TECHNOLOGICALLY ENHANCED NATURALLY OCCURRING RADIOACTIVE MATERIALS (TENORM) STUDY REPORT

Rev. 1

May 2016

Prepared for:

Pennsylvania Department of Environmental Protection
Rachel Carson State Office Building
400 Market Street
Harrisburg, PA 17101

Prepared by:

Perma-Fix Environmental Services, Inc.
325 Beaver Street, Suite 3
Beaver, PA 15009

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Ac	Actinium
ALARA	As Low As Reasonably Achievable
α	Alpha
ANSI	American National Standards Institute
API	American Petroleum Institute
ATD	Alpha Track Detector
Ba	Barium
$BaCO_3$	Barium Carbonate
$BaSO_4$	Barium Sulfate
Bcf	billion cubic feet
β	Beta
Bi	Bismuth
BRP	Bureau of Radiation Protection
Ca	Calcium
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CLP	Contract Laboratory Program
cm	centimeter
cpm	counts per minute
CWT	Centralized Wastewater Treatment
DAC	Derived Air Concentration
DCNR	Department of Conservation and Natural Resources
DEP	Department of Environmental Protection
DEP Laboratory	DEP Bureau of Laboratories
DER	Duplicate Error Ratio
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
dpm	disintegrations per minute
DQL	Data Quality Level
EIC	Electret Ion Chamber
EPA	U.S. Environmental Protection Agency
Fe	Iron
FSP	Field Sampling Plan
ft	foot/feet
ft^2	square foot
ft^3	cubic foot
g	gram
GIS	Geographic Information System
GM	Geiger-Muller
GIS	Geographic Information Systems
GPS	Global Positioning System
HASL	Health and Safety Laboratory
HCl	Hydrochloric Acid
HDPE	High Density Polyethylene
HNO_3	Nitric Acid
HPS	Health Physics Society

hr	hour
IAEA	International Atomic Energy Agency
ICP	Inductively Coupled Plasma
K	Potassium
keV	kilo-electron volt
l	liter
LLD	Lower Level of Detection
µR/hr	microroentgens per hour
µrem/hr	microroentgen equivalent man per hour
mcf	thousand cubic feet
MDC	Minimum Detectable Concentration
Mg	Magnesium
Mn	Manganese
mph	miles per hour
mrem	millirem
MS	Matrix Spike or Mass Spectrometry
MSD	Matrix Spike Duplicate
Na	Sodium
NaCl	Sodium Chloride
NaI	Sodium Iodide
NELAP	National Environmental Laboratory Accreditation Program
NIST	National Institute of Standards and Technology
NJDEP	New Jersey Department of Environmental Protection
NORM	Naturally Occurring Radioactive Material
NPDES	National Pollutant Discharge Elimination System
NRC	U.S. Nuclear Regulatory Commission
O&G	Oil and Gas
OSHA	Occupational Safety and Health Administration
%R	Percent Recovery
±	plus or minus
Pa	Protactinium
PA	Pennsylvania
Pa. C.S.	Consolidated Statutes
PASDA	Pennsylvania Spatial Data Access
Pb	Lead
pCi	picocuries
Perma-Fix	Perma-Fix Environmental Services, Inc.
pH	Potential Hydrogen
Po	Polonium
POTW	Publicly Owned Treatment Works
PPE	Personal Protective Equipment
ppm	parts per million
PSIA	pounds per square inch absolute
QA	Quality Assurance
QAM	Quality Assurance Manual
QAPP	Quality Assurance Project Plan
QC	Quality Control
Ra	Radium

RCRA	Resource Conservation and Recovery Act
RESRAD	Residual Radiation
RG	Regulatory Guide
Rn	Radon
RPD	Relative Percent Difference
SOP	Standard Operating Procedure
Sr	Strontium
Sv	Sievert
TDS	Total Dissolved Solids
TENORM	Technologically Enhanced Naturally Occurring Radioactive Materials
Th	Thorium
Tl	Thallium
TPU	Total Propagated Uncertainty
U	Uranium
µohm	microhm
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
U.S.	United States
USACE	U.S. Army Corps of Engineers
U.S.C.	United States Code
USGS	U.S. Geological Survey
WL	Working Level
WWTP	Wastewater Treatment Plant
XRF	X-ray Fluorescence
yr	year
ZLD	Zero Liquid Discharge

GLOSSARY*

Alpha – A positively charged particle consisting of two protons and two neutrons, emitted in radioactive decay or nuclear fission. They are generally produced in the process of alpha decay but may also be produced in other ways. They are designated by the Greek letter α.

Basic Sediment – Oil and gas production storage impurities/sediment from produced oil at storage tank battery.

Beta – High-energy, high-speed electrons or positrons emitted by certain types of radioactive nuclei. The beta particles emitted are a form of ionizing radiation also known as beta rays. The production of beta particles is termed beta decay. They are designated by the Greek letter β.

Brine – Water that is produced with oil and gas when a well is in production, typically water containing more dissolved inorganic salt than seawater.

Condensate – A low density, high American Petroleum Institute (API) gravity, mixture of hydrocarbons that is present in a gaseous state at formation temperatures and pressures but condenses out of the raw gas to a liquid form at standard temperature of 60 degrees Fahrenheit and pressure 14.7 pounds per square inch (PSIA).

Conventional Formation – A formation that is not an unconventional formation.

Conventional Well – A bore hole drilled or being drilled for the purpose of or to be used for construction of a well regulated under 58 Pa. C. S. § § 3201—3274 (relating to development) that is not an unconventional well, irrespective of technology or design. The term includes, but is not limited to:

- Wells drilled to produce oil.
- Wells drilled to produce natural gas from formations other than shale formations.
- Wells drilled to produce natural gas from shale formations located above the base of the Elk Group or its stratigraphic equivalent.
- Wells drilled to produce natural gas from shale formations located below the base of the Elk Group where natural gas can be produced at economic flow rates or in economic volumes without the use of vertical or nonvertical well bores stimulated by hydraulic fracture treatments or multilateral well bores or other techniques to expose more of the formation to the well bore.
- Irrespective of formation, wells drilled for collateral purposes, such as monitoring, geologic logging, secondary and tertiary recovery, or disposal injection.

Drill Cuttings – Rock cuttings and related mineral residues generated during the drilling of an oil or gas well.

Drilling Fluid Waste – Oil and gas drilling mud and other drilling fluids (other than fracturing fluid and spent lubricant).

Drilling Mud – A chemical, water-based, or oil-based mixture pumped into an oil well during drilling in order to seal off porous rock layers, equalize the pressure, cool the bit, and flush out the cuttings. The mud is circulated down the drill pipe, out through the drill bit, across the rock face being drilled, then back to the surface carrying debris from the bottom of the well.

Flowback – The return flow of water and formation fluids recovered from the well bore of an oil or gas well following the release of pressures induced as part of the hydraulic fracture stimulation of a target geologic formation until the well is placed into production.

Flowback Fluid – Flowback fluid is a water based solution that flows back to the surface during and after the completion of hydraulic fracturing. It consists of the fluid used to fracture the target formation. The fluid contains clays, chemical additives, dissolved metal ions, and total dissolved solids (TDS).

Flowback Fracturing Sand – Oil and gas drilling flowback fracturing sand.

Fracturing Fluid Waste – Oil and gas fracturing/stimulation fluid waste and/or flowback.

Gamma – Electromagnetic radiation of an extremely high frequency and high energy. Gamma rays are ionizing radiation, and are thus biologically hazardous. They are classically produced by the decay of atomic nuclei as they transition from a high energy state to a lower state known as gamma decay, but may also be produced by other processes. Natural sources of gamma rays include gamma decay from naturally occurring radioisotopes, and secondary radiation from atmospheric interactions with cosmic ray particles. They are designated by the Greek letter γ.

Gas – A fluid, combustible or noncombustible, which is produced in a natural state from the earth and maintains a gaseous or rarified state at standard temperature of 60 degrees Fahrenheit and pressure of 14.7 PSIA. This product type must be reported in Mcf (1,000 cubic feet) at a standard temperature of 60 degrees Fahrenheit and pressure of 14.7 PSIA.

Horizontal Drill Cuttings – Drill cuttings from the horizontal portion of an oil or gas well.

Hydraulic Fracturing Fluid – Hydraulically pressurized liquid used to fracture rock in the hydraulic fracturing process. Hydraulic fracturing fluids are used to initiate and/or expand fractures, as well as to transport proppant into fractures. The U.S. O&G industry has used fluids for fracturing geologic formations since the early 1940s.

Leachate – A solution resulting from water that has percolated through solid, e.g., waste in landfill, and potentially leached out some of the soluble constituents.

Marinelli – A lightweight polypropylene sample container with snap-on lid used for gamma spectroscopy analysis.

Natural Gas – A fossil fuel consisting of a mixture of hydrocarbon gases, primarily methane, and possibly including ethane, propane, butane, pentane, carbon dioxide, oxygen, nitrogen, and hydrogen sulfide and other gas species. The term includes natural gas from oil fields known as associated gas or casing head gas, natural gas fields known as nonassociated gas, coal beds, shale beds, and other formations. The term does not include coal bed methane.

NORM – Naturally occurring radioactive material. It is a nuclide that is radioactive in its natural physical state, not man-made, but does not include source or special nuclear material.

Oil – Hydrocarbons in liquid form at formation temperatures and pressures that remain in liquid form at standard temperature of 60 degrees Fahrenheit and pressure 14.7 PSIA.

Produced Water – Water that is produced with oil and gas when the well is in production.

Proppant Sand – Solid treated sand suspended in water or other fluid designed to keep an induced hydraulic fracture open during or following a fracturing treatment.

Radiological Environmental Impact – Impact to the environment from the release and subsequent spreading of radionuclides and from the direct emission of radiation from facilities.

Removable Contamination – The fraction of total surface alpha/beta radioactive contamination easily removed by pressing a 47-mm diameter filter paper to the surface with moderate pressure, i.e., smear sampling. Usually expressed in units of dpm/100 cm^2 of surface area sampled.

Secular Equilibrium – A type of radioactive equilibrium in which the half-life of the precursor (parent) radionuclide is so much longer than that of the product (progeny) radionuclide(s) that the radioactivity of the progeny become equal to the parent over time equal to approximately 10 half-life's of the progeny.

Servicing Fluid – Oil and gas production well maintenance and work-over fluids and/or oil/water-based mud and foam.

Smear Sample – A sample of removable alpha and beta surface radioactivity collected by pressing a 47-mm diameter filter paper to 100 cm^2 of surface area sampled to obtain an assumed fraction of removable material. The filter paper is counted for alpha and beta radioactivity without any preparation.

Spent Lubricant – Oil and gas drilling and/or plug drilling lubricants that have exceeded their useful life.

Student t-test – A test for determining whether or not an observed sample mean differs significantly from a hypothetical normal population mean.

TENORM – Technologically enhanced naturally occurring radioactive materials. It is naturally occurring radioactive material not specifically subject to regulation under the laws of the Commonwealth of Pennsylvania or Atomic Energy Act of 1954 (42 U.S.C. §2011 et seq.), but whose radionuclide concentrations or potential for human exposure have been increased above levels encountered in the undisturbed natural environment by human activities.

Total Contamination – The surface alpha/beta radioactive contamination comprised of fixed and removable components. Total contamination is measured by placing an appropriate alpha/beta detector on the surface to be surveyed so that both the fixed and removable fractions are counted together. Usually expressed in units of dpm/100 cm^2 of surface area surveyed.

Unconventional Formation – A geological shale formation existing below the base of the Elk Sandstone or its geologic equivalent stratigraphic interval where natural gas generally cannot be produced at economic flow rates or in economic volumes except by vertical or horizontal well bores stimulated by hydraulic fracture treatments or by using multilateral wellbores or other techniques to expose more of the formation to the well bore.

Unconventional Well – A bore hole drilled or being drilled for the purpose of or to be used for the production of natural gas from an unconventional formation.

Vertical Drill Cuttings – Drill cuttings from the vertical portion of an oil or gas well.

Well Site – The area occupied by the equipment or facilities necessary for or incidental to the drilling, production, or plugging of a well.

*These definitions are for the purposes of this report only and are not necessarily regulatory definitions.

0.0 SYNOPSIS

In 2013, the Pennsylvania Department of Environmental Protection (DEP) initiated a study to collect data relating to technologically enhanced naturally occurring radioactive material (TENORM) associated with oil and gas (O&G) operations in Pennsylvania. This study included the assessment of potential worker and public radiation exposure, TENORM disposal, and other possible environmental impacts. The study encompassed radiological surveys at well sites, wastewater treatment plants, landfills, gas distribution and end use, and O&G brine-treated roads. The media sampled included solids, liquids, natural gas, ambient air, and surface radioactivity.

The observations and recommendations for future actions based on this peer-reviewed study are:

1. There is little potential for additional radon exposure to the public due to the use of natural gas extracted from geologic formations located in Pennsylvania.

2. There is little or limited potential for radiation exposure to workers and the public from the development, completion, production, transmission, processing, storage, and end use of natural gas. There are, however, potential radiological environmental impacts from O&G fluids if spilled. Radium should be added to the Pennsylvania spill protocol to ensure cleanups are adequately characterized. There are also site-specific circumstances and situations where the use of personal protective equipment by workers or other controls should be evaluated.

3. There is little potential for radiation exposure to workers and the public at facilities that treat O&G wastes. However, there are potential radiological environmental impacts that should be studied at all facilities in Pennsylvania that treat O&G wastes to determine if any areas require remediation. If elevated radiological impacts are found, the development of radiological discharge limitations and spill policies should be considered.

4. There is little potential for radiation exposure to workers and the public from landfills receiving waste from the O&G industry. However, filter cake from facilities treating O&G wastes are a potential radiological environmental impact if spilled, and there is also a potential long-term disposal issue. TENORM disposal protocols should be reviewed to ensure the safety of long-term disposal of waste containing TENORM.

5. While limited potential was found for radiation exposure to recreationists using roads treated with brine from conventional natural gas wells, further study of radiological environmental impacts from the use of brine from the O&G industry for dust suppression and road stabilization should be conducted.

1.0 INTRODUCTION

1.1 Purpose and Objectives of the Study

During the expansion of the Marcellus Shale Gas industry the Pennsylvania Department of Environmental Protection (DEP) staff observed a steady increase in the volume of waste containing technologically enhanced naturally occurring radioactive material (TENORM), generated by the oil and gas (O&G) industry, being disposed in Pennsylvania landfills. TENORM is naturally occurring radioactive material whose radionuclide concentrations or potential for human exposure have been increased above levels encountered in the undisturbed natural environment by human activities.

In 2013, DEP initiated a study to collect information and data needed to effectively manage TENORM from O&G operations for environmental and health protection. This study included the assessment of potential worker and public radiation exposure, evaluation of potential impacts from TENORM waste disposal, and the investigation of possible radiological environmental effects. The survey and sample data will be used to address potential radiological concerns from O&G operations, disposal of waste, and product use.

This study report includes recommendations for future actions to be taken to address issues of concern identified by the study, including additional investigations and surveys.

1.2 Background

The Marcellus Shale formation underlies much of Pennsylvania, with the exception of southeastern Pennsylvania. The organic-rich portion reaches its maximum thickness in the northeastern part of the state. The northwestern borders of Franklin, Cumberland, Lebanon, Berks, Lehigh, and Northampton counties provide the southeastern margin of the Marcellus Shale formation. Between this border and the approximate corridor with US 220/I 99, the Marcellus Shale formation crops out in the folded Ridge and Valley physiographic province where it may be a concern for indoor Radon (Rn). The type of gas found in most areas of the Marcellus Shale throughout Pennsylvania is geologically mature and consists of mostly methane that requires little processing prior to use. This gas is commonly called "dry gas." Marcellus Shale gas found along the westernmost border of Pennsylvania is less geologically mature; therefore, in addition to methane, the gas contains additional hydrocarbons such as ethane, propane, and butane. This gas is commonly called "wet gas" and can be used to produce plastics and other high-value petroleum-based products. **Figure 1-1** depicts the extent of the Marcellus Shale formation within Pennsylvania. **Figure 1-2** shows the approximate dividing line between the wet and dry gas zones in the state.

The Pennsylvania Department of Conservation and Natural Resources (DCNR) has documented that Marcellus Shale can contain from 10 to 100 parts per million (ppm) uranium (U). Typical crustal U concentrations in the United States (U.S.) average 3 ppm.

See **Appendix A** for additional geologic information on other natural gas-producing formations and on heavy metal content.

Figure 1-1. Marcellus Shale Formation in Pennsylvania

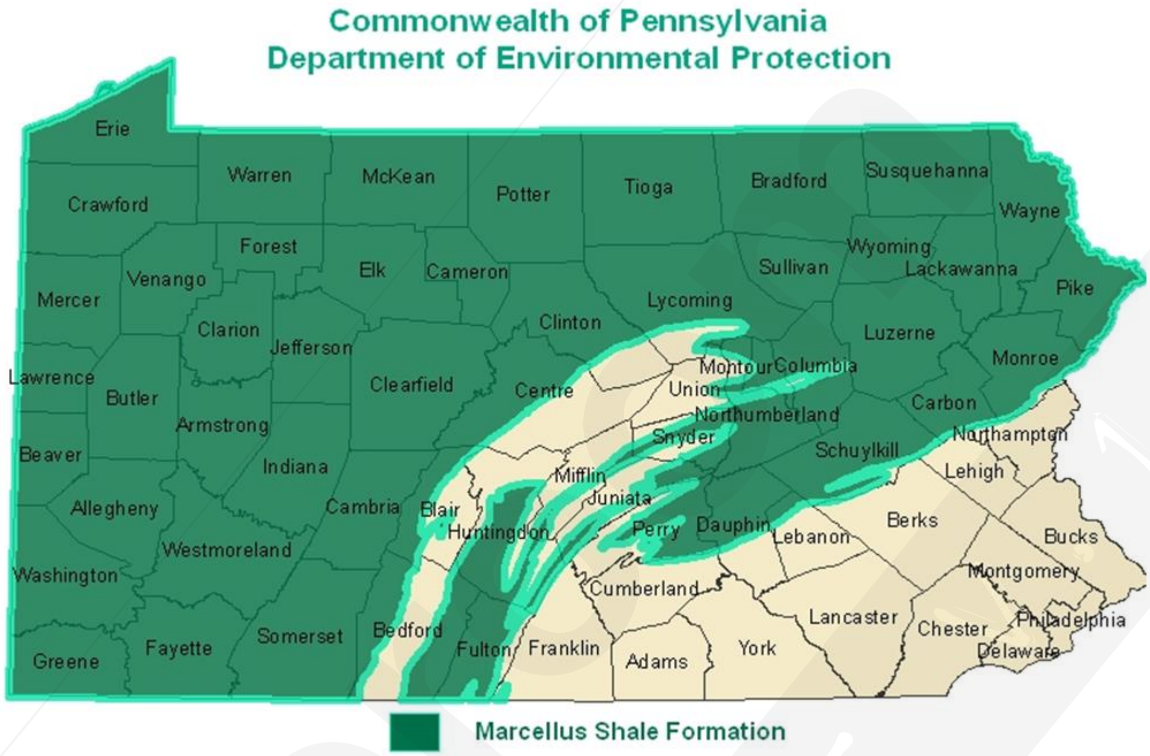
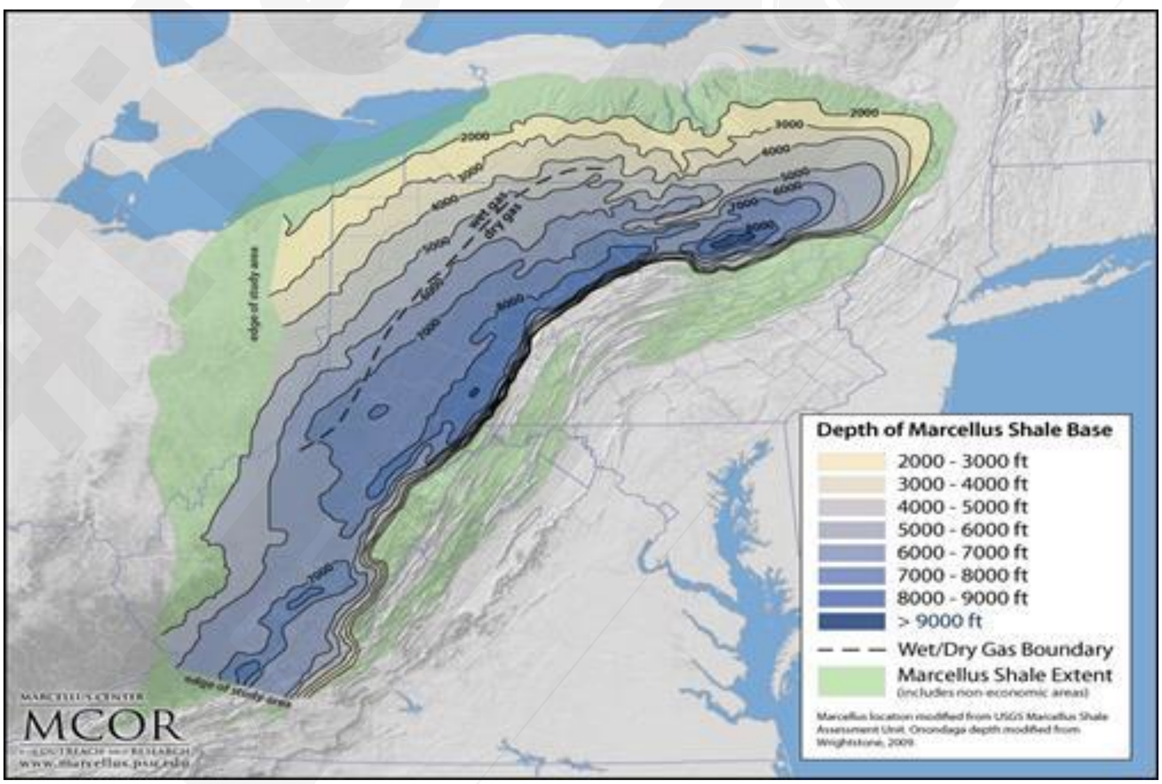


Figure 1-2. Marcellus Shale Formation "Wet" and "Dry" Areas



Source: PSU Marcellus Center for Outreach and Research (MCOR), www.marcellus.psu.edu

Marcellus Shale and other geologic formations rich in O&G resources may contain naturally occurring radioactive material (NORM), specifically U, U-238 parent and thorium (Th), Th-232 parent, and their decay progeny, as well as Potassium-40 (K-40). These series occur naturally and are the most prevalent of the three natural decay series, the third being the actinium (Ac), U-235 parent. The decay series of U and Th are illustrated in **Figures 1-3** and **1-4**, respectively. Surface soil typically contains approximately 1 to 2 picocuries per gram (pCi/g) of both the U and Th series radionuclides with all of the series members at approximately equal activity, i.e., secular equilibrium. The radioactive materials, including TENORM, are brought to the land surface by O&G activities.

Each of the natural decay series includes a Rn gas member. Radon and its progeny are the primary issue of concern associated with natural gas distribution and its end uses.

1.3 Pennsylvania Oil and Gas Operations (Conventional and Unconventional)

Natural gas wells are classified as either conventional or unconventional. Related statutory and regulatory definitions include the following:

Pennsylvania's 2012 Oil and Gas Act (58 Pa. C. S. § 2301)

"Unconventional formation." A geological shale formation existing below the base of the Elk Sandstone or its geologic equivalent stratigraphic interval where natural gas generally cannot be produced at economic flow rates or in economic volumes except by vertical or horizontal well bores stimulated by hydraulic fracture treatments or by using multilateral wellbores or other techniques to expose more of the formation to the well bore.

"Unconventional gas well." A bore hole drilled or being drilled for the purpose of or to be used for the production of natural gas from an unconventional formation.

25 Pa. Code § 78.1

"Conventional formation." A formation that is not an unconventional formation.

"Conventional well."

(i) A bore hole drilled or being drilled for the purpose of or to be used for construction of a well regulated under 58 Pa. C. S. §§ 3201—3274 (relating to development) that is not an unconventional well, irrespective of technology or design.

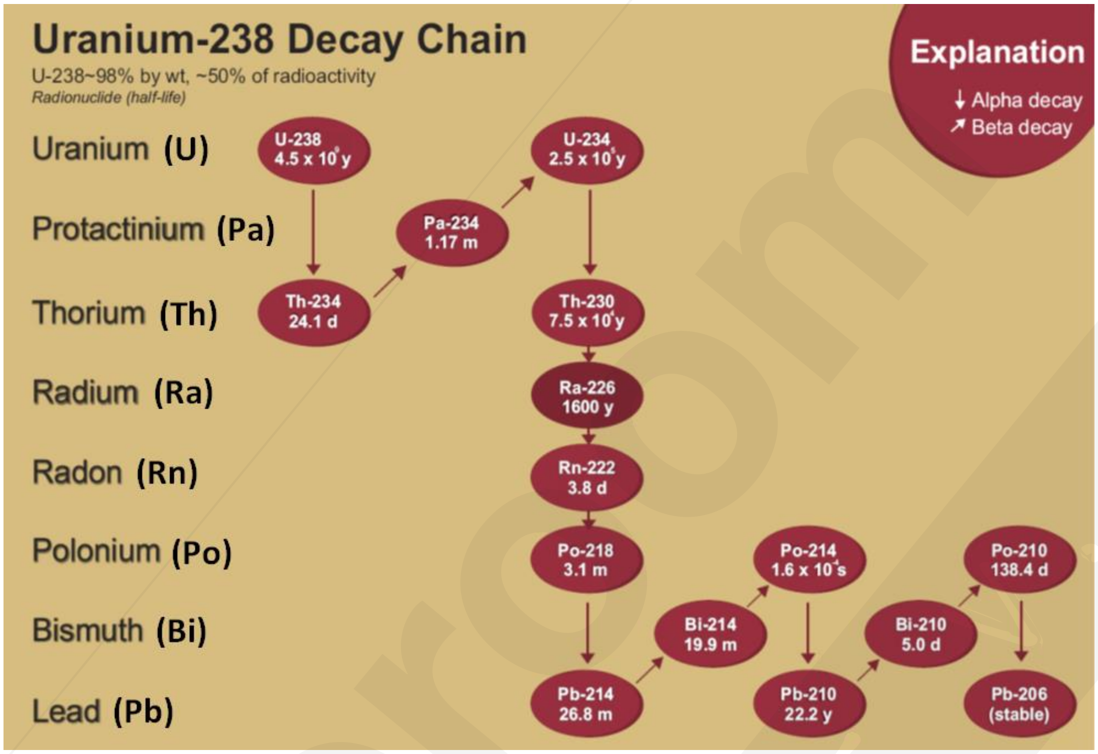
(ii) The term includes, but is not limited to:

(A) Wells drilled to produce oil.

(B) Wells drilled to produce natural gas from formations other than shale formations.

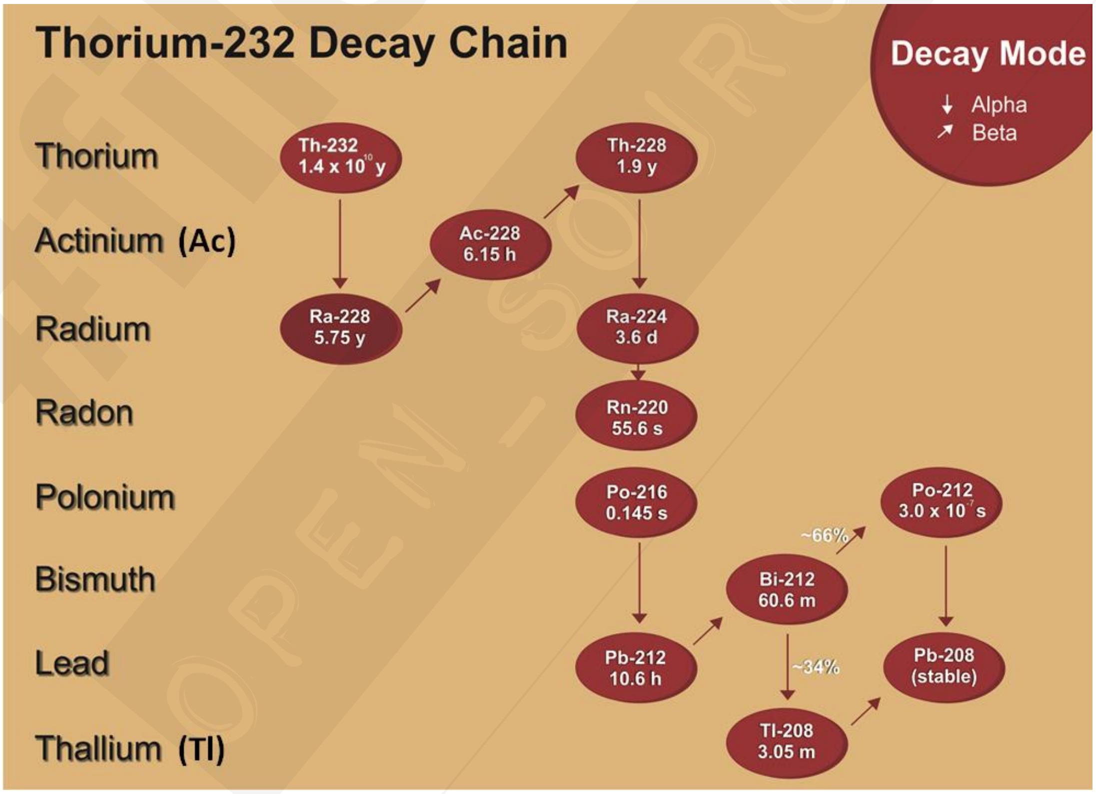
(C) Wells drilled to produce natural gas from shale formations located above the base of the Elk Group or its stratigraphic equivalent.

Figure 1-3. Uranium-238 Decay Chain



Note: y = years, d= days, h = hours, and m = minutes

Figure 1-4. Thorium-232 Decay Chain



Note: y = years, d= days, h = hours, and m = minutes

(D) Wells drilled to produce natural gas from shale formations located below the base of the Elk Group where natural gas can be produced at economic flow rates or in economic volumes without the use of vertical or nonvertical well bores stimulated by hydraulic fracture treatments or multilateral well bores or other techniques to expose more of the formation to the well bore.

(E) Irrespective of formation, wells drilled for collateral purposes, such as monitoring, geologic logging, secondary and tertiary recovery, or disposal injection.

1.4 Subject Media

The types of media evaluated as part of this study result from the product media that either contain TENORM or may be impacted by TENORM due to O&G operations. The product streams evaluated are natural gas and natural gas liquids, i.e., condensates. Other media evaluated includes solid and liquid wastes, soils, ambient air, and gaseous emission products associated with O&G operations.

1.4.1 Media Sampled

1.4.1.1 Solids

Natural gas exploration, extraction and production result in various types of solids that may contain TENORM or may be impacted by TENORM. These materials include drill cuttings, filter sock residuals, impoundment sludge, tank bottom sludge, pipe scale, wastewater treatment plant (WWTP) sludge, and soils. Drill cuttings are wastes brought to the surface during the drilling process. Filter sock residuals and WWTP sludge are generated during the processing of wastewaters generated by O&G activities. Impoundment and tank bottom sludge accumulates as a result of solid material settling out of well site wastewater.

Other solids potentially impacted by radioactive isotopes include soils at WWTP discharge outfalls, soils in the proximity of dirt roads where brines from conventional O&G operations are used for dust suppression, and pipe scale on natural gas transmission infrastructure.

1.4.1.2 Liquids

There are various types of liquids generated during the development and operating life of a gas well including drilling muds, used hydraulic fracturing fluid, brine, and other wastewaters. Liquid wastes are processed at WWTPs for reuse on well sites or to meet National Pollutant Discharge Elimination System (NPDES) criteria prior to discharge to waters of the Commonwealth.

The study classified WWTPs into three categories:

1) Publicly Owned Treatment Works (POTWs) are the most common type of WWTPs. These facilities are designed to process sewage and wastewater from residences and businesses and may take industrial wastewater under specific circumstances. After the wastewater is processed and meets specified chemical criteria, the processed water may be discharged to streams under an NPDES permit.

2) Centralized Waste Treatment (CWT) facilities are designed to process commercial and industrial liquid wastes prior to discharge to receiving streams under an NPDES permit. Additionally, there are some industrial facilities that process wastewater prior to discharge to POTWs for final processing and discharge (pre-treatment).

3) Zero Liquid Discharge (ZLD) facilities are the most modern and utilize distillation and chemical technologies to remove solids from the wastewater. The processed wastewater is returned for reuse at natural gas well sites for hydraulic fracturing of new wells. All centralized ZLD facilities that recycle water to be used for hydraulic fracturing must be permitted by DEP.

Landfill leachate is liquid waste generated by the movement of precipitation through the disposed waste and by the compaction and decomposition of the waste itself. As liquid moves through the waste, contaminants are leached from the disposed material. Landfills are designed to ensure leachate does not enter the groundwater and is collected for treatment. Upon meeting NPDES water quality standards, the treated leachate may be discharged to surface waters. Some landfills operate onsite treatment systems while others are connected to local POTWs, which treat landfill leachate prior to discharge. Because landfills accept natural gas industry wastes such as drill cuttings and treatment sludge that may contain TENORM, there is a potential for leachate from those facilities to also contain TENORM.

1.4.1.3 Natural Gas

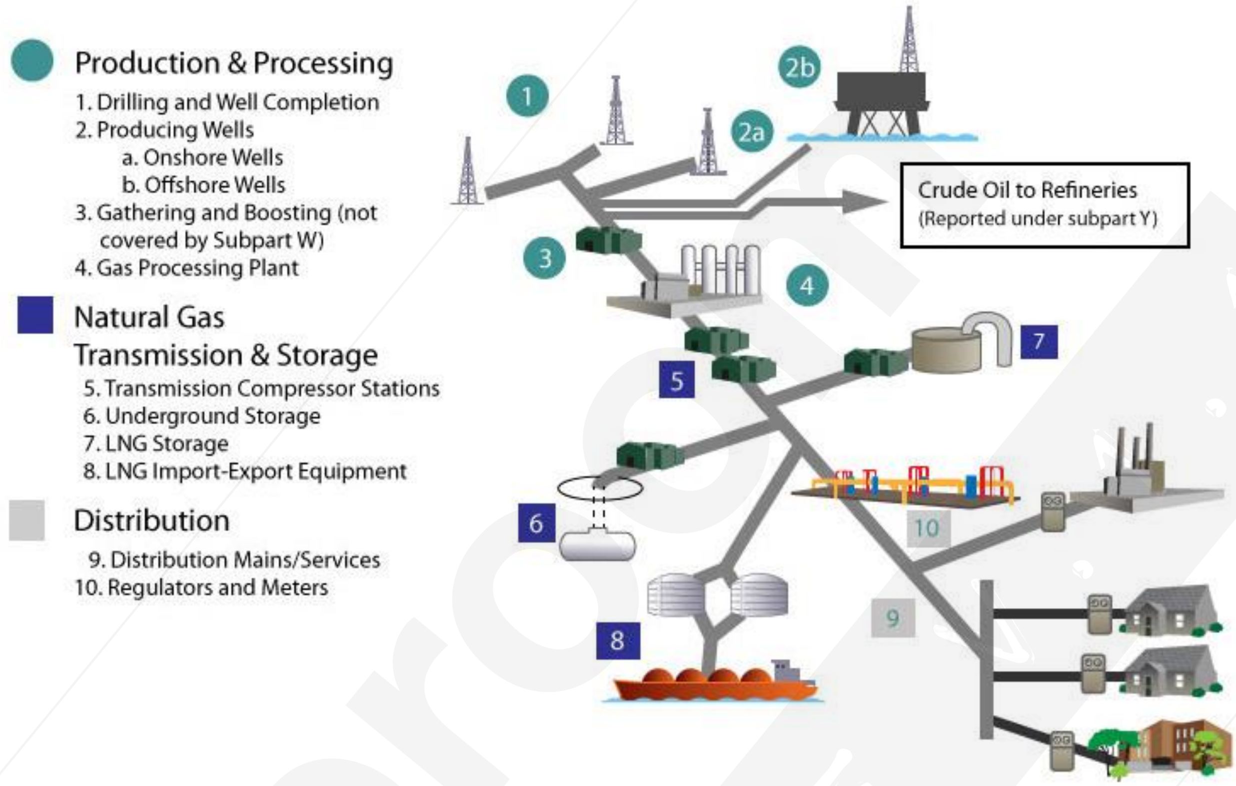
Many facilities, structures, and systems are utilized during the exploration, extraction, and production of natural gas before the product is distributed to the residential, industrial, and commercial end users.

Natural gas samples were collected and evaluated for Rn at compressor stations, natural gas processing plants, and underground storage facilities. Ambient air samples were also collected and evaluated for Rn at well sites, WWTPs, gathering compressor stations, natural gas-fired power plants, and landfills.

Natural gas passes through gathering lines, compressor stations, transmission lines, natural gas processing plants, underground storage facilities, and a network of pipes and valves (see **Figure 1-5**).

<u>Gathering Compressor Stations</u>:
Gathering compressor stations compress the natural gas from the well sites to transport the product to the transmission line network. These facilities include large internal combustion engines and may also include dewatering equipment such as glycol dehydrators and liquid storage tanks. Geographically, they are typically located at a nexus of piping from well sites.

Figure 1-5. Natural Gas Operations



Source: US EPA, http://www.epa.gov/methane/gasstar/basic-information/index.html

Natural Gas Processing:
Natural gas and condensate are also used as feedstock for the synthesis of other products. Natural gas enters a processing facility and undergoes a dehydration process, is refrigerated to remove condensable liquids, then goes through a series of other processes including de-ethanizing/de-propanizing and fractionation. These facilities can be quite large with very extensive piping networks. They also have several intermediate and final product storage tanks and vessels. The operations at these facilities necessitate opening of the product conveyance network for periodic cleaning and maintenance.

Transmission Line Compressor Stations:
These facilities are larger than their gathering station counterparts. Power to the compressors is supplied by natural gas turbine engines, similar to those found on jet aircraft. These facilities normally do not have dehydrating equipment or liquid storage tanks. Dehydration and condensate removal take place further upstream at the well sites and gathering compressor stations. The origin of the natural gas passing through these facilities can be difficult to ascertain. Transmission line compressor stations may be handling natural gas from Pennsylvania, other parts of the U.S., or international sources.

Underground Storage Facilities:
Some deep sandstone formations, such as the Oriskany Sandstone formation, are used for storing natural gas. These underground reservoirs are used to address fluctuations in demand for natural gas.

End Users:
The primary radionuclide of concern in natural gas is Rn-222. Radon is a noble gas and is not destroyed by combustion, nor is it removed by an air emission source control device. Consequently, Rn present in the fuel gas will remain after combustion. However, the process of combustion dilutes the concentration of Rn in the exhaust gas stream by a ratio of 10:1 of ambient air to natural gas when perfect combustion is achieved.

1.5 Facility Selection

Category-specific criteria were used to select specific facilities for inclusion in the study. The criteria differed based on the type of facility. The following lists the various selections.

1.5.1 Well Site Selection

1) A Marcellus Shale formation well site from the dry gas areas predominantly in the northern and central parts of the state.
2) A Marcellus Shale formation well site from the wet gas area found predominantly in the southwestern part of the state.
3) A Utica formation well site and other non-Marcellus Shale formations, e.g., Geneseo, Burket, and Rhinestreet that became available.
4) A conventional O&G well site.

1.5.2 Wastewater Treatment Plant Selection

1) The three types of WWTPs, including POTW facilities, CWT facilities, ZLD facilities.
2) WWTPs that accept wastewater from conventional and unconventional types of well sites.
3) WWTPs that accept waste material from unconventional well sites in the wet gas-producing area rather than the dry gas-producing area.
4) WWTPs where elevated radioactivity readings have been measured from the intake wastewater, produced sludge, effluent discharge, or discharge point stream/river sediments, etc.
5) WWTPs that DEP regional offices have indicated are of particular interest.

1.5.3 Landfill Facility Selection Criteria

1) All Pennsylvania landfills.
2) Nine landfills that accepted the largest amount of TENORM-containing waste during the past year.
3) Large-volume TENORM-containing waste disposal sites where onsite worker exposure measurements could be obtained and representative samples of solids could be collected.

1.5.4 Gas Distribution and End Use Operations Selection Criteria

1) Facilities that compress, carry, and distribute natural gas from the wet gas-producing area of the state.
2) Facilities that compress, carry, and distribute natural gas from the dry gas-producing area of the state.

3) Facilities that distribute or process natural gas produced in Pennsylvania rather than those that distribute or process natural gas from out of state.
4) Major natural gas users, e.g., electrical generator, processing, and storage facilities.

1.5.5 Road Sites Selection Criteria

1) Multiple locations in the southwestern, northwestern, and north-central regions of the state.
2) Roads where liquids from wells in the wet and dry gas-producing areas were applied for dust suppression and road stabilization.
3) Roads where liquids from wells in the wet and dry gas-producing areas were not applied for dust suppression and road stabilization.

1.5.6 Well Component Reconditioning Selection Criteria

Well casing/pipe reconditioning or de-scaling facilities in the state.

1.5.7 Centralized Impoundments

1) A facility in the wet gas-producing area.
2) A facility in the dry gas-producing area.

2.0 STUDY IMPLEMENTATION

2.1 Sampling and Survey Methods

The primary data for this study were gathered using radiological screening surveys and through the sampling and analysis of solid and liquid wastes, soils, ambient air, and gaseous emission products associated with O&G operations.

2.1.1 Field Surveys

2.1.1.1 Scope

Radiological surveys were performed to identify the possible presence and abundance of NORM and TENORM in locations that include the following:

- Well Sites (Section 3.0)
  - Offices and living quarters
  - Storage and maintenance areas
  - Drill rigs and associated equipment
  - Temporary wastewater storage tanks
  - Wastewater impoundments
  - Production equipment
  - Drill cutting pits (closed)
- Wastewater Treatment Plants (Section 4.0)
  - Wastewater off-load areas
  - Influent wastewater storage areas (untreated)
  - Effluent wastewater storage areas (treated)
  - Processing tanks and equipment
  - Offices, break rooms, laboratories
  - Discharge points where applicable
- Landfills (nine study landfills – details provided in Section 5.0)
  - Offices and other occupied spaces
  - Storage and maintenance areas
  - Natural gas processing facilities
  - Leachate processing facilities
  - Earthmoving equipment
- Gas Distribution and End Use (Section 6.0)
  - Compressor stations
  - Natural gas-fired power plants
  - Natural gas processing facilities
- Oil and Gas Brine-Treated Roads (Section 7.0)

2.1.1.2 Instrumentation and Documentation

Radiological instrumentation used for field surveys included portable scalers/ratemeters with various scintillators for detection of alpha (α), beta (β), and/or gamma radiation; portable gamma dose rate meters; portable gamma exposure rate meters; general purpose Geiger-Muller (GM) detectors; and field counters for low-level α and β radiation detection.

All instruments used were calibrated and their operation verified prior to use on each day they were used. The instruments were maintained and operated in accordance with Perma-Fix Environmental Services, Inc. (Perma-Fix) operating procedures by qualified health physics technicians. Records of calibration, daily quality control (QC) checks for the days used, survey results, logbooks, and various other records generated during field screening survey activities are included in **Appendix B**.

2.1.1.3 Activities

General descriptions of the various field surveys performed as part of this study are provided below.

2.1.1.3.1 Radiological Surveys of Facilities and Reference Background Areas

Gamma radiation exposure rates and gross gamma radioactivity surveys were performed at each facility included in the study. The gamma radiation exposure rates were measured using a Bicron Micro-Rem Meter recorded in micro-Roentgen equivalent man per hour (μrem/hr) or a Ludlum Model 19 Micro-R Meter recorded in units of micro-Roentgen per hour (μR/hr). The gross gamma radioactivity surveys were recorded in counts per minute (cpm) using a Ludlum Model 44-10 Sodium Iodide (NaI) detector. To properly evaluate survey data, surveys were also performed in areas outside the influence of the facility to establish natural background.

2.1.1.3.2 Radiological Surveys of Liquid Samples and Tanks

Liquid samples were collected at each of the three types of WWTPs and included influent, effluent, and in-stream discharge points where POTWs, and in limited cases CWTs, are permitted to discharge directly to a receiving stream.

During liquid sampling, gamma radiation exposure surveys were performed. In addition, gamma radiation exposure rates were performed on contact with tanks when possible. Otherwise, measurements were collected in the general proximity of the point of sample collection or tank. To properly evaluate survey data, surveys were also performed in areas outside the influence of the facility to establish natural background.

2.1.1.3.3 Radiological Surveys of Equipment and Structures

Equipment such as drill rigs, well development equipment, etc., was subject to field screening surveys including:

- Gamma radiation exposure rate surveys using a Bicron MicroRem Meter or Ludlum Model 19.
- Gross gamma radioactivity surveys using a Ludlum Model 44-10 NaI detector.
- Total α and β surface radioactivity using a direct frisk Ludlum Model 43-89 detector and/or a Ludlum Model 44-93 and cpm results converted to units of disintegrations per minute per 100 square centimeters (dpm/100 cm^2) of surface area surveyed.

- Removable α and β surface radioactivity by sample collection with smears. Smears were counted on a Ludlum 2929 with a Model 43-10-1 portable scaler/ratemeter and detector. Count results were converted to units of dpm/100 cm^2 of surface area smeared.

To properly evaluate survey data, surveys were also performed in areas outside the influence of the facility to establish natural background.

2.1.1.3.4 Radiological Surveys of Samples

All samples collected were surveyed prior to transportation to the laboratory. The surveys were performed on contact with the sample container and included:

- Gamma radiation exposure rate surveys using a Bicron MicroRem Meter or Ludlum Model 19.
- Gross gamma radioactivity surveys using a Ludlum Model 44-10 NaI detector.
- Total α and β surface radioactivity using a direct frisk Ludlum Model 43-89 detector or a Ludlum Model 44-93 detector.
- Removable α and β surface radioactivity by sample collection with smears. Smears were counted on a Ludlum 2929 with a Model 43-10-1 portable scaler/ratemeter and detector.

To properly evaluate survey data, surveys were also performed in areas outside the influence of the facility to determine natural background.

2.1.2 Field Sampling Activities

2.1.2.1 Scope

DEP sampled solids, liquids, and gas during the study to understand the movement and potential exposure pathways of TENORM from O&G operations. The sampling and analysis of environmental media provides data that are informative in determining radionuclides of concern as well as their potential mobility. The media sampled during this study included:

- Solid samples:
  - Drill cuttings
  - Wastewater treatment sludge/filter cake
  - Wastewater treatment discharge sediment
  - Soil samples
  - Filter sock residuals
- Liquid samples:
  - Flowback and produced water
  - Accumulated liquids from production equipment
  - Wastewater treatment influent and effluent
  - Landfill leachate influent and effluent
- Gas samples:
  - Natural gas (for Rn-222 concentration)
  - Ambient air (for Rn-222 concentration)
- Removable α/β radioactivity surface samples:
  - Removable α radioactivity by smear sampling

− Removable β radioactivity by smear sampling

Collected samples, with the exception of smear samples, were transported to the DEP Bureau of Laboratories (DEP Laboratory) under chain-of-custody control. Five percent of samples were split by Perma-Fix and forwarded by the DEP Laboratory to the independent QC laboratory (GEL Laboratory of Charleston, SC) for filtration, as needed, and analyses. Smear samples were transported to the Perma-Fix laboratory, and 10 percent of the smear samples were forwarded to the DEP Laboratory for duplicate analysis.

2.1.2.2 Solid Sample Methods

Solid samples were collected using clean sampling equipment. Samples were collected using stainless steel trowels and bowls, then promptly transferred into laboratory-approved containers and immediately labeled to maintain identification.

2.1.2.3 Liquid Sample Methods

When sampling tanks through a valve, samples were collected directly into the clean sample container. Otherwise, representative tank samples were collected using a clean high-density polyethylene (HDPE) dipper. The sampled liquids were transferred to clean, laboratory-approved containers. Two consecutive 4-liter (L) samples were obtained at each sample location.

When the samples were received at the DEP Laboratory, they were preserved. Sample preservation is the measure or measures taken to prevent reduction or loss of target analytes. Analyte loss can occur between sample collection and laboratory analysis because of physical, chemical, and biological processes that result in chemical precipitation, adsorption, oxidation, reduction, ion exchange, degassing, or degradation. Preservation stabilizes analyte concentrations for a limited period of time. The first sample was analyzed after preservation without filtration. The second sample was preserved and subsequently filtered in the laboratory using a 0.45-micron mixed cellulose ester filter. The filtered sample was placed into a clean container. The filtrates were maintained for analysis.

2.1.2.4 Gas Sample Methods

Radon concentration in ambient air was measured by various technologies. The technology used was dependent on several factors, including the location, the collection period/detector deployment period, and atmospheric conditions such as relative humidity. Sampling technologies used for this study included:

- Electret ion chambers (EICs)
- Alpha track detectors (ATDs)

Natural gas grab samples were also collected to measure Rn concentrations. Natural gas was collected directly into scintillation cells, referred to as Lucas cells. Two Lucas cells were connected in sequence, which provided a duplicate sample at each sample location. An in-line Millipore® Type HA, 0.45-micron glass fiber filter was used prior to natural gas entering the first cell. This filter prevents sample contamination by Rn particulate progeny.

The natural gas was flowed through the cells for 10 minutes. This provided for purging of the gas lines and the scintillation cells, resulting in the collection of new discrete samples for analysis.

2.1.2.5 Removable Alpha/Beta Surface Radioactivity Smear Sample Method

Smear samples of removable α and β surface radioactivity were collected by pressing a 47-millimeter diameter filter paper to the sampling surface and smearing with moderate pressure approximately 100 cm^2 of surface area.

2.2 Laboratory Methods

2.2.1 Solid Matrix

The following sample types were classified as solid matrices: surface soil impacted by sediments, filter cakes, soils, sludge, drill cuttings, drilling muds, proppant sand, and filter socks, including the materials inside the socks. Upon arrival at the DEP Laboratory, the samples were scanned for radiological activity using a GM pancake probe. The samples were logged with the appropriate standard analysis code that designated the requested radiological analyses.

2.2.1.1 Gamma Spectroscopy

The samples were dried in a Presier Scientific Model 91-2290-83 100°C oven, ground to a fine powder (~80 mesh), weighed into a new 0.5-L Marinelli, sealed with general purpose polyethylene tape, and analyzed by high purity germanium gamma spectroscopy. The following radionuclides were identified or inferred using gamma spectroscopy:

Ra-226	Direct Energy Line	186 keV
Ra-228	Inferred Energy Line	911 keV (Ac-228)
U-235	Direct Energy Line	143 keV
Ac-228	Direct Energy Line	911 keV
Th-232	Inferred Energy Line	911 keV (Ac-228)
U-238	Inferred Energy Line	63.3 keV (Th-234)
Pb-212	Direct Energy Line	238 keV
Pb-214	Direct Energy Line	351 keV
Bi-212	Direct Energy Line	727 keV
Bi-214	Direct Energy Line	609 keV
K-40	Direct Energy Line	1,460 keV

The sample was counted again using gamma spectroscopy after a minimum of 21 days from the first analysis date. The same radionuclides were identified or inferred. Prior to the start of analysis, a daily background and instrument QC check was completed, reviewed, and validated. The gamma spectroscopy reference method is U.S. Department of Energy (DOE) 4.5.2.3.

