of natural background and agreed with published estimated exposure rates for the area. Complete details of the survey and its results are provided in ERG and K2 (2020), which is attachment B to the CAP (Gradient 2020).

3. Characterization of the Bakken Oilfield Waste

The Bakken oilfield waste originated in the Bakken oilfields of North Dakota and is a byproduct of oil and natural gas production. A total of approximately 1,285 tons (1.17×10^6 kg) were disposed of in the landfill from May 2, 2016 to September 16, 2019 in 64 loads. The waste was primarily filter socks, but also contained filters, contaminated soils and equipment, pipe scale, rags, and liquids. Filter socks are essentially large bags that are shaped like human socks and are used to capture particulates that are separated from water during the fracking process.

3.1. Radiological Characterization of the Bakken Oilfield Waste

The radiological characterization, or source term, refers to the total activity, volume, and radionuclide composition of the Bakken oilfield waste that was disposed in the landfill. The source term uses the inventory estimates and the geographical location of the Bakken oilfield waste, coupled with release mechanisms and models to estimate both the weighted-average and potential worst-case quantity of radioactive material that could have been released to the environment (air, soil, and water) per unit time. In this case, the inventory was calculated based on generator waste disposal manifests, the time frame in which the material was disposed in the landfill, the estimated volume of material disposed, available radioanalytical data for the materials, and pertinent published radiological data.

TENORM radionuclides considered in this assessment are presented in Table 3-1. Numerous short-lived radioactive progeny would also be present if any of the parents are present in the source term, these are also accounted for in this analysis. The U-238 and Th-232 decay series are the primary TENORM decay series of concern in the Bakken oilfield waste (see Figure 3-1 and Figure 3-2).

Table 3-1. Relevant TENORM Radionuclides and Their Half-lives[2]

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

[2] The rate at which a radionuclide decays is measured in half-life. The term half-life is defined as the time it takes for one-half of the atoms of a radioactive material to disintegrate.

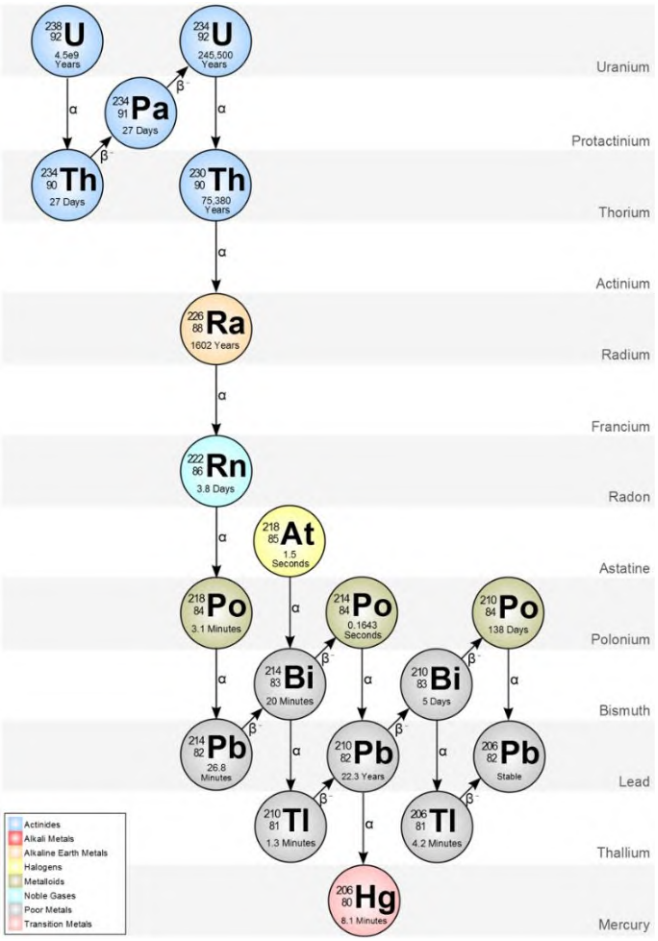

Figure 3-1. Uranium-238 decay scheme showing the short-lived progeny that will be present alongside the parent. Taken from http://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html.

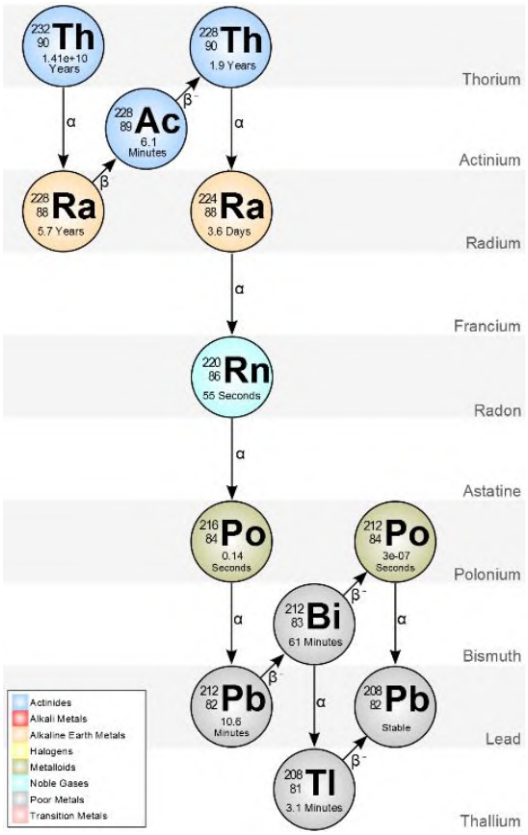

Figure 3-2. Thorium-232 decay series showing the short-lived progeny that will be present alongside the parent. Taken from http://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html.

3.2. Radiological Source Term for Disposal Operations

Two source terms were developed for this analysis. The first is a weighted-average source term based on waste type that most likely represents the actual radiological composition of the Bakken oilfield waste, and the second is an upper-bound or maximum source term to ensure that doses and risks were not underestimated.

3.2.1. Weighted-average Source Term

The weighted-average source term was calculated using the available radioanalytical data for the Bakken oilfield waste and published data specific to North Dakota from Argonne National Laboratory (ANL 2014). Where possible, the waste type breakdown was obtained from data provided by CWMNW Arlington. Where the waste type was unknown, it was assumed to be filter socks, which comprised most of the disposed waste (Table 3-2).

Table 3-2. Summary of Available Data on Waste Type

Waste type	Mass (g)	Percent of total
Filter socks	6.99×10^{8}	81%
Contaminated soils	1.74×10^{7}	2%
Mixed	3.02×10^{7}	3%
Rags	6.12×10^{6}	1%
Contaminated equipment	1.34×10^{4}	0.002%
Scale	1.04×10^{6}	0.1%
Filters	9.78×10^{7}	11%
Liquid	6.69×10^{4}	0.01%
Pipe	1.14×10^{7}	1%
Soil	4.54×10^{5}	0.1%

Radioanalytical data was available for four categories of waste: filter socks, filters, pipe scale, and other. Where the category for the waste type in Table 3-2 was not immediately obvious the following assumptions were used:

- "Pipe" and "Scale" were assigned to the category Pipe Scale
- "Contaminated soil", "Soil", "Mixed", and "Rags" were all assigned to the category Other
- Contaminated equipment and liquid were not considered in the analysis as they represent a negligible quantity of total mass (<<1%).

Table 3-3 provides the waste type breakdown used in calculating the weighted-average source term.

Table 3-3. Waste Type Breakdown for Bakken Oilfield Waste

Waste type	Mass (g)	Percent of total
Filter socks	9.43×10^{8}	81%
Filters	1.32×10^{8}	11%
Pipe scale	1.68×10^{7}	1%
Other	7.31×10^{7}	6%

Weighted-average radionuclide concentrations were then calculated using average values from both the available published radioanalytical data and from ANL (2014, Table 2.1). The ANL data is specific to North Dakota, represents a reasonable approximation for the Bakken oilfield waste, and increases the robustness of the source term characterization.

For each category of waste in Table 3-3, weighted-average radionuclide concentrations were computed with the following assumptions (see Table 3-4):

- Filter socks and pipe scale
    - Pb-210, Ra-226, and Ra-228 values are based on single measurement of Bakken oilfield waste and average filter-sock values from ANL (2014, Table 2.1)
    - Th-232 is based on average filter-sock/pipe-scale values from ANL (2014, Table 2.1)
    - Th-228, Th-230, U-234, and U-238 values are assumed to be the same as filters.

- Filters
  - Average of measurements from Bakken oilfield waste data.
- Other
  - Assumed to be average of filter socks, pipe scale, and filters.

The weighted-average radionuclide concentration is given by

$$CA_j = \sum_{i=1}^{n} \frac{C_{i,j} \times M_i}{M_T} \quad (3\text{-}1)$$

where

CA_j = weighted-average concentration for radionuclide j (pCi g^{-1})
$C_{i,j}$ = concentration of radionuclide j for waste category i (pCi g^{-1})
M_i = mass of Bakken oilfield waste in category i (g)
M_T = total mass of Bakken oilfield waste (g).

The weighted-average concentrations are provided in Table 3-4.

Table 3-4. Weighted-Average Radionuclide Concentrations in Bakken Oilfield Waste

Radionuclide	Weighted-average radionuclide concentration (pCi g^{-1})
U-238	2.83×10^{-2}
U-234	9.67×10^{-2}
Th-230	3.87×10^{-2}
Ra-226	8.93×10^{1}
Pb-210	4.98×10^{2}
Th-232	1.31×10^{1}
Ra-228	4.10×10^{1}
Th-228	4.96

3.2.2. Maximum Source Term

The maximum source term was computed assuming that the entirety of the Bakken oilfield waste contained the maximum measured concentration obtained from the supplied laboratory analytical data for each radionuclide listed in Table 3-1 and represents an extreme upper bound on the likely radiological concentrations. A summary table and the raw analytical data sheets from the analytical laboratory are provided in Appendix B. Maximum concentrations used in this assessment are provided in Table 3-5.

Table 3-5. Maximum Radionuclide Concentrations in Bakken Oilfield Waste

Radionuclide	Maximum radionuclide concentration ($pCi\ g^{-1}$)
U-238	1.18
U-234	2.01
Th-230	7.99×10^{-1}
Ra-226	1.43×10^{2}
Pb-210	8.14×10^{2}
Th-232	4.74×10^{-1}
Ra-228	6.17×10^{1}
Th-228	8.40

3.3. Radiological Source Term for an Excavation and Redisposal Alternative

The purpose of this section is to describe the source term for the excavation and redisposal alternative. The Bakken oilfield waste was disposed in the CWMNW Landfill Unit L-14, comingled with other chemical and hazardous wastes, and covered with on-site cover materials. The total quantity of the mixed wastes was estimated in the CAP (Gradient 2020). This other waste effectively causes dilution of the Bakken oilfield source term per unit mass in the landfill, and this dilution effect is accounted for by computing a mass dilution factor. The dilution factor was calculated based on a 25% fluff factor (Gradient 2020):

$$Dilution\ Factor = \frac{Bakken\ Oilfield\ Waste\ Mass}{Total\ Waste\ Mass} = \frac{1.17\times10^{6}\,kg}{3.50\times10^{6}\,kg} = 0.33$$

Varying the fluff factor between 15% and 50% yielded dilution factors of 0.31 and 0.40, respectively, which demonstrated the results were not sensitive to this parameter. Mixed waste removal parameters are detailed in Table 3-6.

Table 3-6. Mixed Waste Removal Parameters

Parameter	Value	Units
Total Bakken oilfield waste mass	1.17×10^{6}	kg
Total mixed waste mass to be excavated, 25% fluff factor[a]	3.50×10^{6}	kg
Total volume to be removed, including 15% fluff factor[a]	3.80×10^{6}	kg
Total volume to be removed, including 50% fluff factor[a]	2.91×10^{6}	kg

a. Waste expands when removed from the landfill, so the total volume trucked off-site is greater than that excavated. A 25% fluff factor is assumed here. A sensitivity analysis was conducted assuming the fluff factor was 15% and 50%.

Applying the dilution factor to both the maximum and average source terms yields the radionuclide concentrations used for computing doses and risks for the excavate and redispose alternative (Table 3-7).

Table 3-7. Radionuclide Concentrations for the Excavate and Redispose Alternative[a]

Radionuclide	Maximum radionuclide concentration (pCi g^{-1})	Weighted-average radionuclide concentration (pCi g^{-1})
U-238	3.93×10^{-1}	9.45×10^{-3}
U-234	6.70×10^{-1}	3.22×10^{-2}
Th-230	2.66×10^{-1}	1.29×10^{-2}
Ra-226	4.78×10^{1}	2.98×10^{1}
Pb-210	2.71×10^{2}	1.66×10^{2}
Th-232	1.58×10^{-1}	4.36
Ra-228	2.06×10^{-1}	1.37×10^{1}
Th-228	2.80	1.65

a. 25% fluff factor.

4. Exposure Scenarios Considered in the Dose and Risk Assessment

Exposure to radiation from radionuclides present in the Bakken oilfield waste depends on the types of radiation emitted, the environmental media where they may be present currently or in the future, and the location and activities of individuals in the vicinity of the waste. For Bakken oilfield waste individuals may be exposed from inhaling waste particulates released into the atmosphere during disposal or excavation and give a radiation dose to the lung and other tissues. This exposure decreases with distance from the disposal or excavation location due to atmospheric dilution and dispersion. Particles may be deposited on soil and be ingested in tiny quantities, but only if the individual is near the material. Individuals can also be exposed externally if they are very near the waste material. The waste also generates radon gas that can be inhaled and give a dose to the lung and other tissues. Over exceptionally long time periods (i.e., tens of thousands of years), radionuclides may migrate to groundwater and be ingested in drinking water. However, the likelihood that radionuclides from the Bakken oilfield waste would make their way to a potable aquifer for any time in the future is extremely remote.

Pertinent exposure scenarios to identified receptors were examined to develop radiation doses and risks associated with each scenario. Exposure scenarios that were considered include:

- During disposal;
- Closure-in-Place, and
- Excavate and redispose.

Receptors include waste handlers, landfill workers, hypothetical excavation workers, a hypothetical supervisor, the nearest current resident (Figure 4-1), and potential future residents.

4.1. During Disposal

The Bakken oilfield waste was disposed of at CWMNW Arlington over approximately a three-year period between May 2, 2016, and September 16, 2019. The waste was received in a total of 64 shipments. For the exposure assessment, it is assumed that the waste was disposed of entirely by a single individual without the benefit of personal protective equipment (PPE), which was not what is known to actually have occurred but was analyzed to estimate the highest possible risk.

This hypothetical individual in almost all cases was not a CWMNW employee but was employed by CWMNW's customer who transported the waste to the landfill. They are referred to as the waste handler in this report. The CWMNW employee with potential exposure during the disposal process is the landfill inspector who escorts the waste handler to the designated disposal area. This employee's exposure is less than the waste handler's as the landfill inspector maintains at least 4.6 m (15 ft) of distance from the waste handler's vehicle and remains inside the escort vehicle while wearing full PPE. All personnel entering the active disposal area are required to wear PPE, including respirators at all times due to the hazardous chemical nature of the wastes disposed. For these reasons, the dose to the landfill worker will be less than the dose to the waste handler and is not calculated explicitly.

The only other potentially exposed receptor during disposal operations is the current off-site resident, who occupies the home nearest to the CWMNW Arlington landfill, which is 3,260 m (10,700 ft or approximately 2 miles) away (Figure 4-1). Input parameters for each receptor are detailed in Table 4-1, and a detailed discussion is provided in Sections 4.1.1 and 4.1.2.

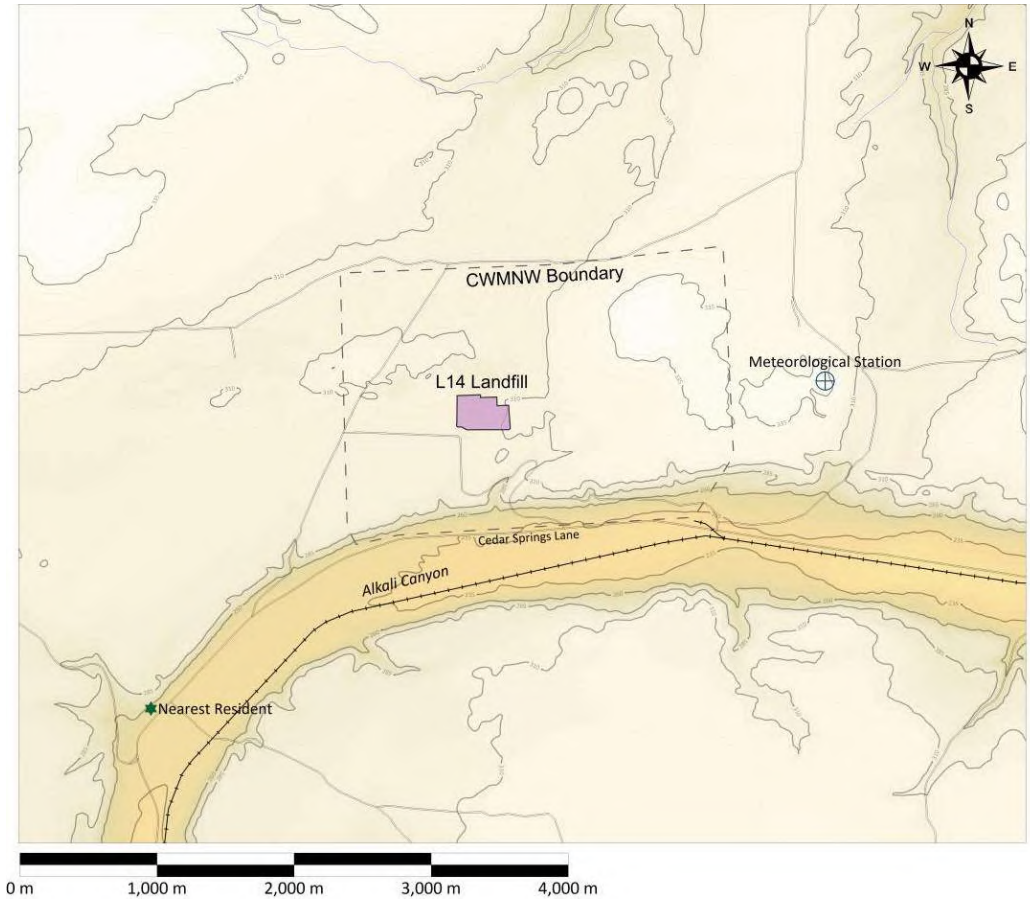

Figure 4-1. Location of nearest resident relative to CWMNW Arlington.

4.1.1. Waste Handler

The waste handler is the person who drives the waste delivery vehicle from the point of origin to the CWMNW Arlington landfill. Once at the designated disposal location inside of Landfill Unit

L-14, they operate the offloading controls outside the truck that allow the waste to be physically deposited into the landfill. This individual is the maximally exposed individual during the disposals as they are outside their truck in full PPE. For the purposes of this analysis, the exposure to the waste handler does not consider the required PPE, and thus the calculated doses represent overestimates of the actual exposures.

Relevant pathways of exposure for the waste handler are:

- Inhalation of particulates
- Inadvertent ingestion of soil
- External exposure.

As noted previously, it is assumed that the same individual is the waste handler for all the Bakken oilfield waste. This in fact was not the case; therefore, the calculated doses and risks are overestimates of the actual doses.

4.1.2. Current Off-site Resident

The current off-site resident occupies the closest home to the CWMNW Arlington landfill. This is in Alkali Canyon, approximately 3,260 m (10,700 ft or approximately 2 miles) southwest from Landfill Unit L-14 where the Bakken oilfield waste is located. This receptor is located upwind of the facility operations to the southwest. The only potentially complete pathway of exposure is inhalation of fugitive particulates, and the analysis does not consider the decrease in air concentrations inside the residence which would lower the resulting dose and risk. This receptor is included in the analysis as the nearest off-site human receptor.

Table 4-1. Exposure Parameters for Disposal Operations

Parameter	Value	Units	Reference
Daily inhalation rate – waste handler	43.2	m^3	EPA (2011)[a]
Daily inhalation rate – current off-site resident	20.0	m^3	EPA (1991)[b]
Soil ingestion rate	4.81	mg per disposal	EPA (2016)[c]
Minutes per disposal	7	minutes	Per CWMNW
Number of disposals	64	unitless	Per CWMNW
Distance to current off-site resident	3261.20	m	Per CWMNW

a. Represents a weighted-average calculated using short-term inhalation rates for construction workers assuming two hours light intensity, four hours moderate intensity, and two hours heavy intensity.
b. Default exposure factor for estimating the reasonable maximum exposure for a resident per EPA 1991 guidance.
c. Total soil ingestion is 330 mg per day.

4.2. Alternative 1: Closure-in-Place Scenario

This alternative assumes that the Bakken oilfield waste material is left in place and regular landfill operations continue to cover the material until the landfill is closed after 30 years and capped in compliance with the approved closure plan in the facility's permit. Both the weighted-average and maximum source terms were analyzed for this alternative. Receptors and exposure

pathways are detailed in the sections that follow. Additional details on this alternative can be found in the CAP (Gradient 2020). Input parameters are listed in Table 4-2.

4.2.1. Landfill Worker

The landfill worker represents individuals who currently operate equipment or perform other tasks within the landfill footprint on a regular basis. The analysis estimates their risk based on an assumption of a 30-year career continuing to work at the landfill. These individuals are in enclosed cabs of equipment while wearing full PPE, including respirators, while working in the landfill. No credit has been taken in the dose calculations for either the respirator or the shielding provided by the heavy equipment. Both of these factors serve to overestimate the calculated doses. For this scenario, the only complete pathway of exposure is inhalation of outdoor radon. Because radon is a long-term exposure concern, doses are reported assuming 30 years of exposure.

4.2.2. Current Off-site Resident

The current off-site resident occupies the closest residence to the CWMNW Arlington landfill. The resident is located approximately 3,261 m (10,700 ft) to the southwest from Landfill Unit L-14 where the Bakken oilfield waste was disposed. For this scenario, the only complete pathway of exposure is inhalation of outdoor radon. Because radon is a long-term exposure concern, doses are reported assuming 30 years of exposure.

4.2.3. Future Off-site Resident

The future off-site resident is assumed to live at the same location as the current off-site resident, but far into the future. Complete pathways of potential exposure include:

- Inhalation of outdoor radon, which includes 30 years of exposure
- Ingestion of groundwater; the model is run to maximum concentration and dose.

4.2.4. Future On-site Resident

The hypothetical future resident is assumed to live on Landfill Unit L-14, which is a highly unlikely case included to understand the possible risk if land use restrictions placed on the landfill following closure were to fail or be forgotten in the future. A groundwater well is located at the immediate downgradient edge of Landfill Unit L-14 (see Section 5 for details). Complete pathways for these individuals include:

- Inhalation of outdoor radon, which includes 30 years of exposure
- Ingestion of groundwater; the model is run to maximum concentration and dose.

Table 4-2. Exposure Parameters for Alternative 1

Parameter	Value	Units	Reference
Dose factor for radon	760	mrem WLM^{-1}	Yu et al. (2001)
Hours exposed, landfill worker	2,040	hours	[a]
Hours exposed, current off-site resident	6,760	hours	[b]
Hours exposed, future off-site resident	8,400	hours	[c]

Parameter	Value	Units	Reference
Hours exposed, future on-site resident	8,400	hours	[c]
χ/Q, landfill worker	3.03×10^{-4}	s m^{-3}	[d]
χ/Q, future on-site resident	3.03×10^{-4}	s m^{-3}	[d]
χ/Q, current off-site resident	2.71×10^{-7}	s m^{-3}	[d]
χ/Q, future off-site resident	2.71×10^{-7}	s m^{-3}	[d]

a. Assumed 170 hours per month for 12 months.
b. Assumed total hours per year – 2,000 working hours per year.
c. Assumed 350 days per year, 24 hours per day.
d. Annual averages based on AERMOD calculations See Section 5.1.4 for details. The landfill worker and future on-site resident are assumed to be located at the Bakken oilfield waste in Landfill Unit L-14. The current off-site resident is located 3,261 m (10,700 ft) from the Bakken oilfield waste. The future off-site resident is assumed to be located at the same place as the current off-site resident.

4.3. Alternative 2: Excavate and Redispose Bakken Oilfield Waste

This analysis is limited to the radiological risks associated with this alternative. Physical risks, such as transport risks, are discussed in detail in the Corrective Action Plan (Gradient 2020). This alternative assumes that the Bakken oilfield waste is excavated using heavy equipment and loaded into trucks for off-site disposal via public roads. Details of the excavation, trucking, and redisposal process can be found in the CAP as well (Gradient 2020). Input parameters for the dose calculations are the same as those for the disposal operations (Table 4-1) with two exceptions. First, the calculated time per removal load is approximately 66 minutes (Gradient 2020) rather than the 7 minutes for disposal. Second, the volume of waste to be removed differs from that disposed of due to mixing with other landfill wastes as described in Section 0. The waste is assumed to be removed using 20-yard dumpsters that hold 6.2 cubic meters of material each. Thus, the total number of truck loads required for removal operations is 322 (see Gradient [2020] for details). Inhalation and soil ingestion rates are the same as those used for disposal operations.

4.3.1. Excavation Worker

The excavation worker represents workers who are involved in the hypothetical excavation process. They are not landfill employees. The same individual is assumed to be present for all 322 loads, which for calculation purposes are assumed to occur in a single year. In reality, the excavation would occur over a period of approximately 10 years. As with the other receptors, no credit is taken for PPE worn by the worker, meaning that the dose to the worker is overestimated. Some shielding from the cab of the heavy equipment is accounted for in the external dose calculations. Complete pathways of exposure include:

- Inhalation of particulates
- Ingestion of soil
- External exposure.

4.3.2. Supervisor

The supervisor monitors the hypothetical excavation process and ensures it is conducted safely. The same individual is assumed to be present for all 322 loads, which for calculation

purposes are assumed to occur in a single year. In reality, the excavation would occur over a period of approximately 10 years. As with the other receptors, no credit is taken for PPE worn by the worker, meaning that the supervisor's dose is overestimated. Complete pathways of exposure include:

- Inhalation of particulates
- Ingestion of soil
- External exposure.

4.3.3. Current Off-site Resident

This individual currently occupies the closest home to the CWMNW Arlington landfill. The current off-site resident is located approximately 3,261 m (10,700 ft) to the southwest from Landfill Unit L-14 where the Bakken oilfield waste is located. The complete pathway of potential exposure is inhalation of particulates.

5. Dose and Risk Calculation Methodology

This section provides the details of the methodology used to calculate the doses and risks from radiological exposures, distinguishing between the air pathway and the groundwater pathway.

5.1. Atmospheric Pathway Modeling Methods

Radionuclide emissions during disposal and hypothetical removal operations 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 any material that is attached to a filter sock. Modeling using aggregate material results in a worst-case inhalation scenario. The exposure scenarios are illustrated in Figure 5-1 and Figure 5-2. Full details of the calculations can be found in Appendix C.

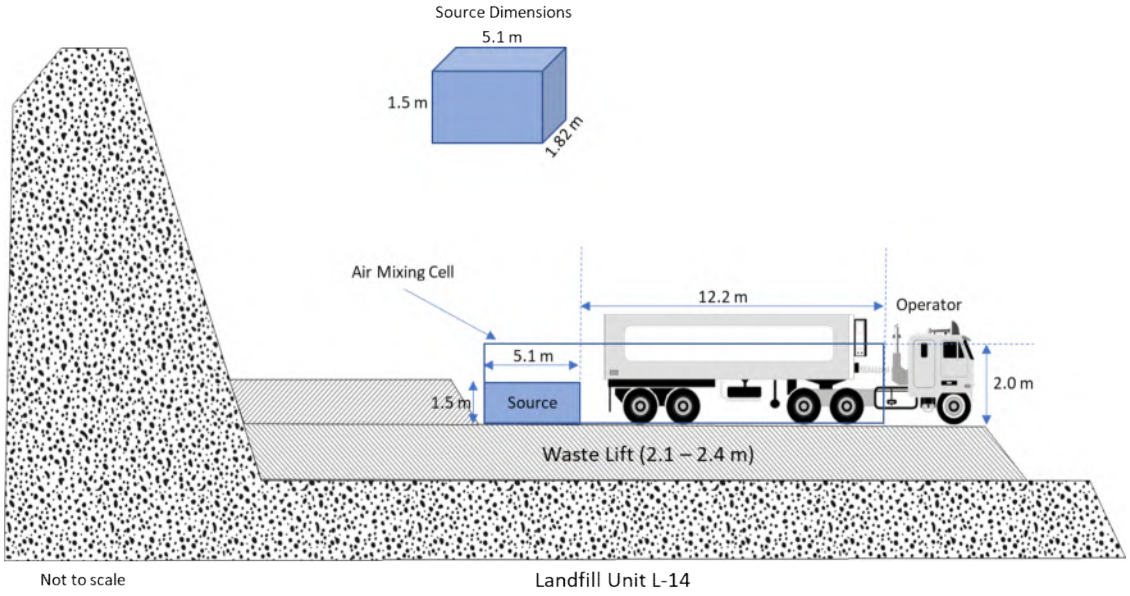

Figure 5-1. Conceptual model of exposure for the waste handler during disposal of the Bakken oilfield waste, which is indicated as "Source" in the figure.

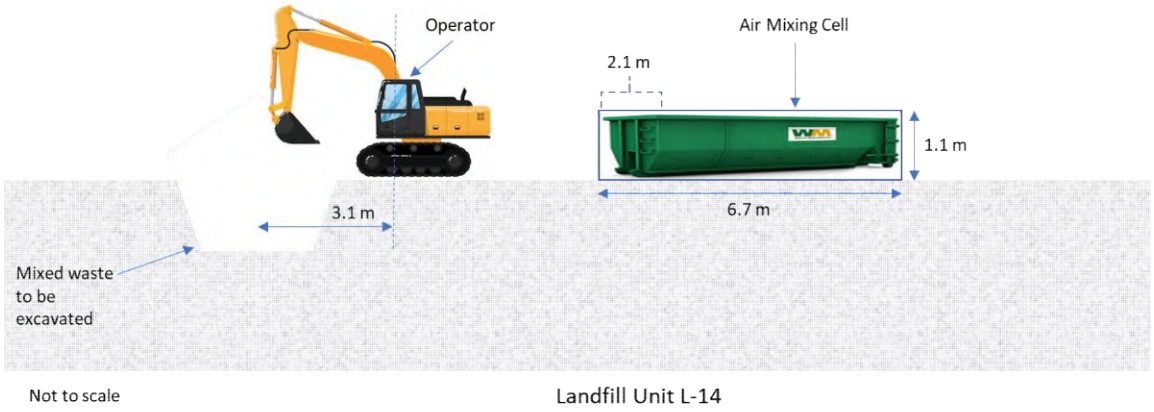

Figure 5-2. Conceptual model of exposure for the excavation worker during hypothetical removal of the Bakken oilfield waste.

The emission factor is calculated as:

$$E = k(0.0016)\frac{\left(U/2.2\right)^{1.3}}{\left(MC/2\right)^{1.4}} \qquad (5\text{-}1)$$

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.

The product of the mass of Bakken oilfield waste in a load and the emission factor yields the mass of material that is available for suspension in air. The quantity of radionuclides released to the air is the product of the mass released to air and the representative radionuclide concentration:

$$Q = E \times M \times C \times y \tag{5-2}$$

where

Q = activity released to air (pCi)
M = mass of one TENORM disposal (Mg)
C = representative radionuclide concentration in Bakken oilfield waste (pCi g^{-1})
y = unit conversion factor, 1,000 g kg^{-1}.

The air concentration is then calculated by assuming the entire mass that is suspended is mixed in a volume of air (defined later as the mixing cell). 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:

$$K = \frac{U}{L} \tag{5-3}$$

where

K = removal rate constant (s^{-1})
U = wind speed (m s^{-1})
L = 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:

$$\begin{aligned} \frac{dQ}{dt} &= -KQ \\ Q(t) &= Q_0 e^{-Kt} \end{aligned} \tag{5-4}$$

where Q_o is the initial activity in the mixing cell defined by Equation (5-2). The time-integrated air concentration that the worker is exposed to is calculated by:

$$TIC = \frac{Q_o}{V}\int_0^{\infty} e^{-kt}dt = \left(\frac{Q_o}{V}\right)\left(-\frac{1}{K}\right)e^{-kt}\Big|_0^{\infty} = -\frac{Q_o}{VK}(0-1) = \frac{Q_o}{VK} \tag{5-5}$$

where

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

The area of the mixing cell for disposals was assumed to be the surface area of the disposal plus a buffer distance that accounts for the length of the trailer (12.2 m, see Figure 5-1). For hypothetical removal operations, no buffer is assumed beyond the 20-yard container (Figure 5-2). The surface area of the disposal is the disposal volume divided by the assumed average height of the pile. The mixing cell volume for disposals is the surface area (including buffer) × the difference between the height of the mixing cell and the average height of the pile. The mixing cell volume for hypothetical removal operations is the volume of the 20-yard dumpster.

$$L = \sqrt{\frac{V_{load}}{H_{load}}} + l$$
$$V = L^2 \left(H_{mc} - H_{load} \right) \quad (5\text{-}6)$$

where

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

Source dimensions for disposal operations are depicted in Figure 5-1, and model parameters are listed in Table 5-1. Parameters that differ for hypothetical removal operations are given in Table 5-2.

Table 5-1. Parameters for Emission Model during Disposal and Transport in Air

Parameter	Value	Units	Notes
Average wind speed, U	4.839	m s^{-1}	From on-site met data
Moisture percent, MC	10.00	percent	Table 13.2.4-1 in Section 13.2.4, mean value for clay in municipal landfills (EPA 1995)
Particle size multiplier, k	0.48	unitless	AP-42 (EPA 1995) – assumes particles ≤15 µm are respirable
Volume of Bakken oilfield waste per disposal, V_{load}	1.03×10^{1}	m^3	Calculation
Bulk density, ρ_b	1.76×10^{3}	kg m^{-3}	Geosyntec Consultants (2020)
Buffer distance, l	12.2	m	Assumed distance from edge of disposal pile to waste handler. Per CWMNW, waste was brought in using ~40-ft trailers
Disposal pile height, H_{load}	1.5	m	Assumed average height of disposed load before compaction
Mixing cell height, H_{mc}	2.0	m	Assumed height of air mixing cell
Length of air mixing cell, L	17.3	m	Calculated from Equation (5-6)
Volume of mixing cell, V	36.87	m^3	Calculated from Equation (5-6)
Removal rate constant, K	0.3	s^{-1}	Calculated from Equation (5-3)

Parameter	Value	Units	Notes
Emission rate, E	4.09×10^{-3}	kg released to air per disposal	Calculated using Equation 2 from AP-42 (EPA 1995)

Table 5-2. Parameters for Emission Model during Hypothetical Removal Operations and Transport in Air

Parameter	Value	Units	Notes
Mass of Bakken oilfield waste per removal, m_{load}	1.09×10^{4}	kg per load	Calculation
Air mixing cell height, H_{mc}	1.1	m	Dimensions of a 20-yard dumpster[a]
Air mixing cell length, L	6.7	m	Dimensions of a 20-yard dumpster[a]
Air mixing cell width, W	2.1	m	Dimensions of a 20-yard dumpster[a]
Volume of mixing cell, V	1.57×10^{1}	m^3	Calculated as length×width×height
Removal rate constant, K	0.7	s^{-1}	Calculated from Equation (5-3)
Emission rate, E	2.45×10^{-3}	kg released to air per disposal	Calculated using Equation 2 from AP-42 (EPA 1995)

a. Dumpster dimensions taken from: https://www.wm.com/us/en/cpn/temp-dumpster.

5.1.1. Inhalation and Ingestion Dose Calculations

This section describes how inhalation and ingestion doses from the emissions described above are calculated. Inhalation doses to on-site receptors are calculated as:

$$DINH = IR \times \sum_{j=1}^{n} TIC_j \times DCINH_j \qquad (5\text{-}7)$$

where

$DINH$ = inhalation effective dose for a Bakken oilfield waste 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.

Inhalation doses to off-site receptors are calculated using the amount of activity suspended into the air and a dispersion factor calculated using AERMOD (see Section 5.1.4).

Ingestion effective doses during disposal or removal operations for on-site receptors assume that a given amount of the Bakken oilfield waste is ingested via adherence to skin and hand, 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 or removal of the Bakken oilfield waste, which is 7 minutes and 66 minutes, respectively. The ingestion effective dose is simply the product of the

effective dose coefficient and the amount of activity ingested. The amount of activity ingested is the soil ingestion rate adjusted for exposure time × the activity concentration of the Bakken oilfield waste. The amount of Bakken oilfield waste ingested is calculated by:

$$D_{ing} = SIR \times y \times ET \times \sum_{j=1}^{n} \mathrm{CA}_j DCING_j \quad (5\text{-}8)$$

where

SIR = soil ingestion rate, 330 mg day^{-1}
y = unit conversion factor: 1 g 1,000 mg^{-1}; 1 day 8 hours^{-1}
ET = exposure time (hours)
D_{ing} = effective dose from ingestion (mrem)
CA_j = weighted-average concentration in Bakken oilfield waste for radionuclide j (pCi g^{-1})
$DCING_j$ = ingestion effective dose coefficient (mrem pCi^{-1}).

Ingestion of contaminated soils is not a complete exposure pathway for off-site individuals.

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 1999b) and International Commission on Radiation Protection (ICRP) Reports 68 and 72 (ICRP 1994, 1996). Inhalation and ingestion dose coefficients are given in Table 5-3.

Table 5-3. Inhalation and Ingestion Dose Coefficients

Radionuclide	Inhalation dose coefficient (mrem pCi^{-1})	Ingestion dose coefficient (mrem pCi^{-1})
U-238	3.21×10^{-2}	2.13×10^{-4}
U-234	3.74×10^{-2}	2.15×10^{-4}
Th-230	3.85×10^{-1}	9.36×10^{-4}
Ra-226	3.82×10^{-2}	1.68×10^{-3}
Pb-210	4.01×10^{-2}	1.03×10^{-2}
Th-232	4.26×10^{-1}	1.03×10^{-3}
Ra-228	6.34×10^{-2}	5.92×10^{-3}
Th-228	1.75×10^{-1}	9.34×10^{-4}

5.1.2. External Dose Calculations

External doses for the waste handler during disposals and the excavation worker and supervisor during hypothetical removal operations were calculated using a dose factor (Table 5-4) computed using the MicroShield code (Grove Engineering, Inc. 2013). The source-receptor geometry is as shown in Figure 5-1 and Figure 5-2. The source for the waste handler during disposals is represented by a rectangular volume having the dimensions illustrated in Figure 5-1 and a material with the chemical composition of cement (limestone and clay) and aggregate (silica

sand) having a density of 1.3 g cm^{-3}. No shielding from the truck was assumed. The same source geometry and material was assumed for the excavation worker, but this worker is separated by 3.05 m of air and 0.095 cm of steel representing the cab of an excavator. The dose rate included photon buildup in the source. The external doses are computed as:

$$D = ET \times \sum_{i=1}^{n} DF_i \times C_i \quad (5\text{-}9)$$

where

ET = exposure time (hours)
DF_i = dose factor for radionuclide i computed using the MicroShield code (mrad hr^{-1} per pCi g^{-1})
C_i = concentration of radionuclide i.

Table 5-4. External Dose Factors Computed Using MicroShield

Radionuclide	Dose factor for waste handler and excavation worker (mrad hr^{-1} per pCi g^{-1})	Dose factor for supervisor (mrad hr^{-1} per pCi g^{-1})
Ra-226	4.49×10^{-6}	5.65×10^{-5}
Ra-228	6.67×10^{-6}	8.32×10^{-5}

5.1.3. Radon Exposure and Dose

Radon-222 emissions from the landfill resulting from the Bakken oilfield waste disposals were calculated using U.S. 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 the Bakken oilfield waste and the other chemical and hazardous wastes (hereafter referred to as mixed waste). The flux from the bare surface is given by:

$$J_t = 10^4 C \rho_b E \sqrt{\lambda D_t}\, \tanh\left(\sqrt{\frac{\lambda}{D_t}} x_t\right) \quad (5\text{-}10)$$

where

J_t = flux from the surface of the Bakken oilfield waste layer in the disposal cell (pCi m^{-2} s^{-1})
C = Ra-226 concentration in the mixed waste (pCi g^{-1})
D_t = radon diffusion coefficient in the mixed waste (m^2 s^{-1})
λ = radon decay constant (2.1×10^{-6} s^{-1})
ρ_b = bulk density of the mixed waste (g cm^{-3})
E = Rn-222 emanation coefficient (unitless)
x_t = thickness of compacted mixed waste (cm), calculated as shown in section 5.2.5.

Both the maximum and weighted-average Ra-226 concentrations were used. This waste is then covered with soil and other chemical/hazardous wastes, and ultimately the Unit will be capped

in compliance with the facility's closure plan contained in CWMNW's permit. The radon flux after burying and covering the waste is given by:

$$
\begin{aligned}
J_c &= \frac{2J_t e^{-b_c x_c}}{\left(1+\sqrt{a_t/a_c}\,\tanh\left(b_t x_t\right)\right)+\left(1-\sqrt{a_t/a_c}\,\tanh\left(b_t x_t\right)\right)e^{-2b_c x_c}} \\
b_i &= \sqrt{\lambda/D_i}\,, i = c \text{ or } t \\
a_i &= \phi D_i\left(1-\left(1-k\right)m_i\right)^2 \\
m_i &= 10^{-2} MP\left(\frac{1}{\rho_b}-\frac{1}{\rho_s}\right)
\end{aligned}
\qquad (5\text{-}11)
$$

where

J_c	=	radon flux from the disposal cell surface (pCi m^{-2} s^{-1})
ρ_s	=	particle density (g cm^{-3})
ϕ	=	porosity (unitless)
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:

$$D_i = 0.07\exp\left[-4\left(m-m\phi^2-m^5\right)\right] \qquad (5\text{-}12)$$

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

Doses from outdoor radon are dependent on the radon progeny concentrations in outdoor 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 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):

$$EEC = 0.105A + 0.516B + 0.379C \qquad (5\text{-}13)$$

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:

$$WLM = WL\frac{\text{hours exposed}}{170\text{ hours}}$$
$$D = 760\ \frac{\text{mrem}}{\text{WLM}} \times WLM \quad (5\text{-}14)$$

Radon model parameters are given in Table 5-5.

Table 5-5. Radon Model Parameters

Parameter	Value	Units	Notes
Waste thickness, x_t	0.18	m	Assumes each disposal is spread out over a single 25'×25' disposal cell
Cover thickness, x_c	32.84	m	Average waste depth from final grade as calculated from data provided by CWMNW
Dry-weight percent moisture, waste, *MP*	5.20	percent	Calculation
Dry-weight percent moisture, cover, *MP*	5.20	percent	Calculation
Bulk density, waste, ρ_b	1.76	g cm^{-3}	2,970 lb yd^{-3} per Geosyntec Consultants (2020)
Bulk density, cover, ρ_b	1.76	g cm^{-3}	2,970 lb yd^{-3} per Geosyntec Consultants (2020)
Porosity, waste, ϕ	0.41	unitless	Assumption based on waste material type, sandy loam[3]
Porosity, cover, ϕ	0.41	unitless	CWMNW Updated Hydrogeologic Conceptual Site Model Report (2008)
Particle density, waste, ρ_s	2.98	g cm^{-3}	Calculated using $\rho s = \rho b/(1-\phi)$
Particle density, cover, ρ_s	2.98	g cm^{-3}	Calculated using $\rho s = \rho b/(1-\phi)$
Radon emanation coefficient, *E*	0.2	unitless	Typical value for uranium mill tailings
Max Ra-226 concentration, *C*	1.43×10^{2}	pCi g^{-1}	See section 3
Weighted-average Ra-226 concentration, *C*	8.93×10^{1}	pCi g^{-1}	See section 3
Total area of Bakken oilfield waste disposals, *A*	3.72×10^{3}	m^2	Total area for all 64 disposals

Waste thickness was calculated using the average volume of the waste and assuming each load was spread out over a single 25'×25' disposal cell. Cover thickness was calculated using CWMNW

[3] Sandy loam was chosen for the groundwater assessment as it transmits water more readily. It was used for the radon assessment for consistency.

estimates on the depth from final grade. Radium-226 (the radon source) was assumed to be uniformly distributed within this thickness. Worst-case Ra-226 concentrations were estimated by placing the entire Ra-226 inventory for both the maximum and weighted-average source terms in one disposal cell and applying the bulk density of compacted waste. 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.

The waste is relatively dry with a calculated dry-weight percent moisture of 5.20%, calculated assuming an infiltration rate of 1 mm per year. 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 tailing covers have moisture contents ranging from 6% to 11%. Thus, a dry-weight percent moisture of ~5% is considered worst-case as it maximizes fluxes.

