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## **E-42 TASK FORCE REPORT**

## **REVIEW OF TENORM IN THE OIL & GAS INDUSTRY**

June 2015

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## E-42 TASK FORCE REPORT REVIEW OF TENORM IN THE OIL & GAS INDUSTRY

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#### **June 2015**

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### FOREWARD

In 2012, the E-42 Task Force was charged by the Conference of Radiation Control Program Directors (CRCPD) Executive Board to examine and review the Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) radiological, environmental, regulatory, and health and safety issues. It was quickly discovered that there was a vast amount of data and publications that discussed many different TENORM issues. The difficulty for the E-42 Task Force was to remain on target and address the specific concerns of the CRCPD Executive Board.

This Report provides a *limited* summary of the changes in TENORM issues post 2003, centering on unconventional oil and gas recovery, especially with the concerns related to hydraulic fracturing. The E-42 Task Force reviewed and looked at some of those changes, particularly those impacting the oil and gas industry regarding radiation exposure and environmental impact issues. North Dakota and Pennsylvania had TENORM studies that were being performed in parallel with this Report; therefore there are few references to those studies in this Report.

The focus areas within the Report are:

- to assess and provide recommendations for TENORM human radiation exposure and environmental issues; and as well as
- to assess and evaluate TENORM worker and public awareness and training issues. The Report also compiles a summary of the guidance and regulations for TENORM established by various standards setting authorities. This summary is provided in Appendix B (Table B-2).

An attempt was made to provide the reader with an estimate of the potential environmental impact from the management and disposal of wastes from unconventional oil and gas recovery operations. This was done by utilizing available data to estimate industry average concentrations and volumes. Common disposal scenarios for TENORM materials containing the estimated source term were then modeled using RESRAD to produce dose estimates. Except where otherwise noted, the default parameters were utilized since it was not within the scope of this paper to establish site-specific environmental parameters. The default parameters in RESRAD may or may not be conservative representations of real world exposure scenarios and the use of site specific parameters, therefore, is strongly encouraged. As a result, the reader should review these dose estimates in the context of qualitative assessments only and rely upon site-specific data for accurate assessments of environmental impact. The E- 42 Task Force is making the following recommendations to the CRCPD Executive Board:

- Establish a more consistent definition of TENORM.
- Review the acceptance criteria in *SSRCR Part N* for adequacy, using a consistent dose and regulatory approach.
- Further evaluate of the extent and quantification of lead-210 (Pb-210) and polonium-210 (Po-210) contamination and exposure to radon for radiation protection of oil and gas workers.
- Review and insert applicable TENORM radiation safety training requirements in the *SSRCR Part N*.
- Work with stakeholders to establish a radiation exposure baseline for oil and gas workers exposed to TENORM activities.
- Develop consolidated TENORM safety guidance and identify best practices for use by oil and gas facilities.
- Incorporate TENORM assessment in the early phases of oil and gas permitting.
- Amend existing regulatory programs, including *SSRCR Part N*, to include an assessment of TENORM. This should also address the lack of effluent restrictions in *SSRCR Part N* and the current land application exemption limit of 0.037 Bq/g (10 pCi/g), which does not account for buildup of radium in soil.
- Collect and maintain a compendium of state regulations and guidelines pertaining to the management and disposition of TENORM.
- Compile and maintain a database of the concentrations volumes and radiation fields associated with the oil and gas operations and activities.

The emphasis of this Report is on the need for nationwide scientific consistency in a more standard regulatory framework to ensure public health and protection of the environment.

Outh

Jared Thompson, E-42 Chairperson Conference of Radiation Control Program Directors, Inc.

## PREFACE

This E-42 Task Force Report was prepared in accordance with the following Conference of Radiation Control Program Directors (CRCPD) charge issued December 2013, as follows:

Publish a "Report" that examines and reviews the TENORM radiological, environmental, regulatory, and health and safety issues observed since the publication of the CRCPD E-4 report (1994) and the E-36 Implementation Guidance (2003).

#### The "Report" will at least summarize the following TENORM issues:

- a. Provide assessments and propose recommendations for the following:
  - TENORM Radiation Exposure Issues Occupational/Public, ٠ including but not limited to regulatory impacts and health and safety.
  - TENORM Environmental Impacts from industry technologies, including but not limited to disposal options for various types of TENORM waste.
- b. Assess and evaluate TENORM Worker Awareness Training and general Public Awareness Information.

Ruth E. McBurney, CHP **Executive Director Conference of Radiation Control** Program Directors, Inc.

## ACKNOWLEDGMENTS

The E-42 Task Force would like to acknowledge and thank the following individuals for contributions to this E-42 Task Force Report.

• Patrick Kelly – Radiochemist/Health Physicist - SC&A, Inc.

Mr. Kelly authored *Appendix D* - *Radioanalytical Protocols* for this Report. This appendix contains laboratory protocols and methodology for the analysis of radionuclides from TENORM activates. This contribution provides excellent guidance to regulators and the oil and gas stakeholders.

• Mark Krohn, Senior Health Physicist and TENORM Consultant – SC&A, Inc.

Mr. Krohn participated in many of the E-42 Task Force meetings and provided data, field knowledge and experience with TENORM radiation safety training and TENORM remediation activities. His knowledge and experience greatly benefited the E-42 Task Force in gaining clarity and understanding of many different technical activities associated with TENORM.

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The Chair of the E-42 Task Force would like to personally thank his secretary, Kay Page with the Arkansas Department of Health. Mrs. Page reviewed and made correction on multiple drafts of the Report. She was very meticulous and thorough in making the necessary changes. Her assistance and professionalism is greatly appreciated.

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## ABSTRACT

Conference of Radiation Control Program Directors, Inc., *Task Force E - 42 Task Force Report Review of TENORM in the Oil & Gas Industry*, CRCPD E-15-2, June 2015, 119 pages.

This document examines and reviews the Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) radiological, environmental, regulatory, and health and safety issues observed since the publication of the CRCPD E-4 report (CRCPD94-2) and the E-36 Implementation Guidance (2003).

This document provides assessments and proposes recommendations on radiation exposure, radiation safety training, and environmental impacts related to TENORM in the oil and gas industry.

#### **INTRODUCTION**

Significant changes in Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) issues have occurred since the publishing of: NORM Report #3: Report of the E-4 Committee on NORM Contamination and Decontamination/Decommission, Report 3 *(CRCPD 1994);* and Implementation Guidance for Regulation and Licensing of Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) Part N of the Suggested State Regulations for Control of Radiation (SSRCR), prepared by the CRCPD Task Force on TENORM (E-36) *(CRCPD 2003)*.

