DEVELOPMENT OF TENORM RULES FOR THE STATE OF MONTANA

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ACRONYMS AND ABBREVIATIONS

AEA	Atomic Energy Act and Amendments
ALARA	As Low As Reasonably Achievable
ANSI	American National Standards Institute
ANL	Argonne National Laboratory
ASTSWMO	Association of State and Territorial Solid Waste Management Officials
Bq	Becquerel
Bq/kg	Becquerel per kilogram
CDPHE	Colorado Department of Public Health and Environment
CFR	Code of FeAcronderal Regulations
Ci	Curie
COGCC	Colorado Oil and Gas Conservation Commission
CRCPD	Conference of Radiation Control Program Directors
DEQ	Montana Department of Environmental Quality
DOT	U.S. Department of Transportation
E&P	Exploration and production
EPA	U.S. Environmental Protection Agency
GPS	Global positioning system
IAEA	International Atomic Energy Agency
K-40	Radioactive isotope of potassium
MEI	Maximally exposed individual
mrem	Millirem
mrem/y	Millirem per year
mSv	Millisieverts
NARM	Naturally-Occurring and Accelerator-Produced Radioactive Materials
NAS	National Academy of Sciences
NCRP	National Council on Radiation Protection and Measurements
NDDH	North Dakota Department of Health
NORM	Naturally Occurring Radioactive Material
PaDEP	Pennsylvania Department of Environmental Protection
pCi	Trillionths of a Ci
pCi/g	Picocuries per gram
PPE	Personal protective equipment
ppm	Parts per million
RSP	Radiation safety program

SSRCR	Suggested State Regulations for Control of Radiation
TEDE	Total effective dose equivalent
TENORM	Technologically Enhanced Naturally Occurring Radioactive Materials
Tetra Tech	Tetra Tech Inc.
µCi	Millionths of a Ci
µR/hr	Microroentgens per hour
U.S.C.	United States Code
USNRC (NRC)	U.S. Nuclear Regulatory Commission

1.0 PURPOSE

The Montana Department of Environmental Quality (DEQ) requested technical expertise from Tetra Tech Inc. (Tetra Tech) to assist and provide guidance in developing rules regarding disposal of technologically enhanced radioactive material (TENORM) within the State of Montana. The primary objective in development of these TENORM regulations is to ensure that they are specifically tailored to Montana and are protective of human health and the environment. Services for this technical expertise request are provided via this report under Task Order No. 50 and DEQ Contract No. 414038-T050.

1.1 INTRODUCTION

Naturally Occurring Radioactive Material (NORM) includes radionuclides that are present in the earth's crust, primarily uranium and its decay products, thorium and its decay products, and an isotope of potassium (K-40). In addition, radioactive isotopes of carbon and hydrogen result from interaction of stable isotopes with cosmic radiation; these are called cosmogenic naturally occurring radionuclides.

The average concentrations of uranium and thorium in the earth's crust are 2.8 parts per million (ppm) uranium and 10.7 ppm thorium. The average concentration of potassium in the earth's crust is 2.8 percent (National Council on Radiation Protection and Measurements [NCRP] 1992). K-40 constitutes approximately 0.012 percent of potassium. The concentrations of NORM in earthen materials vary significantly, depending on the type of mineral and the region. Historically, many uranium deposits were discovered as outcrops with significantly elevated concentrations. Materials that are derived from the earth's crust are potentially radioactive. Natural chemical processes as well as anthropogenic activities can concentrate radionuclides in materials brought to the surface during oil and gas exploration and production. Naturally occurring radionuclides may also be brought to the surface through mining (such as uranium and rare earth mineral recovery) or processing (for example, phosphate fertilizer production).

TENORM is defined as "naturally occurring radioactive material whose radionuclide concentrations are increased by, or as a result of, past or present human practices." TENORM does not include source material and byproduct material, as both are defined in the Atomic Energy Act (AEA) of 1954, as amended [42 United States Code [U.S.C.] 2011 et seq.], and relevant regulations implemented by the United States Nuclear Regulatory Commission (Argonne National Laboratory [ANL] 2014).

Sources of solid waste-bearing TENORM include:

- Mining residues such as waste rock (overburden) and residues from processing ore other than for uranium and thorium[1].
- Coal ash
- Oil and gas production wastes
- Wastewater treatment sludges
- Drinking water treatment wastes
- Fertilizer production waste

[1] Residues from the processing of ores for their uranium or thorium content are covered under the Atomic Energy Act.

Uranium, thorium, and their decay products in wastes pose a potential for human and ecological exposure to radiation. These materials must be managed to minimize the radiological risk to workers and members of the public.

The following section provides a detailed Scope of Work as presented to Tetra Tech by the DEQ. This report summarizes the results of the technical evaluation to satisfy this Scope of Work and objectives identified by the DEQ in October 2016.

1.2 Scope of Work

This report addresses potential radiation exposures posed by disposal in Montana landfills of TENORM, including oil and gas exploration and production (E&P) wastes. It suggests a regulatory scheme to minimize radiation doses to workers and members of the public. The following items are included in this Scope of Work:

- Provide a summary of scientific research regarding regulation of TENORM.
- Summarize the rationale other states used for determining TENORM regulatory standards.
- Summarize elements of the Argonne National Laboratory study that may be relevant to development of Montana waste management regulations.
- Evaluate and communicate advantages and disadvantages of utilizing prescribed TENORM value thresholds and how they are protective of human health and the environment.
- Evaluate and communicate advantages and disadvantages of utilizing site specific (risk-based) TENORM thresholds and how they are protective of human health and the environment.
- Advise DEQ on appropriate TENORM acceptance criteria and daily and intermediate cover requirements.
- Evaluate and report whether 270 picocuries (the (U.S. Nuclear Regulatory Commission [NRC] threshold for transport, labeling, placarding, and spills) or another threshold, is reasonable and environmentally protective for landfilling TENORM in Montana.
- Provide options for regulations that guide management of spikes or "hot spots" in loads received by the permitted facilities or hot spot areas in landfills.
- Describe options for the facility operator to accurately measure radioactivity at a landfill to determine cumulative concentrations and exposure.
- Provide copies of all research materials as an appendix to the draft and final TENORM Findings Report.
- Incorporate all DEQ comments on the draft report into the final report.

1.3 Background on TENORM

Uranium (^{238}U, ^{235}U) and thorium (^{232}Th) are primordial naturally-occurring radionuclides. They have been present in the earth's crust since its formation. They are each the parent nuclide in a decay series that includes other radionuclides. The ^{238}U decay series includes longer lived radionuclides ^{234}U, ^{230}Th, and ^{226}Ra, as well as radon (^{222}Rn) and its short-lived decay products. ^{235}U constitutes only 0.72 percent by weight of natural uranium. The ^{232}Th decay series includes ^{228}Ra and ^{228}Th as well as ^{220}Rn and its short-lived progeny. Decay schemes for primordial radionuclides are shown in Figures 1 and 2.

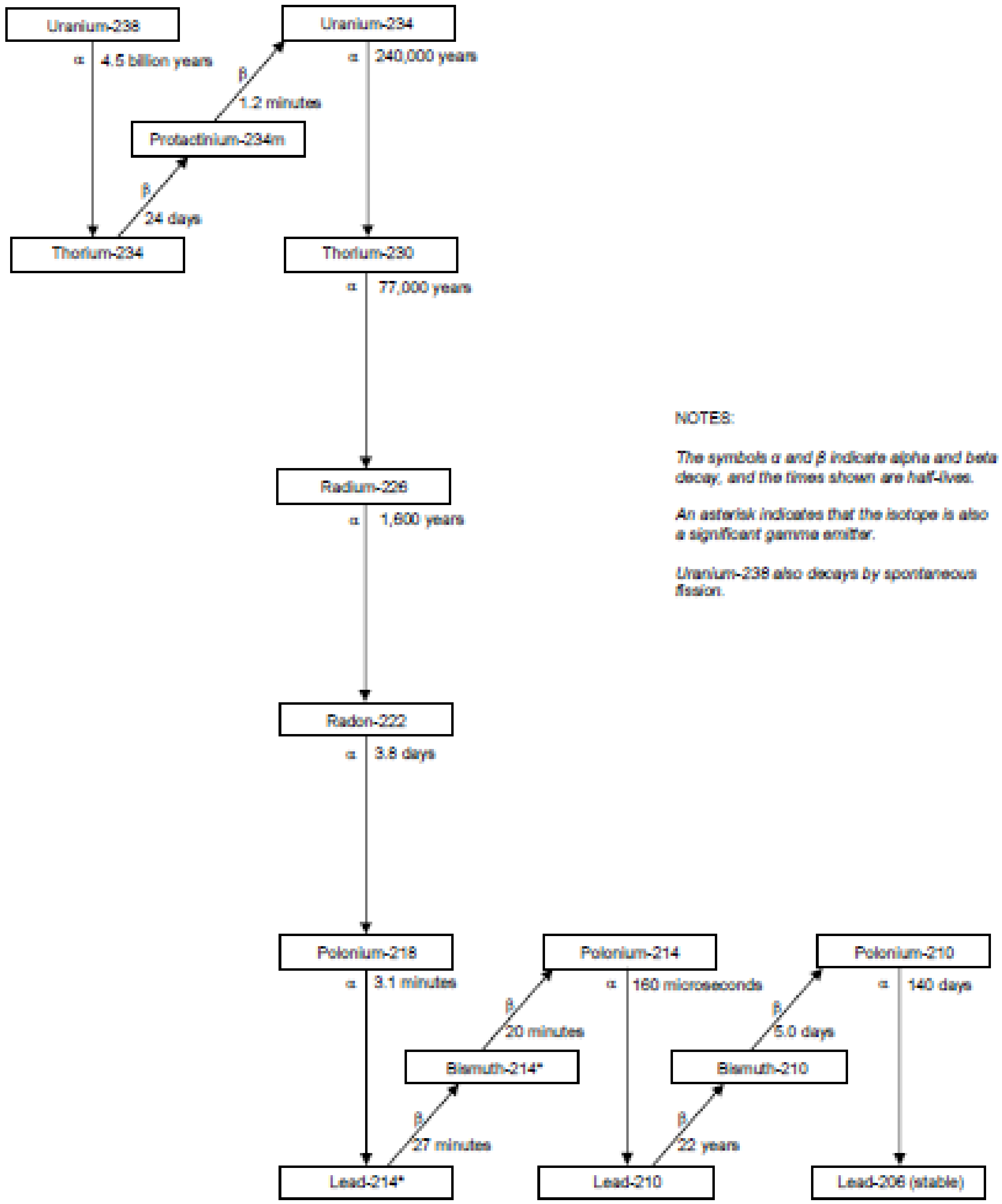

Figure 1 Natural Decay Series of Uranium-238 [Taken from Argonne (2014)]

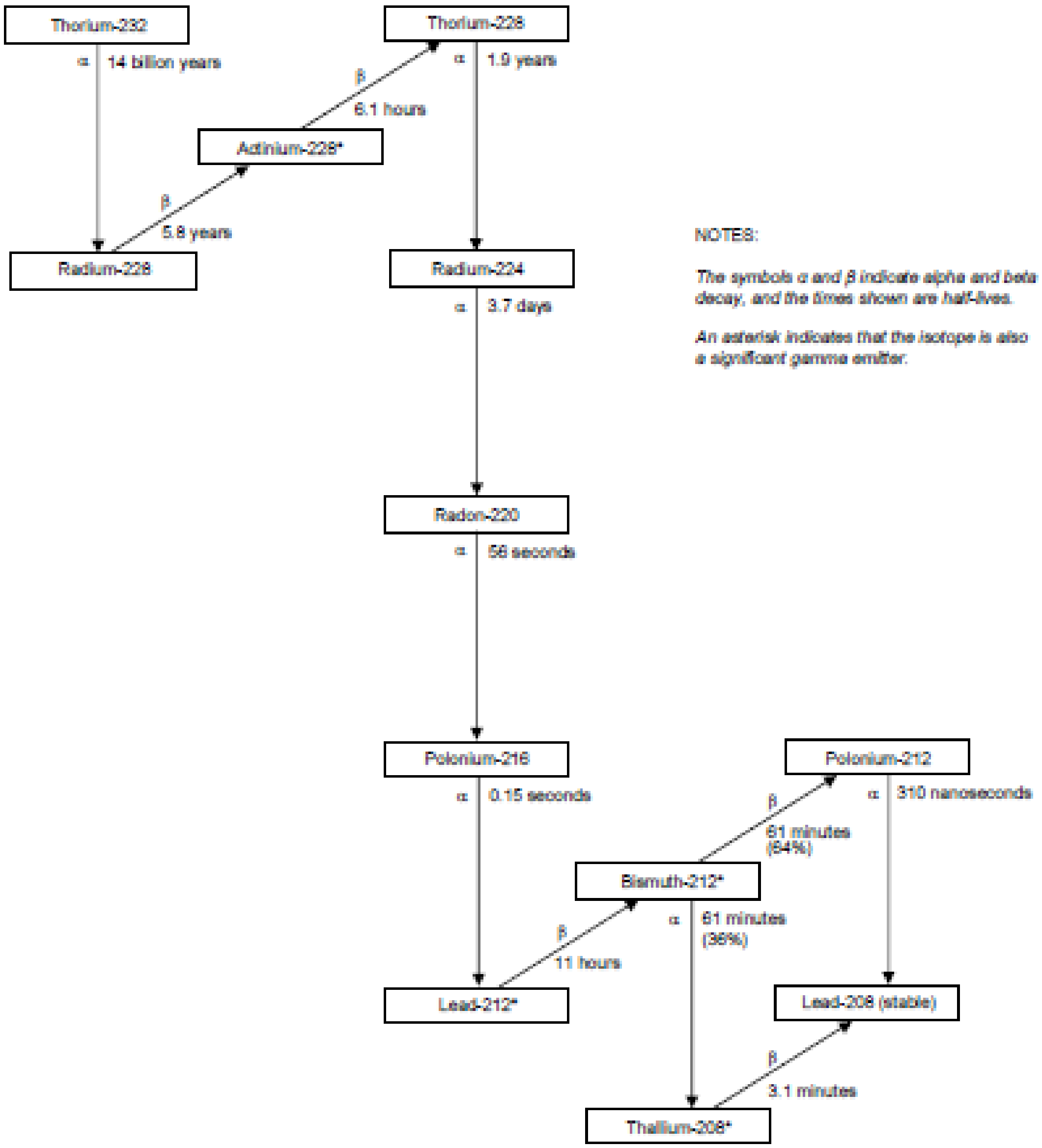

Figure 2 Natural Decay Series of Thorium-232 [Taken from Argonne (2014)]

1.3.1 *Terminology and Natural Background Radiation Levels*

The amount of radioactivity in a material is expressed in terms of the becquerel (Bq), or more commonly in the United States, the curie (Ci). The Ci is a very large amount of radioactivity, so when natural radioactivity is of concern, the activity is usually expressed in terms of millionths of a Ci (µCi) or trillionths of a Ci (pCi). The activity concentration in TENORM is expressed as becquerels per kilogram (Bq/kg) or picocuries per gram (pCi/g). The average background activity concentrations in soil are approximately 0.9 pCi/g ^{238}U and 1.2 pCi/g ^{232}Th (NCRP 1992).[2] The average background activity concentrations of ^{238}U and ^{232}Th in natural soils in the U. S. are 0.9 pCi/g and 1.2 pCi/g, respectively (NCRP 1992). If the decay chains are in equilibrium, the ^{226}Ra and 228Ra activity concentrations would the same as the ^{238}U and ^{232}Th activity concentrations. The NCRP (1992) document does not provide numerical values for ^{226}Ra and 228Ra average activity concentrations.