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 is likely a worst-case assumption because, again, the material in question was primarily associated with filter socks. However, as no data exists for estimating emanation coefficients from filter socks, the value for uranium mill tailings was deemed appropriate.

Radon concentrations for off-site receptors were calculated using χ/Q values derived from AERMOD as described in Section 5.1.4.

5.1.4. AERMOD Atmospheric Transport Modeling

Dispersion in air was calculated using the U.S. Environmental Protection Agency model AERMOD v19191 (EPA 2004) and one year of site-specific meteorological data (2010) obtained from the nearby meteorological tower (see Figure 2-1) operated by CWMNW. The meteorological data was processed with AERMET v12345, and the processed surface and upper air files were provided by CWMNW. For dispersion calculations, no deposition or plume depletion was assumed, which maximizes the air concentration. An area source (254 m east-west, 149 m north-south) located in the center of the landfill was used to calculate annual dispersion factors. This area represents the area in which the Bakken oilfield waste was disposed. The nearest resident was placed at UTM (zone 10) coordinates 711495E, 5053538N, and the future resident and landfill worker were placed at the center of the source (UTM 713932E, 5055692N). Air concentrations were calculated at 1 m above ground level.

AERMOD was used to calculate the dispersion factor or χ/Q (concentration [pCi m^{-3}] divided by release rate [pCi s^{-1}]). The χ/Q value has units of s m^{-3} and was calculated assuming a unit release rate from the source (1 pCi s^{-1}). Thus, the AERMOD concentration at either the future resident or nearest resident divided by the source release rate (1 pCi s^{-1}) yields the χ/Q value. The concentration for the actual release is found by multiplying the χ/Q value by the actual source release rate. Annual average χ/Q values were 3.03×10^{-4} s m^{-3} for the nearest future resident and landfill worker and 2.71×10^{-7} s m^{-3} for the nearest resident. For excavation and removal of waste, a 95% 1-hour average χ/Q value at the nearest resident was used. The 95% percentile is the 95th highest 1-hr χ/Q value calculated over the entire year (8,760 hours) of meteorological record. The 95% 1-hour χ/Q value for the nearest resident was 2.83×10^{-7} s m^{-3}. In this case, the χ/Q value is multiplied by the total activity released, instead of by the release rate, to yield the time-integrated concentration (pCi-s m^{-3}).

5.2. Groundwater Pathway Modeling

As discussed in Section 2.2.2, the Selah member of the Ellensburg formation underlies Landfill Unit L-14. To assess potential exposures via the groundwater pathway, unsaturated zone transport modeling was performed, which assumed leachate can migrate through the landfill's engineered double geomembrane and geosynthetic liner system and through its primary, secondary, and tertiary leachate collection and detection systems, through the unsaturated portion of the Selah to the saturated portion of the Selah (upper Selah aquifer). In this section, a conceptual and mathematical unsaturated and saturated zone transport model is presented to determine radionuclide travel times and pore water concentrations in the unsaturated and saturated zone, and potential maximum radiation doses and carcinogenic risks from ingesting water from a well in the upper Selah aquifer downgradient of Landfill Unit L-14, assuming liquid migration can occur. Note that the upper Selah aquifer is not used for drinking water or irrigation, and pore water in the unsaturated zone is not available for consumption as there is an insufficient amount to allow it to be pumped. Water balance calculations in CH2M HILL (2008) indicates groundwater does not discharge from the Selah south into Alkali Canyon but is lost through evapotranspiration.

5.2.1. Previous Modeling Efforts

Burns & McDonnell, Inc. (1998) developed a flow and transport model for Landfill Unit L-14 using the semi-analytical model MULTIMED for unsaturated transport and MODFLOW for the saturated portion. The unsaturated flow and transport portion of the MULTIMED model assumes steady-state infiltration and initial tracer concentrations in a source zone, and thereby provides tracer fluxes and concentrations as a function of time that may be input to MODFLOW as an upper boundary condition. The MODFLOW simulation was discretized into four layers that included the upper Selah water-bearing unit, the Intermediate Grey Clay, the lower Selah water-bearing unit, and the underlying water-bearing units of the Priest Rapids Member. The model included leakage from the upper Selah through the Grey Clay and into the lower Selah, and leakage from the lower Selah into the saturated portion of the Priest Rapids Basalt. The purpose of the model was to evaluate the effectiveness of a proposed groundwater monitoring network for early warning of a potential release of materials from the landfill. Concentrations were expressed in terms of the normalized concentration. The normalized concentration is the concentration in the aquifer divided by the concentration in the source. Based on modeling from a sump source that drained into the upper Selah, normalized concentrations in the upper Selah, Grey Clay, lower Selah, and underlying Priest Rapids were approximately 0.0019, 0.0003, <0.0001, and 0.0001, respectively. Thus, concentrations in the saturated portions of the Priest Rapids Basalt were predicted to be a factor of ~19 less than concentrations in the upper Selah (0.0019/0.0001 = 19).

This model was considered a "worst case" model because the vertical leakage rates from the upper Selah to the Priest Rapids was based on vertical hydraulic conductivities ranging from 5.0×10^{-9} to 4.6×10^{-7} cm s^{-1}. Recent analysis of leakage between the upper Selah aquifer to underlying saturated zones in the Priest Rapids Basalt (CH2M Hill 2008) indicated vertical hydraulic conductivities were unlikely to be greater than 5×10^{-10} cm s^{-1} and may be less than 1×10^{-10} cm s^{-1} Thus, movement of water from the upper Selah to the underlying Priest Rapids Basalt is much lower than what was assumed in the Burns & McDonnell, Inc. (1998) model. Consequently, concentrations in the saturated portions of the Priest Rapids Basalt would be substantially less than

predicted by Burns & McDonnell, Inc. (1998), and likely zero. For these reasons, we used the upper Selah aquifer as a means of bounding any potential impacts in saturated zones in the Priest Rapids Basalt. It should also be noted that the regional aquifer used for domestic sources and irrigation lies huntress of feet below the Priest Rapids Basalt. Any impacts to the saturated portion of the Priest Rapids Basalt will be at least a factor of 19 less than in the upper Selah aquifer.

5.2.2. Conceptual Model for Flow and Transport to the Upper Selah Aquifer

A generalized conceptual model for assessment of the groundwater pathway is illustrated in Figure 5-3. The Bakken oilfield waste is represented by a rectangular area source of fixed thickness. Radionuclide concentrations are assumed to be uniform throughout the source. Radionuclides associated with the Bakken oilfield waste partition into the infiltrating water and move downward through Landfill Unit L-14.

During active facility operations, leachate moves through the waste mass, is captured by the primary geomembrane liner system, and conveyed via the geosynthetic leachate collection layer on top of the primary geomembrane liner at the bottom of the landfill. The primary leachate collection layer channels the leachate to the primary sump, where it is removed as needed from the primary sump. Landfill L-14 has a geomembrane-lined secondary leachate detection layer underneath the primary geomembrane that conveys any potential leaks to the secondary leak detection sump. Additionally, Landfill Unit L-14 has a geomembrane-lined tertiary sump acting as a redundant leak detection and protection system for potential leachate leaks in the secondary sump. Notwithstanding the multiple redundant leak protection systems, a small fraction of leachate is assumed to pass through all three liner systems during operations. During closure of Landfill Unit L-14 an evapotranspiration cap will be installed over the entire waste footprint in compliance with the facility's closure plan. The evapotranspiration cap is designed to exclude infiltrating waters from entering the waste cell, thus discontinuing the addition of liquids into the landfill. The leachate collection system will remain in operation until the end of the post closure period, at which point all leachate is expected to be drained from the landfill waste mass.

For purposes of modeling, a worst-case scenario is assumed for the time after site closure, where the leachate collection system is assumed to cease operation and the engineered liner system is assumed to fail hydrologically, allowing any infiltrating precipitation to pass through the landfill and into the underlying vadose zone (or unsaturated zone). Over time, the hydrologic effectiveness of the engineered cap is assumed to degrade, resulting in infiltration through the engineered landfill cover system equivalent to natural background infiltration. In this assumed failure mode, leachate travels downward vertically through the vadose zone and enters the aquifer over a footprint area equivalent to the simulated Bakken oilfield waste block in Landfill Unit L-14. Radionuclides that enter the aquifer mix vertically within a defined region and migrate downgradient to a receptor well assumed to be (1) 100 m downgradient from the downgradient edge to the source (POC 1 in Figure 5-3) and (2) on the downgradient edge of the source footprint (POC 2 in Figure 5-3).

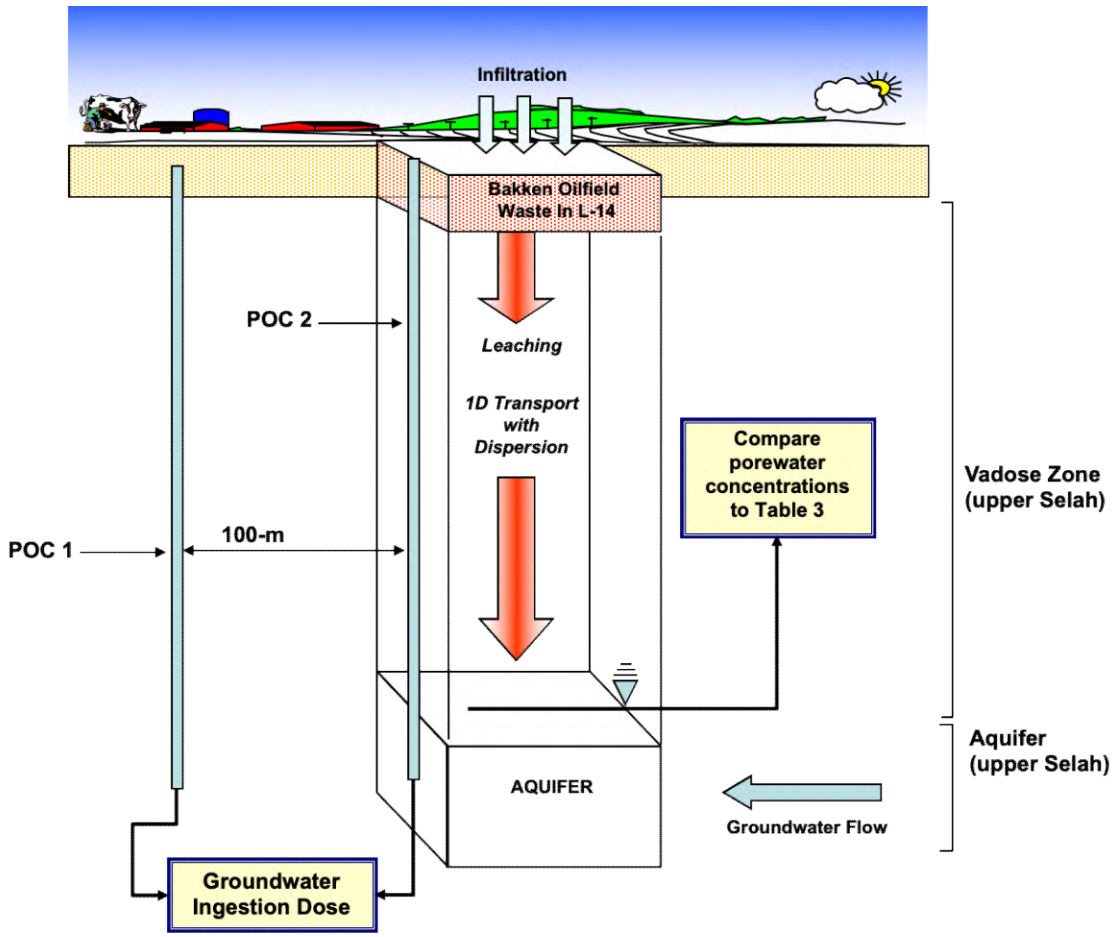

Figure 5-3. Generalized conceptual model for assessment of the groundwater pathway.

5.2.3. Mathematical Model and Code Selection

The conceptual model is typically represented mathematically by established equations for water flow in a porous medium and contaminant transport via advection, dispersion, and diffusion. For water flow in the unsaturated zone, the general one-dimensional equation is given by:

$$q = K\left(\frac{\partial H}{\partial z} + \frac{\partial \psi}{\partial z}\right) \tag{5-15}$$

where

q = specific discharge or Darcy flux (m yr^{-1})
θ = volumetric moisture content (m^3 m^{-3})
H = elevation head (m)
ψ = suction or pressure head from capillary forces (m)
K = unsaturated hydraulic conductivity (m yr^{-1})
z = distance positive downward from the top of the column (m).

The general equation for one-dimensional transport in the vadose zone under transient flow conditions is given by:

$$Rd\ A\ \theta\frac{\partial C}{\partial t} = A\frac{\partial}{\partial z}\left(\theta D\frac{\partial C}{\partial z}\right) - A\frac{\partial qC}{\partial z} - \left(Rd\,\theta\,\lambda + Rd\frac{\partial \theta}{\partial t}\right)AC \quad (5\text{-}16)$$

where

C = radionuclide solute concentration (pCi m^{-3})
D = dispersion coefficient (m^2 yr^{-1})
A = cross-sectional area perpendicular to flow (m^2)
Rd = retardation coefficient (unitless)
λ = first order decay constant (yr^{-1}).

The retardation coefficient (Rd) is given by:

$$Rd = 1 + \frac{K_d \rho_b}{\theta} \quad (5\text{-}17)$$

where

K_d = soil-water partitioning coefficient (cm^3 g^{-1})
ρ_b = bulk density (g cm^{-3}).

For steady-state saturated conditions, these equations greatly simplify in that the terms $\partial\theta/dt$, $\partial\theta/\partial z$, and $\partial q/\partial z$ are zero in Equation (5-16). Solutions to these equations for different boundary and initial conditions range from simple semi-analytical assessment models like RESRAD ONSITE (Kamboj et al. 2018) to detailed numerical research-grade models like HYDRUS (Simunek et al. 2013) for unsaturated modeling and MODFLOW/MT3D for saturated zone modeling.

For this problem, the system was represented mathematically through a series of mixing cells that are connected via rate constants. This modeling approach is implemented in the GoldSim®[4] modeling software that has become an industry standard for low-level radioactive waste (LLRW) performance assessment (PA) models, but is equally applicable to any system involving long-term performance of engineered disposal cells.

This model is quantitatively represented in the Mixing Cell Model (MCM) code (Rood 2004b, 2005). MCM is an established model for evaluating performance of engineered disposal facilities. It is used at Idaho National Laboratory (DOE-ID 2007, 2008, 2011, 2012, 2018) and was also applied to the U.S. Ecology Site on the Hanford Reservation (Rood 2004a) and was used in the TENORM analysis at the Blue Ridge Landfill (RAC 2016). The MCM model has been benchmarked with HYDRUS and has shown comparable results. Furthermore, the model has been used to abstract complex three-dimensional vadose zone models into a simpler formulation that incorporates the salient features of the system (DOE-ID 2007).

MCM is a one-dimensional unsaturated flow and transport model but can also be used for saturated conditions. The model domain is discretized into a series of mixing cells where the model calculates water and solute balance. Unit gradient conditions (i.e., $\partial\psi/\partial z$=0, $\partial H/\partial z$=1) are assumed for each cell in the unsaturated zone. The continuity equation states:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} \quad (5\text{-}18)$$

[4] https://www.goldsim.com

Combining Equations (5-15) and (5-18) with the unit gradient assumption gives the water balance equation in MCM.

$$\frac{\partial \theta}{\partial t} = -\frac{\partial K(\theta)}{\partial z} \tag{5-19}$$

Water balance is based on the constituent relationships of hydraulic conductivity [$K(\theta)$], pressure, and moisture content as described by van Genuchten (1980). Solute transport is based on a linearization of the advection-dispersion into fully mixed cells. One-dimensional dispersion and diffusion are addressed through either the dispersion implicit in model discretization or explicitly. The model addresses transient as well as steady-state water infiltration and is thus well-suited for assessments involving landfills with engineered covers that may degrade over time. Transient infiltration occurs because infiltration-reducing covers do not last indefinitely, resulting in infiltration through the waste and into the vadose zone that changes over time. The MCM model was used to compute water fluxes and solute transport in the vadose zone.

For the aquifer, the GWSCREEN code is typically used (Rood 1994, 2002) because it interfaces with output from MCM. 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. However, for this application, a saturated MCM simulation was used instead because GWSCREEN does not perform differential transport among radioactive progeny. When flow velocities in the aquifer are rapid compared to unsaturated flow, this limitation in GWSCREEN makes little difference. However, horizontal flow velocities in the upper Selah aquifer are slow, allowing substantial ingrowth of radioactive progeny during transport across the source region. For this reason, a saturated MCM model was used instead of GWSCREEN because MCM addresses differential transport of radioactive progeny. Differential transport occurs because each radionuclide has element-specific soil water partitioning coefficients that determine the speed at which the radionuclide travels in groundwater. Output from GWSCREEN and saturated MCM were compared to provide confidence in the MCM saturated simulation.

The conceptual model for unsaturated flow and transport in MCM is illustrated in Figure 5-4. The upper-boundary condition for the flow model was the infiltration rate through the waste cell and into vadose zone, and the lower boundary is free drainage flow into the aquifer. The infiltration into the waste cell accounts for the presence of a geosynthetic engineered cover system. For transport, a zero-flux boundary condition was applied at the top and initial inventories assigned to the first layer.

For the saturated zone, the hydraulic conductivity and moisture content were fixed in each cell at the Darcy velocity and saturated aquifer porosity, respectively. Thus, a water flow simulation was not necessary (i.e., Darcy velocity is assigned). The upper-boundary condition for transport in the aquifer was the radionuclide fluxes from the MCM unsaturated simulation.

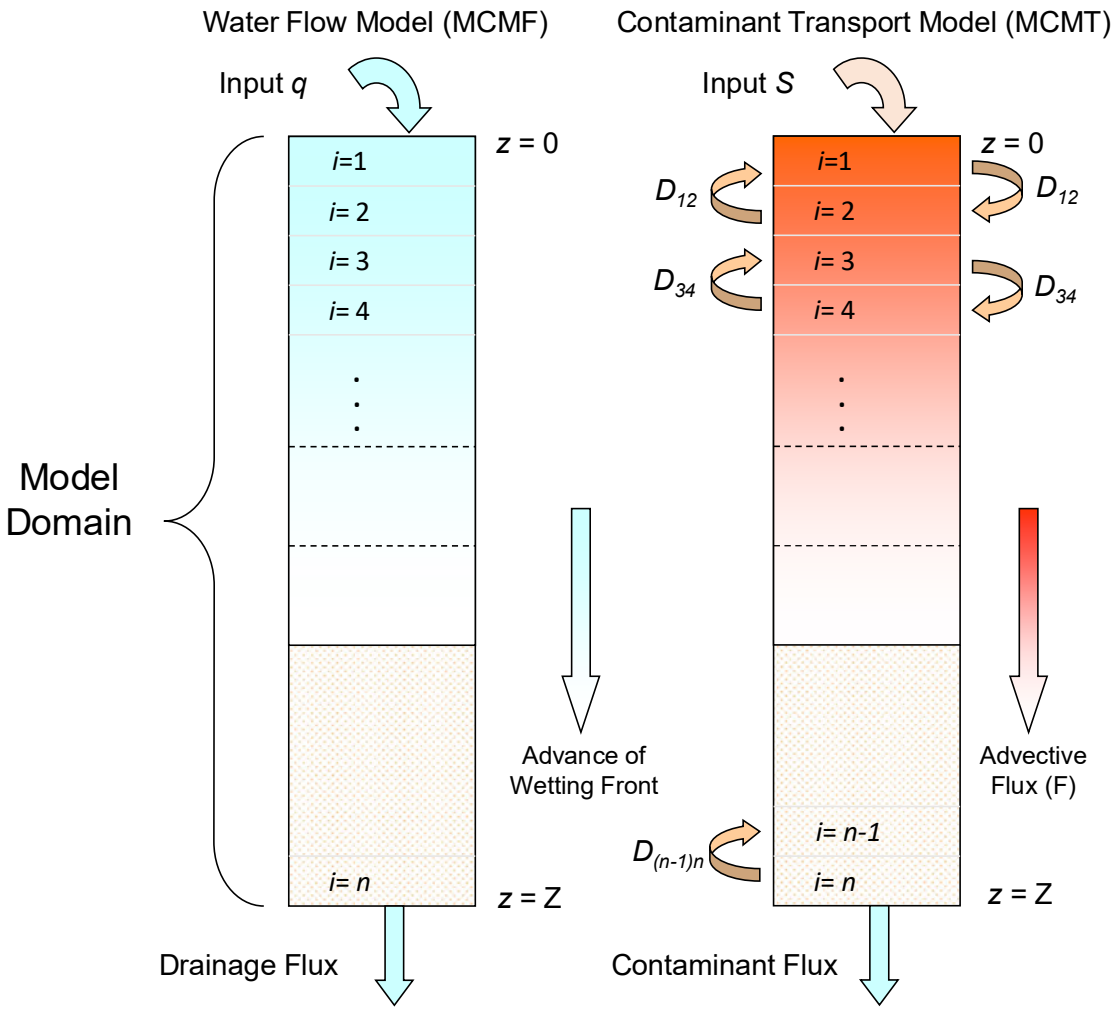

Figure 5-4. The MCM conceptual model for water flow (left) and contaminant transport (right). The model domain is discretized into n cells and extends to a depth of $z = Z$. Interchange between cells is indicated by the variable $D_{i,j}$, where i is the index of the donor cell and j is the index of the receiving cell. The variable q is the water flux, and S is the source or radionuclide flux (Rood 2005).

5.2.4. Modeled Decay Series

The two decay series modeled, which were described in Section 3, were ^{238}U (see Figure 3-1) and ^{232}Th (see Figure 3-2). The long simulation times that are encountered in groundwater modeling require that decay and ingrowth be accounted for in the modeling. However, many of the decay chain members in both decay series are short-lived and do not occur in the environment without the presence of their parent. These short-lived members do not require explicit treatment and can be assumed to be in secular equilibrium with their parent. Radiological doses and risks from these short-lived members are not ignored because the dose and risk coefficients of the short-lived progeny are added to their parent such that ingestion of the parent also assumes ingestion of the progeny in the environment. Thus, instead of modeling the full decay series, an abbreviated decay series is modeled. The abbreviated ^{238}U decay series is given by:

$$^{238}\text{U} \rightarrow ^{234}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra} \rightarrow ^{210}\text{Pb} \rightarrow ^{206}\text{Pb (stable)}.$$

The abbreviated ^{232}Th decay series is given by:

$$^{232}\text{Th} \rightarrow ^{228}\text{Ra} \rightarrow ^{228}\text{Th} \rightarrow ^{208}\text{Pb (stable)}.$$

5.2.5. Source Configuration and Receptor Locations

Based on landfill manifests, there were 64 shipments of Bakken oilfield waste that were disposed in Landfill Unit L-14. The total waste mass was reported to be 1,285 tons (2,569,320 lbs or 1,167,873 kg). After disposal and burial, the bulk density of the disposal material was reported to be 1,770 kg m^{-3}. Assuming each disposal load was spread across the 25 ft × 25 ft (58 m^2) grid block, the total area of disposal was 64 × 58 m^2 = 3,716 m^2. In reality, the individual disposal loads of Bakken oilfield waste in Landfill Unit L-14 are estimated to have been spread over an area of 28,883 m^2 based on Figure 5-5. Thus, the compressed source assumed for modeling results in a bounding estimate of radionuclide pore water concentrations because the activity is compressed into a smaller volume than what actually occurred.

The thickness of the waste in the model is calculated as:

$$T = \frac{1{,}167{,}873 \text{ kg}}{1{,}770 \text{ kg/m}^3} \times \frac{1}{3{,}716 \text{ m}^2} = 0.178 \text{ m}$$

For the model, the source is assumed to represent a square area source with the length of a side equal to $(3{,}716)^{1/2}$ = 60.96 m and a waste thickness of 0.178 m.

Figure 5-5 illustrates the actual and modeled areal extent of the source region and the location of the hypothetical receptor wells where groundwater impacts (concentrations, doses, and risks) are evaluated. Receptor wells are assumed to be in the upper Selah aquifer and placed on the downgradient edge of the source where maximum concentrations occur. A 100-m downgradient receptor is also added based on U.S. DOE performance assessments allowing a 100-m receptor well for comparing predicted concentrations and doses with DOE and NRC LLRW performance objectives.

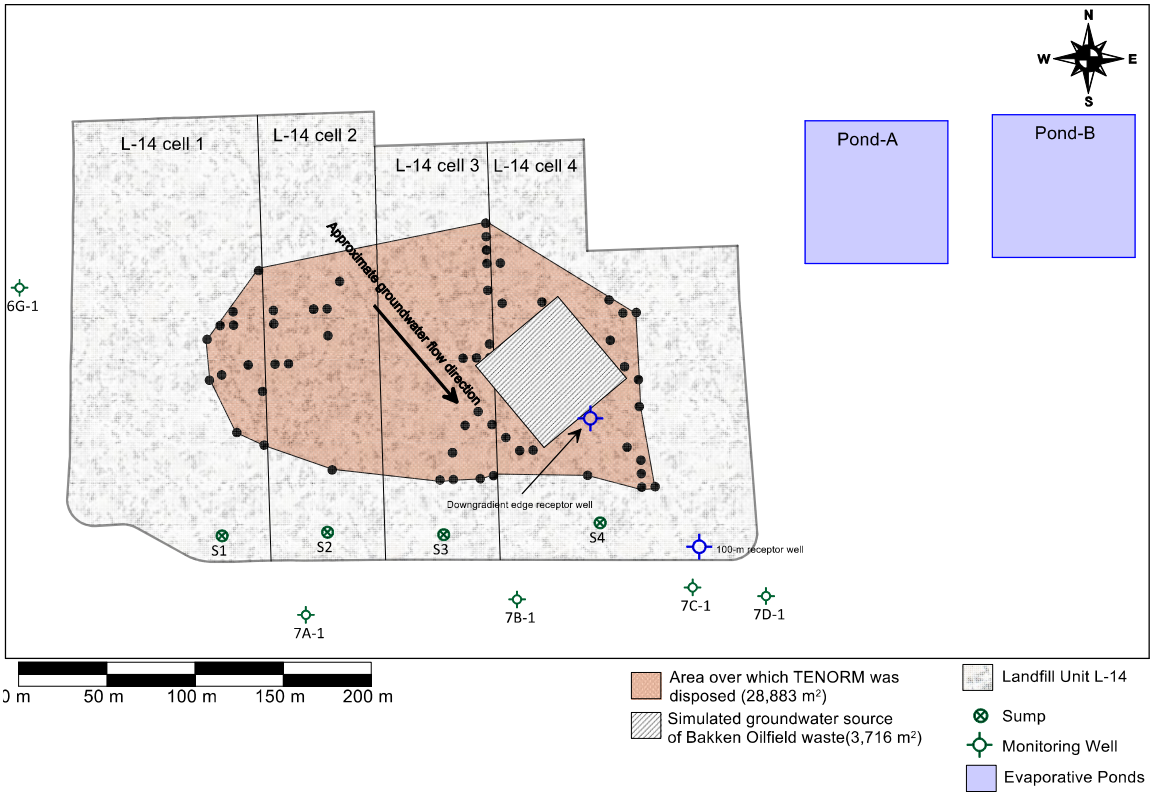

Figure 5-5. Landfill Unit L-14, the area over which the Bakken oilfield waste disposals (dots) were reported, the simulated groundwater Bakken oilfield source, and the receptor well locations.

The source configuration described here was intended to address the Bakken oilfield waste disposals in question in a pessimistic manner only (i.e., it does not underestimate the concentrations and resultant doses).

5.2.6. Summary of Groundwater Pathway Modeling Assumptions

The assumptions for the unsaturated and saturated zone transport model are summarized below:

- Bakken oilfield waste inventory assumes maximum radionuclide concentrations from the available data for all shipments and therefore overestimates the actual radionuclide inventory in Landfill Unit L-14.
- Bakken oilfield waste is compressed into a single source cell measuring 60.96 m on each side. This assumption results in higher predicted (modeled) concentrations in the upper Selah aquifer (i.e., minimizes radionuclide dilution if material is assumed to be spread over a larger area).
- Radionuclide fluxes to the upper Selah aquifer are distributed across an area equal to the modeled source area in Landfill Unit L-14.
- The model assumes releases of leachate through the entire engineered liner system and leachate detection systems after the site has been capped and no leachate is being generated. Thus, it represents an extremely pessimistic scenario.

- Concentrations, doses, and risks are evaluated at the downgradient edge of the source within the upper Selah aquifer, which is where the highest results are encountered. Results at this receptor location represent a pessimistic estimate.
- Results at a well 100 m downgradient from the source are also presented because this is the compliance point for DOE and NRC LLRW performance assessments.
- Results are presented in the upper Selah aquifer, which is the first occurrence of groundwater. This aquifer is highly confined to the north of the landfill with very low flow to the south, has no receptors, and dissipates in the Alkali Canyon face. Concentrations, doses, and risks in the underlying aquifers will be significantly less than concentrations in the Selah based on hydrogeologic conditions.

It is noted that the results of the modeling effort represent a pessimistic estimate of impacts for groundwater at the Arlington site and is presented as an absolute worst-case scenario that is highly unlikely. Modeling of actual conditions would incorporate the spatial distribution of the Bakken oilfield waste disposals, minimal infiltration of water through the final engineered landfill cap, and minimal movement of liquids through the engineered triple-liner and leachate collection system.

5.2.7. Groundwater Parameters

Groundwater model parameters include infiltration, material properties, dispersion coefficients, and element-specific soil-water partitioning coefficients (K_d). Radionuclide-independent properties are provided in Table 5-6 followed by a discussion of some of the parameters.

Table 5-6. Radionuclide-Independent Groundwater Modeling Parameters

Parameter	Value	Reference/comments
Infiltration		
Infiltration, natural (mm yr^{-1})	3.5	DOE (2018) – see discussion
Infiltration, cover (mm yr^{-1})	1.0	Bounding assumption for an engineered cover
Infiltration, leakage from liner (mm yr^{-1})	0.5	Bounding assumption
Engineered cover		
Cover longevity (years)	200	Assumed cover lifetime in RAC (2016)
Cover failure time (years)	100	Assumed time from the onset of cover failure to complete failure and when infiltration returns to a natural state RAC (2016)
Source properties		
Length and width (m)	60.96	Calculated
Thickness of TENORM (m)	0.178	Calculated
Bulk density (g cm^{-3})	1.77	email from J. Denson to E. Caffrey, May 6, 2020
Porosity	0.46	Carsel and Parrish (1988)
Saturated hydraulic conductivity (m yr^{-1})	387.2	Carsel and Parrish (1988)
Residual moisture	0.145	Carsel and Parrish (1988)

Parameter	Value	Reference/comments
van Genuchten α (m^{-1})	1.6	Carsel and Parrish (1988)
van Genuchten *n*	1.37	Carsel and Parrish (1988)
Free water diffusion coefficient (m^2 yr^{-1})	0.0158	DOE (2018)
Vadose zone		
Vadose zone thickness (m)	24.0	Burns & McDonnell, Inc. (1998)
Vertical hydraulic conductivity in Selah (m yr^{-1})	0.145	Maximum value in Table 6-1 of Burns & McDonnell, Inc. (1998)
Porosity	0.46	Carsel and Parrish (1988) and Burns & McDonnell, Inc. (1998)
Residual moisture	0.037	Carsel and Parrish (1988) and Burns & McDonnell, Inc. (1998)
van Genuchten α (m^{-1})	1.6	Carsel and Parrish (1988) and Burns & McDonnell, Inc. (1998)
van Genuchten *n*	1.37	Carsel and Parrish (1988) and Burns & McDonnell, Inc. (1998)
Bulk density (g cm^{-3})	1.15	Table 4-2 in CH2M Hill (2008)
Saturated zone		
Saturated horizontal hydraulic conductivity (m yr^{-1})	6.28	Geometric mean from values in Table 4-4 in CH2M Hill (2008)
Hydraulic gradient (m/m)	0.029	Figure 4-7 in CH2M Hill (2008)
Porosity	0.46	Carsel and Parrish (1988)
Bulk density (g cm^{-3})	1.15	Table 4-2 in CH2M Hill (2008)
Longitudinal dispersivity (m)	6.096	See discussion
Transverse dispersivity (m)	3.05	See discussion
Vertical dispersivity (m)	0.6096	See discussion
Saturated thickness (m)	15.24	Figure 4-2 in CH2M Hill (2008)
Well screen (mixing) thickness (m)	5	Assumed – see discussion
Exposure scenario		
Water ingestion (L yr^{-1})	730	Water ingestion rate for determining maximum contaminant limits in 40 CFR 141 (2 L day^{-1})
Exposure duration, effective dose (years)	1	One-year for annual effective dose
Exposure duration, carcinogenic risk (years)	30	Assumed the individual resides at same location for 30 years

5.2.7.1. Infiltration

The transport of radionuclides from to the landfill to the aquifer is driven by the infiltration of precipitation from the landfill surface. A good estimate of the amount of infiltration through Landfill Unit L-14 was made by taking the annual amount of liquids collected in the leachate collection system divided by the area of the landfill. This overstates the leachate generation as newer cells in the landfill transmit precipitation to the leachate system much faster than older cells. Volumes of leachate collected in each of the four disposal cells vary with the area of the cell and

volume of waste in place (see Table 5-7). The oldest cells (L-14 cells 1 and 2) have the greatest waste mass and cover soils and no exposed liner. The newest cell (L-14 cell 4) has an exposed liner in the eastern portion of the cell. Water that falls as precipitation on L-14 cell 4 contacts the exposed liner and is transmitted to the leachate collection system with minimal evaporation. Consequently, this cell collected the most leachate during 2019. A thin layer of waste over the liner (L-14 cell 3) will also transmit water at a higher rate to the sump compared to cells 1 and 2 because as soon as water hits the impermeable liner it is channeled to the sump. Liquids that fall on the surface of the older cells infiltrates into thicker soil covers and waste mass and is held in the pore spaces where evaporation removes a substantial fraction. Note that the infiltration for L-14 cells 1 and 2 are about the same (~2.2 mm yr^{-1}), while L-14 cell 3 is slightly greater (3.67 mm yr^{-1}). These infiltration rates are comparable to those estimated at the Hanford reservation (DOE 2018) of 3.5 mm yr^{-1} and provide a good estimate of natural infiltration in the Arlington environment.

Table 5-7. Volume of Water Collected in Each of the L-14 Landfill Cells in 2019, Area of Each Cell, and Estimated Infiltration

Cell	Volume (gal yr^{-1})[a]	Volume (m^3 yr^{-1})	Area of cell (m^2)[b]	Infiltration (m yr^{-1})
L-14 cell 1	15,361	58.148	26,331.5	0.00221
L-14 cell 2	9,538	36.105	16,651.3	0.00217
L-14 cell 3	147,402	557.98	15,202.1	0.0367
L-14 cell 4	730,884	2,766.7	28,605.1	0.0967
Total	903,185	3,418.9	86,790	0.0394
Total, L-14 cell 1 through L-14 cell 3	---	---	58,185	0.0588

a. From J. Denson email dated May 5, 2020.
b. Calculated from the GIS coverages provided by Waste Management.

For this assessment, the Hanford estimate of 3.5 mm yr^{-1} is used to represent natural background infiltration. It is slightly greater than the site-specific value for 2019 from the Arlington results but provides a reasonable long-term average for the region. The model assumes operation of the landfill continues for the next 30 years and the leachate collection system will continue to operate during this time. This is a pessimistic assumption as the landfill will continue to operate for several decades. Although the leachate collection systems and liner preclude infiltration from the waste cells entering the vadose zone, a leakage rate of 0.5 mm yr^{-1} through the liner system into the vadose zone was assumed for modeling purposes.

Upon closure of the landfill, an engineered evapotranspiration cover will be placed over the entire landfill surface and the leachate collection system will continue to operate until no further leachate accumulates in the sumps. The evapotranspiration cover will be designed for zero infiltration. Drainage of moisture from the waste is modeled to continue for 30 years. The model assumes during this period that all three leachate collection systems are breached and moisture in the waste at the time of closure is allowed to drain into the vadose zone. The engineered cover is assumed to limit infiltration to 1 mm yr^{-1} based on preliminary cover designs assumed for performance assessments at the Idaho National Laboratory (DOE-ID 2018). This is a pessimistic assumption because the cover will be designed to prevent infiltration (i.e., zero infiltration) that will overestimate the leachate flux from the closed landfill to the vadose zone. Recent studies of

geosynthetic covers and liners in low-level waste facilities (Benson 2016; Tian et al. 2017) suggest minimum cover service life is in the range of 730–1,400 years.

The model assumes the hydrologic integrity of the evapotranspiration cover lasts 200 years. The actual cover system is designed to last significantly longer. The 200-year cover lifetime and 1 mm yr^{-1} infiltration is considered a pessimistic scenario that will overestimate radionuclide releases to the vadose zone from the closed landfill. The model assumes over the next 100 years (year 200 through 300), the cover degrades, and infiltration linearly increases its natural level (3.5 mm yr^{-1}) at 300 years and continues at that rate indefinitely. The actual and modeled infiltration conditions are summarized in Table 5-8.

Table 5-8. Summary of Actual and Modeled Infiltration Conditions

Time period from presen	Actual/expected conditions	Modeled conditions
0 to 30 years	Landfill continues operations, and no leachate water is released to vadose zone.	Landfill continues to operate, and 0.5 mm yr^{-1} of leachate water is released to vadose zone.
30 to 60 years	Evapotranspiration cover with zero infiltration is placed over the landfill at closure, and the leachate collection system operates until no further leachate is available to be collected.	Evapotranspiration cover with 1 mm yr^{-1} infiltration is placed over landfill at closure. No leachate collection occurs and liner fails, allowing leachate in waste to drain into the vadose zone.
60 to 230 years	Evapotranspiration cover with zero infiltration continues to operate, resulting in no leachate generation.	Evapotranspiration cover with 1 mm yr^{-1} infiltration continues to operate, allowing leachate to enter vadose zone.
230 to 330 years	Evapotranspiration cover with zero infiltration continues to operate, resulting in no leachate generation.	Evapotranspiration cover degrades hydrologically, allowing infiltration to increase linearly from 1 mm yr^{-1} in year 230 to 3.5 mm yr^{-1} in year 330.
>330	Evapotranspiration cover with zero infiltration may continue to operate up to 1,400 years or longer. If the cover fails hydrologically, infiltration is not expected to be greater than natural infiltration.	Infiltration through closed landfill is fixed at the natural rate of 3.5 mm yr^{-1}.

5.2.7.2. Unsaturated Hydrologic Parameters

Unsaturated parameters include the unsaturated thickness van Genuchten fitting parameters that describe the relationship between unsaturated hydraulic conductivity, pressure, and moisture content, and the bulk density. The unsaturated thickness below landfill unit L-14 was estimated to be between ~23 m (75 ft) in the northwest to ~34 m (112 ft) in the southeast (Figure 4-6 in CH2M

Hill [2008]). For the model, the value used by Burns & McDonnell, Inc. (1998) of 24 m (rounded from 24.4 m) was chosen.

There are no site-specific hydrologic parameters for waste materials or the Selah formation, so literature values were used for the van Genuchten α and n, the residual moisture content, and the total porosity as described below. Based on review of the lithology and measurements of vertical saturated hydraulic conductivity of the Selah Member, previous modeling (Burns & McDonnell, Inc. 1998) assumed the van Genuchten fitting parameters α, *n*, and total porosity of silt as described in Carsel and Parrish (1988), and these parameters were retained for this simulation. The vertical saturated hydraulic conductivity was the maximum reported in Burns & McDonnell, Inc. (1998). For the waste, a material with a higher saturated hydraulic conductivity was used (sandy loam) with van Genuchten parameters and saturated hydraulic conductivity from Carsel and Parrish (1988).

Bulk density for the Selah in both the saturated and unsaturated zones were from Table 4-2 in CH2M Hill (2008). For the waste, the bulk density of 2,970 lbs yd^{-3} (1.77 g cm^{-3}) was provided by CWMNW[5].

5.2.7.3. Aquifer Parameters

The aquifer properties include total porosity, saturated hydraulic conductivity, thickness of the saturated zone, and the hydrologic gradient. The bulk density and total porosity of the unsaturated Selah were assumed for the saturated portion. The horizontal saturated hydraulic conductivity was taken from Table 4-4 in CH2M Hill (2008) and represented the geometric mean of the six minimum and maximum values reported by Dames and Moore (1987) and the three values measured by RUST Environmental & Infrastructure (RUST 1998a) (2.0×10^{-5} cm s^{-1}). The hydraulic gradient (0.029 m/m) was taken from Figure 4-7 in CH2M Hill (2008). The calculated Darcy velocity in the aquifer is then:

$$v = K_{sat}\frac{dh}{dx} = 2.0\times10^{-5}\ \text{cm/s}\ \times 0.029\ \text{m/m}\ \times\ 3.1536\times10^{7}\ \text{s/yr} = 0.182\ \text{m/yr}$$

and the pore velocity would be (0.182 m/yr)/0.46 = 0.396 m/yr. This value is lower than the horizontal flow velocity estimated in CH2M Hill (2008) of 2 ft yr^{-1} (0.61 m yr^{-1}) and overestimates radionuclide concentrations in the aquifer. Higher Darcy velocities result in greater dilution and dispersion and thereby reduced predicted concentrations in the aquifer.

The saturated zone thickness of the of the upper Selah aquifer underlying Landfill Unit L-14 ranges from 9.1 m (30 ft) in the northeastern portion to 18.3 m (60 ft) in the southwestern portion (Figure 4-2 in CH2M Hill [2008]). A value of 15.24 m (50 ft) was chosen because it represents the largest area in Figure 4-2 of CH2M Hill (2008) underling Landfill Unit L-14.

5.2.7.4. Dispersion Coefficients

Dispersion in groundwater is the sum of mechanical dispersion and molecular diffusion, although in advective-dominated systems, molecular diffusion is negligible. Mechanical dispersion is calculated as the product of the dispersivity and the pore water velocity. The dispersion coefficients are calculated by:

[5] Email from J. Denson to E. Caffrey, dated May 6, 2020.

$$D_x = \alpha_L u + D_e$$
$$D_y = \alpha_T u + D_e \quad (5\text{-}20)$$
$$D_z = \alpha_V u + D_e$$

where

D_x, D_y, D_z = longitudinal, transverse, and vertical dispersion coefficient, respectively (m^2 s^{-1})
α_L, α_T, α_V, = longitudinal, transverse, and vertical dispersivity, respectively (m)
u = pore water velocity (m s^{-1})
D_e = effective molecular diffusion coefficient (m^2 s^{-1}).

The dispersivity is an empirically derived parameter that varies with scale length. Xu and Eckstein (1995) developed regression equations that described the longitudinal dispersivity (spreading parallel the flow) to scale length, which can be approximated by the scale length divided by 10. The scale length in the aquifer is the length of the source parallel to groundwater flow (60.69 m). Thus, α_L, = 60.96 m/10 = 6.096 m. The transverse and vertical dispersivity are approximated by data in Gelhar et al. (1992), which show that the transverse dispersivity is approximately one-half the longitudinal dispersivity and the vertical dispersivity is $1/10^{th}$ the longitudinal dispersivity. For the vadose, zone, the longitudinal dispersivity was assigned $1/10^{th}$ the unsaturated thickness.

Molecular diffusion was considered for the unsaturated zone where unsaturated pore velocities are on the order of 0.0091 m yr^{-1} (2.9×10^{-8} cm s^{-1}). The measured effective diffusion coefficient for a non-sorbing specie in grout reported in DOE (2018) was 2.9×10^{-8} cm s^{-1}. The free water diffusion coefficient is defined as the effective diffusion coefficient divided by the tortuosity, which was given as 5.8×10^{-3}. Thus, the free-water diffusion coefficient (which is input in MCM) was 2.9×10^{-8} cm $s^{-1}/5.8\times10^{-3}$ = 0.0158 cm s^{-1}. The free-water diffusion coefficient is modified by the porosity and saturation of the media in MCM using the formulation in Millington and Quirk (1961) and only applied to radionuclides to the aqueous phase.

$$D_e = D_m \frac{\theta^{10/3}}{\theta_s^2} \quad (5\text{-}21)$$

where

D_e = effective diffusion coefficient in water (m^2 s^{-1})
D_m = free-water molecular diffusion coefficient (m^2 s^{-1}).

The MCM model is one-dimensional; thus, only longitudinal dispersivity is considered. Using the dispersivity parameters and the GWSCREEN code, which embodies the three-dimensional semi-analytical groundwater model developed by the NRC (Codell et al. 1981), a comparison was made between the one- and three-dimensional solution to confirm it provided comparable results (See Section 5.2.7.9).