This Report looks at some of those changes, particularly those impacting the oil and gas industry regarding radiation exposure and environmental impact issues, and provides recommendations for areas that may need additional CRCPD attention to assure protection of workers, the public, and the environment. Additionally, this Report looks at the status of information that is provided to workers and the public for their radiological protection, and provides recommendations for areas that may need additional CRCPD attention.

It should be noted that historically, the term Naturally Occurring and Accelerator-Produced Radioactive Materials (NARM) was used to describe naturally occurring and accelerator-produced radioactive materials that were not included in the radioactive materials subject to regulation under the *Atomic Energy Act*, (AEA 1954) and therefore left to the states to regulate. That condition is no longer applicable since accelerator-produced radioactive materials and discrete sources of radium-226 (Ra-226) are now regulated under the *Atomic Energy Act* due to changes brought about by the *Energy Policy Act of 2005* (USEPA 2005).

Naturally Occurring Radioactive Material (NORM) has been further divided between NORM in its undisturbed natural state, and TENORM, which is NORM that has undergone some type of technological enhancement, but excludes discrete Ra-226 sources.

There have been a number of significant developments over the last ten years that have impacted the hazards associated with TENORM. The most significant have been with respect to unconventional shale oil and gas operations, and to a lesser extent possible contamination of drinking water aquifers (among other industrial sectors<sup>1</sup>). Numerous stakeholder groups have expressed concern over alleged environmental damages and insults to worker and public health and safety related to unconventional drilling methods, primarily horizontal drilling combined with enhanced stimulation. The current preferred method for enhanced stimulation is hydraulic fracturing (fracking).

Fracking activities produce and receive the following that often contain NORM:

- flowback water, brines, and other liquids (e.g., produced water, condensates) generated from oil and gas well fields;
- residuals from treatment facilities;
- scales;
- sediments;
- sludges;
- contaminated material and equipment (e.g., filter socks); and
- liquid discharges.

In addition, the gas and oil itself may contain elevated levels of radon. Although data and studies of TENORM in conventional oil and gas wells are fairly comprehensive, data characterizing TENORM associated with unconventional shale oil and gas exploration and production are more limited. While directional drilling and enhanced stimulation have been used in various capacities for decades, only in the last decade have the techniques been combined and refined to exploit shale deposits. This has resulted in significant changes to the radiological issues surrounding fracking. One of the purposes of this Report is to help further develop an understanding of TENORM associated with this growing industry and evolving technology.

Guidance directly or indirectly applicable to the management of TENORM has been issued by various standard-setting bodies. Sixteen states have standards for the management of TENORM in general and TENORM specifically associated with the oil and gas industry. A summary of these guidelines and standards is provided in Appendix B.

Extensive developments of the oil and gas industry due to the introductions of new techniques have occurred since the publication of these documents and the issuance of many of these regulations. It appears that the locations (i.e. shale plays<sup>2</sup>), volumes, and concentrations of TENORM that now need to be managed

<sup>&</sup>lt;sup>1</sup> Other industrial sectors include, but are not limited to: uranium overburden, hard rock mine wastes, rare earth minerals processing, phosphogypsum, fossil fuel combustion residuals (e.g., fly ash), and geothermal exploration. These industrial sectors are not addressed in this report.

<sup>&</sup>lt;sup>2</sup> A play is defined as a set of known or postulated oil and or gas accumulations sharing similar geologic, geographic, and temporal properties, such as source rock,

are significantly greater than those that existed when the original documents were published. New standards and revisions are being considered in some states and localities.

Many of the regulatory revisions currently underway relative to fracking are focused on the chemicals injected to frack the well; few if any address the presence or disposition of TENORM produced in the fracking process. In addition, the public and private sectors continue to collect data and operational experience that further the understanding of the nature and content of TENORM and the potential for radiological exposure as a result of oil and gas activities. One result of preparing this Report was to begin to compile in one place the guidance established by standard-setting bodies and the regulations either developed or being developed by state authorities.

A primary charge to the E-42 Task Force is to examine and review changes impacting oil and gas industry related to TENORM issues since the publication of previous guidelines and state regulations. This Report attempts to summarize the ongoing research and publications by government and non-governmental organizations and consolidates the body of new literature. This begins the process of expanding and refining our understanding of the issues, and identifies knowledge gaps and policy issues in order to better address issues associated with the management of TENORM associated with the oil and gas industry in the United States.

The following issues are of particular interest:

There is a need to review the CRCPD definition of TENORM. Currently, CRCPD and Agreement States that have adopted *SSRCR Part N, Regulation and Licensing of Technologically Enhanced Naturally Occurring Radioactive Material* (CRCPD 2004) limit the definition of TENORM only to material where the natural concentration of NORM has been enhanced. Some other organizations have a broader definition, which includes material being defined as TENORM if that material is moved from a relatively inaccessible location to a more accessible location, even if the concentration of NORM in the material is unchanged, such that there is an increased chance of exposure or environmental mobility. It should be noted that earlier versions of *SSRCR Part N* did include materials removed from their place of initial existence and made more accessible to the human biosphere.

The current definition of TENORM excludes byproduct material to avoid dual regulation. As has been noted the definition of byproduct material was expanded in the *Energy Policy Act of 2005* (EPA 2005) to include purposely

migration pathways, timing, trapping mechanism, and hydrocarbon type (Biewick, L.R.H., G.L. Gunther and C.C. Skinner 2002).

concentrated discrete sources of Ra-226 (referred to as 11e. (3) Byproduct material). The United States Nuclear Regulatory Commission (USNRC) has interpreted the definition of 11e. (3) Byproduct material to also include diffuse Ra-226 that originated from 11e. (3) discrete sources (CFR 2007).

A more complete understanding is needed of the geochemical processes that result in some plays in the United States having substantially higher levels of Ra-226 in cuttings and residual and produced waters than others. In addition, even within the same plays the concentration of Ra-226 in produced water varies by several orders of magnitude and the concentration and volumes in an individual well likely also will vary overtime.

There may be physical, chemical and radiological differences in the cuttings, residuals and produced water between conventional and unconventional wells and wells developed using conventional and unconventional drilling and enhanced stimulation techniques. Thus, there is a need to determine the reasons for the differences that results in variation in TENORM content.

In addition to the environmental settings, there is a need to better understand the variability in the radionuclide composition, including Lead-210 (Pb-210) and Polonium-210 (Po-210), in the scale and sludge associated with the oil and gas equipment in use. The radionuclide content is one of the reasons for the variability in the beta/gamma radiation fields in the vicinity of systems, structures, and components that-are affected by TENORM, along with shielding and attenuation. A better understanding of these mechanisms may lead to improved methods of measurement and worker protection.