2.2.1.2 X-ray Fluorescence

After gamma spectroscopy analyses were complete, the dried solid samples were analyzed for various elements using X-ray fluorescence (XRF). The samples were weighed into XRF sample cups, covered with a Prolene® film, and analyzed using an X-ray spectrometer. Forty-eight elements were analyzed using XRF. The XRF analyses were conducted using a DEP Laboratory-developed method. Standard QC calibration verification instrument checks were performed using National Institute of Standards and Technology (NIST) primary traceable standards.

2.2.1.3 Alpha Spectroscopy

One percent of solid samples analyzed by gamma spectroscopy were selected and analyzed using alpha spectroscopy for U-238, U-235, U-234, Th-232, Th-230, and Th-228. Prior to analysis, the samples were digested using Health and Environmental Chemistry: Analytical Techniques, Data Management, and Quality Assurance ER200 and ER230 sample preparation methods. A 10-gram (g) aliquot of the original solid sample matrix was digested and diluted to a final volume of 4 L, resulting in a concentration of 2.5 g/L. The isotopes and iron (Fe) carrier added were precipitated from the liquid as hydroxides, re-solubilized in hydrochloric acid (HCl), and then passed over a column of anion exchange resin, which removed the Fe and other interfering isotopes. Each isotopic fraction was concentrated, converted to the nitrate salt, and applied to a second anion exchange column. After washing the resin, the isotope was eluted, electrodeposited, and analyzed for isotopic U and Th. Instrument background, secondary, and pulser counts were obtained at the beginning and end of every sample batch. The alpha spectroscopy reference method is Standard Methods 7500-U C.

2.2.2 Liquid Matrix

The following sample types received at the DEP Laboratory were classified as liquid matrices:

- WWTP influent and effluent liquids
- Landfill leachates
- Well site liquids/fluids including:
  - Hydraulic fracturing fluid
  - Flowback fluid
  - Produced water

Based on solid content, a portion of the drilling mud samples were analyzed as liquids. Upon arrival at the DEP Laboratory, the samples were scanned for radiological activity using a GM pancake probe. The samples were preserved with nitric acid (HNO_3) to a potential hydrogen (pH) less than 2 and logged with the appropriate standard analysis code that designates the requested radiological analyses. After being acidified, samples were maintained a minimum of 16 hours prior to analysis. Samples were vacuum filtered using a 0.45-micron mixed cellulose ester filter. The filtrate was collected and transferred into a clean gallon cubitainer. The filtered solids were analyzed for gamma-emitting radionuclides using gamma spectroscopy (see solid matrix). The liquid samples were counted for gross α-, gross β-, and gamma-emitting radionuclides.

2.2.2.1 Gamma Spectroscopy

The liquid samples were measured to 3 L, placed into a clean 4-L Marinelli, sealed with general purpose polyethylene tape, and analyzed. The following radionuclides were identified or inferred using gamma spectroscopy:

Ra-226	Direct Energy Line	186 keV
Ra-228	Inferred Energy Line	911 keV (Ac-228)
U-235	Direct Energy Line	143 keV
Ac-228	Direct Energy Line	911 keV
Th-232	Inferred Energy Line	911 keV (Ac-228)
U-238	Inferred Energy Line	63.3 keV (Th-234)
Pb-212	Direct Energy Line	238 keV
Pb-214	Direct Energy Line	351 keV
Bi-212	Direct Energy Line	727 keV
Bi-214	Direct Energy Line	609 keV
K-40	Direct Energy Line	1,460 keV

The samples were counted again using gamma spectroscopy after a minimum of 21 days from the date of their first analysis. The same radionuclides were identified or inferred each day analyses were performed. Prior to the start of analysis, a background and standard QC calibration verification check was completed, reviewed, and validated.

2.2.2.2 Gross Alpha Gross Beta Analyses

An aliquot of sample was evaporated to less than 5 milliliters. The evaporated volume was transferred to a 2-inch diameter planchet using 10 percent HNO_3 and dried. The dried sample was placed in a desiccator for 72 hours. The samples were flamed to convert the hydroscopic salts to oxides. The samples were counted for gross α- and gross β-emitting radionuclides using a gas proportional counter. Standard QC calibration verification and daily background checks were completed, reviewed, and validated at the beginning and end of analysis. The gross α and gross β reference method is EPA 900.0.

2.2.2.3 X-Ray Fluorescence

The liquid samples were analyzed for various metals using XRF. The samples were weighed into XRF sample cups, covered with a Prolene® film, and analyzed using an X-ray spectrometer. Forty-eight elements were identified using XRF. The XRF analyses were conducted using a DEP Laboratory-developed method. Standard QC calibration verification instrument checks were performed using NIST primary traceable standards.

2.2.2.4 Inorganic Analyses

During the third round of sampling, additional analyses including basic inorganic analyses were included as part of the study. The samples were received by the DEP Laboratory and logged with the appropriate standard analysis code that designated the requested inorganic analyses. The analyses included hardness (SM2340 B), pH (SM4500H-B), specific conductance at 25.0°C (SM2510B), total chloride (SM4500-CL E), total sulfate (EPA 375.2), total dissolved solids at 180°C (USGS I-1750), and total suspended solids (USGS I-3765).

2.2.3 Gas Matrix

Natural gas samples were collected at various locations using scintillation cells and analyzed for Rn concentration. The scintillation cells were counted in one of two counters: the Pylon AB-5

Portable Radiation Monitor or the Ludlum Model 2200 Scaler-Ratemeter. The counter used was dependent upon the type of scintillation cell used to collect the sample. All samples were allowed to equilibrate for a minimum of four hours before being counted. In all cases, the first count was not used in the calculations to allow for "dark adaptation" of the instruments. The next three counts were each individually calculated and the average and standard deviation calculated. The average result, plus or minus (±) two standard deviations, and the minimum detectable activity are reported in the data tables.

Natural gas is composed mostly of methane, which is lighter and less dense than air. Alpha counting efficiency is directly proportional to the density of the gas counted. Because the scintillation cells were calibrated using a known concentration of Rn in ambient air, density correction was applied to all Rn in natural gas results. A correction factor (Jenkins et al., 2014) was used for this effect to prevent biasing the results. The final calculated Rn concentrations were divided by 1.054. This reduced all results by five percent to correct for the bias.

2.2.4 Filter Matrix – Smears

All smear samples were collected by Perma-Fix technicians and transported to the Perma-Fix Laboratory for analysis. All smear samples were counted for gross α and gross β radioactivity. Ten percent of those smear samples were then forwarded to the DEP Laboratory for duplicate analysis as a QC measure.

Upon arrival at the Perma-Fix laboratory, the samples were logged. The smear samples were placed on a 2-inch diameter planchet and analyzed for gross α and gross β particles using a Ludlum Model 2929 Meter equipped with a Ludlum Model 43-10-1 Smear Counter (zinc-sulfide scintillation detector). A standard QC background and calibration verification count was performed each day the smear counter was used.

Upon receipt at the DEP Laboratory, the samples were logged. The smear samples were placed on a 2-inch diameter planchet and analyzed for gross α and gross β particles using a gas proportional counter. Prior to the start of analysis, an instrument source check and background check were completed, reviewed, and validated. The gross α and gross β filter analyses were conducted using the DEP Laboratory-developed method. A standard QC calibration verification instrument check was performed with NIST traceable sources.

2.3 <u>Survey and Sample Analyses Data Management</u>

All of the solid and liquid samples were analyzed by the DEP Laboratory using gamma spectroscopy. The result, the standard two-sigma error (95 percent confidence level) and the minimum detectable concentration (MDC) were reviewed for each of the following radionuclides as reported:

- Natural Uranium Decay Series Results (U-238, Ra-226, Pb-214, and Bi-214)
- Natural Thorium Decay Series Results (Th-232, Ra-228, Ac-228, Pb-212, and Bi-212)
- Natural Actinium Decay Series Results (U-235)
- Miscellaneous (K-40)

2.3.1 Limitations on Gamma Spectroscopy Results

The following limitations on gamma spectroscopy of radioactive samples were considered when reviewing the analytical results for solid and liquid samples:

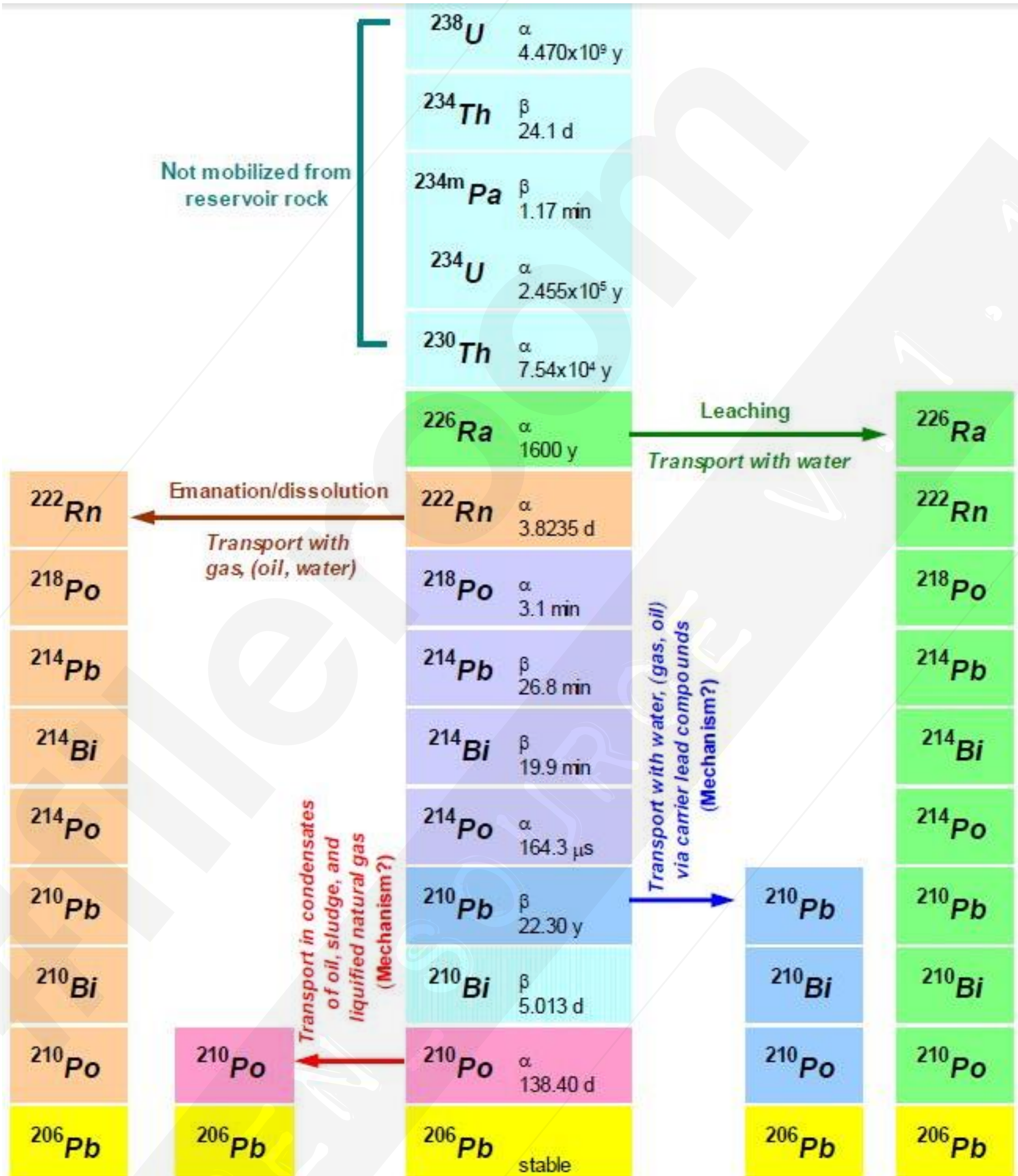
- Gamma spectroscopy cannot directly measure radium (Ra)-228. Rather, Ra-228 is inferred from a short-lived progeny of Ra-228, Ac-228, which is readily detected by gamma spectroscopy when the radionuclides are in secular equilibrium. Due to the relative half-lives of Ra-228 (5.8 years) and Ac-228 (6.1 hours) after 24 hours, this is always the case for the samples collected as part of the study.
- Gamma spectroscopy cannot directly measure Th-232. Consequently, Th-232 is inferred from the short-lived progeny of Th-232, Ac-228, when the radionuclides are in secular equilibrium. Due to the difference in solubility between Th and Ra, this is not the case in liquid samples or in solid samples of wastewater residue, sludge and filter cake. Only the soluble Ra and progeny of Ra are present in those samples. Consequently, knowledge of the status of the secular equilibrium of the Th decay series within the sample matrix is necessary to properly evaluate gamma spectroscopy results. **Figures 2-1** and **Figure 2-2** present the solubility of the Uranium and Thorium Series.
- Uranium-238 can be detected by gamma spectroscopy, but the gamma emission used is of low energy and low yield, resulting in a high MDC and high standard error compared to the other radionuclides in the environment. Consequently, the U-238 result is not used as positive identification of U-238 without knowledge of the status of U series secular equilibrium and the identification of additional, more statistically robust U progeny.
- Uranium is insoluble in water while Ra is water soluble. Therefore, wastewater, produced and flowback fluids, and wastewater treatment solids (sludge and filter cake) contain Ra and its progeny but do not include U.

Only the radionuclides present in a given sample are reported in the following sections. The average, median, standard deviation, and minimum and maximum values are also provided at the bottom of each table for each set of results. Please note:

- When the reported result is less than the MDC, a value equal to ½ the MDC is used in the derivation of average, median, standard deviation, and minimum and maximum values.
- When "<" precedes the reported result, the value is the MDC.

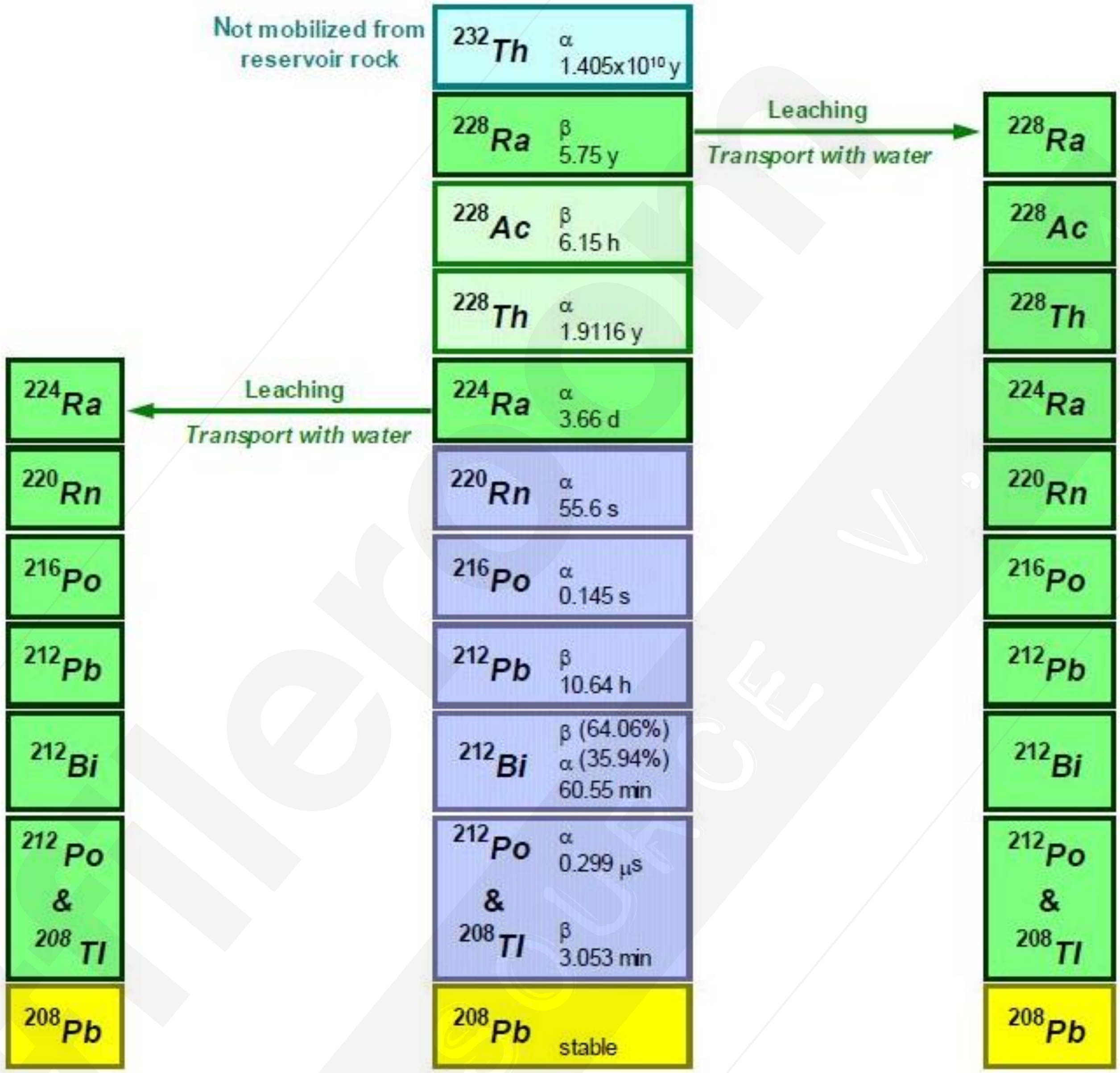
Appendix C contains the gamma spectroscopy analytical analysis results for each radionuclide identified along with their associated standard two-sigma counting error (error) and the MDC for the analyses.

Figure 2-1. Solubility of the Uranium Series in Oil and Gas Produced Water



Source: IAEA 2010.

Figure 2-2. Solubility of the Thorium Series in Oil and Gas Produced Water



Source: IAEA 2010.

2.3.2 Radium-226 Quantification by Gamma Spectroscopy

Radium-226 may be measured directly by detection of its 186.2 kilo-electron volt (keV) energy line, 3.28 percent yield. For liquid samples and sludge/filter cake samples that do not contain U, this yields an accurate Ra-226 result. However, in soil and drill cutting samples, the presence of U-235 causes interference with direct Ra-226 detection because one of its gamma lines is of similar energy, 185.7 keV at 54 percent yield. In solid samples where natural U including U-238 and Ra-226 are at equal activity and U-235 is at 1/22 the activity of U-238, the theoretical overestimation of Ra-226 was quantified assuming the gamma peaks for Ra-226 and U-235 completely overlap. The theoretical overestimation of Ra-226 is presented in **Table 2-1**.

The short-lived equilibrium progeny of Ra, Pb-214 and Bi-214, may be used to infer Ra-226 concentrations in soil or drill cuttings when U-235 is present in the sample. The parent of these progeny, Rn-222, is a gas and has a half-life of 3.8 days. When the soil or drill cuttings sample is collected, some of the Rn gas escapes the solid matrix. Therefore, samples are sealed to allow the Rn gas to in-grow to reestablish equilibrium after the sample has been sealed.

2.3.3 Criteria for Comparison to Analytical Analyses Results

Table 2-2 presents criteria against which the analytical results and assessments of this study were evaluated.

2.3.4 Normal Background Radioactivity Values

Table 2-3 presents average, minimum, and maximum background radioactivity values for soil in the U.S. used as a reference point when reviewing analytical results of solid samples.

2.3.5 Data Presentation

A large volume of survey and sample analytical analyses data were generated. The next five sections present the survey and sampling data for Well Sites, WWTPs, Landfills, Gas Distribution and End Use, and Brine-Treated Roads.

All numbers in this report have been rounded to three significant figures. Actual significant figures for each reported value can be found in **Appendix C**, *Gamma Spectroscopy Analytical Results*.

Table 2-1. Theoretical Overestimation of Ra-226 Activity in Solid Samples with Natural Uranium Analyzed by Gamma Spectroscopy

Radionuclide	(pCi/g)	(pCi/g)	(pCi/g)	(pCi/g)	(pCi/g)	(pCi/g)	(pCi/g)
U-238	1.00	2.00	3.00	4.00	5.00	10.0	20.0
U-235	0.05	0.09	0.14	0.18	0.23	0.45	0.91
Ra-226	1.00	2.00	3.00	4.00	5.00	10.0	20.0
Excess Ra-226[a]	0.75	1.51	2.26	3.02	3.77	7.54	15.1
Reported Ra-226	1.75	3.51	5.26	7.02	8.77	17.5	35.1
Excess U-235[b]	0.06	0.12	0.18	0.24	0.30	0.60	1.21
Reported U-235	0.11	0.21	0.32	0.42	0.53	1.06	2.11

[a]Excess Ra-226 is calculated by converting the U-235 value to Ra-226 activity by a factor equal to the ratio of the gamma yields, i.e., 50.4/3.28.
[b]Excess U-235 is calculated by converting the Ra-226 value to Ra-226 activity by a factor equal to the ratio of the gamma yields, i.e., 3.28/50.4.

Table 2-2. Criteria for Comparison

Parameter	Criteria	Reference	Potentially Apply to:
Volumetric Solids	3 pCi/g Total Radium (Ra-226 + Ra-228) above background	American National Standards Institute (ANSI)/Health Physics Society (HPS) N13.53-2009, Control and Release of Technologically Enhanced NORM (TENORM) (2009)	Sediment, Beneficial Use Surface Soil, Surface Soil on Well Sites
Volumetric Solids	5 pCi/g Total Radium (Ra-226 + Ra-228) above background	EPA Directive No. 9200.4-35, Remediation Goals for Radioactively Contaminated CERCLA Sites (2000)	Sediment, Beneficial Use Surface Soil, Surface Soil on Well Sites
Volumetric Solids	270 pCi/g Total Radium (Ra-226 + Ra-228)	U.S. Department of Transportation (DOT), 49 CFR 173.436, Radioactive Material (in regards to transportation)	Sludge, Filter Cake, Filter Socks, Scale, Cuttings
Volumetric Liquids	5 pCi/L Total Radium (Ra-226 + Ra-228) in drinking water	EPA Drinking Water Standard, 40 CFR 141.66	Effluent Water from Well Sites
Volumetric Liquids	60 pCi/L Total Radium (Ra-226 + Ra-228) direct discharge	U.S. Nuclear Regulatory Commission (NRC), 10 CFR Part 20 Appendix B, Table 2, Liquid Effluent	Effluent Water from Well Sites and Wastewater Facilities
Volumetric Liquids	600 pCi/L Total Radium (Ra-226 + Ra-228) discharge to sanitary sewer	U.S. NRC, 10 CFR Part 20 Appendix B, Table 2, Liquid Effluent (assumes dilution and solubility of Ra)	Effluent Water from Well Sites and Wastewater Facilities
Total Alpha Surface Contamination	100 dpm/100 cm^2	U.S. NRC, Regulatory Guide 1.86, Termination of Operating Licenses for Nuclear Reactors (1974)—Criteria for Ra-226	Structural surfaces on well sites and within wastewater facilities, and equipment released from sites

Table 2-2. Criteria for Comparison

Parameter	Criteria	Reference	Potentially Apply to:
Total Beta Surface Contamination	1,000 dpm/100 cm^2	U.S. NRC, Regulatory Guide 1.86, Termination of Operating Licenses for Nuclear Reactors (1974)—Criteria for natural Th including Ra-228	Structural surfaces on well sites and within wastewater facilities, and equipment released from sites
Removable Alpha Surface Contamination	20 dpm/100 cm^2 (of surface area smear sampled)	U.S. NRC, Regulatory Guide 1.86, Termination of Operating Licenses for Nuclear Reactors (1974)—Criteria for Ra-226	Structural surfaces on well sites and within wastewater facilities, and equipment released from sites
Removable Beta Surface Contamination	200 dpm/100 cm^2 (of surface area smear sampled)	U.S. NRC, Regulatory Guide 1.86, Termination of Operating Licenses for Nuclear Reactors (1974)—Criteria for natural Th including Ra-228	Structural surfaces on well sites and within wastewater facilities, and equipment released from sites
Volumetric Gas	4 pCi/L	EPA, 402/K-12/002, A Citizen's Guide to Radon (2012)	Buildings, General Public
Volumetric Gas	30 pCi/L Derived Air Concentration (DAC)	U.S. NRC, 10 CFR Part 20 Appendix B, Table 1, Col 3	Occupational Exposure
Volumetric Gas	100 pCi/L	Occupational Safety and Health Administration (OSHA) 29 CFR 1910.1096	General Public Workforce
Annual Exposure	25 mrem/year plus as low as reasonably achievable (ALARA)	U.S. NRC, 10 CFR 20.1402-20.1403, Radiological Criteria for Unrestricted Use	General Public
Annual Exposure	100 mrem/year	U.S. NRC, 10 CFR 20.1301, Radiation Dose Limits for Members of the Public	General Public Workers not trained as Radiation Workers, i.e., well site and water facilities workers

Table 2-2. Criteria for Comparison

Parameter	Criteria	Reference	Potentially Apply to:
Annual Exposure	5,000 mrem/year	U.S. NRC, 10 CFR 20.1201, Occupational Dose Limits for Adults	Radiation Workers

Table 2-3. Natural Background Radioactivity Values for U.S. Soil

Material	U-238 (pCi/g)	Ra-226 (pCi/g)	Th-232 (pCi/g)	K-40 (pCi/g)
Soil (Average)[a]	0.95	1.1	0.95	10
Soil (Minimum)[a]	0.11	0.22	0.11	2.7
Soil (Maximum) [a]	3.8	4.3	3.5	19

[a]UNSCEAR, Sources and Effects of Ionizing Radiation (UNSCEAR 2000).

3.0 WELL SITES

Thirty-eight well sites, including four conventional wells and 34 unconventional wells, were sampled from June 2013 through July 2014. Data from five phases of well development and completion were collected: vertical drilling, horizontal drilling, hydraulic fracturing, flowback, and production. A listing of the well types, formations, phases, and geographic regions is provided below.

- 4 Conventional Wells
  - Formations
    - 1 in the Lower Devonian/Oriskany
    - 3 in the Upper Devonian
  - Phase
    - Production Phase
- 34 Unconventional Wells
  - Formations
    - 29 in the Lower Devonian/Marcellus
    - 2 in the Lower Devonian/Marcellus Sandstone
    - 1 in the Upper Devonian/Burket
    - 2 in the Middle Ordovician/Utica
  - Phases
    - 10 sampled during the vertical drilling phase
    - 10 sampled during the horizontal drilling phase
    - 10 sampled during the hydraulic fracturing phase
    - 9 sampled during the flowback phase
    - 19 sampled during the production phase
      - 9 sampled for fluids and Rn
      - 10 sampled for just Rn
  - Regions
    - 1 in the Northeast Region
    - 17 in the North-central Region
    - 4 in the Northwest Region
    - 16 in the Southwest Region

3.1 <u>Radiological Survey Results</u>

Radiological surveys were conducted at each well site resulting in four data sets:

- *Removable α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Total α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Gross Gamma Radiation Scan* measurements recorded in units of cpm
- *Gamma Radiation Exposure Rate* measurements recorded in units of µR/hr

3.1.1 Removable Alpha/Beta Surface Radioactivity Measurement Results

Measurements of removable α/β surface radioactivity were performed to assess potential internal radiation worker exposure through ingestion and/or inhalation. The results were evaluated using the NRC Regulatory Guide 1.86 (RG 1.86) guidelines. RG 1.86 Table 1 requires that α and β levels be evaluated separately. The primary α emitter of concern is Ra-226 with a removable criterion of 20 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a removable criterion of 200 dpm β/100 cm^2. The average removable α and β levels at each well site were below the RG 1.86 criteria. The maximum removable α and β levels were 14.9 dpm/100 cm^2 and 123 dpm/100 cm^2, respectively, also below the RG 1.86 criteria. The summary results of removable α/β radioactivity for each of the well sites surveyed are presented in **Table 3-1.** Individual smear sample removable α/β results are presented in **Appendix D.**

3.1.2 Total Alpha/Beta Surface Radioactivity Measurement Results

Measurements of total α/β surface radioactivity were performed to assess potential worker internal radiation exposure through ingestion and/or inhalation. The results were evaluated using the RG 1.86 Table 1 guidelines. RG 1.86 requires that α and β activity be evaluated separately. The primary α emitter of concern is Ra-226 with a total criterion of 100 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a total criterion of 1,000 dpm β/100 cm^2. The maximum average total α and β levels measured at any single well site were 93.0 dpm/100 cm^2 and 1,630 dpm/100 cm^2. The maximum total α and β levels measured were 754 dpm/100 cm^2 and 2,503 dpm/100 cm^2. The summary results of total α and β surface radioactivity for each of the well sites surveyed are presented in **Table 3-2**. Individual total α/β measurement results are presented in **Appendix D.**

3.1.3 Gross Gamma Radiation Scan Results

Gross gamma radiation scans recorded in cpm were performed on well sites to identify areas of radioactivity above local background levels. Summary results for each of the well sites surveyed and each phase surveyed are presented in **Table 3-3**. The highest average gross gamma radiation count rate was 14,519 cpm (approximately 18 μR/h), and the maximum gamma radiation scan result measured was 30,823 cpm (approximately 39 μR/h). A graphic display of the gamma radiation scan results (figures) at each facility was prepared using geographic information system (GIS) software. Figures are presented in **Appendix E**.

3.1.4 Gamma Radiation Exposure Rate Results

Gross gamma radiation scan results in units of cpm presented in **Table 3-3** were converted to μR/hr using the 800 cpm per μR/hr conversion factor appropriate for Ra-226 gamma energy as detected with 2-inch by 2-inch NaI detectors, rounded to one significant figure (Table 6.4, NaI Scintillation Detector Scan MDCs for Common Radiological Contaminants, NUREG-1507, Minimum Detectable Concentrations With Typical Radiation Survey Instruments for Various Contaminants and Field Conditions, USNRC June 1998). The exposure rate results for each well site are presented in **Table 3-4**. The highest average exposure rate measured at any single site was 18.1 μR/hr, and the maximum gamma exposure rate measured was 38.5 μR/hr.

3.2 Solid Sample Results

3.2.1 Vertical Phase Drill Cuttings

Vertical cuttings were sampled at 11 unconventional well sites and analyzed using gamma spectroscopy to identify gamma-emitting members of the natural U, Th, and Ac decay series. The gamma spectroscopy results are presented in **Table 3-5**. XRF analysis was also performed on the vertical drill cuttings to identify non-gamma-emitting isotopes of U-238 and Th-232. XRF ppm concentration data for Th was converted to pCi/g of Th-232 using the specific activity of 0.110 pCi/g Th-232 per ppm of Th. XRF ppm concentration data for U was converted to pCi/g of U-238 using the specific activity of 0.334 pCi/g U-238 per ppm of U. Both the ppm and the pCi/g results for 10 well sites are presented in **Table 3-6**. All of the XRF analytical results are presented in **Appendix F**.

There were two methods for managing drill cuttings at the well sites. The first method, called a "half round," accumulates cuttings in a large mixing container where the materials were stabilized prior to shipment to the landfill. This method does not provide an opportunity to collect samples at discrete depths; consequently, a composited sample was collected during vertical drilling. This method was used at nine of the 10 well sites.

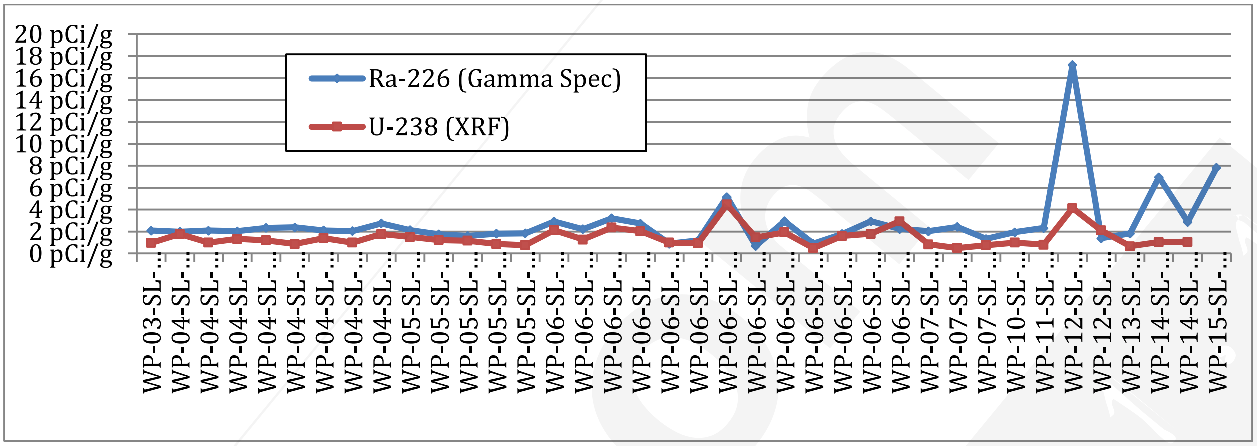
The second method loads the cuttings into roll-off containers from the shaker tables. This method enables sampling of cuttings from discrete depths. Each container was labeled with the start and end depth of the collected material. The formations sampled are presented in **Table 3-6** for these vertical drill cuttings. This method was used at one well site.

The U series activities are variable because the vertical cuttings represent different geologic formations lying above the target natural gas-containing shale. These vertical drill cuttings are mostly siltstones and sandstones. Potassium-40 (K-40) concentrations provide an indication of the type of formation. Shale has higher levels of K-40 than sandstone. Shale is typically in the range of 25-30 pCi/g of K-40 while sandstone typically contains approximately 5 pCi/g of K-40.

The U-238 measured using XRF and the Ra-226 measured using gamma spectroscopy were compared to confirm secular equilibrium of the U decay series within drill cuttings. **Figure 3-1** provides a graphic representation of this comparison and shows agreement between the two U series radionuclides, indicating secular equilibrium. Although the gamma spectroscopy results for Ra-226 are consistently higher than the XRF results for U-238, both values trend together, i.e., increase and decrease together. The high bias of the Ra-226 gamma spectroscopy results is due in part from the U-235 interference when identifying Ra-226 using gamma spectroscopy of the 186 keV gamma line. (Refer to Section 2.3.2 for a complete discussion of Ra-226 detection using gamma spectroscopy.) U-235, which is also present in drill cuttings, also emits gamma at 186 keV, causing a consistent positive bias of Ra-226 results.

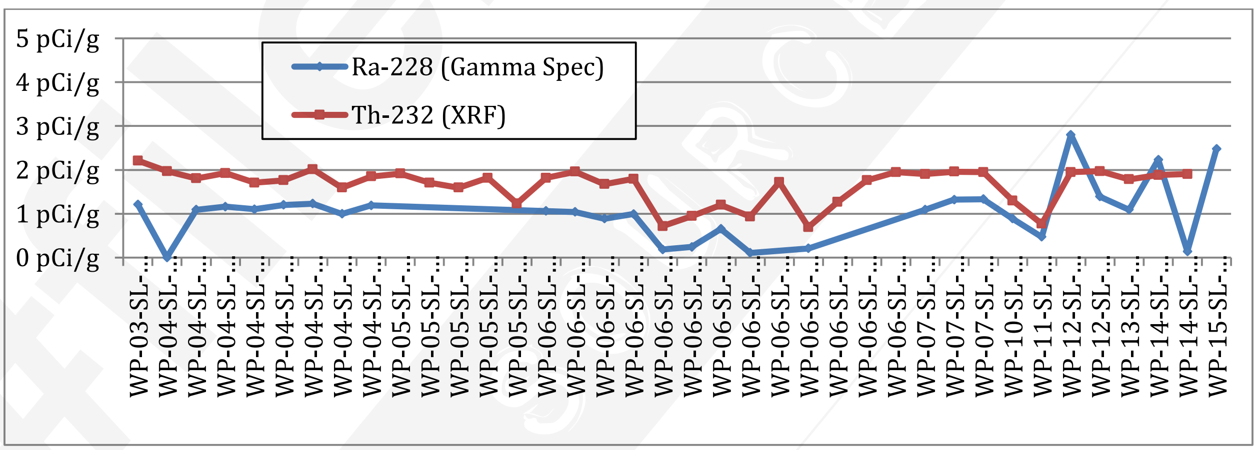
Th-232 and Ra-228 do not emit gamma rays identifiable by gamma spectroscopy; consequently, the levels were inferred from the Ac-228 gamma rays. The Th-232 series radionuclide activity levels all typify natural background for soil (reference Table 2-3).

Figure 3-1. Comparison of Ra-226 Gamma Spectroscopy Results to U-238 XRF Results in Vertical Drill Cuttings



The Th-232 identified using XRF and the Ra-228 inferred using gamma spectroscopy were compared to confirm secular equilibrium of the Th decay series within drill cuttings. **Figure 3-2** provides a graphic representation of this comparison and shows agreement between the two Th series radionuclides.

Figure 3-2. Comparison of Ra-228 Gamma Spectroscopy Results to Th-232 XRF Results in Vertical Drill Cuttings



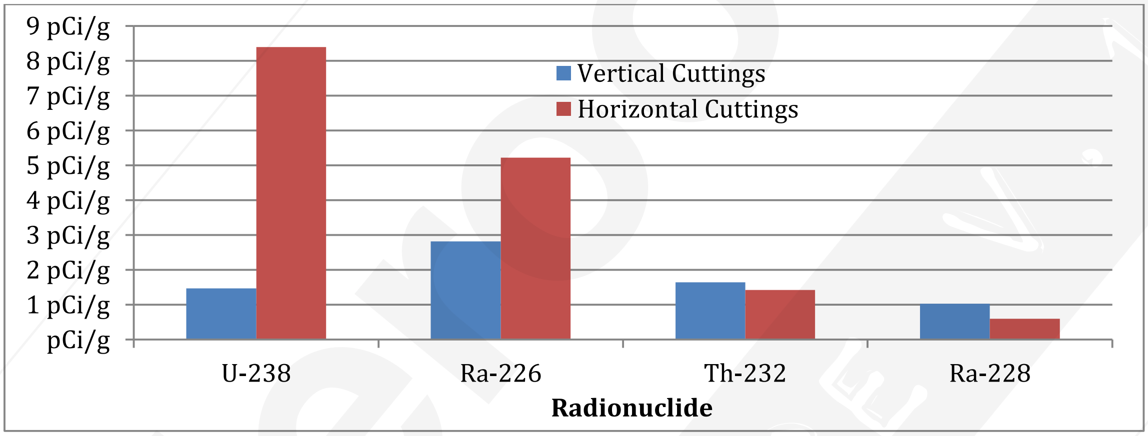
The Th-232 to Ra-228 values for most samples trend together, i.e., when the activity concentration of one increases, there is a comparable increase in the other.

3.2.2 Horizontal Phase Drill Cuttings

The same two cuttings management methods described for vertical drill cuttings were also used for horizontal drill cuttings. A total of 18 samples were collected from the horizontal well bore target formations on 10 well sites. The gamma spectroscopy and XRF results are presented in **Tables 3-7** and **3-8**.

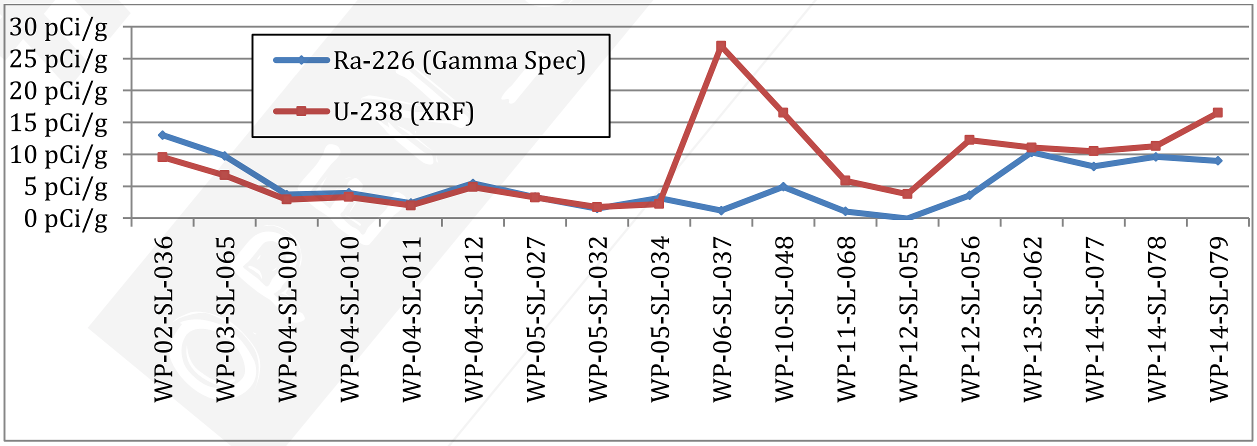
Figure 3-3 presents the analytical results for vertical and horizontal cutting samples. The horizontal drill cuttings had higher concentrations of Ra-226 than the vertical drill cuttings as determined using a student t-test. The two-sample student t-test was used to compare the horizontal drill cuttings Ra-226 results with the vertical drill cuttings Ra-226 results. ProUCL version 5.0 was used to perform the student t-test on the data. The Null Hypothesis tested is that the mean value of the vertical drill cuttings Ra-226 results and the mean value of the horizontal drill cuttings Ra-226 results are statistically different at the 95 percent confidence level. The Null Hypothesis was accepted; mean values are statistically different at the 95 percent confidence level. The same t-test was run on the U-238 results for vertical and horizontal drill cuttings. Again, the difference between the mean values of U-238 for vertical and horizontal drill cuttings is statistically different at the 95 percent confidence level. **Appendix G** presents the t-test output files.

Figure 3-3. Comparison of Analytical Analyses Results for Horizontal and Vertical Drill Cutting Samples



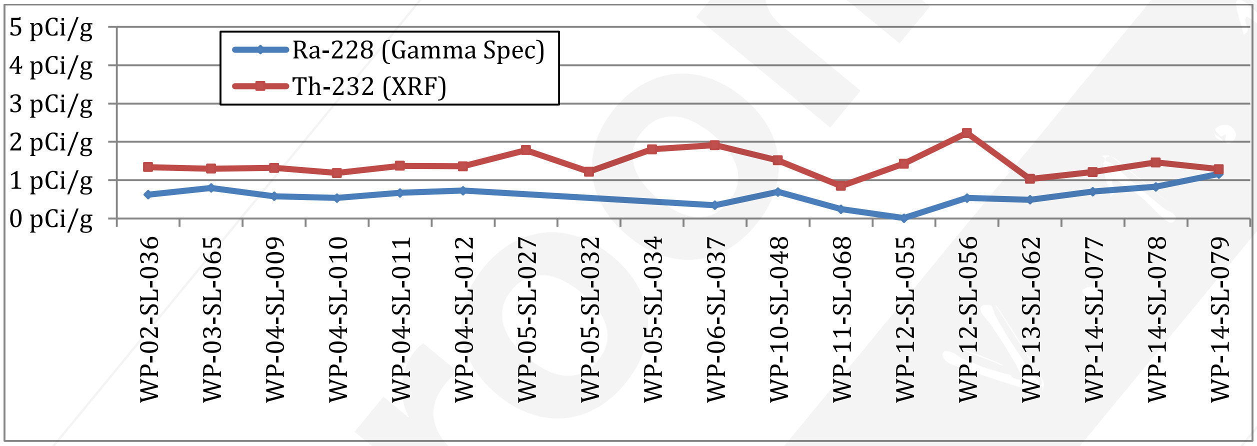
The U concentration (ppm) measured using XRF was converted to pCi/g of U-238 using the specific activity of 0.334 pCi/g U-238 per ppm of U. The U-238 measured using XRF and the Ra-226 measured using gamma spectroscopy were compared to confirm secular equilibrium of the U decay series within drill cuttings. **Figure 3-4** provides a graphic representation of this comparison and shows agreement between the two U series radionuclides, indicating secular equilibrium.

Figure 3-4. Comparison of Ra-226 Gamma Spectroscopy Results to U-238 XRF Results in Horizontal Drill Cuttings



The Th concentration (ppm) measured using XRF was converted to pCi/g of Th-232 using the specific activity of 0.110 pCi/g Th-232 per ppm of Th. The Th-232 measured using XRF and the Ra-228 inferred using gamma spectroscopy were compared to confirm secular equilibrium of the Th decay series within drill cuttings. **Figure 3-5** provides a graphic representation of this comparison.

Figure 3-5. Comparison of Ra-228 Gamma Spectroscopy Results to Th-232 XRF Results in Horizontal Drill Cuttings



The Th-232 to Ra-228 values trend together, i.e., when the activity concentration of one increases, there is a comparable increase in the other.

3.2.3 Drilling Mud

In addition to drill cuttings, drilling mud was also collected when in use on the sites. A total of 14 drilling mud samples were collected during both the vertical and horizontal phases of drilling. The drilling mud was evaluated as a drilling solid or a drilling liquid as determined when received by the laboratory. Nine of those samples were analyzed as solids and the other five as liquids. The gamma spectroscopy results for solids are presented in **Table 3-9**.

Analytical results for the drilling mud demonstrate secular equilibrium within the U and Th natural decay series, i.e., the activity concentrations within the natural series radionuclides identified are approximately equal. All results were within the range of typical natural background found in surface soils (reference Table 2-3), given the overestimation of Ra-226 in the presence of U-235 as discussed in Section 2.3.2.

3.2.4 Hydraulic Fracturing Proppant Sand

During hydraulic fracturing, 10 well sites were surveyed and sampled. The proppant sand was collected from the sand hoppers prior to being mixed with fluids and injected into the well. The gamma spectroscopy results are presented in **Table 3-10**.

The sand contained nominal concentrations of U and Th series. The sand did not contain radioactivity exceeding that of natural background levels found in surface soil (reference **Table 2-3**).

3.2.5 Flowback Solids

A total of eight well sites were surveyed and sampled during the flowback phase. From the eight well sites, sufficient volumes to perform analytical analysis of solids were only present at four of the eight well sites. The gamma spectroscopy results are presented in **Table 3-11**.

Uranium and Th are at or below background activity levels. Radium-226 was elevated above background levels for soil (reference Table 2-3) ranging from 0.763 to 7.73 pCi/g.

3.3 Liquid Sample Results

Liquid sampling included drilling mud, hydraulic fracturing fluids, flowback fluids, and produced water.

3.3.1 Drilling Liquid (Mud)

A total of 14 drilling mud samples were collected from both vertical and horizontal phases. The drilling mud was evaluated as a drilling solid or a drilling liquid as determined when received by the laboratory. Five of the samples were analyzed as liquids. Because of the large concentrations of solids in the samples, gross α and gross β analyses were performed on only two samples. The results for Ra-226, Ra-228, K-40, gross α and gross β are presented in **Table 3-12**.

3.3.2 Hydraulic Fracturing Fluid

Hydraulic fracturing fluid was sampled prior to injection into the well. The well sites sampled during the study utilized hydraulic fracturing fluid made up of either fresh water, reused flowback liquid, produced water, or a combination of the three to perform the hydraulic fracturing phase. If a combination of fluids was used for fracturing, only the produced water was collected as a sample because it was not possible to collect a sample after the hydraulic fracturing fluid had been mixed for injection. The results for Ra-226, Ra-228, K-40, gross α and gross β are presented in **Table 3-13**.

Radium-226 was detected within the hydraulic fracturing fluid ranging from 64.0 to 21,000 pCi/L. Ra-228 was also detected ranging from 4.50 to 1,640 pCi/L. Table 2-2 contains several volumetric liquids criteria for relative comparison: 5 pCi/L total Ra EPA maximum contaminant level for drinking water, 60 pCi/L total Ra USNRC direct discharge, and 600 pCi/L total Ra USNRC discharge to sanitary sewer.

3.3.3 Flowback Fluid

Flowback fluid is the injected hydraulic fracturing fluid and other fluids returning to the surface of the well prior to the well entering production. The results for Ra-226, Ra-228, K-40, gross α and gross β are presented in **Table 3-14**.

Radium-226 concentrations were elevated, ranging from 551 to 25,500 pCi/L. Radium-228 was also elevated, ranging from 248 to 1,740 pCi/L. Table 2-2 contains several volumetric liquids criteria for relative comparison: 5 pCi/L total Ra EPA drinking water, 60 pCi/L total Ra USNRC direct discharge, and 600 pCi/L total Ra USNRC discharge to sanitary sewer.

3.3.4 Produced Water

Twelve wells were sampled for produced water, including four conventional and eight unconventional wells. The results for unfiltered and filtered Ra-226, Ra-228, K-40, gross α and gross β are presented in **Tables 3-15** and **3-16**.

Radium-226 concentrations in unfiltered samples were elevated, ranging from 40.5 to 26,600 pCi/L. Radium-228 concentrations were also elevated, ranging from 26.0 to 1,900 pCi/L.

Radium-226 concentrations were also elevated in filtered samples, ranging from 87.0 to 24,100 pCi/L. Radium-228 concentrations were also elevated, ranging from 44.0 to 1,860 pCi/L.

3.4 Radon Sample Results

3.4.1 Ambient Air Samples During Flowback

Seventeen ambient air samples for evaluation of Rn concentration were collected during flowback at four different well sites. The EICs were distributed around the well site approximately 3 feet (ft) above grade and at available locations as close as 6 ft and as far as 40 ft from the well head. The EICs collected data from four to seven days. The results are presented in **Table 3-17**. The Rn analytical reports are presented in **Appendix H**.

The Rn measurement results during flowback in ambient air range from 0.200 to 1.70 pCi/L while typical ambient background Rn concentrations range from 0.00 to 1.11 pCi/L (with a median value of 0.39 pCi/L) in outdoor ambient air in the U.S., as reported by EPA.

3.4.2 Production Gas Radon

Twenty-two production site natural gas samples were collected in eight counties (Washington, Tioga, Lycoming, McKean, Forest, Sullivan, Bradford and Jefferson). Seventeen of the natural gas samples were collected from Marcellus Shale, and five natural gas samples were collected from other geologic formations.

The production site natural gas samples for Rn were collected between the well head and the separator unit(s). A typical sampling location is shown in **Figure 3-6**. All natural gas samples were collected directly into scintillation cells, referred to as Lucas Cells. Section 2.0 describes the sample collection in detail.

The sample results are presented in **Table 3-18.** The results ranged from 3.00 to 148 pCi/L. The median Rn concentration in natural gas is 41.8 pCi/L. The Rn analysis analytical reports are presented in **Appendix H**.

3.5 Well Site Worker Exposure Assessment

The study included radiation measurements collected on 21 well sites to provide a comprehensive evaluation of potential personnel radiation exposure from working on well sites. The measurements included:

Figure 3-6. Natural Gas Radon Sampling Location

- Gamma radiation count rate using a NaI detector (gross cpm), converted to exposure rate potential, to estimate potential external gamma exposure.
- Total α/β surface radioactivity measurements using a scintillation detector to evaluate potential β external exposure as well as α/β surface activity having the potential to become removable and, therefore, becoming a potential internal exposure.
- Removable α/β surface radioactivity measurements (dpm/100 cm^2) by smear samples counted on an α/β counter to estimate potential α and β internal exposure.
- Ambient air samples analyzed for Rn concentration to estimate Rn inhalation exposure.

The measurements were taken during four work phases on natural gas well sites to ensure appropriate evaluation of potential exposure to TENORM present on well sites. The phases are:

- Vertical/Horizontal Drilling – personnel are potentially exposed to drill cuttings while working on the site.
- Hydraulic Fracturing – personnel are potentially exposed to radioactivity in hydraulic fracturing fluid while working on the site.
- Flowback – personnel are potentially exposed to radioactivity in flowback water while working on the site.
- Production – personnel are potentially exposed to radioactivity in produced water while working on the site.