5.2.7.5. Well Screen Thickness

The well screen thickness is the depth in the saturated zone where radionuclides are mixed vertically and thereby averaged over the vertical column of water. The conceptual model assumes leachate enters the top of the aquifer and is mixed vertically within this thickness. The conceptual model does not account for water withdrawn from the well, which maximizes concentrations because it does not take credit for additional dilution from clean water drawn downgradient and

laterally from the source. The well screen thickness for performance assessments at the Idaho National Laboratory (DOE-ID 2007, 2011, 2018) was 15 m and assumes no effects from pumping. For this assessment, a screen thickness of 5 m was assumed to account for the narrow saturated-zone thickness.

To check the validity of this assumption, RESRAD OFFSITE v4 (NRC 2020) was run using the CWMNW conceptual model and model parameters (assuming a steady-state infiltration of 3.5 mm yr^{-1}), and the U-238 inventory assuming a zero K_d. The zero K_d was necessary because maximum concentrations with the base case uranium K_d are achieved after 10,000 years and RESRAD limits the maximum simulation time to 10,000 years. The well water concentration in RESRAD OFFSITE is dependent on the water usage requirements, assumed well pumping rate, and the depth of the aquifer contributing to the well. If the aquifer is not able to provide the water usage requirements, then radionuclide concentrations are diluted by the additional makeup water necessary to meet the water usage requirements. For example, if the depth in the aquifer is shallow and the aquifer is low yielding, then the well will not be able to produce enough water to meet the water usage requirements and makeup water will be added. The upper Selah aquifer is a very low-yielding aquifer and is not capable of supporting withdrawal for use as a drinking water source. The default RESRAD value for the depth in the aquifer contributing to the well is 10 m. Using the RESRAD OFFSITE default pumping rate of 5,100 $m^3\ yr^{-1}$, the maximum well water concentration for a well located on the downgradient edge of the source was 0.15 pCi L^{-1}; using 1 $m^3\ yr^{-1}$ pumping rate (the minimum value allowed) gave a maximum concentration of 3.76 pCi L^{-1}. The corresponding concentration calculated with MCM and a 5-m mixing thickness was 3.61 pCi L^{-1}, which matches reasonably well with the RESRAD value assuming minimal pumping. Also, under the low pumping rate scenario, RESRAD radionuclide concentrations in the aquifer are almost uniform with depth, ranging from 3.76 pCi L^{-1} at the surface to 3.4 pCi L^{-1} near the bottom of the aquifer. Thus, the aquifer is well mixed vertically. Ignoring well drawdown from pumping results in higher well water concentrations. Furthermore, assuming a 5-m well screen thickness provides results that are consistent with the RESRAD modeling assuming no drawdown.

5.2.7.6. Equilibrium Soil-Water Partitioning Coefficients (K_d)

The equilibrium soil-water partitioning coefficient or K_d (mL g^{-1}) is defined by:

$$K_d = \frac{C_s}{C_a} \tag{5-22}$$

where

C_s = concentration in soil at equilibrium (pCi g^{-1})
C_a = concentration in aqueous solution at equilibrium (pCi mL^{-1}).

The K_d is important because it defines how fast the radionuclide moves in groundwater. If the K_d is zero, then all of the radionuclides are in the aqueous phase and they move at the same velocity as the water. A K_d greater than zero indicates some fraction of the radionuclide is sorbed to soil or solids and therefore retards its movement. The amount of retardation is quantified by the retardation factor (R_d) given by:

$$R_d = 1 + \frac{K_d \rho_b}{\theta} \quad (5\text{-}23)$$

where

ρ_b = bulk density (g cm^{-3})
θ = moisture content (m^3 m^{-3}).

Note that R_d has no units; for a K_d value of zero, the R_d is 1.0. The K_d value is element-specific, highly variable, and depends on the chemical forms and geochemistry of the soil and water. Table 5.9 lists K_d values from the literature for the elements of interest for various lithologies and default or recommended values used in assessment models. The values for Hanford reflect sorption in material containing gravel, which reduces the K_d.

Table 5-9. Linear Sorption Coefficients (K_d) from the Literature and their Geometric Mean (GM)

Element	Sand (mL g^{-1})[a]	Clay (mL g^{-1})[a]	RESRAD (mL g^{-1})[b]	Hanford (mL g^{-1})[c]	INL (mL g^{-1})[d]	NRC (1992)[e]	Geometric mean (mL g^{-1})
U	35	1,600	50	1	10	15	27
Th	3,200	5,800	60,000	1,000	500	3,200	3,482
Ra	500	9,100	70	14	500	500	322
Pb	270	550	100	--	270	270	255

a. Sheppard and Thibault (1990).
b. Kamboj et al. (2018); Yu et al. (2001); NRC (2020).
c. DOE (2018).
d. Sondrup et al. (2018).
e. Kennedy and Strenge (1992).

The geometric mean (GM) values in Table 5-9 were used in the groundwater transport model. Generally, higher K_d values result in lower pore water concentrations and longer radionuclide transit times, which would correspond to lower doses farther out in time. The use of the GM as the central tendency will overestimate impacts (i.e., shorter transit times and higher pore water concentrations) because the GM is always lower than the arithmetic average in lognormally distributed data. The GM values listed in Table 5-9 were compared to the range of values in EPA (1999a), shown in Table 5-10, for a pH of 7.6, which is the reported pH of Selah porewater (Table 4-5 in CH2M Hill [2008]). The GM values are generally within the lower range of the values given in Table 5-10, except for lead, where the GM value of 255 L g^{-1} is less than the lowest lead value of 710 mL g^{-1}. In contrast, the values in Table 5-9 for Hanford reflect sorption in soils containing gravel. In general, little sorption occurs in pure gravel because of the lack of sorption sites. In material containing gravel, sorption mainly occurs in the interstitial silts and clays. For Hanford, K_d values were reduced based on the percentage of gravel in the lithology.

Table 5-10. Ranges of K_d values in EPA (1999a) for a pH of ~7.6

Element	Minimum K_d (mL g^{-1})	Maximum K_d (mL g^{-1})	Comments
U	63	630,000	Table 5.17 in EPA (1999a) for a pH=7
U	0.4	250,000	Table 5.17 in EPA (1999a) for a pH=8
Th	1,700	17,000	Table 5.15 in EPA (1999a) for an assumed dissolved Th content of $<1\times10^{-9}$ Molar
Th	300,000	300,000	Table 5.15 in EPA (1999a) for an assumed dissolved Th content of $>1\times10^{-1}$ Molar
Pb	4,360	23,270	Table 5.9 in EPA (1999a) for an assumed equilibrium lead concentration of 0.1-0.9 µg L^{-1}
Pb	710	2,300	Table 5.9 in EPA (1999a) for an assumed equilibrium lead concentration of 100-200 µg L^{-1}

5.2.7.7. Model Discretization

The MCM model contains two modules, a flow module (MCMF) and a contaminant transport module (MCMT) (see Figure 5-4). Water fluxes and moisture content as a function of time calculated with MCMF are read by MCMT. Thus, the discretization of the flow and transport modules must be identical. For the vadose zone, the first cell in the MCM model domain is in the landfill and represents the region where the Bakken oilfield waste was disposed. The thickness of this cell (0.178 m) was derived in Section 5.2.5 and is composed of material having higher hydraulic conductivity than the Selah Formation. The remainder of the vadose zone was discretized in the 30, 1-m-thick cells all having the hydrologic properties of the Selah Formation. Radionuclide fluxes were extracted at cell 25 (24.178 m) and input to the aquifer model. The vadose zone model domain was extended because the lower-boundary condition in MCMT does not include diffusive fluxes. Thus, by extending the domain past the aquifer and extracting fluxes at the 24.178 m depth allowed for fluxes entering the aquifer to represent the sum of advective and diffusive components.

In the aquifer model, the Darcy velocity and saturated porosity are specified and thus a MCMF simulation is not necessary. The first cell in the aquifer model represents the region in the aquifer that receives fluxes from the vadose zone. Consequently, the thickness of this cell is the length of the source projected into the aquifer. Although MCMT is one-dimensional, the model allows input of a length and width that is applied to all cells. These parameters are important for determining initial concentrations and whether solubility limits are exceeded. For the aquifer model, the width dimension was 60.96 m (width of the source) and the length dimension was the 5-m mixing thickness. The saturated porosity of the aquifer is 0.46; thus, fluxes entering the aquifer in a 60.96 m × 60.96 m area are mixed in 60.96 m × 60.96 m × 5 m × 0.46 = 8,547 m^3 volume of water. The remainder of the aquifer was composed of 50, 2-m-thick cells such that the last cell would represent a receptor 100 m downgradient from the downgradient edge of the source.

5.2.7.8. Initial Conditions and Modeled Water Fluxes

The initial condition for water flow in the vadose zone is the moisture content in each layer. The initial moisture content at the start of the simulation (the year of disposal of the Bakken oilfield waste) was established with a MCMF flow simulation assuming natural background infiltration rates for times prior to construction of the facility, followed by a 30-year operational period of a liner-leachate collection system that represents the construction and operation of the facility up to the disposal of the Bakken oilfield waste. The initial moisture profile reflects the drainage of water

from the infiltration shadow after 30 years of operation of the facility. The initial condition for radionuclide transport was the radionuclide inventories in the 0.178-m-thick source zone and zero concentration everywhere else (Table 5-11). Radionuclide inventories were calculated from the maximum and weighted-average radionuclide concentrations reported in Table 3-5 and Table 3-4, respectively. The inventory is given by:

$$Q = C_w \times M_w \tag{5-24}$$

where

Q = radionuclide inventory (Ci)
Cw = radionuclide concentration (Ci kg^{-1})
Mw = mass of Bakken oilfield waste 1.17×10^6 kg.

Table 5-11. Initial Radionuclide Concentrations and Inventories in the Source Layer

Radionuclide	Maximum inventory (Ci)	Weighted-average inventory (Ci)
U-238	1.38E-03	3.31E-05
U-234	2.35E-03	1.13E-04
Th-230	9.33E-04	4.52E-05
Ra-226	1.67E-01	1.04E-01
Pb-210	9.51E-01	5.82E-03
Th-232	5.54E-04	1.53E-03
Ra-228	7.21E-02	4.79E-03
Th-228	9.81E-03	5.79E-03

Water fluxes and the saturation ratio (defined as the moisture content divided by the total porosity) in the vadose (Figure 5-6 and Figure 5-7) vary in time and space because:

- Placement of the landfill liner with a leachate collection system creates an infiltration shadow while the facility is operating,
- Placement of an infiltration-limiting cover over the facility at closure and concurrently the assumed failure of the landfill leachate liner,
- Finally, subsequent failure of the engineered cover over time results in a return of infiltration to its natural state.

The facility is assumed to continue operating for another 30 years following disposal of the Bakken oilfield waste after which an engineered cover is installed and the leachate liner is assumed to then concurrently fail. As explained in Table 5-8, the leachate collection system will continue to operate after closure of Landfill Unit L-14 and installation of the cover. Leachate collection will continue until no further leachate accumulates in the sumps. The model assumption that the liner system, leachate collection system, and redundant detection systems fail at closure and the moisture in the waste is allowed to drain into the vadose zone. This significantly overestimates the release of radionuclides from the landfill in real world scenarios and is considered a highly pessimistic modeling scenario. The model also assumes the lower levels in the vadose zone continue to drain from the previous natural infiltration until about 400 years after the present. This is followed by an increase in infiltration to natural background conditions as the engineered barrier (cover) fails. The

water fluxes nearest the bottom of the landfill reflect the changes in infiltration most directly. Water fluxes in deeper layers reflect the attenuation of infiltration changes at the surface. The saturation ratio (see Figure 5-7) in the landfill materials where the Bakken oilfield waste was disposed reflects the higher hydraulic conductivity compared to the low conductivity materials of the Selah Formation. The higher hydraulic conductivity results in greater drainage of water and lower saturation ratios.

A rough estimate of the vadose zone water travel time (*VZWTT*) can be calculated by:

$$VZWTT = \frac{T}{q/\left(SR\,\theta_s\right)} \tag{5-25}$$

where

T = vadose zone thickness (24 m)
q = Darcy velocity in the vadose zone (m yr^{-1})
SR = saturation ratio (unitless)
θ_s = saturated porosity (m^3 m^{-3}).

Assuming a Darcy velocity equal to the natural infiltration of 3.5 mm yr^{-1}, a saturation ratio of 0.84 (see Figure 5-7), and the total porosity of the Selah Formation of 0.46, the *VZWTT* is 2,650 years. This value is within the range of estimated water travel times based on groundwater age dating of 1,000 to 5,000 years (Section 4.1.2.1 in CH2M Hill [2008]). Radionuclide travel times would be the *VZWTT* times the R_d for the radionuclide (Equation [5-8]).

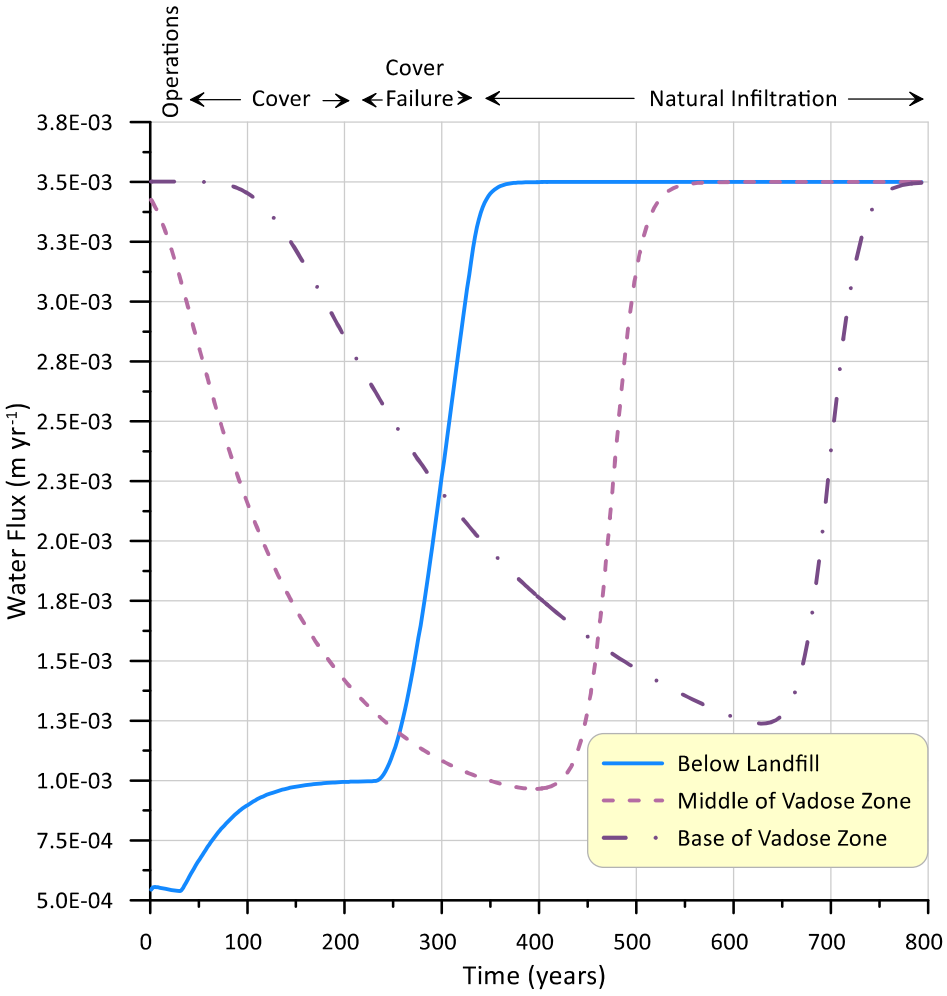

Figure 5-6. Vadose zone water fluxes as a function of time staring at the time when the Bakken oilfield waste was disposed.

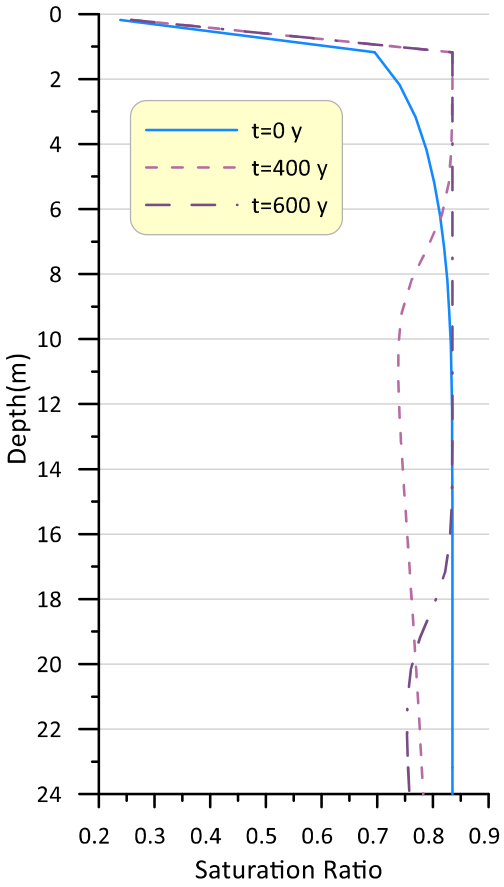

Figure 5-7. Saturation ratio depth profiles for initial condition (t=0 y), and 400 years and 600 years after the start of the simulation.

5.2.7.9. Comparison of 1-D Dispersion to 2-D and 3-D Dispersion

A three-dimensional transport simulation was made using GWSCREEN and aquifer parameters inTable 5-6 (Figure 5-8) using U-238 as a tracer. The radionuclide flux to the aquifer was computed using MCMT unsaturated simulation. The cross section shows that maximum concentration occurs on the downgradient edge of the source and concentrations exhibit little variation with depth to the 5-m level.

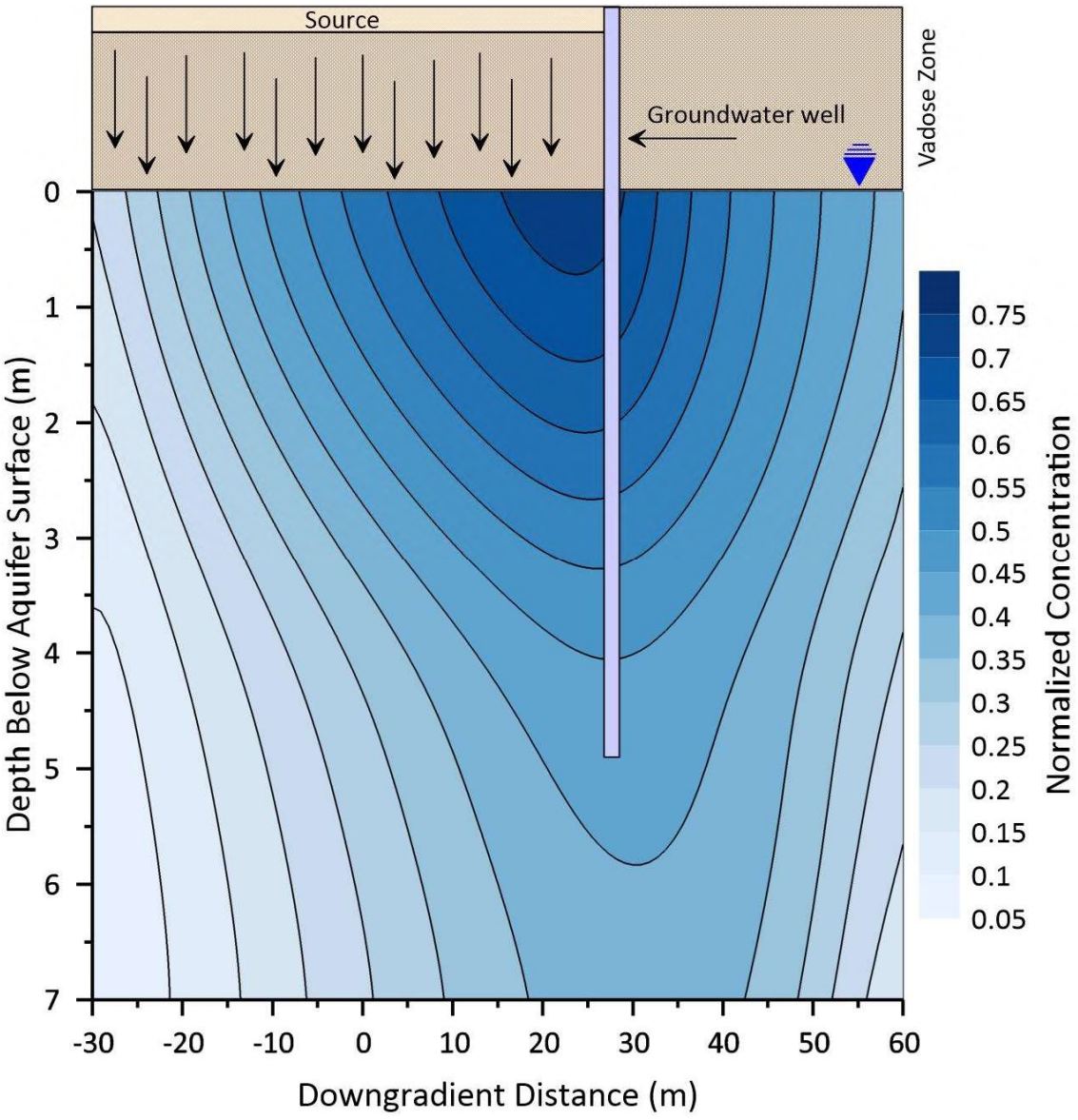

Figure 5-8. Cross section of U-238 aquifer concentration calculated with GWSCREEN with MCMT fluxes from the unsaturated zone.

A second GWSCREEN simulation was performed using the 2-D vertically averaged solution and an averaging thickness of 5 m. Concentrations were output at the downgradient edge of the source and at a well 100 m downgradient and compared with the MCMT output for the same unsaturated flux. The results (Figure 5-9) show that peak concentrations at the downgradient well from both models were in general agreement. The peak time for GWSCREEN was earlier than MCMT; this is attributed to the source region in MCMT treated as one cell instead of discretized into a series of cells. At the well 100 m downgradient, GWSCREEN concentrations were lower that the MCMT concentrations because of transverse dispersion in GWSCREEN. The MCMT concentration at the well 100 m downgradient was effectively the same as the concentration at the downgradient edge because pore velocities in the aquifer are low, resulting in little longitudinal dispersion compared to advective flow. Only the time to peak concentration was longer.

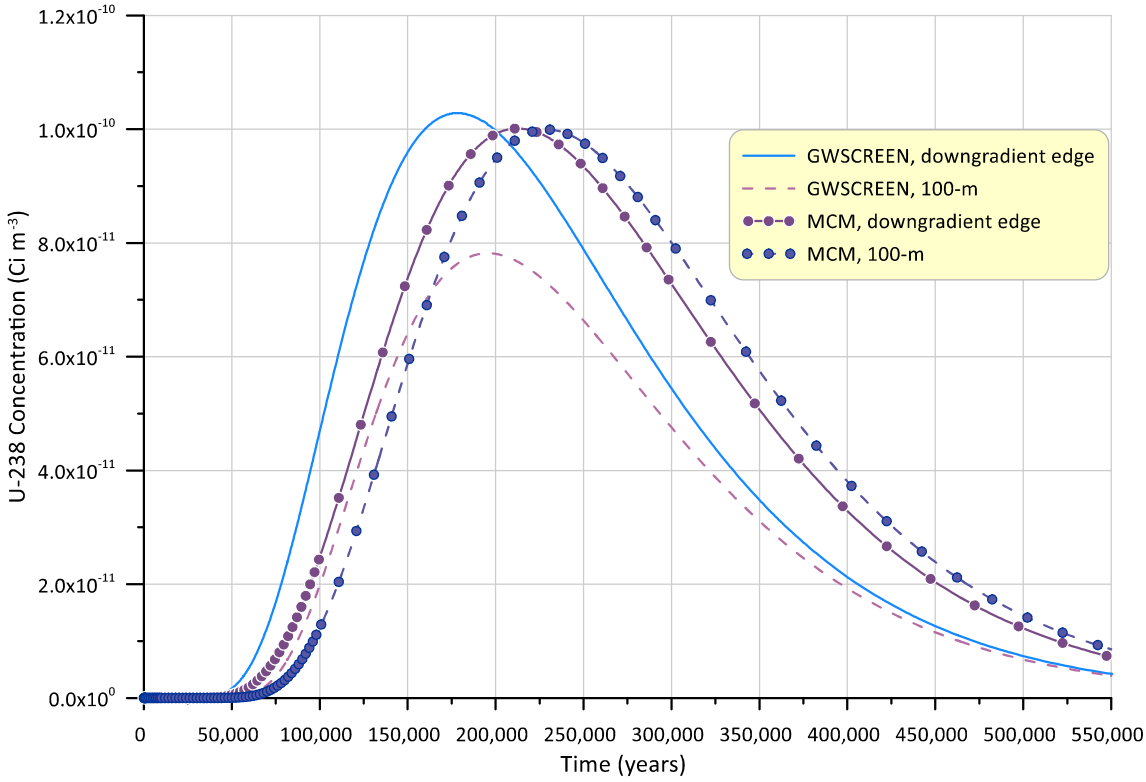

Figure 5-9. Comparison of U-238 concentration calculated with a 2-D GWSCREEN simulation and the MCMT aquifer model at the downgradient edge of the source and the 100-m well.

5.2.8. Dose and Risk Calculations for Groundwater Assessment

The effective dose coefficients and carcinogenic risk coefficients for morbidity (Table 5-12) were from DOE-Std-1196 (DOE 2011) and Federal Guidance Report 13 (EPA 1999b). These data were obtained from RESRAD ONSITE v7.2 (Kamboj et al. 2018) code. The "+D" designation indicates the dose coefficient includes short-lived progeny assumed to be in secular equilibrium with their parent in the environment. The half-life cutoff time for inclusion was 180 days.

Table 5-12. Effective Dose Coefficients and Cancer Morbidity Risk Coefficients

Radionuclide (progeny)	Dose coefficient for ingestion (rem Ci^{-1})	Cancer morbidity risk coefficient for water ingestion (risk Ci^{-1})
U-238+D (Th-234, Pa-234)	2.11×10^{5}	8.71×10^{1}
U-234	2.15×10^{5}	7.07×10^{1}
Th-230	9.36×10^{5}	9.14×10^{1}
Ra-226+D (Po-218, Pb-214, Bi-214, Po-214)	1.68×10^{6}	3.85×10^{2}
Pb-210+D (Bi-210, Po-210)	1.03×10^{7}	2.67×10^{3}
Th-232	1.03×10^{7}	1.01×10^{2}
Ra-228+D (Ac-228)	5.92×10^{7}	1.04×10^{3}

Radionuclide (progeny)	Dose coefficient for ingestion (rem Ci^{-1})	Cancer morbidity risk coefficient for water ingestion (risk Ci^{-1})
Th-228+D (Ra-224, Po-216, Pb-212, Bi-212, Tl-208, Po-212)	9.35×10^{5}	3.00×10^{2}

The annual effective dose from groundwater ingestion is given by:

$$D_{GWING} = C_a \times IR \times DC \times ED \quad (5\text{-}26)$$

where

D_{GWING} = annual effective dose from groundwater ingestion (mrem)
C_a = aqueous-phase radionuclide concentration in aquifer (pCi L^{-1})
IR = annual water ingestion rate (L yr^{-1})
DC = effective dose coefficient for ingestion (mrem pCi^{-1})
ED = exposure duration (1 yr).

The cancer morbidity risk from groundwater ingestion is given by:

$$R_{GWING} = C_{a30} \times IR \times RC \times ED \quad (5\text{-}27)$$

where

R_{GWING} = carcinogenic morbidity risk from groundwater ingestion (unitless)
C_{a30} = aqueous-phase radionuclide concentration in aquifer averaged over exposure duration (pCi L^{-1})
IR = annual water ingestion rate (L yr^{-1})
RC = morbidity risk coefficient for water ingestion (risk pCi^{-1}).
ED = exposure duration (30 yrs).

5.3. Surface Water Assessment

As described in Section 2.2.3, surface water from the site is not connected hydraulically to any regional surface water body. Any stormwater falling on the facility during the operational period and the post closure period is conveyed to on-site stormwater retention ponds that do not discharge to the nearby water bodies.

6. Dose and Risk Estimates during Disposal of the Bakken Oilfield Waste at the CWMNW Landfill

The calculated radiation doses and cancer morbidity risks for the exposure scenarios described in Section 4 are presented and discussed here. Full details of the calculations and complete results, including cancer mortality risks, are available in Appendix C.

6.1. Doses and Risks during Disposal

This section summarizes the doses and cancer morbidity risks for the receptors described above during the original disposal of the Bakken oilfield waste. The waste handler represents the maximally exposed individual for the disposals of the Bakken oilfield waste, as the handler is physically the closest to the material. No credit is taken in the calculations for the required PPE; therefore, actual exposures would have been significantly lower. Landfill workers located in the lead truck or in the office/laboratory will have lower exposures as they do not exit the vehicle during disposal and are physically far removed from the disposals. The nearest off-site receptor is farther removed from the disposals.

6.1.1. Waste Handlers

As described above, the waste handler is the person who drives the waste delivery vehicle from the point of origin to the CWMNW Arlington landfill. Once at the designated disposal location inside of Landfill Unit L-14, the waste handler operates the offloading controls outside the truck that allow the waste to be physically deposited into the landfill. This individual is the maximally exposed individual during the disposals because the waste handler is outside the truck in full PPE. For the purposes of this analysis, no credit is taken for the PPE. The effective doses in Table 6-1 and Table 6-2 are annual averages and assume all disposals occurred in a single year.

Table 6-1. Annual Effective Dose for the Waste Handler, Maximum Source Term

Radionuclide	Inhalation dose (mrem)	Ingestion dose (mrem)	Total dose (mrem)
U-238	4.81×10^{-4}	7.76×10^{-5}	5.59×10^{-4}
U-234	9.54×10^{-4}	1.33×10^{-4}	1.09×10^{-3}
Th-230	3.91×10^{-3}	2.30×10^{-4}	4.14×10^{-3}
Ra-226	6.95×10^{-2}	7.42×10^{-2}	1.44×10^{-1}
Pb-210	4.15×10^{-1}	2.57	2.99
Th-232	2.56×10^{-3}	1.50×10^{-4}	2.71×10^{-3}
Ra-228	4.96×10^{-2}	1.13×10^{-1}	1.62×10^{-1}
Th-228	1.87×10^{-2}	2.42×10^{-3}	2.11×10^{-2}
Total	**5.6×10^{-1}**	**2.8**	**3.3**

For the maximum source term, the external dose was 7.9×10^{-3} mrem, again assuming the same individual attended all disposals.

Table 6-2. Annual Effective Dose for the Waste Handler, Weighted-average Source Term

Radionuclide	Inhalation dose (mrem)	Ingestion dose (mrem)	Total dose (mrem)
U-238	1.16×10^{-5}	1.86×10^{-6}	1.34×10^{-5}
U-234	4.59×10^{-5}	6.40×10^{-6}	5.23×10^{-5}
Th-230	1.89×10^{-4}	1.11×10^{-5}	2.00×10^{-4}
Ra-226	4.33×10^{-2}	4.62×10^{-2}	8.96×10^{-2}
Pb-210	2.54×10^{-1}	1.57	1.83

Radionuclide	Inhalation dose (mrem)	Ingestion dose (mrem)	Total dose (mrem)
Th-232	7.08×10^{-2}	4.15×10^{-3}	7.49×10^{-2}
Ra-228	3.30×10^{-2}	7.47×10^{-2}	1.08×10^{-1}
Th-228	1.10×10^{-2}	1.43×10^{-3}	1.25×10^{-2}
Total	**4.1×10^{-1}**	**1.7**	**2.1**

For the weighted-average source term, the external dose was 5.0×10^{-3} mrem, again assuming the same individual attended all disposals.

The dominant pathway of exposure for the waste handler was ingestion. Again, no credit is taken for the required PPE that is worn by all persons in the active areas of the landfill. Thus, these doses represent bounding, or worst-case scenarios. The maximum total dose was 3.3 mrem for the waste handler, which is a tiny fraction of the dose received from exposure to natural background in the United States.

Cancer risks are expressed as a unitless probability (*e.g.*, 1 in 1 million, or 1×10^{-6}) and represent the incremental probability of an individual developing cancer over a lifetime as a result of exposures related to the Bakken oilfield wastes. The risk is incremental because it refers to the probability of cancer above and beyond the background rate of cancer in the general population, which on average is approximately 40 out of 100 for men and 39 out of 100 for women (American Cancer Society 2020)

Cancer morbidity risks for each source term are presented in Table 6-3 and Table 6-4. Even for the most exposed receptor, the waste handler, cancer morbidity risks are all at the extreme lower end of EPA's guidance range of 1×10^{-6} to 1×10^{-4}. The maximum morbidity risk for the most exposed individual, the waste handler, was 2.4×10^{-6}, which is at the very low end of the EPA's acceptable risk range. This analysis demonstrates that no adverse effects are likely from the original disposal of the Bakken oilfield waste.

Table 6-3. Cancer Morbidity Risk for the Waste Handler, Maximum Source Term

Radionuclide	Total inhalation morbidity risk	Total ingestion morbidity risk	Total external morbidity risk
U-238	1.40×10^{-10}	4.52×10^{-11}	8.77×10^{-9}
U-234	2.91×10^{-10}	5.91×10^{-11}	4.32×10^{-13}
Th-230	2.89×10^{-10}	2.93×10^{-11}	5.57×10^{-13}
Ra-226	2.10×10^{-8}	2.27×10^{-8}	1.04×10^{-6}
Pb-210	1.45×10^{-7}	8.63×10^{-7}	2.92×10^{-9}
Th-232	2.61×10^{-10}	1.94×10^{-11}	1.38×10^{-13}
Ra-228	4.10×10^{-9}	2.72×10^{-8}	2.38×10^{-7}
Th-228	1.53×10^{-8}	1.09×10^{-9}	1.03×10^{-8}
Pathway totals	1.87×10^{-7}	9.15×10^{-7}	1.30×10^{-6}
Total			**2.4×10^{-6}**

Table 6-4. Cancer Morbidity Risk for the Waste Handler, Weighted-average Source Term

Radionuclide	Total inhalation morbidity risk	Total ingestion morbidity risk	Total external morbidity risk
U-238	3.37×10^{-12}	1.08×10^{-12}	2.11×10^{-10}
U-234	1.40×10^{-11}	2.84×10^{-12}	2.08×10^{-14}
Th-230	1.40×10^{-11}	1.42×10^{-12}	2.70×10^{-14}
Ra-226	1.31×10^{-8}	1.42×10^{-8}	6.46×10^{-7}
Pb-210	8.89×10^{-8}	5.28×10^{-7}	1.78×10^{-9}
Th-232	7.19×10^{-9}	5.37×10^{-10}	3.81×10^{-12}
Ra-228	2.72×10^{-9}	1.81×10^{-8}	1.58×10^{-7}
Th-228	9.02×10^{-9}	6.44×10^{-10}	6.08×10^{-9}
Pathway totals	1.21×10^{-7}	5.61×10^{-7}	8.12×10^{-7}
Total			**1.5×10^{-6}**

6.1.2. Current Off-site Residents

The nearest current off-site resident is located about 3,260 m (10,700 ft or roughly 2 miles) from the disposal facility. The only complete pathway of exposure for the current off-site resident is inhalation of particulates that may have been blown off-site. The calculated doses and cancer morbidity risks for the off-site resident during disposal are summarized in Table 6-5.

Table 6-5. Doses and Risks for the Current Off-site Resident, during Disposal

Radionuclide	Inhalation dose, max source term (mrem)	Inhalation dose, weighted-avg source term (mrem)	Total morbidity risk, max source term	Total morbidity risk, weighted-avg source term
U-238	6.50×10^{-10}	1.56×10^{-11}	1.81×10^{-16}	4.35×10^{-18}
U-234	1.29×10^{-9}	6.20×10^{-11}	3.76×10^{-16}	1.81×10^{-17}
Th-230	5.28×10^{-9}	2.55×10^{-10}	3.74×10^{-16}	1.81×10^{-17}
Ra-226	9.40×10^{-8}	5.85×10^{-8}	2.72×10^{-14}	1.69×10^{-14}
Pb-210	5.61×10^{-7}	3.43×10^{-7}	1.88×10^{-13}	1.15×10^{-13}
Th-232	3.46×10^{-9}	9.56×10^{-8}	3.37×10^{-16}	9.30×10^{-15}
Ra-228	6.71×10^{-8}	4.45×10^{-8}	5.30×10^{-15}	3.52×10^{-15}
Th-228	2.53×10^{-8}	1.49×10^{-8}	1.97×10^{-14}	1.17×10^{-14}
Total	**7.6×10^{-7} mrem**	**5.6×10^{-7} mrem**	**2.4×10^{-13}**	**1.6×10^{-13}**

These doses are extremely low, and the cancer morbidity risks are effectively zero. This analysis demonstrates that no adverse effects are likely from the original disposal of the Bakken oilfield waste.

7. Dose and Risk Estimates for Remediation Alternatives

The calculated doses and risks for the exposure scenarios for the two remediation alternatives described in Section 4 are presented here. Full details of the calculations and complete results are available in Appendix C.

7.1. Alternative 1: Closure-in-Place

As described above and in detail in the CAP (Gradient 2020), this alternative assumes the Bakken oilfield waste is left in place and covered with other chemical/hazardous wastes accepted by the landfill.

This section summarizes the doses and cancer morbidity risks for the relevant receptors assuming the Bakken oilfield waste is left in place. For the closure-in-place alternative, viable exposure pathways include inhalation of outdoor radon, which represents a long-term exposure hazard, and thus risks are presented assuming 30 years of exposure (see Table 7-1 and Table 7-2), and ingestion of groundwater. The maximum dose that is calculated to occur is 0.12 mrem for a future on-site resident at 260,000 years into the future and results primarily from ingestion of groundwater (section 7.1.1). This dose corresponds to a risk of getting cancer of 1×10^{-6}, or a one in a million.

In addition to the doses and risks, the radon flux calculated at the surface of the Landfill Unit L-14 is also of interest. The radon flux for the maximum source term was 3.0×10^{-11} pCi m^{-2} s^{-1}; for the weighted-average source term, the radon flux was 1.9×10^{-11} pCi m^{-2} s^{-1}, substantially below the limit for uranium mill tailings disposal cells and the Department of Energy (DOE) performance criteria for low-level radioactive waste disposal sites of 20 pCi m^{-2} s^{-1} (DOE 2007; EPA 1998).

Table 7-1. Radon Results[a], Maximum Source Term

Receptor	Radon concentration (pCi L^{-1})	WLM[b]	Radon dose (mrem)	Cancer morbidity risk – 30 years
Landfill worker	3.40×10^{-14}	4.08×10^{-15}	3.1×10^{-12}	2.0×10^{-16}
Current off-site resident	3.03×10^{-17}	1.21×10^{-17}	9.2×10^{-15}	5.9×10^{-19}
Future off-site resident	3.03×10^{-17}	1.50×10^{-17}	1.1×10^{-14}	7.3×10^{-19}
Future on-site resident	3.40×10^{-14}	1.68×10^{-14}	1.3×10^{-11}	8.2×10^{-16}

a. Represents outdoor radon concentration, dose, and risk.
b. Assuming equilibrium factor is unity.

Table 7-2. Radon Results[a], Weighted-average Source Term

Receptor	Radon concentration (pCi L^{-1})	WLM[b]	Radon dose (mrem)	Cancer morbidity risk – 30 years
Landfill worker	2.12×10^{-14}	2.54×10^{-15}	1.9×10^{-12}	1.2×10^{-16}
Current off-site resident	1.89×10^{-17}	7.52×10^{-18}	5.7×10^{-15}	3.7×10^{-19}
Future off-site resident	1.89×10^{-17}	9.34×10^{-18}	7.1×10^{-15}	4.6×10^{-19}
Future on-site resident	2.12×10^{-14}	1.05×10^{-14}	7.9×10^{-12}	5.1×10^{-16}

a. Represents outdoor radon concentration, dose, and risk.
b. Assuming equilibrium factor is unity.

Exposures for all receptors are several orders of magnitude below the EPA's acceptable risk level of 1×10^{-6} and are effectively zero. This analysis demonstrates that no adverse effects are likely from the original disposal of the Bakken oilfield waste.

7.1.1. Groundwater Pathway Results

Any potential exposures associated with the groundwater pathway occur at substantially longer times than any of the other exposure pathways. This is a result of the long unsaturated water travel times and radionuclide sorption in the landfill, unsaturated zone, and aquifer. Results presented for the groundwater pathway include porewater concentrations in the unsaturated zone, annual effective doses assuming groundwater ingestion, and cancer morbidity risk from groundwater ingestion. In summary, no appreciable concentrations, effective doses, and cancer morbidity risks occur before 60,000 years from present. Maximum radionuclide concentrations, effective doses, and cancer morbidity risks occur ~260,000 years from the present and are well below applicable limits.

The radionuclide flux from the unsaturated zone to the aquifer, shown in Figure 7-1, demonstrates that no appreciable radionuclide fluxes occur before 60,000 years. Lead-210 has the highest flux and is not a result of the initial Pb-210 inventory, but rather is from ingrowth from parents (U-234, Th-230, and Ra-226). After 10,000 years, Th-230, Ra-226, and Pb-210 are about 50% of the initial U-234 activity. The lower K_d value for lead relative to radium and thorium results in higher porewater concentrations and greater transport speeds.

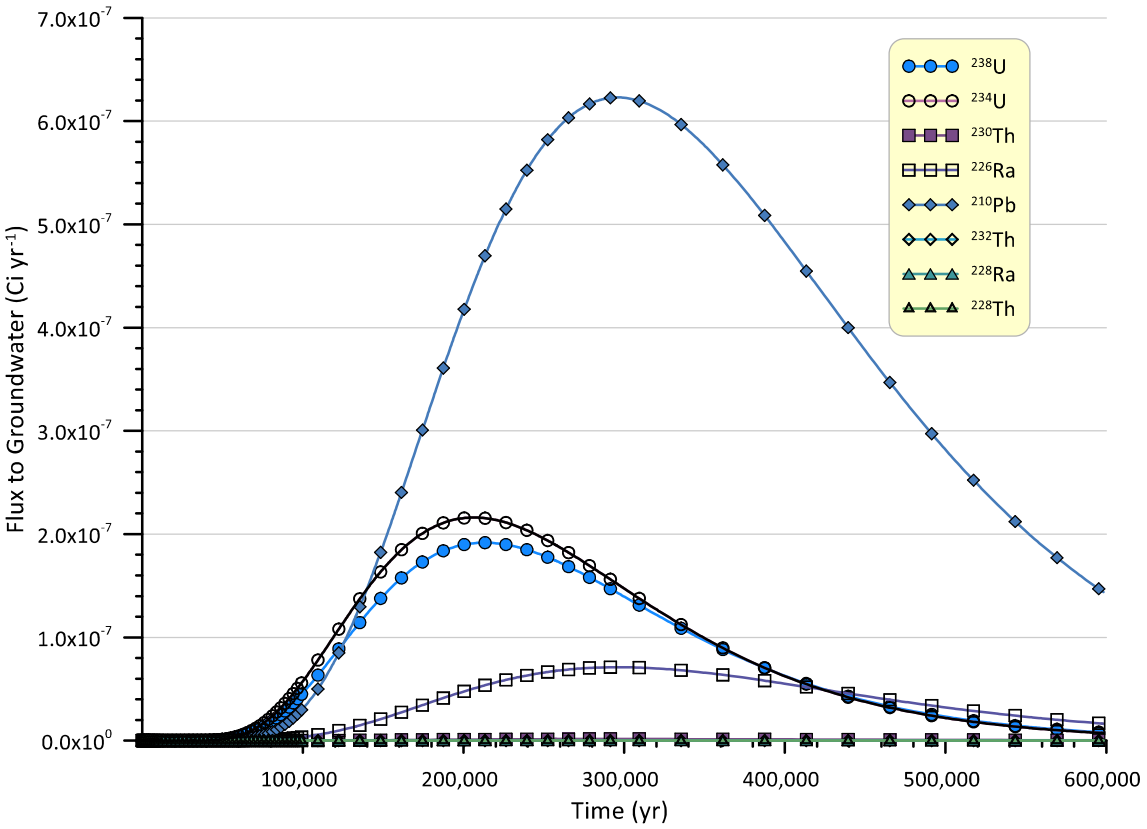

Figure 7-1. Radionuclide flux from the unsaturated zone to the aquifer for the maximum radionuclide inventory.