### INDUSTRIAL AND REGULATORY BASELINE

#### **Industrial Baseline**

As discussed in the introduction, the oil and gas industry has undergone and continues to undergo a metamorphosis. Primarily this is because of the advent of unconventional drilling, also known as horizontal drilling, and enhanced stimulation, also known as fracking, which is being done in unconventional formations such as shale oil and gas formations and other tight sedimentary formations. As indicated in Figure 1, the geographical extent of the regions of the United States potentially impacted by these technological developments is enormous.

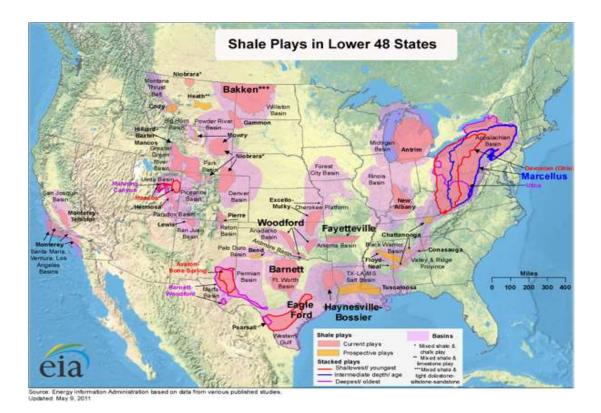


Figure 1. Major Shale Gas Locations in the United States (GWPC 2009).

Also see the report by the U.S. Government Accountability Office (USGAO), Oil and Gas – Information on Shale Resources, Development, and Environmental and Public Health Risks (GAO 2012).

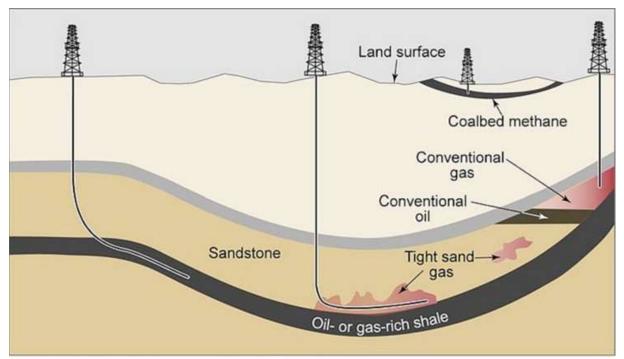
The technologies being used to exploit these resources are in many ways similar to conventional technologies of vertical drilling, but in some ways they are different in terms of the magnitude and extent of the concentration and volumes of TENORM that are being produced and must be managed.

For example, Figure 2 reveals the fundamental differences between conventional and unconventional drilling in:

- coal beds;
- conventional gas pools;
- conventional oil pools;
- tight sand gas; and
- shale oil and gas formations.

These differences primarily:

- reduce the volume of flowback water at wells that employ enhanced stimulation (which include both conventional vertical wells and unconventional wells that employ horizontal drilling); and
- reduce the quantities of and radionuclide concentration of drill cuttings, produced water, and contaminated equipment among the alternative oil and gas exploration and production processes and formations.



Sources: U.S. Energy Information Administration and U.S. Geological Survey.

Figure 2. Differing Techniques for Resource Exploitation (TMWC 2014).

The various systems and components associated with both conventional and unconventional drilling where TENORM may accumulate include:

- tanks;
- pipes;
- storage ponds and pits;
- spill locations; and
- other equipment such as pumps, compressors, etc., that might contain or have come in contact with cuttings, produced water, and drilling mud.

Unconventional drilling in shale formations results in a larger intersection of host formations containing NORM that increases the likelihood of generating TENORM. The main differences between conventional and unconventional drilling with respect to TENORM in residuals are in the amount of equipment and the volume and liquids, solids, waste, and residues from activities offsite (such accumulation of filter socks), that might contain TENORM and will require appropriate management and disposition to protect the public to the potential harmful effects of TENORM. In addition there is some evidence that the concentration of TENORM may be somewhat higher at facilities involved in unconventional drilling. Appendix A presents a listing of reports that provide more information on the differences between conventional and unconventional drilling.

#### **Regulatory Baseline**

These changes in the TENORM issues associated with the rapid expansion of unconventional drilling in unconventional formations have highlighted some aspects of the existing regulatory structure that need to be revisited to ensure they continue to be adequate in today's environment. Appendix B summarizes the current regulations and standards that apply to the management of TENORM in the oil and gas industry. These regulations should be reviewed and as necessary, updated, streamlined, and established on a sound scientific basis that strikes a balance between costs and benefits that likely differ among technologies and sites.

The E-42 Task Force review of the regulations summarized in Appendix B and the experience of many of the participants on the E-42 Task Force reveals a recurring overarching theme. This concerns the inconsistencies in regulations and the possible need for consensus on the scope and requirements of a TENORM permitting process.

Currently, *SSRCR Part N* addresses exemption criteria applicable to all facilities handling TENORM (CRCPD 2004). However, the E-42 Task Force recognizes that oil and gas facilities and many of its supporting facilities, such as pipelines and produced water treatment facilities, require one or more licenses and/or

permits from a number of state regulatory authorities. Often the overall licensing and permitting requirements are established by the state (Departments of Health, Departments of Environmental Protection, Divisions of Air Quality, Departments of Conservation, Oil and Gas Commissions, etc.). Some states explicitly address the management of TENORM as part of the overall licensing and permitting process. For example, the Commonwealth of Pennsylvania requires a Radiation Monitoring Action Plan as part of the overall permitting process. Such plans are often submitted very early in the permitting process, before the facility is given authorization to begin construction and operation.

The E-42 Task Force believes that all such facilities should be required to file supporting material that addresses TENORM issues. Specifically, one of the issues of concern to the E-42 Task Force is whether or not it should be a regulatory requirement to identify possible TENORM prior to any drilling. Should the applicant be required to describe the operation (example flow diagrams and plot plans) and the types, quantities, and radionuclide composition of water and solids that are anticipated to be received, stored, produced, handled, processed, shipped, and disposed of as part of the life cycle of the facility? If so, the application should also include a description of the cleanup criteria for releasing a site for unrestricted use and the handling, disposal, and or reuse of the equipment upon termination of operations, as well as arrangements for financial assurance to ensure adequate cleanup. Included among this descriptive material should be analyses that estimate the radiation doses, both external and internal, that might be experienced by workers at the site, taking into consideration uncertainties in facility design and operation and possible off-normal conditions.