3.5.1 External Gamma Exposure

Gross gamma scan results in units of cpm presented in **Table 3-3** were converted to μR/hr using the 800 cpm per μR/hr conversion factor appropriate for Ra-226 gamma energy as detected with 2-inch by 2-inch NaI detectors [Table 6.3, NaI Scintillation Detector Count Rate Versus Exposure Rate (cpm/μR/hr), NUREG-1507, Minimum Detectable Concentrations With Typical Radiation Survey Instruments for Various Contaminants and Field Conditions, USNRC June 1998]. The local background gamma exposure rate across all well sites surveyed was measured at 5 μR/hr. The exposure rate results are presented in **Table 3-4**.

The lowest exposure rates measured and the maximum exposure time were during drilling. The highest exposure rates measured were in the proximity of holding tanks for produced water. The gamma dose rates during drilling ranged from background (measured at 5 μR/hr) to a maximum of 38.5 μR/hr, and the highest average exposure rate at any of the well sites was 18.1 μR/hr. Assuming the time period of exposure is a full occupational year of 2,000 hours, the average well site external gamma exposure was estimated as follows:

Maximum Average Well Site External Gamma Exposure Estimate

$$(18.1 - 5)\ \mu R/hr \times 2000\ hr/yr \times (1\ mrem/1{,}000\ \mu R\ gamma) = 26.2\ mrem/yr$$

The result is less than the 100 mrem/yr dose equivalent limit for a member of the public. Actual exposure is dependent upon the actual exposure rates and occupancy time for individual workers.

3.5.2 Internal Alpha/Beta Exposure

Results for α/β surface radioactivity measurements are provided in Sections 3.1.1 and 3.1.2. Ten of the 491 α measurements and 69 of the 491 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. Only one of 493 α removable surface activity measurements and one of 493 β removable surface radioactivity measurements exceeded RG 1.86 criteria, indicating the total α/β surface radioactivity measured is fixed to the surface and not readily available for inhalation or ingestion.

3.5.3 Internal Radon Exposure

The Rn measurement results in ambient air during flowback range from 0.200 to 1.70 pCi/L, while typical ambient background Rn concentrations range from 0.00 to 1.11 pCi/L, with a median of 0.39 pCi/L in outdoor ambient air in the U.S., as reported by EPA.

3.6 <u>Well Site Data Assessments</u>

3.6.1 Comparison of Different Geological Formations Based on X-Ray Fluorescence Data

Eighteen drill cutting samples were collected and analyzed for Th and U using XRF. The samples were collected from the Lower Devonian/Marcellus, Upper Devonian/Burket, and the Middle Ordovician/Utica geologic formations. The data for the three geologic formations, including the average, median, standard deviation, and ratios of Th to U are presented in **Table 3-19**.

XRF ppm concentration data for Th was converted to pCi/g of Th-232 using the specific activity value of 0.110 pCi/g Th-232 per ppm of Th. XRF ppm concentration data for U was converted to pCi/g of U-238 using the specific activity value of 0.334 pCi/g of U-238 per ppm of U. Ratios of U/Th are also presented in **Table 3-19**.

3.6.2 Filtered Versus Unfiltered Sample Data Evaluation

Appendix I contains the assessment of filtered and unfiltered liquid sample results for the entire TENORM study. The conclusion from this evaluation is that there is no apparent trend or bias that filtering produces. There were some subsets of data where either the unfiltered results or the filtered results appear to be significantly higher. There was no statistically significant correlation found within any sample group. Because the liquid samples were preserved by addition of acid prior to filtering, the radioactive particulates may have entered solution and were therefore not removed by filtering.

3.6.3 Conventional Versus Unconventional Produced Water Data Evaluation

There was a significant difference observed in the produced water from conventional and unconventional O&G well sites. **Tables 3-15** and **3-16** present gamma spectroscopy results for conventional and unconventional produced water for both filtered and unfiltered samples. Two distinct differences in magnitude of activity and in the ratio of Ra-226 to Ra-228 are summarized in **Figure 3-7**.

Figure 3-7. Conventional vs Unconventional Produced Water Radium Concentrations

O&G Production	Filtered Samples	No. of Samples	Average Ra-226 (pCi/L)	Average Ra-228 (pCi/L)	Ratio of Ra-226/Ra-228
Conventional	No	4	336	295	1.14
Unconventional	No	9	8,340	986	8.46
Conventional	Yes	4	334	288	1.16
Unconventional	Yes	9	8,220	985	8.35

The Ra-226 activity in unconventional well site produced water is approximately 20 times greater than that observed in conventional well site produced water. The ratio of Ra-226 to Ra-228 in unconventional well site produced water is approximately eight times greater than that found in conventional well site produced water. The higher ratio of Ra-226 to Ra-228 for unconventional well site produced water reflects the higher ratio of U to Th observed in Marcellus Shale horizontal cuttings sample results. The U to Th ratio is approximately six. Filtering of the samples does not appreciably change the activity concentration or the relationship between Ra-226 and Ra-228.

3.7 <u>Potential Offsite Environmental Impact</u>

A potential offsite environmental impact could result from the removal of materials and/or equipment with total and/or removable α/β surface radioactivity above applicable guidelines. The highest total α surface radioactivity measurement was 754 dpm/100 cm^2. Additional measurements exceeded the RG 1.86 Ra-226 total surface contamination guideline of 100 dpm/100 cm^2. The highest total β measurement was 2,503 dpm/100 cm^2. This and several other measurements exceeded the RG 1.86 Th-232 total surface contamination guideline of

1,000 dpm/100 cm^2. These readings were on equipment associated with wastewater handling/storage, and this equipment is likely to be reused.

Table 3-1. Removable Alpha and Beta Surface Radioactivity Measurement Results Summary[a,b]

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WP-01-FS-045	12	4.24	12.4	2.36	4.92	93.7	93.7	0.00	93.7
WP-01-FS-081	7	4.24	4.24	0.00	4.24	102	102	0.00	102
WP-01-FS-128	3	4.24	12.4	4.79	6.96	118	118	0.00	118
WP-02-FS-083	27	4.24	4.24	0.00	4.24	102	102	0.00	102
WP-03-FS-029	15	4.15	4.15	0.78	4.15	109	109	0.00	109
WP-03-FS-082	14	4.24	4.24	0.00	4.24	86.7	86.7	0.00	86.7
WP-04-FS-014	10	4.24	7.24	1.07	4.24	93.7	93.7	0.00	93.7
WP-04-FS-084	22	4.24	4.24	0.18	4.24	95.7	95.7	0.00	95.7
WP-04-FS-085	29	4.24	4.24	0.00	4.24	108	108	0.00	108
WP-05-FS-077	3	4.15	4.15	0.00	4.15	113	113	0.00	113
WP-05-FS-089	26	4.15	4.15	0.00	4.15	98.9	98.9	0.00	98.9
WP-06-FS-026	3	4.14	4.14	0.00	4.14	112	112	0.00	112
WP-06-FS-091	29	4.24	4.24	0.00	4.24	102	102	0.00	102
WP-06-FS-092	23	4.24	4.24	0.00	4.24	95.5	95.5	0.00	95.5
WP-06-FS-093	4	4.15	4.15	0.00	4.15	111	111	0.00	111
WP-07-FS-094	12	4.24	4.24	0.00	4.24	102	102	0.00	102
WP-08-FS-010	5	4.24	4.24	0.00	4.24	123	123	0.00	123
WP-08-FS-095	5	4.24	4.24	0.00	4.24	102	102	0.00	102
WP-09-FS-097	7	4.15	4.15	0.00	4.24	102	102	0.00	102
WP-09-FS-098	3	4.24	4.24	0.00	4.24	113	113	0.00	113
WP-10-FS-003	21	4.24	4.24	0.00	4.24	93.7	93.7	0.00	93.7
WP-10-FS-004	21	4.14	4.15	0.00	4.15	93.7	93.7	0.00	93.7
WP-10-FS-009	8	4.15	4.15	0.00	4.15	113	113	0.00	113
WP-11-FS-023	17	4.15	4.15	0.00	4.15	109	109	0.00	109
WP-11-FS-037	15	4.15	4.15	0.00	4.15	113	113	0.00	113

Table 3-1. Removable Alpha and Beta Surface Radioactivity Measurement Results Summary[a,b]

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WP-11-FS-102	17	4.15	4.15	0.00	4.15	109	109	0.00	109
WP-12-FS-017	23	4.24	4.24	0.00	4.24	93.7	93.7	0.00	93.7
WP-12-FS-018	4	4.14	4.14	0.00	4.14	113	113	0.00	113
WP-12-FS-019	19	4.24	4.24	0.00	4.24	93.7	93.7	0.00	93.7
WP-13-FS-041	17	4.24	4.24	0.00	4.24	123	123	0.00	123
WP-13-FS-042	18	4.24	4.24	0.00	4.24	123	123	0.00	123
WP-14-FS-035	20	4.15	12.2	2.47	4.96	114	114	0.00	114
WP-14-FS-036	23	4.15	14.9	2.36	4.62	114	114	0.00	114
WP-14-FS-107	4	4.15	4.15	0.00	4.15	114	114	0.00	114
WP-15-FS-028	7	4.15	4.15	0.00	4.15	114	114	0.00	114

[a]Smear samples were performed on facility, system, and structure surfaces.
[b]During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 3-2. Total Alpha and Beta Surface Radioactivity Measurement Results Summary[a,b]

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WP-01-FS-045	12	30.5	30.5	0.00	30.5	364	2,503	618	1,190
WP-01-FS-081	7	19.0	19.0	0.00	19.0	279	1,710	460	777
WP-02-FS-083	27	7.44	14.9	2.84	8.82	288	676	75.5	305
WP-03-FS-029	16	30.5	30.5	0.00	30.5	357	884	137	587
WP-03-FS-082	14	7.44	79.0	19.2	16.0	266	364	28.6	282
WP-04-FS-014	10	30.5	30.5	0.00	30.5	364	2,220	812	1,170
WP-04-FS-084	22	7.46	69.6	16.4	13.7	325	325	0.00	325
WP-04-FS-085	29	7.46	29.8	7.06	11.3	317	651	69.6	337
WP-05-FS-077	3	30.5	30.5	0.00	30.5	513	698	96.0	592
WP-05-FS-089	26	7.46	164	46.6	26.0	280	542	59.0	299
WP-06-FS-026	30.5	30.5	30.5	0.00	30.5	646	1,920	652	1,200
WP-06-FS-091	29	7.46	24.9	4.00	8.92	297	297	0.00	297
WP-06-FS-092	23	7.44	44.6	8.00	9.38	278	527	54.0	292
WP-06-FS-093	4	30.5	30.5	0.00	30.5	268	268	0.00	268
WP-07-FS-094	12	7.44	19.8	4.16	9.71	291	988	201	349
WP-08-FS-010	5	30.5	30.5	0.00	30.5	557	721	65.0	624
WP-08-FS-095	5	19.0	19.0	0.00	19.0	279	279	0.00	279
WP-09-FS-097	7	7.44	29.8	8.69	13.5	285	285	0.00	285
WP-09-FS-098	3	30.5	30.5	0.00	30.5	268	268	0.00	268
WP-10-FS-003	21	30.5	754	167	93.0	268	1,580	417	676
WP-10-FS-004	21	30.5	258	69.4	60.0	268	1,580	410	709
WP-10-FS-009	8	30.5	30.5	0.00	30.5	1,390	1,890	145	1,630
WP-11-FS-023	17	30.5	30.5	0.00	30.5	364	1,410	294	966
WP-11-FS-037	15	30.5	30.5	0.00	30.5	268	1,020	223	583
WP-11-FS-102	17	30.5	30.5	0.00	30.5	268	1,410	294	960

Table 3-2. Total Alpha and Beta Surface Radioactivity Measurement Results Summary[a,b]

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WP-12-FS-017	23	30.5	30.5	0.00	30.5	268	884	145	374
WP-12-FS-018	4	30.5	30.5	0.00	30.5	839	951	51.0	910
WP-12-FS-019	19	30.5	30.5	0.00	30.5	268	1,550	378	513
WP-13-FS-041	17	30.5	30.5	0.00	30.5	371	1,430	303	1,010
WP-13-FS-042	18	30.5	30.5	0.00	30.5	275	1,380	273	799
WP-14-FS-035	20	30.5	30.5	0.00	30.5	268	721	130	315
WP-14-FS-036	23	30.5	30.5	0.00	30.5	268	483	55.0	284
WP-14-FS-107	4	27.8	27.8	0.00	27.8	69.3	69.3	0.00	69.3
WP-15-FS-028	6	30.5	30.5	0.00	30.5	268	268	0.00	268

[a]Static measurements were performed on facility, system, and structure surfaces.
[b]During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 3-3. Gross Gamma Scan Results Summary[a]

Site	Phase	Scan Max[b] (cpm)	Scan Min[b] (cpm)	Scan Average[b] (cpm)	Scan Std Dev (cpm)	No. Data Points
WP-01	Fracturing	16,608	7,209	13,028	1,349	4,857
WP-01	Flowback	17,299	6,653	14,519	1,246	4,474
WP-01	Production	16,641	9,019	13,787	1,075	4,891
WP-02	Horizontal	9,363	4,262	5,371	1,041	8,318
WP-03	Vertical	13,650	4,758	7,254	1,531	7,438
WP-04	Vertical	15,961	7,249	13,378	902	7,083
WP-04	Horizontal	16,099	7,210	13,260	1,139	6,470
WP-04	Fracturing	22,724	8,055	14,322	1,234	4,554
WP-04	Flowback	17,057	10,982	13,938	750	5,411
WP-04	Production	17,031	8,545	13,019	895	3,624
WP-05	Horizontal	9,394	3,181	7,236	724	5,552
WP-05	Fracturing	8,293	3,925	6,668	825	3,033
WP-06	Vertical	8,906	4,424	6,357	560	8,518
WP-06	Horizontal	8,280	4,756	6,097	356	8,562
WP-06	Flowback	8,231	4,722	6,014	464	5,037
WP-06	Fracturing	10,803	3,049	8,033	692	2,532
WP-07	Vertical	8,437	4,675	6,318	483	12,519
WP-08	Fracturing	7,454	3,710	5,387	470	4,602
WP-09	Fracturing	30,823	2,686	5,380	1,146	4,354
WP-10	Horizontal	15,258	8,924	12,916	970	3,440
WP-10	Flowback	16,013	8,508	13,817	790	1,856
WP-10	Production	16,528	10,447	13,257	835	2,946
WP-11	Vertical	15,603	10,050	12,412	771	3,091
WP-11	Horizontal	14,781	4,368	12,075	1,252	2,960
WP-11	Production	13,505	9,914	12,281	503	1,168
WP-12	Vertical	11,479	5,543	8,005	1,144	3,204
WP-12	Horizontal	11,360	5,328	8,034	1,073	3,525
WP-13	Vertical	15,088	8,068	13,096	628	2,924
WP-13	Horizontal	15,357	8,119	12,916	966	3,234
WP-14	Vertical	6,772	1,992	3,854	684	2,840
WP-14	Horizontal	5,891	2,302	3,449	468	1,821
WP-14	Flowback	7,421	3,181	4,421	648	3,273
WP-15	Vertical	8,557	4,398	6,093	573	2,230
WP-16	Production	10,833	4,623	7,753	1,361	290
WP-17	Production	8,797	4,183	6,179	907	277
WP-19	Production	7,046	2,494	4,314	1,013	238
WP-20	Production	5,422	2,790	4,166	537	366

Table 3-3. Gross Gamma Scan Results Summary[a]

Site	Phase	Scan Max[b] (cpm)	Scan Min[b] (cpm)	Scan Average[b] (cpm)	Scan Std Dev (cpm)	No. Data Points
WP-21	Production	5,307	2,677	3,870	572	182

[a] Gross gamma scans were performed on site ground surfaces outside facilities, structures, and systems, and include soil, asphalt, gravel, and concrete matrices.
[b] Convert count rate data to exposure rate by dividing count rate by 800 to yield μR/hr.

Table 3-4. Results Summary of NaI Count Rate Data Converted to Exposure Rates

Site	Phase	Scan Max (μR/hr)	Scan Min (μR/hr)	Scan Average (μR/hr)	Scan Std Dev (μR/hr)	No. Data Points
WP-01	Fracturing	20.8	9.00	16.3	1.70	4,857
WP-01	Flowback	21.6	8.30	18.1	1.60	4,474
WP-01	Production	20.8	11.3	17.2	1.30	4,891
WP-02	Horizontal	11.7	5.30	6.70	1.30	8,318
WP-03	Vertical	17.1	5.90	9.10	1.90	7,438
WP-04	Vertical	20.0	9.10	16.7	1.10	7,083
WP-04	Horizontal	20.1	9.00	16.6	1.40	6,470
WP-04	Fracturing	28.4	10.1	17.9	1.50	4,554
WP-04	Flowback	21.3	13.7	17.4	0.900	5,411
WP-04	Production	21.3	10.7	16.3	1.10	3,624
WP-05	Horizontal	11.7	4.00	9.00	0.900	5,552
WP-05	Fracturing	10.4	4.90	8.30	1.00	3,033
WP-06	Vertical	11.1	5.50	7.90	0.700	8,518
WP-06	Horizontal	10.4	5.90	7.60	0.400	8,562
WP-06	Flowback	10.3	5.90	7.50	0.600	5,037
WP-06	Fracturing	13.5	3.80	10.0	0.900	2,532
WP-07	Vertical	10.5	5.80	7.90	0.600	12,519
WP-08	Fracturing	9.30	4.60	6.70	0.600	4,602
WP-09	Fracturing	38.5	3.40	6.70	1.40	4,354
WP-10	Horizontal	19.1	11.2	16.1	1.20	3,440
WP-10	Flowback	20.0	10.6	17.3	1.00	1,856
WP-10	Production	20.7	13.1	16.6	1.00	2,946
WP-11	Vertical	19.5	12.6	15.5	1.00	3,091
WP-11	Horizontal	18.5	5.50	15.1	1.60	2,960
WP-11	Production	16.9	12.4	15.4	0.600	1,168
WP-12	Vertical	14.3	6.90	10.0	1.40	3,204
WP-12	Horizontal	14.2	6.70	10.0	1.30	3,525
WP-13	Vertical	18.9	10.1	16.4	0.800	2,924
WP-13	Horizontal	19.2	10.1	16.1	1.20	3,234
WP-14	Vertical	8.50	2.50	4.80	0.900	2,840

Table 3-4. Results Summary of NaI Count Rate Data Converted to Exposure Rates

Site	Phase	Scan Max (μR/hr)	Scan Min (μR/hr)	Scan Average (μR/hr)	Scan Std Dev (μR/hr)	No. Data Points
WP-14	Horizontal	7.40	2.90	4.30	0.600	1,821
WP-14	Flowback	9.30	4.00	5.50	0.800	3,273
WP-15	Vertical	10.7	5.50	7.60	0.700	2,230
WP-16	Production	13.5	5.80	9.70	1.70	290
WP-17	Production	11.0	5.20	7.70	1.10	277
WP-19	Production	8.80	3.10	5.40	1.30	238
WP-20	Production	6.80	3.50	5.20	0.700	366
WP-21	Production	6.60	3.30	4.80	0.700	182

Table 3-5. Vertical Solids, Drill Cuttings – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)	Th-232 (pCi/g)
WP-03-SL-038	2.09	1.21	23.4	< 1.27	0.127	1.18
WP-04-SL-001	1.99	1.06	9.01	< 1.50	< 0.173	1.06
WP-04-SL-002	2.09	1.09	20.2	1.86	< 0.149	1.07
WP-04-SL-003	2.04	1.16	20.3	< 1.43	< 0.146	1.14
WP-04-SL-004	2.34	1.10	18.1	1.85	< 0.181	1.08
WP-04-SL-005	2.39	1.20	20.2	1.67	< 0.158	1.18
WP-04-SL-006	2.11	1.23	24.4	0.827	< 0.061	1.20
WP-04-SL-007	2.05	0.994	22.5	< 0.934	< 0.070	0.971
WP-04-SL-008	2.75	1.19	23.6	1.30	0.097	1.16
WP-05-SL-028	2.13	1.08	21.6	1.56	< 0.138	1.05
WP-05-SL-029	1.75	1.07	17.3	< 1.31	0.198	1.05
WP-05-SL-030	1.61	0.939	15.9	< 0.565	< 0.092	0.920
WP-05-SL-031	1.81	1.05	21.7	0.835	< 0.107	1.03
WP-05-SL-033	1.84	0.701	12.6	< 1.62	< 0.136	0.687
WP-06-SL-014	2.93	1.06	22.7	1.27	0.178	1.05
WP-06-SL-015	2.22	1.04	21.0	1.52	< 0.165	1.03
WP-06-SL-016	3.21	0.885	26.9	2.07	< 0.140	0.871
WP-06-SL-017	2.73	0.991	24.0	1.64	0.166	0.976
WP-06-SL-018	0.900	0.181	3.26	< 1.13	< 0.081	0.177
WP-06-SL-019	1.19	0.242	6.81	0.469	< 0.058	0.238
WP-06-SL-020	5.15	0.654	8.90	< 0.923	< 0.096	0.642
WP-06-SL-021	0.698	0.107	18.8	0.164	0.016	0.110
WP-06-SL-022	2.96	0.802	18.4	1.29	< 0.121	0.782
WP-06-SL-023	0.899	0.208	4.97	< 1.29	< 0.097	0.197
WP-06-SL-024	1.79	0.416	12.3	< 0.790	< 0.067	0.407

Table 3-5. Vertical Solids, Drill Cuttings – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)	Th-232 (pCi/g)
WP-06-SL-025	2.94	0.769	18.4	0.987	< 0.169	0.751
WP-06-SL-026	2.24	0.592	14.2	< 1.21	< 0.171	0.578
WP-07-SL-039	2.03	1.09	20.1	< 1.45	< 0.194	1.07
WP-07-SL-040	2.43	1.32	23.6	0.788	0.147	1.29
WP-07-SL-041	1.33	1.33	20.8	< 0.869	< 0.172	1.30
WP-10-SL-045	1.94	0.885	16.5	0.959	< 0.106	0.866
WP-11-SL-047	2.32	0.472	12.7	< 0.949	< 0.082	0.191
WP-12-SL-052	17.2	2.80	17.6	< 3.01	< 0.311	2.74
WP-12-SL-053	1.39	1.39	16.6	< 2.25	< 0.302	1.37
WP-13-SL-059	1.83	1.09	20.4	< 1.75	< 0.231	1.07
WP-14-SL-073	6.97	2.23	20.9	< 1.54	< 0.210	2.18
WP-14-SL-074	2.88	0.140	22.2	1.41	0.104	1.37
WP-15-SL-075	7.82	2.48	19.5	< 1.39	< 0.126	2.45
Average	2.82	1.01	18.0	0.960	0.085	1.01
Std. Dev.	2.79	0.572	5.64	0.484	0.046	0.555
Median	2.10	1.06	19.8	0.819	0.074	1.05
Minimum	0.698	0.107	3.26	0.164	0.016	0.110
Maximum	17.2	2.80	26.9	2.07	0.198	2.74

[a] Values reported as < are the method MDC.

Table 3-6. XRF Uranium and Thorium for Vertical Cuttings

Study ID	Date	Formation	Thorium Result (ppm)	Thorium Error (ppm)	Th-232 (pCi/g)	Uranium Result (ppm)	Uranium Error (ppm)	U-238 (pCi/g)
WP-03-SL-038	07/26/13	Varies	20.1	0.400	2.21	2.90	0.200	0.969
WP-04-SL-001	06/17/13	Varies	17.9	0.400	1.97	5.30	0.300	1.77
WP-04-SL-002	06/17/13	Varies	16.4	0.400	1.80	3.00	0.200	1.00
WP-04-SL-003	06/17/13	Varies	17.5	0.400	1.93	4.00	0.300	1.34
WP-04-SL-004	06/17/13	Varies	15.5	0.400	1.71	3.60	0.200	1.20
WP-04-SL-005	06/17/13	Varies	16.0	0.400	1.76	2.60	0.200	0.868
WP-04-SL-006	06/17/13	Varies	18.3	0.400	2.01	4.20	0.300	1.40
WP-04-SL-007	06/17/13	Varies	14.5	0.400	1.60	3.00	0.200	1.00
WP-04-SL-008	06/17/13	Varies	16.8	0.400	1.85	5.30	0.300	1.77
WP-05-SL-028	07/08/13	Varies	17.4	0.400	1.91	4.50	0.300	1.50
WP-05-SL-029	07/08/13	Varies	15.5	0.400	1.71	3.70	0.200	1.24
WP-05-SL-030	07/08/13	Varies	14.5	0.400	1.60	3.50	0.200	1.17
WP-05-SL-031	07/08/13	Varies	16.5	0.400	1.82	2.60	0.200	0.868
WP-05-SL-033	07/08/13	Varies	11.2	0.400	1.23	2.30	0.200	0.768
WP-06-SL-014	07/01/13	Varies	16.5	0.400	1.82	6.40	0.300	2.14
WP-06-SL-015	07/01/13	Varies	17.8	0.400	1.96	3.80	0.300	1.27
WP-06-SL-016	07/01/13	Varies	15.2	0.400	1.67	7.10	0.300	2.37
WP-06-SL-017	07/01/13	Varies	16.3	0.400	1.79	6.10	0.300	2.04
WP-06-SL-018	07/01/13	Varies	6.50	0.400	0.715	3.00	0.200	1.00
WP-06-SL-019	07/01/13	Varies	8.60	0.400	0.946	2.80	0.200	0.935
WP-06-SL-020	07/01/13	Varies	10.9	0.400	1.20	13.4	0.500	4.48
WP-06-SL-021	07/01/13	Varies	8.50	0.400	0.935	4.40	0.200	1.47
WP-06-SL-022	07/01/13	Varies	15.6	0.400	1.72	5.80	0.300	1.94
WP-06-SL-023	07/01/13	Oriskany	6.30	0.300	0.693	1.50	0.100	0.501
WP-06-SL-024	07/08/13	Varies	11.5	0.400	1.27	4.80	0.300	1.60
WP-06-SL-025	07/08/13	Varies	16.0	0.400	1.76	5.40	0.300	1.80
WP-06-SL-026	07/08/13	Varies	17.7	0.500	1.95	8.80	0.500	2.94
WP-07-SL-039	08/05/13	Varies	17.3	0.400	1.90	2.50	0.200	0.835
WP-07-SL-040	08/05/13	Varies	17.8	0.400	1.96	1.50	0.100	0.501
WP-07-SL-041	08/05/13	Varies	17.7	0.400	1.95	2.30	0.200	0.768
WP-10-SL-045	08/26/13	Varies	11.8	0.400	1.30	3.00	0.200	1.00
WP-11-SL-047	08/27/13	Varies	7.00	0.400	0.770	2.40	0.100	0.802
WP-12-SL-052	09/05/13	Varies	17.7	0.500	1.95	12.4	0.500	4.14
WP-12-SL-053	09/05/13	Varies	17.9	0.400	1.97	6.30	0.300	2.10
WP-13-SL-059	10/15/13	Varies	16.2	0.400	1.78	2.00	0.200	0.668
WP-14-SL-073	01/31/14	Varies	17.1	0.400	1.88	3.10	0.200	1.04
WP-14-SL-074	01/31/14	Varies	17.3	0.400	1.90	3.20	0.200	1.07
		Average	15.0		1.64	4.39		1.47

Table 3-6. XRF Uranium and Thorium for Vertical Cuttings

Study ID	Date	Formation	Thorium Result (ppm)	Thorium Error (ppm)	Th-232 (pCi/g)	Uranium Result (ppm)	Uranium Error (ppm)	U-238 (pCi/g)
		Std. Dev.	3.66		0.403	2.64		0.881
		Median	16.3		1.79	3.60		1.20
		Minimum	6.30		0.693	1.50		0.501
		Maximum	20.1		2.21	13.4		4.48

Table 3-7. Horizontal Solids, Drill Cuttings – Uranium Series Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)	Th-232 (pCi/g)
WP-02-SL-036	13.0	0.621	18.3	4.96	0.789	0.608
WP-03-SL-065	9.76	0.797	26.2	4.19	0.265	0.786
WP-04-SL-009	3.69	0.581	12.6	0.803	0.130	0.568
WP-04-SL-010	3.96	0.535	12.6	0.917	0.240	0.524
WP-04-SL-011	2.37	0.668	16.8	0.575	0.144	0.654
WP-04-SL-012	5.43	0.727	15.3	< 2.53	0.220	0.712
WP-05-SL-027	3.31	0.772	18.3	1.88	0.201	0.755
WP-05-SL-032	1.50	0.711	14.2	< 2.09	< 0.158	0.696
WP-05-SL-034	3.17	0.861	20.1	< 1.32	< 0.152	0.841
WP-06-SL-037	1.17	0.346	6.33	0.830	< 0.085	0.339
WP-10-SL-048	4.92	0.694	31.5	< 2.30	< 0.250	0.680
WP-11-SL-068	1.06	0.241	7.41	< 0.835	< 0.091	0.237
WP-12-SL-055	< 0.183	< 0.031	1.47	< 0.485	< 0.058	< 0.031
WP-12-SL-056	3.56	0.535	11.7	1.57	0.153	0.527
WP-13-SL-062	10.3	0.487	8.70	3.11	0.391	0.478
WP-14-SL-077	8.09	0.702	17.5	2.78	0.384	0.689
WP-14-SL-078	9.60	0.828	20.4	3.09	0.302	0.813
WP-14-SL-079	8.97	1.16	16.7	2.24	0.277	1.14
Average	5.22	0.627	15.3	1.76	0.223	0.615
Std. Dev.	3.80	0.254	7.13	1.36	0.180	0.249
Median	3.83	0.681	16.0	1.21	0.211	0.667
Minimum	0.092	0.016	1.47	0.243	0.029	0.016
Maximum	13.0	1.16	31.5	4.96	0.789	1.14

Table 3-8. XRF Uranium and Thorium for Horizontal Cuttings

Study ID	Date	Target Formation / Gas Type	Thorium Result (ppm)	Thorium Error (ppm)	Th-232 (pCi/g)	Uranium Result (ppm)	Uranium Error (ppm)	U-238 (pCi/g)
WP-02-SL-036	07/24/13	Marcellus / Wet	12.2	0.400	1.34	28.6	0.500	9.55
WP-03-SL-065	11/08/13	Marcellus / Wet	11.8	0.400	1.30	20.1	0.600	6.71
WP-04-SL-009	06/20/13	Marcellus / Dry	12.0	0.500	1.32	8.70	0.400	2.91
WP-04-SL-010	06/20/13	Marcellus / Dry	10.8	0.500	1.19	9.90	0.400	3.31
WP-04-SL-011	06/20/13	Marcellus / Dry	12.5	0.400	1.38	5.90	0.300	1.97
WP-04-SL-012	06/20/13	Marcellus / Dry	12.4	0.400	1.36	14.6	0.500	4.88
WP-05-SL-027	07/08/13	Burkett / Wet	16.2	0.400	1.78	9.70	0.400	3.24
WP-05-SL-032	07/08/13	Burkett / Wet	11.1	0.400	1.22	5.20	0.300	1.74
WP-05-SL-034	07/08/13	Burkett / Wet	16.4	0.500	1.80	6.60	0.400	2.20
WP-06-SL-037	07/25/13	Utica / Wet	17.4	1.30	1.91	80.8	1.30	27.0
WP-10-SL-048	08/30/13	Marcellus / Dry	13.8	0.800	1.52	49.4	1.00	16.5
WP-11-SL-068	11/14/13	Utica / Dry	7.70	0.500	0.847	17.6	0.500	5.88
WP-12-SL-055	09/11/13	Marcellus / Dry	13.0	0.800	1.43	11.3	0.500	3.77
WP-12-SL-056	09/11/13	Marcellus / Dry	20.3	1.20	2.23	36.6	1.20	12.2
WP-13-SL-062	10/21/13	Marcellus / Dry	9.40	0.500	1.03	33.1	0.600	11.1
WP-14-SL-077	02/07/14	Marcellus / Dry	11.0	0.500	1.21	31.4	0.700	10.5
WP-14-SL-078	02/07/14	Marcellus / Dry	13.3	0.500	1.46	33.8	0.700	11.3
WP-14-SL-079	02/07/14	Marcellus / Dry	11.7	0.700	1.29	49.4	0.900	16.5
		Average	12.9		1.42	25.2		8.40
		Std. Dev.	3.01		0.331	20.0		6.70
		Median	12.3		1.35	18.9		6.30
		Minimum	7.70		0.847	5.20		1.74
		Maximum	20.3		2.23	80.8		27.0

Table 3-9. Drilling Solids, Mud – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)	Th-232 (pCi/g)
WP-03-SL-066	1.51	0.178	4.93	< 0.436	< 0.085	0.176
WP-04-SL-013	1.58	0.221	4.31	< 0.866	< 0.073	0.216
WP-05-SL-035	0.675	0.182	3.54	< 0.375	< 0.054	0.179
WP-10-SL-046	3.66	0.266	6.91	< 1.61	< 0.034	0.261
WP-10-SL-049	3.35	0.335	7.32	1.73	< 0.035	< 0.870
WP-11-SL-069	1.04	0.195	3.84	< 0.673	< 0.058	0.191
WP-12-SL-054	1.28	0.122	1.47	1.10	< 0.081	0.120
WP-13-SL-060	2.78	0.296	5.96	< 0.692	0.086	0.290
WP-13-SL-063	3.72	0.328	6.53	0.700	0.143	0.322
Average	2.18	0.236	4.98	0.651	0.063	0.243
Std. Dev.	1.20	0.074	1.89	0.504	0.038	0.095
Median	1.58	0.221	4.93	0.433	0.043	0.216
Minimum	0.675	0.122	1.47	0.188	0.017	0.120
Maximum	3.72	0.335	7.32	1.73	0.143	0.435

Table 3-10. Proppant Sand – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)	Th-232 (pCi/g)
WP-04-SL-050	0.180	0.053	0.733	0.139	< 0.025	0.047
WP-05-SL-058	0.225	0.135	7.25	< 0.200	< 0.037	0.115
WP-06-SL-070	0.170	0.026	0.069	0.323	< 0.018	0.025
WP-08-SL-044	0.246	0.065	0.162	< 0.020	< 0.004	0.045
WP-09-SL-043	0.301	0.045	0.199	< 0.426	< 0.050	0.044
WP-10-SL-067	0.218	0.018	0.136	< 0.369	< 0.036	0.018
WP-11-SL-072	0.275	0.025	0.070	< 0.203	< 0.033	0.025
WP-12-SL-064	0.358	0.038	0.386	< 0.426	< 0.042	0.037
WP-14-SL-081	0.266	< 0.026	4.99	< 0.442	< 0.035	0.102
WP-25-SL-042	0.188	0.018	< 0.061	< 0.267	< 0.029	< 0.013
Average	0.243	0.044	1.40	0.157	0.015	0.046
Std. Dev.	0.059	0.036	2.55	0.091	0.006	0.035
Median	0.236	0.032	0.181	0.159	0.017	0.041
Minimum	0.170	0.013	0.031	0.010	0.002	0.007
Maximum	0.358	0.135	7.25	0.323	0.025	0.115

Table 3-11. Flowback Solids, Sand – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)	Th-232 (pCi/g)
WP-04-SL-061	7.73	0.619	0.659	< 1.86	< 0.199	0.609
WP-09-SL-057	0.763	0.194	0.457	< 0.711	< 0.083	0.191
WP-11-SL-080	2.76	0.611	1.68	< 0.783	< 0.091	0.603
WP-12-SL-071	2.58	0.353	0.597	< 0.985	< 0.080	0.343
Average	3.46	0.444	0.848	0.542	0.057	0.437
Std. Dev.	2.99	0.208	0.561	0.265	0.029	0.205
Median	2.67	0.482	0.628	0.442	0.044	0.473
Minimum	0.763	0.194	0.457	0.356	0.040	0.191
Maximum	7.73	0.619	1.68	0.930	0.100	0.609

Table 3-12. Drilling Fluids – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta[a] (pCi/L)
WP-02-LQ-002	4,690	372	9,910	ND	ND
WP-06-LQ-001	1,510	162	4,340	1,580	3,940
WP-06-LQ-003	2,010	216	5,220	ND	ND
WP-12-LQ-009	1,800	184	420	3,820	1,250
WP-14-LQ-026	4,940	466	11,400	ND	ND
Average	2,990	280	6,260	2,700	2,600
Std. Dev.	1,678	133	4,430	1,580	1,900
Median	2,010	216	5,220	2,700	2,600
Minimum	1,510	162	420	1,580	1,250
Maximum	4,940	466	11,400	3,820	3,940

[a]ND – Sample Matrix was not suitable for analysis.

Table 3-13. Fracturing Fluids – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WP-04-LQ-008	21,000	1,640	< 565	37,000	11,200
WT-05-LQ-013	872	78.0	195	1,870	398
WP-06-LQ-016	64.0	< 9.00	< 21.0	< 1.39	4.41
WP-08-LQ-007	3,080	723	444	5,020	1,610
WP-09-LQ-006	2,000	442	338	3,400	< 879
WP-10-LQ-015	10,300	600	< 298	13,500	2,310
WP-11-LQ-023	115	14.0	44.0	< 3.76	< 1.63
WP-14-LQ-046	2,270	189	456	5,760	1,200
WP-14-LQ-047	2,160	218	423	5,650	1,010
WP-19-LQ-004	16,200	1,250	435	54,100	14,900
WP-19-LQ-005	105	< 9.00	25.0	< 113	< 186
Average	5,290	469	255	11,500	3,020
Std. Dev.	7,250	547	178	17,700	5,080
Median	2,160	218	283	5,020	1,010
Minimum	64.0	4.50	10.5	0.695	0.815
Maximum	21,000	1,640	456	54,100	14,900

Table 3-14. Flowback Fluids – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WP-01-LQ-010	7,310	589	151	15,300	4,070
WP-04-LQ-014	25,500	1,740	500	71,000	21,300
WP-06-LQ-017	551	248	416	< 576	742
WP-08-LQ-012	4,280	1,140	500	7,270	1,820
WP-09-LQ-011	2,880	863	448	10,700	4,380
WP-10-LQ-045	8,690	633	2,630	11,100	1,960
WP-11-LQ-035	1,540	564	927	2,250	1,320
WP-12-LQ-022	4,550	507	< 177	10,100	2,440
WP-14-LQ-052	21,100	1,430	461	32,000	5,400
Average	8,490	857	680	17,800	4,830
Std. Dev.	8,840	486	769	21,900	6,370
Median	4,550	633	461	10,700	2,440
Minimum	551	248	88.5	288	742
Maximum	25,500	1,740	2,630	71,000	21,300

Table 3-15. Unfiltered Produced Waters – Gamma Spectroscopy and Miscellaneous Results

Study ID	Well Type	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WP-01-LQ-048	Unconventional	2,050	366	132	3,890	< 225
WP-04-LQ-039	Unconventional	26,600	1,900	328	30,000	7,600
WP-08-LQ-021	Unconventional	5,020	1,280	592	11,300	3,270
WP-09-LQ-019	Unconventional	4,490	1,140	571	9,760	2,570
WP-10-LQ-050	Unconventional	7,730	434	191	14,000	3,620
WP-10-LQ-055	Unconventional	6,710	470	149	41,700	4,560
WP-11-LQ-043	Unconventional	1,700	636	852	2,420	1,500
WP-12-LQ-041	Unconventional	14,500	1,710	408	21,800	6,810
WP-16-LQ-027	Conventional	819	896	220	< 2,570	1,140
WP-19-LQ-029	Conventional	< 81.0	26.0	103	< 465	< 402
WP-20-LQ-031	Conventional	145	42.0	129	< 2,440	< 987
WP-21-LQ-033	Conventional	340	214	< 31.0	< 1,230	< 830
WP-05-LQ-037	Unconventional	6,300	941	667	10,700	2,300
	Average	5,880	773	335	11,500	2,660
	Std. Dev.	7,450	604	260	12,800	2,460
	Median	4,490	636	220	9,760	2,300
	Minimum	40.5	26.0	15.5	233	113
	Maximum	26,600	1,900	852	41,700	7,600

Table 3-16. Filtered Produced Waters – Gamma Spectroscopy and Miscellaneous Results

Study ID	Well Type	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WP-01-LQ-049	Unconventional	1,930	373	129	2,750	933
WP-04-LQ-040	Unconventional	24,100	1,860	323	33,000	7,180
WP-08-LQ-020	Unconventional	4,940	1,350	518	11,200	4,050
WP-09-LQ-018	Unconventional	4,470	1,240	560	8,780	3,040
WP-10-LQ-051	Unconventional	8,060	466	164	19,900	4,050
WP-10-LQ-054	Unconventional	7,130	479	3,950	10,900	3,530
WP-11-LQ-044	Unconventional	1,520	602	751	2,440	1,500
WP-12-LQ-042	Unconventional	15,100	1,610	389	18,000	4,050
WP-16-LQ-028	Conventional	849	851	< 34.0	1,440	1,610
WP-19-LQ-030	Conventional	87.0	44.0	71.0	< 608	< 420
WP-20-LQ-032	Conventional	106	48.0	129	< 1,040	< 857
WP-21-LQ-034	Conventional	292	210	144	< 1,860	< 863
WP-05-LQ-038	Unconventional	6,720	883	485	11,400	3,370

Table 3-16. Filtered Produced Waters – Gamma Spectroscopy and Miscellaneous Results

Study ID	Well Type	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
	Average	5,790	770	587	9,350	2,650
	Std. Dev.	6,980	591	1,030	9,750	2,020
	Median	4,470	602	323	8,780	3,040
	Minimum	87.0	44.0	17.0	304	210
	Maximum	24,100	1,860	3,950	33,000	7,180

Table 3-17. Ambient Radon at Well Sites During Flowback

Study ID	County	Date	Radon Concentration (pCi/L)	Error (± Std. Dev.) (pCi/L)	MDC (pCi/L)
WP-01-RA	Sullivan	9/2013	< 0.300	0.000	0.300
			0.800	0.000	0.300
			0.500	0.400	0.300
			< 0.300	0.000	0.300
			< 0.300	0.000	0.300
WP-09-RA	Washington	9/2013	0.700	0.600	0.300
			0.600	0.200	0.300
			0.600	0.200	0.300
			1.70	1.60	0.300
WP-08-RA	Washington	9/2013	0.500	0.800	0.300
			0.200	0.200	0.300
			0.600	0.600	0.300
			0.700	0.400	0.300
WP-04-RA	Tioga	10/2013	0.500	0.200	0.300
			0.200	0.200	0.300
			0.500	0.600	0.300
			0.700	0.200	0.300

E-PERM samples with short-term electrets were deployed. MDC for a four-day exposure at 50 percent error is 0.300 pCi/L.

Table 3-18. Natural Gas Samples from Production Sites

Study ID	County	Gas Source	Radon Concentration (pCi/L)	Error (±2 Std. Dev.) (pCi/L)	MDA (pCi/L)
WP-08-RG	Washington	Marcellus Shale	79.6	0.800	0.300
WP-09-RG	Washington	Marcellus Shale	78.8	4.20	0.300
WP-22-RG	Tioga	Marcellus Shale	42.8	0.200	0.100
WP-23-RG	Tioga	Marcellus Shale	39.6	0.800	0.200
WP-24-RG	Tioga	Marcellus Shale	73.8	0.400	0.200
WP-25-RG	Tioga	Marcellus Shale	44.4	2.60	0.200
WP-26-RG	Lycoming	Oriskany Sandstone	19.9	0.200	0.200
WP-27-RG	Tioga	Marcellus Shale	38.4	3.40	0.300
WP-28-RG	Tioga	Marcellus Shale	40.8	5.20	0.400
WP-16-RG	Washington	Marcellus Shale	50.0	5.20	0.300
WP-17-RG	Washington	Marcellus Shale	49.5	5.80	0.500
WP-19-RG	McKean	Upper Devonian Shale	18.3	4.40	0.400
WP-20-RG	McKean	Upper Devonian Shale	88.2	10.6	0.700
WP-21-RG	Forest	Upper Devonian Shale	92.2	6.40	0.400
WP-04-RG	Tioga	Marcellus Shale	49.6	29.6	1.20
WP-05-RG	McKean	Marcellus Shale	148	15.6	1.50
WP-12-RG	Lycoming	Marcellus Shale	37.6	33.4	2.20
WP-11-RG	Tioga	Utica	5.70	1.20	0.500
WP-29-RG	Sullivan	Marcellus Shale	23.4	4.00	0.240
WP-30-RG	Bradford	Marcellus Shale	25.5	2.70	0.200
WP-31-RG	Bradford	Marcellus Shale	3.00	1.20	0.300
WP-14-RG	Jefferson	Marcellus Shale	5.60	0.100	0.140
		Average	47.9		
		Median	41.8		
		Standard Deviation	34.5		
		Minimum	3.00		
		Maximum	148		

Note: All results adjusted to account for the fact that Rn was counted in methane, but the scintillation cells were calibrated for Rn in air. Range of α particles is greater in methane than in air. All results divided by 1.054, according to Jenkins et. al., Health Physics, Vol. 106, No. 3, March 2014.

Table 3-19. Thorium and Uranium XRF Data for Drill Cuttings By Formation

Formation	Thorium Result (ppm)	Th-232 Concentration (pCi/g)	Uranium Result (ppm)	U-238 Concentration (pCi/g)	U/Th	U-238/ Th-232
Marcellus	13.8	1.52	49.4	16.5	3.58	10.9
Marcellus	13.0	1.43	11.3	3.77	0.870	2.64
Marcellus	20.3	2.23	36.6	12.2	1.80	5.48
Marcellus	9.40	1.03	33.1	11.1	3.52	10.7
Marcellus	11.8	1.30	20.1	6.71	1.70	5.16
Marcellus	12.0	1.32	8.70	2.91	0.730	2.20
Marcellus	10.8	1.19	9.90	3.31	0.920	2.78
Marcellus	12.5	1.38	5.90	1.97	0.470	1.43
Marcellus	12.4	1.36	14.6	4.88	1.18	3.59
Marcellus	11.7	1.29	49.4	16.5	4.22	12.8
Marcellus	13.3	1.46	33.8	11.3	2.54	7.73
Marcellus	11.0	1.21	31.4	10.5	2.85	8.67
Marcellus	12.2	1.34	28.6	9.55	2.34	7.13
Average	12.6	1.40	25.6	8.60	2.10	6.20
Median	12.2	1.30	28.6	9.60	1.80	5.50
Standard Deviation	2.57	0.280	15.0	5.01	1.23	3.72
Minimum	9.40	1.03	5.90	1.97	0.470	1.43
Maximum	20.3	2.23	49.4	16.5	4.22	12.8
Burket	16.2	1.78	9.70	3.24	0.600	1.82
Burket	16.4	1.80	6.60	2.20	0.400	1.22
Burket	11.1	1.22	5.20	1.74	0.470	1.42
Average	14.6	1.60	7.17	2.39	0.490	1.49
Median	16.2	1.78	6.60	2.20	0.470	1.42
Standard Deviation	3.00	0.330	2.30	0.770	0.100	0.300
Minimum	11.1	1.22	5.20	1.74	0.400	1.22
Maximum	16.4	1.80	9.70	3.24	0.600	1.82
Utica	7.70	0.850	17.6	5.88	2.29	6.92
Utica	17.4	1.91	80.8	27.0	4.64	14.1
Average	12.6	1.38	49.2	16.4	3.46	10.5
Median	12.6	1.38	49.2	16.4	3.46	10.5
Standard Deviation	6.86	0.750	44.7	14.9	1.67	5.10
Minimum	7.70	0.850	17.6	5.88	2.29	6.92
Maximum	17.4	1.91	80.8	27.0	4.64	14.1

4.0 WASTEWATER TREATMENT PLANTS

A total of 29 WWTPs were surveyed and/or sampled. This included 10 POTWs, 10 CWTs and nine ZLDs. The results, by wastewater facility, are presented in this section.

4.1 Publicly Owned Treatment Works

A total of 10 POTWs were surveyed and/or sampled. There were three rounds of surveys conducted over a seven-month period (April 2013 through October 2013); however, not all POTWs were sampled in all three rounds. Six of the 10 POTWs are considered ***influenced*** **(POTW-I)** by having received wastewater from the O&G industry, mainly the effluent of CWTs. Four POTWs are considered ***non-influenced*** (**POTW-N**) by having never received wastewater from the O&G industry. As such, surveying was conducted for the 10 POTWs as follows:

- 5 **POTW-I's** were surveyed in all three rounds,
- 1 **POTW-I** was surveyed in two rounds, and
- 4 **POTW-N's** were surveyed one time.

4.1.1 Radiological Survey Results

Radiological surveys were conducted at each **POTW-I**, resulting in four data sets:

- *Removable α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Total α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Gross Gamma Radiation Scan* measurements recorded in units of cpm
- *Gamma Radiation Exposure Rate* measurements recorded in units of μR/hr

4.1.1.1 Removable Alpha/Beta Surface Radioactivity Measurement Results

Measurements of removable radioactivity were performed to assess potential internal radiation exposures of workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 guidelines, Table 1. RG 1.86 requires that α and β surface radioactivity levels be evaluated separately. The primary α emitter of concern is Ra-226, with a removable criterion of 20 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a removable criterion of 200 dpm β/100 cm^2. The average removable α and β surface radioactivity levels at each WWTP were below the RG 1.86 criteria. The maximum removable α and β surface radioactivity levels were 22 dpm/100 cm^2 and 161 dpm/100 cm^2. The results of removable α and β surface radioactivity for the **POTW-I** plants are presented in **Table 4-1.** Individual removable α and β surface radioactivity measurement results are presented in **Appendix D**.

4.1.1.2 Total Alpha/Beta Surface Radioactivity Measurement Results

Measurements of total radioactivity were performed to assess potential internal radiation exposures of workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 guidelines, Table 1. RG 1.86 requires that α and β surface radioactivity levels be evaluated separately. The primary α emitter of concern is Ra-226, with a total surface radioactivity criterion of 100 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a total surface radioactivity criterion of 1,000 dpm β/100 cm^2. The maximum average total α and β surface radioactivity measured at any single facility were 313 dpm/100 cm^2 and 10,000 dpm/100 cm^2, respectively. The maximum total α and β concentrations measured at any single facility were 1,190 dpm/100 cm^2 and 38,000 dpm/ 100 cm^2. The summary results of total α and β surface radioactivity for the **POTW-I** plants surveyed are presented in **Table 4-2**. Individual total α and β surface radioactivity measurement results are presented in **Appendix D**.

4.1.1.3 Gross Gamma Radiation Scan Results

Gross gamma radiation scans recorded in cpm were performed on open land areas and accessible areas of the WWTPs to identify areas with elevated gross gamma radiation levels. Summary results for the **POTW-I** are presented in **Table 4-3**. The highest average count rate for the plants was 29,034 cpm, and the maximum count rate recorded was 205,446 cpm. A graphic display of the gamma radiation scan results (figures) at each facility was prepared using geographic information system (GIS) software. Figures are presented in **Appendix E**.

4.1.1.4 Gamma Radiation Exposure Rate Results Summary

Gross gamma radiation scan results in units of cpm presented in **Table 4-3** were converted to μR/hr using 800 cpm per μR/hr, a conversion factor appropriate for Ra-226 gamma energy as detected with 2-inch by 2-inch NaI detectors, rounded to one significant figure (Table 6.4, NaI Scintillation Detector Scan MDCs for Common Radiological Contaminants, NUREG-1507, Minimum Detectable Concentrations With Typical Radiation Survey Instruments for Various Contaminants and Field Conditions, USNRC June 1998). **Table 4-4** presents statistical results for each **POTW-I**. The highest average gamma radiation exposure rate was 36.3 μR/hr, and the maximum gamma radiation exposure rate measured was 257 μR/hr.