Radiation doses to humans are generally expressed in terms of millisieverts (mSv), or more commonly in the U.S., in millirem (mrem)[3]. The dose unit represents the amount of energy absorbed in human tissue, the distribution of the energy, and the sensitivity of the whole body or individual organs to radiation. The dose in rem indicates the potential long-term human health risk. Radiation doses to individuals in the U.S. from natural background radiation range from approximately 200 mrem per year (mrem/y) to more than 1,000 mrem/y in high background locations primarily in the Rocky Mountain region. The average background radiation dose in the United States is approximately 311 mrem/y (NCRP, 2009). Estimated natural background doses by source are given in Table 1.

Table 1 Annual Average Natural Background Radiation Doses in the U.S. and Montana

Source	Average U.S. Background (mrem/y) (NCRP, 2009)	Estimated Average Montana Background (mrem/y)
Cosmic Radiation (radiation from outer space)	33	45[4]
Terrestrial Radiation (radiation from the earth's crust)	21	50[5]
Internal Radiation (from ingestion or inhalation)	29	29
Indoor radon	228	1,000[6] (indoor radon dose is highly variable and ranges from 200 to over 1,000 mrem/y, depending on location and specific residence characteristics)
Total	310	1,124

[2] *The internationally accepted units for radioactivity and radiation dose (Bq and Sv) are most often quoted in references; however, this report will use the common units (Ci and rem).*
[3] *One mSv is equal to 100 mrem; one Bq is equal to 27 pCi.*
[4] *Estimated from American Nuclear Society dose calculator based on average elevation of 4,500 ft. (www.ans.org/pi/resources/dosechart, accessed 10/27/16)*
[5] *Estimated from NCRP (2009) map of annual average terrestrial radiation doses*
[6] *Calculated based on estimated average screening level radon concentration in Montana homes of 5.9 pCi/L (www.mt-radon.info/MT_general.html, accessed 10/27/16)*

Note: TENORM facilities are not licensed by the Nuclear Regulatory Commission (NRC); they are regulated by each state. For comparison, the remainder of this paragraph briefly discusses the rules that apply to NRC-licensed or agreement state-licensed facilities (such as nuclear power plants and uranium mills): The maximum allowable radiation dose to a radiation worker at a nuclear power plant or other facility licensed by the NRC is 5,000 mrem/y excluding background and medical radiation doses. The maximum allowable radiation dose to a member of the public from an operation licensed by the NRC (or an Agreement State[7]) is 100 mrem/y, excluding background and medical radiation doses. Radiation doses are to be kept As Low As Reasonably Achievable (ALARA) below the regulatory dose limits.

1.3.2 Radium Concentrations in TENORM

TENORM concentrations in waste produced in mining (for example, waste rock, overburden and protore), phosphate fertilizer production and in coal ash range from near background to several hundred pCi/g. Activity concentrations in oil and gas production TENORM wastes range from near background to thousands of pCi/g (found in pipe scale). The ranges of ^{226}Ra concentrations in various sources of TENORM are given in Table 2 (EPA, 2000):

Table 2 Range of ^{226}Ra Concentrations by TENORM Source

TENORM Material	Units	Range of ^{226}Ra Concentrations		
		Low	Average	High
Soils of the United States	pCi/g	0.2	1.1	4.2
Uranium Mining Overburden	pCi/g	3	3.0	Low hundreds
Uranium In-Situ Leach Evaporation Pond Solids	pCi/g	300	-	3,000
Phosphate Ore (Florida) Phosphogypsum Phosphate Fertilizer	pCi/g	7	17.3-39.5 11.7-24.5 5.7	6.2-53.5 36.7 21
Coal Ash – Bottom Ash Fly Ash	pCi/g	1.6 2	3.5-4.6 5.8	7.7 9.7
Petroleum (oil and gas) Produced water Pipe/Tank Scale	 pCi/L pCi/g	 0.1 <0.25	 <200	 9,000 >100,000
Water Treatment Sludge Treatment Plant Filters	pCi/L pCi/g	1.3 -	11 40,000	11,686 -
Rare Earths Monazite Xenotime Bastnasite	pCi/g	5.7	-	3,244
Titanium Ores Rutile Ilmenite Wastes	pCi/g	3.9	8.0 19.7 5.7 12	24.5
Zircon Wastes	pCi/g	- 87	68 -	- 1300
Aluminum (Bauxite) Ores Product Wastes	pCi/g	4.4 - -	- 0.23 3.9-5.6	7.4 - -
Geothermal Energy Waste Scales	pCi/g	10	132	254

[7] *Agreement States have established an agreement with the NRC to regulate the use and possession of radioactive materials within their states.*

Average activity concentrations in oil and gas and E&P wastes in North Dakota, as reported in the Argonne study on TENORM in North Dakota (ANL 2014), are given in Table 3. Uranium concentrations in the waste, and NORM concentrations in drill cuttings, were not reported in the North Dakota study.

Table 3 Average Activity Concentrations in Oil and Gas E&P Wastes (ANL 2014)

Type of Waste	Average Activity Concentration (pCi/g)				
	^{210}Pb	^{232}Th	^{226}Ra	^{228}Ra	^{228}Ra+^{226}Ra
Scale	5,270	71.7	548	332	880
Sludge/Filter Cake	67.2	17.2	58.3	15.4	73.7
Filter Sock	36.9	12.7	32.8	13.8	46.6
Proppant	8.5	9.1	8.2	9.9	18.1

Proppant is a natural material used in fracturing that may contain low levels of NORM.

The Pennsylvania Department of Environmental Protection (PaDEP) commissioned a study by PermaFix to collect data on Oil and Gas TENORM in Pennsylvania (PaDEP 2016). The report includes the results of radiological analyses of solid oil and gas E&P wastes including drill cuttings, drilling solids (muds), proppant sand, flowback solids (sand), and "selected landfill solids" including filter cake and sediments. The TENORM concentrations are summarized in Table 4. The concentrations varied significantly by geologic formation.

Table 4 TENORM Concentrations in Oil and Gas Production Waste Solids (PaDEP 2016)

Type of Material	Average Radionuclide Concentrations (pCi/g)[1]				
	^{238}U	^{232}Th	^{226}Ra	^{228}Ra	^{226}Ra + ^{228}Ra
Vertical Solids (drill cuttings)	0.96 (1.64)[2]	1.01 (1.47)[2]	2.82	1.01	3.83
Horizontal Solids (drill cuttings)	1.76 (8.40)[2]	0.615 (1.42)[2]	5.22	0.627	5.85
Drilling solids (muds)	0.651	0.243	2.18	0.236	2.42
Proppant sand	0.157	0.046	0.243	0.044	0.287
Flowback solids (sand)	0.542	0.437	3.46	0.444	3.90
Sediments	0.675	1.62	3.57	1.65	5.22
Filter Cake	No data	No data	24.3	3.85	28.2

[1]pCi/g = picocuries per gram
[2]Reported value based on x-ray fluorescence analysis.

Typical drill cuttings tend to have NORM concentrations in the range of background, with horizontal cuttings showing slightly higher levels than vertical cuttings. Drill cuttings with NORM concentrations exceeding surface background levels are, by definition, TENORM because the materials have been brought to the surface, where they are accessible to humans. Analysis of drill cuttings in the Greater Wattenberg Field in Weld County, Colorado, indicated NORM concentrations in the range of background, similar to the Pennsylvania measured concentrations (COGCC 2014).

The Pennsylvania study reported TENORM concentrations in liquids including landfill leachate. The results of their analyses are discussed in Section 3. Liquid oil and gas production wastes are generally disposed of in deep wells, or applied to land surfaces for beneficial use such as dust suppression.

2.0 STATE TENORM REGULATIONS

Under the Atomic Energy Act and Amendments (AEA) (42 USC 2011 et seq.) the NRC does not have jurisdiction over NORM or TENORM unless it qualifies as source material — natural uranium or thorium at concentrations greater than 0.05 percent by weight. For natural uranium at 0.05 percent by weight, the activity concentration of ^{238}U and each of its decay products is 165 pCi/g; for natural thorium at 0.05 percent by weight, the activity concentration of ^{232}Th and its decay products is 55 pCi/g. Note that, given the variety of possible TENORM materials and processing histories, it is not, in general, possible to accurately infer a material's radium activity concentrations from the $^{238}U/^{232}Th$ activity concentrations. However, depending on the type and origin of the material, the radium activity concentrations may well be about the same as their respective $^{238}U/^{232}Th$ values. As a first approximation during field work, we do often assume that the radium values are likely to be similar to the $^{238}U/^{232}Th$ values. Laboratory analysis is then used to determine the actual values. There are several exceptions to this rule, including what the NRC considers "unimportant quantities" (10 Code of Federal Regulations [CFR] 40.13). There is also a special exemption for rare earth products that contain NORM; rare earth materials with NORM concentrations less than 0.250 percent by weight are exempt from regulation under 10 CFR 20 or 10 CFR 40 (10 CFR 40.13(c)(1)). Amendments to the AEA include some forms of NORM such as uranium and thorium processing wastes (11e.(2)) and discrete NORM (11e.(3), 11e.(4)). Transportation of NORM is regulated by the Department of Transportation under 49 CFR 171-173 regardless of the applicability of the AEA. It is up to the states to regulate most NORM that does not qualify as source material or 11e.(2), (3), or (4).

2.1 AGREEMENT STATES AND NON-AGREEMENT STATES

Use and possession of radioactive materials that fall under the purview of the AEA are regulated by the NRC or an agreement state. As noted previously, certain states have established agreements with the NRC such that they are permitted to regulate all or, in some cases, a portion of, the AEA radioactive materials. Currently, 37 states, including North Dakota, are Agreement States and have promulgated regulations that are at least as restrictive as the NRC regulations in Chapter 10 of the CFR. Wyoming is not an Agreement State, but has submitted a letter of intent to the NRC to become one. Montana, South Dakota, and Idaho are not Agreement States, so use and possession of applicable radioactive materials are under the jurisdiction of the NRC. TENORM is not regulated by the NRC; thus, the states have jurisdiction and the responsibility for promulgating regulations that are protective of public health and the environment.

2.2 CONFERENCE OF RADIATION CONTROL PROGRAM DIRECTORS AND TERRITORIAL SOLID WASTE MANAGEMENT OFFICIALS

The Conference of Radiation Control Program Directors (CRCPD) is a non-profit, non-governmental organization "dedicated to radiation protection." The membership is made up primarily of state and local government radiation protection professionals, but is open to others with an interest in radiation protection. CRCPD has developed suggested state regulations for management of TENORM: Regulation and Licensing of TENORM Suggested State Regulations for Control of Regulation (SSRCR), Volume 1, Part N (CRCPD 2004). The document covers issues concerning possessing, using, processing, manufacturing, distributing, transferring and disposing of TENORM, and discusses licensing of TENORM uses.

Part N exempts concentrations of radium of 5 pCi/g or less, and certain uses of TENORM, including disposal of zircon sands and water treatment sludges that are land-applied, as long as the concentration is less than 10 pCi/g total radium before application. Other exemptions are applied for specific uses of TENORM. Otherwise, Part N addresses licensing and financial assurance mechanisms.

The CRCPD recommendations for protection of the public from radiation associated with TENORM are essentially the same as for other radioactive materials. For example, CRCPD recommends 1 mSv per year (100 mrem/y) maximum dose for members of the public. The recommendation for sites to be released for unrestricted use is based on a combination of the 25 mrem/y dose limit and a limit on radium concentrations in soil. A Sum of Fractions approach is taken with regard to determining whether a site meets the criteria. That is, the estimated dose divided by 25 mrem/y, plus the radium concentration divided by 5 pCi/g, must not exceed 1.0. The doses and radium concentrations are specified to be above-background values.

The 2015 E-42 Task Force Report, "Review of TENORM in the oil and gas industry" (CRCPD 2015), attempts to estimate "the potential environmental impact from the management and disposal of wastes from unconventional oil and gas recovery operations." Industry data, along with common disposal scenarios for TENORM materials, were used in RESRAD computer code (ANL) analyses to estimate doses.

The recommendations in the E-42 report include the following:

- Reconsider the CRCPD definition of TENORM and review Part N to ensure that byproduct material regulated by the NRC is excluded from the definition.
- Review the current criteria for acceptance found in Part N.
- Require quantification of ^{210}Pb, ^{210}Po and radon, and implementation of necessary worker protection standards.
- Require appropriate training for oil and gas TENORM workers.
- Incorporate TENORM assessment into oil and gas permitting.
- Amend existing processes for permitting oil and gas operations to include an assessment of TENORM. Areas of concern are land application of solids and discharge of liquid effluents containing TENORM with the potential for buildup of radon.

The Association of State and Territorial Solid Waste Management Officials (ASTSWMO) issued a guidance report for solid waste managers in 2011 (ASTSWMO 2011). The report provides a summary of sources of TENORM and guidelines for TENORM disposal. American National Standards Institute (ANSI) N13.53 recommends maximum allowable doses from TENORM disposal, which are 100 mrem/y above background from all pathways and sources of radiation associated with facility operations and an annual dose rate of 25 mrem/y above background from residual radioactivity (except radon and its short-lived decay products) from remediated land and facilities that have been released for unrestricted use. The ASTSWMO report recommends facility controls including:

- Restricting TENORM to 1 percent to 10 percent of the volume in a cell.
- Immediate coverage of the material.
- Appropriate training of workers.
- Dust control.
- Liner and leachate collection and recovery system.
- Leachate sampling.

- Groundwater monitoring.
- Institutional controls after closure.