Based on these analyses, the applicant should determine the degree to which a radiation protection program, including training, might be needed for workers and visitors to the site. For example, at a minimum, awareness training is needed if TENORM is expected to be present at the site. A more comprehensive radiation protection program and training will be needed if the anticipated doses are in excess of some trigger level (action or alert level), such as 0.25 mSv or 1 mSv/yr (25 or 100 mrem/yr). In addition, consideration needs to be given to the establishment of trigger levels expressed in terms of concentrations in residual radionuclides in soil, residue, and equipment prior to releasing a site or equipment for unrestricted use.

Notwithstanding the results of these analyses, consideration should be given to requiring that the application include descriptions of post-operational radiation surveys and TENORM sampling and analyses programs. The extent of the survey, sampling, and training programs (i.e., the overall radiation protection program) should be:

- commensurate with the level of potential exposures anticipated to be experienced by the workers; and
- the levels of contamination.

Should the anticipated exposures exceed some trigger level, and/or the potential exists for internal exposure, personnel dosimetry and protective clothing, including respiratory protection, should be incorporated into the radiation protection program. In addition, the application should include consideration to establishing unrestricted release criteria for the site and its equipment. Such survey programs are needed:

- to confirm the predictions made in the applications;
- to ensure that exposures remain below established radiation protection standards; and
- to comply with prudent as low as reasonable achievable (ALARA) designs and practices.

This material should be provided in the permit application to a level of detail commensurate with the level of anticipated exposure and the types and quantities of TENORM that will be handled at the facility.

## CHARACTARISTICS OF OIL AND GAS TENORM

A vast body of literature has been compiled that characterizes the concentrations of naturally occurring radionuclides in the geologic formations, the source of the TENORM that finds its way to the various facilities that comprise the oil and gas industry. Included among the reference documents is *NORM Report #3: Report of the E-4 Committee on NORM Contamination and Decontamination/Decommission, Report 3* (CRCPD 1994). The report provides a useful starting point for understanding the geologic formations and industrial activities known to be associated with elevated NORM levels. *NORM Report #3* (CRCPD 1994):

- provides background for understanding why the industries that exploit the natural resources found in certain geologic formations are challenged with managing TENORM;
- explains that NORM is present virtually everywhere, but certain types of geologic formations have elevated levels of NORM;
- explains that in the process of exploiting the natural resources associated with these formations, the products, byproducts, equipment, and waste products associated with many different industries tend to extract and concentrate the NORM in these

formations and bring the material into contact with industry workers and members of the public;

- provides a concise explanation of the origin of TENORM in the oil and gas industry, and the physical and chemical processes that result in mobilization and concentration of naturally occurring radionuclides, especially Ra-226, in the oil and gas industry; and
- briefly describes the complex geochemical and industrial processes that result in TENORM.

E-4 Report (CRCPD 1994) concludes with the following summary:

In summary, there are a number of physical and chemical processes which may move radionuclides from ore bodies and in situ mineral deposits and concentrate them in the biosphere. In most circumstances, where mineral extraction is intended to retrieve radioactive materials for the purpose of exploiting their radioactivity, appropriate controls are applied. Where minerals remain in undisturbed geological settings, no exposure to radiation levels above the ambient background level occurs. However, where technological enhancement involves chlorination, changes in pH, changes in reductionoxidation potential, changes in solubility, or preferential adsorption or absorption, and sufficiently large volumes of material are processed, the potential for increased radionuclide concentration should be anticipated. (CRCPD 1994)

While characterizing and quantifying the hazards and risks to workers and the public associated with TENORM in the oil and gas industry has occurred in some situations, in other situations it has not occurred, particularly in states that do not actively regulate TENORM. This is further complicated in situations where the radiological hazards have expanded significantly as a result of more recent developments in oil and gas production. This section of the Report identifies a path forward for increasing our understanding of the exposure conditions and scenarios and their magnitude, and for making judgments regarding the need for regulations and other controls or facility design and operating protocols that might help to manage TENORM in a cost-effective manner. It also lists the literature available that can contribute to our understanding of this subject.

An understanding of the potential hazards associated with TENORM in the oil and gas industry requires an understanding of:

- the many components that comprise the oil and gas industry;
- the types, concentrations, and volumes of TENORM associated with each component of the oil and gas industry; and

• the normal and off-normal operations and maintenance activities associated with the various components of the oil and gas industry that can give rise to radiation exposures to workers and members of the public.

These potential radiological hazards are discussed in the following sections of this Report.

### OVERVIEW OF OCCUPATIONAL RADIATION EXPOSURE ISSUES ASSOCIATED WITH THE OIL AND GAS INDUSTRY

An important task in evaluating the occupational radiation exposure issues associated with TENORM in the oil and gas industry is identifying the categories of the industry's workers that are likely to experience external or internal radiation exposures from TENORM.

The oil and gas industry is large and complex, and a comprehensive analysis is required to ensure that these workers are adequately trained and, if necessary, monitored for radiation exposure. A number of reports have been published that address radiation protection of workers in industries associated with TENORM and should be consulted as references for worker protection. The most recent such published reports address worker and public radiological issues primarily specific to the oil industry in North Dakota and the natural gas industry in Pennsylvania. These reports have been used to inform this section.

See Figure 3 that illustrates where opportunities for worker exposure may occur. Naturally-Occurring Radioactive Materials (NORM) can be encountered, and concentrated at each of these steps.

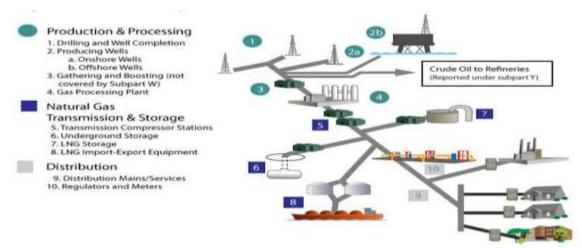


Figure 3. Various Activities Involved in Natural Gas Drilling, Storage and Transportation (PaDEP 1992).

# CATEGORIES OF WORKERS AND ASSOCIATED RADIATION PROTECTION ISSUES

This section expands upon the occupational radiation protection measures that are emerging due to increased concern for workers involved in unconventional drilling. This discussion includes the following categories of worker and associated radiation protection issues.