4.1.2 Solid Sample Results

4.1.2.1 Filter Cake Samples

Filter cakes were sampled at **POTW-I** and **POTW-N** plants and analyzed using gamma spectroscopy for U, Th, and Ac series decay chains. The gamma spectroscopy results are presented in **Tables 4-5** and **4-6**.

The analytical results for **POTW-I** plants presented in **Table 4-5** show Ra-226 and Ra-228 are present above typical background concentrations in soil. The average Ra-226 result was 20.1 pCi/g with a large variance in the distribution, and the maximum result was 55.6 pCi/g. The average Ra-228 result was 7.63 pCi/g, and the maximum result was 32.0 pCi/g Ra-228.

The radioactivity levels at **POTW-N** plants presented in **Table 4-6** were also above typical background concentrations in soil with Ra-226 average and maximum results of 9.72 pCi/g and 35.4 pCi/g. The average and maximum Ra-228 results were 2.26 pCi/g and 7.26 pCi/g.

4.1.2.2 Sediment-Impacted Soil Samples

Sampling was performed at only three of the **POTW-I** plants due to limited accessibility at the other plants. A total of seven samples were collected at the effluent discharge points and analyzed for U, Th, and Ac series decay chains by gamma spectroscopy. The gamma spectroscopy results are presented in **Table 4-7**.

The analytical results for **POTW-I** sediment-impacted soil samples indicate Ra-226 and Ra-228 are present at concentrations above typical background in soil. The average Ra-226 result was 9.00 pCi/g, and the maximum result was 18.2 pCi/g. The average Ra-228 result was 3.52 pCi/g, and the maximum result was 6.25 pCi/g.

4.1.3 Liquid Sample Results

Influent and effluent liquid sampling was performed at six **POTW-I** plants and four **POTW-N** plants. Filtered and unfiltered samples were analyzed for U, Th, and Ac decay series, and for gross α/β radioactivity levels. The filtered and unfiltered analyses are presented separately in **Tables 4-8** through **4-15** for both influenced and non-influenced POTWs. A comparison of the influenced and non-influenced POTW results and the filtered and unfiltered sample results is presented in Section 4.1.5.1.

4.1.4 Indoor Radon Sampling Results

ATDs were deployed in the **POTW-I** plants at various indoor locations such as break rooms, labs, offices, etc., to measure Rn concentrations. The results were evaluated using the EPA action level of 4 pCi/L. The ATDs were deployed in late July or early August 2013 and were all recovered from the field in February 2014. The results ranged from 0.200 to 8.70 pCi/L. One result exceeded the action level. The results are presented in **Table 4-16**. The Rn analytical reports are presented in **Appendix H**.

4.1.5 POTW Data Comparisons

4.1.5.1 POTW-I / POTW-N Comparison

Thirty-two influent and effluent sample radionuclide and gross α/β concentration results from **POTW-I's** and **POTW-N's** were compared to determine if there was a difference in the radionuclide activity content. **Tables 4-17** through **4-20** present and compare the average Ra concentration results and gross α/β concentration results from all influent and effluent filtered and unfiltered samples for all **POTW-I** and **POTW-N** plants. Twenty-nine of the 32 average concentration results for both filtered and unfiltered influent and effluent samples were higher for **POTW-I** plants than the **POTW-N** plants.

4.1.5.2 Radium-226/Radium-228 Sediment-Impacted Soil and Effluent Results Comparison

The sediment-impacted soil radioactivity levels were compared to filtered and unfiltered effluent results for Ra-226 and Ra-228 and are presented in **Table 4-21**. In cases where no results were reported for a member of the data pair (sediment-effluent pair), or when a result was reported as less than MDC, the data pair comparison was not evaluated.

The sediment-impacted soil sample results are above typical background for soil. However, there is no readily apparent relationship between the sediment-impacted soil sample and effluent sample results. The effluent wastewater discharged over time may contribute to the activity in the sediment-impacted soil, but a correlation between the sediment-impacted soil activity and the effluent samples could not be made from the study as performed.

The ratio of Ra-226 to Ra-228 was also calculated for a variety of sample types including sediments, filtered effluents, and unfiltered effluents from POTWs and CWTs. The results are presented in **Table 4-22**. The average ratio ranged from 2.4 to 11.4.

4.1.6 POTW Worker Exposure Assessment

4.1.6.1 External Gamma Radiation Exposure

The gamma radiation exposure rate survey results are provided in Section 4.1.1.4. The maximum average gamma radiation exposure rate measured at any of the POTW plants was 36.3 μR/hr. The lowest background gamma radiation exposure rate measured at any of the sites was 5 μR/hr. Assuming the time period of exposure is a full occupational year of 2,000 hours, the maximum average POTW annual external gamma radiation exposure was estimated as follows:

Maximum Average POTW External Gamma Radiation Exposure Estimate

$$(36.3 - 5)\ \mu R/hr \times 2{,}000\ hr/yr \times (1\ mrem/1{,}000\ \mu R\ gamma) = 62.6\ mrem/yr$$

This is an estimate of the maximum average gamma radiation exposure at a single facility based on 2,000 hours in one year. The result is less than the 100 mrem/yr dose equivalent limit for a member of the public. Actual exposure is dependent upon the actual exposure rates and occupancy time for individual workers.

The maximum gamma radiation exposure rate measured at the POTWs was 257 μR/hr on contact with the outside of a wastewater tank. Consequently, the public dose limit of 100 mrem per year could potentially be reached by a person working 400 hours within the immediate proximity of the tank. Actual annual exposure for a POTW worker is dependent upon the exposure rates and time worked in proximity to the tank.

4.1.6.2 Internal Alpha/Beta Radiation Exposure

The total and removable α/β survey surface radioactivity summary results are provided in Sections 4.1.1.1 and 4.1.1.2. Nine of the 566 α measurements and 68 of the 566 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. One of the 286 removable α measurements and none of the 286 removable β measurements exceeded the RG 1.86 criteria. Fixed or removable α and β surface radioactivity may present a potential inhalation or ingestion hazard if disturbed during routine system maintenance.

4.1.6.3 Internal Radon Exposure

The Rn measured in indoor air averaged 1.74 pCi/L. This average is below the EPA action level of 4 pCi/L, and very near the U.S. average indoor Rn level of 1.3 pCi/L, as reported by EPA.

4.1.7 POTW Radiological Environmental Impacts

Seven sediment-impacted soil samples were collected at the effluent discharge points of three of the **POTW-I's**. Radium-226 activity concentrations above typical soil background activity concentrations were identified in all sediment samples, with 18.2 pCi/g being the maximum reported result.

The presence of Ra in sediment-impacted soil at effluent discharge points indicates effluent wastewater contained Ra. Radium and gross α and β radioactivity were identified in effluent samples. **Table 4-21** presents filtered and unfiltered effluent average sample results and sediment-impacted soil results for POTWs sampled during the study.

4.2 Centralized Wastewater Treatment Plants

Three survey rounds were conducted at nine of the 10 CWTs. The 10th facility was added after the first survey round was completed, resulting in only two surveys at that facility.

4.2.1 Survey Results

Radiological surveys were conducted at each CWT resulting in four data sets:

- *Removable α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Total α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Gross Gamma Radiation Scan* measurements recorded in units of cpm
- *Gamma Radiation Exposure Rate* measurements recorded in units of μR/hr

4.2.1.1 Removable Alpha/Beta Surface Radioactivity Measurement Results

Measurements of removable radioactivity were performed to evaluate potential internal radiation exposures of workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 surface radioactivity guidelines, Table 1. RG 1.86 requires that α and β surface radioactivity levels be evaluated separately. The primary α emitter of concern is Ra-226, with a removable surface radioactivity criterion of 20 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a removable surface radioactivity criterion of 200 dpm β/100 cm^2.

The average removable α and β surface radioactivity levels were all below the RG 1.86 criteria. The maximum removable α and β surface radioactivity levels were 38.1 dpm/100 cm^2 and 133 dpm/100 cm^2. The summary results of removable α and β surface radioactivity are presented in **Table 4-23.** Individual removable α and β surface radioactivity measurement results are presented in **Appendix D**.

4.2.1.2 Total Alpha/Beta Surface Radioactivity Measurement Results

Measurements of total α and β surface radioactivity were performed to evaluate potential internal radiation exposures of workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 surface radioactivity guidelines, Table 1. RG 1.86 requires that α and β surface radioactivity levels be evaluated separately. The primary α emitter of concern is Ra-226, with a total surface radioactivity criterion of 100 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a total surface radioactivity criterion of 1,000 dpm β/100 cm^2.

Eighteen of the 28 average total α surface radioactivity measurements were below the RG 1.86 surface radioactivity criterion. Three of the 28 average total β surface radioactivity measurements were below the RG 1.86 surface radioactivity criterion. The maximum total α and β surface radioactivity levels were 3,220 dpm/100 cm^2 and 50,400 dpm/100 cm^2. The summary results of total α and β surface radioactivity measurements are presented in **Table 4-24**. Individual total α and β surface radioactivity measurement results are presented in **Appendix D**.

4.2.1.3 Gross Gamma Radiation Scan Results

Gross gamma radiation scans recorded in cpm were performed on open land areas and accessible areas of the CWT facilities to identify any areas with levels above local background. The summary results of the gross gamma radiation scans for each plant are presented in **Table 4-25**. The highest average count rate for the plants was 19,281 cpm, and the maximum count rate recorded was 401,688 cpm. A graphic display of the gamma radiation scan results at each facility was prepared using GIS software. The resulting figures are in **Appendix E**.

4.2.1.4 Gamma Radiation Exposure Rate Results Summary

Gross gamma radiation scan results in units of cpm presented in **Table 4-25** were converted to μR/hr by dividing by 800 cpm per μR/hr, a conversion factor appropriate for Ra-226 gamma energy as detected with 2-inch by 2-inch NaI detectors rounded to one significant figure (Table 6.4, NaI Scintillation Detector Scan MDCs for Common Radiological Contaminants, NUREG-1507, Minimum Detectable Concentrations With Typical Radiation Survey Instruments for Various Contaminants and Field Conditions, USNRC June 1998). **Table 4-26** presents statistical results for each CWT facility. The highest average gamma radiation exposure rate was 24.1 μR/hr, and the maximum gamma radiation exposure rate measured was 502 μR/hr.

4.2.2 Solid Sample Results

4.2.2.1 Filter Cake Samples

Three survey rounds were conducted at nine of the 10 CWTs. The 10th facility was added after the first survey round was completed, resulting in only two surveys at that facility. Also, the 10th facility is a primary treatment facility, so it does not produce a filter cake. A total of 25 filter cake samples were collected from the nine plants. The results are presented in **Table 4-27**. The analytical results indicate all the CWT filter cake samples contain elevated Ra-226 and Ra-228 above typical background levels for soil. The maximum results were 294 pCi/g of Ra-226 and 177 pCi/g of Ra-228.

4.2.2.2 Solids/Sediment Samples

Four of the CWTs surveyed and sampled as part of the study are permitted to discharge effluent wastewater to the environment. If the discharge point was accessible, surface soil impacted by sediment was sampled. The gamma spectroscopy results are presented in **Table 4-28**. The Ra-226 results ranged from 2.50 to 421 pCi/g. The Ra-228 results ranged from 0.978 to 86.9 pCi/g. Uranium and Th were also detected at surface soil typical background levels in some of the samples because of natural soil collected along with the sediment.

4.2.2.3 Solids/Biased Samples

Gamma radiation walkover scans identified areas with radioactivity above local background. At three of these locations, a biased soil sample was collected to determine the amount of activity at or near the surface. The gamma spectroscopy results are presented in **Table 4-29**. Radium above soil typical background levels to a maximum of 444 pCi/g Ra-226 and 83.1 pCi/g Ra-228 was identified in biased soil samples.

4.2.3 Liquid Samples

Samples of influent and effluent, both filtered and unfiltered, were analyzed. Three survey rounds were conducted at nine of the 10 CWTs. The 10th facility was added after the first survey round was completed, resulting in only two surveys at that facility. Also, the 10th facility is only a primary treatment facility, with the influent and the effluent essentially the same. Consequently, only the influent was sampled at the 10^{th} facility. A total of 31 effluent and 26 influent samples were collected for filtered and unfiltered analysis. The filtered and unfiltered analyses are presented separately. The gamma spectroscopy results, gross α, and gross β are presented in **Tables 4-30** through **4-33**. Radium (Ra-226 and Ra-228) was routinely detected in all sample types with little difference between influent and effluent or between filtered and unfiltered results as presented for Ra-226 in **Figure 4-1**.

Figure 4-1. CWT Influent and Effluent Liquid Ra-226 Minimum, Maximum, and Average

Wastewater Source	Filtered or Not	Min (pCi/L)	Max (pCi/L)	Ave (pCi/L)
Effluent	Filtered	18.0	14,900	2,100
Effluent	Unfiltered	42.0	15,500	1,840
Influent	Filtered	57.0	14,100	1,550
Influent	Unfiltered	17.5	13,400	1,870

4.2.4 Indoor Radon Sampling Results

ATDs were deployed in the CWT plants at various indoor locations such as break rooms, labs, offices, etc., and the results were evaluated using the EPA action level of 4.0 pCi/L. The results ranged from 0.900 to 5.00 pCi/L. Two results exceeded the action level. The results of the analyses are presented in **Table 4-34**. The Rn analytical reports are presented in **Appendix H**.

4.2.5 Filtered Versus Unfiltered Sample Data Evaluation

Appendix I presents a complete evaluation of filtered versus unfiltered liquid samples for the entire study. The conclusion from this evaluation is that there is no apparent trend or bias that filtering produces. There were some subsets of data where either the unfiltered results or the filtered results appear to be significantly higher. There was no statistically significant correlation found within any sample group. Because the liquid samples were preserved by addition of acid prior to filtering, the radioactive particulates may have entered solution and were therefore not removed by filtering.

4.2.6 CWT Exposure Assessment

4.2.6.1 CWT External Radiation Exposure

The maximum average gamma radiation exposure rate measured at any of the CWT plants was 24.1 μR/hr. The lowest background gamma radiation exposure rate measured at any of the sites was 5 μR/hr. Assuming the time period of exposure is a full occupational year of 2,000 hours, the maximum average CWT annual external gamma radiation exposure was estimated as follows:

Maximum Average CWT External Gamma Radiation Exposure Estimate

$$(24.1 – 5)\ \mu R/hr \times 2{,}000\ hr/yr \times (1\ mrem/1{,}000\ \mu R\ gamma) = 38\ mrem/yr$$

This is an estimate of the maximum average gamma radiation exposure based on 2,000 hours in one year. The result is less than the 100 mrem/yr dose equivalent limit for a member of the public. Actual exposure is dependent upon the actual exposure rates and occupancy time for individual workers.

The maximum gamma radiation exposure rate measured was 502 μrem/hr on contact with the outside of a wastewater tank. Work in proximity of the tank could potentially result in an exposure of 100 mrem in 200 hours of annual exposure or 10 percent of an employee's 2,000-hour occupational year. Actual annual exposure for a CWT worker is dependent upon actual exposure rates and actual time worked in the proximity of the tank.

4.2.6.2 CWT Potential Internal Alpha/Beta Radioactivity Exposure

The total and removable α/β surface radioactivity survey results are discussed in Sections 4.2.1.1 and 4.2.1.2. One hundred eighty-six of the 777 α measurements and 461 of the 777 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. Seven of the 805 removable α measurements and 6 of the 805 removable β measurements exceeded the RG 1.86 criteria. The average of the β total surface radioactivity measurements exceeded the RG 1.86 criteria in 10 of the 11 CWT facilities surveyed. The average of the α total surface radioactivity measurements exceeded the RG 1.86 criteria in four of the 11 CWT facilities surveyed. The corresponding removable radioactivity measurements are mostly less than the RG 1.86 criteria, indicating the total radioactive contamination measured is fixed to the surface and not immediately available for inhalation or ingestion. Fixed α and β surface radioactivity may present a potential inhalation or ingestion hazard if disturbed during routine system maintenance.

4.2.6.3 Internal Radon Exposure

The Rn in indoor area air averaged 2.00 pCi/L. This average is below the EPA action level of 4 pCi/L and only slightly above the U.S. average indoor level of 1.3 pCi/L, as reported by EPA.

4.2.7 CWT Radiological Environmental Impacts

Sediment-impacted soil was collected at the accessible effluent discharge points at the CWTs. A total of nine samples were collected. Radium above typical soil background levels to a maximum of 508 pCi/g of total Ra was identified in the sediment-impacted soil samples. Effluent wastewater also contained Ra and is the likely source of the Ra in sediment-impacted soil above soil typical background levels.

4.3 Zero Liquid Discharge Plants

4.3.1 Survey Results

Radiological surveys were conducted at each ZLD facility resulting in four data sets:

- *Removable α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Total α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Gross Gamma Radiation Scan* measurements recorded in units of cpm
- *Gamma Radiation Exposure Rate* measurements recorded in units of μR/hr

4.3.1.1 Removable Alpha/Beta Surface Radioactivity Measurement Results

Measurements of removable surface radioactivity were performed to evaluate potential internal radiation exposures of workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 guidelines, Table 1. RG 1.86 requires that α and β surface radioactivity levels be evaluated separately. The primary α emitter of concern is Ra-226, with a removable surface radioactivity criterion of 20 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a removable surface radioactivity criterion of 200 dpm β/100 cm^2. The average removable α and β surface radioactivity levels were below the RG 1.86 criteria. The maximum removable α and β surface radioactivity levels were 294 dpm/100 cm^2 and 342 dpm/100 cm^2. The summary results of removable α and β surface radioactivity are presented in **Table 4-35.** Individual removable α and β surface radioactivity measurement results are presented in **Appendix D**.

4.3.1.2 Total Alpha/Beta Surface Radioactivity Measurement Results

Measurements of total α and β surface radioactivity were performed to evaluate potential internal radiation exposures of workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 guidelines, Table 1. RG 1.86 requires that α and β surface radioactivity levels be evaluated separately. The primary α emitter of concern is Ra-226, with a total surface radioactivity criterion of 100 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series with a total surface radioactivity criterion of 1,000 dpm β/100 cm^2. The highest average total α and β surface radioactivity levels were 239 dpm/100 cm^2 and

4,740 dpm/100 cm^2. The maximum total α and β surface radioactivity levels were 1,410 dpm/100 cm^2 and 49,700 dpm/100 cm^2. The summary results of total α and β surface radioactivity measurements are presented in **Table 4-36**. Individual total α and β surface radioactivity measurement results are presented in **Appendix D**.

4.3.1.3 Gross Gamma Radiation Scan Results

Gross gamma radiation scans recorded in cpm were performed on open land areas and accessible areas of the plant to identify levels of elevated gross gamma radiation. The results of the gross gamma radiation scans are presented in **Table 4-37**. The highest average count rate for the plants was 34,513 cpm, and the maximum count rate recorded was 356,274 cpm. A graphic display of the gamma radiation scan results (figures) at each facility was prepared using GIS software. The resulting figures are in **Appendix E**.

4.3.1.4 Gamma Radiation Exposure Rate Results Summary

Gross gamma radiation scan results in units of cpm presented in **Table 4-37** were converted to μR/hr by dividing by 800 cpm per μR/hr, a conversion factor appropriate for Ra-226 gamma energy as detected with 2-inch by 2-inch NaI detectors rounded to one significant figure (Table 6.4, NaI Scintillation Detector Scan MDCs for Common Radiological Contaminants, NUREG-1507, Minimum Detectable Concentrations With Typical Radiation Survey Instruments for Various Contaminants and Field Conditions, USNRC June 1998). **Table 4-38** presents statistical results for each ZLD facility. The highest average gamma radiation exposure rate was 43.1 μR/hr, and the maximum gamma radiation exposure rate measured was 445 μR/hr.

4.3.2 Solid Sample Results

4.3.2.1 Filter Cake Samples

Three survey rounds were conducted at each of the nine ZLD plants and a total of 31 filter cake samples were collected from the nine plants. The gamma spectroscopy results are presented in **Table 4-39**. Radium-226 and Ra-228 were measured in ZLD filter cake samples at concentrations above typical background levels for surface soils. Radium-226 concentrations ranged from 3.08 to 480 pCi/g, and Ra-228 concentrations ranged from 0.580 to 67.3 pCi/g.

4.3.2.2 Solids/Biased Samples

A single biased surface soil sample was collected. The gamma spectroscopy results are presented in **Table 4-40**. The Ra-226 and Ra-228 were measured in concentrations above typical background levels. The Ra-226 concentration was 37.1 pCi/g, and the Ra-228 concentration was 7.47 pCi/g.

4.3.3 Liquid Samples

Three survey and sample events were conducted at each of the nine ZLD plants. A total of 30 effluent samples and 26 influent samples were collected. The filtered and unfiltered sample analyses results are presented separately. The results of the U series, Th Series, and Ac series with K-40, gross α, and gross β are presented in **Tables 4-41** through **4-44**. Radium (Ra-226 and

Ra-228) was routinely detected in all sample types with an approximate 50 percent difference between influent and effluent, but little difference between filtered and unfiltered results, as presented for Ra-226 results below in **Figure 4-2**.

Figure 4-2. ZLD Influent and Effluent Liquid Ra-226 Minimum, Maximum, and Average

Wastewater Source	Filtered or Not	Min (pCi/L)	Max (pCi/L)	Ave (pCi/L)
Effluent	Filtered	29.0	12,500	2,780
Effluent	Unfiltered	33.0	11,900	2,610
Influent	Filtered	38.5	20,900	4,660
Influent	Unfiltered	134	17,100	4,710

4.3.4 Indoor Radon Sampling Results

ATDs were deployed in the ZLD plants at various indoor locations such as break rooms, laboratories, offices, etc., and the results were evaluated using the EPA action level of 4 pCi/L. The results ranged from 0.500 to 4.90 pCi/L. Two results exceeded the action level. The results of the analyses are presented in **Table 4-45**. The Rn analytical reports are presented in **Appendix H**.

4.3.5 Filtered Versus Unfiltered Sample Data Evaluation

Appendix I contains a complete evaluation of filtered versus unfiltered liquid samples for the entire study. The conclusion from this evaluation is that there is no apparent trend or bias that filtering produces. There were some subsets of data where either the unfiltered results or the filtered results appear to be significantly higher. There was no statistically significant correlation found within any sample group. Since the liquid samples were preserved by addition of acid prior to filtering, the radioactive particulates may have entered solution and were therefore not removed by filtering.

4.3.6 ZLD Worker Exposure Assessment

4.3.6.1 ZLD Worker Potential External Gamma Radiation Exposure

The maximum average gamma radiation exposure rate measured at any of the ZLD plants was 43.1 μR/hr. The lowest background gamma radiation exposure rate measured at any of the sites was 5 μR/hr. Assuming the time period of exposure is a full occupational year of 2,000 hours, the maximum average ZLD annual external gamma radiation exposure was estimated as follows:

Maximum Average ZLD External Gamma Radiation Exposure Estimate

$$(43.1 - 5)\ \mu R/hr \times 2{,}000\ hr/yr \times (1\ mrem/1{,}000\ \mu R\ gamma) = 76\ mrem/yr$$

This is an estimate of the maximum average gamma radiation exposure based on 2,000 hours in one year. The result is less than the 100 mrem/yr dose equivalent limit for a member of the public. Actual exposure is dependent upon the actual exposure rates and occupancy time for individual workers.

The maximum gamma radiation exposure rate measured was 445 μrem/hr on contact with the outside of a wastewater tank. Work performed in the immediate proximity to the tank could potentially result in an exposure of 100 mrem in 225 hours of annual exposure, or about 10 percent of an employee's 2,000-hour occupational year. Actual annual exposure for a ZLD worker is dependent upon actual exposure rates and actual time worked in the proximity of the tank.

4.3.6.2 ZLD Worker Potential Internal Alpha/Beta Exposure

The total and removable α/β survey surface radioactivity results are discussed in Sections 4.3.1.1 and 4.3.1.2. One hundred fifty-nine of the 566 α measurements and 175 of the 566 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. Fourteen of the 589 removable α measurements and two of the 589 removable β measurements exceeded the RG 1.86 criteria. The highest average total α and β surface radioactivity levels were 239 dpm/100 cm^2 and 4,740 dpm/100 cm^2. The maximum total α and β surface radioactivity levels were 1,410 dpm/100 cm^2 and 49,700 dpm/100 cm^2. The corresponding removable surface radioactivity measurements are mostly less than the RG 1.86 criteria, indicating the total surface radioactivity measured is fixed to the surface and not immediately available for inhalation or ingestion. Fixed α and β surface radioactivity may present a potential inhalation or ingestion hazard if disturbed during routine system maintenance.

4.3.6.3 ZLD Worker Potential Internal Radon Exposure

The Rn in ambient indoor area air averaged 2.29 pCi/L. The average is above the average typical background indoor level of 1.30 pCi/L in the U.S. as reported by EPA.

4.3.6.4 Gamma Radiation Exposure during Transport of Wastewater and Wastewater Sludge

Gamma radiation exposure was estimated for the transport of wastewater from well sites to WWTPs, and sludge from WWTPs to landfills. This was done for the driver of the transport truck. The truck driver spends the most time near the TENORM-influenced wastewater during transport.

It was assumed a truck driver hauled full containers with either wastewater or sludge/filter cake for four hours per day and made return trips with empty containers for four hours per day. The driver was assumed to work 40 hours per week for 10 weeks per year hauling O&G wastewater or sludge. Therefore, the total exposure time was assumed to be 200 hours per year as calculated below:

Estimated Duration of Gamma Radiation Exposure for Truck Driver per Year

4 hr/day x 5 days/wk x 10 wks/yr = 200 hrs/yr

Radiation exposure rates to the driver were not measured; they were modeled using the computer program MicroShield®. The MicroShield® output files are presented in **Appendix J**. Two external exposure scenarios were evaluated:

1. Exposure rate to a driver hauling wastewater based on the maximum measured concentrations of Ra-226 and Ra-228 in wastewater.

2. Exposure rate to a driver hauling sludge or filter cake based on the maximum measured concentrations of Ra-226 and Ra-228 in sludge.

The input and output of MicroShield® based on the two scenarios are summarized in **Figure 4-3**.

Figure 4-3. MicroShield® External Exposure Scenarios Input/Output

Parameter	**Scenario**	
	Wastewater Truck Maximum Measured Concentration, Scenario 1	**Sludge/Filter Cake Roll-off Maximum Measured Concentration, Scenario 2**
Volume	3,800 gallons	20 cubic yards
Shielding Material	Stainless steel, 0.5 cm thick	Iron, 0.3 cm thick
Ra-226 and Progeny Input Concentration	18,400 pCi/L	480 pCi/g
Ra-228 and Progeny Input Concentration	1,440 pCi/L	183 pCi/g
Resulting Driver Exposure Rate (µrem/hr)	14.7	1,340
Exposure Rate per Radium Concentration	0.000741 µrem/hr / pCi/L of total Ra	2.02 µrem/hr / pCi/g of total Ra

Maximum Wastewater Truck Driver External Gamma Radiation Exposure Estimate

0.000741 µrem/hr / pCi/L x 2,380 pCi/L x 200 hr/yr x (1 mrem/1,000 µrem gamma) = 0.35 mrem/yr

This is an estimate of the maximum annual gamma radiation exposure based on the maximum total Ra activity concentration of influent wastewater measured and 200 hours exposure in one year. The result is less than the 100 mrem/yr dose equivalent limit for a member of the public. Actual exposure is dependent upon the actual exposure rates and occupancy time for individual workers.

Maximum Sludge Truck Driver External Gamma Radiation Exposure Estimate

2.02 µrem/hr / pCi/g x 129 pCi/g x 200 hr/yr x (1 mrem/1,000 µrem gamma) = 52 mrem/yr

This is an estimate of the maximum annual gamma radiation exposure based on the maximum total Ra activity concentration in sludge measured and 200 hours of exposure in one year. The result is less than the 100 mrem/yr dose equivalent limit for a member of the public. Actual exposure is dependent upon the actual exposure rates and occupancy time for individual workers.

The sludge truck driver assessment is conservative due to the following: solid samples were dried prior to gamma spectroscopy analysis, artificially increasing the activity concentration results in direct proportion to the moisture content of the sample, i.e., after removal of the weight of the wastewater within the sludge sample. In addition, the MicroShield® activity input includes all of the Ra progeny in secular equilibrium. Often the sludge is "fresh," i.e., progeny ingrowth has not progressed to secular equilibrium and the progeny activity is only a fraction of the Ra activity.

4.3.7 Alpha Spectroscopy Analysis of Filter Cake

Elevated Ra-226 and Ra-228 and progeny activity were detected in CWT and ZLD filter cake samples analyzed by gamma spectroscopy. Due to the low solubility in water of U and Th, relative to Ra, U and Th were not present in wastewater and resulting filter cake at the elevated levels observed for Ra. Because gamma spectroscopy analysis of solid and liquid samples is limited in regards to the quantification of U and Th isotopes (Section 2.3), α spectroscopy analysis to measure U (U-238, U-234, and U-235) and Th (Th-232, Th-230, and Th-228), isotope activity levels was performed on 10 filter cake samples. The results are presented in **Table 4-46**. The U-238, U-234, and Th-230, all members of the natural U decay series above Ra-226, were measured at approximately 1/3 of typical background activity in soil. Uranium-235 is only identified once > MDC. Th-232, a member of the natural Th decay series above Ra-228, was measured at approximately ¼ of typical background activity in soil. Only Th-228, a progeny of Ra-228, was measured at activity concentrations comparable to Ra-228 identified by gamma spectroscopy. The α spectroscopy results confirm the low solubility of U and Th, resulting in low activity levels in wastewater and sludge/filter cake.

Table 4-1. POTW-I Removable Alpha and Beta Surface Radioactivity Measurement Results Summary

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-12-FS-024	10	8.15	8.15	0.000	8.15	38.0	38.0	0.000	38.0
WT-12-FS-074	19	6.90	6.90	0.000	6.90	60.5	60.5	0.000	60.5
WT-12-FS-075	17	9.15	9.15	0.000	9.15	34.8	34.8	0.000	34.8
WT-13-FS-034	17	9.15	9.15	0.000	9.15	38.5	38.5	0.000	38.5
WT-13-FS-119	32	6.40	16.4	1.76	6.71	56.0	56.0	0.000	56.0
WT-13-FS-120	20	9.10	9.10	0.000	9.10	34.8	34.8	0.000	34.8
WT-14-FS-027	12	9.10	9.10	0.000	9.10	41.5	41.5	0.000	41.5
WT-14-FS-121	20	4.25	4.25	0.000	4.25	65.0	65.0	0.000	65.0
WT-14-FS-122	20	8.85	8.85	0.000	8.85	30.0	30.0	0.000	30.0
WT-15-FS-031	8	8.85	8.85	0.000	8.85	30.0	30.0	0.000	30.0
WT-15-FS-032	14	6.40	22.0	4.93	6.00	56.0	161	27.9	63.5
WT-15-FS-033	5	9.15	9.15	0.000	9.15	38.5	38.5	0.000	38.5
WT-16-FS-043	16	9.10	9.10	0.000	9.10	41.5	41.5	0.000	41.5
WT-16-FS-123	19	7.30	7.30	0.000	7.30	65.5	65.5	0.000	65.5
WT-16-FS-124	22	9.10	9.10	0.000	9.10	35.0	35.0	0.000	35.0
WT-17-FS-051	20	8.00	8.00	0.000	8.00	30.8	30.8	0.000	30.8
WT-17-FS-125	15	8.70	8.70	0.000	8.70	38.3	38.3	0.000	38.3

Note: During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 4-2. POTW-I Total Alpha and Beta Surface Radioactivity Measurement Results Summary

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-12-FS-024	10	29.4	29.4	0.000	29.4	100	563	144	413
WT-12-FS-074	19	7.30	43.7	10.1	19.7	308	308	0.000	308
WT-12-FS-075	17	7.45	54.5	14.2	18.27	269	1,550	268	870
WT-13-FS-034	17	30.5	74.4	13.7	37.0	847	2,130	325	1,290
WT-13-FS-119	15	18.6	875	220	88.8	305	728	117	337
WT-13-FS-120	20	19.0	164	33.9	30.2	280	1,530	391	811
WT-14-FS-027	13	30.5	30.5	0.000	30.5	773	1,540	197	1,130
WT-14-FS-121	20	18.6	112	26.1	37.0	254	1,490	352	515
WT-14-FS-122	20	30.5	89.3	20.3	38.8	268	1,630	359	784
WT-15-FS-031	8	30.5	1,190	437	313	268	38,000	14,800	10,000
WT-15-FS-032	4	18.6	18.6	0.000	18.6	263	466	102	313
WT-15-FS-033	5	30.5	30.5	0.000	30.5	735	1,360	259	1,070
WT-16-FS-043	16	30.5	30.5	0.000	30.5	676	29,800	7,170	2,930
WT-16-FS-123	19	7.45	24.9	6.39	11.4	276	1,140	272	498
WT-16-FS-124	22	7.45	34.7	10.2	12.7	273	1,200	295	593
WT-17-FS-051	20	7.45	54.5	13.4	16.0	313	929	159	363
WT-17-FS-125	15	29.8	134	32.8	61.0	313	2,760	704	773

Note: During the calculations to convert from raw counts to dpm the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same then all measurements were below half of the MDC.

Table 4-3. POTW-I Gross Gamma Radiation Scan Results Summary

Site	GWS Max[a] (cpm)	GWS Min[a] (cpm)	GWS Average[a] (cpm)	GWS Std Dev (cpm)	No. Data Points
12	9,514	4,966	7,184	633	7,129
13	9,362	3,404	5,072	829	4,408
13	20,761	3,608	6,019	2,694	8,553
13	18,203	3,486	5,418	2,082	5,474
14	33,141	3,112	5,582	2,517	7,638
14	29,220	3,867	6,110	2,272	7,302
14	32,253	3,680	6,435	3,812	3,275
15	131,626	3,804	20,392	14,569	3,508
15	162,535	5,684	18,319	16,130	7,334
15	205,446	5,452	29,034	36,865	3,052
16	10,005	3,463	5,671	870	9,390
16	13,915	3,723	5,628	1,050	9,520
16	13,597	3,473	6,871	1,722	2,026
17	150,649	3,305	9,194	10,116	4,509
17	156,738	3,478	11,137	17,801	3,003

[a]Convert count rate data to exposure rate by dividing count rate by 800 to yield μR/hr.

Table 4-4. POTW-I Results Summary of NaI Count Rate Data Converted to Exposure Rates

Site	GWS Max (μR/hr)	GWS Min (μR/hr)	GWS Average (μR/hr)	GWS Std Dev (μR/hr)	No. Data Points
12	11.9	6.21	8.98	0.791	7,129
13	11.7	4.26	6.34	1.04	4,408
13	26.0	4.51	7.52	3.37	8,553
13	22.8	4.36	6.77	2.60	5,474
14	41.4	3.89	6.98	3.15	7,638
14	36.5	4.83	7.64	2.84	7,302
14	40.3	4.60	8.04	4.77	3,275
15	165	4.76	25.5	18.2	3,508
15	203	7.11	22.9	20.2	7,334
15	257	6.82	36.3	46.1	3,052
16	12.5	4.33	7.09	1.09	9,390
16	17.4	4.65	7.04	1.31	9,520
16	17.0	4.34	8.59	2.15	2,026
17	188	4.13	11.5	12.6	4,509
17	196	4.35	13.9	22.3	3,003

Table 4-5. POTW-I Filter Cake Results Summary – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)
WT-12-SL-030	6.37	1.56	4.04
WT-12-SL-048	9.75	1.87	6.94
WT-12-SL-085	5.16	0.854	2.69
WT-13-SL-021	6.50	3.08	3.96
WT-13-SL-060	21.3	2.99	9.38
WT-13-SL-065	17.4	8.69	3.93
WT-14-SL-017	55.6	32.0	7.77
WT-14-SL-052	9.27	2.80	14.3
WT-14-SL-068	13.1	6.73	6.71
WT-15-SL-057	41.9	19.7	12.9
WT-16-SL-026	5.01	1.29	6.95
WT-16-SL-044	52.6	5.21	7.78
WT-16-SL-073	2.71	0.894	0.822
WT-17-SL-059	35.1	19.2	6.14
Average	20.1	7.63	6.74
Std. Dev.	18.5	9.40	3.71
Median	11.4	3.04	6.83
Minimum	2.71	0.854	0.822
Maximum	55.6	32.0	14.3

Table 4-6. POTW-N Filter Cake Results Summary – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)
WT-26-SL-094	3.97	1.31	5.47
WT-26-SL-095	3.61	1.46	5.41
WT-27-SL-096	2.33	0.817	6.51
WT-27-SL-097	5.76	1.12	4.31
WT-28-SL-098	7.36	1.84	6.57
WT-28-SL-099	3.78	1.07	6.55
WT-29-SL-100	35.4	7.26	7.66
WT-29-SL-101	15.6	3.28	7.34
Average	9.72	2.26	6.23
Std. Dev.	11.2	2.16	1.10
Median	4.87	1.39	6.53
Minimum	2.33	0.817	4.31
Maximum	35.4	7.26	7.66

Table 4-7. POTW-I Sediment Sample Results Summary – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)
WT-14-SL-018	4.25	1.96	10.3
WT-14-SL-053	1.83	0.799	8.71
WT-14-SL-069	3.94	1.96	5.53
WT-15-SL-020	16.6	6.25	15.7
WT-15-SL-056	18.2	6.19	13.0
WT-15-SL-067	15.3	5.77	24.5
WT-17-SL-058	2.91	1.69	6.20
Average	9.00	3.52	12.0
Std. Dev.	7.29	2.42	6.58
Median	4.25	1.96	10.3
Minimum	1.83	0.799	5.53
Maximum	18.2	6.25	24.5

Table 4-8. POTW-I Filtered Effluent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-12-LQ-098	134	< 18.0	< 66.0	< 196	< 392
WT-12-LQ-159	< 127	< 25.0	81.0	< 5.77	10.6
WT-12-LQ-295	77.0	< 13.0	42.0	195	365
WT-13-LQ-054	< 126	< 22.0	73.0	< 29.6	< 18.9
WT-13-LQ-193	101	< 16.0	46.0	< 114	< 198
WT-13-LQ-209	363	< 10.0	53.0	< 123	< 203
WT-14-LQ-044	< 130	< 24.0	56.0	< 25.8	< 163
WT-14-LQ-171	87.0	< 12.0	60.0	< 111	< 186
WT-14-LQ-215	104	< 13.0	71.0	< 118	< 202
WT-15-LQ-052	191	< 24.0	< 81.0	< 21.3	< 16.2
WT-15-LQ-185	< 139	< 25.0	< 98.0	< 5.67	8.70
WT-15-LQ-223	120	25.0	52.0	< 161	< 198
WT-16-LQ-079	101	< 8.00	34.0	< 2.26	5.77
WT-16-LQ-145	57.0	< 6.00	55.0	< 6.96	11.3
WT-16-LQ-241	335	< 9.00	< 32.0	4.64	10.7
WT-17-LQ-191	154	< 18.0	< 48.0	< 121	< 187
WT-17-LQ-217	116	12.0	< 33.0	< 127	< 203
Average	129	9.34	48.1	42.9	75.0
Std. Dev.	93.1	5.35	19.0	49.6	88.8
Median	101	8.50	50.5	35.1	87.3
Minimum	57.0	3.00	16.0	1.13	5.77
Maximum	363	25.0	81.0	195	365

< – indicates a value less than the reported number which is the MDC.

Table 4-9. POTW-I Unfiltered Effluent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-12-LQ-097	< 67.0	< 10.0	51.1	< 284	< 396
WT-12-LQ-160	94.0	< 11.0	41.0	9.63	10.9
WT-12-LQ-296	59.0	< 5.00	40.0	< 192	< 207
WT-13-LQ-053	113	< 8.00	37.0	< 36.5	< 135
WT-13-LQ-194	82.0	< 5.00	55.0	< 117	< 187
WT-13-LQ-210	< 35.0	< 23.0	< 11.0	< 144	< 194
WT-14-LQ-043	122	< 18.0	80.0	< 84.2	< 158
WT-14-LQ-172	340	< 15.0	< 58.0	< 464	< 218
WT-14-LQ-216	< 128	< 27.0	< 106	< 136	< 193
WT-15-LQ-051	80.0	< 9.00	53.0	< 177	< 163
WT-15-LQ-186	135	< 9.00	< 27.0	11.0	9.60
WT-15-LQ-224	< 79.0	27.0	64.0	< 235	< 209
WT-16-LQ-080	100	< 9.00	33.0	< 3.13	7.16
WT-16-LQ-146	< 67.0	< 11.0	< 41.0	< 2.16	7.71
WT-16-LQ-242	107	< 9.00	44.0	< 2.51	10.5
WT-17-LQ-192	100	21.0	82.0	1,110	337
WT-17-LQ-218	156	35.0	31.0	< 152	< 197
Average	103	10.4	42.6	125	82.1
Std. Dev.	73.7	9.40	21.5	269	79.3
Median	97.0	5.75	40.5	63.3	87.5
Minimum	17.5	2.50	5.50	1.08	7.16
Maximum	340	35.0	82.0	1,110	337

< – indicates a value less than the reported number which is the MDC.

Table 4-10. POTW-N Filtered Effluent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-26-LQ-300	< 74.0	15.0	60.0	< 7.65	5.29
WT-27-LQ-304	< 44.0	< 5.00	42.0	< 10.8	5.72
WT-28-LQ-308	< 23.0	< 5.00	53.0	< 4.78	7.64
WT-29-LQ-312	116	17.0	56.0	< 4.83	14.6
Average	46.6	9.25	52.8	3.51	8.31
Std. Dev.	47.4	7.84	7.72	1.43	4.31
Median	29.5	8.75	54.5	3.12	6.68
Minimum	11.5	2.50	42.0	2.39	5.29
Maximum	116	17.0	60.0	5.40	14.6

< – indicates a value less than the reported number which is the MDC.

Table 4-11. POTW-N Unfiltered Effluent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-26-LQ-299	328	< 9.00	< 34.0	< 6.46	5.75
WT-27-LQ-303	115	< 7.00	57.0	< 7.48	7.48
WT-28-LQ-307	78.0	< 14.0	49.0	< 5.18	7.15
WT-29-LQ-311	59.0	5.00	66.0	< 191	< 209
Average	145	5.00	47.3	26.3	31.2
Std. Dev.	124	1.47	21.3	46.2	48.9
Median	96.5	4.75	53.0	3.49	7.32
Minimum	59.0	3.50	17.0	2.59	5.75
Maximum	328	7.00	66.0	95.5	105

< – indicates a value less than the reported number which is the MDC.

Table 4-12. POTW-I Filtered Influent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-12-LQ-096	66.0	8.00	49.0	< 5.64	< 7.91
WT-12-LQ-157	109	< 14.0	32.0	< 13.2	< 5.01
WT-12-LQ-293	100	8.00	63.0	< 290	< 230
WT-13-LQ-056	< 154	< 29.0	137	< 207	< 394
WT-13-LQ-195	115	< 20.0	< 68.0	< 183	< 201
WT-13-LQ-211	58.0	6.00	53.0	< 13.2	< 8.48
WT-14-LQ-042	260	< 48.0	< 171	< 16.8	< 15.5
WT-14-LQ-169	< 77.0	< 12.0	< 41.0	489	< 199
WT-14-LQ-213	82.0	10.0	63.0	< 323	< 230
WT-15-LQ-050	498	< 28.0	< 82.0	< 17.3	< 16.1
WT-15-LQ-183	245	103	< 141	11.0	9.60
WT-15-LQ-225	255	91.0	31.0	490	< 207
WT-16-LQ-077	< 84.0	< 17.0	119	< 2.63	6.24
WT-16-LQ-143	5,910	878	44.0	11,400	11,300
WT-16-LQ-243	66.0	5.00	43.0	< 3.31	6.75
WT-17-LQ-189	< 121	23.0	33.0	< 117	< 198
WT-17-LQ-219	< 74.0	20.0	49.0	< 154	< 196
Average	497	76.8	56.9	768	722
Std. Dev.	1,450	216	31.4	2,740	2,730
Median	91.0	12.0	49.0	58.5	98.0
Minimum	37.0	5.00	20.5	1.32	2.51
Maximum	5,910	878	137	11,400	11,300

< – indicates a value less than the reported number which is the MDC.

Table 4-13. POTW-I Unfiltered Influent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-12-LQ-095	< 113	< 19.0	< 59.0	< 220	< 392
WT-12-LQ-158	90.0	< 15.0	< 54.0	6.28	10.1
WT-12-LQ-294	345	< 7.00	< 21.0	< 110	< 201
WT-13-LQ-055	91.0	< 16.0	69.0	< 14.4	76.4
WT-13-LQ-196	95.0	< 15.0	72.0	< 287	< 224
WT-13-LQ-212	96.0	< 9.00	54.0	< 13.4	14.5
WT-14-LQ-041	259	< 48.0	< 171	< 14.8	17.2
WT-14-LQ-170	57.0	20.0	65.0	< 118	< 199
WT-14-LQ-214	120	9.00	47.0	< 301	< 227
WT-15-LQ-049	< 73.0	< 15.0	< 50.0	< 4.32	4.89
WT-15-LQ-184	514	48.0	< 67.0	240	< 196
WT-15-LQ-226	479	227	< 102	1,190	493
WT-16-LQ-078	343	< 9.00	< 5.00	< 1.85	7.50
WT-16-LQ-144	106	< 9.00	30.0	< 3.91	9.94
WT-16-LQ-244	131	41.0	65.0	< 7.48	9.64
WT-17-LQ-190	100	14.0	56.0	< 120	< 200
WT-17-LQ-220	178	20.0	45.0	< 125	< 203
Average	190	28.1	46.1	125	85.9
Std. Dev.	146	52.9	22.4	283	114
Median	120	9.00	47.0	55.0	92.0
Minimum	36.5	3.50	2.50	0.925	4.89
Maximum	514	227	85.5	1,190	493

< – indicates a value less than the reported number which is the MDC.

Table 4-14. POTW-N Filtered Influent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-26-LQ-298	134	10.0	30.0	13.0	6.62
WT-27-LQ-302	64.0	< 5.00	38.0	15.2	11.6
WT-28-LQ-306	84.0	< 14.0	62.0	4.57	12.4
WT-29-LQ-310	58.0	< 4.00	52.0	< 5.29	8.38
Average	85.0	5.38	45.5	8.85	9.75
Std. Dev.	34.5	3.82	14.3	6.17	2.71
Median	74.0	4.75	45.0	8.79	9.99
Minimum	58.0	2.00	30.0	2.65	6.62
Maximum	134	10.0	62.0	15.2	12.4

< – indicates a value less than the reported number which is the MDC.

Table 4-15. POTW-N Unfiltered Influent Results Summary – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-26-LQ-297	113	< 10.0	< 33.0	< 173	< 207
WT-27-LQ-301	92.0	32.0	44.0	< 192	< 209
WT-28-LQ-305	91.0	< 10.0	43.0	< 169	< 207
WT-29-LQ-309	114	< 9.00	< 29.0	< 4.21	8.63
Average	103	11.6	29.5	67.3	80.0
Std. Dev.	12.7	13.6	16.2	43.7	47.6
Median	103	5.00	29.8	85.5	104
Minimum	91.0	4.50	14.5	2.11	8.63
Maximum	114	32.0	44.0	96.0	105

< – indicates a value less than the reported number which is the MDC.

Table 4-16. POTW-I Ambient Radon

Facility	Location	Radon (pCi/L)	Percent Error
WT-17-RA-001	Lab	2.20	4%
WT-17-RA-002	Filter Press Room	3.10	3%
WT-17-RA-003	Not Given	0.200	12%
WT-15-RA-001	Old Lab	0.700	7%
WT-12-RA-001	Filter Press Room	0.500	8%
WT-12-RA-002	Break Room	0.500	8%
WT-14-RA-001	Press Room Shelf	0.700	7%
WT-14-RA-002	Break Room	8.70	2%
WT-16-RA-001	Filter Press Room	0.600	9%
WT-16-RA-002	Break Room	1.20	7%
WT-13-RA-001	Load and Filter	0.900	6%
WT-13-RA-002	Lab	1.60	5%
	Average	1.74	
	Median	0.800	
	St. Dev.	2.34	
	Minimum	0.200	
	Maximum	8.70	

Note: ATDs. Lower level of detection (LLD) for 10 pCi/L-day is 0.1 pCi/L for 90-day test, 0.3 pCi/L for 30-day test.

Table 4-17. POTW-I vs POTW-N Average Concentrations Comparison for Filtered

Filtered Sample Set Averages for:	Ra-226 (pCi/L)	Ra-228 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
POTW-I Effluent	129	9.34	42.9	75.0
POTW-N Effluent	46.6	9.25	3.51	8.31
POTW-I Influent	497	76.8	768	722
POTW-N Influent	85.0	5.38	8.85	9.75

Table 4-18. POTW-I vs POTW-N Average Concentrations Comparison for Unfiltered

Unfiltered Sample Set Averages for:	Ra-226 (pCi/L)	Ra-228 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
POTW-I Effluent	103	10.4	125	82.1
POTW-N Effluent	145	5.00	26.3	31.2
POTW-I Influent	190	28.1	125	85.9
POTW-N Influent	103	11.6	67.3[a]	80.0

[a]All sample results were < MDC value reported.

Table 4-19. Average Radium, Gross Alpha, and Gross Beta Concentrations for Filtered Influent and Effluent POTW Samples

Filtered Sample Set Averages for:	Ra-226 (pCi/L)	Ra-228 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
POTW-I Influent	497	76.8	768	722
POTW-I Effluent	129	9.34	42.9	75.0
POTW-N Influent	85.0	5.38	8.85	9.75
POTW-N Effluent	46.6	9.25	3.51	8.31

Table 4-20. Average Radium, Gross Alpha, and Gross Beta Concentrations for Unfiltered Influent and Effluent POTW Samples

Unfiltered Sample Set Averages for:	Ra-226 (pCi/L)	Ra-228 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
POTW-I Influent	190	28.1	125	85.9
POTW-I Effluent	103	10.4	125	82.1
POTW-N Influent	103	11.6	67.3[a]	80.0
POTW-N Effluent	145	5.00	26.3	31.2

[a]All sample results were < MDC value reported.