Radionuclide concentration limits in water are specified in ODOE 345-050-0035 (Table 7-3). These concentrations were compared against unsaturated porewater concentrations at the unsaturated/saturated interface. Table 7-4 shows the unsaturated porewater concentration at the unsaturated/saturated interface and compares these concentrations to those in Table 3 of ODOE-050-0035 for the maximum inventory and the weighted-average inventory. For multiple radionuclides, the sum of ratios (SOR) must be less than 1.0. For the maximum inventory, the maximum SOR was 0.00182; for the weighted-average inventory, the maximum SOR was 7.5×10^{-5}. Thus, unsaturated pore water concentrations are substantially lower than the Table 3 values in ODOE-050-0035.

Additionally, unsaturated pore water concentrations were also less than the federal maximum contaminant limits (MCLs) for drinking water stated in 40 CFR 141. The MCL for Ra-226 and Ra-228 combined is 5 pCi L^{-1}, 15 pCi L^{-1} for Th-228, Th-230 and Th-232, and a uranium mass concentration of 30 µg L^{-1}. Uranium mass is dominated by U-238 and the activity concentration of U-238 that corresponds to 30 µg L^{-1} is about 10 pCi L^{-1}. Although MCLs do not apply to unsaturated pore water and only apply to drinking water at the tap, this comparison shows that the pore water concentrations in the unsaturated zone meet the drinking water MCLs and concentrations at any seep or discharge point in the Selah will also meet federal MCLs.

Maximum groundwater ingestion effective dose (Table 7-5 and Figure 7-2) was 0.12 mrem yr^{-1} for the maximum inventory and 0.0046 mrem yr^{-1} for the weighted-average inventory for the receptor located on the downgradient edge of the source. Doses and risks at the 100-m receptor

were ~78% of the doses at the downgradient edge. These doses are substantially below the annual effective dose limit of 25 mrem in 10 CFR Part 61, DOE Order 435.1, and recommended in the American National Standards Institute (ANSI) standard for TENORM (ANSI/HPS 2009). Maximum doses occur well after the 10,000-year and 1,000-year time of compliance for NRC and DOE, respectively. The corresponding cancer morbidity risk was 1.0×10^{-6} and 3.8×10^{-8} for the maximum and weighted-average inventory, respectively. These risks are less than the target EPA cancer risk range of 10^{-6} to 10^{-4}. Maximum doses and risks occurred ~260,000 years from the present, and ^{210}Pb, ^{234}U, and ^{226}Ra were the primary dose/risk contributors.

Table 7-3. Radionuclide Concentration Limits in Table 3 of ODOE 345-050-0035 and Federal Maximum Contaminant Limits (MCLs)

Radionuclide	Table 3 Value (μCi mL^{-1})	Federal MCL (pCi L^{-1})
U-238a	4.00×10^{-5}	10.1
U-234a	3.00×10^{-5}	186,750
Th-230	2.00×10^{-6}	15
Ra-226	3.00×10^{-8}	5
Pb-210	1.00×10^{-7}	b
Th-232	2.00×10^{-6}	15
Ra-228	3.00×10^{-8}	5
Th-228	7.00×10^{-6}	15

a. The MCL for uranium is 30 µg L^{-1}. This value was converted to an activity concentration using specific activities from Browne and Firestone (1986) of 3.36E-7 Ci g^{-1} for U-238 and 6.23E-3 Ci g^{-1} for U-234.
b. No MCL for Pb-210

Table 7-4. Radionuclide Unsaturated Pore Water Concentrations at the Unsaturated/Saturated Interface and Comparison to Table 3 Values

Time window (years)	U-238	U-234	Th-230	Ra-226	Pb-210	Th-232	Ra-228	Th-228	SOR[a]
Radionuclide concentration in unsaturated pore water for maximum inventory (pCi L^{-1})									
<250y	2.89E-53	4.92E-53	5.52E-59	3.98E-60	1.61E-60	0.00E+00	0.00E+00	0.00E+00	N/A
250-500y	3.18E-49	5.41E-49	1.45E-54	2.46E-55	1.65E-55	0.00E+00	0.00E+00	0.00E+00	N/A
500-1000y	1.26E-35	2.15E-35	4.56E-41	6.39E-42	3.93E-42	2.32E-88	1.14E-82	1.06E-83	N/A
1000-5000y	9.56E-18	1.62E-17	2.58E-22	2.52E-22	2.80E-22	3.31E-69	5.92E-68	5.48E-69	N/A
5000,10,000y	9.27E-12	1.56E-11	5.74E-16	1.15E-15	1.38E-15	7.99E-62	1.08E-60	9.96E-62	N/A
10,000-100,000y	2.45E-01	3.74E-01	5.23E-04	5.17E-03	6.52E-03	8.62E-38	9.49E-37	8.78E-38	N/A
100,000-400,000y	4.80E-01	6.90E-01	3.62E-03	3.92E-02	4.94E-02	7.02E-27	7.63E-26	7.06E-27	N/A
>400,000y	2.34E-01	3.05E-01	3.38E-03	3.67E-02	4.63E-02	1.99E-20	2.15E-19	1.99E-20	N/A
Ratio of unsaturated pore water concentrations to Table 3 values for maximum inventory									
<250y	7.23E-58	1.64E-57	2.76E-62	1.33E-61	1.61E-62	0.00E+00	0.00E+00	0.00E+00	2.36E-57
250-500y	7.95E-54	1.80E-53	7.25E-58	8.20E-57	1.65E-57	0.00E+00	0.00E+00	0.00E+00	2.60E-53
500-1000y	3.16E-40	7.17E-40	2.28E-44	2.13E-43	3.93E-44	1.16E-91	3.80E-84	1.51E-87	1.03E-39
1000-5000y	2.39E-22	5.39E-22	1.29E-25	8.40E-24	2.80E-24	1.65E-72	1.97E-69	7.83E-73	7.90E-22
5000,10,000y	2.32E-16	5.20E-16	2.87E-19	3.85E-17	1.38E-17	4.00E-65	3.59E-62	1.42E-65	8.05E-16
10,000-100,000y	6.12E-06	1.25E-05	2.62E-07	1.72E-04	6.52E-05	4.31E-41	3.16E-38	1.25E-41	2.56E-04
100,000-400,000y	1.20E-05	2.30E-05	1.81E-06	1.31E-03	4.94E-04	3.51E-30	2.54E-27	1.01E-30	1.82E-03
>400,000y	5.86E-06	1.02E-05	1.69E-06	1.22E-03	4.63E-04	9.93E-24	7.17E-21	2.84E-24	1.70E-03
Radionuclide concentration in pore water for weighted-average inventory (pCi L^{-1})									
<250y	6.93E-55	2.37E-54	2.65E-60	1.91E-61	7.75E-62	0.00E+00	0.00E+00	0.00E+00	N/A
250-500y	7.63E-51	2.60E-50	6.97E-56	1.18E-56	7.94E-57	0.00E+00	0.00E+00	0.00E+00	N/A
500-1000y	3.03E-37	1.03E-36	2.19E-42	3.07E-43	1.89E-43	6.41E-88	3.15E-82	2.91E-83	N/A
1000-5000y	2.29E-19	7.75E-19	1.24E-23	1.21E-23	1.34E-23	9.12E-69	1.63E-67	1.51E-68	N/A
5000,10,000y	2.22E-13	7.44E-13	2.74E-17	5.51E-17	6.56E-17	2.20E-61	2.97E-60	2.75E-61	N/A
10,000-100,000y	5.87E-03	1.65E-02	2.34E-05	2.32E-04	2.92E-04	2.38E-37	2.62E-36	2.42E-37	N/A
100,000-400,000y	1.15E-02	2.89E-02	1.49E-04	1.61E-03	2.03E-03	1.93E-26	2.10E-25	1.95E-26	N/A
>400,000y	5.62E-03	1.14E-02	1.36E-04	1.48E-03	1.86E-03	5.47E-20	5.93E-19	5.49E-20	N/A
Ratio of pore water concentrations to Table 3 values for weighted-average inventory									
<250y	1.73E-59	7.89E-59	1.33E-63	6.38E-63	7.75E-64	0.00E+00	0.00E+00	0.00E+00	9.62E-59
250-500y	1.91E-55	8.67E-55	3.48E-59	3.94E-58	7.94E-59	0.00E+00	0.00E+00	0.00E+00	1.06E-54
500-1000y	7.58E-42	3.44E-41	1.09E-45	1.02E-44	1.89E-45	3.20E-91	1.05E-83	4.16E-87	4.20E-41
1000-5000y	5.73E-24	2.58E-23	6.18E-27	4.02E-25	1.34E-25	4.56E-72	5.44E-69	2.16E-72	3.21E-23
5000,10,000y	5.56E-18	2.48E-17	1.37E-20	1.84E-18	6.56E-19	1.10E-64	9.89E-62	3.92E-65	3.29E-17
10,000-100,000y	1.47E-07	5.52E-07	1.17E-08	7.72E-06	2.92E-06	1.19E-40	8.72E-38	3.46E-41	1.13E-05
100,000-400,000y	2.88E-07	9.63E-07	7.46E-08	5.37E-05	2.03E-05	9.67E-30	7.01E-27	2.78E-30	7.50E-05
>400,000y	1.41E-07	3.80E-07	6.79E-08	4.92E-05	1.86E-05	2.74E-23	1.98E-20	7.84E-24	6.84E-05

a. Sum of ratios.

N/A Not Applicable.

Table 7-5. Groundwater Ingestion Effective Dose and Carcinogenic Morbidity Risk for the Maximum and Weighted-Average Inventory

Time window (years)	U-238	U-234	Th-230	Ra-226	Pb-210	Th-232	Ra-228	Th-228	Total
Radionuclide effective dose for the maximum inventory at the downgradient edge of the source (mrem)									
<250y	2.33E-56	4.05E-56	1.87E-61	2.30E-62	5.55E-62	0.00E+00	0.00E+00	0.00E+00	6.38E-56
250-500y	4.87E-52	8.45E-52	9.34E-57	2.72E-57	1.10E-56	0.00E+00	0.00E+00	0.00E+00	1.33E-51
500-1000y	1.59E-38	2.76E-38	2.47E-43	6.00E-44	2.23E-43	0.00E+00	1.27E-85	1.85E-87	4.35E-38
1000-5000y	3.36E-20	5.80E-20	3.97E-24	6.85E-24	4.66E-23	1.49E-72	1.58E-70	1.20E-52	9.17E-20
5000,10,000y	4.11E-14	7.06E-14	1.12E-17	3.98E-17	2.90E-16	7.14E-65	5.58E-63	3.12E-53	1.12E-13
10,000-100,000y	3.80E-03	5.92E-03	3.05E-05	5.31E-04	4.10E-03	5.64E-40	3.57E-38	5.22E-40	1.44E-02
100,000-400,000y	1.55E-02	2.19E-02	5.34E-04	1.04E-02	8.01E-02	8.86E-29	5.53E-27	8.09E-29	1.20E-01
>400,000y	1.12E-02	1.48E-02	5.33E-04	1.03E-02	8.00E-02	3.38E-22	2.11E-20	3.08E-22	1.17E-01
Radionuclide effective dose for the weighted-average inventory at the downgradient edge of the source (mrem)									
<250y	5.60E-58	1.95E-57	8.97E-63	1.11E-63	2.67E-63	0.00E+00	0.00E+00	0.00E+00	2.51E-57
250-500y	1.17E-53	4.06E-53	4.49E-58	1.31E-58	5.27E-58	0.00E+00	0.00E+00	0.00E+00	5.23E-53
500-1000y	3.82E-40	1.33E-39	1.18E-44	2.88E-45	1.07E-44	0.00E+00	3.49E-85	5.11E-87	1.71E-39
1000-5000y	8.06E-22	2.78E-21	1.90E-25	3.28E-25	2.23E-24	4.12E-72	4.35E-70	5.29E-53	3.59E-21
5000,10,000y	9.87E-16	3.37E-15	5.32E-19	1.90E-18	1.39E-17	1.97E-64	1.54E-62	3.12E-53	4.37E-15
10,000-100,000y	9.11E-05	2.61E-04	1.36E-06	2.38E-05	1.84E-04	1.56E-39	9.85E-38	1.44E-39	5.61E-04
100,000-400,000y	3.71E-04	8.88E-04	2.13E-05	4.13E-04	3.20E-03	2.44E-28	1.53E-26	2.23E-28	4.61E-03
>400,000y	2.68E-04	5.54E-04	2.12E-05	4.11E-04	3.18E-03	9.32E-22	5.81E-20	8.49E-22	4.44E-03
Radionuclide carcinogenic morbidity risk for the maximum inventory at the downgradient edge of the source									
<250y	2.89E-61	4.00E-61	5.47E-67	1.58E-67	4.31E-67	0.00E+00	0.00E+00	0.00E+00	6.89E-61
250-500y	6.03E-57	8.33E-57	2.74E-62	1.87E-62	8.53E-62	0.00E+00	0.00E+00	0.00E+00	1.44E-56
500-1000y	1.97E-43	2.72E-43	7.22E-49	4.13E-49	1.73E-48	0.00E+00	6.68E-91	1.78E-92	4.69E-43
1000-5000y	4.16E-25	5.72E-25	1.16E-29	4.71E-29	3.62E-28	4.40E-78	8.31E-76	1.15E-57	9.89E-25
5000,10,000y	5.09E-19	6.96E-19	3.27E-23	2.73E-22	2.26E-21	2.10E-70	2.94E-68	3.00E-58	1.21E-18
10,000-100,000y	4.70E-08	5.84E-08	8.94E-11	3.65E-09	3.19E-08	1.66E-45	1.88E-43	5.03E-45	1.41E-07
100,000-400,000y	1.92E-07	2.16E-07	1.56E-09	7.12E-08	6.23E-07	2.61E-34	2.92E-32	7.79E-34	1.03E-06
>400,000y	1.38E-07	1.46E-07	1.56E-09	7.11E-08	6.22E-07	9.95E-28	1.11E-25	2.96E-27	9.79E-07
Radionuclide carcinogenic morbidity risk for the weighted-average inventory at the downgradient edge of the source									
<250y	6.93E-63	1.92E-62	2.63E-68	7.60E-69	2.07E-68	0.00E+00	0.00E+00	0.00E+00	2.61E-62
250-500y	1.45E-58	4.01E-58	1.32E-63	8.98E-64	4.10E-63	0.00E+00	0.00E+00	0.00E+00	5.45E-58
500-1000y	4.73E-45	1.31E-44	3.47E-50	1.98E-50	8.32E-50	0.00E+00	1.84E-90	4.92E-92	1.78E-44
1000-5000y	9.99E-27	2.74E-26	5.57E-31	2.26E-30	1.74E-29	1.21E-77	2.29E-75	5.10E-58	3.74E-26
5000,10,000y	1.22E-20	3.32E-20	1.56E-24	1.31E-23	1.08E-22	5.79E-70	8.11E-68	3.00E-58	4.55E-20
10,000-100,000y	1.13E-09	2.58E-09	3.99E-12	1.63E-10	1.43E-09	4.57E-45	5.19E-43	1.39E-44	5.30E-09
100,000-400,000y	4.60E-09	8.76E-09	6.25E-11	2.84E-09	2.49E-08	7.18E-34	8.04E-32	2.15E-33	3.84E-08
>400,000y	3.32E-09	5.46E-09	6.20E-11	2.83E-09	2.47E-08	2.74E-27	3.06E-25	8.17E-27	3.64E-08

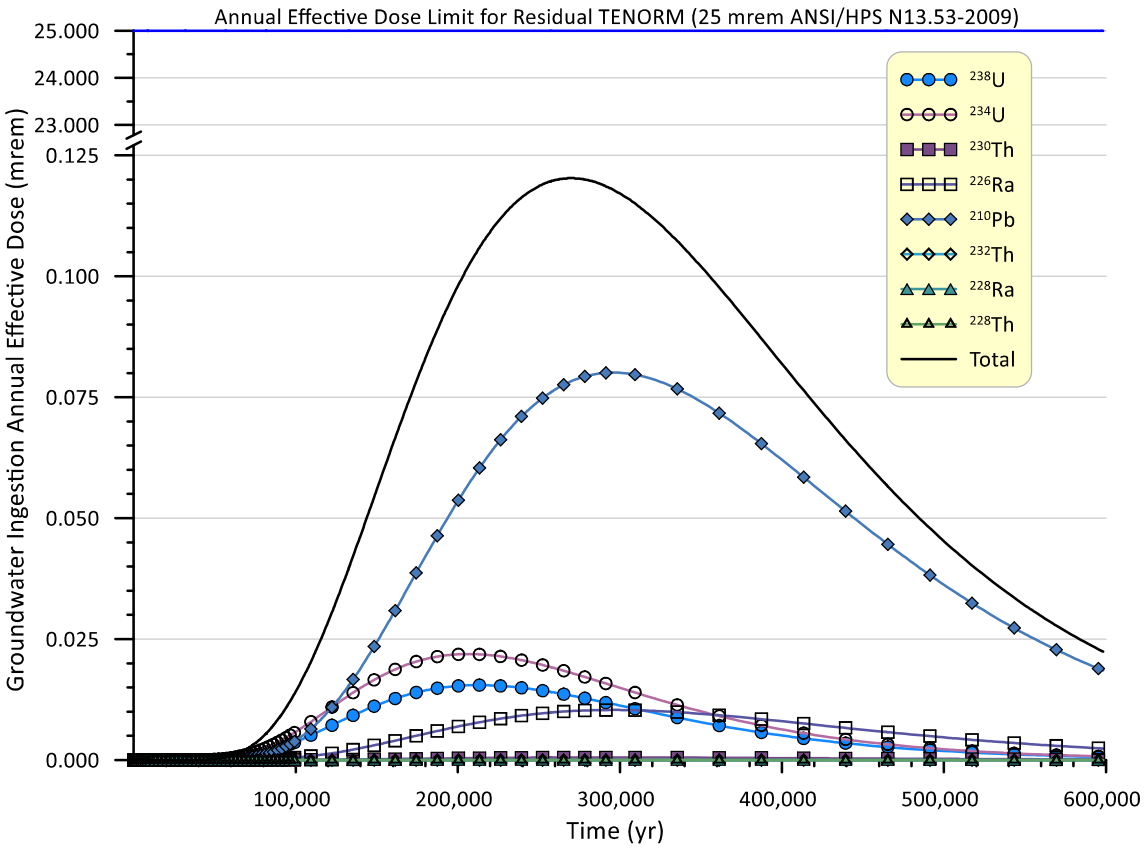

Figure 7-2. Effective dose from groundwater ingestion at the downgradient edge of the source as a function of time for the maximum inventory.

7.1.1.1. Sensitivity Case for Groundwater Assessment

A sensitivity case was run where the minimum K_d values in Table 5-10 were used instead of the geometric mean. The maximum inventory was used in the simulation and all other parameters remained the same. Thus, this sensitivity case represents the most improbable and extreme overstated estimate of the impacts from the groundwater pathway. The maximum annual effective dose (Table 7-6) was 0.87 mrem and occurred in the 10,000–100,000-year time window. Both ^{226}Ra and ^{210}Pb represented about 45% of the total dose. The maximum cancer morbidity risk was 9.4×10^{-6} and occurred in the 10,000–100,000-year time window. The ratio of the unsaturated pore water concentration to Table 3 values had a maximum SOR of 0.0046. Thus, even with minimum K_ds, maximum inventory, and worst-case assumptions regarding the performance of the Landfill Unit L-14 liner and cover, annual effective doses were more than an order of magnitude below the 25 mrem per year dose limit. The cancer morbidity risks were at the lower end of the EPA acceptable target risk range of 10^{-6} to 10^{-4}, and the SOR of unsaturated pore water concentrations was substantially lower than 1.0.

Table 7-6. Groundwater Ingestion Effective Dose, Cancer Morbidity Risk and Ratio of Unsaturated Pore Water Concentrations to Table 3 Values for the Maximum Inventory and Minimum K_d Values

Time window (years)	U-238	U-234	Th-230	Ra-226	Pb-210	Th-232	Ra-228	Th-228	Total
Radionuclide effective dose at the downgradient edge of the source for the maximum inventory and minimum K_d values (mrem)									
<250y	1.31E-23	2.26E-23	4.14E-29	1.84E-29	5.03E-30	9.13E-89	1.01E-57	4.67E-60	3.57E-23
250-500y	7.08E-20	1.23E-19	5.54E-25	5.93E-25	2.75E-25	2.45E-84	2.42E-59	1.32E-61	1.94E-19
500-1000y	2.04E-09	3.54E-09	1.63E-14	1.80E-14	8.45E-15	1.23E-70	6.26E-53	2.85E-55	5.58E-09
1000-5000y	6.98E-02	1.20E-01	1.14E-05	1.78E-04	1.49E-04	8.82E-51	9.11E-47	4.14E-49	1.91E-01
5000,10,000y	3.11E-01	5.33E-01	2.10E-04	7.34E-03	6.38E-03	3.14E-43	1.81E-40	8.23E-43	8.58E-01
10,000-100,000y	3.15E-01	5.40E-01	6.31E-04	3.89E-02	3.42E-02	5.72E-20	1.21E-17	5.51E-20	8.73E-01
100,000-400,000y	5.03E-10	7.83E-10	3.27E-04	2.08E-02	1.83E-02	2.80E-11	5.67E-09	2.58E-11	3.93E-02
>400,000y	5.29E-31	7.01E-31	5.11E-05	3.24E-03	2.85E-03	2.00E-07	4.01E-05	1.82E-07	6.14E-03
Ratio of unsaturated pore water concentrations to Table 3 values for maximum inventory and minimum K_d values									
<250y	8.38E-26	1.90E-25	1.16E-30	1.94E-29	2.62E-31	1.73E-88	1.61E-57	1.99E-61	2.74E-25
250-500y	3.82E-22	8.67E-22	1.28E-26	5.16E-25	1.17E-26	1.99E-84	2.12E-59	3.17E-63	1.25E-21
500-1000y	1.08E-11	2.44E-11	3.75E-16	1.57E-14	3.62E-16	1.31E-70	9.79E-53	1.20E-56	3.52E-11
1000-5000y	1.19E-04	2.69E-04	1.00E-07	6.41E-05	2.64E-06	1.60E-51	1.40E-46	1.72E-50	4.54E-04
5000,10,000y	2.46E-04	5.54E-04	9.59E-07	1.40E-03	5.93E-05	3.19E-44	2.04E-40	2.50E-44	2.22E-03
10,000-100,000y	2.33E-04	5.22E-04	1.89E-06	4.38E-03	1.88E-04	1.59E-21	3.92E-18	4.81E-22	4.61E-03
100,000-400,000y	1.83E-13	3.72E-13	9.64E-07	2.29E-03	9.81E-05	5.56E-13	1.31E-09	1.61E-13	2.39E-03
>400,000y	1.92E-34	3.32E-34	1.52E-07	3.61E-04	1.55E-05	3.17E-09	7.40E-06	9.09E-10	3.76E-04
Carcinogenic morbidity risk at the downgradient edge of the source for maximum inventory and minimum K_d values									
<250y	1.62E-28	2.23E-28	1.21E-34	1.26E-34	3.91E-35	2.69E-94	5.35E-63	4.50E-65	3.85E-28
250-500y	8.77E-25	1.21E-24	1.62E-30	4.08E-30	2.14E-30	7.22E-90	1.28E-64	1.27E-66	2.09E-24
500-1000y	2.53E-14	3.49E-14	4.77E-20	1.23E-19	6.57E-20	3.61E-76	3.30E-58	2.74E-60	6.02E-14
1000-5000y	8.65E-07	1.19E-06	3.35E-11	1.22E-09	1.16E-09	2.59E-56	4.80E-52	3.98E-54	2.06E-06
5000,10,000y	3.85E-06	5.26E-06	6.16E-10	5.05E-08	4.96E-08	9.23E-49	9.54E-46	7.92E-48	9.21E-06
10,000-100,000y	3.90E-06	5.33E-06	1.85E-09	2.68E-07	2.66E-07	1.68E-25	6.39E-23	5.31E-25	9.36E-06
100,000-400,000y	6.22E-15	7.72E-15	9.59E-10	1.43E-07	1.42E-07	8.23E-17	2.99E-14	2.48E-16	2.86E-07
>400,000y	6.55E-36	6.91E-36	1.50E-10	2.23E-08	2.22E-08	5.87E-13	2.11E-10	1.75E-12	4.46E-08

7.2. Alternative 2: Excavate and Redispose

As described above and in detail in the CAP (Gradient 2020), this alternative assumes the Bakken oilfield waste is excavated from the landfill and trucked off-site to an alternative disposal facility.

Beyond the scope of this analysis are the much greater and real risks posed by disturbing the hazardous wastes currently safely disposed in Landfill Unit L-14. Disturbing these wastes during the excavation of the Bakken oilfield wastes would create unknown mixtures of unidentifiable chemicals with the real risk of creating adverse reactions between the disturbed wastes, thus creating exposures to workers and the environment. The excavation of these wastes would present an unacceptable, if not extreme, risk to human health and the environment under this scenario. To a lesser extent, but equally as valid, the radiation doses and risks to transport drivers and receptors at the alternative disposal facility are not addressed by this assessment.

Radon inhalation represents a long-term radiation exposure concern and is thus not considered for the excavation and re-disposal alternative. All doses and risks presented here assume that the same individual attends all 322 removal loads. Full details of the calculations and complete results are available in Appendix C.

7.2.1. Excavation Workers and Supervisor

During hypothetical retrieval and removal operations, both the excavation worker and supervisor would be exposed via inhalation of particulates, ingestion of soil, and external soil exposure. The excavation worker is assumed to operate the heavy equipment needed to excavate the waste. The supervisor is assumed to monitor the excavation operations on the ground. No credit is taken for the PPE worn by the excavation worker or supervisor. The excavation worker is assumed to be somewhat shielded from external radiation by the equipment (see Section 5.1.2). The supervisor is on the ground near the removal operations; thus, there is no shielding assumed for this receptor. Effective doses are shown in Table 7-7 for the maximum source term; in Table 7-8 for the weighted average source term.

Table 7-7. Effective Dose for the Excavation Worker and Supervisor, Maximum Source Term

Radionuclide	Inhalation dose (mrem)	Ingestion dose (mrem)	Total dose (mrem)
U-238	4.39×10^{-4}	1.23×10^{-3}	1.67×10^{-3}
U-234	8.70×10^{-4}	2.11×10^{-3}	2.97×10^{-3}
Th-230	3.56×10^{-3}	3.64×10^{-3}	7.20×10^{-3}
Ra-226	6.34×10^{-2}	1.17	1.24
Pb-210	3.78×10^{-1}	4.07×10^{1}	4.11×10^{1}
Th-232	2.34×10^{-3}	2.38×10^{-3}	4.71×10^{-3}
Ra-228	4.52×10^{-2}	1.78	1.83
Th-228	1.70×10^{-2}	3.82×10^{-2}	5.53×10^{-2}
Total	**5.11×10^{-1}**	**4.37×10^{1}**	**4.4×10^{1}**

Assuming the maximum source term, the external dose to the excavation worker in the equipment cab was 1.2×10^{-1} mrem; to the supervisor on the ground, it was 1.5 mrem.

Table 7-8. Effective Dose for the Excavation Worker and Supervisor, Weighted-average Source Term

Radionuclide	Inhalation dose (mrem)	Ingestion dose (mrem)	Total dose (mrem)
U-238	1.05×10^{-5}	2.95×10^{-5}	4.00×10^{-5}
U-234	4.18×10^{-5}	1.01×10^{-4}	1.43×10^{-4}
Th-230	1.72×10^{-4}	1.76×10^{-4}	3.49×10^{-4}
Ra-226	3.95×10^{-2}	7.31×10^{-1}	7.71×10^{-1}
Pb-210	2.31×10^{-1}	2.49×10^{1}	2.51×10^{1}
Th-232	6.45×10^{-2}	6.56×10^{-2}	1.30×10^{-1}
Ra-228	3.00×10^{-2}	1.18	1.21

Radionuclide	Inhalation dose (mrem)	Ingestion dose (mrem)	Total dose (mrem)
Th-228	1.01×10^{-2}	2.26×10^{-2}	3.27×10^{-2}
Total	**3.76×10^{-1}**	**2.69×10^{1}**	**2.7×10^{1}**

Assuming the weighted-average source term, the external dose to the excavation worker was 7.8×10^{-2} mrem; to the supervisor, it was 9.8×10^{-1} mrem. Cancer morbidity risks for each source term are presented in Table 7-97-9 and Table 7-10.

Table 7-9. Cancer Morbidity Risk for the Excavation Worker and Supervisor, Maximum Source Term

Radionuclide	Total inhalation morbidity risk	Total ingestion morbidity risk	Total external morbidity risk
U-238	1.28×10^{-10}	7.14×10^{-10}	1.39×10^{-7}
U-234	2.65×10^{-10}	9.35×10^{-10}	6.83×10^{-12}
Th-230	2.63×10^{-10}	4.64×10^{-10}	8.81×10^{-12}
Ra-226	1.91×10^{-8}	3.60×10^{-7}	1.64×10^{-5}
Pb-210	1.32×10^{-7}	1.37×10^{-5}	4.62×10^{-8}
Th-232	2.37×10^{-10}	3.08×10^{-10}	2.18×10^{-12}
Ra-228	3.73×10^{-9}	4.30×10^{-7}	3.77×10^{-6}
Th-228	1.39×10^{-8}	1.73×10^{-8}	1.63×10^{-7}
Pathway totals	1.70×10^{-7}	1.45×10^{-5}	2.05×10^{-5}
Total			**3.5×10^{-5}**

Table 7-10. Cancer Morbidity Risk for the Excavation Worker, Weighted-average Source Term

Radionuclide	Total inhalation morbidity risk	Total ingestion morbidity risk	Total external morbidity risk
U-238	3.07×10^{-12}	1.71×10^{-11}	3.33×10^{-9}
U-234	1.27×10^{-11}	4.50×10^{-11}	3.28×10^{-13}
Th-230	1.27×10^{-11}	2.24×10^{-11}	4.26×10^{-13}
Ra-226	1.19×10^{-8}	2.24×10^{-7}	1.02×10^{-5}
Pb-210	8.10×10^{-8}	8.35×10^{-6}	2.82×10^{-8}
Th-232	6.55×10^{-9}	8.49×10^{-9}	6.03×10^{-11}
Ra-228	2.48×10^{-9}	2.86×10^{-7}	2.50×10^{-6}
Th-228	8.21×10^{-9}	1.02×10^{-8}	9.62×10^{-8}
Pathway totals	1.10×10^{-7}	8.88×10^{-6}	1.28×10^{-5}
Total			**2.2×10^{-5}**

7.2.2. Current Off-site Resident

The nearest current off-site resident is located about 3,260 m (10,700 ft or roughly 2 miles) from the disposal facility. The only complete pathway of exposure for the current off-site resident is inhalation of particulates that may be blown off-site during hypothetical removal operations. The

calculated doses and cancer morbidity risks for the off-site resident during hypothetical removal operations are summarized in Table 7-11.

Table 7-11. Doses and Risks for the Current Off-site Resident, Alternative 2

Radionuclide	Inhalation dose, max source term (mrem)	Inhalation dose, weighted-avg source term (mrem)	Total morbidity risk, max source term	Total morbidity risk, weighted-avg source term
U-238	6.52×10^{-10}	1.57×10^{-11}	1.90×10^{-16}	4.56×10^{-18}
U-234	1.29×10^{-9}	6.22×10^{-11}	3.94×10^{-16}	1.90×10^{-17}
Th-230	5.29×10^{-9}	2.56×10^{-10}	3.92×10^{-16}	1.90×10^{-17}
Ra-226	9.42×10^{-8}	5.87×10^{-8}	2.84×10^{-14}	1.77×10^{-14}
Pb-210	5.62×10^{-7}	3.44×10^{-7}	1.97×10^{-13}	1.20×10^{-13}
Th-232	3.47×10^{-9}	9.59×10^{-8}	3.53×10^{-16}	9.74×10^{-15}
Ra-228	6.72×10^{-8}	4.47×10^{-8}	5.55×10^{-15}	3.69×10^{-15}
Th-228	2.53×10^{-8}	1.50×10^{-8}	2.07×10^{-14}	1.22×10^{-14}
Total	**7.6×10^{-7} mrem**	**5.6×10^{-7} mrem**	**2.5×10^{-13}**	**1.6×10^{-13}**

8. Intruder Assessment

At the request of the Oregon Department of Energy, an intruder assessment was conducted. This assessment assumes that at some point in the future a hypothetical individual inadvertently drills through the Bakken oilfield waste while installing a water well. This person is then assumed to use the excavated materials produced while drilling the water well, including both the Bakken oilfield waste and other chemical and hazardous wastes, as a foundation for a home (see Figure 8-1).

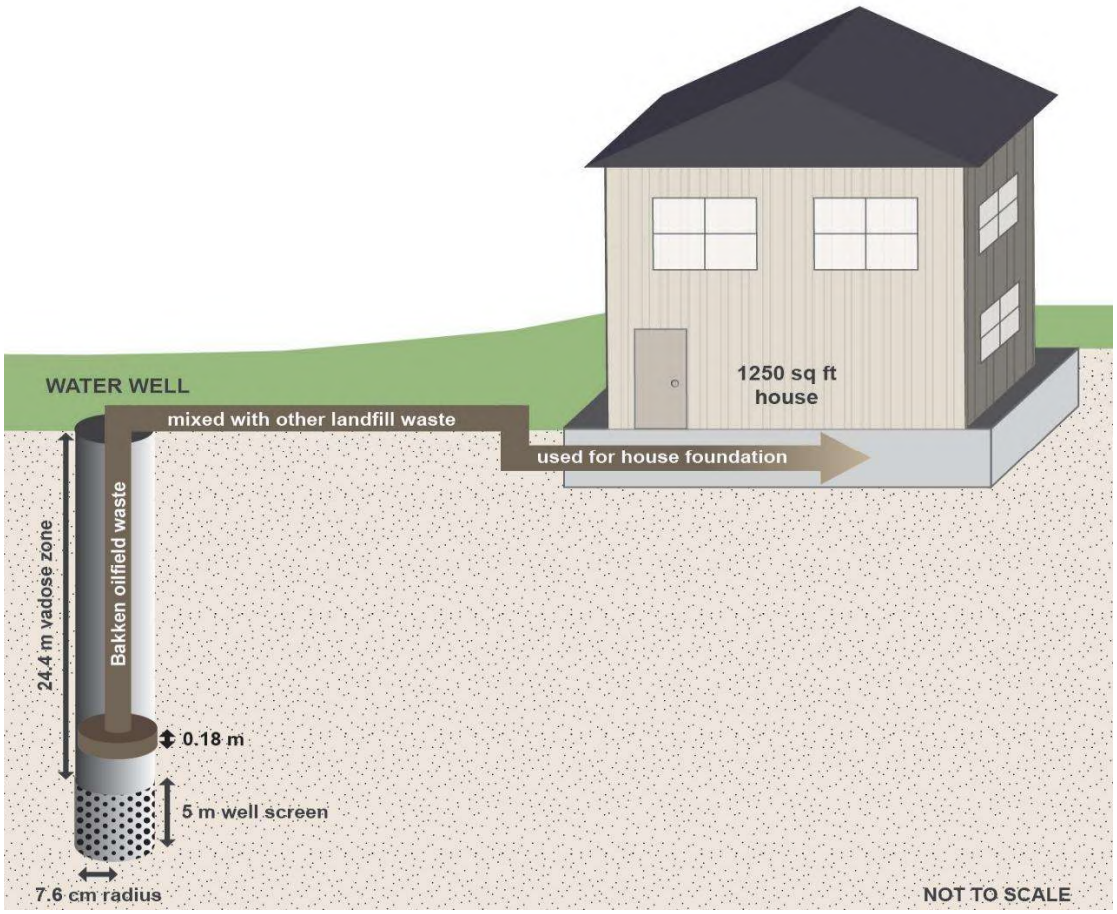

Figure 8-1. Conceptual model of exposure for the intruder.

RESRAD ONSITE v7.2 was used for this assessment. To assume the most pessimistic case for this scenario, no cover is assumed to exist over the hazardous waste before the house is placed. Further, the actual depth to the waste will be significantly greater than is assumed for this assessment, as materials are still being added to Landfill Unit L-14, which means that this assessment represents an extremely pessimistic scenario. Pathways of exposure examined for this assessment are indoor and outdoor radon inhalation and external exposure. Dose from groundwater ingestion is also considered here, with the calculations as described in Section 5.2. The intruder is assumed to draw water from the well located at the immediate downgradient edge of the source.

As with the remediation source term, the intruder source term is a diluted version of the disposal source term. The water well is assumed to be 24.4 m deep with a 5 m well screen. It is physically located within the landfill waste mass (see Section 5.2). According to the Oregon Water Resources Department[6], the nearest water well to the Arlington site is 6 inches in diameter. The source term paraments for this assessment are listed in Table 8-1.

[6] Well reports can be accessed here: https://www.oregon.gov/owrd/programs/GWWL/WCC/Pages/FindaWellLog.aspx.

Table 8-1. Intruder Assessment Source Term Parameters

Parameter	Value	Units	Notes
Total mass of Bakken oilfield waste	1.17×10^{6}	kg	Arlington landfill manifest data provided by CWMNW
Bulk density	1.76×10^{3}	kg m^{-3}	2970 lb yd^{-3} per Geosyntec Consultants (2020)
Total Bakken oilfield waste volume in dirt excavated from water well	3.29×10^{-3}	m^3	Calculation assuming 0.18 m thickness of TENORM. Calculation assumes 3 in (7.62 cm) well radius.
Total Bakken oilfield waste mass in dirt excavated from water well	5.80×10^{3}	g	Calculation using bulk density
Total volume of other landfill waste brought to surface during water well drilling	5.36×10^{-1}	m^3	Calculation assumes 3 in (7.62 cm) well radius, 24.4 m to water table plus 5 m well screen for a total depth of 29.4 m
Total mixed waste volume brought to surface	5.40×10^{-1}	m^3	Calculation assuming 1.15 g cm^{-3} bulk density of Selah

Given this, the dilution factor was calculated as:

$$Dilution\ Factor = \frac{Excavated\ Bakken\ Oilfield\ Waste\ Mass}{Total\ Mixed\ Waste\ Mass} = \frac{5.80\times10^{3}\,g}{6.21\times10^{5}\,g} = 0.01$$

The dilution factor was then applied to the maximum source term given in Table 3-5. Radionuclide concentrations used in the intruder assessment are given in Table 8-2. Input parameters that differ from RESRAD defaults are given in Table 8-3.

Table 8-2. Radionuclide Concentrations for the Intruder Assessment

Radionuclide	Radionuclide concentration (pCi g^{-1})
U-238	1.10×10^{-2}
U-234	1.88×10^{-2}
Th-230	7.46×10^{-3}
Ra-226	1.34
Pb-210	7.61
Th-232	4.43×10^{-3}
Ra-228	5.76×10^{-1}
Th-228	7.85×10^{-2}

Table 8-3. RESRAD-ONSITE Input Parameters for Intruder Assessment

Parameter	Value	Units	Notes
Area of contaminated zone	116.13	m^2	1,250 sq ft house, single story per 1987 Pathway Exemption Court Case[a]
Thickness of contaminated zone	0.0046	m	Volume of waste divided by square footage of home
Density of contaminated zone	1.76	g cm^{-3}	2,970 lb yd^{-3} per Geosyntec Consultants (2020)
Contaminated zone total porosity	0.41	unitless	Assumption based on waste material type – sandy loam
Average annual wind speed	4.839	m sec^{-1}	Extracted from meteorological data provided by CWMNW via email on 3/17/2020
Precipitation	0.235	m yr^{-1}	Reference: https://www.usclimatedata.com/climate/arlington/oregon/united-states/usor0013
Total porosity of the cover material	0.41	unitless	CWMNW Updated Hydrogeologic Conceptual Site Model Report (2008)
Average building air exchange rate	1.00	hr^{-1}	Per 1987 Pathway Exemption Court Case[a]
Height of the building (room)	2.44	m	Per 1987 Pathway Exemption Court Case[a]
Emanating power of Rn-222 gas	0.20	m^2	Assumption; value is typical of uranium mill tailings

a. Teledyne Wah Chang v. Energy Facility Siting Council, dated 5 March 1987.

8.1. Intruder Assessment Results

The doses and cancer morbidity risks are presented in Table 8-4. This analysis demonstrates that no adverse effects are likely should the Bakken oilfield waste be exhumed and used as the foundation for a home in the distant future.

Table 8-4. Intruder Assessment Results

Pathway	Dose (mrem)	Total cancer morbidity risk
Inhalation of indoor and outdoor radon	2.47×10^{-1}	1.89×10^{-6}
External exposure	6.49×10^{-1}	3.38×10^{-6}
Ingestion of groundwater	1.20×10^{-1}	1.03×10^{-6}
Total	**1.02 mrem**	**6.3×10^{-6}**

9. Ecological Assessment

For the closure-in-place alternative, an ecological assessment is provided to evaluate the radiological impacts to biota to ensure there are no deleterious effects. This assessment is in

addition to the radiological assessment for human receptors evaluated in Section 7. The ecological assessment is conducted using the ERICA (Environmental Risk from Ionizing Contaminants: Assessment and Management) Tool (Brown et al. 2008; Larsson 2008), which combines data on environmental transfer of radionuclides and dosimetry to obtain a measure of exposure that is then compared to exposure levels defined by regulators or levels at which deleterious effects are known to occur. The ERICA tool has a hierarchical structure consisting of three tiers of impact assessment. After the first two tiers, the user is given a "stoplight" that is either red (further assessment recommended), yellow (potential concern, further assessment warranted), or green (negligible concern). The first tier is the most general and represents a worst-case scenario. Tier 1 is media-concentration-based and uses pre-calculated environmental media concentration limits to estimate risk quotients. If the calculated risk quotient is less than unity at the end of the Tier 1 assessment, no further calculations are necessary. Otherwise, a Tier 2 assessment is required. Tier 2 calculates dose rates and allows the user to examine and edit most of the parameters used in the calculation, including concentration ratios, distribution coefficients, percentage dry weight soil or sediment, dose conversion coefficients, radiation weighting factors, and occupancy factors. Tier 3 allows for a probabilistic assessment by assigning probability distribution functions to each underlying parameter value.

First a Tier 1 assessment was performed using the maximum activity concentrations provided in Table 3-5, and assigning a dose rate screening value of 40 μGy hr^{-1} for terrestrial mammals and 400 μGy hr^{-1} for birds and plants, consistent with U.S. Department of Energy and ICRP guidance (DOE 2002; ICRP 2014). The Tier 1 assessment exceeded these screening values for generic lichen and bryophyte receptors, so a Tier 2 assessment was conducted.

The Tier 2 assessment was performed for generic large mammals, generic burrowing mammals, birds, flying insects, reptiles, shrubs, and grasses. The maximum dose rate in the Tier 2 assessment was 2.5×10^{2} μGy hr^{-1} for shrubs. All dose rates were substantially less than the screening values; thus, the assessment was considered complete, and no deleterious ecological effects from radiation are likely to occur should the closure-in-place alternative be selected.

10. Summary

The calculated doses and risks for different pessimistic exposure scenarios and timeframes are compared to a selection of radiation doses and risks from other sources, including natural and anthropogenic background near the site. Risks are evaluated against the EPA's recommended acceptable risk level of one in 10,000 (10^{-4}) to one in one million (10^{-6}).

During the disposals, the maximally exposed individual—the waste handler—received a maximum dose of 3.3 mrem, assuming the maximum source term, taking no credit for the PPE required, and assuming the same individual attended all disposals. For these reasons, the actual dose was significantly lower. The maximum dose is 94 times lower than the U.S. average background radiation dose. The increased risk of cancer mortality for the waste handler is very low, at 0.0000017 (1.7×10^{-6}), well within the EPA's acceptable risk range. The current off-site resident received a negligible dose during the disposals, and their increased cancer risk is also essentially zero, at 0.00000000000023 (2.3×10^{-13}).

Two remediation alternatives were also examined, one in which the waste is left in place, and the other in which it is excavated and trucked to an off-site disposal location. For the leave- in-place option, exposures for all receptors are less than 1 mrem per year, including the worst-case

scenario of an on-site resident far into the future who consumes the groundwater. The maximum cancer risk is for the future on-site receptor, at 0.000001 (1×10^{-6}), which is the bottom of the EPA's acceptable risk range. The risks for all other receptors are essentially zero. For the excavation alternative, the maximum dose is to the on-site supervisor, at approximately 46 mrem. The cancer mortality risk for the supervisor is within the EPA's acceptable risk range at 0.000025 (2.5×10^{-5}), but is substantially greater than the risk if the material is left in place.