## Workers Who Perform Maintenance on Equipment That Is Contaminated with TENORM

Examples of this type of equipment may include equipment used to extract, handle or process oil and natural gas that can have scale contaminated with radium and high radon buildup. These scales present external and internal hazards. Workers in confined spaces such as tanks that contain sediments and sludges also can be exposed to TENORM and internal and external exposures can occur. Workers who handle sock filters and filter cake can also be exposed. In addition, gas lines and equipment can have high levels of Po-210 and Pb-210 that present internal hazards. These radionuclides are difficult to detect because they are pure alpha/beta emitters and can result in possible internal exposures to workers if inadvertently inhaled or ingested. This equipment is periodically taken out of production and sent back to the shops for refurbishing, where the potential for exposure to Pb-210 and Po-210 can be increased due to the refurbishing activities.

## Workers at the Shops Where Bits, Pumps, Lift Valves, etc., Are Cleaned and Maintained

This work can include rattling, grinding and fabrication and repair that can mobilize TENORM on the equipment.

#### Workers Who Handle Equipment That Is Used Downhole in Gas Wells

This equipment may include equipment such as gas lift valves that become contaminated with Po-210 and Pb-210 on interior surfaces.

#### Inspectors of the Large Interstate and Intercontinental Gas Lines

The inspections include running a pipeline inspection gauge (PIG), a device used for inspecting and scraping pipe interiors, through the gas lines. Many times when the PIG is retrieved, it could be highly contaminated with Pb-210 and Po-210.

## Workers at Centralized Waste Treatment (CWT) Facilities and Zero Discharge Facilities Who Handle Sediments and Filters

Elevated gamma exposure rates may be present near some tanks and filter banks. If allowed to dry, residues could become an inhalation hazard.

## Workers at Publically Owned Treatment Works (POTW) Where the Wastewater Is Sent

Although this practice is being discouraged, it is still practiced in some locations. The hazards to workers are similar to those at Centralized Water Treatment Facilities.

#### Workers at Injection Wells, Recycling and Disposal Facilities

Workers are primarily exposed to external radiation, but in some instances (e.g., spills), inhalation or ingestion could be a hazard. Workers who handle scrap at recycling facilities may have a potential for exposure; however most recyclers monitor for radiation and reject all contamination.

#### Workers Who Transport Produced Water, Production Water, and Other Residuals

Workers who may dispose of waste by applying it to the land (land apply) or otherwise discharge TENORM-contaminated liquids to the ground.

#### Workers at Natural Gas Plants (Dry) and Natural Gas Liquid Plants (Wet) and Workers Involved in the Processing and Handling of Produced (Raw) Natural Gas

Processing this gas for industrial use and in order to meet U.S. pipeline specifications results in the removal of hydrocarbons heavier (i.e., less volatile) than methane, pentane, as well as nitrogen, sulfur, carbon dioxide, and water vapor. These heavier molecular weight fractions of raw natural gas are referred to as Natural Gas Liquids. These are comprised of ethane, propane, butane, and pentane. Because radon is less volatile than methane, it can remain in the Natural Gas Liquids after separation.

#### Estimating External and Internal Radiation Doses

Once the categories of workers who may be exposed to radiation hazards have been identified, the next task is to estimate the expected external and internal radiation doses that they are likely to receive. In addition to the scenarios cited, other occupational situations may arise that require analysis. The E-42 Task Force believes that exposure scenarios and dose estimates should be:

• developed from industry specific assessments;

- based on empirical data from measurements and sampling when possible; and
- reviewed by the regulatory authorities, standard-setting bodies, and the research and academic community.

Another important issue pertains to the establishment of trigger levels using gamma and/or beta survey equipment. As indicated in this section, alpha emitting TENORM can accumulate on the inside of piping and equipment. Although this buildup may not pose a hazard to workers during normal operations, it can become a hazard to others if the pipe and equipment is released for unrestricted use.

Gamma surveys are relatively easy to perform and should be part of a periodic monitoring program and conducted prior to the release of any such materials and equipment. However gamma surveys alone are not sufficient when gamma emitters are shielded. Furthermore, these surveys may not adequately capture exposure hazards present from alpha and beta emitters such as Pb-210 and Po-210. Given the high radiotoxicity and the potential for which an Annual Limit Intake (ALI) can be reached by workers, this circumstance warrants additional investigation. There may be situations in which internal doses contribute a significant fraction of a worker's total dose. Therefore, even qualitative screening for elevated count rates of beta/gamma and alpha activity should be a routine step before allowing individuals to work on internals of equipment.

Detection of these radionuclides requires direct access to or sampling of the solids deposited on the interior surfaces of pipelines and drilling equipment. The detection of pure beta emitters (e.g., Pb-210) requires specific detection instrumentation designed to detect beta emitters, e.g., Geiger–Müller (GM) tubes with open/closed probes. Po-210 is a pure alpha emitter and also requires specific detection instrumentation (e.g., zinc sulfide (ZnS) scintillator probe). These types of survey instruments will detect the presence of Pb-210 and Po-210, but the quantification of the concentration of these radionuclides in solids, residues and scale would require special radiochemical analysis. Radioanalytical protocols are included in Appendix D.

Environmental deposition of radium from TENORM activities can, as a result of radon production, impact both doses to the public and to workers. Radon produced as a result of radium deposition can accumulate in buildings and structures and easily exceed either a .25 mSv (25 mrem) or 1.0 mSv (100 mrem) annual dose above background. As a result, it is important to investigate and assess exposure to radon for those individuals who work in or occupy structures built on land that has been subject to radium disposition. Radon monitoring and mitigation should be performed in these situations to reduce potential exposures to workers or members of the public. This is further discussed in the section of this Report entitled "Environmental Impact from

Technologically Enhanced Concentrations of Radionuclides in Oil and Gas Waste Streams."

Whereas individuals, whose work is authorized by federal and state radioactive materials licenses, have occupational criteria for exposure to radon (10 CFR 20), there are no such protective standards for other workers. The U.S. Occupational, Safety and Health Administration (USOSHA) has radiation exposure limits in its regulations; however they have not been updated in almost 40 years and are not consistent with allowable doses from the International Council on Radiation Protection (ICRP) and National Council on Radiation Protection (NCRP) and others.

However, there is a national consensus standard published by the American National Standards Institute (ANSI). *ANSI N13.53-2009 Control and Release of TENORM* has recommended limits for "Occupational Radiation Exposure as Non-Radiation Workers" (ANSI 2009, sec. 2.2.6.). The ANSI standard also has environmental release limits for outdoor radon equivalent to 0.0185 Bq/L (0.5 pCi/L) at downwind locations or property boundary, and limits equivalent to 0.148 Bq/L (4pCi/L), along with criteria for calculating working levels (WL) and sum of fractions for when thoron is also present (ANSI 2009), as described in Appendix B of this document.

Selected excerpts *ANSI N13.53-2009 Control and Release of TENORM* are presented here for informational purposes.