Table 4-21. POTW-I Sediment and Effluent Results for Ra-226 and Ra-228

Sample Set	Study ID	Sample Type	Ra-226	Units	Ra-228	Units	Ra-226/ Ra-228 Ratio
POTW 1 Round 2	WT-17-SL-058	Sediment	2.91	pCi/g	1.69	pCi/g	1.72
	WT-17-LQ-218	Effluent - Unfiltered	156	pCi/L	35.0	pCi/L	4.46
	WT-17-LQ-217	Effluent - Filtered	116	pCi/L	12.0	pCi/L	9.67
POTW 2 Round 1	WT-14-SL-018	Sediment	4.25	pCi/g	1.96	pCi/g	2.17
	WT-14-LQ-043[a]	Effluent - Unfiltered	122	pCi/L	9.00	pCi/L	13.6
	WT-14-LQ-044[a]	Effluent - Filtered	65.0	pCi/L	12.0	pCi/L	5.42
POTW 2 Round 2	WT-14-SL-053	Sediment	1.83	pCi/g	0.799	pCi/g	2.29
	WT-14-LQ-172[a]	Effluent - Unfiltered	340	pCi/L	7.50	pCi/L	45.3
	WT-14-LQ-171	Effluent - Filtered	87.0	pCi/L	6.00	pCi/L	14.5
POTW 2 Round 3	WT-14-SL-069	Sediment	3.94	pCi/g	1.96	pCi/g	2.01
	WT-14-LQ-216	Effluent - Unfiltered	64.0	pCi/L	13.5	pCi/L	4.74
	WT-14-LQ-215	Effluent - Filtered	104	pCi/L	6.50	pCi/L	16.0
POTW 3 Round 1	WT-15-SL-020	Sediment	16.6	pCi/g	6.25	pCi/g	2.66
	WT-15-LQ-051	Effluent - Unfiltered	80.0	pCi/L	4.50	pCi/L	17.8
	WT-15-LQ-052[a]	Effluent - Filtered	191	pCi/L	12.0	pCi/L	15.9
POTW 3 Round 2	WT-15-SL-056	Sediment	18.2	pCi/g	6.19	pCi/g	2.94
	WT-15-LQ-186[a]	Effluent - Unfiltered	135	pCi/L	4.50	pCi/L	30.0
	WT-15-LQ-185[a]	Effluent - Filtered	69.5	pCi/L	12.5	pCi/L	5.56
POTW 3 Round 3	WT-15-SL-067	Sediment	15.3	pCi/g	5.77	pCi/g	2.65
	WT-15-LQ-224	Effluent - Unfiltered	39.5	pCi/L	27.0	pCi/L	1.46
	WT-15-LQ-223	Effluent - Filtered	120	pCi/L	25.0	pCi/L	4.80

[a] Result was not detected, ½ of the reported MDC was presented.

Table 4-22. POTW Sediment and Effluent Ratios for Ra-226/Ra-228

Ratio Statistic	Sediments (CWT + POTW)	Sediments (CWT)	Sediments (POTW)	Unfiltered (CWT + POTW)	Unfiltered (CWT)	Unfiltered (POTW)	Filtered (CWT + POTW)	Filtered (CWT)	Filtered (POTW)
Average	3.00	3.40	2.40	8.40	11.4	5.30	5.70	3.80	8.30
Std Dev	0.900	0.900	0.400	6.70	8.30	3.40	3.90	3.60	3.00
Max	4.80	4.80	2.90	21.3	21.3	10.0	10.4	9.20	10.4
Min	1.70	2.30	1.70	1.00	1.00	2.00	1.10	1.10	4.80

Table 4-23. Summary of Removable Alpha and Beta Surface Contamination Results at CWT Plants

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-01-FS-021	22	7.30	18.6	2.90	8.27	62.5	62.5	0.000	62.5
WT-01-FS-108	38	8.00	18.6	2.61	8.05	62.5	62.5	0.000	62.5
WT-01-FS-109	25	8.00	18.1	2.02	8.40	30.8	30.8	0.000	30.8
WT-02-FS-012	20	7.30	15.8	1.33	7.51	62.5	62.5	0.000	62.5
WT-02-FS-066	41	8.15	8.15	0.000	8.15	38.0	38.0	0.000	38.0
WT-02-FS-067	29	8.00	29.4	4.56	9.18	30.8	30.8	0.000	30.8
WT-03-FS-040	5	6.90	6.90	0.000	6.90	60.5	60.5	0.000	60.5
WT-03-FS-110	10	8.00	8.00	0.000	8.00	31.0	31.0	0.000	31.0
WT-03-FS-111	16	6.90	6.90	0.000	6.90	60.5	60.5	0.000	60.5
WT-04-FS-025	19	9.15	9.15	0.000	9.15	113	113	0.000	113
WT-04-FS-112	37	7.70	38.1	4.94	8.50	62.0	62.0	0.000	62.0
WT-04-FS-113	25	9.10	9.10	0.000	9.10	69.6	69.6	0.000	69.6
WT-05-FS-044	25	9.11	9.11	0.000	9.11	41.5	41.5	0.000	41.5
WT-05-FS-114	45	6.40	13.6	1.07	6.56	56.0	56.0	0.000	56.0
WT-05-FS-115	23	9.10	9.10	0.000	9.10	32.5	32.5	0.000	32.5
WT-07-FS-022	14	9.15	9.15	0.000	9.15	23.3	23.3	0.000	23.3
WT-07-FS-071	35	7.30	7.30	0.000	7.30	62.5	62.5	0.000	62.5
WT-07-FS-072	15	8.00	8.00	0.000	8.00	36.6	36.6	0.000	36.6
WT-08-FS-015	25	9.10	9.10	0.000	9.10	41.5	41.5	0.000	41.5
WT-08-FS-062	46	7.70	7.70	0.000	7.70	62.0	62.0	0.000	62.0
WT-08-FS-063	32	9.10	9.10	0.000	9.10	41.5	41.5	0.000	41.5
WT-09-FS-013	17	9.10	9.10	0.000	9.10	41.5	41.5	0.000	41.5
WT-09-FS-060	27	4.25	31.1	5.40	5.77	65.0	133	13.1	67.5
WT-09-FS-061	20	8.85	8.85	0.000	8.85	30.0	30.0	0.000	30.0
WT-10-FS-002	22	8.15	8.15	0.000	8.15	38.0	38.0	0.000	38.0
WT-10-FS-046	34	6.90	6.90	0.000	6.90	60.5	60.5	0.000	60.5

Table 4-23. Summary of Removable Alpha and Beta Surface Contamination Results at CWT Plants

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-10-FS-047	20	9.10	9.10	0.000	9.10	32.5	32.5	0.000	32.5
WT-11-FS-005	15	8.15	8.15	0.000	8.15	36.0	36.0	0.000	36.0

Note: During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 4-24. Summary of Total Alpha and Beta Surface Contamination Results at CWT Plants

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-01-FS-021	22	30.5	1,540	315	211	929	50,400	10,900	8,780
WT-01-FS-108	30	7.30	476	133	172	283	32,700	7,030	5,310
WT-01-FS-109	25	14.9	448	113	152	287	13,200	3,870	4,090
WT-02-FS-012	20	30.5	332	77.9	58.9	268	8,220	1,710	1,690
WT-02-FS-066	41	7.30	403	120	92.6	240	8,260	2,060	1,590
WT-02-FS-067	29	19.1	473	114	74.5	286	9,040	1,900	1,140
WT-03-FS-040	5	19.0	347	144	115	334	6,310	2,710	2,410
WT-03-FS-110	10	7.45	487	204	194	288	7,120	2,070	1,940
WT-03-FS-111	13	18.6	3,220	877	348	249	30,200	8,170	3,150
WT-04-FS-025	20	30.5	565	157	123	268	8,560	2,290	3,210
WT-04-FS-112	38	18.6	540	137	142	297	14,600	3,720	3,200
WT-04-FS-113	25	7.45	1,600	310	144	291	14,200	3,940	3,480
WT-05-FS-044	25	7.44	179	44.6	61.5	325	3,370	771	1,230
WT-05-FS-114	32	7.30	180	45.1	53.2	257	3,060	829	1,340
WT-05-FS-115	23	19.0	243	82.2	71.9	306	7,380	1,480	1,290
WT-07-FS-022	14	30.5	922	250	132	891	6,650	1,490	2,480
WT-07-FS-071	36	18.6	1,000	206	130	249	5,330	1,210	1,140
WT-07-FS-072	13	19.0	1,390	399	213	310	6,620	1,990	1,740
WT-08-FS-015	25	30.5	208	43.9	50.9	572	3,270	780	1,920
WT-08-FS-062	46	19.1	194	39.5	56.0	284	3,880	1,010	1,370
WT-08-FS-063	32	7.45	94.2	27.5	40.8	290	2,580	696	1,050
WT-09-FS-013	18	30.5	258	56.0	51.0	728	11,900	2,540	2,260
WT-09-FS-060	26	18.6	117	27.3	35.3	354	7,120	1,600	1,280
WT-09-FS-061	20	35.7	35.7	0.000	35.7	286	6,640	1,540	1,690
WT-10-FS-002	22	29.4	224	54.9	53.1	121	2,730	623	395
WT-10-FS-046	34	18.6	476	81.9	44.0	288	5,770	972	623

Table 4-24. Summary of Total Alpha and Beta Surface Contamination Results at CWT Plants

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-10-FS-047	21	7.45	174	37.6	24.0	297	1,760	366	482
WT-11-FS-005	15	30.5	114	26.6	49.0	617	3,380	746	1,350

Note: During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 4-25. Summary of NaI Count Rate Data at CWTs

Site	GWS Max[a] (cpm)	GWS Min[a] (cpm)	GWS Average[a] (cpm)	GWS Std Dev (cpm)	No. Data Points
1	152,322	4,717	18,543	19,037	2,192
1	252,693	3,273	12,750	24,179	9,513
1	178,291	4,843	17,806	23,505	2,077
2	69,545	4,844	13,849	10,904	2,360
2	33,174	3,850	8,141	2,490	4,743
2	203,895	4,909	19,281	29,028	2,057
3	12,172	5,208	8,375	916	1,162
3	13,983	4,579	7,790	1,655	3,741
3	111,523	5,120	13,819	14,182	2,950
4	288,000	5,448	11,725	24,058	6,492
4	401,688	5,445	15,883	38,194	6,720
4	20,932	7,065	9,310	1,114	3,015
5	20,666	4,751	7,273	752	12,166
5	10,640	5,766	7,532	650	7,274
5	10,369	5,805	7,414	625	5,977
7	9,397	5,124	6,742	796	825
8	27,735	2,611	6,927	3,495	2,924
8	9,915	2,718	5,223	975	6,552
8	24,840	2,723	7,302	3,383	1,812
9	33,141	3,112	5,582	2,517	7,638
9	29,220	3,867	6,110	2,272	7,302
10	12,455	4,175	5,880	1,093	5,790
10	13,200	7,756	5,708	1,398	7,756
11	150,649	3,305	9,194	10,116	4,509
11	156,738	3,478	11,137	17,801	3,003

[a]Convert count rate data to exposure rate by dividing count rate by 800 to yield µrem/hr.

Table 4-26. Results Summary of NaI Count Rate Data Converted to Exposure Rates

Site	GWS Max (µR/hr)	GWS Min (µR/hr)	GWS Average (µR/hr)	GWS Std Dev (µR/hr)	No. Data Points
1	190	5.90	23.2	23.8	2,192
1	316	4.09	15.9	30.2	9,513
1	223	6.05	22.3	29.4	2,077
2	86.9	6.06	17.3	13.6	2,360
2	41.5	4.81	10.2	3.11	4,743
2	255	6.14	24.1	36.3	2,057
3	15.2	6.51	10.5	1.15	1,162
3	17.5	5.72	9.74	2.07	3,741
3	139	6.40	17.3	17.7	2,950
4	360	6.81	14.7	30.1	6,492
4	502	6.81	19.9	47.7	6,720
4	26.2	8.83	11.6	1.39	3,015
5	25.8	5.94	9.09	0.940	12,166
5	13.3	7.21	9.42	0.813	7,274
5	13.0	7.26	9.27	0.781	5,977
7	11.7	6.41	8.43	1.00	825
8	34.7	3.26	8.66	4.37	2,924
8	12.4	3.40	6.53	1.22	6,552
8	31.1	3.40	9.13	4.23	1,812
9	41.4	3.89	6.98	3.15	7,638
9	36.5	4.83	7.64	2.84	7,302
10	15.6	5.22	7.35	1.37	5,790
10	16.5	9.70	7.14	1.75	7,756
11	188	4.13	11.5	12.6	4,509
11	196	4.35	13.9	22.3	3,003

Table 4-27. CWT Solids, Filter Cake – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)
WT-01-SL-009	208	106	< 1.33
WT-01-SL-037	261	137	< 2.01
WT-01-SL-084	256	132	12.0
WT-02-SL-006	120	75.0	15.7
WT-02-SL-036	118	66.0	12.8
WT-02-SL-081	164	97.2	13.0
WT-03-SL-012	56.6	13.5	10.7
WT-04-SL-013	59.9	57.3	7.65
WT-04-SL-050	35.1	36.0	5.04
WT-04-SL-062	70.1	59.4	5.22
WT-04-SL-063	165	91.7	8.74
WT-05-SL-022	82.1	49.8	9.91
WT-05-SL-061	10.1	5.03	6.06
WT-05-SL-064	104	52.4	9.13
WT-08-SL-027	67.5	6.46	7.47
WT-08-SL-047	35.7	3.59	10.5
WT-08-SL-072	52.1	4.46	4.13
WT-08-SL-088	41.1	3.45	< 0.553
WT-08-SL-089	15.7	2.44	17.4
WT-09-SL-019	174	108	9.05
WT-09-SL-054	269	164	13.7
WT-09-SL-066	294	177	16.1
WT-10-SL-029	3.88	0.363	0.969
WT-10-SL-049	5.97	0.687	2.89
WT-06-SL-045	24.7	2.74	11.1
Average	108	58.1	8.45
Std. Dev.	91.0	55.7	5.03
Median	70.1	52.4	9.05
Minimum	3.88	0.363	0.277
Maximum	294	177	17.4

< – indicates a value less than the reported number which is the MDC.

Table 4-28. CWT Solids, Sediment – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)
WT-01-SL-010	105	29.7	8.44
WT-01-SL-038	37.2	12.4	7.17
WT-01-SL-083	76.8	20.0	8.31
WT-02-SL-007	5.86	2.59	4.55
WT-02-SL-035	3.60	1.37	4.67
WT-02-SL-082	2.50	0.978	9.26
WT-03-SL-011	4.72	1.54	6.34
WT-04-SL-014	101	22.7	10.1
WT-04-SL-051	421	86.9	10.0
Average	84.2	19.8	7.65
Std. Dev.	133	27.4	2.11
Median	37.2	12.4	8.31
Minimum	2.50	0.978	4.55
Maximum	421	86.9	10.1

Table 4-29. CWT Solids, Biased Soil – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)
WT-01-SL-008	117	30.6	17.0	< 2.46	1.83
WT-02-SL-034	13.3	4.26	5.06	< 3.14	< 0.331
WT-04-SL-015	444	83.1	10.5	< 3.37	< 0.774
Average	191	39.3	10.9	1.50	0.794
Std. Dev.	225	40.1	5.98	0.240	0.904
Median	117	30.6	10.5	1.57	0.387
Minimum	13.3	4.26	5.06	1.23	0.166
Maximum	444	83.1	17.0	1.69	1.83

< – indicates a value less than the reported number which is the MDC.

Table 4-30. CWT Filtered Effluent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta (pCi/L)
WT-01-LQ-023	110	< 19.0	334	< 1,270	< 847
WT-01-LQ-115	< 169	55.0	406	< 1,040	< 909
WT-01-LQ-281	287	< 18.0	235	< 2,040	< 879
WT-02-LQ-021	113	< 15.0	116	13.1	< 263
WT-02-LQ-111	86.0	< 16.0	140	< 1,340	< 872
WT-02-LQ-279	55.0	6.00	174	< 1,950	< 870
WT-03-LQ-029	< 36.0	< 5.00	52.0	< 50.1	45.7
WT-03-LQ-121	91.0	< 11.0	52.0	< 104	< 190
WT-03-LQ-287	86.0	< 9.00	62.0	< 192	< 208
WT-04-LQ-031	76.0	37.0	403	< 692	< 422
WT-04-LQ-165	104	94.0	618	< 2,200	< 940
WT-04-LQ-201	320	68.0	339	< 1,040	< 802
WT-05-LQ-058	215	118	595	< 762	504
WT-05-LQ-197	150	< 9.00	282	< 950	608
WT-05-LQ-207	181	80.0	607	< 1,810	< 938
WT-07-LQ-015	5,510	849	888	ND	7,660
WT-07-LQ-109	1,630	324	586	2,330	1,080
WT-07-LQ-273	8,810	1,740	360	21,400	8,700
WT-08-LQ-081	84.0	< 9.00	< 30.0	1.13	< 0.998
WT-08-LQ-085	12,700	1,110	304	22,800	5,810
WT-08-LQ-151	< 79.0	< 15.0	49.0	8.25	1.98
WT-08-LQ-153	14,900	1,300	598	22,700	4,570
WT-08-LQ-237	12,400	1,220	388	40,700	12,100
WT-09-LQ-046	< 73.0	< 12.0	148	ND	69.4
WT-09-LQ-175	503	319	181	< 1,120	< 895
WT-09-LQ-227	273	164	188	< 2,550	< 989
WT-10-LQ-094	150	< 17.0	< 96.0	< 204	< 393
WT-10-LQ-161	363	10.0	203	< 126	< 187
WT-10-LQ-291	77.0	< 13.0	55.0	< 161	< 196
WT-11-LQ-187	1,700	943	238	5,520	1,670
WT-11-LQ-221	2,090	976	228	4,160	1,730
Average	2,100	316	285	4,460	1,650
Std. Dev.	4,250	510	221	9,847	3,013
Median	166	37.0	232	540	444
Minimum	18.0	2.50	15.0	1.13	0.499
Maximum	14,900	1,740	888	40,700	12,100

[a]ND – Non-detectable; sample matrix was not suitable for analysis.
< – indicates a value less than the reported number which is the MDC.

Table 4-31. CWT Unfiltered Effluent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228[a] (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-01-LQ-024	104	< 18.0	296	< 1,340	< 871
WT-01-LQ-116	< 196	26.0	381	< 1,130	< 844
WT-01-LQ-282	114	< 15.0	270	< 2,650	< 1,000
WT-02-LQ-022	64.0	< 5.00	113	< 689	< 444
WT-02-LQ-112	< 116	< 18.0	140	< 1,250	< 804
WT-02-LQ-280	108	< 10.0	162	< 2,600	< 994
WT-03-LQ-030	61.0	< 8.00	29.0	< 260	< 181
WT-03-LQ-122	126	< 13.0	36.0	< 142	< 191
WT-03-LQ-288	362	11.0	< 30.0	< 213	< 211
WT-04-LQ-032	124	84.0	406	ND	480
WT-04-LQ-166	117	112	568	< 1,030	1,280
WT-04-LQ-202	< 131	< 27.0	361	< 1,450	< 846
WT-05-LQ-057	357	133	565	< 595	< 453
WT-05-LQ-198	< 202	89.0	688	< 1,320	< 500
WT-05-LQ-208	240	92.0	648	< 912	< 845
WT-07-LQ-110	1,670	318	571	2,370	1,060
WT-07-LQ-274	8,050	1,740	1,450	33.6	5,380
WT-08-LQ-082	87.0	< 4.00	37.0	< 1.66	< 1.17
WT-08-LQ-086	10,300	912	371	18,900	4,900
WT-08-LQ-152	85.0	6.00	42.0	4.68	< 2.01
WT-08-LQ-154	15,500	1,250	414	17,100	4,440
WT-08-LQ-238	12,700	1,200	355	42,300	12,900
WT-09-LQ-045	161	28.0	118	0.260	< 341
WT-09-LQ-176	594	331	200	1,810	1,540
WT-09-LQ-228	404	166	233	1,410	< 869
WT-10-LQ-093	42.0	6.00	80.0	< 294	< 397
WT-10-LQ-162	< 138	< 27.0	217	< 205	202
WT-10-LQ-292	< 95.0	< 10.0	69.0	< 224	< 209
WT-11-LQ-188	1,840	996	264	3,460	1,410
WT-11-LQ-222	1,470	1,100	252	3,880	1,320
Average	1,840	289	312	3,430	1,330
Std. Dev.	4,070	486	291	8,750	2,610
Median	121	27.0	258	565	423
Minimum	42.0	2.00	15.0	0.260	0.585
Maximum	15,500	1,740	1,450	42,300	12,900

[a]ND – Non-detectable; sample matrix was not suitable for analysis.
< – indicates a value less than the reported number which is the MDC.

Table 4-32. CWT Filtered Influent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta (pCi/L)
WT-01-LQ-025	1,760	711	345	ND	3,040
WT-01-LQ-117	2,810	1,120	603	10,500	2,970
WT-01-LQ-283	1,900	961	304	3,940	1,950
WT-02-LQ-019	1,650	747	272	ND	2,810
WT-02-LQ-113	1,660	913	247	2,360	1,900
WT-02-LQ-277	1,770	962	300	3,930	2,760
WT-03-LQ-027	116	< 16.0	< 63.0	< 129	< 149
WT-03-LQ-119	121	< 19.0	< 54.0	< 205	< 202
WT-03-LQ-285	126	< 5.00	36.0	< 227	< 212
WT-04-LQ-033	175	172	419	< 369	276
WT-04-LQ-167	445	392	626	660	1,510
WT-04-LQ-203	216	173	394	< 1,450	< 846
WT-05-LQ-060	57.0	56.0	< 111	< 2,550	< 998
WT-05-LQ-199	118	48.0	547	< 579	587
WT-05-LQ-205	242	78.0	514	< 1,040	< 802
WT-07-LQ-013	1,390	203	163	2,290	1,310
WT-07-LQ-107	1,930	322	505	3,420	893
WT-07-LQ-275	1,410	203	219	1,920	853
WT-08-LQ-083	87.0	6.00	37.0	6,110	1,570
WT-08-LQ-155	14,100	1,520	526	22,200	4,640
WT-08-LQ-239	7,080	615	203	28,400	7,820
WT-09-LQ-047	469	247	121	1,310	< 811
WT-09-LQ-173	300	238	176	1,950	1,360
WT-10-LQ-092	97.0	< 15.0	95.0	< 220	< 392
WT-10-LQ-163	132	< 10.0	345	< 294	276
WT-10-LQ-289	102	8.00	55.0	< 312	< 231
Average	1,550	361	273	3,862	1,430
Std. Dev.	3,015	431	198	7,086	1,760
Median	300	203	247	1,293	853
Minimum	57.0	2.50	27.0	64.5	74.5
Maximum	14,100	1,520	626	28,400	7,820

[a]ND – Non-detectable; sample matrix was not suitable for analysis.
< – indicates a value less than the reported number which is the MDC.

Table 4-33. CWT Unfiltered Influent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta (pCi/L)
WT-01-LQ-026	1,430	740	333	4,830	1,780
WT-01-LQ-118	2,870	1,110	592	8,400	3,440
WT-01-LQ-284	1,820	984	243	2,940	1,420
WT-02-LQ-020	1,740	835	245	3,220	1,890
WT-02-LQ-114	3,630	1,920	< 373	47,100	12,800
WT-02-LQ-278	1,790	1,010	279	4,220	1,650
WT-03-LQ-028	100	< 8.00	33.0	< 188	< 163
WT-03-LQ-120	327	< 17.0	< 55.0	< 116	< 199
WT-03-LQ-286	66.0	6.00	48.0	< 158	< 212
WT-04-LQ-034	214	229	459	ND	1,030
WT-04-LQ-168	453	467	< 69.0	< 1,700	1,130
WT-04-LQ-204	286	228	433	< 883	< 842
WT-05-LQ-059	146	77.0	493	< 910	< 430
WT-05-LQ-200	492	86.0	550	< 575	591
WT-05-LQ-206	238	126	526	< 2,040	1,200
WT-07-LQ-014	1,330	188	171	1,890	485
WT-07-LQ-108	2,330	366	468	3,490	1,180
WT-07-LQ-276	1,030	203	227	1,740	638
WT-08-LQ-084	5,920	367	159	7,960	2,550
WT-08-LQ-156	13,400	1,520	544	27,700	6,870
WT-08-LQ-240	6,940	623	184	27,600	10,200
WT-09-LQ-048	950	328	< 99.0	< 746	343
WT-09-LQ-174	458	222	151	2,050	1,040
WT-10-LQ-091	< 37.0	< 6.00	67.0	< 198	< 393
WT-10-LQ-164	< 98.0	< 8.00	328	< 117	375
WT-10-LQ-290	< 35.0	< 6.00	59.0	< 123	< 203
Average	1,870	436	262	5,920	2,000
Std. Dev.	3,010	515	192	11,600	3,220
Median	492	228	227	1,380	1,030
Minimum	17.5	3.00	27.5	58.0	81.5
Maximum	13,400	1,920	592	47,100	12,800

[a]ND – Non-detectable; sample matrix was not suitable for analysis.
< – indicates a value less than the reported number which is the MDC.

Table 4-34. CWT Radon Sample Results

Facility	Location	Radon (pCi/L)	Percent Error
WT-05-RA-001	Conference Room	3.10	3%
WT-05-RA-002	Near Filter Press	0.900	6%
WT-04-RA-001	Filter Press 2	1.90	4%
WT-04-RA-002	2nd Fl. Office	1.60	5%
WT-04-RA-003	Break Room	1.60	5%
WT-08-RA-001	On fuse panel	4.00	4%
WT-08-RA-002	Lab	1.50	6%
WT-09-RA-001	Office	2.00	4%
WT-09-RA-002	Filter Press Area	3.00	3%
WT-10-RA-001	Under Filter Press	1.20	5%
WT-07-RA-001	Lab Fridge	1.40	7%
WT-07-RA-002	Clarifier Elec. Panel	0.900	8%
WT-03-RA-001	Influent Wastewater Pump	1.30	7%
WT-03-RA-002	Wastewater Receiving Office	1.20	8%
WT-02-RA-001	Office	1.20	7%
WT-02-RA-002	Filter Press	1.30	7%
WT-01-RA-001	Wastewater Receiving Off.	5.00	4%
WT-01-RA-002	Top of Filter Press	2.90	5%
	Average	2.00	
	Median	1.55	
	St. Dev.	1.14	
	Minimum	0.900	
	Maximum	5.00	

ATDs. LLD for 10 pCi/L-day is 0.1 pCi/L for 90-day test, 0.3 pCi/L for 30-day test.

Table 4-35. Summary of Removable Alpha and Beta Surface Contamination Results at ZLDs

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-06-FS-039	24	7.30	7.30	0.000	7.30	61.5	61.5	0.000	61.5
WT-06-FS-116	46	7.70	18.4	1.57	7.92	62.0	62.0	0.000	34.0
WT-06-FS-117	33	9.35	25.1	3.22	10.1	34.0	34.0	0.000	34.0
WT-18-FS-011	15	6.90	6.90	0.000	6.90	123	123	0.000	123
WT-18-FS-058	31	7.30	7.30	0.000	7.30	65.5	193	22.8	69.6
WT-18-FS-059	20	6.40	22.0	3.77	7.54	32.8	32.8	0.000	32.8
WT-19-FS-078	13	9.15	9.15	0.000	9.15	38.5	38.5	0.000	38.5
WT-19-FS-079	17	6.40	6.40	0.000	6.40	56.0	56.0	0.000	56.0
WT-19-FS-080	18	6.40	6.40	0.000	6.40	32.8	32.8	0.000	32.8
WT-20-FS-020	16	9.10	9.10	0.000	9.10	41.6	41.6	0.000	41.6
WT-20-FS-068	39	6.40	30.5	4.91	7.93	56.0	56.0	0.000	56.0
WT-20-FS-069	32	6.40	22.0	3.07	7.25	33.0	33.0	0.000	33.0
WT-21-FS-030	4	7.85	17.7	2.05	8.28	36.4	36.4	0.000	36.4
WT-21-FS-126	45	7.30	35.6	5.45	8.68	62.5	62.5	0.000	62.5
WT-21-FS-127	39	8.00	294	3.42	8.55	36.6	36.6	0.000	36.6
WT-22-FS-001	10	7.15	7.15	0.000	7.15	37.5	37.5	0.000	37.5
WT-22-FS-048	28	7.30	38.4	5.88	8.41	63.0	342	52.8	72.5
WT-22-FS-049	18	8.00	8.00	0.000	8.00	30.8	30.8	0.000	30.8
WT-23-FS-007	23	8.70	30.4	4.53	9.64	76.5	76.5	0.000	76.5
WT-23-FS-054	33	4.24	4.24	0.000	4.24	65.0	65.0	0.000	65.0
WT-23-FS-055	25	9.10	9.10	0.000	9.10	32.5	32.5	0.000	32.5
WT-24-FS-016	20	7.85	7.85	7.85	0.000	36.5	36.5	0.000	36.5
WT-24-FS-064	21	8.00	8.00	0.000	8.00	30.8	30.8	0.000	30.8
WT-24-FS-065	41	6.90	6.90	0.000	6.90	60.5	307	39.5	68.0
WT-25-FS-006	23	7.15	70.7	17.6	12.7	37.5	37.5	0.000	37.5

Table 4-35. Summary of Removable Alpha and Beta Surface Contamination Results at ZLDs

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-25-FS-052	25	8.85	22.9	2.81	9.41	60.0	60.0	0.000	60.0
WT-25-FS-053	25	6.40	36.2	8.18	9.58	32.8	65.9	6.61	34.1

Note: During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 4-36. Summary of Total Alpha and Beta Surface Contamination Results at ZLDs

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-06-FS-039	23	30.5	139	32.2	47.3	1,950	49,700	9,810	4,740
WT-06-FS-116	46	19.1	691	134	103	474	7,760	1,420	2,540
WT-06-FS-117	33	7.45	248	53.0	81.5	1,210	8,710	1,540	2,440
WT-18-FS-011	15	18.6	194	44.4	75.0	415	4,200	1,131	2,100
WT-18-FS-058	20	730	199	57.1	78.9	211	7,190	1,610	2,360
WT-18-FS-059	20	19.1	249	60.3	69.1	277	4,670	1,080	1,720
WT-19-FS-078	13	30.5	114	23.2	36.9	943	2,370	411	1,550
WT-19-FS-079	17	7.30	72.9	22.2	27.3	277	1,490	369	553
WT-19-FS-080	18	19.1	54.7	10.1	22.5	318	705	91.2	339
WT-20-FS-020	16	30.5	719	215	222	268	6,990	2,230	3,080
WT-20-FS-068	27	7.30	554	154	150	249	8,830	2,240	2,030
WT-20-FS-069	32	19.1	741	165	174	321	8,800	1,840	1,550
WT-21-FS-030	23	30.5	645	159	111	780	13,400	2,730	2,440
WT-21-FS-126	44	18.6	452	127	127	264	17,900	3,420	2,540
WT-21-FS-127	39	7.45	537	111	49.8	283	3,090	713	960
WT-22-FS-001	10	30.5	273	87.0	85.2	269	3,180	1,050	1,620
WT-22-FS-048	28	7.30	836	226	133	249	15,500	3,290	2,080
WT-22-FS-049	18	19.1	1,410	350	239	265	6,380	1,640	1,730
WT-23-FS-007	25	7.45	273	73.1	83.5	313	6,230	1,380	1,550
WT-23-FS-054	32	18.6	72.9	14.6	25.1	250	2,660	537	920
WT-23-FS-055	25	7.45	193	43.3	43.1	313	4,520	905	927
WT-24-FS-016	20	305	466	123	107	268	4,420	977	2,150
WT-24-FS-064	21	7.45	711	187	125	288	4,380	980	1,060
WT-24-FS-065	41	18.6	476	90.8	69.2	260	9,410	1,530	985
WT-25-FS-006	13	30.5	213	55.4	89.5	802	3,980	921	1,660

Table 4-36. Summary of Total Alpha and Beta Surface Contamination Results at ZLDs

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
WT-25-FS-052	25	7.45	373	109	97.3	307	3,820	1,040	1,120
WT-25-FS-053	24	19.1	433	97.9	81.7	321	4,900	1,140	893

Note: During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 4-37. Summary of NaI Count Rate Data at ZLDs

Site	GWS Max[a] (cpm)	GWS Min[a] (cpm)	GWS Average[a] (cpm)	GWS Std Dev (cpm)	No. Data Points
6	11,264	3,689	6,618	1,435	1,077
6	11,273	4,157	6,315	1,037	4,716
18	7,446	2,692	4,507	714	3,570
18	34,596	2,748	7,432	5,069	2,032
19	15,542	10,665	13,449	573	3,379
19	15,603	11,347	13,667	560	4,098
19	52,815	4,506	13,153	3,995	2,813
20	11,574	3,266	5,966	1,814	7,086
20	73,475	3,771	8,426	8,110	9,495
21	66,958	4,752	12,383	7,293	1,911
21	34,908	4,335	6,912	2,613	15,435
21	46,611	4,351	7,797	4,423	8,792
22	42,518	4,857	10,358	5,297	1,544
22	39,712	4,065	6,937	4,905	5,063
23	12,198	5,546	8,585	1,250	6,265
23	13,938	5,662	9,014	1,348	7,512
24	12,234	5,164	7,419	1,279	1,712
24	11,844	6,541	8,985	1,211	2,959
25	28,597	7,558	12,955	2,243	5,371
25	31,290	2,819	12,524	2,352	8,019
25	356,274	4,464	34,513	63,202	2,006

[a]Convert count rate data to exposure rate by dividing count rate by 800 to yield μR/hr.

Table 4-38. Results Summary of NaI Count Rate Data Converted to Exposure Rates

Site	GWS Max (μR/hr)	GWS Min (μR/hr)	GWS Average (μR/hr)	GWS Std Dev (μR/hr)	No. Data Points
6	14.1	4.61	8.27	1.79	1,077
6	14.1	5.20	7.89	1.30	4,716
18	9.31	3.37	5.63	0.893	3,570
18	43.2	3.44	9.29	6.34	2,032
19	19.4	13.3	16.8	0.716	3,379
19	19.5	14.2	17.1	0.700	4,098
19	66.0	5.63	16.4	4.99	2,813
20	14.5	4.08	7.46	2.27	7,086
20	91.8	4.71	10.5	10.1	9,495
21	83.7	5.94	15.5	9.12	1,911
21	43.6	5.42	8.64	3.27	15,435
21	58.3	5.44	9.75	5.53	8,792
22	53.1	6.07	12.9	6.62	1,544
22	49.6	5.08	8.67	6.13	5,063
23	15.2	6.93	10.7	1.56	6,265
23	17.4	7.08	11.3	1.69	7,512
24	15.3	6.46	9.27	1.60	1,712
24	14.8	8.18	11.2	1.51	2,959
25	35.7	9.45	16.2	2.80	5,371
25	39.1	3.52	15.7	2.94	8,019
25	445	5.58	43.1	79.0	2,006

Table 4-39. ZLD Solids, Filter Cake – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)
WT-06-SL-046	159	14.2	7.67
WT-06-SL-074	31.7	3.48	14.9
WT-18-SL-025	8.02	2.01	26.3
WT-18-SL-043	6.14	1.63	21.7
WT-18-SL-076	19.1	1.95	5.95
WT-19-SL-023	4.62	1.44	17.5
WT-19-SL-041	127	11.0	16.6
WT-19-SL-070	3.08	0.580	7.46
WT-20-SL-024	26.9	2.62	11.2
WT-20-SL-042	20.0	2.24	10.0
WT-20-SL-075	22.7	2.21	13.4
WT-20-SL-086	11.1	1.40	6.51
WT-20-SL-087	10.2	1.41	6.55
WT-21-SL-004	6.46	1.54	21.1
WT-21-SL-039	29.3	9.34	10.8
WT-21-SL-078	25.8	7.09	25.4
WT-21-SL-092	214	43.6	12.5
WT-21-SL-093	212	40.5	10.3
WT-22-SL-003	281	17.8	14.1
WT-22-SL-032	145	19.2	15.9
WT-22-SL-079	134	13.1	2.75
WT-23-SL-016	78.9	18.1	8.62
WT-23-SL-055	33.6	6.87	4.28
WT-23-SL-077	26.0	3.39	1.61
WT-24-SL-001	420	58.7	5.25
WT-24-SL-002	41.6	5.26	3.02
WT-24-SL-031	480	67.3	5.16
WT-24-SL-080	289	46.3	5.26
WT-25-SL-028	221	25.1	2.76
WT-25-SL-040	185	24.2	3.27
WT-25-SL-071	206	32.4	3.47
Average	112	15.7	8.53
Std. Dev.	128	18.6	6.09
Median	33.6	6.98	6.55
Minimum	3.08	0.580	1.61
Maximum	480	67.3	25.4

Table 4-40. ZLD Solids, Biased Soil – Uranium Series Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)
WT-21-SL-005	37.1	7.47	16.6	3.81	< 0.201

< – indicates a value less than the reported number which is the MDC.

Table 4-41. ZLD Filtered Effluent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
WT-06-LQ-076	12,000	908	< 552	19,600	4,840
WT-06-LQ-149	11,200	806	385	13,300	3,340
WT-06-LQ-245	8,360	571	273	13,700	2,100
WT-18-LQ-070	335	< 16.0	159	< 485	< 413
WT-18-LQ-139	86.0	< 10.0	648	< 383	435
WT-18-LQ-253	94.0	< 10.0	149	701	< 832
WT-19-LQ-062	< 127	< 21.0	56.0	0.0970	135
WT-19-LQ-133	< 58.0	< 8.00	55.0	< 293	< 225
WT-19-LQ-229	126	< 11.0	338	< 412	< 234
WT-20-LQ-066	8,930	1,090	< 339	11,800	2,440
WT-20-LQ-135	12,500	941	206	31,100	6,190
WT-20-LQ-251	11,100	910	316	14,400	4,110
WT-21-LQ-011	3,470	503	807	6,830	2,160
WT-21-LQ-123	5,050	750	646	10,900	2,650
WT-21-LQ-261	4,690	725	885	10,200	2,890
WT-22-LQ-007	418	< 17.0	487	< 542	284
WT-22-LQ-105	3,280	241	738	5,040	1,530
WT-22-LQ-269	2,310	163	183	2,690	515
WT-23-LQ-038	580	111	186	1,660	602
WT-23-LQ-040	< 82.0	< 14.0	< 30.0	5.05	3.10
WT-23-LQ-177	110	12.0	54.0	< 145	< 191
WT-23-LQ-179	587	96.0	670	< 1,340	< 504
WT-23-LQ-257	< 69.0	< 7.00	< 41.0	23.6	< 4.03
WT-23-LQ-259	2,540	280	< 64.0	9,610	3,210
WT-24-LQ-001	1,830	277	429	2,540	655
WT-24-LQ-101	2,260	204	339	3,660	1,520
WT-24-LQ-265	292	120	799	< 2,090	< 967
WT-25-LQ-088	173	< 12.0	190	< 1,140	< 827
WT-25-LQ-127	163	15.0	113	< 1,100	< 475
WT-25-LQ-235	59.0	< 10.0	134	< 479	< 424
Average	2,780	272	327	5,250	1,370
Std. Dev.	3,880	348	270	7,220	1,560
Median	580	111	206	1,660	515
Minimum	29.0	3.50	15.0	0.0970	2.02
Maximum	12,500	1,090	885	31,100	6,190

< – indicates a value less than the reported number which is the MDC.

Table 4-42. ZLD Unfiltered Effluent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta (pCi/L)
WT-06-LQ-075	12,100	914	275	13,700	3,770
WT-06-LQ-150	11,300	866	326	27,300	6,530
WT-06-LQ-246	7,950	523	256	37,600	12,600
WT-18-LQ-069	5,490	875	982	14,100	3,820
WT-18-LQ-140	< 80.0	< 20.0	674	< 140	573
WT-18-LQ-254	106	< 10.0	143	< 641	< 780
WT-19-LQ-061	130	< 19.0	102	ND	92.6
WT-19-LQ-134	104	< 16.0	111	< 108	< 198
WT-19-LQ-230	< 66.0	< 11.0	333	< 280	231
WT-20-LQ-065	8,830	1,090	400	14,500	3,540
WT-20-LQ-136	1,580	221	4,310	40,900	8,340
WT-20-LQ-252	11,900	862	299	42,800	13,900
WT-21-LQ-012	3,770	552	821	5,540	1,850
WT-21-LQ-124	5,120	785	612	16,000	5,530
WT-21-LQ-262	4,370	721	926	13,100	4,020
WT-22-LQ-008	165	19.0	439	< 275	< 460
WT-22-LQ-106	2,730	250	723	8,940	1,630
WT-22-LQ-270	2,240	178	190	5,100	1,260
WT-23-LQ-037	531	121	160	1,570	358
WT-23-LQ-039	116	< 12.0	31.0	4.94	< 1.78
WT-23-LQ-178	< 85.0	< 16.0	< 60.0	< 217	< 203
WT-23-LQ-180	800	109	497	1,220	871
WT-23-LQ-258	87.0	< 12.0	< 42.0	5.12	26.1
WT-23-LQ-260	2,640	308	340	13,300	4,030
WT-24-LQ-002	2,040	269	431	2,750	< 424
WT-24-LQ-102	2,480	301	358	4,440	1,300
WT-24-LQ-266	293	102	748	< 810	< 836
WT-25-LQ-087	< 146	< 31.0	158	< 917	< 831
WT-25-LQ-128	601	305	4,840	< 448	< 417
WT-25-LQ-236	< 126	< 25.0	158	< 1,030	< 475
Average	2,610	295	670	8,990	2,510
Std. Dev.	3,470	337	1,120	13,000	3,697
Median	800	178	340	2,160	573
Minimum	33.0	5.00	21.0	4.94	0.890
Maximum	12,100	1,090	4,840	42,800	13,900

< – indicates a value less than the reported number which is the MDC.
[a]ND – Non-detectable; sample matrix was not suitable for analysis.

Table 4-43. ZLD Filtered Influent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta[a] (pCi/L)
WT-06-LQ-073	12,100	1,100	393	21,400	4,530
WT-06-LQ-147	11,300	1,290	302	23,500	5,630
WT-06-LQ-247	3,910	230	215	13,100	4,340
WT-18-LQ-072	278	< 24.0	234	< 427	< 412
WT-18-LQ-141	< 77.0	< 14.0	848	< 175	592
WT-19-LQ-064	950	901	16,600	ND	ND
WT-19-LQ-131	131	13.0	281	< 175	< 190
WT-19-LQ-231	1,140	91.0	718	4,770	1,860
WT-20-LQ-068	13,200	1,390	399	18,700	4,740
WT-20-LQ-137	20,900	603	< 187	59,400	10,700
WT-20-LQ-249	18,400	1,410	491	36,000	7,680
WT-21-LQ-009	2,580	338	517	ND	2,403
WT-21-LQ-125	3,360	515	584	4,750	1,340
WT-21-LQ-263	6,190	687	350	17,100	4,460
WT-22-LQ-005	106	10.0	299	< 257	2,400
WT-22-LQ-103	16,300	847	< 371	30,800	3,730
WT-22-LQ-271	590	51.0	105	754	< 198
WT-23-LQ-035	1,300	413	421	828	425
WT-23-LQ-181	564	94.0	135	2,080	492
WT-23-LQ-255	226	28.0	158	497	< 207
WT-24-LQ-003	2,580	332	552	3,630	1,530
WT-24-LQ-099	1,920	153	341	2,300	395
WT-24-LQ-267	832	380	568	< 1,330	< 838
WT-25-LQ-090	6,650	660	202	8,920	1,030
WT-25-LQ-129	2,100	181	187	2,290	396
WT-25-LQ-233	903	127	169	3,220	1,320
Average	4,660	431	998	10,200	2,350
Std. Dev.	6250	443	3,260	15,000	2,730
Median	1,920	332	302	3,220	1,330
Minimum	38.5	7.00	93.5	87.5	95.0
Maximum	20,900	1,410	16,600	59,400	10,700

[a]ND – Non-detectable; sample matrix was not suitable for analysis.
< – indicates a value less than the reported number which is the MDC.

Table 4-44. ZLD Unfiltered Influent – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta[a] (pCi/L)
WT-06-LQ-074	12,200	1,090	7,210	17,700	5,920
WT-06-LQ-148	11,100	1,240	350	25,500	5,950
WT-06-LQ-248	4,300	250	243	7,700	1,570
WT-18-LQ-071	1,310	142	318	ND	ND
WT-18-LQ-142	134	< 21.0	761	497	806
WT-19-LQ-063	1,470	777	13,300	ND	ND
WT-19-LQ-132	11,700	1000	< 247	2,230	2,080
WT-19-LQ-232	1,600	81.0	701	2,800	1,180
WT-20-LQ-067	13,600	1,390	288	16,200	6,060
WT-20-LQ-138	210	19.0	123	49,200	10,600
WT-20-LQ-250	16,500	1,310	529	88,000	23,400
WT-21-LQ-010	3,030	429	605	6,590	1,610
WT-21-LQ-126	2,620	421	528	6,920	2,400
WT-21-LQ-264	6,560	727	415	18,900	4,530
WT-22-LQ-006	216	14.0	136	110	105
WT-22-LQ-104	17,100	903	332	52,400	11,500
WT-22-LQ-272	750	43.0	234	1,240	231
WT-23-LQ-036	1,280	437	410	ND	2,240
WT-23-LQ-182	665	95.0	160	1,300	535
WT-23-LQ-256	221	41.0	153	1,120	423
WT-24-LQ-004	2,700	457	651	3,640	1,320
WT-24-LQ-100	2,100	181	220	3,380	782
WT-24-LQ-268	632	388	558	< 1,470	1,060
WT-25-LQ-089	6,870	628	269	9,270	977
WT-25-LQ-130	1,560	140	114	1,810	466
WT-25-LQ-234	1,930	199	161	4,470	1,400
Average	4,710	453	867	13,800	3,530
Std. Dev.	5,310	433	2,600	22,100	5,340
Median	1,930	388	318	4,060	1,400
Minimum	134	10.5	114	110	105
Maximum	17,100	1,390	13,300	88,000	23,400

[a]ND – Non-detectable; sample matrix was not suitable for analysis.
< – indicates a value less than the reported number which is the MDC.

Table 4-45. ZLD Radon in Ambient Air Results

Facility	Location	Radon (pCi/L)	Percent Error
WT-06-RA-001	Filter Press	2.20	5%
WT-06-RA-002	Lab	2.40	5%
WT-18-RA-001	Centrifuge	0.900	8%
WT-18-RA-002	Lab	4.30	4%
WT-20-RA-001	Transfer Panel	1.90	5%
WT-20-RA-002	Break Area	2.60	5%
WT-23-RA-001	Break Room	0.500	8%
WT-23-RA-002	Ctrl Panel/Boiler Room	1.70	6%
WT-23-RA-003	First Floor	0.900	8%
WT-21-RA-001	Locker Room Shelf	3.70	4%
WT-21-RA-002	Back of Filter Cake Room	2.60	5%
WT-24-RA-001	Filter Press	2.90	5%
WT-24-RA-002	Office	1.90	6%
WT-22-RA-001	Filter Press Room	4.90	4%
WT-22-RA-002	Wastewater Receiving Office	0.900	8%
	Average	2.29	
	Median	2.20	
	St. Dev.	1.28	
	Minimum	0.500	
	Maximum	4.90	

Note: ATDs. LLD for 10 pCi/L-day is 0.1 pCi/L for 90-day test, 0.3 pCi/L for 30-day test.

Table 4-46. ZLD and CWT Filter Cake Sample Alpha Spectroscopy Results

Study ID	U-238 (pCi/g)	U-234 (pCi/g)	Th-230 (pCi/g)	Th-232 (pCi/g)	Th-228 (pCi/g)	U-235 (pCi/g)
WT-04-SL-063	0.306	0.361	0.307	< 0.205	76.2	< 0.134
WT-25-SL-028	< 0.068	< 0.084	< 0.050	< 0.041	9.87	< 0.084
WT-22-SL-079	0.225	0.281	0.431	< 0.198	8.07	< 0.031
WT-19-SL-041	0.683	0.830	0.502	0.401	8.55	0.163
WT-01-SL-084	< 0.265	< 0.266	< 0.686	< 0.685	1.81	< 0.403
WT-08-SL-047	0.922	0.910	0.525	0.428	7.18	< 0.116
WT-06-SL-046	0.708	0.746	0.473	0.157	8.76	< 0.079
WT-04-SL-050	< 0.246	< 0.248	< 0.237	< 0.145	6.03	< 0.250
WT-09-SL-054	< 0.064	< 0.053	< 0.160	< 0.159	48.3	< 0.065
WT-23-SL-055	0.268	0.291	< 0.173	< 0.111	5.52	< 0.052
Average	0.343	0.374	0.289	0.176	18.0	0.077
St. Dev	0.314	0.334	0.195	0.154	24.3	0.064
Median	0.247	0.286	0.325	0.101	8.31	0.050
Minimum	0.032	0.027	0.025	0.021	1.81	0.016
Maximum	0.922	0.910	0.525	0.428	76.2	0.202

5.0 LANDFILLS

Leachate samples were collected at 51 PA landfills. Nine of the 51 landfills were selected to be surveyed and sampled in more detail due to the volume of waste accepted from the O&G industry. Surveys at the nine selected landfills included scans of gamma radiation and measurements of total and removable α/β surface radioactivity. Ambient air at the fence line of these landfills was sampled for Rn analysis, and filter cake was sampled from three of these landfills.

5.1 Leachate

Samples of leachate were collected from 51 landfills and analyzed using gamma spectroscopy for Ra-226 and Ra-228. The gamma spectroscopy results are presented in **Table 5-1** for the 42 landfills not selected based on volume of O&G waste accepted and **Table 5-2** for the nine landfills selected based on the volume O&G waste accepted. Radium was detected above the MDC value in 38 of 51 samples. Sample results from the 42 unselected landfills showed Ra-226 results that ranged from 36.5 to 416 pCi/L with an average of 116 pCi/L. Radium-226 results from the nine selected landfills ranged from 67.0 pCi/L to 378 pCi/L with an average of 125 pCi/L. Radium-228 results ranged from 2.50 to 55.0 pCi/L with an average of 11.9 pCi/L in the 42 unselected landfills. Radium-228 results from the nine selected landfills ranged from 3.00 pCi/L to 84.0 pCi/L with an average of 18.0 pCi/L.

Due to high solids content, the samples were not filtered in the field or at the laboratory. The aqueous portion was decanted from 10 of the 51 samples after they had been allowed to settle. The aqueous portion was analyzed for Ra-226 and Ra-228. These results are presented in **Table 5-3** along with the original gamma spectroscopy results for the entire sample. The entire sample results include dissolved and undissolved Ra-226 and Ra-228 and are generally one to two orders of magnitude higher than analyses of only the aqueous phase, indicating that the Ra-226 and Ra-228 in these samples were mostly in the form of undissolved solids.

5.2 Nine Selected Landfills

5.2.1 Influent and Effluent Leachate

Nine influent and seven effluent leachate samples were collected at the nine selected landfills. All nine landfills treat leachate onsite. The samples were analyzed using gamma spectroscopy. The results of the Ra-226, Ra-228, K-40, as well as gross α and gross β activity levels are presented in **Table 5-4** for effluent samples and in **Table 5-5** for influent samples. Radium was detected in all but 3 of the leachate samples. Radium-226 results ranged from 67.0 to 378 pCi/L with an average of 142 pCi/L for effluent samples. Radium-228 results ranged from 3.00 to 1,100 pCi/L with an average of 178 pCi/L for effluent samples. Radium-226 results ranged from 48.5 to 116 pCi/L with an average of 83.4 pCi/L for influent samples. Radium-228 results ranged from 4.00 to 15.0 pCi/L with an average of 7.94 pCi/L for influent samples. The influent and effluent samples from the same facility do not represent the same leachate at different times in treatment.

5.2.2 Leachate Filter Cake

Filter cake from three of the nine landfills was sampled and analyzed using gamma spectroscopy. The results of the Ra-226 and Ra-228 analyses are presented in **Table 5-6**. Radium was detected in all of the filter cake samples. Radium-226 results ranged from 8.73 to 53.0 pCi/g, with an average of 24.3 pCi/g. Radium-228 results ranged from 1.53 to 5.03 pCi/g, with an average of 3.85 pCi/g.