2.3 North Dakota TENORM Landfill Regulations

The State of North Dakota tasked ANL with developing a rationale and specific provisions for state regulation of oil and gas NORM in landfills (ANL 2014). The ANL report is summarized in Section 3.5. The final North Dakota TENORM landfill regulations, promulgated in 2015, include a maximum average concentration limit of 50 pCi/g total radium, and an annual volume limit of 10 percent of all material accepted at the landfill (up to 25,000 tons of material in any year and 3,000 tons in any month, unless larger amounts from special cleanup projects are pre-approved by the State). *(Note: North Dakota excludes drill cuttings, frack sands and mud from its definition of TENORM; they constitute a large fraction of E&P wastes. Since the State of Montana includes all of these materials in its own definition of TENORM, the volume limits in the North Dakota regulations are not directly relevant to discussions of Montana's regulations.)* TENORM must be covered daily by a minimum of 1 foot of non-TENORM material. Other requirements include the depth of final landfill cover, leachate collection systems, and reporting. The regulation requires compliance with North Dakota radiation protection standards 33-10-04.2 and 33-10-10.1, which adopt by reference 10 CFR 20 dose limits. Previous North Dakota regulations applicable to TENORM limited the concentration in landfills to 5 pCi/g ^{226}Ra+^{228}Ra.

2.4 Other States with TENORM Regulations

State NORM regulations and policies, where they formally exist, are variable with regard to dose limits and acceptance criteria for landfills. Current state regulations pertaining to Naturally Occurring and Accelerator Produced Radioactive Materials (NARM) and TENORM are summarized in a document produced by the ASTSWMO Radiation Focus Group, issued in December 2014 (ASTSWMO 2014). The CRCPD E-42 Task Force Report provides a detailed list of existing state regulations (CRCPD, 2015).

2.4.1 Existing Montana Requirements for Solid Waste Management

The Montana DEQ revised its Solid Waste Program requirements in 2015 to address oil and gas resource development (DEQ 2015). Exempted and nonhazardous E&P wastes are regulated as Special Wastes, solid wastes that have unique handling, transportation, or disposal requirements, to ensure protection of the public health, safety, and welfare, and the environment. The regulation requires collection of characterization samples at a rate of at least one composite sample per 200 cubic yards of material. The waste must be analyzed for ^{226}Ra, ^{228}Ra, and ^{210}Pb. Additionally, processed waste must be analyzed for ^{232}Th and ^{210}Po. Radiological disposal criteria for TENORM are summarized in Table 5.

Table 5 TENORM Waste Management/Disposal Criteria

Landfill Design Requirements	E&P Radionuclide Concentration Limits
Leachate collection and removal system and synthetic liner	^{226}Ra/^{228}Ra less than or equal to 50 pCi/g[1]
No leachate collection system and engineered clay or synthetic liner	^{226}Ra/^{228}Ra less than or equal to 15 pCi/g
Natural clay liner	^{226}Ra/^{228}Ra less than or equal to 15 pCi/g

[1]pCi/g = picocuries per gram

2.4.2 Colorado TENORM Policy

Colorado regulates the use and possession of radioactive materials under an agreement with the NRC, so that Colorado is an "agreement state." The Colorado Department of Public Health and Environment (CDPHE) has developed a draft TENORM Policy and Guidance document that addresses requirements for management of TENORM (CDPHE 2014). As noted previously, most TENORM is not covered under the AEA and its amendments. Therefore, the states are responsible for developing regulations to protect the public. States regulate radium, the primary radioactive component in TENORM sources. The policy and guidance in Colorado is not regulation, but is intended to "provide the department's position on a threshold which provides reasonable protection to members of the public from the hazards associated with the handling and disposition of these materials (TENORM)…" Radioactive materials are not permitted in Colorado solid waste facilities by statute and regulation. The TENORM policy grants relief from that prohibition and allows special approval for certain operations (Grice 2016).

The basis for state authority to regulate TENORM is in the Colorado Radiation Control Act, which gives the state authority over all forms of radioactivity. The CDPHE policy states that materials with combined $^{226}Ra/^{228}Ra$ concentrations less than 3 pCi/g above background, natural uranium activity concentrations no greater than 30 pCi/g, and natural thorium concentrations no greater than 3 pCi/g, may be managed "without consideration of the radioactive constituents". Materials that require a radioactive materials license include those with $^{226}Ra/^{228}Ra$ concentrations in excess of 50 pCi/g, or natural uranium and natural thorium at 0.05 percent by weight (339 pCi/g for natural uranium and 55 pCi/g for natural thorium). TENORM with concentrations less than 50 pCi/g but greater than 3 pCi/g are managed in accordance with the CDPHE policy.

The Colorado policy limits the dose to any member of the public from unlicensed facilities involving TENORM to 25 mrem/y above background, including the dose from radon decay products. While the NRC does not have jurisdiction over radium and source material with uranium and thorium concentrations equal to or less than 0.05 percent, agreement states such as Colorado and North Dakota are permitted to regulate any level of radium and to require licensing. As noted above, Colorado facilities accepting TENORM with $^{226}Ra/^{228}Ra$ at concentrations greater than 50 pCi/g are required to have a license. The Colorado radiation control regulations limit the dose to members of the public from licensed facilities to 100 mrem/y. Before license termination and release for unrestricted use, licensed facilities must meet a dose limit of 25 mrem/y consistent with the NRC decommissioning dose limit (10CFR20.1402). The NRC, with jurisdiction over non-agreement states such as Montana, does not regulate TENORM at levels less than 0.05 percent uranium and thorium. However, non-agreement states are not precluded from promulgating rules regarding TENORM under state regulations and statutes.

3.0 RELEVANT SCIENTIFIC STUDIES

This section:

- Provides a summary of scientific research regarding the regulation of TENORM.
- Summarizes the rationale other states used for establishing TENORM regulatory standards.
- Summarizes elements of the Argonne study that may be relevant to the development of Montana waste management regulations.

3.1 OVERVIEW AND HISTORY

The U. S. Environmental Protection Agency (EPA) has made efforts in the past to provide a technological basis for regulation of TENORM. The National Academy of Sciences (NAS) was tasked to investigate and report on the scientific and technical basis for differences between the EPA and other organizations with regard to NORM (NAS 1999). The EPA reported to Congress in June 2000 with regard to the NAS findings (EPA 2000). That report is attached.

While EPA has not promulgated specific TENORM regulations, other EPA regulations such as the Clean Air Act address NORM issues. In effect, it is left to the states to develop specific TENORM policies and regulations for disposal of TENORM wastes.

3.2 U.S. STUDIES

Two detailed studies specifically related to oil and gas production wastes have been conducted in the past few years: one in North Dakota authored by ANL scientists, and one in Pennsylvania conducted by PaDEP. Several other studies have assessed soil radionuclide concentrations in oil and gas production waste.

3.2.1 Pennsylvania Department of Environmental Protection Study

PaDEP (in consultation with Perma-Fix) conducted a study to gather data on TENORM generated by the oil and gas industry in the state (PaDEP 2016). The purpose of the study was to collect the information necessary "to effectively manage TENORM from oil and gas (O&G) operations for environmental and health protection." The study covered all aspects of exploration and development including issues related to landfill disposal of wastes generated by the industry. While the PaDEP report is comprehensive, this summary addresses only the landfill disposal aspects as they could apply to the State of Montana. The Marcellus shale formation that underlies the State of Pennsylvania is not completely comparable to the Bakkan that underlies North Dakota and Montana; however, certain lessons learned from the PaDEP study are applicable.

The conclusions and recommendations from the 2-year study related specifically to disposal of E&P wastes are as follows:

- There is little potential for radiation exposure to workers and the public from landfills receiving waste from the oil and gas industry.

- There is limited potential for radiation exposure from roads treated with brine from conventional natural gas wells, but there should be further study of radiological environmental impacts from the use of brine for dust suppression and road stabilization.

The PaDEP study (2016) collected data from existing landfills including all Pennsylvania landfills, nine other landfills that accepted the largest amounts of TENORM, and other large-volume TENORM-containing waste disposal sites. Radiation measurements were reported for:

- Offices and other occupied spaces
- Storage and maintenance area
- Natural gas processing facilities
- Leachate processing facilities
- Earthmoving equipment

The PaDEP study cites various regulatory and other criteria used to provide comparison information for their measurements/observations. The most useful in the context of the recommendations to DEQ in this report is the dose limit for members of the public cited in NRC regulations (10 CFR 20.1301), and noted as the consensus of various guidance documents issued by the International Atomic Energy Agency, the International Commission on Radiological Protection, The National Council on Radiation Protection and Measurements, and the American National Standards Institute. Based on review of these documents, this report recommends that the dose limit for a member of the public living near an operating TENORM landfill should be no greater than 100 mrem/y total effective dose equivalent (TEDE).

The PaDEP study analyzed leachate samples from 51 Pennsylvania landfills, including nine that were selected for further study based on the volume of TENORM waste accepted from the oil and gas industry. In addition, filter cake from three of the nine selected landfills was analyzed. Sediment-impacted soil was collected at discharge points from the three landfills in the study that discharged effluent water to the environment. The unfiltered leachate samples were analyzed for radium isotopes by gamma spectroscopy and for gross alpha and gross beta. The results of the analyses are given in the following table.

Table 6 Landfill Leachate Radionuclide Concentrations

Source	Units	Average Radionuclide Concentrations[8]			
		226Ra	**228Ra**	**Gross alpha**	**Gross beta**
Leachate All landfills	pCi/L	116	11.9	94.4	389
Leachate Selected landfills	pCi/L	125	18.0	106	176
Influent leachate Selected landfills	pCi/L	83.4	7.94	97.5	224
Effluent leachate Selected landfills	pCi/L	142	178	89.7	157
Leachate filter cake	pCi/g	24.3	3.85	Not applicable	Not applicable
Sediment impacted soil	pCi/g	3.57	1.65	Not applicable	Not applicable

[8] *Most of the individual 228Ra analyses were below the detection limit, as were nearly all of the gross alpha analyses. It is not clear how the average values were calculated.*

Radon concentrations in ambient air were measured at the fenceline around the selected landfills. The concentrations ranged from 0.2 pCi/L to 0.9 pCi/L. Surveys were also conducted to evaluate the surface contamination in facilities to estimate the potential dose to workers.

The study evaluated radon ingrowth within filter cake samples. Radon ingrowth is an important factor determining the direct gamma radiation levels from such materials, since the gamma radiation emitted by radium is nearly all attributable to the short-lived, solid decay products of radon. Rn-222 has a 3.8 day half-life and so is not present in freshly separated ^{226}Ra. The ^{222}Rn concentration, and thus the direct gamma radiation exposure rate, increases over time until it approaches equilibrium conditions at approximately 21 days. The PaDEP study showed that ^{222}Rn concentrations in wastewater treatment sludge were at about half of their theoretical equilibrium value at the time of removal and reached a maximum at approximately 18 days.

The maximum gamma exposure rate measured at any of the nine selected landfills was 13.5 microroentgen per hour (μR/hr). Assuming a background exposure rate of 5 μR/hr and a conversion of 0.001 mrem per μR, the estimated annual dose from external gamma radiation attributable to landfill operations based on this information would be:

$$\text{Dose} = (13.5\ \mu\text{R/hr} - 5\ \mu\text{R/hr}) \times (2{,}000 \text{ hours per year}) \times (0.001\ \text{mrem}/\mu\text{R}) = 17\ \text{mrem/y}.$$

The study notes that there is "little potential for internal alpha and beta radiation exposure to landfill workers" and that the radon levels were consistent with background levels. The report concludes that:

- "There is little potential for radiological exposure to workers and members of the public from leachate at landfills.
- "There is little difference in radium detected in leachate from the nine landfills selected based on the volume of oil and gas industry waste accepted and from the 42 other landfills.
- "There is limited potential for radiological environmental impacts from spills or discharges of effluent or influent leachate at landfills that accept oil and gas waste for disposal.
- "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 oil and gas waste for disposal.
- "There is a potential for radiological environmental impacts from spills and the long-term disposal of landfill filter cake from landfills that accept oil and gas waste for disposal.
- "There is little potential for radiological exposure to workers and members of the public from sediment-impacted soil at landfills that accepted oil and gas waste for disposal.
- "There may be a radiological environmental impact to soil from the sediments from landfill leachate treatment facilities that treat leachate from landfills that accept oil and gas waste for disposal.
- "There is little potential for additional radon exposure to workers and the members of the public at or from landfills that accept oil and gas waste for disposal.
- "There is little potential for internal alpha and beta surface radioactivity exposure to workers and members of the public at landfills that accept oil and gas waste for disposal.
- "There is little potential for exceeding public dose limits from external gamma radiation for workers and members of the public at landfills that accept oil and gas waste for disposal."

The PaDEP Report has the following recommendations for 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 oil and gas operations…
- "Add total radium (^{226}Ra and ^{228}Ra) to the annual suite of contaminants of concern in leachate sample analyses."

3.2.2 Denver-Julesburg Basin Study

The Denver-Julesburg Basin study was conducted by the Colorado Oil and Gas Conservation Commission (COGCC) to evaluate the concentrations of TENORM in drill cuttings from the Greater Wattenberg Field in Weld County, Colorado, in response to an October 2011 STRONGER[9] recommendation that the COGCC "gather information on the occurrence and level of NORM in E&P wastes in Colorado" (COGCC 2014). The results showed no radionuclide activity in drill cuttings in excess of the range of natural background.

3.3 NCRP, NAS, and ANSI Studies

The NCRP is developing a commentary on TENORM in oil and gas production. The NCRP sponsored a workshop in February 2016 focused on managing TENORM in the oil and gas industry as a prelude to preparation of the commentary. However, no specific consensus recommendations resulted from the workshop.

The National Academy of Sciences produced a report on TENORM in 1999 (NCRP 1999). The report concluded that exposure and dose/risk assessments used in developing standards should be reasonably realistic and that risk assessments for TENORM should consider exposure to chemical agents associated with NORM. The report does not specifically address landfill disposal of TENORM except as it applies to uranium mill tailings.

ANSI, in conjunction with the Health Physics Society, developed an ANSI standard with regard to the Control and Release of TENORM: ANSI/HPS N13.53-2009 (ANSI 2009). The ANSI standard provides "general guidance and normative criteria for the control and release" of TENORM. ANSI/HPS N13.53-2009 includes dose limits and release criteria for management of TENORM in material, products and waste. The standard is not specific to oil and gas E&P waste but covers most forms of TENORM, with certain exemptions. The dose criteria proposed in the N13.53-2009 include:

- Annual dose limit of 1 mSv (100 mrem) above background from all pathways and sources of radioactivity (except radon and its short-lived decay products) and practices associated with site and facility operations.
- Annual dose limit of 0.25 mSv (25 mrem) above background from all appropriate pathways associated with the presence of residual sources of radioactivity (except radon and its short-lived decay products*) from land and facilities that are eventually released for unrestricted use*.
- The recommended annual dose limit for non-workers is 1 mSv (100 mrem).