Occupational doses received during manufacturing, handling, use, storage, transportation, and distribution of products containing TENORM shall be controlled under normally encountered conditions such that the following limits shall not be exceeded:

...an annual limit of 1.0 mSv (100 mrem) above background and including ALARA, from all pathways associated with the presence of radioactivity (except radon and its short-lived decay products.) The dose limit is expressed as total effective dose equivalent (TEDE) from internal and external exposures.

...annual average radon concentration of 150 Bq m–3 (4 pCi L–1), an equivalent radon gas limit based on working level (WL) concentration using relevant guidelines from the U.S. Environmental Protection Agency (USEPA), or a radon gas or WL concentration defined by the Occupational Safety and Health Administration (USOSHA) and Mine Safety and Health Administration (MSHA).

Work conditions likely to result in doses or exposure to radon in excess of the above limits under routine conditions shall warrant the implementation of a formal occupational radiation protection and monitoring program and use of appropriate engineered controls and administrative safety measures. A radiological assessment shall confirm whether (a) doses from external and internal exposures are above these limits in light of working conditions and types of TENORM-bearing materials being used or (b) the practice is subject to regulatory oversight under appropriate state or federal regulations with occupational dose limits established for "radiation workers," including those addressing health and safety program managed in compliance with OSHA or MSHA requirements. (ANSI 2009)

There are additional provisions relative to calculating working levels and sum of fractions calculations for when radon-220 (Rn-220) is also present.

### ENVIRONMENTAL IMPACTS FROM TECHNOLOGICALLY ENHANCED CONCENTRATIONS OF RADIONUCLIDES IN OIL AND GAS WASTE STREAMS

Wastes<sup>3</sup> exhibiting elevated levels of radioactivity generated from oil and gas production take the form of:

- drill cuttings;
- drilling fluids and mud;
- produced water;
- flowback water;
- filters;
- condensate; and
- accumulated sediments (i.e. tank bottoms or sludges).

These and others are described and discussed in Appendix C-1.

Radioactivity can also concentrate in the mineral scales that form in pipes, storage tanks, or other extraction equipment. Spills and mismanagement of these materials also may present completed pathways to receptors. Uranium and thorium are naturally present in these oil and gas producing formations as are their progeny. However, due to the low solubility of the parent nuclides, secular equilibrium is disrupted and their radium progeny are disproportionately represented in the waste streams. (Thorium follows transient equilibrium as it has a short-lived radionuclide near the top of decay series.) Although uranium and thorium will be present in drill cuttings and sometimes found in sludges and sediment, they are usually present in much lower concentrations than radium. Consequently, the radionuclide of concern in these wastes are primarily Ra-226, radium–228 (Ra-228), and their progeny; although unsupported Pb-210 and Po-210 have been found as well (IAEA

<sup>&</sup>lt;sup>3</sup> Although referred as waste, some of the solids and liquids can be beneficially reused.

2003)<sup>4</sup>. Radon, a noble gas, is present both as a result of extraction from the formation and as a product of radium decay in the resulting waste streams. As radon further decays, Pb-210 and Po-210 can concentrate in gas valves, filters, pipelines, railcars, and trailers. Because radon is a gas, and preferentially follows other gaseous phases of refinement and transportation, the nuclides of concern shift once past the compressor station and points at which the volatile fractions of natural gas are removed. (Radon preferentially follows ethane and propane.)

The environmental fate of each waste stream is based upon the commonly employed disposal options. Where sufficient data are available (average volumes generated and the typical radioactivity associated with each waste form), a measure of the environmental impact is provided in terms of increased natural background radiation.

Finally, the magnitude of the resulting environmental impact is provided in terms of a conservative estimate of total effective dose equivalent (TEDE) dose to the average member of the critical group. The data supporting each waste stream characterization (radionuclides and concentrations, as well as chemical, physical form and volume) are consolidated for the reader into Appendix C-1. The data is the basis for the following summary and any resulting recommendations.

- produced water containing 0.05-190 Bq/L of Pb-210;
- hard scale containing 0.02-75 Bq/g of Pb-210; and
- sludge containing 0.1-1300 Bq/g of Pb-210 (IAEA 2003, Table III, p. 56).

<sup>&</sup>lt;sup>4</sup> International Atomic Energy Agency (IAEA) reports:

<sup>•</sup> crude oil as containing 0-0.01 Bq/g of Po-210;

natural gas containing 0.002-0.08 Bq/m3 of Po-210 and 0.005-0.02 Bq/m3 of Pb-210;

## CHARACTERIZATION OF WASTE STREAM: RADIONUCLIDES AND CONCENTRATIONS, CHEMICAL AND PHYSICAL FORM, AVERAGE VOLUMES

#### **Drill Cuttings**

The volume of cuttings is a function of drill diameter and depth, estimated to be between 0.03 and 0.3 cubic meters for each vertical foot drilled (USEPA 2000). This volume is greatly increased when conventional drill methods (vertical) are then compounded with horizontal drilling. Conventional oil well depth averages approximately 4,000 feet (1,219 m). Based on the range of drill cuttings given, one could maximally predict 1,200 cubic meters of cuttings from a traditional Southwest Energy reports an average of 5,356 feet (1,633 m) of lateral well. well length. On the extreme, in 2011, Halliburton reported drilling a 9,124 foot (2,781 m) lateral length. Drilling depth and length is reportedly even higher in North Dakota with total lengths in excess of 20,000 feet (6,096 m). Intuitively, drill cuttings greatly increase with the implementation of horizontal drilling with modest estimates doubling the volume. Although most data place drill cutting radionuclide concentrations equal to that of the formation, special attention should be paid to those cuttings saturated with drilling mud as these can have substantially higher radioactivity.

#### **Drilling Fluids and Muds**

As drilling fluid is continuously cycled down the drill string and back to the surface and reused from well to well, it gradually takes on the salinity and radioactivity of the formation water, commonly called brine water. Moreover, as the drill fluid saturates and coats the drill cuttings, the characteristics of the rock will be dominated by that of the drilling fluid and brine water. Data reviewed report drilling fluid from high volume hydraulic fracturing operations as ranging from 333 to 555 Bq/L (9,000 to 15,000 pCi/L) and estimated a volume of 151,000 liters per well (USGS 2011; NYS 2009; USEPA 2013). A general trend observed in the literature reviewed was that radionuclide concentrations were higher in horizontally drilled wells than those typically seen in conventional vertical bores. This likely is due to the greater surface area of exposure between the drilling fluids and the regions of the formation elevated in radionuclide concentration.