5.2.3 Effluent Discharge Sediment-Impacted Soil

At three landfills that discharged effluent water to the environment, a sediment-impacted soil sample was collected at each of the three effluent outfalls. The gamma spectroscopy results are presented in **Table 5-7**. Radium was detected in all of the samples. Radium-226 results ranged from 2.82 to 4.46 pCi/g with an average of 3.57 pCi/g. Radium-228 results ranged from 0.979 to 2.53 pCi/g with an average of 1.65 pCi/g.

5.2.4 Ambient Air

Ambient air was sampled at the fence line of each of the nine selected landfills and analyzed for Rn concentration. A combination of EIC and ATD monitors were used. Because it was impractical to place monitors on the actual working face of the landfill, monitors were deployed at the fence line around the landfill in roughly the four cardinal directions. The exact locations of the monitors are depicted in **Appendix E**. Duplicate monitors were placed at each location, inside a single Tyvek® bag. The Tyvek® bag is permeable to Rn gas, but impermeable to particulate matter. The monitors were hung on the fence line approximately 5 ft above grade. Deployment of the Rn monitors ranged from 74 to 103 days. Monitor device selection was based upon availability at the time of deployment. The results are presented in **Table 5-8**. Radon activity ranged from 0.200 to 0.900 pCi/L. The Rn monitor analytical reports are presented in **Appendix H**.

5.2.5 Surveys

Radiological surveys were conducted at each of the nine selected landfills, resulting in four data sets:

- *Removable α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Total α/β surface radioactivity* measurements recorded in units of dpm/100 cm^2
- *Gross Gamma Radiation Scan* measurements recorded in units of cpm
- *Gamma Radiation Exposure Rate* measurements recorded in units of μR/hr

5.2.5.1 Removable Alpha/Beta Surface Radioactivity Measurement Results

Measurements of removable α/β surface radioactivity were performed to assess potential internal radiation exposures to workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 guidelines, Table 1. RG 1.86 requires that α and β radioactivity levels be evaluated separately. The primary α emitter of concern is Ra-226, with a removable criterion of 20 dpm α/100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series, with a removable criterion of 200 dpm β/100 cm^2. The average removable α and β levels at each landfill were below the RG 1.86 criteria. The maximum removable α and β levels were also below the RG 1.86 criteria. The results of removable α and β surface radioactivity for the subject landfills surveyed are presented in **Table 5-9.** Individual removable α and β surface radioactivity measurement results are presented in **Appendix D**.

5.2.5.2 Total Alpha/Beta Surface Radioactivity Measurement Results

Measurements of total α/β surface radioactivity were performed to assess potential internal radiation exposures to workers through ingestion and/or inhalation. The results were evaluated using the RG 1.86 guidelines, Table 1. RG 1.86 requires that α and β levels be evaluated separately. The primary α emitter of concern is Ra-226, with a total criterion of 100 dpm α/ 100 cm^2. The primary β emitter of concern is Ra-228 of the natural Th decay series, with a total criterion of 1,000 dpm β/100 cm^2. All average total α and β surface radioactivity levels were below the RG 1.86 criteria. The maximum total α and β concentrations were 84.6 dpm/100 cm^2 and 3,630 dpm/100 cm^2. The summary results of total α and β surface radioactivity for the nine selected landfills surveyed are presented in **Table 5-10**. Individual total α and β surface radioactivity measurement results are presented in **Appendix D**.

5.2.5.3 Gross Gamma Radiation Scan Results

Gross gamma radiation scans, recorded in cpm, were performed on open land areas and accessible areas of the nine selected landfills to identify areas with gamma radiation levels above local background. Summary results for the selected landfills are presented in **Table 5-11**. The highest average count rate at any of the nine selected landfills was 10,816 cpm, and the maximum count rate recorded at any of the nine selected landfills was 74,928 cpm. A graphic display of the gamma scan results at each facility was prepared using GIS software and is presented in **Appendix E**.

5.2.5.4 Gamma Exposure Rate Results Summary

Gross gamma scan results in units of cpm presented in **Table 5-11** were converted to μR/hr by using 800 cpm per μR/hr, a conversion factor appropriate for Ra-226 gamma energy as detected with 2-inch by 2-inch NaI detectors, rounded to one significant figure (Table 6.4, NaI Scintillation Detector Scan MDCs for Common Radiological Contaminants, NUREG-1507, Minimum Detectable Concentrations With Typical Radiation Survey Instruments for Various Contaminants and Field Conditions, USNRC June 1998). **Table 5-12** presents statistical results for each of the nine selected landfills. The highest average exposure rate was 13.5 μR/hr, and the maximum gamma exposure rate measured was 93.7 μR/hr.

5.3 <u>Radon Ingrowth Within Filter Cake From WWTP to Landfills</u>

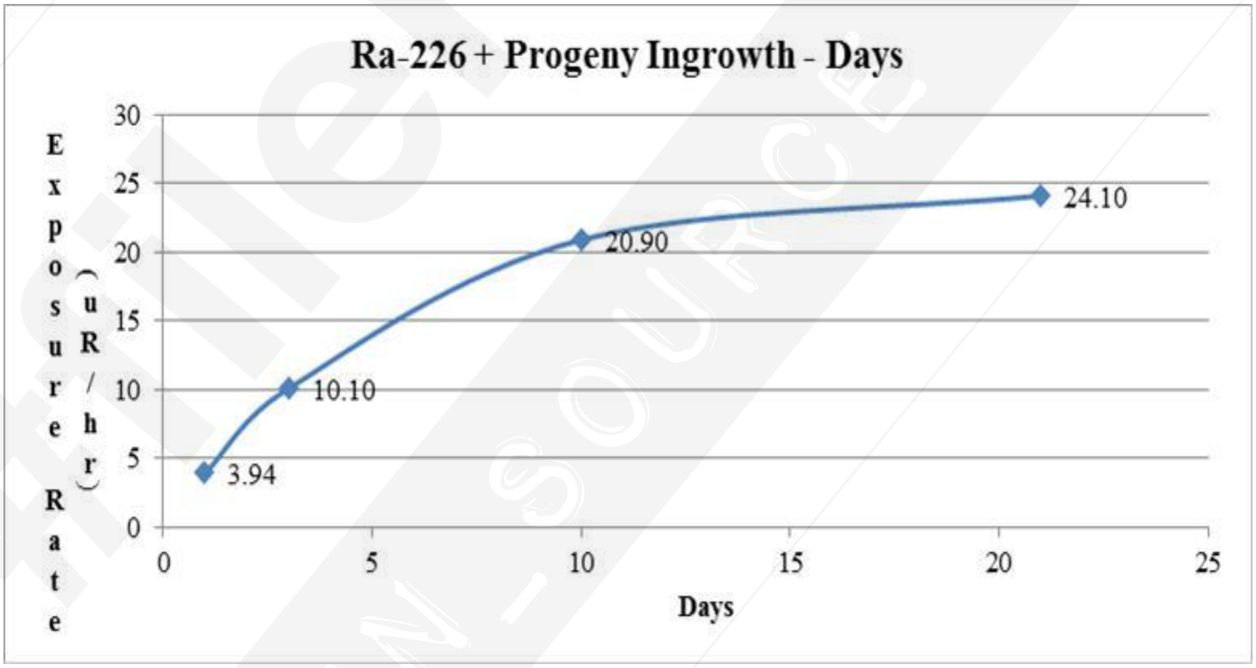
Radon in filter cake is the result of the decay of Ra, which is referred to as ingrowth. Radium-226 from the U series and Ra-228 from the Th series are present in flowback and produced water. Radioactive precursors to Ra (U-238 and Th-232) are not present due to their relative insolubility. When these wastewaters are processed at WWTPs, the Ra is removed and concentrated in the resulting filter cake or sludge.

During handling and/or transport, the sludge or filter cake may be disturbed and some of the Rn gas may escape, greatly reducing the gamma-emitting progeny that follow Rn-222 in the natural decay series. Using the software program MicroShield®, the following source terms were evaluated to determine the resulting gamma exposure rate measured 6 inches from the outside of a standard roll-off container filled with sludge at a concentration of 13.4 pCi/g of Ra-226. The source terms assume that all of the Rn and progeny are removed at day zero. Ingrowth of Rn and progeny was calculated for each time period in accordance with half-lives to determine the subsequent source terms, as follows:

a. 0-day ingrowth (13.4 pCi/g of Ra-226 only)
b. 1-day ingrowth (13.4 pCi/g of Ra-226 + 16 percent progeny)
c. 3-day ingrowth (13.4 pCi/g of Ra-226 + 41 percent progeny)
d. 10-day ingrowth (13.4 pCi/g of Ra-226 + 86 percent progeny)
e. 21-day ingrowth (13.4 pCi/g of Ra-226 + 100 percent progeny)

The results of the MicroShield® modeling are presented in **Figure 5-1**. The exposure rate increased rapidly to approximately 21 days post ingrowth, at which time the maximum exposure rate was achieved. Starting from zero Rn progeny to full equilibrium after 21 days, the exposure rate measured 6 inches from the outside of the roll-off container increased six-fold. Based on the MicroShield® modeling results, there may be an increase of six times the gamma exposure rate measured 6 inches from the surface of the roll-off container during the first 21 days after a wastewater treatment sludge is generated. This is a theoretical curve and assumes all of the Rn is removed when the sludge is formed at time zero.

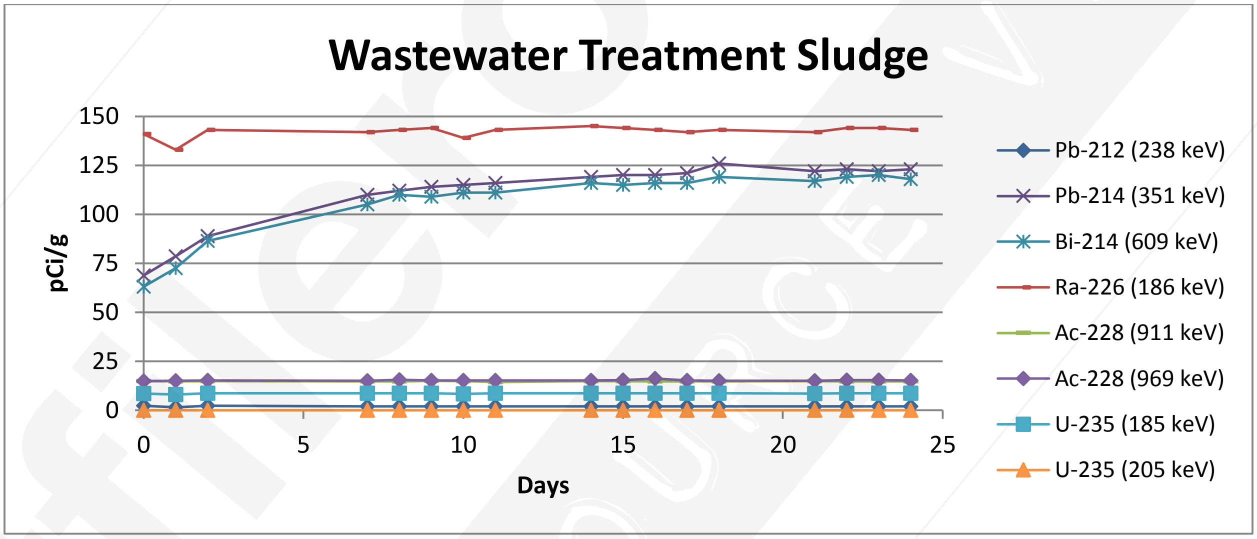
Figure 5-1. Ra-226 Progeny Ingrowth (Days Post Removal) versus Exposure Rate from 13.34 pCi/g Ra-226



To further evaluate the Rn and short-lived progeny ingrowth in wastewater sludge, a series of recently generated sludge samples were collected at six WWTPs and analyzed using gamma spectroscopy. The samples were analyzed when received and then 15 additional times over the next 24 days. The activity results versus time, post sample, were plotted. Radon ingrowth is demonstrated in each set of sample results. **Figure 5-2** and **Table 5-13** present the data from one of the sludge samples. The following was observed:

- The Pb-214 and Bi-214, short-lived progeny of Rn-222, increased from approximately 50 percent of the Ra-226 activity in the sample to 85 percent of the Ra-226 activity. Radium-226 was identified directly from the 186 keV gamma line. The average of the Pb-214 and Bi-214 results was 69.6 pCi/g at day zero and 120 pCi/g at day 24 compared to the Ra-226 activity of 142 pCi/g each day.
- Radon gas progeny were present at 50 percent of the Ra-226 activity in the recently generated sludge. Only 50 percent of the Rn gas escapes the sludge during processing.
- The Rn gas only increased to 85 percent of the Ra-226 parent activity in three weeks. This could be due to leakage of Rn through the sample container seal.
- The reported U-235 activity (185.7 keV gamma line) was consistently measured at 8.64 pCi/g, matching the theoretical overestimation of 8.7 pCi/g of U-235 based on 142 pCi/g of Ra-226. See Section 2.3.2 and Table 2-1 for a detailed discussion of Ra-226 and U-235 identification and potential overestimation using gamma spectroscopy. The U-235 identified by the 205 keV line was consistently 0 pCi/g.

Figure 5-2. Ra-226 Progeny Ingrowth versus Days (Days Post Removal)



5.4 <u>Landfill Worker Exposure Assessment</u>

5.4.1 Landfill External Radiation Exposure

The maximum average gamma radiation exposure rate measured at any of the nine selected landfills was 13.5 µR/hr. The minimum, limiting local background was 5 µR/hr. Assuming the duration of exposure is a full occupational year of 2,000 hours, the external gamma radiation exposure at the landfill was estimated as follows:

Maximum Average Landfill External Gamma Exposure Estimate

(13.5 – 5) µR/hr x 2,000 hr/yr x (1 mrem/1,000 µR gamma) = 17 mrem/yr

This is an estimate of the maximum average exposure based on 2,000 hours in one year. The result is less than the 100 mrem/yr dose equivalent limit for a member of the public. Actual exposure is dependent upon the actual exposure rates and occupancy time for individual workers.

The maximum exposure rate measured at any of the nine selected landfills was 93.7 μR/hr. Work in this area would result in an exposure of 100 mrem in 1,130 hours of annual exposure of an employee's 2,000-hour occupational year. Actual annual exposure for a landfill worker is dependent upon actual exposure rates and actual time worked in the proximity of the tank.

5.4.1.1 Landfill Worker Potential Internal Alpha/Beta Radioactivity Exposure

The total and removable α/β survey results are presented in Sections 5.2.5.1 and 5.2.5.2. None of the 195 α measurements and 17 of the 195 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. None of the 205 removable α or β surface radioactivity measurements exceeded the RG 1.86 criteria. The average values for total and removable α and β surface radioactivity are below the RG 1.86 criteria, indicating that there is little potential for internal α and β exposure to landfill workers.

5.4.1.2 Landfill Worker Internal Radon Exposure

The results of the landfill ambient air Rn samples are presented in Section 5.2.4. The Rn in ambient air at the fence line of the landfills ranged from 0.200 to 0.900 pCi/L consistent with U.S. background levels of 0.00 – 1.11 pCi/L in outdoor ambient air. Consequently, the potential for internal Rn exposure is low.

Table 5-1. Landfill Leachate – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/l)	Ra-228 (pCi/l)	K-40 (pCi/l)	Gross Alpha (pCi/l)	Gross Beta (pCi/l)
LF-10-LQ-024	322	< 20.0	201	< 140	< 192
LF-11-LQ-025	109	13.0	485	< 145	491
LF-12-LQ-026	102	< 6.00	558	< 129	440
LF-13-LQ-027	81.0	< 11.0	369	< 155	284
LF-14-LQ-028	101	19.0	1,110	< 167	1,110
LF-15-LQ-029	121	< 10.0	1,060	< 163	1,020
LF-16-LQ-030	114	< 7.00	122	< 136	< 191
LF-17-LQ-031	342	< 21.0	524	< 126	489
LF-18-LQ-032	120	< 25.0	764	< 161	703
LF-19-LQ-033	159	< 105	1,040	< 193	1,200
LF-20-LQ-034	< 130	< 110	615	182	806
LF-21-LQ-035	< 87.0	< 10.0	670	< 162	850
LF-22-LQ-036	< 77.0	< 13.0	332	< 156	531
LF-23-LQ-037	< 148	< 26.0	268	< 306	489
LF-24-LQ-038	145	< 15.0	477	< 134	489
LF-25-LQ-039	79.0	< 12.0	175	< 118	< 199
LF-26-LQ-040	< 146	< 31.0	268	< 134	< 190
LF-27-LQ-041	< 108	< 22.0	148	< 205	< 203
LF-28-LQ-042	< 89.0	< 16.0	64.0	< 277	< 221
LF-29-LQ-043	416	< 19.0	181	< 119	< 200
LF-30-LQ-044	84.0	< 6.00	551	< 342	412
LF-31-LQ-045	150	< 9.00	282	< 206	< 203
LF-32-LQ-046	112	< 21.0	127	< 125	< 189
LF-33-LQ-047	< 153	< 37.0	573	< 146	667
LF-34-LQ-048	< 111	< 21.0	423	< 157	401
LF-35-LQ-049	136	< 19.0	758	< 254	728
LF-36-LQ-050	106	22.0	471	< 353	466
LF-37-LQ-051	73.0	19.0	503	< 341	845
LF-38-LQ-052	54.0	< 5.00	249	< 152	550
LF-39-LQ-053	< 82.0	< 18.0	222	< 149	< 194
LF-40-LQ-054	91.0	35.0	505	< 143	239
LF-41-LQ-055	65.0	9.00	383	< 164	286
LF-42-LQ-056	148	< 16.0	< 54.0	< 137	384
LF-43-LQ-057	371	< 8.00	110	< 128	< 199
LF-44-LQ-058	101	< 12.0	629	< 206	365
LF-45-LQ-059	< 73.0	< 14.0	480	< 111	< 208
LF-46-LQ-060	140	15.0	354	< 486	< 416
LF-47-LQ-061	70.0	13.0	131	< 121	< 202
LF-48-LQ-062	57.0	< 5.00	354	< 181	284
LF-49-LQ-063	126	< 9.00	209	< 316	< 232
LF-50-LQ-064	85.0	< 10.0	128	< 112	< 201
LF-51-LQ-065	106	9.00	49.0	< 113	< 202

Table 5-1. Landfill Leachate – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/l)	Ra-228 (pCi/l)	K-40 (pCi/l)	Gross Alpha (pCi/l)	Gross Beta (pCi/l)
Average	116	11.9	404	94.4	389
Std. Dev.	88.0	11.4	272	43.6	311
Median	96.0	9.00	362	77.8	326
Minimum	36.5	2.50	27.0	112	94.5
Maximum	416	55.0	1,110	243	1,200

< – indicates a value less than the reported number which is the MDC.

Table 5-2. Selected Landfill Leachate – Gamma Spectroscopy and Miscellaneous Results

Study ID	Ra-226 (pCi/l)	Ra-228 (pCi/l)	K-40 (pCi/l)	Gross Alpha (pCi/l)	Gross Beta (pCi/l)
LF-01-LQ-002	378	< 20.0	< 72.0	< 3.46	< 2.07
LF-02-LQ-003	136	84.0	637	< 110	295
LF-03-LQ-008	140	16.0	221	< 275	< 202
LF-04-LQ-009	118	< 6.00	64.0	< 253	< 395
LF-05-LQ-023	115	< 20.0	182	< 323	< 233
LF-06-LQ-010	85.0	< 8.00	351	< 160	259
LF-07-LQ-004	< 134	< 35.0	353	< 121	221
LF-08-LQ-017	70.0	9.00	743	< 357	280
LF-09-LQ-005	105	< 8.00	155	< 314	< 233
Average	125	18.0	305	106	176
Std. Dev.	98.1	25.0	245	59.8	98.5
Median	85.0	10.0	221	127	198
Minimum	67.0	3.00	36.0	1.73	1.04
Maximum	378	84.0	743	357	395

< – indicates a value less than the reported number which is the MDC.

Table 5-3. Landfill Leachate Original and Aqueous Sample Analysis Results

Study ID	Original Gamma Spec – Unfiltered Sample			Re-Analysis Using EPA 903.1/904.0 Technique – Aqueous Phase Sample Only					
	Ra226 Result (pCi/L)	Ra226 Error (pCi/L)	Ra226 MDC (pCi/L)	Ra226 Result (pCi/L)	Ra226 Error (pCi/L)	Ra226 MDC (pCi/L)	Ra228 Result (pCi/L)	Ra228 Error (pCi/L)	Ra228 MDC (pCi/L)
LF-17-LQ-031	342	92.0	131	10.3	0.294	0.063	7.82	1.02	0.956
LF-24-LQ-038	145	60.0	91.0	1.91	0.107	0.032	4.27	1.06	1.33
LF-13-LQ-027	81.0	33.0	51.0	1.70	0.103	0.021	2.20	0.806	1.08
LF-45-LQ-059	47.0	45.0	73.0	0.472	0.085	0.090	0.896	0.662	0.998
LF-18-LQ-032	120	73.0	115	6.01	0.218	0.073	5.77	0.946	0.966
LF-10-LQ-024	322	85.0	121	1.22	0.089	0.057	1.41	0.770	1.13
LF-08-LQ-017	70.0	29.0	47.0	0.414	0.067	0.068	1.06	0.732	1.09
LF-12-LQ-026	102	40.0	62.0	0.842	0.086	0.069	2.55	0.771	1.00
LF-01-LQ-002	378	96.0	132	0.066	0.027	0.030	0.643	0.664	1.04
LF-04-LQ-009	118	35.0	53.0	0.124	0.031	0.017	0.976	0.717	1.08

Table 5-4. Selected Landfill Effluent Leachate – Gamma Spectroscopy and Miscellaneous Results

Source of Sample	Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha[a] (pCi/L)	Gross Beta[a] (pCi/L)
Effluent	LF-01-LQ-002	378	< 20.0	< 72.0	< 3.46	< 2.07
Effluent	LF-02-LQ-003	136	84.0	637	< 110	304
Effluent	LF-03-LQ-008	< 140	16.0	221	< 275	< 202
Effluent	LF-04-LQ-009	118	< 6.00	64.0	< 253	< 395
Effluent	LF-07-LQ-004	< 134	< 35.0	353	< 121	221
Effluent	LF-09-LQ-005	105	1,100	18,100	< 314	< 233
Effluent	LF-09-LQ-021	117	15.0	165	ND	ND
	Average	142	178	2,800	89.7	157
	Std. Dev.	107	408	6,750	59.9	106
	Median	117	16.0	221	93.5	157
	Minimum	67.0	3.00	36.0	1.73	1.04
	Maximum	378	1,100	18,100	157	304

[a]ND – Sample Matrix was not suitable for analysis.
< – indicates a value less than the reported number which is the MDC.

Table 5-5. Selected Landfill Influent Leachate – Gamma Spectroscopy and Miscellaneous Results

Source of Sample	Study ID	Ra-226 (pCi/L)	Ra-228 (pCi/L)	K-40 (pCi/L)	Gross Alpha (pCi/L)	Gross Beta (pCi/L)
Influent	LF-01-LQ-019	< 139	< 21.0	236	< 18.3	117
Influent	LF-02-LQ-020	< 120	15.0	755	< 201	524
Influent	LF-03-LQ-015	116	< 14.0	246	< 168	< 203
Influent	LF-04-LQ-016	92.0	< 15.0	571	< 134	416
Influent	LF-05-LQ-023	115	< 20.0	182	< 323	< 233
Influent	LF-06-LQ-010	85.0	< 8.00	351	< 160	259
Influent	LF-07-LQ-011	< 97	< 8.00	278	< 200	< 200
Influent	LF-08-LQ-017	70	9.00	743	< 357	280
Influent	LF-09-LQ-012	95	< 9.00	242	< 195	< 200
	Average	83.4	7.94	400	97.6	224
	Std. Dev.	23.5	3.64	227	49.9	158
	Median	85.0	7.50	278	97.5	117
	Minimum	48.5	4.00	182	9.15	100
	Maximum	116	15.0	755	179	524

< – indicates a value less than the reported number which is the MDC.

Table 5-6. Selected Landfill Solids, Filter Cake – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)
LF-02-SL-002	8.73	4.98	4.83
LF-03-SL-004	53.0	5.03	2.72
LF-04-SL-005	11.1	1.53	2.73
Average	24.3	3.85	3.43
Std. Dev.	24.9	2.01	1.22
Median	11.1	4.98	2.73
Minimum	8.73	1.53	2.72
Maximum	53.0	5.03	4.83

Table 5-7. Selected Landfill Solids, Sediment – Gamma Spectroscopy Results

Study ID	Ra-226 (pCi/g)	Ra-228 (pCi/g)	K-40 (pCi/g)	U-238 (pCi/g)	U-235 (pCi/g)	Th-232 (pCi/g)
LF-01-SL-001	4.46	2.53	15.2	< 2.51	0.177	2.48
LF-02-SL-003	2.82	1.44	12.8	< 0.671	< 0.069	1.41
LF-04-SL-006	3.44	0.979	10.0	< 0.868	< 0.128	0.960
Average	3.57	1.65	12.7	0.675	0.092	1.62
Std. Dev.	0.828	0.796	2.60	0.505	0.075	0.781
Median	3.44	1.44	12.8	0.434	0.064	1.41
Minimum	2.82	0.979	10.0	0.336	0.035	0.960
Maximum	4.46	2.53	15.2	1.26	0.177	2.48

< – indicates a value less than the reported number which is the MDC.

Table 5-8. Selected Landfill Radon Concentrations

Study ID	County	Location	Exp. End Date	Radon Concentration S.D. (pCi/L)	Error (+/- 2 Std. Dev.) (pCi/L)[b]	MDC (pCi/L)
LF-01-RA	McKean	01	1/2014	0.200	0.200	0.200
		02	1/2014	0.400	0.200	0.200
		03	1/2014	0.300	0.200	0.200
		04	1/2014	0.400	0.200	0.200
LF-02-RA	Elk	01	6/2014	0.200	0.200	0.200
		02	6/2014	0.300	0.200	0.200
		03	6/2014	Missing		
		04	6/2014	0.400	0.200	0.200
LF-03-RA	Butler	01	6/2014	0.300	0.200	0.200
		02	6/2014	0.500	0.200	0.200
		03	6/2014	0.900	0.200	0.200
		04	6/2014	0.400	0.200	0.200
LF-04-RA	Butler	01	6/2014	0.300	0.200	0.200
		02	6/2014	0.700	0.200	0.200
		03	6/2014	0.500	0.200	0.200
		04	6/2014	0.400	0.200	0.200
LF-05-RA	Fayette[a]	01	7/2014	< 0.400	NA	0.400
		02	7/2014	< 0.400	NA	0.400
		03	7/2014	< 0.400	NA	0.400
		04	7/2014	< 0.400	NA	0.400
LF-06-RA	Fayette[a]	01	7/2014	< 0.400	NA	0.400
		02	7/2014	< 0.400	NA	0.400
		03	7/2014	< 0.400	NA	0.400
		04	7/2014	< 0.400	NA	0.400
LF-07-RA	Washington[a]	01	7/2014	< 0.400	NA	0.400
		02	7/2014	< 0.400	NA	0.400
		03	7/2014	< 0.400	NA	0.400
		04	7/2014	< 0.400	NA	0.400
LF-08-RA	Somerset[a]	01	7/2014	< 0.400	NA	0.400
		02	7/2014	< 0.400	NA	0.400
		03	7/2014	< 0.400	NA	0.400
		04	7/2014	< 0.400	NA	0.400
LF-09-RA	Cambria[a]	01	7/2014	< 0.400	NA	0.400
		02	7/2014	< 0.400	NA	0.400
		03	7/2014	< 0.400	NA	0.400
		04	7/2014	< 0.400	NA	0.400

The ATD laboratory does not report an error term on devices with results below their MDC.
[a] Represents landfills with ATDs deployed.
[b] An error presented as NA represents a result that was less than the reported MDC.

Table 5-9. Selected Landfill Removable Alpha and Beta Surface Radioactivity Results Summary

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)				Removable Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
LF-01-FS-073	31	4.25	11.3	1.27	4.48	65.0	65.0	0.000	65.0
LF-03-FS-076	27	5.80	5.80	0.000	5.80	63.0	63.0	0.000	63.0
LF-05-FS-050	27	8.30	8.30	0.000	8.30	64.0	64.0	0.000	64.0
LF-08-FS-070	19	5.80	5.80	0.000	5.80	63.0	63.0	0.000	63.0
LF-02-FS-135	30	4.25	4.25	0.000	4.25	65.0	65.0	0.000	65.0
LF-04-FS-132	23	7.30	7.30	0.000	7.30	63.0	63.0	0.000	63.0
LF-06-FS-131	10	5.80	5.80	0.000	5.80	63.0	63.0	0.000	63.0
LF-09-FS-133	30	7.30	7.30	0.000	7.30	63.0	63.0	0.000	63.0
LF-07-FS-134	10	7.30	7.30	0.000	7.30	63.0	63.0	0.000	63.0

Note: During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 5-10. Selected Landfill Total Alpha and Beta Surface Radioactivity Results Summary

Study ID	No. of Data Points	Total Alpha (dpm/100 cm^2)				Total Beta (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average	Minimum	Maximum	Standard Deviation	Average
LF-01-FS-073	26	7.45	39.8	9.42	13.0	301	779	112	332
LF-03-FS-076	28	7.45	84.6	21.7	18.1	288	3,630	642	682
LF-05-FS-050	27	7.45	29.8	6.84	11.4	285	942	221	410
LF-08-FS-070	19	7.45	24.9	5.08	9.81	268	1,900	524	580
LF-02-FS-135	22	18.6	38.9	4.61	20.3	288	1,270	356	692
LF-04-FS-132	22	7.50	69.6	17.5	13.3	274	1,560	371	646
LF-06-FS-131	10	7.45	49.7	13.5	14.9	289	766	194	381
LF-09-FS-133	30	7.45	19.9	5.00	10.8	272	1,360	250	401
LF-07-FS-134	11	7.45	19.9	4.45	9.94	468	1,960	578	730

Note: During the calculations to convert from raw counts to dpm, the calculated value was compared to half of the MDC. If the value was below this number, half of the MDC was inserted into the tables. Where the standard deviation is zero and the minimum, maximum, and average are the same, then all measurements were below half of the MDC.

Table 5-11. Selected Landfill Gross Gamma Radiation Scan Results Summary

Site	GWS Max[a] (cpm)	GWS Min[a] (cpm)	GWS Average[a] (cpm)	GWS Std Dev (cpm)	No. Data Points
LF-01	74,928	3,837	9,250	1,656	9,210
LF-02	16,737	3,299	9,097	2,954	13,977
LF-03	13,900	5,141	8,022	1,713	11,484
LF-04	16,545	5,272	10,742	2,807	8,691
LF-05	14,730	3,783	8,190	2,658	8,942
LF-06	10,994	5,118	7,649	902	9,129
LF-07	11,620	4,530	7,190	1,260	5,432
LF-08	18,894	3,466	6,573	1,909	10,977
LF-09	27,144	4,304	10,816	2,914	9,779

[a]Convert count rate data to exposure rate by dividing count rate by 800 to yield μR/hr.

Table 5-12. Results Summary of NaI Count Rate Data Converted to Exposure Rates

Site	GWS Max (μrem/hr)	GWS Min (μrem/hr)	GWS Average (μrem/hr)	GWS Std Dev (μrem/hr)	No. Data Points
LF-01	93.7	4.80	11.6	2.07	9,210
LF-02	20.9	4.12	11.4	3.69	13,977
LF-03	17.4	6.43	10.0	2.14	11,484
LF-04	20.7	6.59	13.4	3.51	8,691
LF-05	18.4	4.73	10.2	3.32	8,942
LF-06	13.7	6.40	9.56	1.13	9,129
LF-07	14.5	5.66	8.99	1.58	5,432
LF-08	23.6	4.33	8.22	2.39	10,977
LF-09	33.9	5.38	13.5	3.64	9,779

Table 5-13. Gamma Spectroscopy Results (pCi/g) of Sealed Wastewater Treatment Sludge Sample Over 24 Days

Time (days)	Pb-212 238 keV	Pb-212 300 keV	Pb-214 295 keV	Pb-214 351 keV	Bi-214 609 keV	Bi-214 1,120 keV	Bi-214 1,764 keV	Ra-226 186 keV	Ac-228 911 keV	Ac-228 969 KeV	U-235 184 KeV
T00	2.40	2.11	68.1	68.8	63.0	70.4	77.8	141	14.9	15.0	8.58
T01	1.55	#NA	77.3	78.6	72.5	81.0	90.1	133	14.8	15.1	8.09
T02	2.38	2.52	87.7	88.8	86.5	91.7	78.3	143	14.9	15.3	8.67
T07	2.07	2.21	108	110	105	114	95.5	142	14.8	15.1	8.64
T08	2.01	1.96	110	112	110	117	98.5	143	14.8	15.6	8.71
T09	2.04	2.38	112	114	109	119	100	144	15.1	15.3	8.73
T10	1.99	1.99	113	115	111	120	102	139	14.9	15.3	8.44
T11	1.99	2.21	114	116	111	120	102	143	14.5	15.3	8.68
T14	2.00	2.01	117	119	116	124	105	145	15.0	15.3	8.78
T15	1.98	NA	119	120	115	125	106	144	14.9	15.4	8.72
T16	2.01	1.58	118	120	116	124	106	143	14.8	16.3	8.68
T17	1.98	2.45	119	121	116	125	106	142	14.8	15.2	8.64
T18	1.98	2.03	119	126	119	126	108	143	14.7	15.1	8.69
T21	1.98	1.82	120	122	117	126	108	142	15.0	15.1	8.60
T22	2.05	1.59	120	123	119	128	108	144	14.8	15.4	8.75
T23	2.04	2.02	120	122	120	128	108	144	14.7	15.4	8.72
T24	2.07	1.76	121	123	118	127	109	143	14.8	15.3	8.71

#NA – indicates the analyte was not requested and subsequently not reported by the laboratory.

6.0 GAS DISTRIBUTION AND END USE

Uranium-238 is distributed throughout the crust of the earth, typically at concentrations of 0.33 to 1.0 pCi/g. However, concentrations can be much higher in certain rock types or formations. The U-238 decay series consists of 18 decay progeny, including Rn. Radon is the only member of the decay series that is a gas at typical ambient conditions. All of the other decay series members are solids. Because Rn is a gas, it is highly mobile within the soil and rock matrix and it easily enters into structures. There are two additional potential pathways for Rn entry into structures: well water and natural gas combustion, e.g., cooking and unvented heating. Natural gas samples were collected at underground storage sites, natural gas-fired power plants, gas compression and transmission facilities, and natural gas processing plants.

6.1 Natural Gas in Underground Storage

Natural gas samples were collected at four underground storage sites in Pennsylvania. Duplicate samples were collected at each site during injection into the storage formation and during withdrawal from the storage formation. Sampling during injection was conducted during the period of May to August 2013. Sampling during withdrawal was conducted during the period of January to early February 2014. At three of the sites the samples were obtained from the exhaust of the gas chromatograph, which continuously analyzes the natural gas. At the fourth site, the sample was collected from the injection flow dehydration unit. The results for injection sampling are presented in **Table 6-1**. The results for withdrawal sampling are presented in **Table 6-2**. The results indicate Rn concentrations are lower after underground storage. The Rn analytical reports are presented in **Appendix H**.

6.2 Natural Gas-Fired Power Plants

Two natural gas-fired power plants (PP-01 and PP-02) were surveyed for gamma radiation exposure rates. Natural gas samples were collected at both plants, and ambient Rn measurements were performed at the PP-02 fence line. The natural gas Rn concentration results are presented in **Table 6-3**, and the ambient Rn concentrations measured at the plant fence line are presented in **Table 6-4**. All of the Rn analytical reports are presented in **Appendix H**.

The gamma radiation exposure rate survey at the PP-02 power plant was conducted using a Ludlum Model 19 Micro-R Meter. With the exception of one area, the range of measurement results observed were 5-10 µR/hr, which is within the range of natural background of gamma radiation for Pennsylvania. The exception occurred on the external surface of a pipe elbow where the range of measurement results observed were 15-17 µR/hr. During a subsequent survey event, the measurement results observed at the surface of that pipe elbow were 5-10 µR/hr, which is within the range of natural background of gamma radiation levels.

Ambient air was sampled at the PP-02 power plant site fence line. Eight EIC passive Rn monitors were used. The monitors were deployed at the fence line around the power plant in roughly the four cardinal directions. See figures in **Appendix E** for exact locations. The monitors were placed, in duplicate, inside a single Tyvek® bag. The Tyvek® bag is permeable to Rn gas but impermeable to particulate matter. The monitors were hung on the fence line approximately 5 ft above grade. Deployment of the Rn monitors was for 64 days. The fence line Rn monitor results were all at or below the MDC value for the analysis. The results are presented in **Table 6-4**. The Rn analytical reports are presented in **Appendix H**.

6.3 Compressor Stations

Duplicate natural gas samples were collected at intake flow lines of both facility CS-01 and CS-03. Duplicate samples were collected at the compressor station discharge at facility CS-04. The CS-04 compressor station is associated with the natural gas processing plant (CP-01) discussed below. Because of high pressure in the intake flow lines, duplicate natural gas samples were collected at the continuous natural gas quality analyzer at CS-02. This sample point is a small line off of a main exhaust for CS-02. All compressor stations were receiving predominately Marcellus Shale unconventional natural gas at the time of sample collection. Radon-measured concentrations are presented in **Table 6-5**. The compressor station natural gas Rn results are consistent with the production site Rn sample results. The Rn analytical reports are presented in **Appendix H**.

Ambient air was sampled at the CS-01 compressor station fence line for the measurement of Rn concentrations. Eight EIC passive Rn monitors were used. The monitors were deployed at the fence line around the power plant in roughly the four cardinal directions. See figures in **Appendix E** for exact locations. The monitors were placed, in duplicate, inside a single Tyvek® bag. The Tyvek® bag is permeable to Rn gas but impermeable to particulate matter. The monitors were hung on the fence line approximately 5 ft above grade. Deployment of the Rn monitors was for 62 days. The fence line Rn monitor results ranged from 0.100 to 0.800 pCi/L. The average concentration at each fence line location was within the range of typical ambient background Rn concentrations in outdoor ambient air in the U.S., i.e., 0.00 to 1.11 pCi/L. The results are presented in **Table 6-6**. The Rn analytical reports are presented in **Appendix H**.

6.4 Natural Gas Processing Plant

Two natural gas samples were collected at the processing plant (CP-01) on two separate occasions: March 12, 2014 and September 11, 2014. The results are presented in **Table 6-7**. The Rn analytical reports are presented in **Appendix H**.

Gamma radiation exposure rate surveys were performed during the two site visits. The exposure rate surveys were performed using a Ludlum Model 19 Micro-R Meter. The first survey was performed on a rainy, windy day, limiting the outdoor areas surveyed. The results include:

- Background in areas not impacted by the plant – 5-10 μR/hr.
- General areas of the plant – 5-10 μR/hr.
- Filter housings (exposure rate measured on the outside surface):
  - Contact readings measured on contact with filter housings ranged from background to 75 μR/hr, with two exceptions; one measured 350 μR/hr and the other measured 900 μR/hr.
- Propane processing – radiation exposure rates measured up to 380 μR/hr on contact with heat exchangers, reboilers, pipelines, and pumps.
- Propane storage area:
  - Pipeline exposure rates measured from local background to 400 μR/hr on contact.
  - Ladder to decking area measured 80 μR/hr general area.
  - Decking above ladder measured 50 μR/hr general area.

  - Propane storage tank measured 210 μR/hr on contact.
- Propane tank trailer being filled – 100 μR/hr on contact with the tank.
- Rail yard:
  - Tank filling area – local background to 20 μR/hr general area.
  - Racks of filling pipes – local background to 100 μR/hr on contact.
  - Propane rail car tank – 30 μR/hr on contact.

Radon in natural gas sample results are presented in **Table 6-7**. The highest concentration of Rn, 71.1 pCi/L, was measured in natural gas entering the processing plant. The lowest concentration of Rn, 8.60 pCi/L, was measured in natural gas at the processing plant outflow. The Rn analytical reports are presented in **Appendix H**.

A second visit to the facility was made to survey and sample filter media. The filter housing with the highest exposure rate measured was selected for sampling and gamma spectroscopy analysis. The outside of the filter housing measured 50 μR/hr. The general radiation exposure rate in the area of the filters was 15 μR/hr. The filter housing on the facility propanizer equipment was opened during a filter change-out and a sample of the cardboard filter media was collected. The filter media sample was smeared for removable α and β surface radioactivity. Smear samples of removable α and β surface radioactivity were taken on each of the individual filter cases housing the filter media within the filter bank. The gross α and β removable surface radioactivity results summary statistics of the 11 smear sample counts from the filter case are presented in **Table 6-8**. The average α and β surface radioactivity levels are below the RG 1.86 α and β removable surface radioactivity criterion.

The results of the filter gamma spectrometry analysis are presented in **Table 6-9**. A Pb-210 activity result of 3,580 pCi/g was identified, but no other gamma-emitting NORM radionuclide results were above 1 pCi/g. The gross α and β removable surface radioactivity results for the filter media sample are presented in **Table 6-10**. The results are elevated relative to the RG 1.86 gross α and β removable surface radioactivity criterion.

6.5 Potential Exposure from Gas Scale Inside Pipes and Equipment

Materials deposited on interior surfaces of natural gas plant pipes and equipment are different from conventional oil industry Ra-based pipe scale. Natural gas plant scale typically consists of Rn decay progeny that accumulate on the interior surfaces of plant pipes and equipment without the long-lived Ra parent.

As a result, the only radionuclides that remain and adhere to the interior surfaces of machinery/pipes are the Rn decay progeny Po-210 and Pb-210. These longer-lived decay progeny are not readily detected on the outside of pipes. However, Pb-210 and Po-210 emit α and β radioactive particles that may be a potential inhalation or ingestion hazard when pipes and machinery are opened for maintenance and/or cleaning.

Access to the internal surfaces of pipes and equipment for surveys of surface α and β activity was not available. However, the facility propanizer equipment opened and sampled during filter change-out is representative of interior conditions and was described in Section 6.4. The results are presented in **Table 6-9**. A Pb-210 activity result of 3,580 pCi/g was identified. No other gamma-emitting NORM radionuclides above 1 pCi/g were identified. The results confirm the build-up of the longer-lived Rn decay progeny in equipment and pipes. The concentration of Pb-210 identified may present a potential inhalation or ingestion hazard during routine system maintenance.

6.6 Radon Dosimetry

Radon exposure in homes due to the use of natural gas appliances is presented in this section. Radon is transported with natural gas into structures (homes, apartments, and buildings) that use natural gas for purposes such as heating and cooking.

The incremental increase of Rn-222 for a typical home was estimated using the values and assumptions presented in **Table 6-11** and as follows:

1. Well Site Rn-222 Concentration in Natural Gas – For the Rn gas concentration, only production site samples from Marcellus Shale well sites were used (n=16). The median value was 43.6 pCi/L, and the maximum value was 148 pCi/L. Both of these values are used in the estimations of potential Rn exposure.

2. Natural Gas/Rn-222 Transit Time and Decay – Assumed there is no Rn decay during transit.

3. Radon-222 Influx Rate – The American Gas Association average natural gas use per day value of 5,465 L/day was used. The value does not consider the types of appliances used. The amount of Rn liberated into the home per hour is calculated using the estimated natural gas use per day (5,465 L/day) and the Rn concentration in that natural gas (43.6 and 148 pCi/L). The resulting values are 238,274 pCi/day for the median concentration and 808,820 pCi/day for the maximum concentration. Dividing each value by 24 hours per day results in 9,928 pCi/hr and 33,700 pCi/hr, respectively. These estimates assume that none of the appliances are vented. Consequently, all of the Rn in the natural gas is assumed to be liberated into the residence.

   Rn-222 Influx Rate = (5,465 L/day x 43.64 pCi/L) / 24 hrs/day = 9,928 pCi/hr

   Rn-222 Influx Rate = (5,465 L/day x 148 pCi/L)/ 24 hrs/day = 33,700 pCi/hr

4. Air Exchange Rate – Using a residence volume of 385,152 L and an air exchange rate of 0.68 air changes per hour, 261,903 L/hr of home air is exchanged with outdoor air.

5. Consistent with EPA Rn assessments, an equilibrium factor of 40 percent is assumed.

6. Indoor Rn-222 Activity Concentration – The Rn-222 influx per hour divided by the home air exchange rate per hour, 9,928 pCi/hr / 261,903 L/hr = **0.04 pCi/L for the median value.** The Rn-222 influx per hour divided by the home air exchange rate per hour, 33,700 pCi/hr / 261,903 L/hr = **0.13 pCi/L for the maximum value.** This is the increase in Rn-222 in the home resulting from natural gas use containing both a median value of 43.6 pCi/L and a maximum value of 148 pCi/L of Rn-222.

The increase in Rn concentration of 0.04 and 0.13 pCi/L along with the standard values presented in **Table 6-11** are used to estimate potential additional annual radiation dose to an exposed individual.

Therefore,

$$\frac{0.04\, pCi/L * 0.4}{100} = 0.00016\, WL$$

The cumulative exposure is then WL multiplied by the number of hours exposed divided by 170 hrs/working month.

$$\frac{0.00016\, WL * 6{,}136\, hrs/yr}{170\, hrs/working\ month} = .006\, WLM/yr$$

This value was converted to a radiation dose by multiplying by the dose conversion factor, the tissue weighting factor, and the radiation weighting factor:

$$0.08 * \frac{0.006\, WLM}{yr} * \frac{0.54\, rad}{WLM} * \frac{20\, rem}{rad} * \frac{1000\, mrem}{rem} = 5.2\, mrem/yr$$

The result is **5.2 mrem/yr for the median dose and 17.8 mrem/yr for the maximum whole body effective dose**.

Based on the Rn and natural gas data collected as part of this study and the conservative assumptions made, the incremental Rn increase in a home using natural gas appliances is estimated to be very small and would not be detectable by commercially available Rn testing devices. The radiation dose received by home residents is a small fraction of the allowable general public dose limit of 100 mrem/yr.

Table 6-1. Natural Gas Underground Storage Radon Concentrations, Injection

Site	County	Formation Geology	Sample Results, pCi/L	Injection Average Concentration (pCi/L)	Error (± 2 Std. Dev.) (pCi/L)	MDC (pCi/L)
US 01	Potter	Oriskany Sandstone	32.6 and 26.7	29.6	8.20	0.200
US 02	Tioga	Oriskany Sandstone	25.7 and 21.2	23.5	6.40	0.200
US 03	Armstrong	Sandstone	20.4 and 20.4	20.4	0.000	0.200
US 04	Fayette	Limestone	20.3 and 21.2	20.8	1.20	0.200

Scintillation Cells
Note: All results adjusted to ambient air by dividing by 1.054, according to Jenkins et. al., Health Physics, Vol. 106, No. 3, March 2014.

Table 6-2. Natural Gas Underground Storage Radon Concentrations, Withdrawal

Site	County	Formation Geology	Sample Results, pCi/L	Withdrawal Average Concentration (pCi/L)	Error (± 2 Std. Dev.) (pCi/L)	MDC (pCi/L)
US 01	Potter	Oriskany Sandstone	4.90 and 5.30	5.10	0.600	0.300
US 02	Tioga	Oriskany Sandstone	10.9 and 9.30	10.1	2.20	0.200
US 03	Armstrong	Sandstone	5.60 and 5.90	5.80	0.400	0.200
US 04	Fayette	Limestone	10.8 and 11.7	11.3	1.20	0.400

Scintillation Cells
Note: All results adjusted to ambient air by dividing by 1.054, according to Jenkins et. al., Health Physics, Vol. 106, No. 3, March 2014.

Table 6-3. Natural Gas-Fired Power Plant Samples Analyzed for Radon Content

Site	County	Gas Source	Radon Concentration (pCi/L)	Error (± 2 Std. Dev.) (pCi/L)	MDC (pCi/L)
PP 01	Fayette	Marcellus Shale	33.7	1.80	1.50
PP 02	Berks	Marcellus Shale	35.7	110	0.200

Table 6-4. Natural Gas-Fired Power Plants Ambient Fence Line Radon Monitors (PP 02)

Location	Radon Concentration (pCi/L)	Error (± 2 Std. Dev.) (pCi/L)	MDC (pCi/L)
West Fence	0.300	0.200	0.200
	0.400	0.200	0.200
North Fence	0.100	0.200	0.200
	0.100	0.200	0.200
East Fence	0.000	0.200	0.200
	0.200	0.200	0.200
South Fence	0.200	0.200	0.200
	0.200	0.200	0.200

Table 6-5. Compressor Station Radon Samples

Site	County	Gas Source	Radon Concentration (pCi/L)	Error (± 2 Std. Dev.) (pCi/L)	MDC (pCi/L)
CS-01-RG	Berks	Marcellus Shale	28.8	1.40	0.200
CS-02-RG	Fayette	Mostly Marcellus Shale	39.8	4.40	0.200
CS-03-RG	Clinton	98% Marcellus Shale	34.0	0.200	0.200
CS-04-RG	Washington	Marcellus Shale	58.1	1.10	0.200

Table 6-6. Compressor Station Ambient Fence Line Radon Monitors (CS 01)

Location	Radon Concentration (pCi/L)	Error (± 2 Std. Dev.) (pCi/L)	MDC (pCi/L)
Northeast Fence	0.500	0.200	0.200
	0.800	0.200	0.200
Southeast Fence	0.300	0.200	0.200
	0.300	0.200	0.200
Northwest Fence	0.300	0.200	0.200
	0.100	0.200	0.200
Southwest Fence	0.300	0.200	0.200
	0.200	0.200	0.200

Table 6-7. Natural Gas Processing Plant Radon Samples

Site	County	Gas Source	Radon Concentration (pCi/L)	Error (± 2 Std. Dev.) (pCi/L)	MDC (pCi/L)
CP-01	Washington	Processing Plant Inflow 1	67.7	1.50	0.200
CP-01	Washington	Processing Plant Inflow 2	71.1	1.60	1.60
CP-01	Washington	Processing Plant Outflow to Transmission Line 1	8.60	0.400	0.300
CP-01	Washington	Processing Plant Outflow to Transmission Line 1	9.30	0.400	0.300

Table 6-8. Compressor Station and Natural Gas Processing Plant Filter Case Removable Radioactivity Results

Study ID	No. of Data Points	Removable Alpha (dpm/100 cm^2)			
		Minimum	Maximum	Standard Deviation	Average
CP-01-FS-136	11	4.70	29.6	8.78	15.5
Study ID	**No. of Data Points**	**Removable Beta (dpm/100 cm^2)**			
		Minimum	**Maximum**	**Standard Deviation**	**Average**
CP-01-FS-136	11	8.25	96.0	23.9	32.2

Table 6-9. Compressor and Natural Gas Processing Plant Filter Media, Gamma Spectroscopy

Nuclide	Result (pCi/g)	Error (pCi/g)	MDC (pCi/g)
Ac-228	0.141	0.053	0.077
Bi-212	0.287	0.000	0.373
Bi-214	0.564	0.082	0.054
K-40	1.30	0.216	0.225
Pb-210	3,580	552	14.2
Pb-212	0.066	0.044	0.071
Pb-214	0.629	0.070	0.076
Ra-226	0.585	0.566	0.926
Ra-228	0.141	0.053	0.077
Th-232	0.125	0.047	0.077
U-235	-0.105	0.000	0.382
U-238	-14.7	0.000	3.15

Table 6-10. Natural Gas Processing Plant Filter Media, Gross Alpha/Gross Beta

Sample	Gross Alpha	Gross Beta
Filter Media	708 ± 15.2 dpm/cm^2	1,910 ± 11.9 dpm/cm^2

Table 6-11. Radon Dosimetry Values for a Typical Home

Parameter	Value	Reference
Median Sq. Feet of House	1,700 ft^2	1
Ceiling Height	8 ft	NA
Air Change Rate	0.68	2
Home Occupancy Factor	70% (6,136 hrs/yr)	3
Average Daily Nat. Gas Use	193 ft^3/day (5,465 L/day)	4
Pipeline Distance	260 miles	5
Avg. pipeline speed (gas)	5 mph	6
Dose Conversion Factor	0.54 rad/WLM	7
Tissue Weighting Factor (Bronchial region)	0.08	7
Rad. Weighting Factor, alpha	20 rem/rad	7
Equilibrium Factor	0.4	3
Lung Cancer Risk per Unit Exposure	5.38E-4 per WLM	3

Table References:

1. U.S. Census, American Housing Survey, 2011, Table C-02-AH.
2. Nazaroff, W.W. and Nero, A.V. Radon and its Decay Products in Indoor Air. John Wiley & Sons, 1988.
3. Pawal, D.J. and Puskin, J.S. EPA Assessment of Risks from Radon in Homes. U.S. EPA, June 2003.
4. American Gas Association, Washington, D.C.
5. National Pipeline Mapping System, User Guide, U.S. DOT, 2011.
6. Spectra Energy Transmission, Personal Communication, May 2014.
7. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Annex E, 2006.