[9] *State Review of Oil & Natural Gas Environmental Regulations*

- The annual average radon concentration should not exceed 4 pCi/L or an equivalent radon gas limit based on radon decay product concentrations.

Unrestricted release levels for volumetric contamination proposed in ANSI N13.53-2009 include 3 pCi/g for radium and thorium and associated decay products; 30 pCi/g for natural uranium. Considerations for disposal of TENORM waste are also described in N13.53-2009.

3.4 IAEA TENORM Reports

The International Atomic Energy Agency (IAEA), an agency of the United Nations, has published guidance documents on NORM from specific sources such as rare earth mining and zircon sands, as well as from the oil and gas industry. Use of the IAEA guidance is mandatory for nations that receive financial support for their programs, but is advisory for the United States. The IAEA Safety Report Series No. 34 deals with Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry (IAEA 2003). A significant portion of the report deals with sealed sources and tracers. However, the report also addresses NORM (IAEA 2003). The report defines types of NORM waste that include radium in scales, sludge, and produced water. The report also notes the presence of ^{210}Pb associated primarily with gas production. The report provides data on ranges of NORM radionuclides in oil, gas, and byproducts. The document gives the range of ^{226}Ra in sludge as approximately 1 pCi/g to over 20,000 pCi/g. The range of ^{228}Ra concentrations is significantly lower for sludge, with a maximum value of 1,350 pCi/g. The range of concentrations in pipe scale is significantly greater than for sludge. The reported values demonstrate that ^{232}Th and ^{238}U constitute much lower concentrations, generally less than 1 pCi/g for both nuclides in sludge and less than 14 pCi/g for ^{238}U in scale. The ^{232}Th concentration in scale is negligible.

The report provides general guidance with regard to shallow land burial (landfills), primarily in terms of site selection, institutional controls, and the need for risk assessments to evaluate the long-term impacts arising from groundwater contamination, as well as the need for occupational risk assessment and radiation protection programs. However, the report does not provide any guidance regarding establishing threshold concentrations for landfills, or limitations on dose to workers or the public.

3.5 The Argonne Study

The North Dakota Department of Health (NDDH) tasked ANL with conducting a radiological dose and risk assessment for the disposal of TENORM generated in the oil and gas industry in permitted Industrial Waste and Special Waste Landfills in North Dakota, as a basis for possible changes in NDDH radiologic health and solid waste management rules (ANL 2014). The study was conducted during 2013 and 2014, with a final report published in November 2014. The report encompassed all aspects of disposal of solid oil and gas E&P wastes. The ANL report is specific to oil and gas production wastes but has application to disposal of TENORM wastes in general, in Industrial and Special Waste landfills. The ANL study was reviewed in detail for this report to the DEQ. Details of that review are presented in Appendix D; a summary of certain ANL study results and conclusions is presented below.

3.5.1 Summary of Dose and Risk Assessment Results

Landfill worker doses calculated based on the actual average radionuclide concentrations in North Dakota wastes were estimated to be well below the 100 mrem/y dose limit. Potential doses to members of the public from accidental exposure to improperly managed materials are very low, with a maximum calculated dose below 1 mrem/y for filter socks, assuming average concentrations.

The analysis indicated that the landfill worker is the critical receptor for establishing the average concentrations of TENORM that could be allowed in a landfill with assurance that the dose to any member of the public, including landfill workers, would be less than 100 mrem/y. The depth of cover was a significant factor in estimating the future public dose.

3.5.2 Summary of Argonne Study Conclusions and Recommendations

The Argonne study concludes the following:

- Potential doses to well site workers appear to be acceptable based on average activity concentrations and the appropriate use of PPE.
- The pipe cleaning and storage tank cleaning workers received the highest doses for well site operational scenarios.
- The estimated doses from accidental public exposure to improperly managed filter socks and proppant were a small fraction of the public dose limit of 100 mrem/y under all scenarios modeled.
- The estimated annual dose to the driver involved in transporting TENORM waste to the landfill was a small fraction of the public dose limit of 100 mrem/y.
- Increasing the depth below the surface of the TENORM wastes in the landfill can effectively reduce doses in future-use scenarios.
- Further refinement of data parameters for the hydrologic modeling (such as site-specific distribution coefficient values or site-specific hydrogeological data) is not warranted given that the groundwater exposure pathway is not a significant contributor to dose.
- Initial waste characterization data for TENORM waste stream generated by oil and gas production in North Dakota indicate that thorium may be present in the wastes in addition to radium.

The study also concludes that "establishing a total radium limit that takes into account the levels of thorium that may be present is a conservative approach…"

The Argonne Report makes the following recommendations:

- It may be necessary for some workers (primarily at the well site) to wear personal protective equipment (PPE) to keep exposures to acceptable levels.
- Additional analyses may be necessary to ensure that pipe cleaning and storage tank cleaning workers do not receive annual doses greater than 100 mrem/y.
- North Dakota solid waste landfill regulations may be safely modified so that the maximum exposure to any landfill worker does not exceed 100 mrem/y to allow TENORM wastes containing an average concentration of less than or equal to 50 pCi/g of total radium (independent of background radium levels) to be disposed of in either Special Waste or Industrial Waste Landfills based on the following conditions:
    - No more than 25,000 tons of TENORM wastes are to be disposed of in a single landfill per year. *(Note: North Dakota excludes drill cuttings, frack sands and mud from the definition of TENORM; they constitute a large fraction of E&P wastes. Since the State of Montana includes all of these materials in its own definition of TENORM, the volume*

limit in the ANL recommendations is not directly relevant to discussions of Montana's regulations.)

- The average thorium activity in the waste does not exceed 24 pCi/g. (This concentration assumes a thorium to radium ratio of 49 percent at 50 pCi/g total radium, a conservative assumption.)
- TENORM wastes must eventually be covered by at least 2 meters of a combination of the landfill cover materials and clean wastes that do not contain radionuclides.

4.0 THRESHOLD EVALUATION

The Scope of Work for this project includes the following elements:

- Evaluate and communicate advantages and disadvantages of utilizing prescribed TENORM value thresholds and how they are protective of human health and the environment.
- Evaluate and communicate advantages and disadvantages of utilizing site specific (risk-based) TENORM thresholds and how they are protective of human health and the environment.
- Evaluate and report whether 270 picocuries (the NRC threshold for transport, labeling, placarding, and spills) or another threshold is reasonable and environmentally protective for landfilling TENORM in Montana.

4.1 Threshold Values on Human Health and Environmental Considerations

Prescribed threshold or limiting radionuclide activity concentration values for acceptance of TENORM waste, specifically oil and gas production wastes, were developed for the state of North Dakota based on a risk assessment performed by ANL (ANL 2014). The North Dakota limit is based on a specific assumed mix of radionuclides in TENORM and a limit on the total amount of material that can be disposed of in a landfill. These limits have been incorporated into the North Dakota regulations (Section 2.3). The estimated dose to a landfill worker at the North Dakota concentration limits would be no greater than 100 mrem/y. The doses to members of the public residing near the landfill and under future land use would be lower than the dose to the landfill worker under the proposed scenarios, as determined by the risk assessments.

Threshold or limiting radionuclide concentrations are relatively simple for regulatory agencies to apply, and for industry compliance. They can be effective for TENORM wastes with consistent ratios of radionuclide concentrations. However, threshold limits, such as those established in the North Dakota TENORM regulations, do not allow for flexibility to deal with site-specific conditions and differing radionuclide concentration ratios. A more flexible system allowing use of either a pre-set threshold value, or as an alternative a limit value based on a detailed evaluation of a specific landfill site, may be preferable.

4.2 Utilizing a Site-Specific Threshold Value

Establishing dose criteria for workers and members of the public from landfill disposal of TENORM is the responsibility of the Montana DEQ. As noted previously, the NRC does not regulate TENORM at concentrations below the source material exclusion (0.05 percent uranium or thorium). Therefore, the NRC dose limit for members of the public from operating licensed facilities, 100 mrem/y (10 CFR 20.1301), is not directly applicable to TENORM. However, the Montana DEQ has concluded that the 100 mrem/y limit is applicable to doses to members of the public and workers at landfill operations. In addition, the DEQ accepts the NRC's 25 mrem/y dose limit for facilities released for unrestricted use for landfills that accept TENORM. (Note that Montana solid waste regulations do not allow unrestricted use of reclaimed sites.) These values — 100 mrem/year limits for workers and members of the public near an operating TENORM site, and 25 mrem/year for a member of the public near a closed TENORM site — can be used to establish appropriate concentration limits in soil for radionuclides in a TENORM landfill. These limits are calculated using recognized dose assessment codes.

Dose assessment codes, like the RESRAD family of codes, that use site-specific data and material-specific radionuclide concentrations can be applied to calculate reasonable radionuclide concentration limits (thresholds) or can be used to calculate the potential radiation dose from particular TENORM waste materials. RESRAD calculates the dose to an individual directly on the site - for example, a landfill worker spreading TENORM waste - or a future resident. RESRAD-BUILD can be used to calculate doses to workers indoors, such as in a landfill office or processing facility. RESRAD-OFFSITE can be used to calculate doses to nearby residents during facility operations.

Site-specific conditions that would be applied to the dose analysis include indoor and outdoor occupancy time for the landfill worker and shielding by non-TENORM cover materials. For example, the fraction of the work day spent spreading TENORM waste can be taken into account in calculating the dose to a landfill worker. The dose for the worker managing bare TENORM, and the dose from shielded material, can be calculated and summed to yield the total dose. Material-specific radionuclide concentration ratios can be applied to the dose calculation to estimate the concentration limit based on ^{226}Ra. The maximum allowable concentration of each nuclide should be calculated separately unless the mix of radionuclides in the waste does not vary for materials containing more than one radionuclide. The "sum of ratios" procedure can be applied to ensure that the material in combination does not result in exceeding the dose limit. The sum of ratios is calculated as follows:

$$\text{Sum of ratios} = [C_a/T_a] + [C_b/T_b] + [C_c/T_c] \ldots [C_i/T_i]$$

Where: C = concentration of the radionuclide in the material
T = calculated threshold for the particular radionuclide

If the sum of ratios is less than 1, the mixture of radionuclides meets the dose limit.

This approach requires knowledge of the activity concentration of each of the principal radionuclides present in the TENORM (^{228}Ra, ^{226}Ra, and ^{232}Th) by either direct laboratory analysis of each type of waste to be accepted by the landfill or by source knowledge. A statistically robust method of tracking the cumulative activity concentrations of each of the three nuclides accepted by the landfill is essential to ensuring that the dose to the worker does not exceed 100 mrem/y.[10] A generic threshold value can be calculated using a reasonably conservative assumption for the mix of radionuclides in the TENORM, as was done for the North Dakota study (ANL 2014). For example, a RESRAD analysis assuming 25 percent of the activity in the TENORM is attributable to ^{232}Th, 25 percent to ^{228}Ra, and 50 percent to ^{226}Ra would give a generic total radium threshold of 67 pCi/g, assuming the landfill worker spends 50 percent of his or her time managing the waste or 33 pCi/g if the worker spends full time managing the waste (see Appendix A). Direct gamma radiation accounts for 97 percent of the estimated dose, with incidental ingestion of soil accounting for 2 percent and inhalation of particulates and radon decay products contributing 1 percent. The Appendix A analysis is intended to be an example and not a specific recommendation for the radium threshold for Montana, as more information would be required regarding routine landfill operations and TENORM radionuclide concentration ratios. If flexibility is desired, the threshold for each type of waste must be calculated using site-specific factors and radionuclide ratios.

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[10] *While natural uranium and ^{210}Pb are potentially present in TENORM, they do not contribute significantly to the dose to the landfill worker.*

The following discussion considers the development of a generic threshold value. Assuming the landfill worker spends 50 percent or less of his or her time managing TENORM, and that the mix of radionuclides contains ^{232}Th at a ratio no greater than 25 percent of the total activity (as was assumed for the example described in Appendix A), an average ^{226}Ra+^{228}Ra concentration less than 50 pCi/g is likely to be protective and meet the 100 mrem/y dose limit for the landfill worker. However, workers should be monitored with personal dosimetry to demonstrate that the annual dose will not exceed 100 mrem.

Development of an alternative limit, based on a site-specific, detailed RESRAD assessment performed for a specific landfill, with additional restrictions including more comprehensive worker, public and environmental protection/monitoring requirements (as discussed in Appendix B), should also be acceptable.

A radiation safety program (RSP) commensurate with the potential radiation exposure levels should be developed and implemented at any landfill that accepts TENORM for treatment or disposal. Provisions for acceptance of waste must include radiation protection training for workers in accordance with Occupational Safety and Health Administration (OSHA) regulations. Requirements for personal protection and personal contamination monitoring should be considered, depending on specific allowable TENORM concentrations and the types of operations to be conducted. An adequate environmental radiological monitoring program, including such media as groundwater and ambient air, should be required for any landfill that accepts TENORM. Appendix B includes a description of such programs.

4.3 Regulatory Transportation Considerations

As noted in the Scope of Work, the U.S. Department of Transportation (DOT) exempt concentrations for ^{226}Ra and ^{228}Ra are 270 pCi/g each in the absence of any other radionuclides except their short-lived decay products. Materials with concentrations below those limits are exempt from DOT regulation; however, they are not necessarily exempt from state or federal regulation as radionuclides. The DOT exempt concentrations apply to transportation on public roadways to the landfills authorized to accept such materials. The exempt concentration limits, by themselves, should not be used as justification for establishing TENORM concentrations that can be accepted by a facility. The DOT exempt concentration limits were derived to protect workers (such as truck drivers) and members of the public during transport of radioactive materials and are not directly applicable to disposal of TENORM. The limits on TENORM concentrations in the landfills should be based on site-specific radiation dose assessments for members of the public and landfill workers and should be calculated based on average concentrations in the landfill. Please see Appendix E of this report for a detailed discussion of DOT transport regulations in the context of TENORM.

5.0 TENORM LANDFILL OPERATION CONSIDERATIONS

Operational considerations set forth in the scope of work include the following:

- Provide options for regulations that guide management of spikes or "hot spots" in loads received by the permitted facilities or hot spot areas in landfills.
- Describe options for the facility operator to accurately measure radioactivity at a landfill to determine cumulative concentrations/exposure.
- Advise DEQ on appropriate TENORM acceptance criteria and daily/intermediate cover requirements.