#### Produced and Flowback Waters

Although the volume of produced water will vary greatly by site and over the lifecycle of a well, studies reviewed estimate an average of 9 liters of produced water generated for every liter of oil extracted in conventional drilling. According to the IAEA, this correlates to a typical range of 2.4 million to 4 million liters for oil-producing facilities and 1,495 to 30,000 liters for gas-producing facilities (IAEA 2003).

In addition to the water produced from the formation, high volume hydraulic fracturing operations utilize several million gallons of water to stimulate oil and gas production. Recent estimates specific to high volume hydraulic fracturing place water usage at 3.8 million to 19 million liters for initial well completion, and up 45.4 million liters through site life (Crosby 2013). Due to the fact that water is injected at high pressures, is simultaneously lost to the formation, and is mixed with formation waters, the exact ratio of produced water to injected water is not well established. For this reason, the volumes of water injected are utilized later in this Report to estimate the source term.

However, as data continue to be collected, and publication of studies are pending, preliminary research indicates the resulting mixture of high volume hydraulic fracturing waters are three to five times higher in radium concentration than that of conventional flowback brine waters. As was the case for drilling fluids, this is likely attributable to the increased contact with waters to the radium-bearing regions of the formation. This area is unlined. Additionally, pressures are much higher than in conventional wells and the conditions created are favorable to radium solubilizing into the liquids present.

A great deal of data has been published on the radioactivity of produced waters from unconventional drilling. Table C-1-1 in Appendix C-1 provides a listing of the data reviewed. The radioactivity of produced waters can be summarized as ranging from 0.7 to 1184 Bq/L (19 to 32,000 pCi/L) with the most recent data indicating concentrations of 248 to 333 Bq/L (6,700 to 9,000 pCi/L).

#### Scale

Conventional oil and gas production has long been known to produce TENORMcontaminated scales. As early as 1989, the Louisiana Department of Environmental Quality was reporting the production of scales containing up to 3,700 Bq/g (100,000 pCi/g) of Ra-226 (USOSHA 1989). USEPA in 1993, referring to conventional production, estimated approximately 91 metric tons of scale per oil well is produced annually in the United States. The same reports estimate, cumulatively, 25,000 metric tons of this scale is NORM-contaminated. The radium concentrations average 18 Bq/g (480 pCi/g); highs are reported in excess of 14,800 Bq/g (400,000 pCi/g) (USEPA 2013). This coincides with the reported ranges from the IAEA. In addition to Ra-226 and Ra-228, IAEA reports that Pb-210 will form a thin layer of deposition in production equipment along with stable forms of lead extracted from the formation. The lead deposits were reported with concentrations exceeding 1,000 Bq/g (27,000 pCi/g) (IAEA 2003). The American Petroleum Institute (API) found that the highest concentrations of TENORM are in the wellhead piping and nearby production piping. "Concentrations were as high as tens of thousands of pCi/g." (USEPA 2013). Recent developments in high volume hydraulic fracturing and natural gas production have increased focus on these radionuclides as TENORM contaminants. This is particularly true in the case of natural gas sock filters,

which can have even higher concentrations and pose management and disposal problems. The largest volumes, however, are in water/gas or water/oil separators and gas dehydrators. Although operators may attempt to mitigate scale accumulation through the use of chemical additions, this simply prevents deposition on equipment and passes it through to the produced water. IAEA stated that a commonly accepted premise was that increased amounts of scale production are correlated to well age and the ratio of water to oil. Furthermore, the introduction of salt water into the formation to enhance recovery is known to increase production. The latter may help to explain the higher scale concentrations reported in high volume hydraulic fracturing operations given the use of water injection.

#### Radon

Insufficient data were found to derive an average concentration or volume of radon gas at the wellhead. However, a great deal of literature reviewed indicates a tendency towards closed-loop systems, essentially confining any radon and the resulting Pb-210/Po-210 contamination to the piping and equipment. USEPA reports preferential concentration of radon in the more volatile fractions of extracted gas, propane and ethane. As mentioned previously, the radon progeny plate on gas valves, pipelines, and their conveyances. The deposition is heterogeneous within the equipment. Concentrations tend to be higher in areas where there would be turbulence within the system. However, very little data are available to quantify this contamination. Therefore, although the discussion in Appendix C-2 concentrates on the radon concentrations as they pertain to their resulting release into the environment, primarily the natural gas user's home, the resulting exposure concerns are minimal. Therefore, exposure concerns from radon in any TENORM management programs should pay particular attention to alpha/beta contamination throughout equipment and radon generation from concentrated radium-bearing waste streams. Additional discussion on the disposal of radium in the environment and the resulting radon concerns is addressed in Appendix C.

The subject of dose to an individual as a result of radon and its progeny present difficulty when examining the concept of dose-based criteria for the disposition of TENORM materials. In situations that would result in Ra-226 being present on the surface or in near surface burial, radon-222 (Rn-222) and its progeny can contribute up to and in excess of 90% of the total dose to an individual who occupies a structure that is constructed above the dispositional materials. Computer models using relatively conservative assumptions demonstrate that this is the case for small increases in Ra-226 content above background. Concentrations as small as 0.185 Bq/g (5 pCi/g) frequently contribute in excess of 0.25 mSv (25 mrem) and even 1 mSv (100 mrem) annual dose to an individual when modeled for a future inhabitant of a structure built on these sites. This depends on the attributes and use of the site. The restrictions may also need to address monitoring and control of surface contamination.

Materials slightly above background would be deemed likely to be unacceptable for the clearance and release of a plot of land at an affected site if the dose resulting from radon and its progeny were considered. A more reasonable approach would be to use engineering and/or institutional controls to account for and eliminate dose as a result of radon and its progeny. Plots of land that have elevated concentrations of Ra-226 as a result of TENORM disposition should have environmental covenants or other equivalent land use constraints that are legally attached to the deed that would require runoff controls. These constraints also should require that:

- any structures that exist on that site or are constructed on that site in the future employ radon resistant construction methods;
- the structures are monitored for radon; and
- if necessary, the structures are appropriately mitigated to federal, local, and/or state government standards or recommendations regarding the concentration of radon in indoor air.

#### Accumulated Sediments (Tank Bottoms/Sludges)

Conventional oil production processes generate an estimated 5 million cubic feet (141,000 cubic meters) of accumulated sediment each year (USEPA 2013).

IAEA reports a range of 1 to 10 metric tons per year depending on the facility, and radium concentrations ranging from 0.1 to 14800 Bq/g (2.7 to 400,000 pCi/g) (IAEA 2003). Domestically, the USEPA reports the average concentration of total radium (Ra-226 + Ra-228) in these sediments to be 2.8 Bq/g (75 pCi/g) (USEPA 2013). The concentration of Pb-210 has been reported up to 2.8 Bq/g (27,000 pCi/g) (USEPA 2013).