7.0 OIL AND GAS BRINE-TREATED ROADS

Brine produced from O&G wells and other sources such as brine treatment plants and brine wells is used as a dust suppressant and road stabilizer on unpaved secondary roads in Pennsylvania. The O&G brine used is from conventional formations only. DEP has developed a fact sheet, *Roadspreading of Brine for Dust Control and Road Stabilization*, for use as a guide when utilizing brine on unpaved roads. The fact sheet was developed under the authority of the Clean Streams Law, the Solid Waste Management Act, and Chapters 78 and 101 of DEP's Rules and Regulations (DEP 2013).

For this study, roads in the southwest, northwest, and north-central regions were surveyed and sampled. Most O&G operations occur in these regions. The surveys and sampling included:

- Thirty-two O&G brine-treated roads were surveyed. Thirty-one biased surface samples were collected from the O&G brine-treated roads. The biased locations were selected based on increased instrument audio response monitored by the technician during scan surveys.

- Eighteen reference background roads were surveyed, consisting of roads geographically close to an O&G brine-treated road that had not been identified as O&G brine-treated. Fourteen surface samples were collected from reference background roads.

7.1 <u>Gamma Radioactivity Survey Results</u>

The surveys included gross gamma radiation scans performed using 2-inch x 2-inch NaI detectors and a Ludlum Model 2221 scaler/ratemeter instrument. Two detectors were attached to the hitch of a standard sport utility vehicle (SUV) approximately 3 ft apart. This detector array was offset to provide as much edge/shoulder coverage as possible. Each detector was mounted approximately 6 inches above the road surface. Every road had a complete scan on both sides. A total of four detector passes on each road were conducted. The instrument data were recorded along with the location information using a pair of Trimble™ ProXT global positioning system (GPS) units.

7.1.1 Gross Gamma Radiation Scan Results

Gross gamma radiation scans, recorded in cpm, were performed on 32 road surfaces treated with O&G brine for dust suppression and road stabilization. The gamma radiation count rate data and GPS data were downloaded and placed on maps using the most recent aerial maps available from Pennsylvania Spatial Data Access (PASDA). GIS software was used to develop a graphic display of the gamma scan results. The resulting gamma radiation count rate intensity images are presented in **Appendix E**. The minimum, maximum, median, mean, and standard deviations for each data set are presented in **Table 7-1**. In addition to calculating the file statistics, a two-sample student t-test was performed.

The two-sample student t-test was used to compare the subject road (O&G brine-treated) results with a reference background road. ProUCL version 5.0 was used to perform the student t-test on the data. The Null Hypothesis tested is that the mean value of the treated road gamma radiation count rate data is statistically different from the mean value of the reference background road gamma radiation count rate data at the 95 percent confidence level. The results of the t-test for each pair of road results are included in **Table 7-1**. Fourteen of 29 comparisons of O&G brine-treated and reference background roads are statistically different at the 95 percent confidence level. The t-test output files are included in **Appendix G**.

7.1.2 Gamma Radiation Exposure Rate Results Summary

Gross gamma radiation scan results in units of cpm were converted to μR/hr using 800 cpm per μR/hr, a conversion factor appropriate for Ra-226 gamma energy as detected with 2-inch by 2-inch NaI detectors rounded to one significant figure (Table 6.4, NaI Scintillation Detector Scan MDCs for Common Radiological Contaminants, NUREG-1507, Minimum Detectable Concentrations With Typical Radiation Survey Instruments for Various Contaminants and Field Conditions, USNRC June 1998). **Table 7-2** presents the results for each road.

7.2 Soil Sample Results

Biased surface soil samples were collected based on the audio response of the gamma scan survey instrument ratemeter on 31 of the 32 O&G brine-treated roads. When an area with elevated radioactivity was detected, surface soil samples were collected at that area.

7.2.1 Road Surface Soils Biased Sample Results

The gamma spectroscopy results are presented in **Tables 7-3** through **7-5** for the U, Th, and Ac series radionuclides. A review of the U series radionuclides indicates excess Ra-226 activity in 19 of 33 surface soil samples. For the purposes of this study, excess Ra-226 activity is defined as Ra-226 activity greater than the natural background U decay series activity in surface soil. The excess Ra-226 activity was determined as follows:

- The O&G brine applied to road surfaces contains Ra-226 and its progeny. It does not contain U, which is insoluble. Therefore, the U-238 activity identified in the gamma spectroscopy analysis results represents the natural background U series activity in surface soil for the area. The average U-238 activity of the 31 samples is 0.882 pCi/g.

- U-235 makes up 0.7 percent by weight of natural U, which equates to 1/22 of the U-238 activity. Therefore, 0.040 pCi/g of U-235 is present in the surface soil samples.

- Radium-226 is measured directly by detection of its 186.2 keV energy line (3.28 percent yield). However, the presence of U-235 can cause interference with direct Ra-226 detection because it has a gamma line of similar energy (185.7 keV at 54 percent yield). In solid samples where natural U including U-238 and Ra-226 are at equal activity and U-235 is at 1/22 the activity of U-238, overestimation of Ra-226 is quantified by multiplying the U-235 activity by the ratio of the yields of the similar gamma radiation emissions, i.e., 54/3.28. Therefore, the Ra-226 overestimation in the surface soil samples is equal to 0.659 pCi/g [0.040 pCi/g x (54/3.28) = 0.659 pCi/g].

- After correcting the reported Ra-226 activity by 0.882 pCi/g of natural background activity and 0.659 pCi/g of U-235 bias, 19 of 31 samples have excess Ra ranging from 0.109 to 5.42 pCi/g above natural background.

See Section 2.3 for a complete discussion of the identification of NORM radionuclides by gamma spectroscopy.

The gamma spectroscopy results for the Th series radionuclides indicate the Th series is in secular equilibrium. The Th-232 mean and median values are essentially equal and the standard deviation is a fraction of the mean value, indicating the data is normally distributed. A normal distribution of radioactivity measurements is indicative of natural background radioactivity, which is more homogeneous than contaminated soil. The mean Ra-228 activity of the 31 surface soil samples is 0.977 ± 0.351 pCi/g. The range of the results is from 0.455 to 1.85 pCi/g.

7.2.2 Road Surface Soils – Reference Background Roads Soils

As a point of reference and for comparison, 18 roads in the geographic vicinity of the subject roads that have not been identified as O&G brine-treated were selected for surveying, and 14 biased soil samples were collected. The gamma spectroscopy results of the background samples are presented in **Tables 7-6** through **7-8** for the U, Th, and Ac series radionuclides. A review of the U series radionuclides indicates excess Ra-226 activity in 14 surface soil samples. Excess Ra-226 activity is greater than the natural background U decay series activity in surface soil. The excess Ra-226 activity was determined as follows:

- The O&G brine applied to road surfaces contains Ra-226 and its progeny. It does not contain U, which is insoluble. Therefore, the U-238 activity identified in the gamma spectroscopy analysis results represents the natural background U series activity in surface soil for the area. The average U-238 activity of the 14 samples is 0.819 pCi/g.

- U-235 makes up 0.7 percent by weight of natural U, which equates to 1/22 of the U-238 activity. Therefore, there is 0.037 pCi/g of U-235 present in the surface soil samples.

- Radium-226 is measured directly by detection of its 186.2 keV energy line (3.28 percent yield). However, the presence of U-235 can cause interference with direct Ra-226 detection since it has a gamma line of similar energy (185.7 keV at 54 percent yield). In solid samples where natural U including U-238 and Ra-226 at equal activity and U-235 at 1/22 the activity of U-238, overestimation of Ra-226 is quantified by multiplying the U-235 activity by the ratio of the yields of the similar gamma emissions, i.e., 54/3.28. Therefore, the Ra-226 overestimation in the surface soil samples is equal to 0.037 pCi/g x (54/3.28) = 0.61 pCi/g.

- After correcting the reported Ra-226 activity by 0.819 pCi/g of natural background activity and 0.609 pCi/g of U-235 bias, 11 of 14 samples have excess Ra ranging from 0.0210 to 61.6 pCi/g above natural background.

See Section 2.3 for a complete discussion of the identification of NORM radionuclides by gamma spectroscopy.

The gamma spectroscopy results for the Th decay series are not normally distributed nor indicative of natural Th background radioactivity. Thorium-232 mean and median values are not equal and the standard deviation is large relative to the mean value, indicating the data are not normally distributed and heterogeneous. A normal distribution of radioactivity measurements is indicative of natural background radioactivity, which is more homogeneous than contaminated soil. The mean Ra-228 activity of the 14 surface soil samples is 1.93 $\pm$ 2.81 pCi/g. The range of the results is from 0.396 to 11.2 pCi/g.

The background reference road soil sample results are positive for excess Ra-226 at 11 of 14 roads sampled. Three of the Ra-228 results are greater than 2.98 pCi/g, which is approximately three times natural background for the Th series. The excess Ra is higher than for the identified O&G brine-treated roads. The average excess Ra-226 for roads identified as having been O&G brine-treated is 1.13 pCi/g compared to an average of 8.23 pCi/g on the background reference roads. One possible explanation is that all of the roads have been treated with O&G brine. After the 32 roads had been identified as O&G brine-treated, the reference background roads were selected by proximity to the 32 roads. Nothing precluded the selected background roads from having been treated with O&G brine.

7.3 Public Exposure to Oil and Gas Brine-Treated Roads

A total of 31 samples were collected from roads treated with O&G brine. An additional 14 surface soil samples were taken in reference background areas not expected to be impacted by O&G brine treatment. Both the treated and the reference background roads were positive for excess Ra. To evaluate potential exposure to the public from the O&G brine-treated roads, a source term of 1 pCi/g of Ra-226 and 0.5 pCi/g of Ra-228 was assumed within a 6-inch layer of surface material (treated road surface).

The Argonne National Laboratory RESidual RADioactivity (RESRAD) Version 7.0 code for modeling exposure from residual radioactivity was used to evaluate potential exposure from the O&G brine-treated roads. RESRAD is a computer model designed to estimate radiation doses and risks from residual radioactive materials. RESRAD has been used widely by DOE, its operations and area offices, and its contractors for deriving limits for radionuclides in soil. RESRAD has also been used by EPA, U.S. Army Corps of Engineers (USACE), NRC, industrial firms, universities, and foreign government agencies and institutions. The recreationist is an appropriate exposure scenario based on the remote location of the roads. A recreationist, such as a jogger or hunter, usually spends less time on the impacted area, e.g., two hours a day, three days a week, than a resident. However, a recreationist may have a higher inhalation rate than a resident. Recreational land use addresses exposure to people who spend a limited amount of time at or near a site while playing, fishing, hunting, hiking, or engaging in other outdoor activities. Environmental exposure pathways included in the recreationist scenario include ground external gamma, inhalation, Rn, plant consumption, meat consumption, milk consumption, and soil ingestion.

The estimated total dose from 1 pCi/g of Ra-226 and 0.5 pCi/g of Ra-228 above natural background in surface soil, to a recreationist, in the year of maximum exposure (year 1) is 0.441 mrem/yr, which is below the 100 mrem/yr public exposure criteria based on assumed activity concentrations. The results of the environmental pathways for year 1, the year of maximum dose, are presented in **Table 7-9**. The actual dose received is dependent upon both the excess Ra radioactivity in surface soil and the time spent exposed to the soil surface.

Table 7-1. Gamma Scan Survey Summary

Study ID	GWS Max (cpm)	GWS Min (cpm)	GWS Median (cpm)	GWS Mean (cpm)	GWS Std Dev (cpm)	No. Data Points	NaI BKG (cpm)	T-Test Results (Sample to BKG)
BR-04-SL-011	16,512	7,892	13,022	12,655	1,588	2,906	12,511	Reject
BR-04-SL-010	Part of same road as BR-04-SL-011							
BR-05-SL-009	16,067	10,936	13,431	13,411	732	1,387	12,511	Reject
BR-06-SL-004	15,757	9,875	13,430	13,363	799	1,452	12,511	Reject
BR-07-SL-008	**15,641**	**7,975**	**12,843**	**12,511**	**1,449**	**2,389**	**NA**	**NA**
BR-01-SL-001	17,778	4,106	11,456	11,759	1,564	11,536	11,135	Reject
BR-02-SL-002	**13,268**	**9,766**	**11,050**	**11,135**	**615**	**850**	**NA**	**NA**
BR-08-SL-003	14,234	9,771	11,988	11,990	693	5,590	11,960	Accept
BR-09	**13,565**	**10,313**	**11,998**	**11,960**	**736**	**222**	**NA**	**NA**
BR-10-SL-012	15,179	5,888	11,977	11,968	996	9,253	10,898	Reject
BR-11	**12,762**	**9,449**	**10,882**	**10,898**	**591**	**596**	**NA**	**NA**
BR-13-SL-006	**13,180**	**9,526**	**11,311**	**11,273**	**646**	**961**	**NA**	**NA**
BR-12-SL-005	12,050	6,114	9,121	9,136	895	4,644	11,273	Accept
BR-15-SL-014	**14,509**	**7,695**	**10,816**	**10,873**	**1,128**	**1,359**	**NA**	**NA**
BR-14-SL-013	14,053	2,032	10,861	10,759	1,053	5,395	10,873	Accept
BR-16-SL-015	**12,360**	**9,470**	**10,587**	**10,614**	**461**	**592**	**NA**	**NA**
BR-17-SL-016	13,870	9,100	11,586	11,555	761	4,388	10,614	Reject
BR-18-SL-017	**9,949**	**6,066**	**7,479**	**7,524**	**616**	**727**	**NA**	**NA**
BR-19-SL-018	16,990	6,821	9,395	9,510	921	5,231	7,524	Reject
BR-20-SL-019	**13,511**	**5,404**	**8,747**	**8,825**	**1,317**	**3,944**	**NA**	**NA**
BR-21-SL-020	12,463	6,232	8,560	8,611	899	877	8,825	Reject
BR-22-SL-021	**13,126**	**5,947**	**9,019**	**9,317**	**1,646**	**704**	**NA**	**NA**
BR-23-SL-022	13,740	5,491	9,335	9,376	1,352	3,605	9,317	Accept
BR-24-SL-023	13,217	5,349	8,498	8,590	1,182	3,375	9,317	Accept
BR-25-SL-024	13,248	5,069	7,436	7,781	1,487	1,984	8,226	Accept
BR-26-SL-025	**11,208**	**5,882**	**8,254**	**8,226**	**893**	**343**	**NA**	**NA**
BR-27-SL-026	**11,333**	**5,708**	**8,281**	**8,267**	**955**	**579**	**NA**	**NA**
BR-28-SL-027	12,475	4,597	7,678	7,785	1,234	3,376	8,267	Accept
BR-29-SL-028	14,465	5,309	9,041	9,490	1,924	2,556	7,925	Reject
BR-30-SL-029	**10,360**	**5,687**	**7,965**	**7,925**	**703**	**759**	**NA**	**NA**
BR-31-SL-030	14,415	6,200	9,744	9,801	1,172	7,245	10,093	Accept
BR-32-SL-031	**14,117**	**6,527**	**10,057**	**10,093**	**1,118**	**1,958**	**NA**	**NA**
BR-33-SL-032	10,975	6,030	8,442	8,406	658	2,603	10,093	Accept
BR-34-SL-033	11,448	5,340	8,276	8,211	790	3,347	10,093	Accept
BR-35-SL-034	12,056	5,972	9,036	9,076	925	2,186	10,093	Accept

Table 7-1. Gamma Scan Survey Summary

Study ID	GWS Max (cpm)	GWS Min (cpm)	GWS Median (cpm)	GWS Mean (cpm)	GWS Std Dev (cpm)	No. Data Points	NaI BKG (cpm)	T-Test Results (Sample to BKG)
BR-36-SL-035	**10,981**	**5,693**	**8,566**	**8,502**	**748**	**975**	**NA**	**NA**
BR-37-SL-036	11,617	5,591	8,069	8,059	699	10,257	8,502	Accept
BR-38-SL-037	**10,668**	**6,105**	**8,006**	**7,979**	**662**	**406**	**NA**	**NA**
BR-39-SL-038	10,535	6,124	7,942	7,920	649	1,124	7,979	Accept
BR-40-SL-039	11,617	5,684	7,883	7,866	653	3,712	7,974	Accept
BR-41	**10,227**	**5,868**	**8,001**	**7,974**	**679**	**510**	**NA**	**NA**
BR-42-SL-040	10,859	5,774	7,951	7,950	722	1,560	NA	NA
BR-43-SL-041	12,789	5,048	7,978	7,954	1,036	3,399	NA	NA
BR-44-SL-042	15,498	5,710	9,911	9,995	1,759	5,223	6,260	Reject
BR-45-SL-043	15,390	6,376	11,268	11,015	1,531	1,399	6,260	Reject
BR-46-SL-044	**8,437**	**5,017**	**6,195**	**6,260**	**578**	**917**	**NA**	**NA**
BR-47-SL-045	10,560	5,177	7,252	7,258	822	3,434	6,260	Reject
BR-48-SL-046	12,338	5,208	7,868	7,991	1,239	3,152	6,260	Reject
BR-49-SL-047	14,314	5,523	8,906	9,124	1,418	2,928	6,260	Reject
BR-50-SL-048	12,933	6,066	9,315	9,292	1,067	2,293	6,260	Reject

Notes:
1. **Each group** of O&G brine-treated and associated background road(s) are shaded the same.
2. **Bold** – represents the background population for each shaded or unshaded group, respectively.
3. NA – indicates reference background road.
4. Accept (the Null Hypothesis) indicates there is a statistical difference in the data at the 95 percent confidence level. Reject (the Null Hypothesis) indicates the resulting surveys are statistically the same at the 95 percent confidence level.

Table 7-2. Summary of NaI Gamma Count Rate Data Converted to Exposure Rate

Study ID	GWS Max (µR/hr)	GWS Min (µR/hr)	GWS Median (µR/hr)	GWS Mean (µR/hr)	GWS Std. Dev. (µR/hr)	No. Data Points
BR-04-SL-011	20.6	9.90	16.3	15.8	2.00	2,906
BR-04-SL-010	Part of same road as BR-04-SL-011 – file statistics are same.					
BR-05-SL-009	20.1	13.7	16.8	16.8	0.90	1,387
BR-06-SL-004	19.7	12.3	16.8	16.7	1.00	1,452
BR-07-SL-008	19.6	10.0	16.1	15.6	1.80	2,389
BR-01-SL-001	22.2	5.10	14.3	14.7	2.00	11,536
BR-02-SL-002	16.6	12.2	13.8	13.9	0.800	850
BR-08-SL-003	17.8	12.2	15.0	15.0	0.900	5,590
BR-09	17.0	12.9	15.0	15.0	0.900	222
BR-10-SL-012	19.0	7.40	15.0	15.0	1.20	9,253
BR-11	16.0	11.8	13.6	13.6	0.700	596
BR-13-SL-006	16.5	11.9	14.1	14.1	0.800	961
BR-12-SL-005	15.1	7.60	11.4	11.4	1.10	4,644
BR-15-SL-014	18.1	9.60	13.5	13.6	1.40	1,359
BR-14-SL-013	17.6	2.50	13.6	13.4	1.30	5,395
BR-16-SL-015	15.5	11.8	13.2	13.3	0.600	592
BR-17-SL-016	17.3	11.4	14.5	14.4	1.00	4,388
BR-18-SL-017	12.4	7.60	9.30	9.40	0.800	727
BR-19-SL-018	21.2	8.50	11.7	11.9	1.20	5,231
BR-20-SL-019	16.9	6.80	10.9	11.0	1.60	3,944
BR-21-SL-020	15.6	7.80	10.7	10.8	1.10	877
BR-22-SL-021	16.4	7.40	11.3	11.6	2.10	704
BR-23-SL-022	17.2	6.90	11.7	11.7	1.70	3,605
BR-24-SL-023	16.5	6.70	10.6	10.7	1.50	3,375
BR-25-SL-024	16.6	6.30	9.30	9.70	1.90	1,984
BR-26-SL-025	14.0	7.40	10.3	10.3	1.10	343
BR-27-SL-026	14.2	7.10	10.4	10.3	1.20	579
BR-28-SL-027	15.6	5.70	9.60	9.70	1.50	3,376
BR-29-SL-028	18.1	6.60	11.3	11.9	2.40	2,556
BR-30-SL-029	13.0	7.10	10.0	9.90	0.900	759
BR-31-SL-030	18.0	7.80	12.2	12.3	1.50	7,245
BR-32-SL-031	17.6	8.20	12.6	12.6	1.40	1,958
BR-33-SL-032	13.7	7.50	10.6	10.5	0.800	2,603
BR-34-SL-033	14.3	6.70	10.3	10.3	1.00	3,347
BR-35-SL-034	15.1	7.50	11.3	11.3	1.20	2,186
BR-36-SL-035	13.7	7.10	10.7	10.6	0.900	975
BR-37-SL-036	14.5	7.00	10.1	10.1	0.900	10,257
BR-38-SL-037	13.3	7.60	10.0	10.0	0.800	406

Table 7-2. Summary of NaI Gamma Count Rate Data Converted to Exposure Rate

Study ID	GWS Max (μR/hr)	GWS Min (μR/hr)	GWS Median (μR/hr)	GWS Mean (μR/hr)	GWS Std. Dev. (μR/hr)	No. Data Points
BR-39-SL-038	13.2	7.70	9.90	9.90	0.800	1,124
BR-40-SL-039	14.5	7.10	9.90	9.80	0.800	3,712
BR-41	12.8	7.30	10.0	10.0	0.800	510
BR-42-SL-040	13.6	7.20	9.90	9.90	0.900	1,560
BR-43-SL-041	16.0	6.30	10.0	9.90	1.30	3,399
BR-44-SL-042	19.4	7.14	12.4	12.5	2.20	5,223
BR-45-SL-043	19.2	7.97	14.1	13.8	1.91	1,399
BR-46-SL-044	10.5	6.27	7.74	7.82	0.722	917
BR-47-SL-045	13.2	6.47	9.06	9.07	1.03	3,434
BR-48-SL-046	15.4	6.51	9.84	9.99	1.55	3,152
BR-49-SL-047	17.9	6.90	11.1	11.4	1.77	2,928
BR-50-SL-048	16.2	7.58	11.6	11.6	1.33	2,293

Table 7-3. Road-Biased Soil – Uranium Series Gamma Spectroscopy Results

Study ID	U-238 (pCi/g)	Ra-226 (pCi/g)	Pb-214 (pCi/g)	Bi-214 (pCi/g)
BR-01-SL-001	0.905	2.57	1.36	1.30
BR-04-SL-010	1.08	2.03	0.959	0.872
BR-04-SL-011	< 2.75	1.51	0.991	0.985
BR-05-SL-009	0.792	2.12	1.03	0.932
BR-06-SL-004	< 1.54	2.05	0.891	0.858
BR-12-SL-005	< 1.96	1.81	1.02	1.03
BR-14-SL-013	< 1.45	2.98	1.90	1.82
BR-15-SL-014	1.63	2.55	1.31	1.22
BR-17-SL-016	< 0.901	2.22	1.17	1.07
BR-19-SL-018	< 1.19	1.44	0.598	0.587
BR-21-SL-020	1.27	4.57	2.86	2.69
BR-23-SL-022	1.81	4.38	2.32	2.18
BR-24-SL-023	< 1.03	4.22	2.85	2.67
BR-25-SL-024	1.19	6.96	4.89	4.48
BR-28-SL-027	1.50	3.07	2.02	1.74
BR-29-SL-028	1.52	2.50	1.20	1.15
BR-31-SL-030	< 0.599	1.93	0.840	0.822
BR-33-SL-032	0.624	1.53	0.820	0.751
BR-34-SL-033	0.605	1.22	0.648	0.564
BR-35-SL-034	0.949	1.65	0.867	0.811
BR-37-SL-036	0.790	1.75	0.842	0.771
BR-39-SL-038	< 0.912	1.14	0.638	0.625
BR-40-SL-039	0.930	< 0.057	0.458	0.507
BR-42-SL-040	0.562	1.35	0.626	0.561
BR-43-SL-041	< 0.563	1.18	0.635	0.613
BR-44-SL-042	0.931	1.95	0.909	0.830
BR-45-SL-043	< 0.720	< 0.070	0.590	0.763
BR-47-SL-045	1.39	0.970	0.481	0.443
BR-48-SL-046	< 1.02	1.45	0.716	0.725
BR-49-SL-047	0.696	1.30	0.595	0.547
BR-50-SL-048	0.865	1.99	1.02	0.949
Average	0.882	2.14	1.23	1.16
Std. Dev.	0.410	1.38	0.932	0.852
Median	0.792	1.93	0.909	0.858
Minimum	0.282	0.029	0.458	0.443
Maximum	1.81	6.96	4.89	4.48

< – indicates a value less than the reported number which is the MDC.

Table 7-4. Road-Biased Soil – Thorium Series Gamma Spectroscopy Results

Study ID	Th-232 (pCi/g)	Ra-228 (pCi/g)	Ac-228 (pCi/g)	Pb-212 (pCi/g)	Bi-212 (pCi/g)
BR-01-SL-001	1.08	1.09	1.13	1.40	0.626
BR-04-SL-010	1.31	1.33	1.37	1.62	0.809
BR-04-SL-011	1.49	1.51	1.56	1.56	0.912
BR-05-SL-009	1.43	1.43	1.50	1.73	0.857
BR-06-SL-004	1.16	1.18	1.22	1.22	0.720
BR-12-SL-005	1.14	1.16	1.19	0.987	0.605
BR-14-SL-013	1.15	1.17	1.21	1.57	0.708
BR-15-SL-014	1.16	1.18	1.22	1.51	0.651
BR-17-SL-016	1.29	1.45	1.35	1.59	0.763
BR-19-SL-018	0.746	0.760	0.781	0.926	0.565
BR-21-SL-020	0.882	0.901	0.923	1.16	0.463
BR-23-SL-022	1.26	1.29	1.32	1.60	0.737
BR-24-SL-023	1.48	1.51	1.55	1.79	0.748
BR-25-SL-024	1.81	1.85	1.89	2.07	0.760
BR-28-SL-027	0.711	0.727	0.744	0.675	0.426
BR-29-SL-028	1.04	1.06	1.08	1.37	0.762
BR-31-SL-030	0.771	0.789	0.807	0.971	0.492
BR-33-SL-032	0.701	0.717	0.734	0.846	0.412
BR-34-SL-033	0.581	0.595	0.609	0.764	0.405
BR-35-SL-034	0.798	0.817	0.835	0.909	0.484
BR-37-SL-036	0.768	0.787	0.804	0.917	0.471
BR-39-SL-038	0.670	0.687	0.701	0.704	0.370
BR-40-SL-039	0.616	0.632	0.645	0.213	0.386
BR-42-SL-040	0.664	0.681	0.695	0.782	0.386
BR-43-SL-041	0.684	0.702	0.717	0.875	0.423
BR-44-SL-042	1.11	1.12	1.16	1.38	0.714
BR-45-SL-043	0.863	0.872	0.904	0.210	0.586
BR-47-SL-045	0.450	0.455	0.471	0.559	0.277
BR-48-SL-046	0.773	0.780	0.809	0.864	0.479
BR-49-SL-047	0.577	0.582	0.604	0.685	0.376
BR-50-SL-048	0.515	0.520	0.539	0.688	0.259
Average	0.972	0.979	1.00	1.10	0.569
Std. Dev.	0.334	0.349	0.355	0.465	0.179
Median	0.873	0.872	0.904	0.971	0.565
Minimum	0.450	0.455	0.471	0.210	0.259
Maximum	1.81	1.85	1.89	2.07	0.912

Table 7-5. Road-Biased Soil – Actinium Series and Miscellaneous Gamma Spectroscopy Results

Study ID	U-235 (pCi/g)	K-40 (pCi/g)
BR-01-SL-001	< 0.075	10.6
BR-04-SL-010	< 0.107	21.4
BR-04-SL-011	< 0.212	29.4
BR-05-SL-009	0.117	24.8
BR-06-SL-004	< 0.152	21.7
BR-12-SL-005	< 0.157	7.01
BR-14-SL-013	< 0.183	13.2
BR-15-SL-014	< 0.150	12.5
BR-17-SL-016	< 0.083	17.6
BR-19-SL-018	< 0.114	10.9
BR-21-SL-020	< 0.127	5.61
BR-23-SL-022	< 0.110	13.0
BR-24-SL-023	< 0.103	16.9
BR-25-SL-024	< 0.093	16.3
BR-28-SL-027	0.074	11.4
BR-29-SL-028	< 0.209	20.1
BR-31-SL-030	0.094	8.84
BR-33-SL-032	< 0.045	7.35
BR-34-SL-033	< 0.051	11.3
BR-35-SL-034	0.071	7.21
BR-37-SL-036	< 0.048	8.92
BR-39-SL-038	< 0.007	6.85
BR-40-SL-039	< 0.044	7.22
BR-42-SL-040	< 0.042	7.49
BR-43-SL-041	0.100	8.39
BR-44-SL-042	< 0.055	19.1
BR-45-SL-043	< 0.051	15.0
BR-47-SL-045	< 0.035	6.10
BR-48-SL-046	< 0.071	12.3
BR-49-SL-047	0.102	7.96
BR-50-SL-048	< 0.091	5.40
Average	0.056	12.6
Std. Dev.	0.029	6.19
Median	0.052	11.3
Minimum	0.018	5.40
Maximum	< 0.091	29.4

< – indicates a value less than the reported number which is the MDC.

Table 7-6. Reference Background Road – Uranium Series Gamma Spectroscopy Results

Study ID	U-238 (pCi/g)	Ra-226 (pCi/g)	Pb-214 (pCi/g)	Bi-214 (pCi/g)
BR-02-SL-002	< 1.64	3.07	1.69	1.69
BR-07-SL-008	< 1.58	2.38	1.05	0.965
BR-13-SL-006	< 1.08	6.09	3.81	3.59
BR-16-SL-015	< 1.55	2.24	1.09	0.967
BR-18-SL-017	< 0.753	0.828	0.479	0.445
BR-20-SL-019	< 3.14	63.0	51.0	48.4
BR-22-SL-021	< 1.99	16.1	14.2	12.7
BR-26-SL-025	< 0.919	4.25	3.01	2.85
BR-27-SL-026	0.643	4.10	2.83	2.70
BR-30-SL-029	1.61	2.86	1.55	1.45
BR-32-SL-031	< 0.854	1.69	1.11	0.940
BR-36-SL-035	0.825	1.41	0.640	0.609
BR-38-SL-037	12.7	1.55	0.784	0.711
BR-46-SL-044	8.04	1.13	0.523	0.468
Average	2.18	7.91	5.98	5.61
Std. Dev.	3.61	16.3	13.4	12.7
Median	0.805	2.62	1.33	1.21
Minimum	0.377	0.828	0.479	0.445
Maximum	12.7	63.0	51.0	48.4

< – indicates a value less than the reported number which is the MDC.

Table 7-7. Reference Background Road – Thorium Series Gamma Spectroscopy Results

Study ID	Th-232 (pCi/g)	Ra-228 (pCi/g)	Ac-228 (pCi/g)	Pb-212 (pCi/g)	Bi-212 (pCi/g)
BR-02-SL-002	1.38	1.41	1.45	1.70	0.826
BR-07-SL-008	1.28	1.30	1.34	1.66	0.874
BR-13-SL-006	3.26	3.32	3.43	2.03	0.885
BR-16-SL-015	1.28	1.30	1.34	1.58	0.778
BR-18-SL-017	0.392	0.399	0.410	0.509	0.244
BR-20-SL-019	11.0	11.2	11.5	10.5	1.53
BR-22-SL-021	2.93	2.99	3.06	3.47	0.765
BR-26-SL-025	1.05	1.08	1.10	1.12	0.414
BR-27-SL-026	0.838	0.857	0.877	0.982	0.331
BR-30-SL-029	0.543	0.556	0.568	0.778	0.307
BR-32-SL-031	0.709	0.725	0.742	1.07	0.433
BR-36-SL-035	0.637	0.653	0.667	0.788	0.376
BR-38-SL-037	0.752	0.772	0.788	0.890	0.441
BR-46-SL-044	0.392	0.396	0.410	0.513	0.249
Average	1.89	1.93	1.98	1.97	0.604
Std. Dev.	2.76	2.81	2.89	2.57	0.359
Median	0.944	0.969	0.989	1.10	0.437
Minimum	0.752	0.396	0.410	0.509	0.244
Maximum	11.0	11.2	11.5	10.5	1.53

Table 7-8. Reference Background Road – Actinium Series and Miscellaneous Gamma Spectroscopy Results

Study ID	U-235 (pCi/g)	K-40 (pCi/g)
BR-02-SL-002	< 0.223	13.6
BR-07-SL-008	< 0.149	23.1
BR-13-SL-006	< 0.165	18.1
BR-16-SL-015	< 0.161	12.0
BR-18-SL-017	< 0.131	6.14
BR-20-SL-019	< 0.322	9.32
BR-22-SL-021	< 0.197	20.7
BR-26-SL-025	< 0.085	6.07
BR-27-SL-026	< 0.069	4.87
BR-30-SL-029	< 0.058	6.68
BR-32-SL-031	< 0.050	13.0
BR-36-SL-035	< 0.050	7.18
BR-38-SL-037	< 0.044	8.73
BR-46-SL-044	0.077	4.44
Average	0.066	11.0
Std. Dev.	0.040	6.03
Median	0.071	9.03
Minimum	0.022	4.44
Maximum	0.161	23.1

< – indicates a value less than the reported number which is the MDC.

Table 7-9. Dose Assessment Results for Oil and Gas Brine-Treated Roads

Nuclide	Ground (mrem)	Inhalation (mrem)	Radon (mrem)	Plant (mrem)	Meat (mrem)	Milk (mrem)	Soil (mrem)
Ra-226	5.46E-02	1.25E-05	1.22E-05	0.000E+00	8.30E-02	0.000E+00	3.09E-04
Pb-210	3.40E-05	3.21E-05	0.000E+00	0.000E+00	2.20E-01	0.000E+00	1.55E-03
Ra-228	1.77E-02	4.10E-05	6.17E-05	0.000E+00	4.12E-02	0.000E+00	1.60E-04
Th-228	2.02E-02	2.06E-04	3.38E-04	0.000E+00	1.09E-03	0.000E+00	7.43E-05
Total	9.26E-02	2.92E-04	4.12E-04	0.000E+00	3.45E-01	0.000E+00	2.10E-03

8.0 QUALITY ASSURANCE AND QUALITY CONTROL

The quality assurance (QA) and QC objectives and criteria for this study were established in the study-specific Quality Assurance Project Plan (QAPP) which, along with the FSP, is available on the DEP website.

The purpose of the QAPP is to provide procedures and metrics for evaluating and ensuring that all data are technically sound and legally defensible. This is accomplished by establishing sample collection and preservation procedures, data collection procedures, analytical requirements and data evaluation processes, which result in accurate, precise, representative and complete data.

All sampling and analyses performed for this study were conducted in accordance with the QAPP standards.

8.1 Data Quality Levels (DQLs)

The requirements for this study were based on DQL I for field screening methods and DQL III for Non-Contract Laboratory Program (non-CLP) laboratory methods.

8.2 Quality Control Parameters

The established QC parameters for evaluating data in this study were precision [duplicates, matrix spikes (MS), matrix spike duplicates (MSD)], accuracy (spiked samples, laboratory control samples), and completeness (percentage of valid data).

Precision and accuracy obtained during this study met QC parameters unless otherwise noted.

Completeness is determined by calculating the percentage of valid data. Approximately eight percent of the gross α/β analyses were invalidated due to excessive concentrations of total dissolved solids (TDS). The TDS remaining after the water was evaporated were in excess of the allowable mass. Attempts to dilute the samples to allow valid analyses to be performed were unsuccessful.

8.3 Field Screening

Field surveys were performed by Perma-Fix personnel trained in the use of the survey instrumentation required. DQL I criteria were used to collect the following types of data:

- Gamma radiation exposure rate measurements
- Gross gamma radiation measurements
- Total α and β surface radioactivity
- Removable α and β surface radioactivity
- Background gamma radiation exposure rate and gross gamma radioactivity measurements (outside the influence of sampling areas)
- Liquid and solid samples for off-site analysis

8.4 Sample Identification

Field samples were assigned a unique number to identify information such as the sampling technician, the sequential number corresponding to the sample type, and the order in which it was collected in accordance with the FSP.

8.5 Sample Custody

A field chain-of-custody form or sample submission form was used to record the custody of all samples collected. This chain-of-custody form documented the transfer of the custody from the sampling personnel to another person, to the laboratory, or another party, such as a courier delivery service.

Field samples were packaged and shipped to the laboratory on the day of collection in accordance with chain-of-custody protocols. All samples were transported to the laboratory by the quick courier service or hand delivered to the laboratory. The original chain-of-custody form was sent with the samples. The remaining copy was stored in the field team files.

Further details pertaining to chain-of-custody may be found in the FSP.

8.6 Analytical Procedures

Analytical methods and procedures were established before the study began based on preliminary assumptions and are listed in **Table 8-1**. Additional analytical methods were subsequently added and/or modified when preliminary assumptions were found to be different due to the amount of TDS in the samples. Additional analytical method selection was based on the following:

- Original specified methodologies for radiochemistry failed due to elevated dissolved solids and Barium (Ba) concentrations.
- Alternate EPA methods, which were used as necessary.

All procedures for environmental sample handling, storage, and documentation while in the laboratory's custody and deliverable requirements upon delivery of the data to the user are documented in the laboratory's quality assurance manual (QAM).

8.7 Instrument Calibrations

All field and laboratory equipment were calibrated to NIST traceable standards before use to ensure proper operating accuracy. Laboratory instrument calibration procedures are presented in the laboratory QAMs. Field calibrations were performed in accordance with specified procedures. Prior to the use of field equipment, daily operational QC checks were completed. All daily QC instrumentation checks are presented in **Appendix B.**

8.8 Data Evaluation and Validation

The following subsections describe the field and laboratory data validation processes used for the study.

8.8.1 Validation of Field Data

During the field operations, field measurements were validated at the time of collection by the field sampler through the use of standard operating procedures (SOPs) and field QC checks. Field-obtained data, as well as ongoing QA/QC checks of environmental samples collected, were validated by trained Perma-Fix and DEP field technicians. All field data were reviewed at the time of sample collection.

8.8.2 Validation of Laboratory Data

Prior to reporting laboratory data, the analyst validated the sample results based on the QC criteria specified in the analytical methods. The data validation process included verification of the following steps:

- Ensure the standard regression coefficient is within the acceptable range.
- Ensure standard reference materials were analyzed at the proper frequencies and acceptable results were obtained.
- Ensure the reagent blanks were analyzed at the proper frequency.
- Ensure precision requirements of the plan were met.
- Ensure accuracy requirements of the plan were met.
- Ensure completeness requirements of the plan were met.
- Ensure samples were analyzed within the proper sample holding times.
- Verify all calculations were correct.
- Ensure proper units were reported.
- Ensure the proper methodologies were used.

In addition to the review of analytical results and project-specific precision, accuracy, and completeness requirements, the laboratory department manager or senior chemist performed internal audits of report forms and other data sheets as well as regular reviews of instrument logs, performance test results, and analysts' performance. Where review of analytical results or internal QA/QC checks indicated discrepancies, immediate corrective actions were taken and all data results collected since the previous approved QC audits were reviewed for validity. Specific laboratory procedures for validation of the analytical data generated are described in the laboratory QAMs.

8.9 Data Reporting – Analytical Laboratory

After the data were validated internally by the laboratory, the results were entered into the laboratory's data management system. The laboratory data management system contains the final data results. When data entries were completed, the laboratory director (or his/her designee) issued a final data report. The director then issued the final data report to the data user.

The data reports prepared for this project contain all pertinent information for the data user in determining the applicability and validity of the data. A specified and uniform data reporting format was implemented to facilitate this effort. For this project, DQL III data packages were reported as a DQL IV (CLP-like) deliverable to facilitate data validation and are presented in

Appendix K. The following criteria and information were supplied, as a minimum, for data reports generated for this project:

- A descriptive case narrative describing the internal data validation.
- Completed and legible chains-of-custody for all analyses contained within each submitted data package.
- A laboratory sample record documenting which analyses were performed for the samples contained in the data package is presented in **Table 8-1**.
- All of the laboratory sample identifications and the correlating field sample identifications.
- All applicable analytical results, counting errors, and MDCs reported in the correct number of significant figures and reporting units.
- Included in the individual sample reporting results are the complete sample identifications, the sample dilutions (if necessary), and the individual sample analysis dates.

8.9.1 DQL III Reporting

The following summary forms and raw data deliverable requirements apply for DQL III.

The following forms are required for all analyses using gamma spectroscopy; isotopic U and Th; and gross α, gross β and Ra methods, and were provided by the DEP Laboratory in various forms:

- Narrative and sample identification cross reference
- Copies of chain-of-custody documentation
- Laboratory chronicle
- Method summaries and references
- MS/MSD summary or any laboratory duplicate
- Method blank summary and results
- Instrument performance check summary
- Initial calibration summary for all constituents of interest

8.10 Quality Control Procedures

QC procedures and checks ensure the accuracy of the data.

For any laboratory QC result that was outside of the acceptance criteria, the samples were reanalyzed and/or the results were qualified in the final report.

8.10.1 Field QC Checks

Duplicate samples were collected and analyzed to assess the quality of field sampling techniques. These samples were treated as separate and discrete samples and analyzed by the selected offsite laboratory. The results are provided in Section 8.16.

8.10.2 Internal Laboratory QC Checks

The laboratory followed the internal QC checks specified in the QAPP for each analysis type employed. In addition, these QC checks have met the requirements specified in the respective EPA analytical methods.

8.10.2.1 Initial and Continuing Calibration

Each instrument and measurement system was calibrated prior to use to verify the instrument met performance criteria throughout the course of the analytical cycle. Continuing calibration checks were performed at a minimum frequency in accordance with the DEP Laboratory QAM. For instruments used for radiological analysis, performance checks are conducted each day samples are analyzed. For instruments used for non-radiological analysis, performance checks are conducted for each batch of 20 samples or less.

8.10.2.2 Reagent Blanks

A reagent blank was analyzed with each set of samples received for analysis. No responses above the reportable detection limit were observed in any of the blanks, indicating no possible laboratory contamination. The exact frequency and method of use is presented in the laboratory QAM.

8.10.2.3 Matrix Spike and Duplicate (Matrix Spike Duplicate) Analysis

One in 20 samples were analyzed as MSs and MSDs or one per day, whichever was greater. MS/MSD QC is not required for gamma spectroscopy analysis because no sample preparation is involved. The MS/MSD QC measures the effects of the sample matrix on method performance. The percent recovery for spiked samples was calculated using the equations documented in Section 11.0 of the QAPP and compared to the accuracy criteria specified in the QAM for the associated analytical method. The relative percent difference (RPD) of replicate spikes or replicate analytical results was calculated using the equations documented in Section 11.0 of the QAPP and compared to the precision criteria for the associated analytical method.

8.10.2.4 Calibration Standards

Calibration standards were analyzed as required in the reference methods throughout the course of the analysis. The exact frequencies and methods of use are presented in the laboratory QAM.

8.11 Laboratory Performance Audits

Laboratory performance audits are conducted by the DEP Laboratory QA officer three times per year. Each laboratory analyst is provided a performance evaluation or proficiency test sample containing analytes for the parameters which he/she usually performs. These proficiency test sample results are used to identify issues in sample preparation, analysis techniques, or methodologies. Any issues are identified, investigated, documented on the proper form, resolved with a corrective action plan to eliminate the issues and prevent reoccurrence, and then shared with the accreditation bodies.

The DEP Laboratory internal audits include verification of each analyst's record keeping, proper use and understanding of procedures, and performance documentation. Deficiencies/findings are discussed with the analyst, documented, and resolved through the implementation of a corrective action.

8.12 Laboratory System Audits

Laboratory system audits are conducted by an external third-party assessor once every two years. These audits are used to ensure that all aspects of the DEP Laboratory's QAM are operative and within compliance. This involves a thorough review of all laboratory methods performed and documentation to confirm that all analytical procedures are performed according to the DEP Laboratory's QAM. An external third-party assessment was not conducted during the time period that samples from the TENORM study were received, processed, analyzed, and reported.

8.13 Assessment Procedures for Data Acceptability

The following subsections describe the data validation procedures that were used to evaluate the precision, accuracy, and completeness of the data generated.

8.13.1 Precision

Precision is the evaluation of agreement among individual measurements of the same property under prescribed similar conditions. Precision is assessed by calculating the RPD of replicate spike samples or replicate sample analyses according to the following equation:

Relative Percent Difference: $RPD = \frac{R_1 - R_2}{(R_1 + R_2)/2} \times 100$

Where: R_1 = result 1
R_2 = result 2

8.13.2 Accuracy

Accuracy is the evaluation of closeness of an individual measurement to the true value. Accuracy is measured by calculating the percent recovery (%R) of known levels of spike compounds as follows:

Percent Recovery:

$$\%R = \frac{[spike\ sample] - [unspiked\ sample]}{[spike\ added]} \times 100$$

8.13.3 Completeness

Completeness is the quantification of the amount of valid data obtained from a measurement system, expressed as a percentage of the number of valid measurements that could have been accomplished. More than one completeness check can be evaluated. It is calculated as follows:

$$Completeness\ (\%) = \frac{number\ of\ valid\ samples\ reported}{total\ number\ of\ samples\ analyzed} \times 100$$

8.13.4 Quality Control Charts

Valid QC charts can be prepared after the initial 20 analytical determinations to graphically evaluate precision and accuracy criteria. The charts are prepared by calculating the mean value of the determinations and setting control limits at ± 3 standard deviations from that mean. The following equations are used:

Mean:

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

Where: N = number of samples
X_i = sample value

Standard Deviation:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{X})^2}{N-1}}$$

The control limits must be within acceptance limits or ranges presented in the DEP Laboratory's SOPs. If the values are found to be outside these limits or ranges, the measurement system is examined to determine if possible problems exist. Most of the values were found inside the limits; however, those values which exceeded the control limits were reported with an appropriate data qualifier.

8.14 Preventative Maintenance

Performance of preventative maintenance was completed on equipment to ensure operability. Instrument manuals are kept on file and used for reference whenever equipment required repair or maintenance.

8.14.1 Field Equipment

Field sampling personnel were responsible for preventative maintenance of all field instruments. The field sampling personnel ensured field instrumentation was protected from extreme weather conditions as well as physical hazards.

8.14.2 Laboratory Instruments

Preventative maintenance schedules and/or procedures for laboratory equipment are presented in the DEP Laboratory QAM. No major preventative maintenance was performed on the DEP Laboratory equipment during the time period that samples from the TENORM study were received, processed, analyzed and reported.

8.15 QA Reports to Management

Audit reports have been provided by the DEP Laboratory director (or his/her designee) as a means of tracking program performance. An annual method internal audit was performed covering the period of January 1, 2013, to present. In addition, the state of New Jersey Department of Environmental Protection (NJDEP) performed an audit of the DEP Laboratory management system, QA program, and analytical testing procedures performed by the DEP Laboratory. The NJDEP submitted a February 11, 2013, report to the DEP Laboratory that concluded no findings for the Radiation Measurement Section.

Field QA reports were not necessary due to the size and length of individual sample collection activities. Any problems noted during sampling were immediately communicated to the project certified health physicist.

8.16 Third-Party Quality Control

QC samples were collected as follows:

- Solid Samples – five percent (field replicate/split) QC samples, i.e., one every 20 samples collected to verify results of onsite laboratory per total samples in a calendar year.
- Aqueous Samples – five percent (field replicate/split) QC samples, i.e., one every 20 samples collected to verify results of onsite laboratory per total samples in a calendar year.

The samples were sent offsite to an independent, third-party, accredited laboratory for gamma spectroscopy analysis and compared to the DEP Laboratory gamma spectroscopy analysis of the split sample using NRC Inspection Manual Procedure 84750:

- Divide each offsite laboratory result by its associated uncertainty to obtain the resolution. For purposes of this procedure, the uncertainty is defined as the relative standard deviation, one sigma, of the offsite laboratory results as calculated from counting statistics, i.e., the 95 percent confidence level reported error divided by 1.96.
- Divide each DEP Laboratory result by the corresponding offsite laboratory result to obtain the ratio (DEP Laboratory/offsite laboratory).
- The DEP Laboratory's measurement is in agreement if the value of the ratio falls within the limits shown in the following table for the corresponding resolution:

Criteria for Accepting the DEP Laboratory's Measurements

Resolution	Ratio
<4	Statistics are too poor for comparison
4-7	0.5-2.0
8-15	0.6-1.66
16-50	0.75-1.33
Resolution	**Ratio**
51-200	0.80-1.25
>200	0.85-1.18

The results of the comparison for solid samples are presented in **Tables 8-2** through **8-5** for four of the radionuclides identified using gamma spectroscopy. If either the DEP Laboratory or the third-party laboratory (GEL) result was < MDC value reported, the comparison was not made.

There were 28 comparisons of split solid samples made; 14 passed and 14 failed. The pass/fail rate of 50 percent is likely due to the difficulty with splitting solid samples in regards to the total radioactivity concentration. The performance has been determined to be acceptable based on the following criteria: split sampling of solid samples, especially at low-activity concentrations, rarely results in equal activity for both resulting samples. Radioactive particulate contamination within solids is usually not homogenous, making split sampling improbable to split activity evenly between the two aliquots.

- Mixing or blending of the solid sample prior to splitting into equal aliquots does not ensure the radioactivity is evenly divided.
- Duplicate analysis of the same solid sample is more appropriate as a third-party QC comparison, eliminating the large variability of split samples, but was not possible for this study.
- Liquid samples are much easier to mix prior to splitting and are a more appropriate measure of the agreement between the two laboratories.

The results of the comparison for liquid samples are presented in **Tables 8-6** through **8-9** for four of the radionuclides identified using gamma spectroscopy. If either the DEP Laboratory or the independent laboratory (GEL) result was < MDC value reported, the comparison was not made.