5.1 Hot Spot Identification and Cumulative Radiation Risk

As noted in Section 4.2, threshold radionuclide concentration values for each landfill should be established based on site-specific landfill characteristics and acceptable dose to a member of the pubic and the landfill workers. The threshold values should apply to the average concentration in the materials accepted by the facility. Relatively small volumes of TENORM with radionuclide concentrations greater than the threshold can be accepted by the landfill as long as the cumulative radionuclide concentrations averaged over the period of a year are equal to or less than the threshold value. "Hot spots" with radionuclide activity concentrations significantly greater than the threshold may result in the average exceeding the threshold and the dose to the worker potentially exceeding 100 mrem/y. It is essential for the landfill to maintain a running average of the radionuclide concentrations accepted at the landfill based on the generators' waste profiles and periodic sampling and analysis by the landfill operator. If a generic total radium threshold is established for a facility based on conservative assumptions with regard to radionuclide mix in the TENORM disposed of, a simple computer program that calculates the cumulative average radium concentration in TENORM accepted by the facility may be adequate to demonstrate that the dose to the worker does not exceed 100 mrem/y. However, if the landfill accepts various types of TENORM with different relative concentrations of the radionuclides of concern, a statistically robust computer program must be developed to address the nuclides individually for each type of TENORM and calculate potential doses to the landfill workers. It is not adequate to simply calculate the dose at the end of the calendar year. The average concentrations of radionuclides in TENORM disposed of in the landfill should be compared to the threshold periodically, with the frequency depending on the amounts of material accepted. Landfills with a high volume or high percentage of TENORM should check the running average against the threshold on at least a weekly basis.

Determining whether there is a radioactive material "hot spot" in a truckload of contaminated material that otherwise meets the facility acceptance limit (and the concentrations of individual nuclides) may not be feasible while the load is still contained within the truck. Soil is an effective shield against gamma radiation, so detection of a hot spot buried deep within a 25-ton load (as an example) is not likely when the load is examined externally using a gamma radiation detector. The soil will shield the gamma radiation emanating from the hot spot; a hot volume may therefore be undetectable. Even a relatively large volume of more highly contaminated material can be undetectable if it is located toward the center of a load, especially if the remainder of the material is well under the concentration acceptance limit. The hot spot can be reliably detected only after the contaminated material has been spread out within the landfill.

A hot spot can be detected after the material has been spread for final disposal by adopting a routine process to scan the spread material, using a gamma detector. This process could simply be a routine scan of the newly deposited material before it is covered with clean soil, using a global positioning system (GPS)-based gamma scanning system of the type described in Meyer and others (2005). Such systems have been used on many tens of thousands of acres to assess ^{226}Ra concentrations in surface soil. GPS-based gamma scanning provides an immediate map of the scanned material, highlighting any area that exceeds the facility's predetermined gamma radiation limits. Removal of the hot spot detected would involve immediate excavation of a portion of the layer of new material, placement in an empty delivery truck, and returning it to the generator. An agreement should be in place before material is accepted from a generator, providing that costs associated with excavation of hot spots will be borne by the generator. The agreement should include an increasing penalty for repeated transmittal of non-qualifying waste material, with an ultimate penalty of refusal to receive material from that generator for an extended period. This requirement places an increasing responsibility on the generator's staff to send only qualifying material to the landfill. (Note: if a number of different generators contributed to the area being surveyed after disposal, it may be difficult to identify the source of the hot spot.)

Given a gamma scan map of the spread material, definition of the level of contamination that is determined to be a hot spot is also feasible. Using, for example, the 10x10 meter criterion surface area selected by the EPA for use on the Uranium Mill Tailings Remedial Action Program, the GPS-based gamma scan system could be calibrated to highlight any 10 x 10 meter area in the newly spread material that exceeds an average gamma exposure rate determined to represent a selected radionuclide concentration. The 10 x 10 meter area exceeding the average limit would be excavated, and the material would be returned to the source entity. A secondary limit could also be established such that any smaller area within the 10 x 10 meter area exceeding the average criterion would require excavation of that smaller area. Regular sampling of soils found by gamma scanning to exceed the facility's concentration limits would be used to routinely fine-tune the gamma scan equipment's ^{226}Ra soil concentration calibration coefficient, providing assurance that gradual buildup of gamma-emitting material subsurface to new material would not result in removals in error. This potential (increase of gamma radiation exposure rates caused by the periodic deposition of new materials) would become less significant over time, as cover layers of uncontaminated soil will act as an increasingly thick shield against radiation from previously buried materials.

As noted above, it is important to consider the effect of a “hot spot” buried in a load of waste on the parameter of interest, which is the annual average dose to landfill workers and members of the public. The landfill operator should audit generators to have some confidence that the waste profiles submitted by the generator are accurate. The maximum activity concentration in a “hot spot” that would be acceptable for disposal at the landfill while maintaining the average TENORM concentration below the threshold value must be determined based on the effect of the hot spot on the running average. It may not be necessary to remove a “hot spot” if the average concentration is below the threshold value.

It is up to the generator to define the characteristics of the waste and certify that it meets the waste acceptance criteria for a particular landfill. The landfill should establish a verification procedure involving random sampling and analysis of a fraction of the loads. As described above, the landfill must maintain a running average of the TENORM concentrations in the loads accepted, based on the generator-certified data, to ensure that the average concentrations do not exceed the landfill criteria.

Existing Montana regulations require the generator to analyze composite samples from every 200 cubic yards of material for ^{226}Ra, ^{228}Ra, ^{210}Pb for unprocessed E&P waste and additionally ^{232}Th and ^{210}Po for processed E&P wastes. The maximum allowable concentrations in the landfill under the November 2015 regulations depend on the type of liner and whether there is a leachate collection system. It is expected that the majority of TENORM wastes that will be accepted by a landfill permitted by the Montana DEQ and local authorities will be bulk materials with relatively uniform $^{226}Ra/^{228}Ra$ concentrations.

If the process described above to routinely gamma-scan new material after it is placed the landfill is implemented, accurate measurement of final radionuclide concentrations in soil using the GPS-based gamma scan maps will provide a reliable record of all material deposited at the landfill over time. Average concentrations over all areas within the landfill can be calculated via the routine gamma scan process because the GPS/gamma scan system can be calibrated to provide an estimate of ^{226}Ra concentrations in a layer of contaminated material. Given reasonably uniform placement (thickness) of contaminated material from day to day, ^{226}Ra concentration, volume, and density of the material would allow calculation of the total quantity of ^{226}Ra placed within a site over time. The gamma scan data also provide a record of the current exposure rate over the facility, useful in the estimation of potential worker exposure.

5.2 TENORM Acceptance Criteria and Landfill Cover Requirements

The TENORM acceptance criteria must be based on the acceptable annual dose to the landfill worker and a member of the public, 100 mrem/y. The most important pathway for dose to the landfill worker during operations is direct gamma radiation; if the worker dose remains below 100 mrem during operations, dose to a nearby member of the public will almost certainly remain well below 100 mrem, since gamma radiation from the landfill is rapidly attenuated with the distance to an off-site individual. The highest dose to a member of the public after a landfill is closed and covered would come from ingestion of water and foodstuffs grown on the site or from impacted groundwater off site. However, as noted previously, Montana solid waste regulations prohibit residential use of a reclaimed landfill. Dose to a member of the public should be well below the limit of 25 mrem set by Montana for a reclaimed landfill. A limit on radionuclide concentrations allowed in a landfill can be calculated based on these dose limits using approved computer models such as the RESRAD code.

One approach to setting such a concentration limit involves a “generic” calculation that can be applied to landfills expected to receive “typical” TENORM mixes and likely to receive relatively smaller quantities of TENORM than dedicated sites. A threshold soil concentration limit may be calculated for such a site and could be applied to all such “simple” sites in lieu of requiring site-specific calculations that might indicate the acceptability of a higher limit. Since most oil and gas production wastes have relatively low levels of TENORM, this approach might set a “threshold,” a specific concentration that would likely meet the dose criteria under all such simpler landfill conditions. This threshold regulatory approach would, however, allow flexibility for a landfill to accept higher TENORM concentrations after performing a site-specific RESRAD assessment as discussed previously, based on landfill engineering design and proposed operational plans. The potential dose to the worker or member of the public from a particular site and TENORM concentration mixes can be calculated using the RESRAD family of codes, specifically RESRAD, RESRAD-BUILD, and RESRAD-OFFSITE.

TENORM waste should be covered with a minimum of 6 inches of clean soil (or other wastes with background levels of radioactive materials) periodically during operations in accordance with landfill regulations to limit the area where direct gamma radiation would be a significant potential pathway for exposure to the worker. Six inches of soil will reduce the dose rate from TENORM by about 30 percent, assuming the mix of radionuclides used in the Appendix A RESRAD dose assessment (^{228}Ra, 25 percent; ^{226}Ra, 50 percent, ^{232}Th, 25 percent). Twelve inches of cover will reduce the dose by about 47 percent. The shielding effect of a soil cover depends on the mix of radionuclides. Limiting the open area, plus imposing a requirement for dust control, will also minimize the potential for doses to off-site residents from inhalation of particulate material.

6.0 RECOMMENDATIONS

Under the provisions described in this Task Order, Tetra Tech has addressed the Scope of Work Tasks outlined in Section 1.2, as presented throughout this report. The primary recommendations or guidance requested by DEQ from Tetra Tech are summarized below:

- Advise DEQ on appropriate TENORM acceptance criteria and daily/intermediate cover requirements.

The TENORM acceptance criteria depend on the acceptable dose limits established by the DEQ for the landfill worker and for members of the public during operation (100 mrem/y), and for eventual future land use (25 mrem/y). For comparison, the annual average natural background dose in the U.S. is approximately 311 mrem per year (NCRP 2009). Because elevation and geology significantly affect both direct radiation and radon-related doses, the estimated annual average natural background dose to Montana and other mountain state residents can be significantly higher, averaging up to 1,000 mrem per year (as noted in Section 1, Table 1).

The ANL North Dakota study found that an average $^{226}Ra/^{228}Ra$ concentration of 50 pCi/g meets the 100 mrem per year dose limit for landfill workers, as long as no more than 10 percent of the material in the landfill is TENORM (as defined by North Dakota and as evaluated in the study[11]) and the total amount of TENORM accepted is less than 25,000 tons. Review of all applicable documents and regulations indicates that these limits are probably conservative. *(As noted previously: North Dakota excludes drill cuttings, frack sands and mud from the definition of TENORM. These wastes generally have radionuclide concentrations in the range of background; they constitute a large fraction of E&P wastes. Since the State of Montana includes all of these materials in its own definition of TENORM, the volume limit in the ANL recommendations is not directly relevant to discussions of Montana's regulations.)*

Assuming that the landfill worker spends no more than 50 percent of his or her time managing TENORM and that the mix of radionuclides includes ^{232}Th at a ratio not greater than 25 percent of the total activity (as was assumed for the example described in Appendix A), an average $^{226}Ra+^{228}Ra$ activity concentration less than 50 pCi/g is likely to be protective and should meet the 100 mrem/y dose limit for the landfill worker. DEQ could establish a default acceptance criterion, a "threshold," that would be protective of workers and the public under landfill conditions that comply with the general landfill requirements for groundwater and air monitoring. Such landfills would be expected to operate under a routine set of conditions, receiving a relatively unchanging and specific mix of TENORM radionuclides. For example, a threshold value of 67 pCi/g was calculated for a TENORM mixture of 25 percent ^{228}Ra, 25 percent ^{232}Th, and 50 percent ^{226}Ra, assuming a landfill worker spent only 1,000 hours per year handling TENORM. (See Appendix A.) This calculation and the review/evaluation leading to it suggest that a somewhat more conservative threshold soil TENORM concentration of 50 pCi/g, if selected by DEQ, would be protective of human health and the environment.

TENORM should be covered by at least 6 inches of clean material periodically, preferably daily, to minimize the potential for resuspension of TENORM and to reduce the direct radiation dose to the landfill worker. (Given the mixture of radionuclides described above, 6 inches of soil would reduce the gamma exposure rate by about 30 percent.) A basic radiation protection program as described in

Appendix B would be required to support human health and environmental protection for facilities choosing to operate under the threshold concentration limit. More complex facilities could choose to perform site-specific assessments for DEQ review, potentially indicating that a higher soil concentration limit, and radionuclide concentration mix variations, would be acceptable for such a specific facility. A more comprehensive radiation protection program, also discussed in Appendix B, may be appropriate for such facilities.

- Evaluate and report whether 270 pCi or another threshold is reasonable and environmentally protective for landfilling TENORM in Montana.

The 270 pCi/g DOT exempt concentration for ^{226}Ra was derived to protect truck drivers and the public during transport of radionuclides. An average activity concentration threshold of 270 pCi/g for ^{226}Ra is not specifically applicable to TENORM disposal in a solid waste landfill. However, small volumes of TENORM with concentrations up to the DOT exempt concentration could occasionally be accepted, as long as the cumulative average does not exceed the threshold for the average concentration. Such acceptance of TENORM with radionuclide concentrations above the threshold would require a robust statistical program to calculate the cumulative running average concentrations of all radionuclides. It should also be noted that depending on the ^{232}Th concentration in the TENORM, the material could be licensable under the NRC as source material (^{232}Th concentrations greater than 55 pCi/g).

- Provide options for regulations that guide management of spikes or "hot spots" in loads received by the permitted facilities or hot spot areas in landfills.

As noted in Section 5.1, a gamma scan of TENORM as it is spread in the landfill would identify hot spots that might not be seen in a gamma measurement of a load of material if the "hot spot" is buried in the waste. However, it may not be feasible to track the source of the "hot spot" if the waste from several generators is co-mingled. It is important, in determining whether to take this action, to evaluate the actual consequences of an occasional undetectable "hot spot" in a load of waste in relation to the average concentration threshold established for the landfill based on a dose assessment. Acceptance of occasional higher activity material in relatively small quantities should not appreciably change the overall potential human health and environmental impact of a TENORM landfill.

- Describe options for the facility operator to accurately measure radioactivity at a landfill to determine cumulative concentrations/exposure.

Accurate characterization of the waste is the responsibility of the generator. The existing Montana requirements include collecting a composite sample of TENORM wastes for every 200 cubic yards. In addition, the landfill operator should establish a verification sampling program, based on the type of waste and the potential for radionuclide concentrations at or near site-specific acceptance criteria. For example, drill cuttings or other specific wastes may not need to be sampled, based on concentrations known to be essentially unvarying over time.

The operator needs to maintain a running cumulative average of radionuclide concentrations in the landfill, based on generator information and the results of random sampling conducted by the landfill operator, to ensure that the acceptance criteria are met. Load acceptance monitoring should be conducted using either a portal gamma radiation monitor or appropriate handheld gamma survey meter to verify that the ^{226}Ra/^{228}Ra concentrations are consistent with the generator information and the landfill waste acceptance criteria. While gamma exposure rates are not necessarily reliable indicators of activity concentrations, a “trigger” measured exposure rate that would require either further investigation (for example, gamma scanning of the spread material) or rejection of the load should be established for each landfill. The exposure rate records should be maintained along with documentation of rejected loads and loads requiring further investigation. The data set built over time by a landfill operator will be helpful in establishing specific trigger values that would require further evaluation/investigation. Appendix C provides additional discussion concerning methods that may be used to establish a trigger gamma exposure rate at a specific facility.