Disregarding the physical risks and costs associated with removal operations, which are discussed in detail in the CAP (Gradient 2020), solely from a radiological dose and risk perspective, it is more protective of workers and the public to leave the materials in place. The Corrective Action Plan examines the remediation alternatives holistically (Gradient 2020). Figure 10-1 shows annual average U.S. radiation doses by source alongside the highest average annual receptor dose for each scenario considered for the Arlington facility. All doses are substantially lower than natural background.

This assessment, coupled with the gamma survey of the site, indicate that any impacts from the placement of Bakken oilfield wastes are minimal.

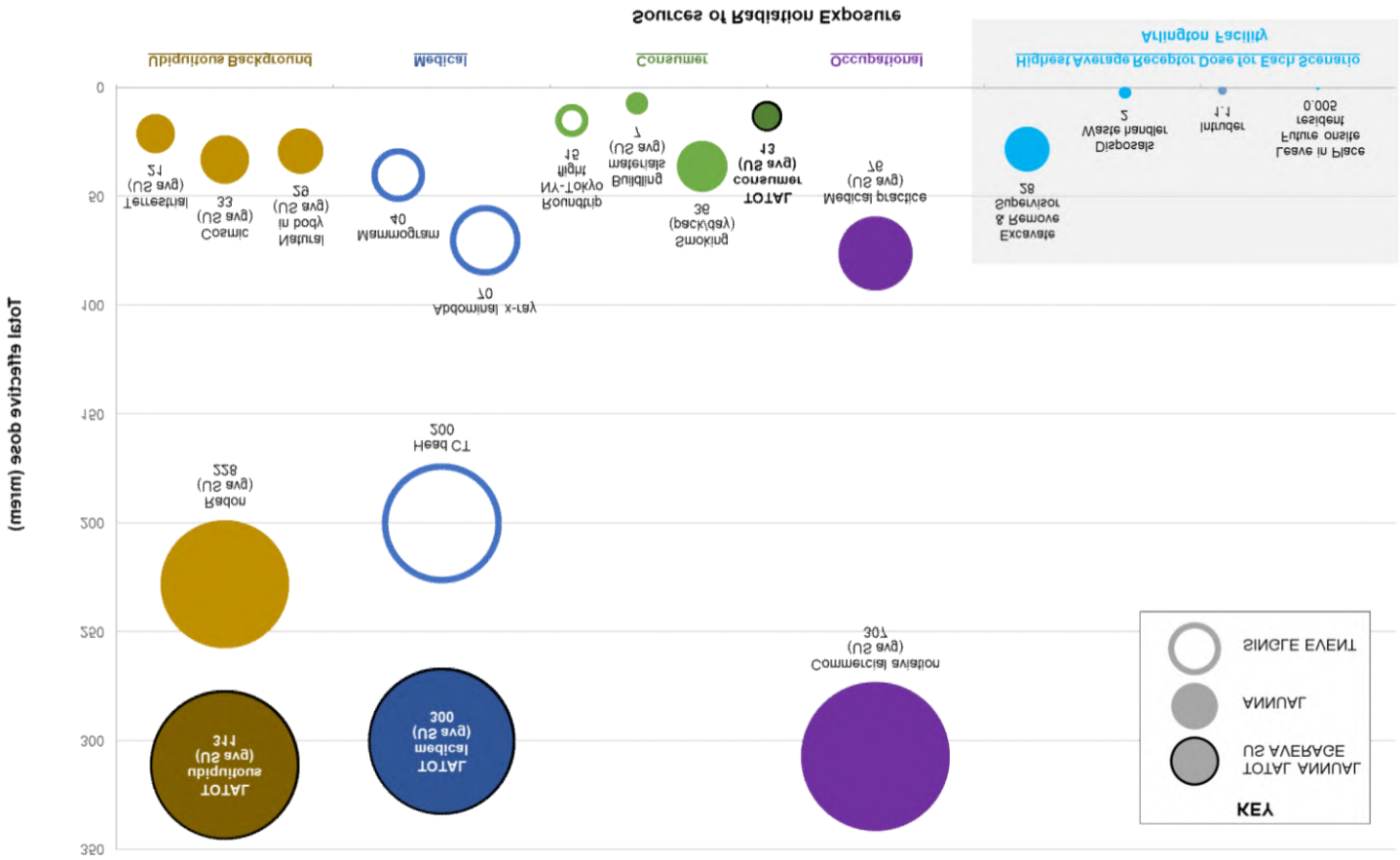

Figure 10-1. This figure shows average U.S. radiation doses by source (NCRP 2009; Mettler et al. 2008) and the highest average annual receptor dose for each scenario (mrem) considered for the Arlington facility. Note that the supervisor's estimated dose (28 mrem) is 11 times lower than the average U.S. ubiquitous background dose received by the public (311 mrem) and 179 times lower than the allowable dose limit to a worker in restricted areas (5,000 mrem).

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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, E.A. Caffrey, H.A. Grogan, C.D. Mangini, J.E. Till. 2020. Analysis of Leachate Management Practices for the Chemical Waste Management of the Northwest Facility in Arlington, OR. RAC Technical Memorandum No. 5-CWMNW Arlington-2020. May 29. Available at: https://www.oregon.gov/energy/safety-resiliency/Pages/Radioactive-Waste-Disposal.aspx.

RUST (RUST Environment & Infrastructure). 1998a. Hydrogeologic Investigation and Engineering Design Report for Landfill L-14, Arlington, Oregon. Prepared for Waste Management, Inc. February.

RUST. 1998b. Updated Site Conceptual Model Report for Arlington Facility, Arlington, Oregon. Prepared for Waste Management, Inc. March.

Sheppard, M.I. and D.H. Thibault. 1990. "Default Soil Solid/Liquid Partition Coefficients, K_{ds}, for Four Major Soil Types: A Compendium," *Health Physics*, 59: 4, pp. 471–482.

Simunek, J.M., M. Sejna, H. Saito, M. Sakai, and M.Th. van Genuchten. 2013. HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media, Ver 4.17. Department of Environmental Sciences, University of California Riverside, Riverside, CA.

Sondrup, A.J., A.L. Schafer and A.S. Rood. 2018. *Performance Assessment for the Idaho National Laboratory Remote Handled Low-Level Waste Disposal Facility*. DOE/ID 11421, Rev 2, U.S. Department of Energy, Idaho Falls Operations Office, Idaho Falls, ID.

Tian, K., C.H. Benson, J.M. Tinjum, T.B. Edil. 2017. "Antioxidant Depletion and Service Life Prediction for HDPE Geomembranes Exposed to Low-Level Radioactive Waste Leachate." *Journal of Geotechnical and Geoenvironmental Engineering* DOI: 10.1061/(ASCE)GT.1943-5606.0001643.

Van Genuchten, M.Th. 1980. "A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils." *Soil Society of America Journal* 44: 892–898.

Xu, M. and Y. Eckstein. 1995. "Use of Weighted Least-Squares Method in Evaluation of the Relationship Between Dispersivity and Field Scale" *Ground Water* 33(6): pp 905-908.

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.

Appendixes

A) RAC Curriculum vitae
B) Bakken Oilfield waste raw analytical data
C) Supporting documentation package

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John E. Till, Ph.D., RADM, USNR (RET)
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, qualified Officer of the Deck and qualified in submarines. Other responsibilities included reactor control officer, electrical division officer, and operations officer.

Special Awards/Positions

2020 Recipient of the Health Physics Society Distinguished Scientific Achievement Award

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 Generation Oversight Committee, 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

Defense Superior Service 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," May 8—May 12, 2017, Presented to staff of the US Nuclear Regulatory Commission, White Flint, MD, 25 attendees

"Environmental Risk Assessment and Analysis," April 27—May 1, 2015, Presented to staff of the US Nuclear Regulatory Commission, White Flint, MD, 15 attendees

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

"Radiological Risk Assessment for Decision-Making, Compliance, and Emergency Response," March 5-9, 2012, Washington, DC, 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.

Till, J.E. 1985. "A Critique of the Environmental Monitoring Program at the Savannah River Plant. Report on Task 1, Review of Facilities, Equipment, and Personnel." *Radiological Assessments Corporation* Report No. 1/85. January 30.

Till, J.E. 1985. "Changes in Risk Resulting from Removal of Class 'C' from a Low-Level Waste Disposal Facility," Testimony submitted to House Committee on Interior and Insular Affairs, July 19.

Till, J.E. 1985. "A Critique of the Environmental Monitoring Program at the Savannah River Plant. Report on Task 2, Review of Sample Locations, Frequency, and Radionuclides Monitored." *Radiological Assessments Corporation* Report No. 8/85. September 10.

Till, J.E. and H.R. Moore. 1985. "A Pathway Analysis Approach for Determining Acceptable Levels of Contamination from Cobalt-60 in Soil at the International Nutronics Irradiation Facility." *Radiological Assessments Corporation* Report No. 7/85, August 28.

Till, J.E., R.L. Toole, and G. Shinopolus. 1985. "Report on the Proposed New Facility for Conversion of UF_6 to UF_4." *Radiological Assessments Corporation* Report RAC-10. January.

Till, J.E., R.W. Shor, and F.O. Hoffman. 1985. "Environmental Effects of the Uranium Fuel Cycle—A Review of Data for Technetium." ORNL/TM-9150, NUREG/CR-3738. February.

Schiager, K.J., W.J. Bair, M.W. Carter, A.P. Hull, and **J.E. Till**. 1986. *"De Minimis* Environmental Radiation Levels: Concepts and Consequences." *Health Physics* **50** (5).

Till, J.E. 1986. "Source Terms for Technetium-99 from Nuclear Fuel Cycle Facilities," in *Technetium in the Environment.* Edited by G. DeSmet and C. Myttenaere. London: Elsevier Applied Science Publishers.

Till, J.E. and R.E. Moore. 1986. *DECOM: A Pathway Analysis Approach for Determining Acceptable Levels of Contamination of Radionuclides in Soil. RAC* Report No. 2/86. *Radiological Assessments Corporation*. February 28.

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Emily A. Caffrey, Ph.D.

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Education

Oregon State University

Ph.D. Radiation Health Physics, January 2016
Minor in Statistics
Advisor: Dr. Kathryn Higley, CHP
Dissertation: *Development and Application of Voxelized Dosimetric Models for Biota: Characterization of the Uncertainty in the International Commission on Radiological Protection's Wildlife Dosimetry System*

M.S. Radiation Health Physics, October 2012
Minor in Statistics
Advisor: Dr. Kathryn Higley, CHP

B.S. Nuclear Engineering, June 2010

Experience

Radian Scientific, LLC
President and Owner (2016-present)
Health Physics Consulting

- My company performs health physics (HP) consulting in collaboration with numerous other small companies. Together we specialize in radiation dose reconstructions, performance assessments, statistical analysis, and data management and analysis for a wide variety of governmental and industry clients. Key projects include:
    - **Sample Management and Analytical Results Tracking (SMART) System implementation at the Hanford Site, WA.** For this project, I developed methods for quantifying measurement uncertainties associated with Hanford's air sampling program. I identified each sampling error parameter, including instrument-specific, location-specific and sample-specific parameters, and developed the appropriate calculations to ensure both measurement and sampling error were propagated correctly through the entire calculation. I worked with the code developers to ensure my calculations were correctly implemented in the software, and I tested the software to ensure it reproduced my calculations correctly.
    - ***McClurg V. Mallinckrodt, LLC* and *Butler V. Mallinckrodt, LLC* historical dose reconstructions.** This project covers an ongoing legal case over radiation exposures from Manhattan era waste in St. Louis, MO. I am responsible for developing the source term, which includes characterization and quantification of radioactive material released to the environment from uranium processing operations that helped produce the first nuclear weapons.
    - **Blue Ridge Landfill.** I performed radiation dose and risk calculations for a municipal landfill in Estill County, KY that inadvertently accepted TENORM (Technologically Enhanced Naturally Occurring Radioactive Material). I produced a report in

collaboration with Gradient, Inc., combining physical risks from moving the materials with the radiological risks of cancer.

- **Waste Control Specialists (WCS) Radioactive Waste Performance Assessment.** For this project, I helped to develop the conceptual and mathematical model for the WCS low level radioactive waste site in Andrews, TX. This included modeling complex radiation transport dynamics through numerous geologic and anthropogenic layers of material using GoldSim software. The purpose of a performance assessment is to determine potential impacts the buried waste might have on future inhabitants of the area. I presented the results to both the Texas Commission on Environmental Quality (TCEQ) and the Department of Energy (DOE).
- **WCS Dose Compliance Module.** This project involved assisting in the development and implementation of a radiation dose-based compliance system. Previously, WCS used a system of concentration-based limits that were radionuclide specific. We transitioned them to a simpler, more cost-effective dose-based system that more accurately reflects possible radionuclide releases from the facility.
- ***Cooper V. Tokyo Electric Power.*** In this legal case, I was responsible for developing the source term, including the quantity and type of radioactive material released to the environment. This project involved in depth knowledge of the Fukushima Daiichi reactors and reactor accident physics. We produced an interim expert report before the case was moved to Japan.

Health Physics Society (HPS)
Ask-The-Experts Editor-in-Chief (2019-present)

- The Health Physics Society sponsors a public information and outreach feature called "Ask-The-Experts" or ATE (see https://hps.org/publicinformation/ate/). This service allows anyone with internet access to ask a radiation-related question and receive an answer from an expert in the field. This outreach endeavor is wildly successful, reaching well over 1.5 million people a year.
- As Editor-in-Chief, I have oversight of the entirety of the ATE feature. Key responsibilities include:
  - Establishing categories and subcategories that cover all aspects of radiation safety;
  - Selecting and managing over 20 topic editors and hundreds of experts;
  - Developing response guidelines for questions with possible legal or ethical implications;
  - Determining which questions are of sufficient interest to post to the website;
  - Creating other items of interest, including FAQs, information sheets, and fact sheets;
  - Tracking and responding to "hot" radiation-related issues that might require special website postings;
  - Identification of experts who can be available for media interactions as needed.

University of Alabama at Birmingham
Adjunct Faculty and Supervised Practice Coordinator (2016-present)
School of Health Professions, Department of Clinical and Diagnostic Sciences

- In 2016, the University of Alabama at Birmingham started a new graduate level health physics program within the School of Health Professions, the only one of its kind in the state of Alabama.
- I assisted the program by developing and teaching all of the core HP classes for the 2016-2017 school year, including: Introduction to Health Physics, Principles of Dosimetry, Advanced Radiation Biology, and Non-ionizing Radiation. I also served as a mentor to the program's first student and graduate, Misty Liverett, who graduated in August 2018 with an employment offer.
- As Supervised Practice Coordinator, I work on developing research collaborations and affiliation agreements with local industry and government. This includes Oak Ridge Associated Universities (ORAU), Huntsville Hospital, NASA, and the nuclear power plants in Alabama (Brown's Ferry and Farley). I work with students to place them at approved sites for their supervised practice hours.
- I also review funding grants and helped to develop content for the health physics website.

Georgia Institute of Technology
Instructor (Fall semester 2019, 2020)
Nuclear & Radiological Engineering and Medical Physics Program
George W. Woodruff School of Mechanical Engineering

- I was asked to teach Radiation Dosimetry, a medical physics graduate level course in Fall 2019, and was asked to return for the Fall 2020 school year.

Oregon State University
Adjunct Faculty (2017-2018)
School of Nuclear Science and Engineering
College of Engineering

- I created an online Radiological Operations Support Specialist preparatory course in support of the Departments of Homeland Security (DHS) and DOE initiative to train, equip, and certify radiation experts to integrate with the incident command system during a radiological response.
- I also redeveloped the External Dosimetry and Shielding course for the online environment.

Oregon State University
Graduate Research Assistant (2010-2016)
School of Nuclear Science and Engineering
College of Engineering

- As a graduate student I performed original research in environmental protection and risk assessment as part of my thesis and dissertation.
- I also completed two research 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 (H-3) separation technologies for groundwater.

- I also created and taught a graduate level course in Liquid Scintillation Counting; taught the introductory course in Nuclear Engineering and Radiation Health Physics; and served as a teaching assistant and lecturer for Radioecology and Radiobiology.
- As the lead graduate student in Dr. Higley's research group, I was also responsible for a multicultural research group of 10 graduate students for over two years.

Australian Nuclear Science and Technology Organization (ANSTO)
Endeavor Research Fellow (2015)

- I was selected for an Endeavor Research Fellowship, a program sponsored by the Australian government that provides funding for short-term research towards a non-Australian Ph.D.
- While at ANSTO I provided innovative computational modeling capabilities to support several research projects.
- I also performed field work at a nuclear waste site near Sydney by obtaining tree cores for plutonium particle analysis.
- I was selected to present my Ph.D. research to the Australian Radiation Protection and Nuclear Safety Agency.

Oregon State University
Radiation Safety Student Technician (2008-2010)
Environmental Health and Safety

- As a student technician, I was responsible for monitoring personnel and laboratories for radiation exposure.
- On my own initiative, I authored operating procedures for the Liquid Scintillation Counter.
- I managed the acquisition, storage, handling, and disposal of radioactive materials.
- I assisted in performing annual inspections of on-campus radiation use laboratories.
- I assisted in verifying that veterinary radiography facilities were in compliance with regulatory requirements.

Mathematics Tutor (2008)
Academic Success Center

- I tutored small groups of students in advanced algebra and integral calculus.

Honors

- Selected as the HPS Young Investigator Delegate to the International Radiation Protection Association (IRPA) 2020 Congress
- Inducted into the Oregon State University Council of Outstanding Early Career Engineers in 2019
- Australian Endeavor Research Fellowship Recipient in 2015
- Inducted into Alpha Nu Sigma Honor Society in 2013
- Selected as an ARCS Scholar in 2012

Volunteer Work

- **HPS Public Information Committee (PIC), member since 2018, Chair 2019-2021**
  - The PIC is responsible for developing and disseminating radiation-related information to the public.
  - As chair, I am responsible for managing a small team of volunteers. Together we manage all HPS social media outlets, develop fact sheets, and are in the process of creating informational videos. The first two videos can be viewed here: https://www.youtube.com/channel/UCOWmRRcBHOAfxud3jmGAAUg/.
- **HPS Program Committee, member 2019-2021**
  - The Program Committee develops and manages the technical program of the HPS annual meeting, including both plenary and special sessions.
  - As a new member, the first meeting I am helping to plan is the 2020 annual meeting. I developed two poster sessions and 12 oral technical sessions.
- **National Council on Radiation Protection Scientific Committee (SC) 1-25, 2016-2018**
  - As a member of SC 1-25, I helped to review recent epidemiologic studies to evaluate whether the new observations were strong enough to support or modify the linear nonthreshold (LNT) model as used in radiation protection today.
  - The SC published *Commentary No. 27 – Implications of Recent Epidemiologic Studies for the Linear-Nonthreshold Model and Radiation Protection* in 2018.
- **President of the Alabama Chapter of the HPS, 2017-2019**
  - When I moved to Huntsville, AL, the local chapter of the HPS was derelict. With the help of my UAB colleagues and students, we revived the chapter, growing membership to over 30 members over the course of two years. We restarted biannual meetings at various locations across the state, including joint meetings with the Atlanta Chapter. I served as president for two years.

Certifications

- The American Board of Health Physics is the certifying body for Health Physicists. To become a "Certified Health Physicist" (CHP) there is a two-part exam. I passed Part I in 2014, and plan to take part II in July 2021.

Affiliations

- Health Physics Society Member since 2010
- American Nuclear Society Member since 2006
- Radiation Research Society Member since 2016
- Alumna of Phi Sigma Rho National Engineering Sorority

Publications

In preparation

Caffrey, E.A., Rood, A.S., Grogan, H.A., and Till, J.E. In preparation. Dose Assessment for Technologically Enhanced Naturally Occurring Radioactive Materials Disposals in Landfills.

Submitted

Caffrey, E.A., Voillequé, P.G., Rood, A.S., Grogan, H.A., Mohler, J.H., Meyer, K.R., and Till, J.E. In preparation. Estimation of Enriched Uranium Released to Air from the Former Apollo Facility, Apollo, Pennsylvania, USA.

Published

Rood, A.S., H.A. Grogan, H.J. Mohler, J.R. Rocco, **E.A. Caffrey**, C. Mangini, J. Cartwright, T. Mathews, C. Shaw, M.E. Packard, and J.E. Till, 2019. Use of Routine Environmental Monitoring Data to Establish A Dose-Based Compliance System for a Low-Level Radioactive Waste Disposal Site. *Health Physics*, Jan;118(1):1-17. DOI: 10.1097/HP.0000000000001116.

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National Council on Radiation Protection and Measurements. 2018. Implications of Recent Epidemiologic Studies for the Linear-Nonthreshold Model and Radiation Protection. NCRP Commentary No. 27. National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Suite 400, Bethesda, Maryland. R.E. Shore (Chair), L.T. Dauer (Co-Chair), H.L. Beck, **E.A. Caffrey**, S. Davis, H.A. Grogan, R.N. Hyer, F.A. Mettler Jr., R.J. Preston, J.E. Till, R. Wakeford, L. Walsh.

Till, J. E., Beck, H. L., Grogan, H. A., & **Caffrey, E.A.**, 2017. A review of dosimetry used in epidemiological studies considered to evaluate the linear no-threshold (LNT) dose-response model for radiation protection. *International Journal of Radiation Biology*, 93:10:1128-1144.

Caffrey, E.A., Johansen, M.P., Caffrey, J.A., & Higley, K.A., 2017. Comparison of Homogeneous and Particulate Lung Dose Rates for Small Mammals. *Health Physics*. 112:6:526-532.

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.

Caffrey E.A., Johansen MP, & Higley KA., 2015. Organ Dose Rate Calculations for Small Mammals at Maralinga, the Nevada Test Site, Hanford, and Fukushima: A Comparison of Ellipsoidal and Voxelized Dosimetric Methodologies. *Radiation Research*. 184:433–41.

Higley, K., Ruedig, E., **Caffrey, E.**, Jia, J., Comolli, M., & Hess, C., 2015. Creation and application of voxelised dosimetric models, and a comparison with the current methodology as used for the International Commission on Radiological Protection's Reference Animals and Plants. *Annals of the ICRP*. 44:s2.

Caffrey E.A., Johansen MP, & Higley KA., 2016. Voxel Modeling of Rabbits for Use in Radiological Dose Rate Calculations. *J Environ Radioact*. 151(2):480–6. doi:10.1016/j.jenvrad.2015.04.008.

Johansen, M.P., Child, D. P., **Caffrey, E.A.**, Davis, E., Harrison, J.J., Hotchkis, M.A.C., & Beresford, N.A. 2016. Accumulation of plutonium in mammalian wildlife tissues following dispersal by accidental-release tests. *J Environ Radioact.* 151(2):387-94. doi:10.1016/j.jenvrad.2015.03.031.

Ruedig, E., **Caffrey, E.A.**, Hess, C., & Higley, K.A., 2014. Monte Carlo Derived Absorbed Fractions for a Voxelized Model of Oncorhynchus Mykiss, a Rainbow Trout. *Radiation and Environmental Biophysics*. 53:3:581-7.

Caffrey, E.A., Leonard, M.A., Napier, J.B., Neville, D.R. and Higley, K.A. 2014. Radioecology: Why Bother? *Journal of Environmental Protection*. 5:3,181-192. doi: 10.4236/jep.2014.53022.

Caffrey, E.A. & Higley, K.A., 2013. Creation of a voxel phantom of the ICRP reference crab. *J Environ Radioact*. 120:14–18.

Cardarelli, R., Wendland, B., Higley, K.A., Paulenova, A., **Caffrey, E.A.**, Ruirui, L. 2013. Assessment of Tritium Removal Technologies. Electric Power Research Institute Interim Report #3002000608.

Cardarelli, R., Oliver, G., Hood, D., **Caffrey, E.A.**, Higley, K.A. 2013. Carbon-14 Background, Pathway, and Dose Calculation Analysis for Nuclear Power Plants: A Sourcebook for Accurate Carbon-14 Dose Calculations. Electric Power Research Institute Report #3002000545, Palo Alto, CA.

Caffrey, E.A., 2012. Improvements in the Dosimetric Models of Selected Benthic Organisms. *Oregon State University Master's Thesis.* Oregon State University. Available at: http://ir.library.oregonstate.edu/xmlui/handle/1957/34305.

Helen A. Grogan, Ph.D.

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Education

Ph.D., Radioecology, Imperial College of Science and Technology, University of London, 1984
B.Sc. 2(1), Botany, University of London, 1980
Diploma of Imperial College, University of London, 1980
Associate of the Royal College of Science, University of London, 1980

Professional Experience

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

Presently works closely with Risk Assessment Corporation (www.racteam.com) assuming responsibilities for the technical aspects of projects.

Cascade Scientific, Inc.
President, Bend, Oregon (1999–present)

Senior 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, U.S. 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
- Development of web-based data management application (known as RACER) that facilitates access to and use of environmental measurement data for a variety of applications, ranging from basic data evaluation to more complex analyses
- Implementation of RACER across Exelon fleet of nuclear power plants and PSEG nuclear power plants to manage environmental effluent and monitoring data
- Development of a dose-based compliance system for low-level radioactive waste disposal facility using routine environmental monitoring data.

- Performance assessment for low-level radioactive waste disposal at the CWF and FWF facilities and licensed Subtitle C hazardous waste at the RCRA landfill, Andrews. Texas
- Development and Implementation of the Sample Management and Analytical Results Tracking (SMART) System for Hanford Mission Support Alliance (MSA)
- Dose and risk calculations for commercial landfills in Kentucky and in Oregon that inadvertently accepted TENORM (Technologically Enhanced Naturally Occurring Radioactive Material).
- Staff consultant to NCRP Secretariat in support of:
    - Scientific Committee 6-11 "Deriving Organ Doses for Medical Radiation Workers Using Personal Monitoring Data with a Focus on Lung" 2018–2020.
    - Scientific Committee 6-12 "Development of Models for Brain Dosimetry for Internally Deposited Radionuclides" 2019–2020.

Independent Consultant
Scientific Consultant, Vero Beach, Florida (1992–1995)

Worked on dose reconstruction projects related to historical releases from the DOE weapons complex.

Intera Information Technologies
Scientific Consultant, Henley-on-Thames, United Kingdom (1989–1992)

Senior consultant for the Environmental Systems Assessment Group 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) (now the Paul Scherrer Institute (PSI), (formerly Swiss Federal Institute for Reactor Research)
Geosphere and biosphere transport modeling program leader (1988–1989)
Guest Scientist, Würenlingen, Switzerland (1984–1987)

Member of the Repository Performance Assessment Group and responsible for the biosphere modeling 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 modeling. 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, 66th Session of United Nations Scientific Committee on the Effects of Atomic Radiation. Vienna, Austria. 10 June–14 June, 2019.

Member, National Council on Radiation Protection and Measurements Scientific Committee 3-1 "Guidance for Emergency Responder Dosimetry," 2014–2019.

Member, U.S. Delegation, 65th Session of United Nations Scientific Committee on the Effects of Atomic Radiation. Vienna, Austria. 11 June–14 June, 2018.

Member, U.S. Delegation, 64th Session of United Nations Scientific Committee on the Effects of Atomic Radiation. Vienna, Austria. 29 May–2 June, 2017.

Member, U.S. Delegation, 63rd Session of United Nations Scientific Committee on the Effects of Atomic Radiation. Vienna, Austria. 27 June–1 July, 2016.

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.

Chair, IAEA consultancy to develop guidance on management of large amounts of radioactive waste after an emergency situation, 2013–2015.

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–present

Health Physics Society

Courses Taught and Offered

Environmental Risk Assessment and Analysis, 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, 22 Attendees

Environmental Risk Assessment and Analysis, 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, Virginia. Risk Assessment Corporation. March 4–8, 2013, 42 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, Virginia. 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 Vegas, 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 Vegas, 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.

Text Book Publications

National Council on Radiation Protection and Measurements. 2019. *Implementation Guidance for Emergency Response Dosimetry*. NCRP Commentary No. 28. National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Suite 400, Bethesda, Maryland. Scientific Committee Members – S.V. Musolino and A. Salame-Alfie (Co-Chairs), B.R Baker, B.R. Buddermeier, J.A. Donnelly Sr., **H.A. Grogan**, W. Haley, W.E. Irwin III, D.A. Pasquale, R.K. Schlueck, J.S. Wieder. May 24.

National Council on Radiation Protection and Measurements. 2018. *Implications of Recent Epidemiologic Studies for the Linear-Nonthreshold Model and Radiation Protection*. NCRP Commentary No. 27. National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Suite 400, Bethesda, Maryland. R.E. Shore (Chair), L.T. Dauer (Co-

Chair), H.L. Beck, E.A. Caffrey, S. Davis, **H.A. Grogan**, R.N. Hyer, F.A. Mettler Jr., R.J. Preston, J.E. Till, R. Wakeford, L. Walsh.

National Council on Radiation Protection and Measurements. 2017. *Guidance for Emergency Response Dosimetry*. NCRP Report No. 179. National Council for Radiation Protection and Measurements, 7910 Woodmont Avenue, Suite 400, Bethesda, Maryland. Scientific Committee Members – S.V. Musolino and A. Salame-Alfie (Co-Chairs), J.L. Bader, D.J. Blumenthal, B.R. Buddermeier, **H.A. Grogan**, W.E. Irwin III, G. Klemic, G.R. Komp, R.W. McBurney, J. Prud´homme, R.K. Schlueck, J.S. Wieder. October 2.

National Council on Radiation Protection and Measurements. 2014. *Decision Making for Late-Phase Recovery from Major Nuclear or Radiological Incidents*. NCRP Report No. 175. National Council for Radiation Protection and Measurements, 7910 Woodmont Avenue, Suite 400, Bethesda, Maryland. Scientific Committee Members: S.Y. Chen (Chair), D.J. Barnett, B.R. Buddemeier, V.T. Covello, K.A. Kiel, J.A. Lipoti, D.M. Scroggs, A. Wallo. Advisors – D.J. Allard, J.D. Edwards, **H.A. Grogan**, A.F. Nisbet. Consultants – J.J. Cardarelli, II, J.A. MacKinney, M.A. Noska.

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, D.C.

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

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, and T. Zheng. The National Academies Press, Washington, D.C.

Peer-Reviewed Publications and Text Book Chapters

Rood, A.S., **H.A. Grogan**, H.J. Mohler, K.R. Meyer, P.G. Voillequé, J.E. Till. 2020. Reconstruction of Atmospheric Concentrations of Enriched Uranium from the Former Apollo Facility, Apollo, Pennsylvania, USA. *J Radiol Prot.* Jan; 211(): https://doi.org/10.1016/j.jenvrad.2019.106045

Rood, A.S., **H.A. Grogan**, H.J. Mohler, J.R. Rocco, E.A. Caffrey, C. Mangini, J. Cartwright, T. Matthews, C. Shaw, M.E. Packard, J.E. Till. 2019. "Use of Routine Environmental Monitoring Data to Establish a Dose-Based Compliance System for a Low-Level Radioactive Waste Disposal Site." *Health Physics*. DOI: 10.1097/HP.0000000000001116 *In Press.*

Shore, R., Beck, H., Boice Jr, J.D., Caffrey, E.A., Davis, S., **Grogan, H.A.**, Mettler, F.A., Preston, R.J., Till, J., Wakeford, R., Walsh, L., and Dauer, L.T. 2019. Response to Letter by Moghissi and Calderone. *Health Phys.* Aug;117(2):224-225.

Shore, R., Beck, H., Boice Jr, J.D., Caffrey, E.A., Davis, S., **Grogan, H.A.**, Mettler, F.A., Preston, R.J., Till, J., Wakeford, R. Walsh, L. and Dauer, L.T. 2019. Reply to Comment on "Implications of recent epidemiologic studies for the linear nonthreshold model and radiation

protection." *J Radiol Prot.* Jun;39(2):655-659. doi: 10.1088/1361-6498/ab077f. Epub 2019 May 24.

Aanenson, J.A., J.E. Till, **H.A. Grogan**. 2018. "Understanding and communicating radiation dose and risk from cone beam computed tomography in dentistry." *The Journal of Prosthetic Dentistry* 120 (3); 353-360. DOI: 10.1016/j.prosdent.2018.01.008.

Till, J.E., H.L. Beck, J.W. Aanenson, **H.A. Grogan**, H.J. Mohler, S.S. Mohler, P.G. Voillequé. 2018. "Dosimetry associated with veterans who participated in nuclear weapons testing." *International Journal of Radiation Biology*, DOI: 10.1080/09553002.2018.1551639.

Till, J.E., H.L. Beck, J.D. Boice Jr, H.J. Mohler, M.T. Mumma, J.W. Aanenson, **H.A. Grogan**. 2018. "Asbestos exposure and mesothelioma mortality among atomic veterans." *International Journal of Radiation Biology*, DOI: 10.1080/09553002.2018.1551641.

Yoder, R.C., L.T. Dauer, S. Balter, J.D. Boice, **H.A. Grogan**, M.T. Mumma, C.N. Passmore, L.N. Rothenberg, R.J. Vetter. 2018. "Dosimetry for the study of medical radiation workers with a focus on the mean absorbed dose to the lung, brain and other organs." *International Journal of Radiation Biology*, DOI: 10.1080/09553002.2018.1549756.

Till, J.E., H.L. Beck, **H.A. Grogan**, E.A. Caffrey. 2017. "A Review of Dosimetry Used in Epidemiological Studies Considered to Evaluate the Linear No-Threshold (LNT) Dose-response Model for Radiation Protection." *International Journal of Radiation Biology*, DOI: 10.1080/09553002.2017.1337280.

Beck, H.L., J.E. Till, J.W. Aanenson, **H.A. Grogan**, J.W. Aanenson, H.J. Mohler, S.S. Mohler, P.G. Voillequé. 2017. "Red Bone Marrow and Male Breast Doses for a Cohort of Atomic Veterans." *Radiat Res*. 187, 221–228.

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, Maryland. September.

Grogan, H.A. 2008. "Model Validation." Chapter 14 in *Radiological Risk Assessment and Environmental Analysis.* New York: Oxford University Press, 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." *Journal of Exposure Analysis and Environmental Epidemiology* 12: 355–372.

Grogan, H.A., W.K. Sinclair, and P.G. Voillequé. 2001. "Risks of Fatal Cancer from Inhalation of Plutonium-239,240 by Humans: A Combined Four Method Approach with Uncertainty Evaluation." *Health Physics* 80 (5): 447–461.

Rood, A.S., **H.A. Grogan** and J.E. Till. 2001. "A Model for a Comprehensive Assessment of Exposure and Lifetime Cancer Incidence Risk from Plutonium Released from the Rocky Flats Plant, 1953-1989." *Health Physics* 82 (2): 182–212.

Little, R.H., **H.A. Grogan,** G.M. Smith, and C. Torres. 1993. "Land Disposal Practices in Europe and North America." *J. Inst. Water and Environmental Management* 7 (4): 354–363.

McKinley, I.G. and **H.A. Grogan.** 1991. "Radionuclide Sorption Databases for Swiss Repository Safety Assessments." *Radiochimica Acta* 52/53: 415–420.

McKinley, I.G. and **H.A. Grogan.** 1991. "Consideration of Microbiology in Modeling the Near-Field of a L/ILW Repository." *Experientia* 47: 573–577.

West, J.M., **H.A. Grogan,** and I.G. McKinley. 1991. "The Role of Microbiology in the Geological Containment of Radioactive Wastes." In *Diversity of Environmental Biogeochemistry.* Developments in Geochemistry: 6. Edited by J. Berthelin. Elsevier Science Publishers B V. 205–215.

Van Dorp, F., **H.A. Grogan,** and C. McCombie. 1989. "Disposal of Radioactive Waste." International Journal of Radiation Applications and Instrumentation Part C. *Radiat. Phys. Chem*. 34 (2): 337–347

Grogan, H.A. and F. van Dorp. 1988. "The Reliability of Environmental Transfer Models Applied to Waste Disposal." In *Reliability of Radioactive Transfer Models.* Edited by G. Deems. Elsevier Applied Science. EUR 11367. 276–284.

Grogan, H.A., N.G. Mitchell, M.J. Minski, and J.N.B. Bell. 1988. "Pathways of Radionuclides from Soils to Wheat." In *Pollutant Transport and Fate in Ecosystems.* Edited by P.J. Coughtrey, M.H. Martin, and M.H. Unsworth. Oxford: Blackwell Scientific Publications. 353–370.

Bell, J.N.B., M.J. Minski, and **H.A. Grogan.** 1988. "Plant Uptake of Radionuclides." *Soil Use and Management* 4 (3): 76–84.

Nair, S., **H.A. Grogan,** M.J. Minski, and J.N.B. Bell. 1983. "Models for the Prediction of Doses from the Ingestion of Terrestrial Foods." In *Ecological Aspects of Radionuclide Releases.* Edited by P.J. Coughtrey, J.N.B. Bell, and T.M. Roberts. Oxford: Blackwell Scientific. 141–159.

Conference Proceedings

Caffrey, E.A., C.D. Mangini, A.S. Rood, **H.A. Grogan**, H.J. Mohler, J.R. Rocco, J.E. Till, J. Cartwright, T. Matthews, C. Shaw. 2019. Implementation of a dose-based compliance system for WCS. Waste Management Symposia 2019. Phoenix, AZ. 3–7 March.

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Colby D. Mangini, Ph.D., CHP

Independent Consultant

Education

Ph.D., Radiation Health Physics, Oregon State University, 2012
Masters of Health Physics, Oregon State University, 2008
B.S., Summa Cum Laude, Physics, Allegheny College, 2004

Professional Experience

Independent Consultant
(2017-present)

Health physics consulting with Risk Assessment Corporation (RAC) beginning May 2017. Contribute to a consulting team specializing in radioactive contaminant transport modeling, dose reconstruction, and other areas of environmental risk assessment. Serve as the teams primary GoldSim modeler on performance assessment work for low-level radioactive waste disposal facilities and licensed Subtitle C hazardous waste at RCRA landfills.

St. Jude Children's Research Hospital
Radiation Safety Officer (2014-2017)

Organized and administered a comprehensive Radiation Safety Program for research laboratories and clinical facilities, which included: a Hitachi 230 MeV proton synchrotron, an IBA cyclotron with 18 MeV protons and 9 MeV deuterons, tritium labeling facility with a manifold loaded with 100 curies of H-3, a High Dose Rate (HDR) brachytherapy unit with Iridium-192 sources, and biomedical research and clinical laboratories with nearly 100 primary investigators. Managed a 10 CFR part 37 compliance program for Category 1 quantities of radioactive material. Developed, implemented, and maintained an effective radiation safety training program for both research and clinical users of radioactive material and radiation- producing equipment. Managed radiation safety staff to meet individual performance levels and divisional operational objectives.

Knolls Atomic Power Laboratory
Principal Scientist (2012-2014)

Investigated observed abnormalities with Naval Reactors' personnel dosimetry system through the use of Monte Carlo computational models. Performed technical reviews for new reactor design concepts in which shipboard dosimeter results could be used to assess and evaluate reactor shielding design objectives. Designed and executed laboratory experiments to validate anticipated dosimeter responses. Lead the Laboratory's Medical Decontamination Facility in support of Emergency Preparedness efforts. Provided Technical Training support as an initial assignment to the Laboratory. Responsible for administrating current technical training curricula and integrating training and knowledge management initiatives throughout the laboratory. Interfaced across the laboratory's technical business areas to identify training opportunities and implemented new technical training programs that support the engineering and science communities.

Oregon State University School of Nuclear Engineering and Radiation Health Physics
Graduate Research Assistant (2010-2012)

Developed an innovative beta-particle physics model for use in Nuclear Regulatory Commission (NRC) licensed skin dosimetry software through extensive programming in scripting, numeric and scientific computing, and radiation particle transport languages. Automated the input file writing, simulation execution, output parsing, and data analysis of over 15,000 Monte Carlo simulations. Reprogrammed FORTRAN source codes to incorporate novel and complex computational techniques for charged particle dosimetry. Influenced the research efforts of Masters Degree students, as well as undergraduates, in an effort to complete NRC funded work by the delivery date. Presented research findings at professional society national conferences. Worked on digital radiation detection systems using VHDL programmed FPGA devices. Selected to teach numerous undergraduate and graduate level courses in the NERHP department, including: Nuclear and Radiation Physics I and II, Nuclear Radiation Detection and Measurement, and Advanced Radiation Detection and Measurement.

Pacific Northwest National Laboratory
National Security Ph.D. Intern (2010)

Worked independently on atmospheric transport modeling in support of the Comprehensive Nuclear Test-Ban Treaty verification regime and the Automated Radioxenon Sampler and Analyzer (ARSA). Automated the modeling tool HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) to provide real-time daily executions of backwards/forwards tracking simulations for 80 different International Monitoring System radionuclide stations. Completed assigned work by collaborating with other National Security interns using iterative and incremental code development techniques. Identified failure points of the modeling process and provided timely coding solutions.

Puget Sound Naval Shipyard
Health Physicist (2009-2010)

Engineered safety procedures for Radiographic Non-Destructive Testing Division and provided oversight to ensure compliance. Implemented REM reduction efforts associated with temporary shielding installation and nuclear functional areas.

United States Navy
Lieutenant, Nuclear Power School Instructor (2005-2009)

Awarded Master Training Specialist designation by the United States Navy, having trained more than 500 enlisted personnel in the following courses: Radiological Controls, Water Chemistry, Materials, and Heat Transfer and Fluid Flow. Promoted to Senior Instructor of Radiological Controls Division. Directed work of 8 junior officer and senior enlisted instructors while coordinating the successful training of over 300 new students every 4 months. Facilitated Applied Health Physics training to instructors on radiation detection and measurement, radioactive contamination control equipment and methods, airborne radioactivity measurement equipment and methods, and ALARA methods. Wrote detailed reports analyzing root cause and trend analysis for program attrition. Provided technical training to enlisted sailors on radiological release and decontamination procedures. Developed and revised over 1000 pages of training manuals, technical procedures, and reports for improved radiological controls training.

Honors

Outstanding Doctoral Dissertation Award in 2012
Inducted into Alpha Nu Sigma Honor Society in 2011
Selected as Achievement Rewards for College Scientists (ARCS) Fellow in 2010
Awarded Master Training Specialist (U.S. Navy) designation in 2007
Recipient of the Richard L. Brown Physics Prize in 2004
Inducted into Phi Beta Kappa Honor Society in 2003

Affiliations

American Academy of Health Physics since 2014
Health Physics Society since 2007

Courses Taught and Offered

The 3rd International RAMP VARSKIN Workshop. Nuclear Regulatory Commission and Federal Authority for Nuclear Regulation (of UAE). Abu Dhabi, UAE. March 25-29, 2018

Mangini, C.D.; Shallow Dose Estimates Using EGS and MCNP. The 3rd Annual RAMP User's Meeting. Nuclear Regulatory Commission. Rockville, MD. October 15 - 20, 2017.

Mangini, C.D.; New in VARSKIN 6. The 2nd Annual RAMP User's Meeting. Nuclear Regulatory Commission. Rockville, MD. October 15 - 20, 2017.

Mangini, C.D.; Case Study: 2008 Region IV Eye Dosimetry. The 2nd Annual RAMP User's Meeting. Nuclear Regulatory Commission. Rockville, MD. October 15 - 20, 2017.

Mangini, C.D.; VARSKIN Electron Dosimetry. The 2nd Annual RAMP User's Meeting. Nuclear Regulatory Commission. Rockville, MD. October 15 - 20, 2017.

The 2nd International RAMP VARSKIN Workshop. Nuclear Regulatory Commission and Atomic Energy Council (of Taiwan). Taipei, Taiwan. April 24-28, 2017

The 1st International RAMP VARSKIN Workshop. Nuclear Regulatory Commission and National Nuclear Regulator (of South Africa). Pretoria, South Africa. May 16-20, 2016

Advanced Radiation Detection and Measurement (NERHP 536). Oregon State University. Corvallis, OR. Summer 2012

Radiation Detection and Measurement (NERHP 236). Oregon State University. Corvallis, OR. Spring 2012

Nuclear and Radiation Physics II (NERHP 235). Oregon State University. Corvallis, OR. Winter 2012

Advanced Radiation Detection and Measurement (NERHP 536). Oregon State University. Corvallis, OR. Summer 2011

Nuclear and Radiation Physics I (NERHP 234). Oregon State University. Corvallis, OR. Fall 2011

Enlisted Heat Transfer and Fluid Flow. U.S. Navy Nuclear Power School. Charleston, SC. 2005-2007.

Enlisted Chemistry, Materials, and Radiological Fundamentals. U.S. Navy Nuclear Power School. Charleston, SC. 2007-2009.

Presentations and Publications

Rood, A.S., H.A. Grogan, H.J. Mohler, J.R. Rocco, E.A. Caffrey, **C. Mangini**, J. Cartwright, T. Mathews, C. Shaw, M.E. Packard, and J.E. Till, 2019. "Use of Routine Environmental Monitoring Data to Establish A Dose-Based Compliance System for a Low-Level Radioactive Waste Disposal Site." Health Physics, DOI: 10.1097/HP.0000000000001116 [in press].