Of the 35 comparisons made on split liquid sample gamma spectroscopy analysis results, 30 met acceptance criteria. The agreement between the DEP Laboratory and the independent laboratory (GEL) gamma spectroscopy results is acceptable.

The following actions and/or conclusions were made based on the split solid sample analytical results:

1. Split sampling of radioactive solid samples does not result in equal radioactivity in the two resulting samples. Solid samples were mixed in the field prior to filling two sample containers (splitting the sample). Low-activity solid sample media does not readily split into equal radioactivity concentration.

2. All of the split solid samples failing the comparison acceptance criteria were reviewed by asking the question: "Would the result of one of the two splits result in a different conclusion?" For example, would the result of one split pass a compliance test that may be applicable to the media and the result of the other split fail? Only one sample, with results of 363 versus 6.02 pCi/g, would result in a different action based on the result.

3. Duplicate analysis of the same sample (no splitting) is a much better comparison of laboratory performance and is recommended for any future sample and analysis study.

In addition, the 5% of the total solid samples selected for QC were re-analyzed by the DEP Laboratory and then forwarded to an offsite laboratory for duplicate analysis. The samples were sent offsite to an independent, third-party, accredited laboratory for gamma spectroscopy analysis and compared to the DEP Laboratory gamma spectroscopy analysis of the same sample using two methods: the duplicate error ratio (DER) in the equation below and RPD equation from Section 8.13.1.

Duplicate Error Ratio: $DER = \frac{|S-D|}{\sqrt{TPU_S{}^2 + TPU_D{}^2}}$

Where:
S = Sample result
D = Duplicate result
TPU_S = Total propagated uncertainty of the sample
TPU_D = Total propagated uncertainty of the duplicate

A DER result less than 1.42 means the sample results may be identical, while a RPD of 35% means that the sample results may be identical. A total of 40 evaluations were made between the DEP Laboratory re-analysis results and the duplicates sent to the third-party laboratory. **Table 8-10** through **Table 8-13** provide the analytical results and the results of the DER and RPD calculations. Evaluating the results with the DER demonstrated the two laboratories produced statistically different results 49% of the time, while the RPD demonstrated a difference 32% of the time. Overall, duplicate analysis provided only slightly better agreement between the two laboratories as did split sample analyses.

The following actions and/or conclusions were made based on the duplicate solid sample analytical results:

1. The activity reported for Bi-214 and Pb-214 were generally higher for the third-party laboratory. This supports the conclusion of improperly sealed containers and the loss of some activity below Rn-222 in the uranium series.
2. A majority of the time the Ra-226 activity was reported higher by the DEP Laboratory. A difference in analytical technique may provide a bias. The DEP Laboratory counts Ra-226 directly while the third-party laboratory reports the Bi-214.
3. The activity reported for Pb-212 was generally higher for the DEP Laboratory than the third-party laboratory, although most of the difference can be attributed to the counting statistics of low activity samples.

Table 8-1. Summary of Analytical Procedures

Sample Type	Media/ Sample Type	Analytical Parameters	Analytical[(a)] Methods	Frequency[(b)]
Cuttings as produced on a drilling rig including cuttings stored temporarily on site in lined pits or containers Solid phase from flowback and produced water Solids accumulated in vessels or on equipment Scale from drilling rigs and associated equipment Soil/salt samples from beneficial reuse areas (Off-site Lab)	Soil/soil-like	Gamma spectroscopy to identify TENORM radionuclides Alpha spectroscopy to identify isotopic U (233/234, 235, and 238) and isotopic Th (228, 230, and 232)	USEPA 901.1 Health and Safety Laboratory (HASL) 300	Once per site
WWTP sludge WWTP discharge sediments (Off-site Lab)	Soil/soil-like	Gamma spectroscopy to identify TENORM radionuclides Alpha spectroscopy to identify isotopic U (U-233/234, 235, and 238) and isotopic Th (Th-228, 230, and 232)	USEPA 901.1 HASL 300	Three times per facility
Flowback and produced waters Accumulated liquids from production equipment (Off-site Lab)	Aqueous (Grab)	Gross α and β Gamma spectroscopy to identify TENORM radionuclides	USEPA 900.0 USEPA 901.1	Once per site
Influent Marcellus Shale industry water (as is and filtered) WWTP effluent discharge water (as is and filtered) (Off-site Lab)	Aqueous (Grab)	Gross α and β Gamma spectroscopy to identify TENORM radionuclides	USEPA 900.0 USEPA 901.1	Quarterly x3
Landfill Leachate	Aqueous (Grab)	Gross α and β Gamma spectroscopy analysis Radium (Ra-226 and Ra-228)	USEPA 900.0 USEPA 901.1 EPA 903.1 and EPA 904.0 equivalent	Once per landfill

Table 8-1. Summary of Analytical Procedures

Sample Type	Media/ Sample Type	Analytical Parameters	Analytical[(a)] Methods	Frequency[(b)]
Gas sampling as necessary (Off-site Lab) Ambient Radon	Gaseous (Grab) Charcoal canister	Radon Radon		As determined by DEP

(a) Analytical methods are as follows:
- Up to 10 percent of the samples, based on the gross α and β and gamma spectroscopy results, are also analyzed by α spectroscopy for U (U-238, U-235, and U-234), Th-232, Ra (Ra-226 and Ra-228), and for any unsupported decay chain radionuclides.
- Analytical method as specified or an equivalent method where appropriate.

(b) QC samples were collected as follows:
- Solid Samples – five percent (field replicate/split) QC samples, i.e., one every 20 samples collected to verify results of onsite laboratory per total samples in a calendar year.
- Aqueous Samples – five percent (field replicate/split) QC samples, i.e., one every 20 samples collected to verify results of on-site laboratory per total samples in a calendar year.

Table 8-2. Bi-214 Split Solid Sample Comparison Results

Study ID	Bi-214 Result (pCi/g)	Bi-214 Err (pCi/g)	Bi-214 MDC (pCi/g)	Bi-214 Resolution / Ratio	Bi-214 Criteria / Pass-Fail
5942116	0.001	0.000	0.016	7.00	NA
5942116GEL	0.556	0.158	0.120	0.002	NA
5942130	26.5	4.16	0.217	5.00	0.5-2.0
5942130GEL	12.1	4.77	0.857	2.19	Fail
5942134	0.638	0.106	0.057	5.00	0.5-2.0
5942134GEL	4.19	1.58	0.461	0.152	Fail
5942145	0.000	0.269	1.05	12.0	0.6-1.66
5942145GEL	1.14	0.185	0.109	0.000	Fail
5942155	3.77	0.317	0.056	21.0	0.75-1.33
5942155GEL	2.63	0.250	0.079	1.43	Fail
5942180	0.780	0.073	0.048	14.0	0.6-1.66
5942180GEL	0.969	0.133	0.074	0.805	Pass
5942189	370	25.3	1.11	377	0.85-1.18
5942189GEL	589	3.06	0.973	0.628	Fail
5942188	24.0	1.97	0.156	58.0	0.80-1.25
5942188GEL	21.6	0.726	0.241	1.11	Pass

NA = one or both results were less than the reported MDC; no comparison performed.

Table 8-3. Pb-212 Split Solid Sample Comparison Results

Study ID	Pb-212 Result (pCi/g)	Pb-212 Err (pCi/g)	Pb-212 MDC (pCi/g)	Pb-212 Resolution / Ratio	Pb-212 Criteria / Pass-Fail
5942116	-0.008	0.000	0.014	NA	NA
5942116GEL	0.533	0.093	0.099	NA	NA
5942130	6.31	0.377	0.484	7.00	0.5-2.0
5942130GEL	11.4	3.02	0.545	0.554	Pass
5942134	1.19	0.137	0.089	3.00	NA
5942134GEL	1.54	1.05	0.318	0.773	NA
5942145	0.909	0.129	0.062	27.0	0.75-1.33
5942145GEL	1.57	0.115	0.085	0.579	Fail
5942155	1.47	0.104	0.036	23.0	0.75-1.33
5942155GEL	1.51	0.131	0.066	0.974	Pass
5942180	0.832	0.072	0.059	21.0	0.75-1.33
5942180GEL	0.898	0.083	0.059	0.927	Pass
5942189	154	20.7	0.998	256	0.85-1.18
5942189GEL	146	1.12	0.743	1.06	Pass
5942188	8.40	0.589	0.178	19.0	0.85-1.18
5942188GEL	2.29	0.238	0.179	3.67	Fail

NA = one or both results were less than the reported MDC; no comparison performed.

Table 8-4. Pb-214 Split Soil Sample Comparison Results

Study ID	Pb-214 Result (pCi/g)	Pb-214 Err (pCi/g)	Pb-214 MDC (pCi/g)	Pb-214 Resolution / Ratio	Pb-214 Criteria / Pass-Fail
5942116	0.289	0.033	0.034	10.0	0.6-1.66
5942116GEL	0.689	0.132	0.120	0.419	Fail
5942130	26.4	1.93	0.217	8.00	0.6-1.66
5942130GEL	17.1	4.43	0.812	1.54	Pass
5942134	6.05	0.527	0.061	5.00	0.5-2.0
5942134GEL	3.89	1.39	0.418	1.56	Pass
5942145	1.21	0.213	0.066	19.0	0.75-1.33
5942145GEL	1.34	0.140	0.104	0.903	Pass
5942155	4.18	0.283	0.054	23.0	0.75-1.33
5942155GEL	3.18	0.271	0.086	1.31	Pass
5942180	0.822	0.072	0.059	16.0	0.6-1.66
5942180GEL	1.25	0.155	0.082	0.658	Pass
5942189	373	62.5	1.03	4.00	0.5-2.0
5942189GEL	6.02	3.13	4.47	62.0	Fail
5942188	26.3	1.73	0.152	66.0	0.80-1.25
5942188GEL	24.4	0.724	0.240	1.08	Pass

Table 8-5. Ra-226 Split Soil Sample Comparison Results

Study ID	Ra-226 Result (pCi/g)	Ra-226 Error (pCi/g)	Ra-226 MDC (pCi/g)	Ra-226 Resolution / Ratio	Ra-226 Criteria / Pass-Fail
5942116	-0.060	0.000	0.183	NA	NA
5942116GEL	0.556	0.158	0.120	NA	NA
5942130	31.7	2.66	2.49	5.00	0.5-2.0
5942130GEL	12.1	4.77	0.857	2.62	Fail
5942134	7.73	0.957	0.756	5.00	0.5-2.0
5942134GEL	4.19	1.58	0.461	1.85	Pass
5942145	1.99	0.418	0.595	12.0	0.6-1.66
5942145GEL	1.14	0.185	0.109	1.75	Fail
5942155	6.14	0.609	0.650	21.0	0.75-1.33
5942155GEL	2.63	0.250	0.079	2.34	Fail
5942180	1.50	0.382	0.579	14.0	0.6-1.66
5942180GEL	0.969	0.133	0.074	1.55	Pass
5942189	421	38.5	8.80	377	0.85-1.18
5942189GEL	589	3.06	0.973	0.715	Fail
5942188	35.1	2.67	1.75	58.0	0.80-1.25
5942188GEL	21.6	0.726	0.241	1.63	Fail

NA = one or both results were less than the reported MDC; no comparison performed.

Table 8-6. Bi-214 Split Liquid Sample Comparison Results

Study ID	Bi-214 Result (pCi/L)	Bi-214 Error (pCi/L)	Bi-214 MDC (pCi/L)	Bi-214 Resolution / Ratio	Bi-214 Criteria / Pass-Fail
5942389	41.0	7.00	7.00	6.00	0.5-2.0
5942389GEL	32.8	11.5	10.6	1.25	Pass
5942390	57.0	6.00	5.00	6.00	0.5-2.0
5942390GEL	29.3	9.13	9.10	1.95	Pass
5942391	181	24.0	22.0	15.0	0.6-1.66
5942391GEL	187	24.6	20.4	0.968	Pass
5942392	229	19.0	8.00	20.0	0.75-1.33
5942392GEL	251	25.0	13.6	0.912	Pass
5942228	458	35.0	8.00	30.0	0.75-1.33
5942228GEL	669	43.5	22.4	0.685	Fail
5942275	4,660	377	37.0	94.0	0.80-1.25
5942275GEL	4,450	92.9	38.8	1.05	Pass
5942276	4,320	38.0	11.0	105	0.80-1.25
5942276GEL	4,860	90.8	34.7	0.889	Pass
5942277	2,020	245	14.0	75.0	0.80-1.25
5942277GEL	2,370	62.2	26.0	0.852	Pass
5942278	2,150	33.0	22.0	71.0	0.80-1.25
5942278GEL	2,230	61.2	26.0	0.964	Pass
5942291	15,300	1,340	44.0	195	0.80-1.25
5942291GEL	16,400	165	62.2	0.933	Pass

Table 8-7. Pb-214 Split Liquid Sample Comparison Results

Study ID	Pb-214 Result (pCi/L)	Pb-214 Error (pCi/L)	Pb-214 MDC (pCi/L)	Pb-214 Resolution / Ratio	Pb-214 Criteria / Pass-Fail
5942389	45.0	8.00	9.00	8.00	0.6-1.66
5942389GEL	52.1	13.1	10.4	0.864	Pass
5942390	64.0	5.00	5.00	3.00	NA
5942390GEL	18.2	10.8	18.2	3.52	NA
5942391	178	23.0	23.0	17.0	0.75-1.33
5942391GEL	201	23.1	17.9	0.886	Pass
5942392	255	18.0	8.00	4.00	0.5-2.0
5942392GEL	43.4	23.9	43.4	5.88	Fail
5942228	510	33.0	9.00	33.0	0.8-1.25
5942228GEL	790	47.2	28.1	0.646	Fail
5942275	4,710	655	30.0	97.0	0.8-1.25
5942275GEL	4,770	96.2	200	0.987	Pass
5942276	4,320	373	20.0	106	0.80-1.25
5942276GEL	5,350	99.3	46.7	0.807	Pass
5942277	2,180	243	16.0	81.0	0.80-1.25
5942277GEL	2,570	61.9	135	0.848	Pass
5942278	2,160	249	28.0	72.0	0.80-1.25
5942278GEL	2,500	67.8	32.7	0.864	Pass
5942291	15,300	1,340	56.0	205	0.85-1.18
5942291GEL	18,100	173	84.4	0.845	Fail

NA = one or both results were less than the reported MDC; no comparison performed.

Table 8-8. Ra-226 Split Liquid Sample Comparison Results

Study ID	Ra-226 Result (pCi/L)	Ra-226 Error (pCi/L)	Ra-226 MDC (pCi/L)	Ra-226 Resolution / Ratio	Ra-226 Criteria / Pass-Fail
5942389	104	60.0	95.0	2.00	NA
5942389GEL	119	127	119	0.874	NA
5942390	117	40.0	63.0	2.00	NA
5942390GEL	135	117	135	0.867	NA
5942391	445	190	300	3.00	NA
5942391GEL	218	137	218	2.04	NA
5942392	453	70.0	98.0	2.00	NA
5942392GEL	221	190	221	2.05	NA
5942228	2,000	158	118	7.00	0.5-2.0
5942228GEL	1,200	324	312	1.67	Pass
5942275	8,360	1,490	533	20.0	0.75-1.33
5942275GEL	5,690	559	564	1.47	Pass
5942276	7,950	835	257	24.0	0.75-1.33
5942276GEL	6,740	560	511	1.18	Pass
5942277	3,910	698	220	18.0	0.75-1.33
5942277GEL	3,120	338	336	1.25	Pass
5942278	4,300	801	362	15.0	0.6-1.66

Table 8-8. Ra-226 Split Liquid Sample Comparison Results

Study ID	Ra-226 Result (pCi/L)	Ra-226 Error (pCi/L)	Ra-226 MDC (pCi/L)	Ra-226 Resolution / Ratio	Ra-226 Criteria / Pass-Fail
5942278GEL	3,100	410	374	1.39	Pass
5942291	25,500	3,270	713	59.0	0.8-1.18
5942291GEL	22,000	731	924	1.16	Pass

NA = one or both results were less than the reported MDC; no comparison performed.

Table 8-9. Ra-228 Split Liquid Sample Comparison Results

Study ID	Ra-228 Result (pCi/L)	Ra-228 Error (pCi/L)	Ra-228 MDC (pCi/L)	Ra-228 Resolution / Ratio	Ra-228 Criteria / Pass-Fail
5942389	94.0	15.0	14.0	8.00	0.6-1.66
5942389GEL	88.4	21.8	19.8	1.06	Pass
5942390	112	12.0	12.0	3.00	Poor Stats
5942390GEL	41.4	28.7	19.4	2.71	Fail
5942391	392	46.0	32.0	17.0	0.75-1.33
5942391GEL	434	49.0	36.2	0.903	Pass
5942392	467	36.0	13.0	21.0	0.75-1.33
5942392GEL	506	47.3	26.0	0.923	Pass
5942228	442	31.0	18.0	24.6	0.75-1.33
5942228GEL	318	54.9	40.0	1.39	Pass
5942275	571	79.0	67.0	10.0	0.6-1.66
5942275GEL	439	86.3	81.7	1.30	Pass
5942276	523	39.0	21.0	11.0	0.6-1.66
5942276GEL	561	98.9	64.2	0.932	Pass
5942277	230	25.0	22.0	9.00	0.6-1.66
5942277GEL	262	57.2	49.2	0.878	Pass
5942278	250	30.0	42.0	9.00	0.6-1.66
5942278GEL	231	52.3	55.4	1.08	Pass
5942291	1,740	164	56.0	26.0	0.75-1.33
5942291GEL	1,980	151	124	0.879	Pass

Table 8-10. Bi-214 Duplicate Sample Comparison Results

Study ID	Bi-214 Result (pCi/g)	Bi-214 Error (pCi/g)	Bi-214 MDC (pCi/g)	DER	RPD
5942107	0.089	0.013	0.012	0.860	68.2
5942107GEL	0.181	0.106	0.181		
5942111	80.9	7.37	0.076	2.91	24.0
5942111GEL	103	1.81	0.799		
5942116	0.500	0.058	0.029	1.36	36.3
5942116GEL	0.722	0.153	0.123		
5942134	6.04	0.714	0.030	0.010	0.170
5942134GEL	6.05	0.396	0.171		
5942145	0.798	0.144	0.025	0.910	25.9
5942145GEL	0.615	0.140	0.120		
5942155	3.96	0.485	0.030	0.280	4.44
5942155GEL	4.14	0.412	0.246		
5942180	0.829	0.133	0.033	0.510	13.3
5942180GEL	0.947	0.191	0.148		
5942186	51.2	4.67	0.046	1.15	10.2
5942186GEL	56.7	1.06	0.420		
5942189	457	81.2	0.567	0.270	4.70
5942189GEL	479	3.76	1.51		
5942189	2.25	0.268	0.028	0.130	2.25
5942189GEL	2.20	0.287	0.176		

Table 8-11. Pb-212 Duplicate Sample Comparison Results

Study ID	Pb-212 Result (pCi/g)	Pb-212 Error (pCi/g)	Pb-212 MDC (pCi/g)	DER	RPD
5942107	0.071	0.009	0.008	0.620	37.7
5942107GEL	0.104	0.052	0.104		
5942111	52.3	9.39	0.179	1.68	35.6
5942111GEL	36.5	0.851	0.730		
5942116	0.563	0.113	0.021	0.450	12.0
5942116GEL	0.635	0.115	0.095		
5942134	1.45	0.154	0.050	4.38	101
5942134GEL	0.475	0.161	0.165		
5942145	0.784	0.112	0.030	1.02	21.9
5942145GEL	0.629	0.103	0.085		
5942155	2.52	0.182	0.039	1.66	19.6
5942155GEL	2.07	0.200	0.193		
5942180	0.865	0.063	0.034	0.170	3.29
5942180GEL	0.837	0.151	0.133		
5942186	13.2	0.862	0.115	8.97	91.6
5942186GEL	4.91	0.334	0.351		
5942189	184	25.9	0.569	2.47	42.1
5942189GEL	120	1.62	1.37		
5942189	1.71	0.180	0.042	0.720	11.1
5942189GEL	1.53	0.175	0.156		

Table 8-12. Pb-214 Duplicate Sample Comparison Results

Study ID	Pb-214 Result (pCi/g)	Pb-214 Error (pCi/g)	Pb-214 MDC (pCi/g)	DER	RPD
5942107	0.087	0.010	0.007	3.09	123
5942107GEL	0.367	0.090	0.092		
5942111	102	6.43	0.138	2.98	17.9
5942111GEL	122	1.94	0.965		
5942116	0.581	0.125	0.021	1.00	32.0
5942116GEL	0.802	0.181	0.283		
5942134	6.50	0.561	0.037	1.88	18.2
5942134GEL	7.80	0.407	0.199		
5942145	0.827	0.110	0.030	0.310	7.40
5942145GEL	0.768	0.156	0.250		
5942155	4.46	0.305	0.036	1.24	13.2
5942155GEL	5.09	0.406	0.255		
5942180	0.859	0.068	0.032	1.32	29.8
5942180GEL	1.16	0.218	0.175		
5942186	57.4	3.64	0.081	2.89	17.5
5942186GEL	68.4	1.13	0.474		
5942189	472	61.4	0.661	2.02	23.2
5942189GEL	596	4.11	7.56		
5942189	2.43	0.212	0.031	1.15	15.6
5942189GEL	2.84	0.287	0.215		

Table 8-13. Ra-226 Duplicate Sample Comparison Results

Study ID	Ra-226 Result (pCi/g)	Ra-226 Error (pCi/g)	Ra-226 MDC (pCi/g)	DER	RPD
5942107	0.250	0.047	0.061	0.600	32.0
5942107GEL	0.181	0.106	0.181		
5942111	114	7.69	1.44	1.39	10.1
5942111GEL	103	1.81	0.799		
5942116	0.820	0.178	0.152	0.420	12.7
5942116GEL	0.722	0.153	0.123		
5942134	7.27	0.804	0.078	1.36	18.3
5942134GEL	6.05	0.396	0.171		
5942145	1.49	0.250	0.235	3.05	83.1
5942145GEL	0.615	0.140	0.120		
5942155	6.14	0.609	0.650	2.72	38.9
5942155GEL	4.14	0.412	0.246		
5942180	1.56	0.178	0.217	2.35	48.9
5942180GEL	0.947	0.191	0.148		
5942186	59.2	3.98	0.585	0.610	4.31
5942186GEL	56.7	1.06	0.420		
5942189	450	60.0	4.39	0.480	6.24
5942189GEL	479	3.76	1.51		
5942189	3.92	0.458	0.290	3.18	56.2
5942189GEL	2.20	0.287	0.176		

9.0 OBSERVATIONS AND RECOMMENDATIONS

Radiological sampling and surveys were conducted at well sites, WWTPs, landfills, gas distribution facilities and facilities that use natural gas, and O&G brine-treated roads. Various samples of solids, liquids, natural gas, and ambient air were collected and analyzed for radiological constituents and in some cases additional parameters. The data and various assessments are presented in Sections 3.0, 4.0, 5.0, 6.0, and 7.0. The following observations were made based upon the data compiled from the samples collected and surveys conducted as part of this study.

9.1 <u>Observations</u>

9.1.1 Well Sites (Section 3.0)

- *There is little potential for internal radiation exposure to workers and members of the public from α and β surface radioactivity from natural gas well site development drilling operations.*

  Ten of the 491 α measurements and 69 of the 491 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. Only 1 of 493 α removable surface activity measurements and 1 of 493 β surface radioactivity measurements exceeded RG 1.86 criteria, indicating the total α/β surface radioactivity measured is fixed to the surface and not readily available for inhalation or ingestion. (Section 3.5.2)

- *There is little potential for exceeding public dose limits from external gamma radiation during the drilling phase of natural gas wells.*

  The gamma dose rates during the drilling phase ranged from background (measured at 5 µR/hr) to a maximum of 38.5 µR/hr, and the highest average exposure rate at any of the well sites was 18.1 µR/hr. (Section 3.5.1)

- *There is little potential for additional Rn exposure to workers and members of the public during the flowback phase of unconventional natural gas wells.*

  The Rn in ambient air measurement results during the flowback phase are within the range of typical ambient background Rn concentrations (0.00 to 1.11 pCi/L in outdoor ambient air in the U.S.). (Section 3.5.3)

- *There is little potential for radiological exposure to workers and members of the public from the handling, hauling, and temporary storage of vertical drill cuttings on natural gas well sites.*

  Vertical drill cuttings contain U, average of 1.47 ± 0.881 pCi/g, and Th, average 1.64 ± 0.403, slightly above typical background in surface soil. Both the U natural decay series and the Th natural decay series are identified in equilibrium. (Table 3-6)

- *There is little potential for radiological exposure to workers and members of the public from handling, hauling, and temporary storage of horizontal drill cuttings on natural gas well sites.*

Horizontal drill cuttings contain U, average 8.40 ± 6.70 pCi/g, and Th, average 1.42 ± 0.331. The Th is slightly above typical background in surface soil. The U activity is higher than typical surface soil background U activity and statistically higher than vertical drill cuttings U activity. Both the U natural decay series and the Th natural decay series are identified in equilibrium. (Table 3-8)

- *There is little potential for radiological exposure to workers and members of the public from hydraulic fracturing proppant sand.*

  Nominal U and Th activity was identified in hydraulic fracturing proppant sand samples. The U and Th activity was less than typical background for surface soil. (Section 3.2.4)

- *There is little potential for radiological exposure to workers and members of the public from drilling mud.*

  Nominal U and Th activity was identified in liquid and solid drilling mud samples. The U and Th activity was less than typical background for surface soil. (Section 3.2.3)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of hydraulic fracturing fluid on natural gas well sites.*

  However, there is a potential for radiological environmental impacts from spills of hydraulic fracturing fluid on natural gas well sites and from spills that could occur from the transportation and delivery of this fluid.

  Radium-226 was detected within the hydraulic fracturing fluid ranging from 64.0 – 21,000 pCi/L. Radium-228 was also detected ranging from 4.50 – 1,640 pCi/L. The hydraulic fracturing fluid was made up of a combination of fresh water, produced water, and reuse flowback fluid. (Section 3.3.2)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of flowback fluid on natural gas well sites.*

  However, there is a potential for radiological environmental impacts from spills of flowback fluid on natural gas well sites and from spills that could occur from the transportation and delivery of this fluid.

  Radium-226 concentrations were detected within flowback fluid samples ranging from 551 – 25,500 pCi/L. Radium-228 was also detected ranging from 248 – 1,740 pCi/L. (Section 3.3.3)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of produced water on natural gas well sites.*

  However, there is a potential for radiological environmental impacts from spills of produced water from unconventional natural gas well sites and from spills that could occur from the transportation and delivery of this fluid.

Radium-226 concentrations were detected in produced water samples ranging from 40.5 – 26,600 pCi/L. Radium-228 concentrations were also detected ranging from 26.0 – 1,900 pCi/L. The Ra-226 activity in unconventional well site produced water is approximately 20 times greater than that observed in conventional well site produced water. The ratio of Ra-226 to Ra-228 in unconventional well site produced water is approximately eight times greater than that found in conventional well site produced water. (Sections 3.3.4 and 3.6.3)

- *There were no statistically significant differences observed between filtered and unfiltered liquid sample analytical results.*

  Because the liquid samples were preserved by addition of acid prior to filtering, the radioactive particulates may have entered solution and were therefore not removed by filtering. (Section 3.6.2)

- *The Rn concentrations in natural gas sampled at Pennsylvania well sites during this study are consistent with the Rn concentrations in natural gas reported by the U.S. Geological Survey (USGS) for Pennsylvania, which range from 1 to 79 pCi/L with an overall median of 37 pCi/L.*

  The Rn in natural gas measured ranged from 3.00 to 148 pCi/L, with a median Rn concentration of 41.8 pCi/L. (Section 3.4.2)

- *There is little potential for additional Rn exposure to workers and members of the public on or near natural gas well sites.*

  With the exception of one outlier at 1.70 pCi/L, the Rn concentrations in ambient air sampled at well sites during this study are consistent with the typical ambient background Rn concentrations of 0.00 to 1.11 pCi/L. It should be noted that the outlier is still well below the EPA guideline for indoor Rn concentration of 4 pCi/L.

9.1.2 Wastewater Treatment Plants (Section 4.0)

9.1.2.1 Publicly Owned Treatment Works

- *There is little potential for internal radiation exposure to workers and members of the public from α and β surface radioactivity at POTWs.*

  Nine of the 566 α measurements and 68 of the 566 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. One of the 286 removable α measurements and none of the 286 removable β measurements exceeded the RG 1.86 criteria. Fixed or removable α and β surface radioactivity may present a potential inhalation or ingestion hazard if disturbed in the future. (Section 4.1.6.2)
- *There is little potential for exceeding public dose limits from external gamma radiation for workers and members of the public at POTWs.*

  The highest average gamma radiation exposure rate was 36.3 μR/hr, and the maximum gamma radiation exposure rate measured was 257 μR/hr. Assuming the time period of exposure is a full occupational year of 2,000 hours, the maximum average POTW annual external gamma radiation exposure was estimated as 62.6 mrem/yr, which is less than the maximum public dose limit of 100 mrem/yr. (Sections 4.1.2.1 and 4.1.6.1)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of filter cake at POTW-I's.*

  However, there is a potential for radiological environmental impacts from spills and the long-term disposal of POTW-I filter cake.

  The filter cake analytical results for POTW-I plants show Ra-226 and Ra-228 are present above typical background concentrations in soil. The average Ra-226 result was 20.1 pCi/g with a large variance in the distribution. The maximum result was 55.6 pCi/g. The average Ra-228 result was 7.63 pCi/g, and the maximum result was 32.0 pCi/g Ra-228. (Section 4.1.2.1)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of filter cake at POTW-N's.*

  There is little potential for radiological environmental impacts from spills and the long-term disposal of POTW-N filter cake.

  The radioactivity levels at **POTW-N** plants presented in **Table 4-6** were above typical background concentrations in soil with Ra-226 average and maximum results of 9.72 pCi/g and 35.4 pCi/g. The average and maximum Ra-228 results were 2.26 pCi/g and 7.26 pCi/g. (Section 4.1.2.1)

- *There is little potential for radiological exposure to workers and members of the public from sediment-impacted soil at POTW-I's.*

  However, there is a radiological environmental impact to soil from the sediments from POTW-I's.

  The analytical results for POTW-I sediment-impacted soil samples indicate Ra-226 and Ra-228 are present at concentrations above typical background in soil. The average Ra-226 result was 9.00 pCi/g, and the maximum result was 18.2 pCi/g. The average Ra-228 result was 3.52 pCi/g, and the maximum result was 6.25 pCi/g. (Section 4.1.2.2)

- *There is little potential for additional Rn exposure to workers and the members of the public inside POTW-I's.*

  Indoor Rn results from POTW-I results ranges from 0.200 to 8.70 pCi/L. One result exceeds the EPA action level of 4 pCi/L. The Rn measured in indoor air averaged 1.74 pCi/L. The average is above the average indoor level of 1.3 pCi/L in the U.S. as reported by EPA. (Section 4.1.4)

9.1.2.2 Centralized Wastewater Treatment Plants

- *There is potential for internal radiation exposure to workers and members of the public from α and β surface radioactivity at CWTs that treat O&G wastewater. Fixed α and β surface* *radioactivity may present a potential inhalation and ingestion hazard if disturbed during routine system maintenance.*

One hundred eighty-six of the 777 α measurements and 461 of the 777 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. Seven of the 805 removable α measurements and 6 of the 805 removable β measurements exceeded the RG 1.86 criteria. The average of the β total surface radioactivity measurements exceeded the RG 1.86 criteria in 10 of the 11 CWT facilities surveyed. The average of the total α surface radioactivity measurements exceeded the RG 1.86 criteria in four of the 11 CWT facilities surveyed. The corresponding removable radioactivity measurements are mostly less than the RG 1.86 criteria, indicating the total radioactive contamination measured is fixed to the surface and not immediately available for inhalation or ingestion. (Section 4.2.6.2)

- *There is little potential for exceeding public dose limits from external gamma radiation for workers and members of the public at CWTs that treat O&G wastewater.*

  Assuming the time period of exposure is a full occupational year of 2,000 hours, and the average maximum exposure rate of 19.1 μR/hr (24.1 μR/hr less the background rate of 5 μR/hr), the maximum average CWT annual external gamma radiation exposure was estimated at 38 mrem/yr. The maximum gamma radiation exposure rate measured was 502 μR/hr on contact with the outside of a wastewater tank. (Section 4.2.6.1)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of filter cake at CWTs that treat O&G wastewater.*

  However, there is a potential for radiological environmental impacts from spills and the long-term disposal of CWT filter cake from CWTs that treat O&G wastewater.

  The analytical results indicate all the CWT filter cake samples contain elevated Ra-226 and Ra-228 above typical background levels for soil. The maximum results were 294 pCi/g of Ra-226 and 177 pCi/g of Ra-228. Five of 27 filter cake samples exceeded the DOT Ra threshold for labeling as radioactive material. (Section 4.2.2.1)

- *There is little potential for radiological exposure to workers and members of the public from sediment-impacted surface soil at CWTs that treat O&G wastewater.*

  However, there is a radiological environmental impact to soil from the sediments from CWTs that treat O&G wastewater.

  Sediment-impacted soil was collected at the accessible effluent discharge points at the CWTs. Radium above typical soil background levels to a maximum of 508 pCi/g of total Ra was identified in the sediment-impacted soil samples. (Section 4.2.7)

- *There is little potential for radiological exposure to workers and members of the public from impacted soil at CWTs that treat O&G wastewater.*

However, there is a radiological environmental impact to surface soil at CWTs that treat O&G wastewater.

Gamma radiation walkover surveys identified areas with radioactivity above local background. At three of these locations, a biased soil sample was collected to determine the amount of activity at or near the surface. Radium above soil typical background levels to a maximum of 444 pCi/g Ra-226 and 83.1 pCi/g Ra-228 was identified in biased soil samples. (Section 4.2.2.3)

- *There is little potential for additional Rn exposure to workers and the members of the public inside CWTs that treat O&G wastewater.*

  Indoor air was sampled and analyzed for Rn concentration at various CWT indoor locations such as break rooms, laboratories, offices, etc. The results ranged from 0.900 to 5.00 pCi/L. Two results exceeded the EPA action level. The Rn measured in indoor air averaged 2.0 pCi/L. The average is above the average indoor level of 1.3 pCi/L in the U.S. as reported by EPA. (Sections 4.2.4 and 4.2.6.3)

9.1.2.3 Zero Liquid Discharge Plants

- *There is potential for internal α and β surface radioactivity exposure to workers and members of the public at ZLDs that treat O&G wastewater. Fixed α and β surface radioactivity may present a potential inhalation and ingestion hazard if disturbed during future routine system maintenance.*

  One hundred fifty-nine of the 566 α measurements and 175 of the 566 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. Fourteen of the 589 removable α measurements and two of the 589 removable β measurements exceeded the RG 1.86 criteria. The highest average total α and β surface radioactivity levels were 239 dpm/100 cm^2 and 4,740 dpm/100 cm^2. The maximum total α and β surface radioactivity levels were 1,410 dpm/100 cm^2 and 49,700 dpm/100 cm^2. The corresponding removable surface radioactivity measurements are mostly less than the RG 1.86 criteria, only 14 of 589 measurements exceeded the applicable criteria, indicating the total surface radioactivity measured is fixed to the surface and not immediately available for inhalation or ingestion. Fixed α and β surface radioactivity may present a potential inhalation or ingestion hazard if disturbed during routine system maintenance. (Section 4.3.6.2)

- *There is little potential for exceeding public dose limits from external gamma radiation for workers and members of the public at ZLDs that treat O&G wastewater.*

  The maximum average gamma radiation exposure rate measured at any of the ZLD plants was 43.1 μR/hr. The lowest background gamma radiation exposure rate measured at any of the sites was 5 μR/hr. Assuming the time period of exposure is a full occupational year of 2,000 hours, the maximum average ZLD annual external gamma radiation exposure was estimated as 76 mrem/yr. The maximum gamma radiation exposure rate measured was 445 μR/hr. (Sections 4.3.1.4 and 4.3.6.1)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of filter cake at ZLDs that treat O&G wastewater.*

  However, there is a potential for radiological environmental impacts from spills and the long-term disposal of filter cake from ZLDs that treat O&G wastewater.

  Radium-226 and Ra-228 were measured in ZLD filter cake samples at concentrations above typical background levels for surface soils. Radium-226 concentrations ranged from 3.08 to 480 pCi/g and Ra-228 concentrations ranged from 0.580 to 67.3 pCi/g. (Section 4.3.2.1)

- *There is little potential for radiological exposure to workers and members of the public from influent and effluent water at ZLDs that treat O&G wastewater.*

  However, there is a potential for radiological environmental impacts from spills of influent and effluent water at ZLDs that treat O&G wastewater.

  Radium (Ra-226 and Ra-228) was routinely detected in all liquid influent and effluent sample types with an approximate 50 percent difference between influent and effluent, but little difference between filtered and unfiltered results. Results ranged from 29.0 to 20,900 pCi/L. (Section 4.3.5)

- *There is little potential for additional Rn exposure to workers and the members of the public at ZLDs that treat O&G wastewater.*

  Indoor air was sampled and analyzed for Rn concentration at various indoor locations such as break rooms, laboratories, offices, etc. The results ranged from 0.50 to 4.90 pCi/L. Two results exceeded the EPA action level. The Rn measured in indoor air averaged 2.29 pCi/L. The average is above the average indoor level of 1.3 pCi/L in the U.S. as reported by EPA. (Sections 4.3.4 and 4.3.6.3)

- *There is little potential for exceeding public dose limits from external gamma radiation for truck drivers from hauling O&G wastewater or sludge/filter cake from facilities that treated O&G wastewater.*

  It was assumed a truck driver hauled full containers with either wastewater or sludge/filter cake for four hours per day and made return trips with empty containers for four hours per day. The driver was assumed to work 40 hours per week for 10 weeks per year hauling O&G wastewater or sludge. The total estimated dose to the wastewater truck driver was 0.35 mrem/yr. The total estimated dose to the sludge truck driver was 52 mrem/yr. (Section 4.3.6.4)

9.1.3 Landfills (Section 5.0)

- *There is little potential for radiological exposure to workers and members of the public from leachate at landfills.*

- *There is little difference in the radium detected in the leachate from the nine landfills selected based on the volume of O&G industry waste accepted and from the 42 other landfills.*

Samples of leachate were collected from the nine landfills selected based on the volume of O&G industry waste received and from the 42 other landfills not selected based on the volume of O&G industry waste received and analyzed using gamma spectroscopy for Ra-226 and Ra-228. Radium was detected above the MDC value in 38 of 51 samples. Radium-226 results ranged from 36.5 to 416 pCi/L with an average of 116 pCi/L in the 42 unselected landfills and 125 pCi/L in the nine selected landfills. Radium-228 results ranged from 2.50 to 55.0 pCi/L with an average of 11.9 pCi/L in the 42 unselected landfills and 18.0 pCi/L in the nine selected landfills. (Section 5.1)

- *There is limited potential for radiological environmental impacts from spills or discharges of effluent or influent leachate at landfills that accept O&G waste for disposal.*

  Nine influent and seven effluent leachate samples were collected at the nine selected landfills. Radium was detected in all of the leachate samples. Radium-226 results ranged from 48.5 to 378 pCi/L with an average of 138 pCi/L for effluent samples and 83.4 pCi/L for influent samples. Radium-228 results ranged from 3.00 to 1,100 pCi/L with an average of 178 pCi/L for effluent samples and 7.94 pCi/L for influent samples. The influent and effluent samples from the same facility do not represent the same leachate at different times in treatment. (Section 5.2.1)

- *There is little potential for radiological exposure to workers and members of the public from handling and temporary storage of filter cake at landfills that accept O&G waste for disposal.*

  However, there is a potential for radiological environmental impacts from spills and the long-term disposal of landfill filter cake from landfills that accept O&G waste for disposal.

  Filter cake from three of the nine selected landfills was sampled and analyzed using gamma spectroscopy. Radium was detected in all of the filter cake samples. Radium-226 results ranged from 8.73 to 53.0 pCi/g, with an average of 24.3 pCi/g. Radium-228 results ranged from 1.53 to 5.03 pCi/g, with an average of 3.85 pCi/g. (Section 5.2.2)

- *There is little potential for radiological exposure to workers and members of the public from sediment-impacted soil at landfills that accepted O&G waste for disposal.*

  However, there may be a radiological environmental impact to soil from the sediments from landfill leachate treatment facilities that treat leachate from landfills that accept O&G waste for disposal.

  The three landfills that had filter cake sampled also discharged effluent water to the environment. At each of the three effluent outfalls, a sediment-impacted soil sample was collected. Radium was detected in all of the samples. Radium-226 results ranged from 2.82 to 4.46 pCi/g with an average of 3.57 pCi/g. Radium-228 results ranged from 0.979 to 2.53 pCi/g with an average of 1.65 pCi/g. (Section 5.2.3)

- *There is little potential for additional Rn exposure to workers and the members of the public at or from landfills that accept O&G waste for disposal.*

Ambient air was sampled at the fence line of each of the nine selected landfills and analyzed for Rn concentration. The Rn in ambient air at the fence line of the landfills ranged from 0.200 to 0.900 pCi/L consistent with U.S. background levels of 0.00 to 1.11 pCi/L in outdoor ambient air.

- *There is little potential for internal α and β surface radioactivity exposure to workers and members of the public at landfills that accept O&G waste for disposal.*

  None of the 195 α measurements and 17 of the 195 β measurements of total surface radioactivity exceeded the RG 1.86 criteria. All average total α and β surface radioactivity levels were below the RG 1.86 criteria. The maximum total α and β concentrations were 84.6 dpm/100 cm^2 and 3,630 dpm/100 cm^2. The average removable α and β levels at each landfill were below the RG 1.86 criteria. The maximum removable α and β levels were also below the RG 1.86 criteria. None of the 205 removable α or β surface radioactivity measurements exceeded the RG 1.86 criteria. (Section 5.4.1.1)

- *There is little potential for exceeding public dose limits from external gamma radiation for workers and members of the public at landfills that accept O&G waste for disposal.*

  The highest average exposure rate was 13.5 μR/hr, and the maximum gamma exposure rate measured was 93.7 μR/hr. The minimum, limiting local background measured was 5 μR/hr. Assuming the duration of exposure is a full occupational year of 2,000 hours, the external gamma radiation exposure at the landfill was estimated as 17 mrem/yr, which is much less than the 100 mrem/yr dose equivalent limit for a member of the public. (Sections 5.3 and 5.4.1)

9.1.4 Gas Distribution and End Use (Section 6.0)

9.1.4.1 Natural Gas in Underground Storage

- *Radon concentrations in natural gas are lower after underground storage.*

  Natural gas samples were collected at four underground storage sites in Pennsylvania. Duplicate samples were collected at each site during injection into the storage formation, and also during withdrawal from the storage formation. (Section 6.1)

9.1.4.2 Natural Gas-Fired Power Plants

- *Radon concentrations in the natural gas sampled entering power plants are consistent with the Rn in natural gas concentrations in samples collected at well sites.*

  The two natural gas sample results from natural gas-fired power plants were 33.7 ± 1.80 pCi/L and 35.7 ± 11.0 pCi/L. (Section 6.2 and Table 6.3)

- *There is little potential for exceeding public dose limits from external gamma radiation for workers and members of the public at natural gas-fired power plants.*

The gamma radiation exposure rate survey results at the PP-02 power plant were within the range of natural background of gamma radiation for PA. The exception occurred on the external surface of a pipe elbow where the range of measurement results observed was 15 to 17 µR/hr. (Section 6.2)

- *There is little potential for additional Rn exposure to workers and the members of the public at or from natural gas-fired power plants.*

  Ambient air was sampled at the PP-02 power plant site fence line. The fence line Rn monitor results were all at or below the MDC value for the analysis. (Section 6.2)

9.1.4.3 Compressor Stations

- *Radon concentrations in the natural gas sampled at compressor stations are consistent with the Rn in natural gas concentrations in samples collected at well sites.*

  All compressor stations were receiving predominately Marcellus Shale unconventional natural gas at the time of sample collection. The range of compressor station natural gas Rn results is 28.8 ± 1.40 to 58.1 ± 1.10 pCi/L, which is consistent with the production site Rn sample results. (Section 6.3 and Table 6.5)

- *There is little potential for additional Rn exposure to workers and the members of the public at or from natural gas compressor stations.*

  Ambient air was sampled at the CS-01 compressor station fence line for the measurement of Rn concentrations. The fence line Rn monitors results ranged from 0.100 to 0.800 pCi/L. The average concentration at each fence line location was within the range of typical ambient background Rn concentrations in outdoor ambient air in the U.S. (Section 6.3)

9.1.4.4 Natural Gas Processing Plant

- *Radon concentrations in natural gas entering the natural gas processing plant are consistent with levels measured at well sites.*

  Radon in natural gas sampled entering the plant measured 67.7 pCi/L. The Rn in natural gas sampled at the processing plant outflow measured 9.30 pCi/L. (Section 6.4 and Table 6.7)

- *There is potential for exceeding public dose limits from external gamma radiation for workers at the natural gas processing plant.*

  Contact readings measured with filter housings ranged from background to 75 µR/hr, with two exceptions; one measured 350 µR/hr and the other measured 900 µR/hr. Radiation exposure rates with values ranging from 20 to 400 µR/hr were measured on additional system components. (Section 6.4)

- *There is potential for internal α and β surface radioactivity exposure to workers at the natural gas processing plant when a filter housing is opened.*

The filter housing on the facility propanizer equipment was opened during a filter change-out and a sample of the cardboard filter media was collected. The filter media sample was smeared for removable α and β surface radioactivity. The average α and β surface radioactivity levels are below the RG 1.86 α and β removable surface radioactivity criterion. The results of samples collected from the facility propanizer equipment filter had a Pb-210 activity result of 3,580 pCi/g, but no other gamma-emitting NORM radionuclide results were above 1 pCi/g. The gross α and β removable surface radioactivity results for the filter media sample are elevated relative to the RG 1.86 gross α and β removable surface radioactivity criterion. (Section 6.5)

9.1.4.5 Radon Dosimetry

- *There is little potential for additional Rn exposure to members of the public in homes using natural gas from Marcellus Shale wells.*

- *The potential radiation dose received by home residents is a small fraction of the allowable general public dose limit of 100 mrem/yr.*

Radon is transported with natural gas into structures (homes, apartments, and buildings) that use natural gas for purposes such as heating and cooking. The incremental increase of potential dose from Rn-222 to occupants of a typical home from use of natural gas was conservatively estimated as 5.2 mrem/yr for the median dose and 17.8 mrem/yr for the maximum dose. Based on the Rn and natural gas data collected as part of this study and the conservative assumptions made, the incremental Rn increase in a home using natural gas appliances is estimated to be very small, and would not be detectable by commercially available Rn testing devices. The average and maximum calculated Rn concentration increase in homes were 0.04 and 0.13 pCi/L. (Section 6.6)

9.1.5 Oil and Gas Brine-Treated Roads (Section 7.0)

- *Radium activity measured in O&G brine-treated road samples is greater than typical surface soil concentrations.*

Biased surface soil samples were collected based on the audio response of the gamma scan survey instrument ratemeter on 31 of the 32 O&G brine-treated roads. When an area with elevated radioactivity was detected, surface soil samples were collected at that area. After correcting the reported Ra-226 activity by 0.882 pCi/g of natural background activity and 0.659 pCi/g of U-235 bias, 19 of 31 samples have excess Ra ranging from 0.109 to 5.42 pCi/g above natural background. (Sections 7.0 and 7.2.1)

- *Radium activity measured in reference background road samples is greater than typical surface soil concentrations. The reference background roads were selected by geographical location to O&G brine-treated roads selected for the study.*

As a point of reference and for comparison, 18 roads in the geographic vicinity of the subject roads that have not been identified as O&G brine-treated were selected for surveying, and 14 biased soil samples were collected. After correcting the reported Ra-226 activity by

0.819 pCi/g of natural background activity and 0.710 pCi/g of U-235 bias, 11 of 14 samples have excess Ra ranging from 0.0210 to 61.5 pCi/g above natural background. Three of the Ra-228 results are greater than 2.98 pCi/g, which is approximately three times natural background for the Th series. (Section 7.2.2)

- *The excess Ra measured in reference background samples is higher than for the identified O&G brine-treated roads.*

  The average excess Ra-226 for roads identified as having been brine-treated is 1.13 pCi/g compared to an average of 8.23 pCi/g on the background reference roads. One possible explanation is that all of the roads have been treated with brine. After the 32 roads had been identified as brine-treated, the reference background roads were selected by proximity to the 32 roads. (Section 7.2.2)

- *There is little potential for members of the public exceeding the public dose limit from exposure to Ra in O&G brine-treated roads.*

  To evaluate potential exposure to the public from the brine-treated roads, a source term of 1 pCi/g of Ra-226 and 0.5 pCi/g of Ra-228 was assumed within a 6-inch layer of surface material (treated road surface). The estimated total dose from 1 pCi/g of Ra-226 and 0.5 pCi/g of Ra-228 above natural background in surface soil, to a recreationist, in the year of maximum exposure (year 1) is 0.441 mrem/yr, which is below the 100 mrem/yr public exposure criteria based on assumed activity concentrations. The actual dose received is dependent upon both the excess Ra radioactivity in surface soil and the time spent exposed to the soil surface. (Section 7.3)

9.2 Recommendations for Future Actions

9.2.1 Well Sites

- Conduct research and investigation of vertical and horizontal drill cuttings for beneficial use, onsite disposal, and future landfill disposal protocols.

- Add sampling and analyses for Ra-226, Ra-228, and additional man-made radionuclides such as tracers used in the O&G industry to Pennsylvania spill response protocol for spills of flowback fluid, hydraulic fracturing fluid, or produced water. Field survey instrumentation should also be available for surveys of areas impacted by the spill.

9.2.2 Wastewater Treatment Plants

- Perform routine survey and assessment of areas impacted with surface radioactivity to determine personnel protective equipment (PPE) use and monitoring during future activity that may cause surface α and β radioactivity to become airborne.

- Conduct additional radiological sampling and analyses and radiological surveys at all WWTPs accepting wastewater from O&G operations to determine if there are areas of contamination that require remediation; if it is necessary to establish radiological effluent discharge limitations; and if the development and implementation of a spill policy is necessary.

9.2.3 Landfills

- Evaluate and, if necessary, modify the landfill disposal protocol for sludges/filter cakes and other solid waste-containing TENORM.

- Conduct additional radiological sampling and analyses and radiological surveys at all facilities that treat leachate from landfills that accept waste from O&G operations to determine if there are areas of contamination that require remediation; if it is necessary to establish radiological effluent discharge limitations; and if the development and implementation of a spill policy is necessary.

- Add total Ra (Ra-226 and Ra-228) to the annual suite of contaminants of concern in leachate sample analyses.

9.2.4 Gas Distribution and End Use

- Survey and sample internal surfaces of natural gas plant piping and filter housings for radiological contamination. This effort should include evaluation of worker exposure and buildup of radioactivity in systems from natural gas processing and transmission. Evaluate monitoring and recommendation of PPE and other controls to be used during pipe clean-out and other activities when internal surfaces are exposed.

9.2.5 Oil and Gas Brine-Treated Roads

- Perform further study of O&G brine-treated roads. This study should evaluate produced water radionuclide concentrations prior to treatment, resultant surface activity and radionuclide concentration of road surfaces and future Ra migration.

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