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ATTACHMENTS
A through I

(included on attached CD)

APPENDIX A
Generic RESRAD Analysis

APPENDIX A

GENERIC RESRAD ANALYSIS

The Montana Department of Environmental Quality (DEQ) is considering setting a maximum allowable annual dose to a worker at a landfill accepting Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) to be 100 millirem (mrem). A generic average concentration threshold for total radium in TENORM that would meet that dose limit can be estimated using the RESRAD dose assessment code.

The RESRAD Code was developed by the U.S. Department of Energy (DOE) to evaluate the radiation doses and risks to the public from residual radioactive materials (Residual Radioactivity). It was first issued in 1989. The version used in this analysis, RESRAD V7, was issued in February 2014. RESRAD is part of a family of codes designed to evaluate doses to individuals and ecological receptors. RESRAD V7 addresses soil contamination and is used to calculate doses to individuals before and after remediation. Further information on the RESRAD codes can be obtained from the User's Manual for RESRAD, Version 6 (Yu 2001).

RESRAD can be used to calculate the dose from a particular radionuclide at a specified concentration in soil or, conversely, a concentration in soil that would result in a user-specified dose to a member of the public. RESRAD can also calculate the total dose from a mixture of radionuclides in soil. The RESRAD summary output provides estimated doses from each individual radionuclide and pathway as well as the total dose, at user-specified time intervals. The code also calculates the peak total dose from the radionuclide mixture.

RESRAD calculates doses for water-independent and water-dependent pathways for the following exposure pathways (See Figure 1):

- External gamma radiation
- Inhalation of radionuclides in airborne particulate matter (re-suspended dust)
- Ingestion of plants grown on the site
- Ingestion of meat from animals raised on the site
- Ingestion of milk from cows grazing on the site.
- Aquatic foods
- Drinking water
- Soil ingestion
- Inhalation of radon decay products.

The user specifies which exposure scenarios represent complete pathways — that is, source to receptor, depending on land use scenario. RESRAD allows the user to specify time periods for dose assessment, but also calculates the maximum annual dose over a 1,000 year period.

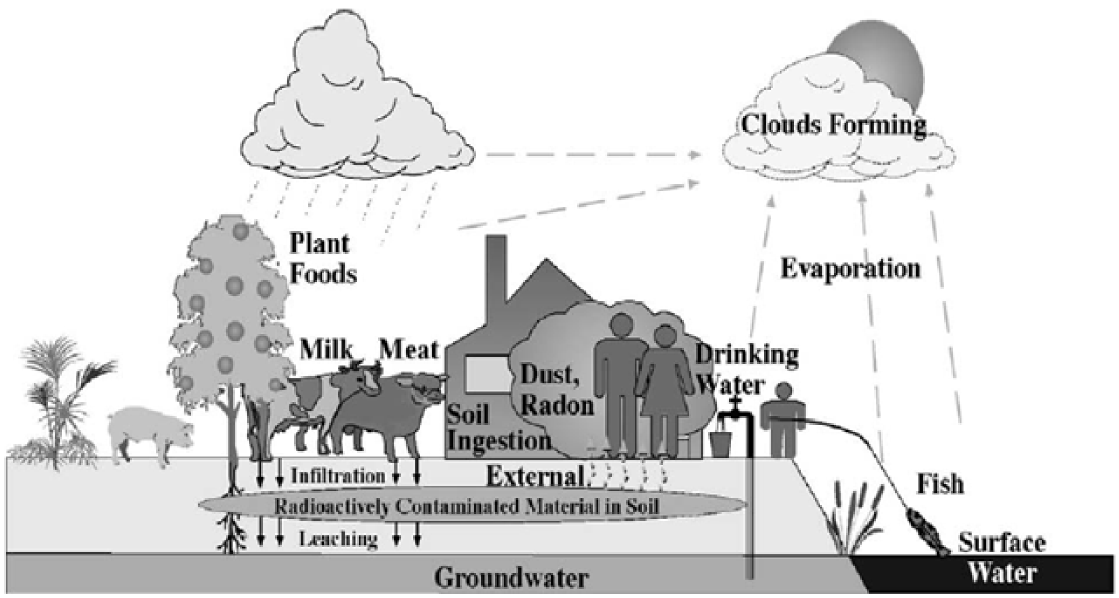

Figure 1: RESRAD Exposure Pathways (from DOE, 1989)

This analysis used nominal values for concentrations of the radionuclides of concern, radium-226 (^{226}Ra), radium-228 (^{228}Ra), and thorium-232 (^{232}Th), in the waste. The landfill worker was assumed to spend 50 percent of his or her time spreading the bare TENORM waste. Since the worker would not be exposed to groundwater on site and would not consume plants or meat raised on site, the only exposure pathways considered in the analysis were direct gamma radiation, inhalation of radionuclides in airborne particulate matter, inhalation of radon decay products, and incidental ingestion of soil. Water and site-grown food ingestion pathways were "turned off" for this analysis. All RESRAD default values for other input parameters, other than occupancy time, were assumed.

The groundwater and soil parameters are not of importance to this analysis as they affect only the doses due to ingestion of food and water. The value for the erosion rate is also not applicable, since the maximum dose occurs at time zero, as is reasonable for the analysis of dose to the landfill worker. The area of the TENORM was assumed to be 10,000 square meters (m^2) with a depth of 1 meter.

For this analysis, the nominal total concentration of the three radionuclides of concern was assumed to be 100 picocuries per gram (pCi/g) with 25 percent attributable to ^{232}Th, 25 percent to ^{228}Ra and 50 percent to ^{226}Ra. ^{228}Th was assumed to be present at the same concentration as ^{232}Th. ^{210}Pb was assumed to be present at the same concentration as ^{226}Ra. The calculated doses are given in Table A-1. The RESRAD summary printout and graphical representation are attached.

Table A-1: RESRAD-calculated Doses for the Landfill Worker (100 pCi/g, distribution discussed above)

Pathway	Units	$^{226}Ra + ^{210}Pb$	^{228}Ra	$^{232}Th + ^{228}Th$	Total
Direct Radiation	mrem/y	63.0	20.3	25.3	108.7
Inhalation of particulates	mrem/y	<0.1	<0.1	0.8	0.9
Inhalation of radon decay products	mrem/y	<0.1	<0.1	0.4	0.5
Incidental soil ingestion	mrem/y	1.9	0.2	0.4	2.4
Total	mrem/y	65.0	20.6	26.9	112.4

Assuming a maximum allowable dose to a landfill worker is 100 mrem/y, the generic threshold for total radium would be as follows:

$$\text{Threshold} = (25 \text{ pCi/g } ^{228}\text{Ra} + 50 \text{ pCi/g } ^{226}\text{Ra})(100 \text{ mrem/y})/(112.4 \text{ mrem/y}) = 67 \text{ pCi/g}$$

This analysis applies only to the specific mix of radionuclides used as input to the RESRAD code and to the assumption that the worker spends 50 percent of his or her time spreading the TENORM waste. This calculation is an example only to demonstrate how a threshold value can be determined. Site-specific information is required to obtain a specific threshold value.

APPENDIX B
Suggested Radiation Safety Program Outline for Landfills Accepting TENORM

APPENDIX B

SUGGESTED RADIATION SAFETY PROGRAM OUTLINE

FOR LANDFILLS ACCEPTING TENORM

This Radiation Safety Program (RSP) outline is designed to provide guidance to landfills accepting soil containing Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) waste. Site-specific Radiation Safety Procedures (RSPs) should be developed commensurate with the radionuclide concentrations and volumes of TENORM proposed for disposal at solid waste landfills in Montana. The RSPs should take a graded approach, with all landfills employing basic radiation awareness training and contamination control. Landfills accepting larger volumes of materials with radionuclide concentrations approaching the concentration threshold should implement more comprehensive radiation protection programs, and environmental monitoring programs, sufficient to keep radiation doses to workers as low as reasonably achievable (ALARA), and to provide adequate data to assess the radiological impact to workers and nearby residents. The elements of such radiation protection programs are provided in this outline. Specific detailed procedures should be developed and implemented for each site. Requirements for the RSPs should be included in the facility license.

1. Landfill worker radiation protection
    a. Radiation worker training
        i. Radiation awareness training: Required for all TENORM workers – should cover the following topics:
            - Basic facts about radiation
            - Routes of exposure to radiation
            - Radiation risk in perspective
            - Work rules
            - Worker rights and responsibilities
        ii. More detailed radiation worker training: Required where higher radionuclide concentrations and volumes of TENORM are to be accepted – Necessary if workers are badged, monitored for inhalation intake, or required to survey for contamination before leaving the site. Such training should include the following topics:
            - Radiation measurements – surveys for personal and equipment contamination
            - Radiation dose
            - Dosimetry badging requirements
            - Procedures for keeping radiation doses ALARA
    b. Direct gamma radiation monitoring
        i. Personal direct radiation dose monitoring (badging) should be considered for landfills that accept TENORM other than drill cuttings and drilling fluids.
        ii. Where implemented, a personal monitoring system could employ badges exchanged quarterly. Optically stimulated luminescent (OSL) monitors are recommended over thermoluminescent dosimeters (TLDs), as they are more

sensitive. OSLs have a minimum detection limit of 1 mrem whereas TLDs commonly have detection limits of 10 mrem.

iii. If a dosimetry system is implemented, it is essential to have a badge storage location that is easily accessible to employees and in a location where radiation levels are typical for the region (a "background" storage location).

c. Dust control and dust monitoring

i. Dust control is essential for worker and environmental protection. Adequate dust control procedures, such as keeping contaminated material moist and covering the material expeditiously to prevent resuspension, must be implemented.

ii. Breathing zone or area air monitoring should be considered for landfills that accept large quantities of TENORM at concentrations near the threshold.

d. Contamination surveys – personal and equipment contamination surveys should be required for landfills accepting TENORM other than drill cuttings and drilling fluids. Surveys should be conducted using an alpha survey meter, as the principal contaminant of concern is ^{226}Ra. A pancake probe type survey meter can be effective if ^{228}Ra is the predominant radionuclide in material being accepted.

e. Bioassay – In general, a bioassay program is neither necessary nor useful for landfills accepting TENORM waste, as long as dust control procedures are adequate. Urine bioassay is useful for soluble uranium but not for radium and thorium; uranium is not expected to be present at significant concentrations in oil and gas exploration and production (E&P) wastes. However, a bioassay program should be considered if a landfill opts to accept other forms of TENORM that may have significantly elevated concentrations of uranium.

2. Environmental monitoring – All landfills accepting TENORM should implement environmental monitoring programs to ensure that doses to members of the public near the operating landfill do not exceed 100 millirems per year (mrem/y). If the doses to the landfill workers are controlled such that they are no greater than 100 mrem/y, it is unlikely that the dose to a nearby member of the public would exceed 100 mrem/y. However, concentrations of radionuclides in air and water, as well as direct gamma radiation doses at the facility boundary, should be monitored to determine whether operations affect the environment and to provide credible information to members of the public. It is essential to select an appropriate control location to measure background air concentration and gamma radiation values, since background radiation levels are not impacts associated with operation of the facility.

a. Direct gamma radiation dose – Environmental optically stimulated luminescense (OSL) dosimeters can be used to measure dose rates at the site boundary. (Note that it is unlikely that such doses would be significantly greater than those measured at the background location.) In general, dosimeters are exchanged and read out quarterly.

b. Radon concentrations – Alpha track radon detectors can be used to monitor radon concentrations at the site boundary. The detectors should be exchanged semi-annually.

c. Air particulate concentrations – If dust is adequately controlled, concentrations downwind of the facility should be similar to upwind (background) concentrations as long as the background location is appropriately selected. Filters should be exchanged weekly to prevent excessive filter loading, and analyzed for ^{226}Ra, ^{228}Ra, and ^{232}Th as composites quarterly.

d. Reporting to DEQ – Environmental data, including output in graphical format, should be reported to the Solid Waste Program on a quarterly basis.

3. Portal monitoring of TENORM loads – Gamma radiation monitoring of TENORM truckloads as they enter a facility can provide an estimate of ^{226}Ra concentrations as long as the radioactive material is reasonably uniformly distributed in the load. However, the actual radium concentration in the material cannot be accurately assessed in this way, because the gamma exposure rate will depend on how much time has elapsed since the ^{226}Ra was separated. The measured gamma radiation level is a function of the short-lived decay products of ^{222}Rn. It takes about 3 weeks for these decay products to reach equilibrium with the parent ^{226}Ra. The generator is therefore required to sample and laboratory-analyze material sent for disposal to a landfill, to ensure more accurate estimation of the radionuclide concentrations entering the landfill. That analysis should include ^{226}Ra, ^{228}Ra, and ^{232}Th. In addition, ^{210}Pb is prevalent in some TENORM wastes and should be measured in such cases. It is not a direct radiation hazard, but could result in doses to future residents of the site through impacts to groundwater.

APPENDIX C
Calculation of Gamma Exposure Rate Screening Level for Landfills Accepting TENORM

APPENDIX C

CALCULATION OF GAMMA EXPOSURE RATE SCREENING LEVEL FOR LANDFILLS ACCEPTING TENORM

Acceptance of shipments at facilities licensed to dispose of technologically enhanced naturally occurring radioactive material (TENORM) is based on the information provided by the generator regarding concentrations of specific radionuclides. The generator is required to collect one composite sample of the TENORM and analyze for ^{226}Ra, ^{228}Ra, and ^{232}Th for every 200 cubic yards of material to be disposed of. The landfill operator is likewise required to analyze a fraction of the loads to verify the information submitted on the waste profiles. However, it is useful to have a real-time measurement criterion that can be applied to each load of TENORM to verify that it is consistent with the waste profile and within the acceptance threshold radioactivity for the landfill. Radium, with its decay products, has a gamma signature in terms of exposure rate that can be measured. However, the exposure rate is contingent on several variables, including the degree of equilibrium between ^{226}Ra and ^{222}Rn since it is the short-lived decay products of ^{222}Rn that emit significant gamma radiation. ^{226}Ra is also a gamma emitter but at a low frequency and low energy. In addition, the material in the load must be homogeneous for the exposure rate to represent the average radionuclide concentrations. The structure of the transport vehicle shields the gamma radiation, reducing the measured exposure rate by an unknown fraction.

While the actual exposure rate to be expected from a load of TENORM is uncertain because of the factors described above, the following calculation provides a conservative estimate of a measured exposure rate that could be used as a "trigger" to require further investigation of the load.