Caffrey, E.A., **Mangini, C.D.**, Rood, A.S., Grogan, H.A., Mohler, J.H., Rocco, J.R., Till, J.E., Cartwright, J., Shaw, C., and Matthews, T. 2019. Implementation of a Dose-based Compliance System for WCS. *Waste Management Symposia 2019.* Phoenix, AZ. 3–7 March.

Rood, A.S., Grogan, H.A., Mohler, J.H., Rocco, J.R., Caffrey, E.A., **Mangini, C.D.**, Cartwright, J., Matthews, T., Shaw, C., and Till, J.E. 2019. Use of Routine Environmental Monitoring Data to Establish a Dose-Based Compliance System for WCS. *Health Physics*. Accepted.

Mangini, C.D.; Hamby, D.M. Scaling Parameters for Beta Dosimetry. *Rad. Prot. Dosimetry*. January 7, 2016

Mohaupt, T.H.; Thuo, K.; **Mangini, C.D**.; Farr, J. Air, Coolant, Beam Bock, and Concrete Shield Activation in a Proton Therapy Center. *Proceedings of the 60th Annual Meeting of the Health Physics Society*. Indianapolis, IN. Health Physics. July 12-16, 2015

Mangini, C.D., Beta-Particle Backscatter Factors and Energy-Absorption Scaling Factors for Use with Dose-Point Kernels. *Oregon State University Doctoral Dissertation.* Oregon State University. Available at: https://ir.library.oregonstate.edu/xmlui/handle/1957/35364

Mangini, C.D.; Caffrey, J.A.; Hamby, D.M. Beta-Particle Backscatter Factors and Energy-Absorption Scaling Factors for Use with Dose-Point Kernel Models. *Proceedings of the 58th Annual Meeting of the Health Physics Society*. Madison, WI. Health Physics. July 7-11, 2013.

Mangini, C.D.; Caffrey, J.A.; Hamby, D.M. Determination of Beta Dose-Point-Kernels for High- Z Sources in Non-homogeneous Geometries. *Proceedings of the 57th Annual Meeting of the Health Physics Society*. Sacramento, CA. Health Physics. July 22-26, 2012.

Mangini, C.D.; Hamby, D.M. Determination of Beta-Particle Dose-Point-Kernels for High-Z Sources Typical in Hot Particle Skin Dosimetry. *Spring Meeting of the Cascade Chapter of the Health Physics Society*. Corvallis, OR. May 4, 2012.

Mangini, C.D.; Caffrey, J.A.; Farsoni, A.T.; Hamby, D.M. A Signal Pulse Processor for Multi Component Signals. *The 44th Annual Midyear Meeting of the Health Physics Society*. Charleston, SC. February 6-9, 2011.

Caffrey, J.A.; **Mangini, C.D**.; Farsoni, A.T.; Hamby, D.M. A Phoswich Detector for Simultaneous Beta and Gamma Spectroscopy. *The 44th Annual Midyear Meeting of the Health Physics Society*. Charleston, SC. February 6-9, 2011.

Technical Reports

Hamby, D.M.; **Mangini, C.D.** VARSKIN 6: A computer code for skin contamination dosimetry. Nuclear Regulatory Commission. Office of Nuclear Regulatory Research. Washington, DC: Report No. *NUREG/CR-6918, Rev. 3*; expected March 2018.

Hamby, D.M.; **Mangini, C.D**.; Caffrey, J.A.; Tang, M. VARSKIN 5: A computer code for skin

contamination dosimetry. Nuclear Regulatory Commission. Office of Nuclear Regulatory Research. Rockville, MD: Report No. *NUREG/CR-6918, Rev. 2*; July 2014.

ARTHUR S. ROOD

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EDUCATION

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

SUMMARY

Over thirty 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 that addressed reconstruction of radionuclide concentrations and doses include the former Rocky Flats Plant in Golden CO, former Uravan uranium mill in western CO, former UMETCO uranium fabrication facility in Apollo PA, Mallinckrodt Chemical Works, St. Louis MO, radionuclide releases to the Columbia River from Hanford Reservation, Fukushima nuclear reactor accident, and Cero Grande fire at Los Alamos NM. Mr. Rood also performed modeling for low-level radioactive waste performance assessments at U.S. Ecology site in Richland Washington, Remote Handled Low-Level Radioactive Waste facility at the Idaho National Laboratory, Waste Control Specialists in Andrews TX, and the Calcine Solid Storage Facility at the Idaho National Laboratory. Other projects include evaluation of ambient air monitoring networks at the Idaho National laboratory and Hanford Reservation, development of contaminant transport models for contaminated soils at Los Alamos National Laboratory, and development radionuclide limits in wastewater and sediments for the 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, 2017). 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 near-field and long-range atmospheric dispersion calculations for evaluation of toxic pollutants emitted to the air from INL facilities using the AERMOD and CALPUFF dispersion models.

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

Chairman 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 & LEADERSHIP POSITIONS

- Licensed Invention, GWSCREEN Software System, Lockheed Martin 1996
- President and Executive Board Member, Desert Eagles Model Airplane Club, 2008–2010, 2015-2017

COURSES TAUGHT

Environmental Risk Assessment for the Nuclear Regulatory Commission, Bethesda Maryland, May, 2017.

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 TESTIMOY

"Reconstruction of Plaintiff Doses Associated with Residues Stored at the St. Louis Airport Storage Site and the Hazelwood Interim Storage Site and Critique of Opinions by Dr. Clark, Dr. Hu, and Dr. Wells." In re: Scott D. McClurg, et al. v. Mallinckrodt, Inc et al. 4:12CV00361 AGF, March 17, 2020.

"Reconstruction of Plaintiff Doses Associated with Residues Stored at the St. Louis Airport Storage Site and the Hazelwood Interim Storage Site and Critique of Opinions by Dr. Cheremisinoff, Ms Sears and Dr Clark." In re: Scott D. McClurg, et al. v. Mallinckrodt, Inc et al. 4:12CV00361 AGF, April 27, 2018.

"Reconstruction of Doses from Atmospheric Releases of Uranium at the Apollo Facility and Critique of Plaintiffs' Expert Opinions." In re: McMunn et al. v Babcock & Wilcox, 2:10-cv-00143-DSC-RCM. February 27, 2013

"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 (chronological order)

Rood, A.S., H.A. Grogan, H.J. Mohler, K.R. Meyer, P.G. Voileque, and J.E. Till, 2019. "Reconstruction of Atmospheric Concentrations of Enriched Uranium from the Former Apollo Facility, Apollo Pennsylvania", USA. *J. of Env Radioactivity*, https://doi.org/10.1016/j.jenvrad.2019.106045

Rood, A.S., H.A. Grogan, H.J. Mohler, J.R. Rocco, E.A. Caffrey, C. Mangini, J. Cartwright, T. Mathews, C. Shaw, M.E. Packard, and J.E. Till, 2019. "Use of Routine Environmental Monitoring Data to Establish A Dose-Based Compliance System for a Low-Level Radioactive Waste Disposal Site." *Health Physics*, DOI: 10.1097/HP.0000000000001116 118(1):1–17; 2020.

R.M Shubbar, D.I. Lee, H.A. Gzar, and **A.S. Rood**, 2019. "Modeling Air Dispersion of Pollutants Emitted from the Daura Oil Refinery, Baghdad-Iraq using the CALPUFF Modeling System." *Journal of Environmental Informatics Letters*, 2(1) pp 28–39 doi: 10.3808.

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 (alphabetical order)

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.

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.

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.

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.

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.

Electric Power Research Institute (EPRI), 2014. *EPRI Recommendations for the National Academies' Pilot Study of Cancer Risks in Populations around Nuclear Facilities*. Report prepared by H. Grogan and **A. Rood**. Technical Report 3002003163. Electric Power Research Institute, Palo Alto, CA.

EPRI. 2016. *Batch and Continuous Releases to the Atmosphere from Nuclear Power Plants: Comparison of Environmental Concentrations and Doses.* Report prepared by H. Grogan and **A. Rood**. Technical Report 3002008166. Electric Power Research Institute, Palo Alto CA. November.

DOE (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.

DOE, 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.

DOE, 2011. *Performance Assessment for the Idaho CERCLA Disposal Facility Landfill*. DOE/ID-10978. Idaho National Laboratory, Idaho Falls, ID.

DOE, 2012. *Performance Assessment for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility*. DOE/ID-11421. Idaho National Laboratory, Idaho Falls, ID.

DOE, 2018. *Performance Assessment for the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility*. DOE/ID-11421, Rev 2. Idaho National Laboratory, Idaho Falls, ID.

DOE, 2018. *Methods, Implementation, and Testing to Support Determination of Performance Assessment Compliance for the RHLLW Disposal Facility WAC*. U.S. Department of Energy Idaho Operations Office

DOE, 2019. *Performance Assessment for the INTEC Calcined Solids Storage Facility at the INL Site*. DOE/ID-12008. Idaho Cleanup Project, U.S. Department of Energy Idaho Operations Office

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.

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.

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.

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.

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.

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

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., 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. *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.

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.

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.

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.

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

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.

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., 2017. DOSEMM: *A Model for Assessment of Airborne Releases and Multimedia Terrestrial Transport and Dose Assessment*. RAC Report No. 01-2017-FINAL. Risk Assessment Corporation, Neeses SC.

Rood, A.S., 2018. *Analysis of the Hanford Site Ambient Air Monitoring Network*. HNF-62564. Mission Support Alliance, Richland Washington,

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.

Sondrup, A.J., and **A.S. Rood**, 2019. *Assessment of INL Ambient Air Radiological Monitoring for Idaho Falls Facilities*. INL/EXT-19-53491. Idaho National Laboratory, Idaho Falls, Idaho.

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.

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PRESENTATIONS AND SYMPOSIUM PROCEEDING (chronological order)

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A.J. Sondrup, A.L. Schafer, B.J Orchard, B.D. Welty, and **A.S. Rood**, 2019. "Natural and Engineered Features Supporting Environmental Performance of Idaho National Laboratory's Remote-Handled Low-Level Waste Disposal Facility. Waste Management 2019, Phoenix, AZ March 4 – March 7, 2019

Rood, A.S., and A.J. Sondrup, 2017. "Quantitative Assessment of Air Monitoring Networks: A Method to Verify How We Know They Work." Annual Site Environmental Report and Environmental Monitoring Workshop, Idaho Falls, Idaho, October 18, 2017.

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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.

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Subsurface Science Symposium, Salt Lake City, Utah, October 7, 2003.

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Till, J.E., G.G. Killough, K.R. Meyer, J.W. Aanenson, and **A.S. Rood**. 2000. "Calculating Soil Action Levels and Uncertainties for Decision-Making during Cleanup of Contaminated Sites." In *Proc. 10th International Congress of the International Radiation Protection Association*. May 14-19, 2000, Hiroshima, Japan

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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.

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Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

November 09, 2018

Jason LaQua
Owl, Inc.
1705 Rd 2054
Culbertson, MT 59218

RE: Project: Yard Sample Solids
Pace Project No.: 10453480

Dear Jason LaQua:
Enclosed are the analytical results for sample(s) received by the laboratory on October 26, 2018. The results relate only to the samples included in this report. Results reported herein conform to the most current, applicable TNI/NELAC standards and the laboratory's Quality Assurance Manual, where applicable, unless otherwise noted in the body of the report.

If you have any questions concerning this report, please feel free to contact me.

Sincerely,

Beverly Faraday
beverly.faraday@pacelabs.com
(406) 384-0559
Project Manager

Enclosures

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

CERTIFICATIONS

Project: Yard Sample Solids
Pace Project No.: 10453480

Virginia Minnesota Certification ID's

315 Chestnut Street, Virginia, MN 55792
Alaska Certification UST-107
Montana Certificate #CERT0103
Minnesota Dept of Health Certification #: 027-137-445
North Dakota Certification: # R-203
Wisconsin DNR Certification # : 998027470
WA Department of Ecology Lab ID# C1007

Pennsylvania Certification IDs

1638 Roseytown Rd Suites 2,3&4, Greensburg, PA 15601
ANAB DOD-ELAP Rad Accreditation #: L2417
Alabama Certification #: 41590
Arizona Certification #: AZ0734
Arkansas Certification
California Certification #: 04222CA
Colorado Certification #: PA01547
Connecticut Certification #: PH-0694
Delaware Certification
EPA Region 4 DW Rad
Florida/TNI Certification #: E87683
Georgia Certification #: C040
Guam Certification
Hawaii Certification
Idaho Certification
Illinois Certification
Indiana Certification
Iowa Certification #: 391
Kansas/TNI Certification #: E-10358
Kentucky Certification #: KY90133
KY WW Permit #: KY0098221
KY WW Permit #: KY0000221
Louisiana DHH/TNI Certification #: LA180012
Louisiana DEQ/TNI Certification #: 4086
Maine Certification #: 2017020
Maryland Certification #: 308
Massachusetts Certification #: M-PA1457
Michigan/PADEP Certification #: 9991
Missouri Certification #: 235
Montana Certification #: Cert0082
Nebraska Certification #: NE-OS-29-14
Nevada Certification #: PA014572018-1
New Hampshire/TNI Certification #: 297617
New Jersey/TNI Certification #: PA051
New Mexico Certification #: PA01457
New York/TNI Certification #: 10888
North Carolina Certification #: 42706
North Dakota Certification #: R-190
Ohio EPA Rad Approval: #41249
Oregon/TNI Certification #: PA200002-010
Pennsylvania/TNI Certification #: 65-00282
Puerto Rico Certification #: PA01457
Rhode Island Certification #: 65-00282
South Dakota Certification
Tennessee Certification #: 02867
Texas/TNI Certification #: T104704188-17-3
Utah/TNI Certification #: PA014572017-9
USDA Soil Permit #: P330-17-00091
Vermont Dept. of Health: ID# VT-0282
Virgin Island/PADEP Certification
Virginia/VELAP Certification #: 9526
Washington Certification #: C868
West Virginia DEP Certification #: 143
West Virginia DHHR Certification #: 9964C
Wisconsin Approve List for Rad
Wyoming Certification #: 8TMS-L

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

SAMPLE SUMMARY

Project: Yard Sample Solids
Pace Project No.: 10453480

Lab ID	Sample ID	Matrix	Date Collected	Date Received
10453480001	**E&P Filter Socks 10242018**	Solid	10/24/18 14:27	10/26/18 11:00

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
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Billings, MT 59101
(406)254-7226

SAMPLE ANALYTE COUNT

Project: Yard Sample Solids
Pace Project No.: 10453480

Lab ID	Sample ID	Method	Analysts	Analytes Reported	Laboratory
10453480001	**E&P Filter Socks 10242018**	EPA 6020A	JJH	2	PASI-V
		ASTM D 2974-13 (2013)	JK1	1	PASI-V
		EPA 901.1	MAH	3	PASI-PA

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS

Project: Yard Sample Solids
Pace Project No.: 10453480

Sample: E&P Filter Socks 10242018 **Lab ID: 10453480001** Collected: 10/24/18 14:27 Received: 10/26/18 11:00 Matrix: Solid

Results reported on a "wet-weight" basis
Comments: • Sample ID, collection dates and times were not present on the sample containers.

Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual
6020A MET ICPMS	Analytical Method: EPA 6020A Preparation Method: EPA 3050							
Thorium	**0.15**	mg/kg	0.0099	10	11/05/18 11:53	11/06/18 12:15	7440-29-1	
Uranium	**0.093**	mg/kg	0.0099	10	11/05/18 11:53	11/06/18 12:15	7440-61-1	
Dry Weight	Analytical Method: ASTM D 2974-13 (2013)							
Percent Moisture	**4.1**	%	0.10	1		11/08/18 10:53		

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA

Project: Yard Sample Solids
Pace Project No.: 10453480

QC Batch: 156015 — Analysis Method: EPA 6020A
QC Batch Method: EPA 3050 — Analysis Description: 6020A MET
Associated Lab Samples: 10453480001

METHOD BLANK: 617442 — Matrix: Solid
Associated Lab Samples: 10453480001

Parameter	Units	Blank Result	Reporting Limit	Analyzed	Qualifiers
Thorium	mg/kg	ND	0.010	11/06/18 11:38	
Uranium	mg/kg	ND	0.010	11/06/18 11:38	

LABORATORY CONTROL SAMPLE: 617443

Parameter	Units	Spike Conc.	LCS Result	LCS % Rec	% Rec Limits	Qualifiers
Thorium	mg/kg	1.2	1.3	103	80-120	
Uranium	mg/kg	1.2	1.3	102	80-120	

MATRIX SPIKE & MATRIX SPIKE DUPLICATE: 617444 617445

Parameter	Units	12118270001 Result	MS Spike Conc.	MSD Spike Conc.	MS Result	MSD Result	MS % Rec	MSD % Rec	% Rec Limits	RPD	Max RPD	Qual
Thorium	mg/kg	0.22	10.9	10.9	2.3	2.3	19	19	75-125	3	20	M6
Uranium	mg/kg	3.6	10.9	10.9	13.9	13.7	95	93	75-125	2	20	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
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QUALITY CONTROL DATA

Project: Yard Sample Solids
Pace Project No.: 10453480

QC Batch: 156324
QC Batch Method: ASTM D 2974-13 (2013)
Analysis Method: ASTM D 2974-13 (2013)
Analysis Description: Dry Weight/Percent Moisture
Associated Lab Samples: 10453480001

SAMPLE DUPLICATE: 619106

Parameter	Units	12118270001 Result	Dup Result	RPD	Max RPD	Qualifiers
Percent Moisture	%	96.7	96.7	0	5	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
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Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS - RADIOCHEMISTRY

Project: Yard Sample Solids
Pace Project No.: 10453480

Sample: E&P Filter Socks 10242018 **Lab ID: 10453480001** Collected: 10/24/18 14:27 Received: 10/26/18 11:00 Matrix: Solid
PWS: Site ID: Sample Type:

Results reported on a "wet-weight" basis
Comments: • Sample ID, collection dates and times were not present on the sample containers.

Parameters	Method	Act ± Unc (MDC) Carr Trac	Units	Analyzed	CAS No.	Qual
Lead-210	EPA 901.1	**814.200 ± 116.570 (16.530) C:NA T:NA**	pCi/g	11/02/18 11:47	14255-04-0	
Radium-226	EPA 901.1	**143.320 ± 21.691 (9.305) C:NA T:NA**	pCi/g	11/02/18 11:47	13982-63-3	RA
Radium-228	EPA 901.1	**61.694 ± 8.300 (1.464) C:NA T:NA**	pCi/g	11/02/18 11:47	15262-20-1	

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: Yard Sample Solids
Pace Project No.: 10453480

QC Batch: 318385
QC Batch Method: EPA 901.1
Analysis Method: EPA 901.1
Analysis Description: 901.1 Gamma Spec
Associated Lab Samples: 10453480001

METHOD BLANK: 1553149
Matrix: Solid
Associated Lab Samples: 10453480001

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Lead-210	0.366 ± 1.202 (1.749) C:NA T:NA	pCi/g	10/29/18 15:14	
Radium-226	0.433 ± 0.920 (1.194) C:NA T:NA	pCi/g	10/29/18 15:14	RA
Radium-228	0.000 ± 0.054 (0.362) C:NA T:NA	pCi/g	10/29/18 15:14	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
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(406)254-7226

QUALIFIERS

Project: Yard Sample Solids
Pace Project No.: 10453480

DEFINITIONS

DF - Dilution Factor, if reported, represents the factor applied to the reported data due to dilution of the sample aliquot.

ND - Not Detected at or above adjusted reporting limit.

TNTC - Too Numerous To Count

J - Estimated concentration above the adjusted method detection limit and below the adjusted reporting limit.

MDL - Adjusted Method Detection Limit.

PQL - Practical Quantitation Limit.

RL - Reporting Limit - The lowest concentration value that meets project requirements for quantitative data with known precision and bias for a specific analyte in a specific matrix.

S - Surrogate

1,2-Diphenylhydrazine decomposes to and cannot be separated from Azobenzene using Method 8270. The result for each analyte is a combined concentration.

Consistent with EPA guidelines, unrounded data are displayed and have been used to calculate % recovery and RPD values.

LCS(D) - Laboratory Control Sample (Duplicate)

MS(D) - Matrix Spike (Duplicate)

DUP - Sample Duplicate

RPD - Relative Percent Difference

NC - Not Calculable.

SG - Silica Gel - Clean-Up

U - Indicates the compound was analyzed for, but not detected.

N-Nitrosodiphenylamine decomposes and cannot be separated from Diphenylamine using Method 8270. The result reported for each analyte is a combined concentration.

Act - Activity

Unc - Uncertainty: SDWA = 1.96 sigma count uncertainty, all other matrices = Expanded Uncertainty (95% confidence interval). Gamma Spec = Expanded Uncertainty (95.4% Confidence Interval)

(MDC) - Minimum Detectable Concentration

Trac - Tracer Recovery (%)

Carr - Carrier Recovery (%)

Pace Analytical is TNI accredited. Contact your Pace PM for the current list of accredited analytes.

TNI - The NELAC Institute.

LABORATORIES

PASI-PA	Pace Analytical Services - Greensburg
PASI-V	Pace Analytical Services - Virginia

ANALYTE QUALIFIERS

M6	Matrix spike and Matrix spike duplicate recovery not evaluated against control limits due to sample dilution.
RA	The reported Ra-226 results were determined using a direct gamma emission (186 keV) shared by both Ra-226 and naturally-occurring U-235. The reported Ra-226 results were determined assuming the shared energy peak is attributable exclusively to Ra-226. Reported results for Ra-226 may be biased high if U-235 is present in the sample.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA CROSS REFERENCE TABLE

Project: Yard Sample Solids
Pace Project No.: 10453480

Lab ID	Sample ID	QC Batch Method	QC Batch	Analytical Method	Analytical Batch
10453480001	**E&P Filter Socks 10242018**	EPA 3050	156015	EPA 6020A	156054
10453480001	**E&P Filter Socks 10242018**	ASTM D 2974-13 (2013)	156324		
10453480001	**E&P Filter Socks 10242018**	EPA 901.1	318385		

Pace Analytical
www.pacelabs.com

Pace Analytical Pittsburgh
1638 Roseytown Road
Suites 2, 3 & 4
Greensburg, PA 15601

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Owl, Inc.
Address:	1705 Road 2054
	Culbertson, MT 59218
Email To:	jason@owlmt.com
Phone: 605-759-1046	Fax:
Requested Due Date/TAT:	

Section B Required Project Information:

Report To:	Jason LaQua
Copy To:	
Purchase Order No.:	
Project Name:	Yard Sample Solids
Project Number:	

Section C Invoice Information:

Attention:	Accounting
Company Name:	Owl, Inc.
Address:	
Pace Quote Reference:	
Pace Project Manager:	Beverly Faraday
Pace Profile #:	

REGULATORY AGENCY

☐ NPDES ☐ GROUND WATER ☐ DRINKING WATER
☐ UST ☐ RCRA ☐ OTHER _____

Site Location STATE: MT

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

Requested Analysis Filtered (Y/N)

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED COMPOSITE START DATE	COLLECTED COMPOSITE START TIME	COLLECTED COMPOSITE END/GRAB DATE	COLLECTED COMPOSITE END/GRAB TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	Total Uranium (mg/kg) by ICP	Total Thorium (mg/kg) by ICP	Gamma spectrum analysis with Peak identification and Ra-226 quantization pCi/g	Gross alpha (pCi/g)	Gross beta (pCi/g)	Pb-210	Percent Moisture	Benzene					Residual Chlorine (Y/N)	Pace Project No./ Lab I.D.
1	E&P Filter Socks 10242018		G			10/24	1427		1									X	X	X			X	X								10453480 001
2																																
3																																
4																																
5																																
6																																
7																																
8																																
9																																
10																																
11																																
12																																

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS			
Do the 3 day tests				[signature]	10/26/18	11:00	NA	N	N	Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Jason LaQua

SIGNATURE of SAMPLER: [signature]

DATE Signed (MM/DD/YY): 10/24/2018

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)

*Important Note: By signing this form you are accepting Pace's NET 30 day payment terms and agreeing to late charges of 1.5% per month for any invoices not paid within 30 days.

Pittsburgh Lab Sample Condition Upon Receipt

Pace Analytical

Client Name: OWL, Inc Project # 10453480

Courier: ☐ Fed Ex ☐ UPS ☒ USPS ☐ Client ☐ Commercial ☐ Pace Other _____

Label _____

LIMS Login

Tracking #: 9505512431018297070825

Custody Seal on Cooler/Box Present: ☐ yes ☒ no Seals intact: ☐ yes ☐ no

Thermometer Used N/A Type of Ice: Wet Blue (None)

Cooler Temperature Observed Temp ____ °C Correction Factor: ____ °C Final Temp: ____ °C

Temp should be above freezing to 6°C

pH paper Lot# N/A

Date and Initials of person examining contents: MDS 10-26-18

Comments:	Yes	No	N/A	
Chain of Custody Present:	✓			1.
Chain of Custody Filled Out:	✓			2.
Chain of Custody Relinquished:		✓		3.
Sampler Name & Signature on COC:	✓			4.
Sample Labels match COC: -Includes date/time/ID Matrix: SL		✓		5. NO ID date or time on sample
Samples Arrived within Hold Time:	✓			6.
Short Hold Time Analysis (<72hr remaining):		✓		7.
Rush Turn Around Time Requested:		✓		8.
Sufficient Volume:	✓			9.
Correct Containers Used: -Pace Containers Used:	✓ ✓			10.
Containers Intact:	✓			11.
Orthophosphate field filtered			✓	12.
Hex Cr Aqueous Compliance/NPDES sample field filtered			✓	13.
Organic Samples checked for dechlorination:			✓	14.
Filtered volume received for Dissolved tests			✓	15.
All containers have been checked for preservation. All containers needing preservation are found to be in compliance with EPA recommendation. exceptions: VOA, coliform, TOC, O&G, Phenolics			✓	16. Initial when completed: MDS Date/time of preservation: Lot # of added preservative:
Headspace in VOA Vials (>6mm):			✓	17.
Trip Blank Present: Trip Blank Custody Seals Present			✓ ✓	18.
Rad Aqueous Samples Screened > 0.5 mrem/hr			✓	Initial when completed: Date:

Client Notification/ Resolution:

Person Contacted: _____ Date/Time: _____ Contacted By: _____

Comments/ Resolution: _____

Barry Farmer 10/29/18

☐ **A check in this box indicates that additional information has been stored in ereports.**

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e. out of hold, incorrect preservative, out of temp, incorrect containers)

***PM review** is documented electronically in LIMS. When the Project Manager closes the SRF Review schedule in LIMS. The review is in the Status section of the Workorder Edit Screen.

WO# : 12118307

12118307

Chain of Custody

☐ Samples were sent directly to the Subcontracting Laboratory.

State Of Origin: MT

Cert. Needed: ☐ Yes ☒ No

Workorder: 10453480 **Workorder Name:** Yard Sample Solids

Owner Received Date: 10/26/2018 **Results Requested By:** 11/9/2018

Report To	Subcontract To
Beverly Faraday Pace Analytical Billings MT 150 N Ninth Street Billings, MT 59101 Phone (406) 384-0559	Pace Analytical Virginia MN 315 Chestnut Street Virginia, MN 55792 Phone (218)742-1042

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers: Unpreserved						Requested Analysis: 6020 Uranium & Thorium												LAB USE ONLY
1	E&P Filter Socks 10242018	PS	10/24/2018 14:27	10453480001	Solid	1						X												
2																								
3																								
4																								
5																								

Transfers	Released By	Date/Time	Received By	Date/Time
1	Ben Thornton	10-31-18 1645	B. Mathews	11/1/18 11:15
2				
3				

Comments

Cooler Temperature on Receipt 2.1.0 °C | **Custody Seal** (Y) or N | **Received on Ice** Y or (N) | **Samples Intact** (Y) or N

****In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document. This chain of custody is considered complete as is since this information is available in the owner laboratory.*

Pace Analytical	Document Name: Sample Condition Upon Receipt Form	Document Revised: 15Mar2016 Page 1 of 1
	Document No.: F-VM-C-001-Rev.10	Issuing Authority: Pace Virginia, Minnesota Quality Office

Sample Condition Upon Receipt

Client Name: Pace Mpls

Project #: WO#: 12118307

PM: CLJ Due Date: 11/08/18

CLIENT: PACE MPLS

Courier: ☑ Fed Ex ☐ UPS ☐ USPS ☐ Client ☐ Commercial ☐ Pace ☐ Other:

Tracking Number:

Custody Seal on Cooler/Box Present? ☑ Yes ☐ No Seals Intact? ☑ Yes ☐ No

Optional: Proj. Due Date: Proj. Name:

Packing Material: ☐ Bubble Wrap ☐ Bubble Bags ☑ None ☐ Other: Temp Blank? ☐ Yes ☑ No

Thermometer Used: ☑ 140792808 Type of Ice: ☐ Wet ☐ Blue ☑ None ☐ Samples on ice, cooling process has begun

Cooler Temp Read °C: 20.7 Cooler Temp Corrected °C: 21.0 Biological Tissue Frozen? ☐ Yes ☐ No ☑ NA

Temp should be above freezing to 6°C Correction Factor: +0.3 Date and Initials of Person Examining Contents: BM 11/2/18

				Comments:
Chain of Custody Present?	☑ Yes	☐ No	☐ N/A	1.
Chain of Custody Filled Out?	☑ Yes	☐ No	☐ N/A	2.
Chain of Custody Relinquished?	☑ Yes	☐ No	☐ N/A	3.
Sampler Name and Signature on COC?	☐ Yes	☑ No	☐ N/A	4.
Samples Arrived within Hold Time?	☑ Yes	☐ No	☐ N/A	5. If Fecal: ☐ <8 hours ☐ >8, <24 hours ☐ >24 hours
Short Hold Time Analysis (<72 hr)?	☐ Yes	☑ No	☐ N/A	6.
Rush Turn Around Time Requested?	☐ Yes	☑ No	☐ N/A	7.
Sufficient Volume?	☑ Yes	☐ No	☐ N/A	8.
Correct Containers Used?	☐ Yes	☐ No	☑ N/A	9.
-Pace Containers Used?	☐ Yes	☐ No	☑ N/A	
Containers Intact?	☑ Yes	☐ No	☐ N/A	10.
Filtered Volume Received for Dissolved Tests?	☐ Yes	☐ No	☑ N/A	11. Note if sediment is visible in the dissolved containers.
Sample Labels Match COC?	☑ Yes	☐ No	☐ N/A	12.
-Includes Date/Time/ID/Analysis Matrix: SL				
All containers needing acid/base preservation will be checked and documented in the pH logbook.	☐ Yes	☐ No	☑ N/A	See pH log for results and additional preservation documentation
Headspace in Methyl Mercury Container	☐ Yes	☐ No	☑ N/A	13.
Headspace in VOA Vials (>6mm)?	☐ Yes	☐ No	☑ N/A	14.
Trip Blank Present?	☐ Yes	☐ No	☑ N/A	15.
Trip Blank Custody Seals Present?	☐ Yes	☐ No	☑ N/A	
Pace Trip Blank Lot # (if purchased):				

CLIENT NOTIFICATION/RESOLUTION Field Data Required? ☐ Yes ☐ No

Person Contacted: Date/Time:

Comments/Resolution:

FECAL WAIVER ON FILE Y N TEMPERATURE WAIVER ON FILE Y N

Project Manager Review: Date: 11/2/18

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e. out of hold, incorrect preservative, out of temp, incorrect containers).

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

September 21, 2017

Jason LaQua
Owl, Inc.
1705 Rd 2054
Culbertson, MT 59218

RE: Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

Dear Jason LaQua:
Enclosed are the analytical results for sample(s) received by the laboratory on September 08, 2017. The results relate only to the samples included in this report. Results reported herein conform to the most current, applicable TNI/NELAC standards and the laboratory's Quality Assurance Manual, where applicable, unless otherwise noted in the body of the report.

If you have any questions concerning this report, please feel free to contact me.

Sincerely,

Beverly Faraday
beverly.faraday@pacelabs.com
(406) 384-0559
Project Manager

Enclosures

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

CERTIFICATIONS

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

Pennsylvania Certification IDs

1638 Roseytown Rd Suites 2,3&4, Greensburg, PA 15601
L-A-B DOD-ELAP Accreditation #: L2417
Alabama Certification #: 41590
Arizona Certification #: AZ0734
Arkansas Certification
California Certification #: 04222CA
Colorado Certification
Connecticut Certification #: PH-0694
Delaware Certification
Florida/TNI Certification #: E87683
Georgia Certification #: C040
Guam Certification
Hawaii Certification
Idaho Certification
Illinois Certification
Indiana Certification
Iowa Certification #: 391
Kansas/TNI Certification #: E-10358
Kentucky Certification #: 90133
Louisiana DHH/TNI Certification #: LA140008
Louisiana DEQ/TNI Certification #: 4086
Maine Certification #: PA00091
Maryland Certification #: 308
Massachusetts Certification #: M-PA1457
Michigan/PADEP Certification
Missouri Certification #: 235
Montana Certification #: Cert 0082
Nebraska Certification #: NE-05-29-14
Nevada Certification #: PA014572015-1
New Hampshire/TNI Certification #: 2976
New Jersey/TNI Certification #: PA 051
New Mexico Certification #: PA01457
New York/TNI Certification #: 10888
North Carolina Certification #: 42706
North Dakota Certification #: R-190
Oregon/TNI Certification #: PA200002
Pennsylvania/TNI Certification #: 65-00282
Puerto Rico Certification #: PA01457
Rhode Island Certification #: 65-00282
South Dakota Certification
Tennessee Certification #: TN2867
Texas/TNI Certification #: T104704188-14-8
Utah/TNI Certification #: PA014572015-5
USDA Soil Permit #: P330-14-00213
Vermont Dept. of Health: ID# VT-0282
Virgin Island/PADEP Certification
Virginia/VELAP Certification #: 460198
Washington Certification #: C868
West Virginia DEP Certification #: 143
West Virginia DHHR Certification #: 9964C
Wisconsin Certification
Wyoming Certification #: 8TMS-L

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

SAMPLE SUMMARY

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

Lab ID	Sample ID	Matrix	Date Collected	Date Received
10402383001	**CH593627B Filters 8-29-17**	Solid	08/29/17 00:00	09/08/17 08:30

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

SAMPLE ANALYTE COUNT

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

Lab ID	Sample ID	Method	Analysts	Analytes Reported	Laboratory
10402383001	**CH593627B Filters 8-29-17**	EPA 901.1	RMK	3	PASI-PA
		EPA 9310	NJV	2	PASI-PA
		HSL-300	LAL	6	PASI-PA

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS - RADIOCHEMISTRY

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

Sample: CH593627B Filters 8-29-17 **Lab ID: 10402383001** Collected: 08/29/17 00:00 Received: 09/08/17 08:30 Matrix: Solid
PWS: Site ID: Sample Type:

Results reported on a "wet-weight" basis
Comments: • Sample collection dates and times were not present on the sample containers.

Parameters	Method	Act ± Unc (MDC) Carr Trac	Units	Analyzed	CAS No.	Qual
Lead-210	EPA 901.1	**168.900 ± 26.930 (11.820) C:NA T:NA**	pCi/g	09/19/17 11:01	14255-04-0	
Radium-226	EPA 901.1	**39.648 ± 7.942 (6.255) C:NA T:NA**	pCi/g	09/19/17 11:01	13982-63-3	RA
Radium-228	EPA 901.1	**22.905 ± 3.285 (1.183) C:NA T:NA**	pCi/g	09/19/17 11:01	15262-20-1	
Gross Alpha	EPA 9310	**79.7 ± 19.8 (8.12) C:NA T:NA**	pCi/g	09/19/17 08:30	12587-46-1	
Gross Beta	EPA 9310	**26.3 ± 7.19 (5.76) C:NA T:NA**	pCi/g	09/19/17 08:30	12587-47-2	
Thorium-228	HSL-300	**8.40 ± 1.52 (0.202) C:NA T:85%**	pCi/g	09/18/17 09:18	14274-82-9	N2
Thorium-230	HSL-300	**0.074 ± 0.073 (0.097) C:NA T:85%**	pCi/g	09/18/17 09:18	14269-63-7	N2
Thorium-232	HSL-300	**0.033 ± 0.059 (0.044) C:NA T:85%**	pCi/g	09/18/17 09:18	7440-29-1	N2
Uranium-234	HSL-300	**0.073 ± 0.071 (0.105) C:NA T:88%**	pCi/g	09/18/17 07:52	13966-29-5	N2
Uranium-235	HSL-300	**0.056 ± 0.068 (0.051) C:NA T:88%**	pCi/g	09/18/17 07:52	15117-96-1	N2
Uranium-238	HSL-300	**0.022 ± 0.052 (0.086) C:NA T:88%**	pCi/g	09/18/17 07:52		N2

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

QC Batch: 271856 Analysis Method: EPA 9310
QC Batch Method: EPA 9310 Analysis Description: 9310 Gross Alpha/Beta
Associated Lab Samples: 10402383001

METHOD BLANK: 1337612 Matrix: Solid
Associated Lab Samples: 10402383001

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Gross Alpha	0.030 ± 0.138 (0.349) C:NA T:NA	pCi/g	09/19/17 08:29	
Gross Beta	-0.022 ± 0.138 (0.349) C:NA T:NA	pCi/g	09/19/17 08:29	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

QC Batch: 271456 Analysis Method: HSL-300
QC Batch Method: HSL-300 Analysis Description: HSL300(AS) Actinides
Associated Lab Samples: 10402383001

METHOD BLANK: 1335605 Matrix: Solid
Associated Lab Samples: 10402383001

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Thorium-228	0.014 ± 0.053 (0.136) C:NA T:81%	pCi/g	09/18/17 12:44	N2
Thorium-230	0.011 ± 0.051 (0.071) C:NA T:81%	pCi/g	09/18/17 12:44	N2
Thorium-232	-0.003 ± 0.051 (0.071) C:NA T:81%	pCi/g	09/18/17 12:44	N2
Uranium-234	0.014 ± 0.048 (0.096) C:NA T:98%	pCi/g	09/18/17 07:52	N2
Uranium-235	0.035 ± 0.062 (0.047) C:NA T:98%	pCi/g	09/18/17 07:52	N2
Uranium-238	0.010 ± 0.048 (0.066) C:NA T:98%	pCi/g	09/18/17 07:52	N2

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

QC Batch: 271668 Analysis Method: EPA 901.1
QC Batch Method: EPA 901.1 Analysis Description: 901.1 Gamma Spec
Associated Lab Samples: 10402383001

METHOD BLANK: 1336516 Matrix: Solid
Associated Lab Samples: 10402383001

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Lead-210	0.000 ± 0.436 (1.564) C:NA T:NA	pCi/g	09/14/17 12:01	
Radium-226	0.180 ± 0.812 (1.107) C:NA T:NA	pCi/g	09/14/17 12:01	
Radium-228	0.045 ± 0.035 (0.220) C:NA T:NA	pCi/g	09/14/17 12:01	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALIFIERS

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

DEFINITIONS

DF - Dilution Factor, if reported, represents the factor applied to the reported data due to dilution of the sample aliquot.

ND - Not Detected at or above adjusted reporting limit.

TNTC - Too Numerous To Count

J - Estimated concentration above the adjusted method detection limit and below the adjusted reporting limit.

MDL - Adjusted Method Detection Limit.

PQL - Practical Quantitation Limit.

RL - Reporting Limit.

S - Surrogate

1,2-Diphenylhydrazine decomposes to and cannot be separated from Azobenzene using Method 8270. The result for each analyte is a combined concentration.

Consistent with EPA guidelines, unrounded data are displayed and have been used to calculate % recovery and RPD values.

LCS(D) - Laboratory Control Sample (Duplicate)

MS(D) - Matrix Spike (Duplicate)

DUP - Sample Duplicate

RPD - Relative Percent Difference

NC - Not Calculable.

SG - Silica Gel - Clean-Up

U - Indicates the compound was analyzed for, but not detected.

N-Nitrosodiphenylamine decomposes and cannot be separated from Diphenylamine using Method 8270. The result reported for each analyte is a combined concentration.

Act - Activity

Unc - Uncertainty: SDWA = 1.96 sigma count uncertainty, all other matrices = Expanded Uncertainty (95% confidence interval). Gamma Spec = Expanded Uncertainty (95.4% Confidence Interval)

(MDC) - Minimum Detectable Concentration

Trac - Tracer Recovery (%)

Carr - Carrier Recovery (%)

Pace Analytical is TNI accredited. Contact your Pace PM for the current list of accredited analytes.

TNI - The NELAC Institute.

LABORATORIES

PASI-PA	Pace Analytical Services - Greensburg

ANALYTE QUALIFIERS

N2	The lab does not hold NELAC/TNI accreditation for this parameter.
RA	The reported Ra-226 results were determined using a direct gamma emission (186 keV) shared by both Ra-226 and naturally-occurring U-235. The reported Ra-226 results were determined assuming the shared energy peak is attributable exclusively to Ra-226. Reported results for Ra-226 may be biased high if U-235 is present in the sample.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, LLC
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA CROSS REFERENCE TABLE

Project: CH593627B Filters 8-29-17
Pace Project No.: 10402383

Lab ID	Sample ID	QC Batch Method	QC Batch	Analytical Method	Analytical Batch
10402383001	**CH593627B Filters 8-29-17**	EPA 901.1	271668		
10402383001	**CH593627B Filters 8-29-17**	EPA 9310	271856		
10402383001	**CH593627B Filters 8-29-17**	HSL-300	271456		

Pace Analytical
www.pacelabs.com

Pace Analytical Pittsburgh
1638 Roseytown Road
Suites 2, 3 & 4
Greensburg, PA 15601

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Owl Inc.
Address:	1705 Rd. 2054
	Culbertson, MT 59218
Email To:	jason@owlmt.com
Phone:	6057591046 Fax:
Requested Due Date/TAT:	

Section B Required Project Information:

Report To:	Beverly Faraday
Copy To:	
Purchase Order No.:	
Project Name:	
Project Number:	

Section C Invoice Information:

Attention:	accounting@owlmt.com
Company Name:	Owl, Inc.
Address:	
Pace Quote Reference:	
Pace Project Manager:	
Pace Profile #:	

REGULATORY AGENCY

☐ NPDES ☐ GROUND WATER ☐ DRINKING WATER
☐ UST ☐ RCRA ☐ OTHER _____

Site Location STATE: MT

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

Requested Analysis Filtered (Y/N)

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED COMPOSITE START DATE	COLLECTED COMPOSITE START TIME	COLLECTED COMPOSITE END/GRAB DATE	COLLECTED COMPOSITE END/GRAB TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N: Total Uranium (mg/kg) by ICP; alternate Isotopic Uranium by Alpha Spec.	Total Thorium (mg/kg) by ICP; Alternate Isotopic Thorium by Alpha Spec	Gamma spectrum analysis with peak identification and Ra-226 quantization (pCi/g)	Radium 228	Gross alpha (pCi/g)	Gross beta (pCi/g)	Pb-210	Percent Moisture				Residual Chlorine (Y/N)	Pace Project No./ Lab I.D. 10402383
1	CH593627B Filters 8-29-17	SL	G			8/29/17												x	x	x	x	x	x	x	x				0001
2																													
3																													
4																													
5																													
6																													
7																													
8																													
9																													
10																													
11																													
12																													

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS			
<= 7 day tests				Ashley Frost/Pace	9-5-17	0830	NNT	N	N	Y

SAMPLER NAME AND SIGNATURE				
PRINT Name of SAMPLER: Jason LaQua		Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
SIGNATURE of SAMPLER:	DATE Signed (MM/DD/YY): 8/29/2017				

*Important Note: By signing this form you are accepting Pace's NET 30 day payment terms and agreeing to late charges of 1.5% per month for any invoices not paid within 30 days.