Assume:

a. The average radium concentration in the load is 50 picoCuries per gram (pCi/g), all attributable to ^{226}Ra with no ^{228}Ra or ^{232}Th present.
b. ^{222}Rn has built in to 50 percent of its equilibrium value. (The Pennsylvania Department of Environmental Protection study [PaDEP] 2016] includes data that show the concentration of ^{222}Rn decay products in wastewater treatment sludge to be approximately 50 percent of equilibrium at time zero [Figure 5-2]. This value may underestimate equilibrium for sludges that are not transported to the landfill within a few days of generation or may overestimate equilibrium for freshly separated ^{226}Ra that is immediately transported to the landfill.)
c. The exposure rate from an infinite layer of ^{226}Ra is 1.9 microroentgen per hour (µR/hr) at the surface. The exposure rate from an infinite layer of ^{232}Th is 2.82 µR/hr per draft Nuclear Regulatory Commission Guide (NUREG) 1506 (NRC 1995).
d. The vehicle walls provide a 75 percent shielding factor from NUREG-1717 (Schneider 2001).
e. The load in the transport vehicle is not an infinitely thick, infinite plane, so a reasonable correction factor would be 0.8.

Estimated exposure rate at the surface of a trailer containing TENORM with ^{226}Ra at 50 pCi/g:

Exp. Rate = (^{226}Ra conc. pCi/g)(exposure factor)(equilibrium fraction)(shielding fraction)(geometry)
Exp. Rate (µR/hr) = (50 pCi/g)(1.9 µR/hr/pCi/g)(0.50)(0.75)(0.8) = 29 µR/hr

The measured exposure rate would include the site background assumed to be approximately 10 µR/hr for a total exposure rate of 39 µR/hr.

Most types of survey meters, such as sodium iodide (NaI) detectors, are energy dependent. That is, they read most accurately at the gamma energy used to calibrate them, generally the ^{137}Cs gamma ray energy. However, they overestimate exposure rate at the lower photon energies in the range of scattered radon decay product gamma radiation. Based on field experience, a NaI detector may read a factor of 1.5 or more higher than the true exposure rate. A reasonable field measurement limit, using a 2" NaI detector to identify 50 pCi/g ^{226}Ra uniformly distributed in a truckload of TENORM, is approximately 60 µR/hr. Use of an energy-independent type of detector such as the microrem meter or a pressurized ion chamber would reduce the uncertainty created by measurement bias, but would also reduce detection sensitivity. The uncertainty attributable to the potential presence of "hot spots" or other non-uniformity, equilibrium status, or the inclusion of ^{228}Ra and ^{232}Th in the TENORM, greatly outweighs the uncertainty caused by measurement bias.

While, initially, a single cut-off gamma exposure rate for a specific landfill, derived without site-specific information such as the one provided above, may be somewhat uncertain, a more reasonable value can be established based on experience at the site. The gamma exposure rates measured from incoming loads can be compared to reported or measured activity concentrations, to derive a more accurate exposure rate that would enable detection of loads that exceed the threshold, and to verify the generator's information. However, it is important to periodically audit the generators to ensure that the waste profiles they submit are accurate.

References:

Nuclear Regulatory Commission (NRC). 1995. Measurement Methods for Radiological Surveys in Support of New Decommissioning Criteria. Draft Report for Comment. NUREG-1506. August.

Schneider, S., D. C. Kocher, G. D. Kerr, P. A. Scofield, F. R. O'Donnell, C. R. Mattsen, S. J. Cotter, J. S. Bogard, J. S. Bland, and C. Wiblin, 2001. Systematic Radiological Assessment of Exemptions for source and Byproduct Materials. NUREG-1717. Division of Risk Analysis and Applications. U. S. Nuclear Regulatory Commission. June.

APPENDIX D
Review – Argonne National Laboratory TENORM Study

APPENDIX D

TETRA TECH REVIEW OF THE TENORM STUDY PERFORMED BY ARGONNE NATIONAL LABORATORY FOR THE STATE OF NORTH DAKOTA

1.1 THE ARGONNE STUDY

The North Dakota Department of Health (NDDH) tasked Argonne National Laboratory (ANL) with conducting a radiological dose and risk assessment for disposal of TENORM generated in the oil and gas industry in permitted Industrial Waste and Special Waste Landfills in North Dakota. This study was intended as a basis for possible changes in NDDH radiologic health and solid waste management rules (ANL 2014). The study was conducted during 2013 and 2014, with a final report published in November 2014. The report encompassed all aspects of disposal of solid oil and gas extraction and production (E&P) wastes. This report is specific to oil and gas production wastes but has application to disposal of technologically enhanced naturally occurring radioactive material (TENORM) wastes, in general, in Industrial and Special Waste landfills. The study has been reviewed in some detail – the detailed Tetra Tech Inc. comments are presented in this appendix. A summary of those comments is presented in the main body of this report.

1.1.1 Dose Assessment Codes Used in the Analysis

Potential radiation doses to members of the public and landfill workers as well as potential doses attributable to transportation of oil and gas TENORM wastes were estimated. In contrast to the Pennsylvania study (Section 3.2.1 of the main report), the Argonne evaluation did not include the use of measured parameters but instead modeled the doses to potential receptors, including landfill workers, using the RESRAD, RESRAD-BUILD, RADTRAN, and TSD-DOSE pathway analysis computer codes. The maximum allowable radium concentration in the landfilled waste was calculated, assuming a maximum allowable annual dose to a member of the public from operating Nuclear Regulatory commission (NRC)- or Agreement State-licensed facilities, 100 millirem (mrem) per year. The dose assessment codes used in the analyses are briefly described in the table below.

Dose Assessment Codes used in Argonne North Dakota TENORM Report

Code	Brief Description	Source
RESRAD	RESRAD is a family of computer models designed to estimate doses and risks from RESidualRADioactive material. RESRAD (onsite) calculates the dose to an individual occupying the impacted site. It is based on user-defined input parameters including occupancy time. The occupancy time is adjusted to account for the type of use, such as occupational, residential, or farming. It is approved for use for dose evaluation by the NRC and by the Department of Energy. The RESRAD family of codes is not specific to TENORM.	Department of Energy/Argonne National Laboratory.

Code	Brief Description	Source
RESRAD-BUILD	RESRAD-BUILD is a model for analyzing the radiological doses attributable to occupancy and decontamination of buildings contaminated with radioactive materials either surficially or in the building material itself. It employs user-defined sources and receptors with occupancy time adjusted for the type of use.	Department of Energy/Argonne National Laboratory
RADTRAN	RADTRAN is a FORTRAN-based computer code for analysis of the risks of transportation of radioactive material.	Sandia National Laboratory
TSD-DOSE	TSD-DOSE is a radiological dose assessment model for treatment, storage and disposal facilities. It was developed to use waste-specific and site-specific data to estimate potential radiation doses to on-site workers and members of the public. It is not specific to TENORM and includes 85 radionuclides. TSD-DOSE incorporates the external gamma dose model used in the RESRAD Code.	Department of Energy/Argonne National Laboratory, Environmental Assessment Division. September 1998

1.1.2 Summary of Argonne Study Results

The Argonne study assessed the risks for workers and members of the public from all phases of oil and gas TENORM waste production, from the well site to landfill disposal. The maximum allowable dose to a worker was assumed to be the same as the maximum allowable dose to a member of the public, 100 mrem/y.

The maximum doses to workers involved in specific well-site operations "including mixing of fracking fluid, produced water filtration, pipe cleaning, storage tank cleaning, equipment cleaning at a gas processing plant, and sludge treatment" were estimated. The analysis assumed that well site workers were equipped with appropriate personal protective equipment (PPE). The estimated doses ranged from 70 mrem for storage tank cleaners to 130 mrem/y for workers engaged in pipe cleaning, when maximum likely radionuclide concentrations were assumed.

The study also evaluated the maximum potential dose from improper management of the waste, including a child playing with a used filter sock or playing in a pile of spilled synthetic proppants, and a load of used filter socks disposed of in an urban dumpster. The maximum calculated doses, also assuming maximum radionuclide concentrations, were less than 5 mrem per year.

Radiation doses and transportation risks were estimated for a driver transporting TENORM waste and an individual living near the landfill. The estimated dose to any individual member of the public was 3.2×10^{-6} mrem/y with an estimated collective dose of 1.3×10^{-4} person-rem/y. The estimated annual dose to the truck driver, assuming 2,000 hours per year, was 20 mrem/y. All doses were small fractions of the maximum allowable dose to a member of the public (100 mrem/y).

The landfill dose assessments demonstrated that the dose to the landfill worker is the limiting factor, when calculating the maximum average TENORM activity concentrations that could be disposed of to ensure that neither a member of the public nor the landfill worker exceeds a dose of 100 mrem/y. The highest doses were estimated for landfill workers receiving, handling, or placing TENORM waste. The estimated dose to any member of the public under future land use scenarios was less than the estimated dose to the landfill worker. The dose for future land use depends on the potential and extent of leaching of radionuclides into groundwater.

The analysis concluded that disposal of TENORM waste in Industrial Landfills and Special Waste Landfills "is appropriate provided that restrictions are placed on the average waste activity concentration, waste volumes disposed per year, and the depth of the TENORM wastes within the landfill." The determination depends on the landfill meeting the following restrictions and conditions:

- A limit of 50 picocuries per gram (pCi/g) for ^{226}Ra plus ^{228}Ra
- A limit of 25,000 tons of TENORM disposed of in a single year.[1]
- Average thorium activity concentration in the waste does not exceed 24 pCi/g assuming a thorium (^{232}Th) to total radium ratio of 0.49 at 50 pCi/g total radium.
- A minimum of two meters of landfill final cover materials and clean wastes that do not contain radionuclides. (Note: The ANL document does not specify that this restriction applies only to the final cover; however, cover thickness is discussed in the section of the report regarding future land use.)

1.1.3 TENORM Waste Streams

The following oil and gas waste streams are known to potentially contain elevated concentrations of TENORM (as defined by the state of North Dakota):

- *Produced water, in other words, formation water that is brought to the surface with the oil and gas.* Produced water generally contains isotopes of radium and their decay products but does not generally contain elevated concentrations of uranium and thorium because they are not as soluble as radium. Produced water is generally disposed of through saltwater disposal wells.
- *Scale, which is a hard, insoluble deposit that may accumulate on surfaces that come into contact with the produced water.*

  Scale generally is in the form of insoluble barium or strontium sulfate with radium co-precipitated. Radium concentrations in scale can become a waste management issue when equipment is serviced.
- *Sludge that accumulates in the bottom or storage and process vessels.*

  Sludge may be composed of sands, scale, rust, solid debris, or any material that settles out of the production stream.
- *Filter cake from filters used to remove solids from produced water, flowback water, or water treatment processes.*

  Filter cake consists of particles separated out from produced water. It may be similar in TENORM composition to sludge.
- *Disposable filter socks used to filter particles out of produced water.*
  Filter socks may present a significant hazard workers or the public if they are disposed of improperly.

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[1] The North Dakota study did not address drill cuttings and drilling fluids as TENORM; thus those wastes are not included in the volume limitation.

TENORM-contaminated equipment and soils, and drill cuttings, were not included in the analysis. Fracking proppant was not included in the dose analysis for the landfill worker or future resident, but was included in the assessment of accidental public exposure resulting from improper management.

1.1.4 Exposure Scenarios

The exposure scenarios evaluated in the Argonne study include both landfill operational phases and future use. Well site operations, transportation of TENORM from production facilities to landfills, and landfill operations constitute the operational phases considered. Residential land use was evaluated as the most conservative current and future exposure scenario. The dose assessments were conducted for the individual who is most likely to receive the highest radiation dose, the maximally exposed individual (MEI), to establish an upper-bound risk for each scenario.

The well site operational phase scenario included the following:

- Hydraulic fracturing fluid mixing worker
- Produced water filtration worker
- Equipment cleaning workers
- Sludge treatment workers.

Accidental exposure scenarios included the following:

- Child using filter socks as a toy
- Filter socks disposed of in a dumpster
- Proppant illegally dumped in an open field used as a playground for children

The transportation scenario included:

- Loading the cargo
- Transport of the material to its final destination
- Stops for maintenance and refueling

The individuals for whom the transportation dose was calculated included:

- Truck driver
- Individuals living along the transportation corridor
- Persons at stops for maintenance or refueling
- Individuals living near the entrance to the landfill

The landfill operations scenarios included:

- Waste placement operator
- Leachate management worker
- Member of the general public

The potential routes of exposure for workers included external irradiation, inhalation of contaminated particulates, and inadvertent ingestion of contaminated materials. The worker doses from landfill operations were calculated using TSD-DOSE. The maximum allowable annual activity that could be disposed of assuming a total of 25,000 tons per year and an annual landfill worker dose of 100 mrem was calculated. The maximum activity concentration was calculated by dividing the maximum allowable activity by 25,000 tons x 2,000 lbs/ton x 454 g/lb. Doses were also evaluated for the population living near the landfill from inhalation of airborne particulate matter, direct external radiation, ingestion of contaminated food, and incidental ingestion of contaminated particulates.

Future land use scenarios include:

- *The resident farmer scenario*, a full-time resident producing most of his or her food on-site and using groundwater from the site for both domestic and agricultural purposes. This scenario is the maximally exposed individual (MEI), even though North Dakota Solid Waste law stipulates that "a perpetual record must be placed on the deed to notify any person conducting a title search that the land has been used as a solid waste disposal facility." Exposure pathways include external radiation and indoor and outdoor radon decay product inhalation, as well as inhalation of contaminated particulates, inadvertent ingestion of contaminated soil, and ingestion of meat, milk and crops.
- *Industrial land use scenario.* Exposure pathways include external radiation, inhalation of radon, inhalation of contaminated particulates, and inadvertent ingestion of soil.
- *Recreational land use scenario.* Exposure pathways include external radiation, inhalation of radon and contaminated particulates, inadvertent ingestion of soil, and consumption of game.
- *Intruder scenario,* an individual who accidentally encounters the wastes after institutional controls are no longer in place. Exposure pathways are essentially the same as for the resident farmer scenario but displaced in time by 100 years.
- *Off-site resident,* an individual living adjacent to the former landfill with a residential well located 100 meters from the edge of the landfill. Exposure pathways include ingestion of groundwater, ingestion of crops, milk and meat produced using the groundwater, and inhalation of radon volatilized from water. However, the radon pathway was not considered a major contributor to the dose.

1.1.5 Risk Assessment Methodology

The computer codes described in Section 3.5.1 of the main report were used to assess the radiation doses to the MEI. The maximum allowable TENORM concentrations were then calculated based on a maximum allowable annual dose for a member of the public of 100 mrem/y. The future use scenarios were initially assumed to produce the highest dose. However, the calculated doses exceeded 100 mrem/y, when the maximum allowable TENORM concentrations calculated for the future land use scenarios were applied to the landfill worker. Additional calculations established a lower allowable TENORM concentration for the landfill worker.