F-ALL-Q-020rev.08, 12-Oct-2007

Pittsburgh Lab Sample Condition Upon Receipt

Pace Analytical

Client Name: Pace, MN

WO# : 10402383

10402383

Courier: ☐ Fed Ex ☐ UPS ☐ USPS ☐ Client ☐ Commercial ☐ Pace Other

Tracking #: 9505 5124 3101 7241 0265 42

Custody Seal on Cooler/Box Present: ☐ yes ☐ no Seals intact: ☐ yes ☐ no

Thermometer Used: NIA Type of ice: Wet Blue (None)

Cooler Temperature Observed Temp: — °C Correction Factor: — °C Final Temp: — °C

Temp should be above freezing to 6°C

Date and initials of person examining contents: AM 9-8-17

Comments:	Yes	No	N/A	
Chain of Custody Present:	X			1.
Chain of Custody Filled Out:	X			2.
Chain of Custody Relinquished:		X		3.
Sampler Name & Signature on COC:	X			4
Sample Labels match COC: -Includes date/time/ID Matrix: SL		X		5. No info on container
Samples Arrived within Hold Time:	X			6.
Short Hold Time Analysis (<72hr remaining):		X		7.
Rush Turn Around Time Requested:		X		8.
Sufficient Volume:	X			9.
Correct Containers Used:	X			10.
-Pace Containers Used:		X		
Containers Intact:	X			11.
Orthophosphate field filtered			X	12.
Hex Cr Aqueous Compliance/NPDES sample field filtered			X	13.
Organic Samples checked for dechlorination:			X	14.
Filtered volume received for Dissolved tests			X	15.
All containers have been checked for preservation.			X	16.
All containers needing preservation are found to be in compliance with EPA recommendation.			X	
exceptions: VOA, coliform, TOC, O&G, Phenolics				Initial when completed: AM Date/time of preservation:
				Lot # of added preservative:
Headspace in VOA Vials (>6mm):			X	17.
Trip Blank Present:		X		18.
Trip Blank Custody Seals Present			X	
Rad Aqueous Samples Screened > 0.5 mrem/hr			X	Initial when completed: Date:

Client Notification/ Resolution:

Person Contacted: Date/Time: Contacted By:

Comments/ Resolution:

By [illegible] 9/8/17

☐ A check in this box indicates that additional information has been stored in ereports.

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e. out of hold, incorrect preservative, out of temp, incorrect containers)

*PM review is documented electronically in LIMS. When the Project Manager closes the SRF Review schedule in LIMS. The review is in the Status section of the Workorder Edit Screen.

Chain of Custody

Pace Analytical®
www.pacelabs.com

Workorder: 10402383 Workorder Name: CH593627B Filters 8-29-17 Owner Received Date: 9/8/2017 Results Requested By: 9/21/2017

Report To	Subcontract To
Beverly Faraday Pace Analytical Billings MT 150 N Ninth Street Billings, MT 59101 Phone (406) 384-0559	Pace Analytical Pittsburgh 1638 Roseytown Road Suites 2,3 & 4 Greensburg, PA 15601 Phone (724)850-5600

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers: Other	Isotopic Thorium	Rad 226, 228 & Pb 210-DC	Gross Alpha & Beta	Isotopic Uranium	LAB USE ONLY
1	CH593627B Filters 8-29-17	PS	8/29/2017 00:00	10402383001	Solid	1	X	X	X	X	001
2											
3											
4											
5											

Requested Analysis

Transfers	Released By	Date/Time	Received By	Date/Time
1			Robert Hart/Pace	9-8-17/0830
2				
3				

Comments

Cooler Temperature on Receipt N/A °C | Custody Seal Y or (N) | Received on Ice Y or (N) | Samples Intact (Y) or N

***In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document. This chain of custody is considered complete as is since this information is available in the owner laboratory.

WO#:30229437

30229437

Pace Analytical
www.pacelabs.com

Pace Analytical Pittsburgh
1638 Roseytown Road
Suites 2, 3 & 4
Greensburg, PA 15601

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company:	Owl Inc.
Address:	1705 Rd. 2054
	Culbertson, MT 59218
Email To:	jason@owlmt.com
Phone:	6057591046
Fax:	
Requested Due Date/TAT:	

Section B Required Project Information:

Report To:	Beverly Faraday
Copy To:	
Purchase Order No.:	
Project Name:	
Project Number:	

Section C Invoice Information:

Attention:	accounting@owlmt.com
Company Name:	Owl, Inc.
Address:	
Pace Quote Reference:	
Pace Project Manager:	
Pace Profile #:	

REGULATORY AGENCY

☐ NPDES ☐ GROUND WATER ☐ DRINKING WATER
☐ UST ☐ RCRA ☐ OTHER _____

Site Location STATE: MT

Section D Required Client Information

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Requested Analysis Filtered (Y/N)

ITEM #	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED COMPOSITE START DATE	COLLECTED COMPOSITE START TIME	COLLECTED COMPOSITE END/GRAB DATE	COLLECTED COMPOSITE END/GRAB TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test ↓ Y/N	Total Uranium (mg/kg) by ICP; alternate Isotopic Uranium by Alpha Spec.	Total Thorium (mg/kg) by ICP; Alternate Isotopic Thorium by Alpha Spec	Gamma spectrum analysis with Radium 228 identification and Ra-226 quantization	Radium 228	Gross alpha (pCi/g)	Gross beta (pCi/g)	Pb-210	Percent Moisture	30	Residual Chlorine (Y/N)	Pace Project No./ Lab I.D. 29437
1	SL	G			8/29/17												X	X	X	X	X	X	X	X			
2																													
3																													
4																													
5																													
6																													
7																													
8																													
9																													
10																													
11																													
12																													

CH593627B Filters 8-29-17

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS			
<= 7 day tests				Ashleaf Frum/Pace	8-31-17	0830	N/A	N	N	Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Jason LaQua

SIGNATURE of SAMPLER: [signature]

DATE Signed (MM/DD/YY): 8/29/2017

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)

*Important Note: By signing this form you are accepting Pace's NET 30 day payment terms and agreeing to late charges of 1.5% per month for any invoices not paid within 30 days.

Pittsburgh Lab Sample Condition Upon Receipt

Pace Analytical

Client Name: Pace, MN Project # 30229437

Courier: ☐ Fed Ex ☐ UPS ☑ USPS ☐ Client ☐ Commercial ☐ Pace Other _____

Label ML

Tracking #: 9505 5124 3101 7241 0365 42 LIMS Login ANV

Custody Seal on Cooler/Box Present: ☐ yes ☑ no Seals intact: ☐ yes ☐ no

Thermometer Used N/A Type of Ice: Wet Blue (None)

Cooler Temperature Observed Temp ~ °C Correction Factor: ~ °C Final Temp: ~ °C

Temp should be above freezing to 6°C

Date and Initials of person examining contents: AM 9-8-17

Comments:	Yes	No	N/A	
Chain of Custody Present:	X			1.
Chain of Custody Filled Out:	X			2.
Chain of Custody Relinquished:		X		3.
Sampler Name & Signature on COC:	X			4.
Sample Labels match COC: -Includes date/time/ID Matrix: SL		X		5. No info on container
Samples Arrived within Hold Time:	X			6.
Short Hold Time Analysis (<72hr remaining):		X		7.
Rush Turn Around Time Requested:	X	X		8. AM 9-8-17
Sufficient Volume:	X			9.
Correct Containers Used: -Pace Containers Used:	X /	/ X		10.
Containers Intact:	X			11.
Orthophosphate field filtered			X	12.
Hex Cr Aqueous Compliance/NPDES sample field filtered			X	13.
Organic Samples checked for dechlorination:			X	14.
Filtered volume received for Dissolved tests			X	15.
All containers have been checked for preservation. All containers needing preservation are found to be in compliance with EPA recommendation. exceptions: VOA, coliform, TOC, O&G, Phenolics			X / X	16. Initial when completed AM Date/time of preservation; Lot # of added preservative
Headspace in VOA Vials (>6mm):			X	17.
Trip Blank Present: / Trip Blank Custody Seals Present		X / X		18.
Rad Aqueous Samples Screened > 0.5 mrem/hr			X	Initial when completed: Date:

Client Notification/ Resolution:

Person Contacted: _____ Date/Time: _____ Contacted By: _____

Comments/ Resolution: _____

☐ **A check in this box indicates that additional information has been stored in ereports.**

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e. out of hold, incorrect preservative, out of temp, incorrect containers)

*PM review is documented electronically in LIMS. When the Project Manager closes the SRF Review schedule in LIMS. The review is in the Status section of the Workorder Edit Screen.

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

January 06, 2015

Jason LaQua
OWL, Inc.
1705 Road 2054
Culbertson, MT 59218

RE: Project: NYW Narbors Yard
Pace Project No.: 10292304

Dear Jason LaQua:
Enclosed are the analytical results for sample(s) received by the laboratory on December 19, 2014. The results relate only to the samples included in this report. Results reported herein conform to the most current TNI standards and the laboratory's Quality Assurance Manual, where applicable, unless otherwise noted in the body of the report.

If you have any questions concerning this report, please feel free to contact me.

Sincerely,

Kelsey M DeVries
kelsey.devries@pacelabs.com
Project Manager

Enclosures

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

CERTIFICATIONS

Project: NYW Narbors Yard
Pace Project No.: 10292304

Minnesota Certification IDs

1700 Elm Street SE Suite 200, Minneapolis, MN 55414
A2LA Certification #: 2926.01
Alaska Certification #: UST-078
Alaska Certification #MN00064
Alabama Certification #40770
Arizona Certification #: AZ-0014
Arkansas Certification #: 88-0680
California Certification #: 01155CA
Colorado Certification #Pace
Connecticut Certification #: PH-0256
EPA Region 8 Certification #: 8TMS-L
Florida/NELAP Certification #: E87605
Guam Certification #:14-008r
Georgia Certification #: 959
Georgia EPD #: Pace
Idaho Certification #: MN00064
Hawaii Certification #MN00064
Illinois Certification #: 200011
Indiana Certification#C-MN-01
Iowa Certification #: 368
Kansas Certification #: E-10167
Kentucky Dept of Envi. Protection - DW #90062
Kentucky Dept of Envi. Protection - WW #:90062
Louisiana DEQ Certification #: 3086
Louisiana DHH #: LA140001
Maine Certification #: 2013011
Maryland Certification #: 322
Michigan DEPH Certification #: 9909
Minnesota Certification #: 027-053-137
Mississippi Certification #: Pace
Montana Certification #: MT0092
Nevada Certification #: MN_00064
Nebraska Certification #: Pace
New Jersey Certification #: MN-002
New York Certification #: 11647
North Carolina Certification #: 530
North Carolina State Public Health #: 27700
North Dakota Certification #: R-036
Ohio EPA #: 4150
Ohio VAP Certification #: CL101
Oklahoma Certification #: 9507
Oregon Certification #: MN200001
Oregon Certification #: MN300001
Pennsylvania Certification #: 68-00563
Puerto Rico Certification
Saipan (CNMI) #:MP0003
South Carolina #:74003001
Texas Certification #: T104704192
Tennessee Certification #: 02818
Utah Certification #: MN000642013-4
Virginia DGS Certification #: 251
Virginia/VELAP Certification #: Pace
Washington Certification #: C486
West Virginia Certification #: 382
West Virginia DHHR #:9952C
Wisconsin Certification #: 999407970

Pennsylvania Certification IDs

1638 Roseytown Rd Suites 2,3&4, Greensburg, PA 15601
ACLASS DOD-ELAP Accreditation #: ADE-1544
Alabama Certification #: 41590
Arizona Certification #: AZ0734
Arkansas Certification
California/TNI Certification #: 04222CA
Colorado Certification
Connecticut Certification #: PH-0694
Delaware Certification
Florida/TNI Certification #: E87683
Guam/PADEP Certification
Hawaii/PADEP Certification
Idaho Certification
Illinois/PADEP Certification
Indiana/PADEP Certification
Iowa Certification #: 391
Kansas/TNI Certification #: E-10358
Kentucky Certification #: 90133
Louisiana DHH/TNI Certification #: LA140008
Louisiana DEQ/TNI Certification #: 4086
Maine Certification #: PA00091
Maryland Certification #: 308
Massachusetts Certification #: M-PA1457
Michigan/PADEP Certification
Missouri Certification #: 235
Montana Certification #: Cert 0082
Nebraska Certification #: NE-05-29-14
Nevada Certification
New Hampshire/TNI Certification #: 2976
New Jersey/TNI Certification #: PA 051
New Mexico Certification
New York/TNI Certification #: 10888
North Carolina Certification #: 42706
North Dakota Certification #: R-190
Oregon/TNI Certification #: PA200002
Pennsylvania/TNI Certification #: 65-00282
Puerto Rico Certification #: PA01457
South Dakota Certification
Tennessee Certification #: TN2867
Texas/TNI Certification #: T104704188
Utah/TNI Certification #: PA014572014-4
Vermont Dept. of Health: ID# VT-0282
Virgin Island/PADEP Certification
Virginia/VELAP Certification #: 460198
Washington Certification #: C868
West Virginia DEP Certification #: 143
West Virginia DHHR Certification #: 9964C
Wisconsin/PADEP Certification
Wyoming Certification #: 8TMS-Q

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

SAMPLE SUMMARY

Project: NYW Narbors Yard
Pace Project No.: 10292304

Lab ID	Sample ID	Matrix	Date Collected	Date Received
10292304001	**Nabors Yard Williston**	Solid	12/04/14 00:00	12/19/14 14:45

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

SAMPLE ANALYTE COUNT

Project: NYW Narbors Yard
Pace Project No.: 10292304

Lab ID	Sample ID	Method	Analysts	Analytes Reported	Laboratory
10292304001	**Nabors Yard Williston**	EPA 8015 Modified	MT	3	PASI-M
		ASTM D2974	JDL	1	PASI-M
		EPA 901.1	MAH	2	PASI-PA

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

PROJECT NARRATIVE

Project: NYW Narbors Yard
Pace Project No.: 10292304

Method: **EPA 8015 Modified**
Description: 8015 GCS THC-Diesel
Client: OWL, Inc.
Date: January 06, 2015

General Information:
1 sample was analyzed for EPA 8015 Modified. All samples were received in acceptable condition with any exceptions noted below.

Hold Time:
The samples were analyzed within the method required hold times with any exceptions noted below.

H3: Sample was received or analysis requested beyond the recognized method holding time.
- Nabors Yard Williston (Lab ID: 10292304001)

Sample Preparation:
The samples were prepared in accordance with EPA 3550 Sonication with any exceptions noted below.

Initial Calibrations (including MS Tune as applicable):
All criteria were within method requirements with any exceptions noted below.

Continuing Calibration:
All criteria were within method requirements with any exceptions noted below.

Surrogates:
All surrogates were within QC limits with any exceptions noted below.

Method Blank:
All analytes were below the report limit in the method blank, where applicable, with any exceptions noted below.

Laboratory Control Spike:
All laboratory control spike compounds were within QC limits with any exceptions noted below.

Matrix Spikes:
All percent recoveries and relative percent differences (RPDs) were within acceptance criteria with any exceptions noted below.

Additional Comments:

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

PROJECT NARRATIVE

Project: NYW Narbors Yard
Pace Project No.: 10292304

Method: **EPA 901.1**
Description: 901.1 Gamma Spec
Client: OWL, Inc.
Date: January 06, 2015

General Information:
1 sample was analyzed for EPA 901.1. All samples were received in acceptable condition with any exceptions noted below.

Hold Time:
The samples were analyzed within the method required hold times with any exceptions noted below.

Method Blank:
All analytes were below the report limit in the method blank, where applicable, with any exceptions noted below.

Laboratory Control Spike:
All laboratory control spike compounds were within QC limits with any exceptions noted below.

Matrix Spikes:
All percent recoveries and relative percent differences (RPDs) were within acceptance criteria with any exceptions noted below.

Additional Comments:

This data package has been reviewed for quality and completeness and is approved for release.

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS

Project: NYW Narbors Yard
Pace Project No.: 10292304

Sample: Nabors Yard Williston **Lab ID: 10292304001** Collected: 12/04/14 00:00 Received: 12/19/14 14:45 Matrix: Solid

Results reported on a "dry-weight" basis

Parameters	Results	Units	Report Limit	DF	Prepared	Analyzed	CAS No.	Qual
8015 GCS THC-Diesel	Analytical Method: EPA 8015 Modified Preparation Method: EPA 3550 Sonication							
TPH-DRO (C10-C28)	**39.3**	mg/kg	10.1	1	12/24/14 11:42	12/29/14 19:25		H3
Surrogates								
o-Terphenyl (S)	80	%.	30-150	1	12/24/14 11:42	12/29/14 19:25	84-15-1	
n-Triacontane (S)	87	%.	30-147	1	12/24/14 11:42	12/29/14 19:25	638-68-6	
Dry Weight	Analytical Method: ASTM D2974							
Percent Moisture	**1.9**	%	0.10	1		12/30/14 11:05		

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA

Project: NYW Narbors Yard
Pace Project No.: 10292304

QC Batch: MPRP/51571
QC Batch Method: ASTM D2974
Analysis Method: ASTM D2974
Analysis Description: Dry Weight/Percent Moisture
Associated Lab Samples: 10292304001

SAMPLE DUPLICATE: 1875176

Parameter	Units	10292781003 Result	Dup Result	RPD	Max RPD	Qualifiers
Percent Moisture	%	4.0	3.7	7	30	

SAMPLE DUPLICATE: 1875251

Parameter	Units	10292191001 Result	Dup Result	RPD	Max RPD	Qualifiers
Percent Moisture	%	68.6	66.7	3	30	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA

Project: NYW Narbors Yard
Pace Project No.: 10292304

QC Batch: OEXT/27736
QC Batch Method: EPA 3550 Sonication
Analysis Method: EPA 8015 Modified
Analysis Description: 8015 Solid GCSV
Associated Lab Samples: 10292304001

METHOD BLANK: 1873330 Matrix: Solid
Associated Lab Samples: 10292304001

Parameter	Units	Blank Result	Reporting Limit	Analyzed	Qualifiers
TPH-DRO (C10-C28)	mg/kg	ND	10.0	12/29/14 18:39	
n-Triacontane (S)	%.	85	30-147	12/29/14 18:39	
o-Terphenyl (S)	%.	84	30-150	12/29/14 18:39	

LABORATORY CONTROL SAMPLE: 1873331

Parameter	Units	Spike Conc.	LCS Result	LCS % Rec	% Rec Limits	Qualifiers
TPH-DRO (C10-C28)	mg/kg	50	44.0	88	70-125	
n-Triacontane (S)	%.			76	30-147	
o-Terphenyl (S)	%.			78	30-150	

MATRIX SPIKE & MATRIX SPIKE DUPLICATE: 1873332 1873333

Parameter	Units	10292304001 Result	MS Spike Conc.	MSD Spike Conc.	MS Result	MSD Result	MS % Rec	MSD % Rec	% Rec Limits	RPD	Max RPD	Qual
TPH-DRO (C10-C28)	mg/kg	39.3	50.9	50.9	64.3	57.7	49	36	30-150	11	30	H3
n-Triacontane (S)	%.						74	81	30-147			
o-Terphenyl (S)	%.						75	77	30-150			

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS - RADIOCHEMISTRY

Project: NYW Narbors Yard
Pace Project No.: 10292304

Sample: Nabors Yard Williston **Lab ID: 10292304001** Collected: 12/04/14 00:00 Received: 12/19/14 14:45 Matrix: Solid
PWS: Site ID: Sample Type:

Results reported on a "dry-weight" basis

Parameters	Method	Act ± Unc (MDC) Carr Trac	Units	Analyzed	CAS No.	Qual
Radium-226	EPA 901.1	**4.938 ± 2.537 (2.763) C:NA T:NA**	pCi/g	01/05/15 13:11	13982-63-3	
Radium-228	EPA 901.1	**4.625 ± 0.765 (0.218) C:NA T:NA**	pCi/g	01/05/15 13:11	15262-20-1	

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: NYW Narbors Yard
Pace Project No.: 10292304

QC Batch: RADC/22824 Analysis Method: EPA 901.1
QC Batch Method: EPA 901.1 Analysis Description: 901.1 Gamma Spec
Associated Lab Samples: 10292304001

METHOD BLANK: 837771 Matrix: Solid
Associated Lab Samples:

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Radium-226	-0.043 ± 0.785 (1.401) C:NA T:NA	pCi/g	12/31/14 13:44	
Radium-228	-0.036 ± 1.452 (0.219) C:NA T:NA	pCi/g	12/31/14 13:44	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALIFIERS

Project: NYW Narbors Yard
Pace Project No.: 10292304

DEFINITIONS

DF - Dilution Factor, if reported, represents the factor applied to the reported data due to changes in sample preparation, dilution of the sample aliquot, or moisture content.

ND - Not Detected at or above adjusted reporting limit.

J - Estimated concentration above the adjusted method detection limit and below the adjusted reporting limit.

MDL - Adjusted Method Detection Limit.

PQL - Practical Quantitation Limit.

RL - Reporting Limit.

S - Surrogate

1,2-Diphenylhydrazine (8270 listed analyte) decomposes to Azobenzene.

Consistent with EPA guidelines, unrounded data are displayed and have been used to calculate % recovery and RPD values.

LCS(D) - Laboratory Control Sample (Duplicate)

MS(D) - Matrix Spike (Duplicate)

DUP - Sample Duplicate

RPD - Relative Percent Difference

NC - Not Calculable.

SG - Silica Gel - Clean-Up

U - Indicates the compound was analyzed for, but not detected.

N-Nitrosodiphenylamine decomposes and cannot be separated from Diphenylamine using Method 8270. The result reported for each analyte is a combined concentration.

Act - Activity

Unc - Uncertainty: SDWA = 1.96 sigma count uncertainty, all other matrices = Expanded Uncertainty (95% confidence interval). Gamma Spec = Expanded Uncertainty (95.4% Confidence Interval)

(MDC) - Minimum Detectable Concentration

Trac - Tracer Recovery (%)

Carr - Carrier Recovery (%)

Pace Analytical is TNI accredited. Contact your Pace PM for the current list of accredited analytes.

TNI - The NELAC Institute.

LABORATORIES

PASI-M	Pace Analytical Services - Minneapolis
PASI-PA	Pace Analytical Services - Greensburg

ANALYTE QUALIFIERS

H3	Sample was received or analysis requested beyond the recognized method holding time.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA CROSS REFERENCE TABLE

Project: NYW Narbors Yard
Pace Project No.: 10292304

Lab ID	Sample ID	QC Batch Method	QC Batch	Analytical Method	Analytical Batch
10292304001	**Nabors Yard Williston**	EPA 3550 Sonication	OEXT/27736	EPA 8015 Modified	GCSV/14784
10292304001	**Nabors Yard Williston**	ASTM D2974	MPRP/51571		
10292304001	**Nabors Yard Williston**	EPA 901.1	RADC/22824		

Pace Analytical™
www.pacelabs.com

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company: Owl, Inc.
Address: 1705 Road 2054
Culbertson, MT 59218
Email To: jason@owlmt.com
Phone: 6057591046 Fax:
Requested Due Date/TAT:

Section B Required Project Information:

Report To:
Copy To:
Purchase Order No.:
Project Name: Narbors Yard
Project Number: NYW 001

Section C Invoice Information:

Attention: Laurie Young
Company Name: Owl, Inc.
Address: 1705 Road 2054
Pace Quote Reference:
Pace Project Manager:
Pace Profile #: 10-112803

REGULATORY AGENCY

☐ NPDES ☐ GROUND WATER ☐ DRINKING WATER
☐ UST ☐ RCRA ☐ OTHER _____

Site Location STATE: _____

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED: COMPOSITE START DATE	COMPOSITE START TIME	COMPOSITE END/GRAB DATE	COMPOSITE END/GRAB TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Y/N	Analysis Test	Residual Chlorine (Y/N)	Pace Project No./ Lab I.D.
1	Nabors Yard Williston	SL	G	12/04															X Rad 226, 228 X DRO - 8015		10292304 001
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
11																					
12																					

Requested Analysis Filtered (Y/N)

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS			
	USPS			Mike Pace	12/19/14	1945	N/A	N	N	Y

Do the same tests as Proj# 10283154

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Jason LaQua
SIGNATURE of SAMPLER: Digitally signed by Jason LaQua DN: cn=Jason LaQua, o, ou, email=jason@owlmt.com, c=US
DATE Signed (MM/DD/YY): 12/17/14

Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)

*Important Note: By signing this form you are accepting Pace's NET 30 day payment terms and agreeing to late charges of 1.5% per month for any invoices not paid within 30 days.

Pace Analytical	Document Name: Sample Condition Upon Receipt Form	Document Revised: 14Jul2014 Page 1 of 1
	Document No.: F-MT-C-184-rev.04	Issuing Authority: Pace Montana Quality Office

Sample Condition Upon Receipt

Client Name: Dual Inc

Project #: WO#: 10292304

10292304

Courier: ☐ Fed Ex ☐ UPS ☒ USPS ☐ Client ☐ Commercial ☐ Pace ☐ Other:

Tracking Number: 9114 9999 4423 8178 7619 50

Custody Seal on Cooler/Box Present? ☐ Yes ☒ No Seals Intact? ☐ Yes ☒ No

Optional: Proj. Due Date: Proj. Name:

Packing Material: ☐ Bubble Wrap ☐ Bubble Bags ☒ None ☐ Other: Temp Blank? ☐ Yes ☒ No

Thermometer Used: ☐ B88A0140728348 ☒ NA Type of Ice: ☐ Wet ☐ Blue ☒ None ☐ Samples on ice, cooling process has begun

Cooler Temp Read: 12/19 MT JA 13.8 Date and Initials of Person Examining Contents: 12/19 MT

Cooler Temp Corrected: 12/19 MT JA 13.8 Biological Tissue Frozen? ☐ Yes ☒ No

Temp should be above freezing to 6°C

Comments:

Chain of Custody Present?	☒ Yes	☐ No	☐ N/A	1.	
Chain of Custody Filled Out?	☒ Yes	☐ No	☐ N/A	2.	
Chain of Custody Relinquished?	☐ Yes	☒ No	☐ N/A	3.	
Sampler Name and Signature on COC?	☒ Yes	☐ No	☐ N/A	4.	
Samples Arrived within Hold Time?	☒ Yes	☐ No	☐ N/A	5.	
Short Hold Time Analysis (<72 hr)? 12/19 MT	☒ Yes	☒ No	☐ N/A	6. DRO Sampled 12/11/14	
Rush Turn Around Time Requested?	☐ Yes	☒ No	☐ N/A	7.	
Sufficient Volume?	☒ Yes	☐ No	☐ N/A	8.	
Correct Containers Used?	☒ Yes	☐ No	☐ N/A	9.	
-Pace Containers Used?	☐ Yes	☒ No	☐ N/A		
Containers Intact?	☒ Yes	☐ No	☐ N/A	10.	
Filtered Volume Received for Dissolved Tests?	☐ Yes	☒ No	☐ N/A	11.	
Sample Labels Match COC? -Includes Date/Time/ID/Analysis Matrix: SL	☒ Yes	☐ No	☐ N/A	12.	
All containers needing acid/base preservation have been checked?	☐ Yes	☐ No	☒ N/A	13. ☐ HNO_3 ☐ H_2SO_4 ☐ NaOH ☐ HCl Sample #	
All containers needing preservation are found to be in compliance with EPA recommendation? (HNO_3, H_2SO_4, HCl<2; NaOH >9 Sulfide, NaOH>12 Cyanide)	☐ Yes	☐ No	☒ N/A	NA	
Exceptions: VOA, Coliform, TOC, Oil and Grease, WI-DRO (water)	☐ Yes	☒ No		Initial when completed: Lot # of added preservative:	
Headspace in VOA Vials (>6mm)?	☐ Yes	☐ No	☒ N/A	14.	
Trip Blank Present?	☐ Yes	☐ No	☒ N/A	15.	
Trip Blank Custody Seals Present?	☐ Yes	☐ No	☒ N/A		
Pace Trip Blank Lot # (if purchased): NA					

CLIENT NOTIFICATION/RESOLUTION Field Data Required? ☐ Yes ☐ No

Person Contacted: Date/Time:

Comments/Resolution:

Project Manager Review: Date: 12/19/14

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DENR Certification Office (i.e out of hold, incorrect preservative, out of temp, incorrect containers)

Pace Analytical™	Document Name: MT to MN Sample Transfer Form	Revised Date: 01May2014 Page: 1 of 1
	Document Number: F-MT-C-179-rev.06	Issuing Authority: Pace Minnesota Quality Office

Shipping (circle):	UPS Fed Ex
Tracking #:	1002 2786 2660
Client:	OWL Inc
Due Date:	5-Jan-2014
Pace WO:	10292304
Project Manager:	Kelsey Jones KMJ

MT to MN Sample Transfer Condition Upon Receipt Form

ANALYSIS REQUESTED

Method Number & Description	Container Type	# of Bottles	Lab ID's	Preservative Yes or No	Verify Arrival Date & Initials
Tests					
DRO 8015	JGCU	1	001	No	12/20/14 KMJ 12/22/14 12/24/14
	Total	1			

REPORTING REQUIREMENTS/ADDITIONAL COMMENTS

MINNESOTA SAMPLE RECEIPT INFORMATION

IR Gun (circle): **80512447, B88A912167504, 72337080** Correction Factor: +0.1		Sample Matrix:	Soil
Cooler Temp Read (°C): 2.4	Cooler Temp Corrected (°C): 2.5	Filtred volume rec'd for dissolved tests:	Yes __ No __ NA X
Arrived on Ice:	Yes X No __	Samples pH have been checked:	Yes __ No __ NA X
Custody Seal Present:	Yes X No __	Trip Blank Present:	Yes __ No __ NA X
Short Hold Time Requested < 72 Hours:	Yes __ No X	Trip Blank Custody Seals Present:	Yes __ No __ NA X
Rush TAT Requested:	Yes __ No X	Pace Trip Blank Lot #:	
Sufficient Sample Volume:	Yes X No __	Sample Composites Required:	Yes __ No __ NA ___
Samples Arrived within Hold Time:	Yes X No __	Report Samples:	Wet Wt. __ Dry Wt.__
Containers Intact:	Yes X No __	Reporting Units:	

CUSTODY TRANSFER

Relinquished by/Affiliation	Date	Time	Accepted By Affiliation	Date	Time
Nathan Pau	12/19/14	1600	ER Race	12/20/14	1000

CLIENT NOTIFICATION/RESOLUTION

Person Contacted: _____ **Date:** _____

Comments/Resolution: _____

Project Manager Review: Cassy Sparks **Date:** 12-23-14

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

January 14, 2016

Jason LaQua
Owl, Inc.
1705 Rd 2054
Culbertson, MT 59218

RE: Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

Dear Jason LaQua:
Enclosed are the analytical results for sample(s) received by the laboratory on December 31, 2015. The results relate only to the samples included in this report. Results reported herein conform to the most current TNI standards and the laboratory's Quality Assurance Manual, where applicable, unless otherwise noted in the body of the report.

If you have any questions concerning this report, please feel free to contact me.

Sincerely,

Beverly Faraday
beverly.faraday@pacelabs.com
Project Manager

Enclosures

cc: Jason LaQua, OWL, Inc.

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

CERTIFICATIONS

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

Pennsylvania Certification IDs

Georgia Certification #: C040
1638 Roseytown Rd Suites 2,3&4, Greensburg, PA 15601
L-A-B DOD-ELAP Accreditation #: L2417
Alabama Certification #: 41590
Arizona Certification #: AZ0734
Arkansas Certification
California Certification #: 04222CA
Colorado Certification
Connecticut Certification #: PH-0694
Delaware Certification
Florida/TNI Certification #: E87683
Georgia Certification #: C040
Guam Certification
Hawaii Certification
Idaho Certification
Illinois Certification
Indiana Certification
Iowa Certification #: 391
Kansas/TNI Certification #: E-10358
Kentucky Certification #: 90133
Louisiana DHH/TNI Certification #: LA140008
Louisiana DEQ/TNI Certification #: 4086
Maine Certification #: PA00091
Maryland Certification #: 308
Massachusetts Certification #: M-PA1457
Michigan/PADEP Certification
Missouri Certification #: 235
Montana Certification #: Cert 0082
Nebraska Certification #: NE-05-29-14
Nevada Certification #: PA014572015-1
New Hampshire/TNI Certification #: 2976
New Jersey/TNI Certification #: PA 051
New Mexico Certification #: PA01457
New York/TNI Certification #: 10888
North Carolina Certification #: 42706
North Dakota Certification #: R-190
Oregon/TNI Certification #: PA200002
Pennsylvania/TNI Certification #: 65-00282
Puerto Rico Certification #: PA01457
Rhode Island Certification #: 65-00282
South Dakota Certification
Tennessee Certification #: TN2867
Texas/TNI Certification #: T104704188-14-8
Utah/TNI Certification #: PA014572015-5
USDA Soil Permit #: P330-14-00213
Vermont Dept. of Health: ID# VT-0282
Virgin Island/PADEP Certification
Virginia/VELAP Certification #: 460198
Washington Certification #: C868
West Virginia DEP Certification #: 143
West Virginia DHHR Certification #: 9964C
Wisconsin Certification
Wyoming Certification #: 8TMS-L

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SAMPLE SUMMARY

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

Lab ID	Sample ID	Matrix	Date Collected	Date Received
10334977001	**NG FILTER CH1032320B-1**	Solid	12/30/15 11:00	12/31/15 12:45
10334977002	**WATER FILTER BAG CH593627B-1**	Solid	12/30/15 11:00	12/31/15 12:45

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SAMPLE ANALYTE COUNT

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

Lab ID	Sample ID	Method	Analysts	Analytes Reported	Laboratory
10334977001	**NG FILTER CH1032320B-1**	EPA 901.1	MAH	3	PASI-PA
		EPA 9310	NEG	2	PASI-PA
		HSL-300	LAL	6	PASI-PA
10334977002	**WATER FILTER BAG CH593627B-1**	EPA 901.1	MAH	3	PASI-PA
		EPA 9310	NEG	2	PASI-PA
		HSL-300	LAL	6	PASI-PA

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ANALYTICAL RESULTS - RADIOCHEMISTRY

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

Sample: NG FILTER CH1032320B-1 **Lab ID: 10334977001** Collected: 12/30/15 11:00 Received: 12/31/15 12:45 Matrix: Solid
PWS: Site ID: Sample Type:

Results reported on a "wet-weight" basis

Parameters	Method	Act ± Unc (MDC) Carr Trac	Units	Analyzed	CAS No.	Qual
Lead-210	EPA 901.1	**808.950 ± 117.380 (17.950) C:NA T:NA**	pCi/g	01/08/16 14:24	14255-04-0	
Radium-226	EPA 901.1	**5.325 ± 2.900 (3.408) C:NA T:NA**	pCi/g	01/08/16 14:24	13982-63-3	
Radium-228	EPA 901.1	**2.908 ± 0.739 (0.832) C:NA T:NA**	pCi/g	01/08/16 14:24	15262-20-1	
Gross Alpha	EPA 9310	**252 ± 46.0 (1.41) C:NA T:NA**	pCi/g	01/12/16 19:48	12587-46-1	
Gross Beta	EPA 9310	**196 ± 35.4 (1.44) C:NA T:NA**	pCi/g	01/12/16 19:48	12587-47-2	1M
Thorium-228	HSL-300	**0.225 ± 0.100 (0.118) C:NA T:76%**	pCi/g	01/12/16 12:55	14274-82-9	N2
Thorium-230	HSL-300	**0.020 ± 0.028 (0.043) C:NA T:76%**	pCi/g	01/12/16 12:55	14269-63-7	N2
Thorium-232	HSL-300	**0.013 ± 0.027 (0.018) C:NA T:76%**	pCi/g	01/12/16 12:55	7440-29-1	N2
Uranium-234	HSL-300	**0.132 ± 0.100 (0.120) C:NA T:90%**	pCi/g	01/13/16 08:31	13966-29-5	N2
Uranium-235	HSL-300	**0.018 ± 0.077 (0.058) C:NA T:90%**	pCi/g	01/13/16 08:31	15117-96-1	N2
Uranium-238	HSL-300	**0.049 ± 0.060 (0.045) C:NA T:90%**	pCi/g	01/13/16 08:31		N2

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS - RADIOCHEMISTRY

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

Sample: WATER FILTER BAG CH593627B-1 **Lab ID: 10334977002** Collected: 12/30/15 11:00 Received: 12/31/15 12:45 Matrix: Solid
PWS: Site ID: Sample Type:

Results reported on a "wet-weight" basis

Parameters	Method	Act ± Unc (MDC) Carr Trac	Units	Analyzed	CAS No.	Qual
Lead-210	EPA 901.1	**168.310 ± 26.839 (11.640) C:NA T:NA**	pCi/g	01/08/16 15:07	14255-04-0	
Radium-226	EPA 901.1	**96.072 ± 14.133 (5.986) C:NA T:NA**	pCi/g	01/08/16 15:07	13982-63-3	
Radium-228	EPA 901.1	**56.163 ± 7.607 (1.041) C:NA T:NA**	pCi/g	01/08/16 15:07	15262-20-1	
Gross Alpha	EPA 9310	**138 ± 27.2 (5.10) C:NA T:NA**	pCi/g	01/12/16 19:48	12587-46-1	
Gross Beta	EPA 9310	**106 ± 19.7 (2.60) C:NA T:NA**	pCi/g	01/12/16 19:48	12587-47-2	
Thorium-228	HSL-300	**6.26 ± 1.07 (0.125) C:NA T:82%**	pCi/g	01/12/16 12:55	14274-82-9	N2
Thorium-230	HSL-300	**0.022 ± 0.033 (0.060) C:NA T:82%**	pCi/g	01/12/16 12:55	14269-63-7	N2
Thorium-232	HSL-300	**0.025 ± 0.027 (0.017) C:NA T:82%**	pCi/g	01/12/16 12:55	7440-29-1	N2
Uranium-234	HSL-300	**0.085 ± 0.087 (0.126) C:NA T:83%**	pCi/g	01/13/16 08:31	13966-29-5	N2
Uranium-235	HSL-300	**0.000 ± 0.089 (0.067) C:NA T:83%**	pCi/g	01/13/16 08:31	15117-96-1	N2
Uranium-238	HSL-300	**0.014 ± 0.068 (0.094) C:NA T:83%**	pCi/g	01/13/16 08:31		N2

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
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Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

QC Batch: RADC/27539 Analysis Method: EPA 9310
QC Batch Method: EPA 9310 Analysis Description: 9310 Gross Alpha/Beta
Associated Lab Samples: 10334977001, 10334977002

METHOD BLANK: 1009702 Matrix: Solid
Associated Lab Samples:

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Gross Alpha	-0.070 ± 0.0935 (0.262) C:NA T:NA	pCi/g	01/12/16 19:48	
Gross Beta	-0.031 ± 0.109 (0.264) C:NA T:NA	pCi/g	01/12/16 19:48	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
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QUALITY CONTROL - RADIOCHEMISTRY

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

QC Batch: RADC/27478 Analysis Method: HSL-300
QC Batch Method: HSL-300 Analysis Description: HSL300(AS) Actinides
Associated Lab Samples: 10334977001, 10334977002

METHOD BLANK: 1007369 Matrix: Solid
Associated Lab Samples:

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Thorium-228	0.067 ± 0.062 (0.103) C:NA T:89%	pCi/g	01/12/16 12:55	N2
Thorium-230	0.004 ± 0.021 (0.013) C:NA T:89%	pCi/g	01/12/16 12:55	N2
Thorium-232	0.010 ± 0.021 (0.013) C:NA T:89%	pCi/g	01/12/16 12:55	N2
Uranium-234	0.079 ± 0.067 (0.068) C:NA T:97%	pCi/g	01/13/16 08:31	N2
Uranium-235	0.037 ± 0.064 (0.106) C:NA T:97%	pCi/g	01/13/16 08:31	N2
Uranium-238	0.001 ± 0.049 (0.099) C:NA T:97%	pCi/g	01/13/16 08:31	N2

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
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(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

QC Batch: RADC/27372 Analysis Method: EPA 901.1
QC Batch Method: EPA 901.1 Analysis Description: 901.1 Gamma Spec
Associated Lab Samples: 10334977001, 10334977002

METHOD BLANK: 1003751 Matrix: Solid
Associated Lab Samples:

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Lead-210	0.000 ± 0.283 (2.470) C:NA T:NA	pCi/g	12/28/15 15:02	
Radium-226	0.000 ± 0.437 (1.743) C:NA T:NA	pCi/g	12/28/15 15:02	
Radium-228	0.009 ± 0.287 (0.388) C:NA T:NA	pCi/g	12/28/15 15:02	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALIFIERS

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

DEFINITIONS

DF - Dilution Factor, if reported, represents the factor applied to the reported data due to dilution of the sample aliquot.

ND - Not Detected at or above adjusted reporting limit.

J - Estimated concentration above the adjusted method detection limit and below the adjusted reporting limit.

MDL - Adjusted Method Detection Limit.

PQL - Practical Quantitation Limit.

RL - Reporting Limit.

S - Surrogate

1,2-Diphenylhydrazine decomposes to and cannot be separated from Azobenzene using Method 8270. The result for each analyte is a combined concentration.

Consistent with EPA guidelines, unrounded data are displayed and have been used to calculate % recovery and RPD values.

LCS(D) - Laboratory Control Sample (Duplicate)

MS(D) - Matrix Spike (Duplicate)

DUP - Sample Duplicate

RPD - Relative Percent Difference

NC - Not Calculable.

SG - Silica Gel - Clean-Up

U - Indicates the compound was analyzed for, but not detected.

N-Nitrosodiphenylamine decomposes and cannot be separated from Diphenylamine using Method 8270. The result reported for each analyte is a combined concentration.

Act - Activity

Unc - Uncertainty: SDWA = 1.96 sigma count uncertainty, all other matrices = Expanded Uncertainty (95% confidence interval). Gamma Spec = Expanded Uncertainty (95.4% Confidence Interval)

(MDC) - Minimum Detectable Concentration

Trac - Tracer Recovery (%)

Carr - Carrier Recovery (%)

Pace Analytical is TNI accredited. Contact your Pace PM for the current list of accredited analytes.

TNI - The NELAC Institute.

LABORATORIES

PASI-PA	Pace Analytical Services - Greensburg

ANALYTE QUALIFIERS

1M	The % recovery for the Gross Beta matrix spike performed on sample 10334977001 was high and outside of Pace's default acceptance criteria at 130.83%. The high bias may be due to sample matrix interference and indicate a high bias in the sample result.
N2	The lab does not hold TNI accreditation for this parameter.

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA CROSS REFERENCE TABLE

Project: NG/PRODUCED FILTER BAG
Pace Project No.: 10334977

Lab ID	Sample ID	QC Batch Method	QC Batch	Analytical Method	Analytical Batch
10334977001	**NG FILTER CH1032320B-1**	EPA 901.1	RADC/27372		
10334977002	**WATER FILTER BAG CH593627B-1**	EPA 901.1	RADC/27372		
10334977001	**NG FILTER CH1032320B-1**	EPA 9310	RADC/27539		
10334977002	**WATER FILTER BAG CH593627B-1**	EPA 9310	RADC/27539		
10334977001	**NG FILTER CH1032320B-1**	HSL-300	RADC/27478		
10334977002	**WATER FILTER BAG CH593627B-1**	HSL-300	RADC/27478		

Pace Analytical
www.pacelabs.com

150 N. 9th St.
Billings, MT 59101

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Page: 1 of 1

Section A Required Client Information:	Section B Required Project Information:	Section C Invoice Information:
Company: Owl Inc.	Report To: jason@owlmt.com	Attention: accounting@owlmt.com
Address: 1705 Rd. 2054	Copy To: christman.clyde@cleanharbors.com	Company Name: Owl, Inc.
Culbertson, MT 59218	kehoe.john@cleanharbors.com	Address:
Email To: jason@owlmt.com	Purchase Order No.:	Pace Quote Reference:
Phone: 6057591046 Fax:	Project Name:	Pace Project Manager:
Requested Due Date/TAT:	Project Number:	Pace Profile #:

REGULATORY AGENCY: ☐ NPDES ☐ GROUND WATER ☐ DRINKING WATER ☐ UST ☐ RCRA ☐ OTHER

Site Location STATE: ____

Section D Required Client Information

SAMPLE ID (A-Z, 0-9 / ,-) Sample IDs MUST BE UNIQUE

Valid Matrix Codes: MATRIX / CODE — DRINKING WATER DW; WATER WT; WASTE WATER WW; PRODUCT P; SOIL/SOLID SL; OIL OL; WIPE WP; AIR AR; OTHER OT; TISSUE TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED COMPOSITE START DATE	COLLECTED COMPOSITE START TIME	COLLECTED COMPOSITE END/GRAB DATE	COLLECTED COMPOSITE END/GRAB TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Y/N	Analysis Test ↓	Total Uranium (mg/kg) by ICP; alternate Isotopic Uranium by Alpha Spec.	Total Thorium (mg/kg) by ICP; Alternate Isotopic Thorium by Alpha Spec	Gamma spectrum analysis with quantization and Ra-226 identification at 0.1pCi/g	Radium 228	Gross alpha (pCi/g)	Gross beta (pCi/g)	Pb-210	Percent Moisture				Residual Chlorine (Y/N)	1033497 Pace Project No./ Lab I.D.
1	NG Filter CH1032320B-1	SL	G	12/30	11:00	12/30	11:05												X	X	X	X	X	X	X	X				N	001
2	Produced Water Filter Bag CH593627B-1	SL	G	12/30	11:00	12/30	11:05												X	X	X	X	X	X		X				N	002
3																															
4																															
5																															
6																															
7																															
8																															
9																															
10																															
11																															
12																															

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS: Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
	USPS			Peterson/Pace	12/31/15	1245	NA	N	N	Y

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: Jason LaQua

SIGNATURE of SAMPLER: [signature] DATE Signed (MM/DD/YY): 12/30/15

*Important Note: By signing this form you are accepting Pace's NET 30 day payment terms and agreeing to late charges of 1.5% per month for any invoices not paid within 30 days.