Hydrologic modeling was used to estimate the groundwater concentrations for time periods up to 10,000 years post-closure. (*Note: The hydrologic modelling methods are described in detail in the Argonne Report but are not covered in this report*.)

1.1.6 Dose and Risk Assessment Results

Doses were calculated using the average and maximum radionuclide concentrations (Table 1). The calculated doses for Well Site Operations are given in the table below.

Total Estimated Annual Doses for Well Site Operations

Operation	Annual Dose at the Average Concentration (mrem/y)	Annual Dose at the Maximum Concentration (mrem/y)
Mixing hydraulic fracturing fluid	20	23
Produced water filtration	0.47	2.2
Pipe cleaning	14	130
Storage tank cleaning	3.8	70
Equipment cleaning at gas processing plant	0.0003	0.012
Sludge treatment workers	1.6	30

Except for produced water filtration workers, the annual dose is almost entirely the result of direct external radiation.

The estimated doses from accidental public exposure were calculated using the average and maximum concentrations. The doses to a child playing with a filter sock, nearly all caused by ingestion, ranged from 0.036 to 0.052 mrem/y for the average concentration and from 0.21 to 0.42 mrem/y using the maximum concentration. The doses varied slightly by year, presumably as a result of the ingrowth and decay of specific radionuclides. The dose to a city dweller, in the event the filter socks are inadvertently disposed of in an urban dumpster, ranged from 0.39 to 0.52 mrem/y for the average concentration and from 2.7 to 4.9 mrem/y using the maximum concentration, primarily the result of direct radiation. The estimated dose to a child assuming a truckload of proppant is dumped in an open field used by children as a playground ranged from 1.2 to 1.7 mrem/y using the average concentration, and from 1.3 to 1.9 mrem/y using the maximum concentration. All of the doses are a small fraction of the 100 mrem/y dose limit.

The doses for the future land use scenarios per pCi/g activity concentration were calculated separately for each nuclide of concern potentially present in TENORM. The analysis resulted in establishing a limiting average concentration for each nuclide. It was assumed that the volume of TENORM waste in the landfill would be restricted to less than 10 percent of the total waste and that no more than 25,000 tons of TENORM waste would be brought to the landfill each year. The limiting average concentrations, taking into consideration all of the future use scenarios and an allowable annual dose to the MEI of 100 mrem/y, are given in the table below.

Limiting Average Concentration for TENORM in Landfills Based on Future Land Use Scenarios

Radionuclide	Limiting Average Radionuclide Concentration in the Landfill (pCi/g[1])	Allowable Concentration in TENORM (pCi/g)	Total Activity that can be Brought into the Landfill in One Year (Ci)[2]
^{210}Pb	1,100	11,000	270
^{226}Ra	13	130	3.3
^{228}Ra	70	700	18
^{232}Th	41	410	10

[1]pCi/g = picocuries per gram

[2]Ci = Curies

1.1.7 Transportation Dose

The potential transportation doses and risks were calculated assuming 25,000 tons of TENORM waste (1,000 shipments) are transported to the landfill in 1 year and a distance of 155 miles (250 kilometers) from the generator to the disposal facility. The estimated maximum concentrations used in the analysis are those calculated for the future land use scenario. The estimated annual doses under routine conditions are presented in the table below.

Estimated Annual Dose from Transport of TENORM to a Landfill

Receptor	Base Case Dose - 1,000 shipments per year (mrem/y)	Maximum Case - 2,000 shipments per year (mrem/y)
Driver	20	20 (more than one driver)
Individual living along the transportation corridor	$1.6 x 10^{-6}$	$3.2 x 10^{-6}$

The potential doses to members of the public from transportation are negligible. The total population dose was determined to be $6.5 x 10^{-5}$ person-rem/y. The calculated individual and population doses are negligible.

The transportation analysis also included an accident scenario. The estimated population dose was 3.6 person-rem/y.

1.1.8 Waste Handling and Placement Operators

The potential doses to waste handling and placement operators were calculated using the maximum concentrations of the individual nuclides derived from the future land use scenarios. The receiving and handling or the waste placement workers received the largest doses. ^{226}Ra and ^{228}Ra contribute the largest amount to the dose, primarily from direct gamma radiation, as indicated by the fact that the dose from those nuclides is not affected by whether the TENORM is in bulk or containerized. A sensitivity analysis demonstrated that the worker dose per pCi/g is approximately four orders of magnitude lower for ^{210}Pb and ^{232}Th than for ^{226}Ra and ^{228}Ra.

1.1.9 Summary of Dose and Risk Assessment Results

Landfill worker doses calculated based on the actual average radionuclide concentrations in North Dakota wastes were well below the 100 mrem/y dose limit. Potential doses to members of the public from accidental exposure to improperly managed filter socks are very low, with a maximum calculated dose below 1 mrem/y assuming average concentrations.

The analysis indicated that the landfill worker is the critical receptor for establishing the average concentrations of TENORM that could be allowed in a landfill with assurance that the dose to any member of the public, including landfill workers, would be less than 100 mrem/y. The depth of cover was a significant factor in estimating the future public dose.

1.1.10 Calculating the Maximum Allowable Radium Concentration for TENORM Disposal in Landfills

The estimated allowable TENORM concentrations for individual radionuclides calculated based on the results of the dose assessment are presented in the table below

Estimated Allowable TENORM Concentrations

Nuclide	Allowable TENORM Concentration (pCi/g)	
	Based on Landfill Worker Scenarios	Based on Future Use Scenarios
^{210}Pb	4,200	11,000
^{226}Ra	98	130
^{228}Ra	180	700
^{232}Th	48	410

As noted above, the landfill worker is the critical receptor. The ANL calculation of allowable TENORM total radium activity concentration takes into account the other radionuclides likely to be present in the material. The concentration of ^{232}Th alone in the waste is a critical factor in determining the total dose, as the allowable concentration of ^{232}Th is less than half the allowable concentration of ^{226}Ra. The ANL study calculated the maximum allowable concentration for an annual dose of 100 mrem using a sum of fractions approach. and the most conservative activity fractions in TENORM wastes. (^{226}Ra: 0.54; ^{228}Ra: 0.14; ^{232}Th:0.33)

Assuming a ^{226}Ra concentration of 0.54 pCi/g; ^{228}Ra, 0.14 pCi/g; 232Th, 0.33 pCi/g the sum of fractions for a total ^{226}Ra/^{228}Ra concentration of 0.68 pCi/g would be as follows:

Sum of fractions = [0.54/98]+[0.14/180]+[0.33/48] = 0.0132

The estimated ^{226}Ra/^{228}Ra concentration that would result in a dose of 100 mrem/y to the landfill worker would be as follows:

Maximum allowable ^{226}Ra/^{228}Ra = 0.68 pCi/g/0.0132 = 51.7 pCi/g

(Note: Rounding errors account for the difference between the ANL value of 51.6 pCi/g and the calculated value of 51.7 pCi/g.)

The important factor in this analysis is that the radium isotopes account for only a fraction of the 100 mrem/y dose. The assumed concentration of ^{232}Th in the TENORM mix accounts for a portion of the dose. A different mix of radionuclides in the TENORM would result in a different estimated maximum allowable total radium concentration. The ANL calculation is conservative in that it assumes a ratio of ^{232}Th activity concentration to total radium that is higher than the average measured value for the TENORM evaluated in the study.

1.1.11 Summary of Argonne Study Conclusions and Recommendations

The Argonne study concludes the following:

- Potential doses to well site workers appear to be acceptable based on average activity concentrations and the appropriate use of PPE.
- For well site operational scenarios, the pipe cleaning and storage tank cleaning workers received the highest doses.
- The estimated doses from accidental public exposure to improperly managed filter socks and proppant were a small fraction of the public dose limit of 100 mrem/y under all scenarios modeled.
- The estimated annual dose the driver involved in transporting TENORM waste to the landfill was a small fraction of the public dose limit of 100 mrem/y.
- Increasing the depth of the TENORM wastes in the landfill can effectively reduce doses in future-use scenarios.
- Further refinement of data parameters for the hydrologic modeling (such as site-specific distribution coefficient values or site-specific hydrogeological data) is not warranted given that the groundwater exposure pathway is not a significant contributor to dose.
- Initial waste characterization data for TENORM waste stream generated by oil and gas production in North Dakota indicate that thorium may be present in the wastes in addition to radium.

The study also concludes that "establishing a total radium limit that takes into account the levels of thorium that may be present is a conservative approach…"

The Argonne Report makes the following recommendations:

- It may be necessary for some workers (primarily at the well site) to wear PPE to keep exposures to acceptable levels.
- Additional analyses may be necessary to ensure that pipe cleaning and storage tank cleaning workers do not receive annual doses greater than 100 mrem/y.
- North Dakota solid waste landfill regulations may be safely modified, such that the maximum exposure to any landfill worker should not exceed 100 mrem/y, by allowing TENORM wastes (note: as defined by North Dakota and as discussed in this study)[2] containing an average concentration less than 50 pCi/g total radium (independent of background radium levels) to be disposed in either Special Waste or Industrial Waste Landfills, based on the following conditions:

[2] The Argonne study did not address drill cuttings, frack sands or drilling fluids, which constitute a significant fraction of oil and gas wastes and tend to have ^{226}Ra concentrations in the range of background.

- No more than 25,000 tons of TENORM wastes are disposed in a single landfill per year. *(As noted previously, North Dakota defines drill cuttings, frack sands and mud as NORM rather than TENORM, excluding them from this landfill tonnage limitation. They constitute a large fraction of E&P wastes. Because the state of Montana includes these materials in its own definition of TENORM, the volume limit in the ANL recommendations is not directly relevant to Montana regulations.)*
- The average thorium activity in the waste does not exceed 24 pCi/g. (This concentration assumes a thorium to radium ratio of 49 percent at 50 pCi/g total radium, a conservative assumption.)
- TENORM wastes must eventually be covered by at least 2 meters of a combination of the landfill cover materials and clean wastes that do not contain radionuclides.

  (Note: While not stated in the report, the last bullet was probably intended to specify radionuclide concentrations above background, since earthen materials contain natural radionuclides.)

APPENDIX E
Discussion of USDOT Transportation Regulations in the Context of TENORM

APPENDIX E

DISCUSSION OF USDOT TRANSPORTATION REGULATIONS IN THE CONTEXT OF TENORM

The exempt concentration for ^{226}Ra in U.S. Department of Transportation (DOT) regulations (49 Code of Federal Regulations [CFR] 173.436) should not be used to determine whether a load meets a specific landfill threshold. In fact, as a result of an exception in the regulations that applies to naturally occurring radionuclides not generated for the purpose of extracting radionuclides and being transported for a purpose other than extraction of radionuclides, a load with ^{226}Ra could be transported without placarding at a concentration 10 times the exempt concentration or 2,700 picocuries per gram (pCi/g) (49 CFR 173.401(b)(4)). If the technologically enhanced naturally occurring radioactive material (TENORM) was generated in the process of removing the radium, the 10x exempt concentration would not apply.

Small quantities of TENORM with radium concentrations as high as 270 pCi/g may be acceptable for disposal in a TENORM landfill as long as the average landfill concentration does not exceed the threshold value. However, consideration should be given to determining whether radioactive material licensing under Nuclear Regulatory Commission (NRC) regulations would apply, before a landfill accepts materials with radium concentrations greater than 165 pCi/g.

The exempt concentration for ^{226}Ra was established in the 2004 revisions to the DOT radioactive materials regulations that were intended to achieve compatibility with the International Atomic Energy Agency (IAEA) transport regulations. The revision included a table of radionuclide-specific concentrations and total consignment activities that would be exempt from regulation. The preamble to the DOT Final Rule, published in the Federal Register (Vol 69, No. 16 pp 3634-3637), describes the basis for the IAEA specific radionuclide concentration exemption levels as being concentrations that would not result in a dose exceeding 0.01 millisieverts per year (mSv/y) (1 millirem per year, or mrem/y). However, in contrast to the exemption levels for man-made radionuclides, the IAEA exemption levels for naturally occurring radioactive materials were determined on the basis of the world-wide distribution of activity concentrations for these radionuclides in soils, rather than on a dose basis (IAEA 2004). The IAEA concluded that doses to individuals "as a consequence of these activity concentrations would be unlikely to exceed about 1 mSv (100 mrem) in a year, excluding the contribution from the emanation of radon…"

TENORM produced by the oil and gas industry contains primarily the radium isotopes but also has been shown to potentially contain elevated levels of natural thorium (^{232}Th) and ^{210}Pb, a decay product of ^{238}U. The exempt concentration for natural thorium is 27 pCi/g with all decay products in equilibrium (49 CFR 173.436). Therefore, ^{232}Th, rather than radium, may be the limiting nuclide in oil and gas production TENORM with regard to determining the exempt status of the shipment.

The DOT regulations include a further exemption for naturally occurring radioactive materials that are transported for a purpose other than extraction of uranium or thorium. Subpart 173 of 49 CFR does not apply to "Natural material and ores containing naturally occurring radionuclides which are either in their natural state or which have only been processed for purposes other than for extraction of the radionuclides, and which are not intended to be processed for the use of these radionuclides, provided the activity concentration of the material does not exceed 10 times the exempt material activity concentration values specified in §173.436, or determined in accordance with the requirements of §173.433." Therefore, the concentrations of ^{226}Ra and ^{228}Ra that are exempt from DOT regulation may, in fact, be 2,700 pCi/g and not 270 pCi/g, since the TENORM to be disposed is not intended for use or extraction of uranium or thorium. This issue requires further investigation by radioactive materials transportation experts. However, as noted above, the DOT exempt concentrations are not directly applicable to development of regulations for disposal of TENORM in landfills.

The Argonne National Laboratory study analyzed the potential doses from transportation of TENORM at concentrations equal to the maximum allowed, based on future use-scenarios based on limiting the dose to a member of the public to 100 mrem/y or less. The doses to members of the public from routine transportation at those concentrations were negligible (3.2×10^{-6} mrem/y for 2,000 shipments per year). The dose to the driver was 20 mrem/y. Individual doses from transportation accidents were not calculated; however, the population dose was estimated to be 7.2 person-rem.

Radiological doses and risks from transportation of TENORM are not likely to be the limiting factor in landfill disposal of oil- and gas-generated TENORM or of TENORM in general. While the Argonne study was specific to oil and gas production wastes, the dose calculations can be generally applied to all TENORM. The Argonne study demonstrated that the dose to the landfill worker rather than a member of the public, under current or future land uses, is likely to be the limiting factor in determining the radionuclide amounts and concentrations allowable in TENORM.