F-ALL-Q-020rev.08, 12-Oct-2007

Pace Analytical	Document Name: Sample Condition Upon Receipt Form	Document Revised: 23Feb2015 Page 1 of 1
	Document No.: F-MT-C-184-rev.06	Issuing Authority: Pace Montana Quality Office

Sample Condition Upon Receipt

Client Name: Online

Project #: WO#: 10334977

10334977

Courier: ☐ Fed Ex ☐ UPS ☒ USPS ☐ Client ☐ Commercial ☐ Pace ☐ Other:

Tracking Number: 9505 5124 3101 5364 0220 00

Custody Seal on Cooler/Box Present? ☐ Yes ☒ No **Seals Intact?** ☐ Yes ☒ No

Optional: Proj. Due Date: Proj. Name:

Packing Material: ☐ Bubble Wrap ☐ Bubble Bags ☒ None ☐ Other: **Temp Blank?** ☐ Yes ☒ No

Thermometer Used: ☐ 140821733 ☒ NA **Type of Ice:** ☐ Wet ☐ Blue ☒ None ☐ Samples on ice, cooling process has begun

Cooler Temp Read: NA **Date and Initials of Person Examining Contents:** 12/31 KLH

Cooler Temp Corrected: NA **Biological Tissue Frozen?** ☐ Yes ☒ No

Temp should be above freezing to 6°C

				Comments:
Chain of Custody Present?	☒ Yes	☐ No	☐ N/A	1.
Chain of Custody Filled Out?	☒ Yes	☐ No	☐ N/A	2.
Chain of Custody Relinquished?	☐ Yes	☒ No	☐ N/A	3.
Sampler Name and Signature on COC?	☒ Yes	☐ No	☐ N/A	4.
Samples Arrived within Hold Time?	☒ Yes	☐ No	☐ N/A	5.
Short Hold Time Analysis (<72 hr)?	☐ Yes	☒ No	☐ N/A	6.
Rush Turn Around Time Requested?	☐ Yes	☒ No	☐ N/A	7.
Sufficient Volume?	☒ Yes	☐ No	☐ N/A	8.
Correct Containers Used?	☒ Yes	☐ No	☐ N/A	9.
-Pace Containers Used?	☐ Yes	☒ No	☐ N/A	
Containers Intact?	☒ Yes	☐ No	☐ N/A	10.
Filtered Volume Received for Dissolved Tests?	☐ Yes	☒ No	☐ N/A	11. Note if sediment is visible in the dissolved container.
Sample Labels Match COC? -Includes Date/Time/ID/Analysis Matrix: SL	☒ Yes 12/31 KLH	☒ No	☐ N/A	12. No Sample labels
All containers needing acid/base preservation have been checked?	☐ Yes	☐ No	☒ N/A	13. ☐ HNO_3 ☐ H_2SO_4 ☐ NaOH ☐ HCl Sample #
All containers needing preservation are found to be in compliance with EPA recommendation? (HNO_3, H_2SO_4, HCl<2; NaOH >9 Sulfide, NaOH>12 Cyanide)	☐ Yes	☐ No	☒ N/A	NA
Exceptions: VOA, Coliform, TOC, Oil and Grease, WI-DRO (water)	☐ Yes	☒ No		Initial when completed: Lot # of added preservative:
Headspace in VOA Vials (>6mm)?	☐ Yes	☐ No	☒ N/A	14.
Trip Blank Present?	☐ Yes	☐ No	☒ N/A	15.
Trip Blank Custody Seals Present?	☐ Yes	☐ No	☒ N/A	
Pace Trip Blank Lot # (if purchased): NA				

CLIENT NOTIFICATION/RESOLUTION **Field Data Required?** ☐ Yes ☐ No

Person Contacted: Date/Time:

Comments/Resolution:

Project Manager Review: Date: 12/31/15

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e out of hold, incorrect preservative, out of temp, incorrect containers)

30169585

Chain of Custody

Pace Analytical
www.pacelabs.com

Workorder: 10334977 Workorder Name:NG/PRODUCED FILTER BAG Owner Received Date: 12/31/2015 Results Requested By: 1/14/2016

Report To	Subcontract To
Beverly Faraday Pace Analytical Services, Inc. 1700 Elm Street, Suite 200 Minneapolis, MN 55414 Phone (612)607-1700 Fax (612)607-6444	Pace Analytical Pittsburgh 1638 Roseytown Road Suites 2,3 & 4 Greensburg, PA 15601 Phone (724)850-5600

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers: Other	Requested Analysis: Rad 228/226 - DC	Pb 210 - Gamma	Gross Alpha/Beta	Uranium/Thorium	LAB USE ONLY
1	NG FILTER CH10323208-1	PS	12/30/2015 11:00	10334977001	Solid	1	X	X	X	X	001
2	WATER FILTER BAG	PS	12/30/2015 11:00	10334977002	Solid	1	X	X	X	X	002
3											
4											
5											

Transfers	Released By	Date/Time	Received By	Date/Time
1			R Big Pace	~~1/5/16~~ 1/5/16 1015
2				
3				

Comments:

Cooler Temperature on Receipt N/A °C | Custody Seal (Y) or N | Received on Ice Y or (N) | Samples Intact (Y) or N

****In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document. This chain of custody is considered complete as is since this information is available in the owner laboratory.*

Sample Condition Upon Receipt

Pace Analytical

Client Name: Pace MN

Project # 1169585

Courier: ☐ Fed Ex ☒ UPS ☐ USPS ☐ Client ☐ Commercial ☐ Pace Other _____

Tracking #: Tonn

Custody Seal on Cooler/Box Present: ☒ yes ☐ no Seals intact: ☒ yes ☐ no Biological Tissue is Frozen: Yes No

Packing Material: Bubble Wrap ___ Bubble Bags ___ None X Other _____

Thermometer Used N/A Type of Ice: Wet Blue None ☐ Samples on ice, cooling process has begun

Cooler Temp.: Observed Temp.: N/A °C Correction Factor: N/A °C Final Temp: N/A °C

Date and initials of person examining contents: 1/5/16 RTB

Temp should be above freezing to 6°C

		Comments:
Chain of Custody Present:	☒Yes ☐No ☐N/A	1.
Chain of Custody Filled Out:	☒Yes ☐No ☐N/A	2.
Chain of Custody Relinquished: RTB 1/5/16	☒Yes ☐No ☐N/A	3.
Sampler Name & Signature on COC:	☒Yes ☐No ☐N/A	4.
Samples Arrived within Hold Time:	☒Yes ☐No ☐N/A	5.
Short Hold Time Analysis (<72hr):	☐Yes ☒No ☐N/A	6.
Rush Turn Around Time Requested:	☒Yes ☐No ☐N/A	7.
Sufficient Volume:	☒Yes ☐No ☐N/A	8.
Correct Containers Used:	☒Yes ☐No ☐N/A	9.
-Pace Containers Used:	☐Yes ☒No ☐N/A	
Containers Intact:	☒Yes ☐No ☐N/A	10.
Filtered volume received for Dissolved tests	☐Yes ☐No ☒N/A	11.
Sample Labels match COC: -Includes date/time/ID/Analysis Matrix: SL	☒Yes ☐No ☐N/A	12.
All containers needing preservation have been checked.	☐Yes ☐No ☒N/A	13.
All containers needing preservation are found to be in compliance with EPA recommendation.	☐Yes ☐No ☒N/A	Initial when completed 1/5/16 RTB; Lot # of added preservative
exceptions: VOA, coliform, TOC, O&G, Phenols	☐Yes ☒No	
Samples checked for dechlorination:	☐Yes ☐No ☒N/A	14.
Headspace in VOA Vials (>6mm):	☐Yes ☐No ☒N/A	15.
Trip Blank Present:	☐Yes ☐No ☒N/A	16.
Trip Blank Custody Seals Present	☐Yes ☐No ☒N/A	
Pace Trip Blank Lot # (if purchased):		

Client Notification/ Resolution: Field Data Required? Y / N

Person Contacted: _____ Date/Time: _____

Comments/ Resolution: _____

Project Manager Review: Courtney Hobbs **Date:** 1/6/16

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e out of hold, incorrect preservative, out of temp, incorrect containers)

30169585

Pace Analytical

Project Number: _____

Client Name: Pace MN

Item No.	Matrix Code	Glass Jar (120 / 250 / 500 / 1L)	Soil kit (2 SB, 1M, soil jar)	Chemistry (250 / 500 / 1L)	Organics (1L)	Nutrient (250 / 500)	Phenolics (250 ml)	TOC (40 ml / 250 ml)	TOX (250 ml)	Total Metals	Dissolved Metals preserved Y N	O & G (1L)	TPH (1L)	VOA (40 ml 30 ml)	Cyanide (250 ml)	Sulfide (500 ml)	Bacterie (120 ml)	Wipes / swipe/ smear/ filter	Radchem Nalgene (125 / 250 / 500 / 1L)	Radchem Nalgene (1/2 gal. / 1 gal.L)	Cubitainer (500 ml / 4L)	Ziploc	Other	Other
001	SL																					1		
002	↓																					↓		

SCURF Back (C016-4 15May2012).xls

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

November 06, 2015

Jason LaQua
OWL, Inc.
1705 Road 2054
Culbertson, MT 59218

RE: Project: Nuverra Tank Farm
Pace Project No.: 10327060

Dear Jason LaQua:
Enclosed are the analytical results for sample(s) received by the laboratory on October 21, 2015. The results relate only to the samples included in this report. Results reported herein conform to the most current TNI standards and the laboratory's Quality Assurance Manual, where applicable, unless otherwise noted in the body of the report.

If you have any questions concerning this report, please feel free to contact me.

Sincerely,

Beverly Faraday
beverly.faraday@pacelabs.com
Project Manager

Enclosures

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

CERTIFICATIONS

Project: Nuverra Tank Farm
Pace Project No.: 10327060

Pennsylvania Certification IDs
Georgia Certification #: C040
1638 Roseytown Rd Suites 2,3&4, Greensburg, PA 15601
L-A-B DOD-ELAP Accreditation #: L2417
Alabama Certification #: 41590
Arizona Certification #: AZ0734
Arkansas Certification
California Certification #: 04222CA
Colorado Certification
Connecticut Certification #: PH-0694
Delaware Certification
Florida/TNI Certification #: E87683
Georgia Certification #: C040
Guam Certification
Hawaii Certification
Idaho Certification
Illinois Certification
Indiana Certification
Iowa Certification #: 391
Kansas/TNI Certification #: E-10358
Kentucky Certification #: 90133
Louisiana DHH/TNI Certification #: LA140008
Louisiana DEQ/TNI Certification #: 4086
Maine Certification #: PA00091
Maryland Certification #: 308
Massachusetts Certification #: M-PA1457
Michigan/PADEP Certification
Missouri Certification #: 235
Montana Certification #: Cert 0082
Nebraska Certification #: NE-05-29-14
Nevada Certification #: PA014572015-1
New Hampshire/TNI Certification #: 2976
New Jersey/TNI Certification #: PA 051
New Mexico Certification #: PA01457
New York/TNI Certification #: 10888
North Carolina Certification #: 42706
North Dakota Certification #: R-190
Oregon/TNI Certification #: PA200002
Pennsylvania/TNI Certification #: 65-00282
Puerto Rico Certification #: PA01457
Rhode Island Certification #: 65-00282
South Dakota Certification
Tennessee Certification #: TN2867
Texas/TNI Certification #: T104704188-14-8
Utah/TNI Certification #: PA014572015-5
USDA Soil Permit #: P330-14-00213
Vermont Dept. of Health: ID# VT-0282
Virgin Island/PADEP Certification
Virginia/VELAP Certification #: 460198
Washington Certification #: C868
West Virginia DEP Certification #: 143
West Virginia DHHR Certification #: 9964C
Wisconsin Certification
Wyoming Certification #: 8TMS-L

Pace Analytical Services, Inc.
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Billings, MT 59101
(406)254-7226

SAMPLE SUMMARY

Project: Nuverra Tank Farm
Pace Project No.: 10327060

Lab ID	Sample ID	Matrix	Date Collected	Date Received
10327060001	**TF101915**	Solid	10/19/15 14:00	10/21/15 16:30

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

SAMPLE ANALYTE COUNT

Project: Nuverra Tank Farm
Pace Project No.: 10327060

Lab ID	Sample ID	Method	Analysts	Analytes Reported	Laboratory
10327060001	**TF101915**	EPA 9310	NEG	2	PASI-PA
		HSL-300	LAL	6	PASI-PA

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

PROJECT NARRATIVE

Project: Nuverra Tank Farm
Pace Project No.: 10327060

Method: **EPA 9310**
Description: 9310 Gross Alpha/Beta
Client: OWL, Inc.
Date: November 06, 2015

General Information:
1 sample was analyzed for EPA 9310. All samples were received in acceptable condition with any exceptions noted below or on the chain-of custody and/or the sample condition upon receipt form (SCUR) attached at the end of this report.

Hold Time:
The samples were analyzed within the method required hold times with any exceptions noted below.

Method Blank:
All analytes were below the report limit in the method blank, where applicable, with any exceptions noted below.

Laboratory Control Spike:
All laboratory control spike compounds were within QC limits with any exceptions noted below.

Matrix Spikes:
All percent recoveries and relative percent differences (RPDs) were within acceptance criteria with any exceptions noted below.

Additional Comments:

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

PROJECT NARRATIVE

Project: Nuverra Tank Farm
Pace Project No.: 10327060

Method: **HSL-300**
Description: HSL300(AS) Actinides
Client: OWL, Inc.
Date: November 06, 2015

General Information:
1 sample was analyzed for HSL-300. All samples were received in acceptable condition with any exceptions noted below or on the chain-of custody and/or the sample condition upon receipt form (SCUR) attached at the end of this report.

Hold Time:
The samples were analyzed within the method required hold times with any exceptions noted below.

Method Blank:
All analytes were below the report limit in the method blank, where applicable, with any exceptions noted below.

Laboratory Control Spike:
All laboratory control spike compounds were within QC limits with any exceptions noted below.

Matrix Spikes:
All percent recoveries and relative percent differences (RPDs) were within acceptance criteria with any exceptions noted below.

Additional Comments:

Analyte Comments:

QC Batch: RADC/26638

N2: The lab does not hold TNI accreditation for this parameter.

- TF101915 (Lab ID: 10327060001)
  - Thorium-228
  - Thorium-230
  - Thorium-232
  - Uranium-234
  - Uranium-235
  - Uranium-238

This data package has been reviewed for quality and completeness and is approved for release.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS - RADIOCHEMISTRY

Project: Nuverra Tank Farm
Pace Project No.: 10327060

Sample: TF101915 **Lab ID: 10327060001** Collected: 10/19/15 14:00 Received: 10/21/15 16:30 Matrix: Solid
PWS: Site ID: Sample Type:

Results reported on a "dry-weight" basis

Parameters	Method	Act ± Unc (MDC) Carr Trac	Units	Analyzed	CAS No.	Qual
Gross Alpha	EPA 9310	**105 ± 23.8 (9.65) C:NA T:NA**	pCi/g	11/03/15 07:19	12587-46-1	
Gross Beta	EPA 9310	**62.1 ± 12.9 (5.13) C:NA T:NA**	pCi/g	11/03/15 07:19	12587-47-2	
Thorium-228	HSL-300	**4.27 ± 0.809 (0.181) C:NA T:40%**	pCi/g	11/05/15 14:36	14274-82-9	N2
Thorium-230	HSL-300	**0.799 ± 0.232 (0.130) C:NA T:40%**	pCi/g	11/05/15 14:36	14269-63-7	N2
Thorium-232	HSL-300	**0.474 ± 0.165 (0.092) C:NA T:40%**	pCi/g	11/05/15 14:36	7440-29-1	N2
Uranium-234	HSL-300	**2.01 ± 0.524 (0.176) C:NA T:64%**	pCi/g	11/05/15 10:14	13966-29-5	N2
Uranium-235	HSL-300	**0.818 ± 0.327 (0.165) C:NA T:64%**	pCi/g	11/05/15 10:14	15117-96-1	N2
Uranium-238	HSL-300	**1.18 ± 0.368 (0.166) C:NA T:64%**	pCi/g	11/05/15 10:14		N2

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: Nuverra Tank Farm
Pace Project No.: 10327060

QC Batch: RADC/26638 Analysis Method: HSL-300
QC Batch Method: HSL-300 Analysis Description: HSL300(AS) Actinides
Associated Lab Samples: 10327060001

METHOD BLANK: 974333 Matrix: Solid
Associated Lab Samples:

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Thorium-228	0.003 ± 0.064 (0.131) C:NA T:74%	pCi/g	11/05/15 14:36	N2
Thorium-230	0.029 ± 0.027 (0.024) C:NA T:74%	pCi/g	11/05/15 14:36	N2
Thorium-232	0.003 ± 0.025 (0.037) C:NA T:74%	pCi/g	11/05/15 14:36	N2
Uranium-234	-0.002 ± 0.047 (0.102) C:NA T:100%	pCi/g	11/05/15 10:14	N2
Uranium-235	-0.004 ± 0.062 (0.086) C:NA T:100%	pCi/g	11/05/15 10:14	N2
Uranium-238	0.007 ± 0.047 (0.078) C:NA T:100%	pCi/g	11/05/15 10:14	N2

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: Nuverra Tank Farm
Pace Project No.: 10327060

QC Batch: RADC/26652 Analysis Method: EPA 9310
QC Batch Method: EPA 9310 Analysis Description: 9310 Gross Alpha/Beta
Associated Lab Samples: 10327060001

METHOD BLANK: 974389 Matrix: Solid
Associated Lab Samples:

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Gross Alpha	0.087 ± 0.0913 (0.176) C:NA T:NA	pCi/g	11/03/15 07:19	
Gross Beta	0.022 ± 0.117 (0.263) C:NA T:NA	pCi/g	11/03/15 07:19	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALIFIERS

Project: Nuverra Tank Farm
Pace Project No.: 10327060

DEFINITIONS

DF - Dilution Factor, if reported, represents the factor applied to the reported data due to dilution of the sample aliquot.

ND - Not Detected at or above adjusted reporting limit.

J - Estimated concentration above the adjusted method detection limit and below the adjusted reporting limit.

MDL - Adjusted Method Detection Limit.

PQL - Practical Quantitation Limit.

RL - Reporting Limit.

S - Surrogate

1,2-Diphenylhydrazine decomposes to and cannot be separated from Azobenzene using Method 8270. The result for each analyte is a combined concentration.

Consistent with EPA guidelines, unrounded data are displayed and have been used to calculate % recovery and RPD values.

LCS(D) - Laboratory Control Sample (Duplicate)

MS(D) - Matrix Spike (Duplicate)

DUP - Sample Duplicate

RPD - Relative Percent Difference

NC - Not Calculable.

SG - Silica Gel - Clean-Up

U - Indicates the compound was analyzed for, but not detected.

N-Nitrosodiphenylamine decomposes and cannot be separated from Diphenylamine using Method 8270. The result reported for each analyte is a combined concentration.

Act - Activity

Unc - Uncertainty: SDWA = 1.96 sigma count uncertainty, all other matrices = Expanded Uncertainty (95% confidence interval). Gamma Spec = Expanded Uncertainty (95.4% Confidence Interval)

(MDC) - Minimum Detectable Concentration

Trac - Tracer Recovery (%)

Carr - Carrier Recovery (%)

Pace Analytical is TNI accredited. Contact your Pace PM for the current list of accredited analytes.

TNI - The NELAC Institute.

LABORATORIES

PASI-PA Pace Analytical Services - Greensburg

ANALYTE QUALIFIERS

N2 The lab does not hold TNI accreditation for this parameter.

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA CROSS REFERENCE TABLE

Project: Nuverra Tank Farm
Pace Project No.: 10327060

Lab ID	Sample ID	QC Batch Method	QC Batch	Analytical Method	Analytical Batch
10327060001	**TF101915**	EPA 9310	RADC/26652		
10327060001	**TF101915**	HSL-300	RADC/26638		

Pace Analytical
www.pacelabs.com

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Section A Required Client Information:

Company: Nuverra Environmental
Address: 13195 26 St Nw
Arnegard, ND 58835
Email To: jason@owlmt.com
Phone: 6057591046 Fax:
Requested Due Date/TAT:

Section B Required Project Information:

Report To: Jason LaQua
Copy To: kehoe.john@cleanharbors.com
hall.michaelj@cleanharbors.com
Purchase Order No.:
Project Name: Nuverra Tank Farm
Project Number:

Section C Invoice Information:

Attention: accounting@owlmt.com
Company Name: Owl, Inc.
Address: 1705 Rd 2054, 59218
Pace Quote Reference:
Pace Project Manager:
Pace Profile #:

REGULATORY AGENCY
☐ NPDES ☐ GROUND WATER ☐ DRINKING WATER
☐ UST ☐ RCRA ☐ OTHER
Site Location STATE: ND

Section D Required Client Information

SAMPLE ID
(A-Z, 0-9 / ,-)
Sample IDs MUST BE UNIQUE

Valid Matrix Codes

MATRIX	CODE
DRINKING WATER	DW
WATER	WT
WASTE WATER	WW
PRODUCT	P
SOIL/SOLID	SL
OIL	OL
WIPE	WP
AIR	AR
OTHER	OT
TISSUE	TS

ITEM #	SAMPLE ID	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED COMPOSITE START DATE	COLLECTED COMPOSITE START TIME	COLLECTED COMPOSITE END/GRAB DATE	COLLECTED COMPOSITE END/GRAB TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Requested Analysis Filtered (Y/N) Y/N	Analysis Test: Total Uranium	Total Thorium by ICP	Gross Alpha (pCi/g)	Gross Beta (pCi/g)	Residual Chlorine (Y/N)	Pace Project No./ Lab I.D.
1	TF101915	SL	G	10/19/15	2pm	12/19/15	2pm												X	X	X	X			10327060 001
2																									
3																									
4																									
5																									
6																									
7																									
8																									
9																									
10																									
11																									
12																									

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS: Temp in °C	Received on Ice (Y/N)	Custody Sealed Cooler (Y/N)	Samples Intact (Y/N)
	VBS			Nathan Rau	10/20/15	1630	21.1	N	N	Y
					10/21/15					

SAMPLER NAME AND SIGNATURE
PRINT Name of SAMPLER: Jason LaQua
SIGNATURE of SAMPLER:
DATE Signed (MM/DD/YY): 10/20/15

*Important Note: By signing this form you are accepting Pace's NET 30 day payment terms and agreeing to late charges of 1.5% per month for any invoices not paid within 30 days.

Pace Analytical	Document Name: Sample Condition Upon Receipt Form	Document Revised: 23Feb2015 Page 1 of 1
	Document No.: F-MT-C-184-rev.06	Issuing Authority: Pace Montana Quality Office

Sample Condition Upon Receipt

Client Name: Owl Inc.

Project #: WO#: 10327060

Courier: ☐ Fed Ex ☐ UPS ☒ USPS ☐ Client ☐ Commercial ☐ Pace ☐ Other:

Tracking Number: 9505 5124 3101 5293 0133 99

Custody Seal on Cooler/Box Present? ☐ Yes ☒ No Seals Intact? ☐ Yes ☒ No

Optional: Proj. Due Date: Proj. Name:

Packing Material: ☐ Bubble Wrap ☐ Bubble Bags ☒ None ☐ Other: Temp Blank? ☐ Yes ☒ No

Thermometer Used: ☒ 140821733 ☐ NA Type of Ice: ☐ Wet ☐ Blue ☒ None ☐ Samples on ice, cooling process has begun

Cooler Temp Read: 21.3 Date and Initials of Person Examining Contents: 10/21 mh

Cooler Temp Corrected: 21.1 Biological Tissue Frozen? ☐ Yes ☒ No

Temp should be above freezing to 6°C

				Comments:
Chain of Custody Present?	☒ Yes	☐ No	☐ N/A	1.
Chain of Custody Filled Out?	☒ Yes	☐ No	☐ N/A	2.
Chain of Custody Relinquished?	☒ Yes	☐ No	☐ N/A	3.
Sampler Name and Signature on COC?	☒ Yes	☐ No	☐ N/A	4.
Samples Arrived within Hold Time?	☒ Yes	☐ No	☐ N/A	5.
Short Hold Time Analysis (<72 hr)?	☐ Yes	☒ No	☐ N/A	6.
Rush Turn Around Time Requested?	☐ Yes	☒ No	☐ N/A	7.
Sufficient Volume?	☒ Yes	☐ No	☐ N/A	8.
Correct Containers Used?	☒ Yes	☐ No	☐ N/A	9.
-Pace Containers Used?	☒ Yes	☐ No	☐ N/A	
Containers Intact?	☒ Yes	☐ No	☐ N/A	10.
Filtered Volume Received for Dissolved Tests?	☐ Yes	☒ No	☐ N/A	11. Note if sediment is visible in the dissolved container.
Sample Labels Match COC?	☒ Yes	☐ No	☐ N/A	12.
-Includes Date/Time/ID/Analysis Matrix: SL				
All containers needing acid/base preservation have been checked?	☐ Yes	☐ No	☒ N/A	13. ☐ HNO_3 ☐ H_2SO_4 ☐ NaOH ☐ HCl Sample #
All containers needing preservation are found to be in compliance with EPA recommendation? (HNO_3, H_2SO_4, HCl<2; NaOH >9 Sulfide, NaOH>12 Cyanide)	☐ Yes	☐ No	☒ N/A	NA
Exceptions: VOA, Coliform, TOC, Oil and Grease, WI-DRO (water)	☐ Yes	☒ No		Initial when completed: Lot # of added preservative:
Headspace in VOA Vials (>6mm)?	☐ Yes	☐ No	☒ N/A	14.
Trip Blank Present?	☐ Yes	☐ No	☒ N/A	15.
Trip Blank Custody Seals Present?	☐ Yes	☐ No	☒ N/A	
Pace Trip Blank Lot # (if purchased): NA				

Field Data Required? ☐ Yes ☐ No

CLIENT NOTIFICATION/RESOLUTION

Person Contacted: Date/Time:

Comments/Resolution:

Project Manager Review: Date: 10/22/15

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e out of hold, incorrect preservative, out of temp, incorrect containers)

Chain of Custody

Pace Analytical®
www.pacelabs.com

Workorder: 10327060 **Workorder Name:** Nuverra Tank Farm **Owner Received Date:** 10/21/2015 **Results Requested By:** ~~11/3/2015~~ 10/22 MF 11/4/15

30163018

Report To	Subcontract To
Beverly Faraday Pace Analytical Services, Inc. 1700 Elm Street, Suite 200 Minneapolis, MN 55414 Phone (612)607-1700 Fax (612)607-6444	Pace Analytical Pittsburgh 1638 Roseytown Road Suites 2,3 & 4 Greensburg, PA 15601 Phone (724)850-5600

Item	Sample ID	Sample Type	Collect Date/Time	Lab ID	Matrix	Preserved Containers: Other	Requested Analysis: Isotopic Uranium	Thorium	Gross Alpha	Gross Beta	LAB USE ONLY
1	TF101915	PS	10/19/2015 14:00	10327060001	Solid	1	X	X	X	X	001
2											
3											
4											
5											

Transfers	Released By	Date/Time	Received By	Date/Time
1	[signature]	10/22/15 11:00	[signature]	10-23-15 9:30
2				
3				

Comments

Cooler Temperature on Receipt N/A °C **Custody Seal** Y or N **Received on Ice** Y or (N) **Samples Intact** (Y) or N

****In order to maintain client confidentiality, location/name of the sampling site, sampler's name and signature may not be provided on this COC document.*
This chain of custody is considered complete as is since this information is available in the owner laboratory.

BLM

Sample Condition Upon Receipt

Pace Analytical

Client Name: Pace MN

Project # 30163018

Courier: ☑ Fed Ex ☐ UPS ☐ USPS ☐ Client ☐ Commercial ☐ Pace Other _____

Tracking #: 6021 2789 1082

Custody Seal on Cooler/Box Present: ☑ yes ☐ no Seals intact: ☑ yes ☐ no Biological Tissue is Frozen: Yes No

Packing Material: Bubble Wrap ___ Bubble Bags ___ None ✓ Other _____

Thermometer Used N/A Type of Ice: Wet Blue (None) ☐ Samples on ice, cooling process has begun

Cooler Temp.: Observed Temp.: N/A °C Correction Factor: _____°C Final Temp: _____°C

Date and Initials of person examining contents: BLM 10-23-15

Temp should be above freezing to 6°C

		Comments:
Chain of Custody Present:	☑Yes ☐No ☐N/A	1.
Chain of Custody Filled Out:	☑Yes ☐No ☐N/A	2.
Chain of Custody Relinquished:	☑Yes ☐No ☐N/A	3.
Sampler Name & Signature on COC:	☐Yes ☑No ☐N/A	4.
Samples Arrived within Hold Time:	☑Yes ☐No ☐N/A	5.
Short Hold Time Analysis (<72hr):	☐Yes ☑No ☐N/A	6.
Rush Turn Around Time Requested:	☑Yes ☐No ☐N/A	7.
Sufficient Volume:	☑Yes ☐No ☐N/A	8.
Correct Containers Used:	☑Yes ☐No ☐N/A	9.
-Pace Containers Used:	☐Yes ☑No ☐N/A	
Containers Intact:	☑Yes ☐No ☐N/A	10.
Filtered volume received for Dissolved tests	☐Yes ☐No ☑N/A	11.
Sample Labels match COC:	☑Yes ☐No ☐N/A	12.
-Includes date/time/ID/Analysis Matrix: SL		
All containers needing preservation have been checked.	☐Yes ☐No ☑N/A	13.
All containers needing preservation are found to be in compliance with EPA recommendation.	☐Yes ☐No ☑N/A	
exceptions: VOA, coliform, TOC, O&G, Phenols	☐Yes ☑No	Initial when completed: BLM Lot # of added preservative:
Samples checked for dechlorination:	☐Yes ☐No ☑N/A	14.
Headspace in VOA Vials (>6mm):	☐Yes ☐No ☑N/A	15.
Trip Blank Present:	☐Yes ☐No ☑N/A	16.
Trip Blank Custody Seals Present	☐Yes ☐No ☑N/A	
Pace Trip Blank Lot # (if purchased): _____		

Client Notification/ Resolution: Field Data Required? Y / N

Person Contacted: _____ Date/Time: _____

Comments/ Resolution: _____

Project Manager Review: Carrie Fenno **Date:** 10/26/15

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e out of hold, incorrect preservative, out of temp, incorrect containers)

Pace Analytical

Project Number: 30163018

Client Name: Pace MN

Item No.	Matrix Code	Glass Jar (120 / 250 / 500 / 1L)	Soil kit (2 SB, 1M, soil jar)	Chemistry (250 / 500 / 1L)	Organics (1L)	Nutrient (250 / 500)	Phenolics (250 ml)	TOC (40 ml / 250 ml)	TOX (250 ml)	Total Metals	Dissolved Metals preserved Y N	O & G (1L)	TPH (1L)	VOA (40 ml 30 ml)	Cyanide (250 ml)	Sulfide (500 ml)	Bacteria (120 ml)	Wipes / swipe/ smear/ filter	Radchem Nalgene (125 / 250 / 500 / 1L)	Radchem Nalgene (1/2 gal. / 1 gal.L)	Cubitainer (500 ml / 4L)	Ziploc	Other	Other
001	SL																					1		

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

June 22, 2015

Lewis Vigen
Secure On Site Services
13964 West Front Street
Williston, ND 58801

RE: Project: Owl Pipe 061115 Owl Pipe Seale
Pace Project No.: 10310377

Dear Lewis Vigen:
Enclosed are the analytical results for sample(s) received by the laboratory on June 15, 2015. The results relate only to the samples included in this report. Results reported herein conform to the most current TNI standards and the laboratory's Quality Assurance Manual, where applicable, unless otherwise noted in the body of the report.

If you have any questions concerning this report, please feel free to contact me.

Sincerely,

Kim Roccoforte for
Kang Khang
kang.khang@pacelabs.com
Project Manager

Enclosures

cc: Sarah Kostreva, Secure Energy

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

CERTIFICATIONS

Project: Owl Pipe 061115 Owl Pipe Seale
Pace Project No.: 10310377

Pennsylvania Certification IDs
1638 Roseytown Rd Suites 2,3&4, Greensburg, PA 15601
ACLASS DOD-ELAP Accreditation #: ADE-1544
Alabama Certification #: 41590
Arizona Certification #: AZ0734
Arkansas Certification
California/TNI Certification #: 04222CA
Colorado Certification
Connecticut Certification #: PH-0694
Delaware Certification
Florida/TNI Certification #: E87683
Guam/PADEP Certification
Hawaii/PADEP Certification
Idaho Certification
Illinois/PADEP Certification
Indiana/PADEP Certification
Iowa Certification #: 391
Kansas/TNI Certification #: E-10358
Kentucky Certification #: 90133
Louisiana DHH/TNI Certification #: LA140008
Louisiana DEQ/TNI Certification #: 4086
Maine Certification #: PA00091
Maryland Certification #: 308
Massachusetts Certification #: M-PA1457
Michigan/PADEP Certification
Missouri Certification #: 235
Montana Certification #: Cert 0082
Nebraska Certification #: NE-05-29-14
Nevada Certification
New Hampshire/TNI Certification #: 2976
New Jersey/TNI Certification #: PA 051
New Mexico Certification
New York/TNI Certification #: 10888
North Carolina Certification #: 42706
North Dakota Certification #: R-190
Oregon/TNI Certification #: PA200002
Pennsylvania/TNI Certification #: 65-00282
Puerto Rico Certification #: PA01457
South Dakota Certification
Tennessee Certification #: TN2867
Texas/TNI Certification #: T104704188
Utah/TNI Certification #: PA014572014-4
Vermont Dept. of Health: ID# VT-0282
Virgin Island/PADEP Certification
Virginia/VELAP Certification #: 460198
Washington Certification #: C868
West Virginia DEP Certification #: 143
West Virginia DHHR Certification #: 9964C
Wisconsin/PADEP Certification
Wyoming Certification #: 8TMS-Q

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Billings, MT 59101
(406)254-7226

SAMPLE ANALYTE COUNT

Project: Owl Pipe 061115 Owl Pipe Seale
Pace Project No.: 10310377

Lab ID	Sample ID	Method	Analysts	Analytes Reported	Laboratory
10310377001	**Owl Pipe 061115**	EPA 901.1	MAH	3	PASI-PA

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

ANALYTICAL RESULTS - RADIOCHEMISTRY

Project: Owl Pipe 061115 Owl Pipe Seale
Pace Project No.: 10310377

Sample: Owl Pipe 061115 **Lab ID: 10310377001** Collected: 06/11/15 17:00 Received: 06/15/15 09:50 Matrix: Solid
PWS: Site ID: Sample Type:

Results reported on a "wet-weight" basis

Parameters	Method	Act ± Unc (MDC) Carr Trac	Units	Analyzed	CAS No.	Qual
Lead-210	EPA 901.1	**12.652 ± 3.468 (3.072) C:NA T:NA**	pCi/g	06/18/15 13:48	14255-04-0	
Radium-226	EPA 901.1	**9.915 ± 2.259 (2.008) C:NA T:NA**	pCi/g	06/18/15 13:48	13982-63-3	
Radium-228	EPA 901.1	**4.977 ± 0.768 (0.243) C:NA T:NA**	pCi/g	06/18/15 13:48	15262-20-1	

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL - RADIOCHEMISTRY

Project: Owl Pipe 061115 Owl Pipe Seale
Pace Project No.: 10310377

QC Batch: RADC/24843 Analysis Method: EPA 901.1
QC Batch Method: EPA 901.1 Analysis Description: 901.1 Gamma Spec
Associated Lab Samples: 10310377001

METHOD BLANK: 908948 Matrix: Solid
Associated Lab Samples:

Parameter	Act ± Unc (MDC) Carr Trac	Units	Analyzed	Qualifiers
Lead-210	0.016 ± 1.592 (2.378) C:NA T:NA	pCi/g	06/17/15 13:16	
Radium-226	0.736 ± 1.316 (1.699) C:NA T:NA	pCi/g	06/17/15 13:16	
Radium-228	0.011 ± 0.131 (0.292) C:NA T:NA	pCi/g	06/17/15 13:16	

Results presented on this page are in the units indicated by the "Units" column except where an alternate unit is presented to the right of the result.

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALIFIERS

Project: Owl Pipe 061115 Owl Pipe Seale
Pace Project No.: 10310377

DEFINITIONS

DF - Dilution Factor, if reported, represents the factor applied to the reported data due to dilution of the sample aliquot.

ND - Not Detected at or above adjusted reporting limit.

J - Estimated concentration above the adjusted method detection limit and below the adjusted reporting limit.

MDL - Adjusted Method Detection Limit.

PQL - Practical Quantitation Limit.

RL - Reporting Limit.

S - Surrogate

1,2-Diphenylhydrazine decomposes to and cannot be separated from Azobenzene using Method 8270. The result for each analyte is a combined concentration.

Consistent with EPA guidelines, unrounded data are displayed and have been used to calculate % recovery and RPD values.

LCS(D) - Laboratory Control Sample (Duplicate)

MS(D) - Matrix Spike (Duplicate)

DUP - Sample Duplicate

RPD - Relative Percent Difference

NC - Not Calculable.

SG - Silica Gel - Clean-Up

U - Indicates the compound was analyzed for, but not detected.

N-Nitrosodiphenylamine decomposes and cannot be separated from Diphenylamine using Method 8270. The result reported for each analyte is a combined concentration.

Act - Activity

Unc - Uncertainty: SDWA = 1.96 sigma count uncertainty, all other matrices = Expanded Uncertainty (95% confidence interval). Gamma Spec = Expanded Uncertainty (95.4% Confidence Interval)

(MDC) - Minimum Detectable Concentration

Trac - Tracer Recovery (%)

Carr - Carrier Recovery (%)

Pace Analytical is TNI accredited. Contact your Pace PM for the current list of accredited analytes.

TNI - The NELAC Institute.

LABORATORIES

PASI-PA Pace Analytical Services - Greensburg

REPORT OF LABORATORY ANALYSIS

Pace Analytical Services, Inc.
150 N Ninth Street
Billings, MT 59101
(406)254-7226

QUALITY CONTROL DATA CROSS REFERENCE TABLE

Project: Owl Pipe 061115 Owl Pipe Seale
Pace Project No.: 10310377

Lab ID	Sample ID	QC Batch Method	QC Batch	Analytical Method	Analytical Batch
10310377001	**Owl Pipe 061115**	EPA 901.1	RADC/24843		

REPORT OF LABORATORY ANALYSIS

Pace Analytical
www.pacelabs.com

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

Page: of

Section A Required Client Information:	Section B Required Project Information:	Section C Invoice Information:
Company: Seaone Energy	Report To: Lewis Vigen	Attention: Sara Kastron
Address: 580 W. 400 S	Copy To:	Company Name: Seaone Energy
		Address:
Email To: lvigen@seaone.net	Purchase Order No.:	Pace Quote Reference:
Phone: 801-425-6523	Project Name: GWL Pipe Scale	Pace Project Manager:
Requested Due Date/TAT:	Project Number: GWL Pipe 060115	Pace Profile #:

REGULATORY AGENCY: ☐ NPDES ☐ GROUND WATER ☐ DRINKING WATER ☐ UST ☐ RCRA ☐ OTHER

Site Location STATE: UT

Requested Analysis Filtered (Y/N)

Section D Required Client Information

Matrix Codes (MATRIX / CODE): Drinking Water DW; Water WT; Waste Water WW; Product P; Soil/Solid SL; Oil OL; Wipe WP; Air AR; Tissue TS; Other OT

ITEM #	SAMPLE ID (A-Z, 0-9 / ,) Sample IDs MUST BE UNIQUE	MATRIX CODE (see valid codes to left)	SAMPLE TYPE (G=GRAB C=COMP)	COLLECTED: COMPOSITE START DATE	COLLECTED: COMPOSITE START TIME	COLLECTED: COMPOSITE END/GRAB DATE	COLLECTED: COMPOSITE END/GRAB TIME	SAMPLE TEMP AT COLLECTION	# OF CONTAINERS	Preservatives: Unpreserved	H_2SO_4	HNO_3	HCl	NaOH	$Na_2S_2O_3$	Methanol	Other	Analysis Test Y/N	Residual Chlorine (Y/N)	Pace Project No./ Lab I.D.
1	GWL Pipe 060115			6/11/15	1700				3	2								X		10310377 001
2																				
3																				
4																				
5																				
6																				
7																				
8																				
9																				
10																				
11																				
12																				

ADDITIONAL COMMENTS	RELINQUISHED BY / AFFILIATION	DATE	TIME	ACCEPTED BY / AFFILIATION	DATE	TIME	SAMPLE CONDITIONS
	Lewis Vigen	6/11/15	1700	Megan Fox	6/12	0930	NCL N N 2

SAMPLER NAME AND SIGNATURE

PRINT Name of SAMPLER: James Ball

SIGNATURE of SAMPLER: [signature] DATE Signed (MM/DD/YY): 6/11/15

Temp in °C | Received on Ice (Y/N) | Custody Sealed Cooler (Y/N) | Samples Intact (Y/N)

*Important Note: By signing this form you are accepting Pace's NET 30 day payment terms and agreeing to late charges of 1.5% per month for any invoices not paid within 30 days.

F-ALL-Q-020rev.07, 15-May-2007

WO#: 10310377

10310377

Sample Condition Upon Receipt

Pace Analytical

Client Name: Duke Energy Carolinas

Courier: ☑ Fed Ex ☐ UPS ☐ USPS ☐ Client ☐ Commercial ☐ Pace Other _____

Tracking #: 8026 8454 5683

Custody Seal on Cooler/Box Present: ☐ yes ☑ no Seals intact: ☐ yes ☐ no Biological Tissue is Frozen: Yes No

Packing Material: Bubble Wrap ____ Bubble Bags ____ None ✓ Other _____

Thermometer Used NA Type of Ice: Wet Blue (None) ☐ Samples on ice, cooling process has begun

Cooler Temp.: Observed Temp.:_____°C Correction Factor: _____°C Final Temp:_____°C

Date and Initials of person examining contents: MM 6-15

Temp should be above freezing to 6°C

		Comments:
Chain of Custody Present:	☑Yes ☐No ☐N/A	1.
Chain of Custody Filled Out:	☑Yes ☐No ☐N/A	2.
Chain of Custody Relinquished:	☑Yes ☐No ☐N/A	3.
Sampler Name & Signature on COC:	☑Yes ☐No ☐N/A	4.
Samples Arrived within Hold Time:	☑Yes ☐No ☐N/A	5.
Short Hold Time Analysis (<72hr):	☐Yes ☑No ☐N/A	6.
Rush Turn Around Time Requested:	☐Yes ☑No ☐N/A	7.
Sufficient Volume:	☑Yes ☐No ☐N/A	8.
Correct Containers Used:	☑Yes ☐No ☐N/A	9.
-Pace Containers Used:	☐Yes ☑No ☐N/A	
Containers Intact:	☑Yes ☐No ☐N/A	10.
Filtered volume received for Dissolved tests	☐Yes ☐No ☑N/A	11.
Sample Labels match COC:	☑Yes ☐No ☐N/A	12.
-Includes date/time/ID/Analysis Matrix: WT		
All containers needing preservation have been checked.	☐Yes ☐No ☑N/A	13.
All containers needing preservation are found to be in compliance with EPA recommendation.	☐Yes ☐No ☑N/A	
exceptions: VOA, coliform, TOC, O&G, Phenols	☐Yes ☑No	Initial when completed MM Lot # of added preservative
Samples checked for dechlorination:	☐Yes ☐No ☑N/A	14.
Headspace in VOA Vials (>6mm)	☐Yes ☐No ☑N/A	15.
Trip Blank Present:	☐Yes ☐No ☑N/A	16.
Trip Blank Custody Seals Present	☐Yes ☐No ☑N/A	
Pace Trip Blank Lot # (if purchased):		

Client Notification/ Resolution: Field Data Required? Y / N

Person Contacted: _____ Date/Time: _____

Comments/ Resolution: _____

Project Manager Review: _____ Date: 4/15/15

Note: Whenever there is a discrepancy affecting North Carolina compliance samples, a copy of this form will be sent to the North Carolina DEHNR Certification Office (i.e. out of hold, incorrect preservative, out of temp, incorrect containers)