Considering that large volumes of comingled production and brine water are associated with high volume hydraulic fracturing operations, the resulting impoundment will likely increase these amounts considerably. As previously discussed, the increase in salinity and water is linked to increases in scale formation. When these scales are removed, they are deposited as TENORM sediment. At the time of writing this Report, several reports are pending that may provide additional data on both the concentration and volume of high volume hydraulic fracturing sediments.

#### Spills, Leaks and Improper Disposals

All of the sources discussed in this section of the Report can contribute to soil, surface and groundwater contamination depending on the size and location of the spill, leak or improper disposal. While most spills are relatively small, they can occur frequently and can accumulate over space and time. It is possible that TENORM in produced water may be more mobile than usual due to the addition of chemicals that makes slurry.

#### **Disposal Pathways and Environmental Impacts**

The previous paragraphs have attempted to quantify the source terms (volumes and concentrations) for each waste stream. Additionally, when data were available, a comparison between conventional and unconventional production was provided. However, the reader should not use volumes and concentrations as the basis for estimating the potential for public dose. Exposure is not simply a result of radioactivity present, but the exposure pathway as well. Consider for instance:

- a ton of drill cuttings at 1.11 Bq/g (30 pCi/g) uranium/radium;
- waste water treatment sludge at 11.1 Bq/g (300 pCi/g) radium; or
- a ton of scale at 37.0 Bq/g (1,000 pCi/g) radium.

The magnitude of dose is not as clear when the scale is disposed of in an injection well and the drill cuttings are used for landfill cover.

The following section examines the common disposal pathway for each of the waste streams discussed. Based on the source terms described, the potential for public exposure is presented.

Calculations of radiological impact, whether screening or realistic, involve assumptions of not only the concentrations and volumes involved (i.e., source term), but the chemical and physical characteristics that dictate mobility and environmental fate. In short, many modeling scenarios in this section utilized RESRAD  $6.5^5$  with default parameters, unless otherwise specified. These were chosen because they have been commonly associated with a reasonably realistic set of conservative factors applicable across multiple geographic areas and providing sound bounding numbers. The resulting doses are likely much lower and should be adjusted to the source term and site conditions existing in a particular region. However, it should be noted that because many of the waste forms share common environmental deposition methods, the federal regulations and guidelines that are applicable to these disposal options help to define the variables in modeling.

For landfills, these include requirements for:

- cover;
- specified porosity;
- liner requirements; and

<sup>&</sup>lt;sup>5</sup> RESRAD is a computer model designed to estimate radiation doses and risks from RESidual RADioactive materials and is used for the evaluation of radioactively contaminated sites. https://web.evs.anl.gov/resrad/home2/resrad.cfm

• hydrogeological siting requirements.

40 CFR Part 503 Standards for the Use or Disposal of Sewage Sludge, & United States Regulations and Practical Experience on Biosolids Reuse and Disposal land application regulations define minimum depth to the water table, minimum erodibility, and several other factors that greatly control the dose to the receptor. If the environmental pathways are subject to these related regulations, the modeling scenarios can be greatly simplified.

Radon has not been incorporated into the derived doses for the reasons previously discussed in this Report. Should a specific area have restrictions on building codes, mandatory radon mitigation, or other factors that impact the exposure pathways, these also should be utilized to effectively refine the model. Where available, these requirements have been incorporated into modeling scenarios. Recommendations are that assumptions about residency, radon mitigation, land use, and the variables in need of additional research be clearly defined. This should be done so that the dose, and consequently the environmental deposition methods, can be carefully assessed and crafted into adequately protective legislation.

After reviewing available data on the waste forms generated in the oil and gas industry, it appears that all generally fall into one of four primary disposal options:

- land application;
- landfill disposal;
- discharge as a liquid effluent; or
- deep well injection.

Intermediate processing steps are not listed; however, where these are significant environmental impact, they are discussed. These intermediate steps ultimately lead to the same four disposal ends. Once a particular disposal option is selected, the result is the deposition of radioactive material into the environment. Each option presents a set of exposure pathways to the biota that dictate both the environmental impact and overall sustainability of such a disposal method. For the convenience of the reader, the disposal options, a discussion on the pathways created, and estimations on the environmental impact are provided in Appendix C-2.

#### Land Application

Land application, also called land dispersal or land farming, has been a long standing waste disposal method that has been available to the petroleum industry according to API reports. Other methods of waste disposal that create similar exposure pathways are the application of liquid effluents for road deicing, dust suppression, or irrigation. Aside from repeated mention of these sludges containing heavy metals and other carcinogens, any TENORM carried to the surface and allowed to settle out will be contained in these sludges as well. The use of evaporation and percolation pits for dewatering, along with the containment of drilling wastes in reserve pits or tanks, provides just such a mechanism. Fortunately, the accumulation of radionuclides in soil can be modeled with software to arrive at dose estimates through an all-pathway analysis. In this manner, should a regulatory body elect to allow land application, the permissible increase in soil concentrations is dictated by the allowable fraction of the public dose limit.

Based upon the models and resulting doses in Appendix C-2, it is clear that land application of TENORM needs to have bounding numbers on the allowable increases. Land application should be conducted under comprehensive regulatory programs that limit:

- application rate;
- application site;
- surface runoff; and
- irrigation intervals.

The E-42 Task Force recommends that state programs allowing land application of TENORM adapt existing regulatory programs to control radium by virtue of the restrictions they already have in place. For example, the National Pollution Discharge Elimination System (NPDES) program, USEPA Part 503 Biosolids Program land application regulations, irrigation restrictions, could be a way to mitigate these types of TENORM exposures.

#### Intermediate Treatment

Chemical constituents and the capability of handling them aside, it is important to note that the treatment facilities may or may not recognize the presence of TENORM in their influent. Since most treatment works are not specifically tailored to handle TENORM, there likely will be a variable component of radium discharged with the liquid effluent rather than diverted to sludge. The concentration of radium kept in solution and discharged via an effluent (presumably a permitted NPDES outfall) varies as a function of:

- treatment process;
- residency time in the treatment works; and
- average daily flow through the facility.

Individual facility assessments will be required to determine if the 2.22 Bq/L (60 pCi/L) (sum of the fractions of Ra-226/Ra-228) concentration guidelines are exceeded.

Efforts to characterize radium in wastewater treatment facilities have been underway in several states. Although their focus is generally on radium originating from drinking water treatment, the environmental consequence of radium in backwash waters is applicable when considering the fate of radium in hydraulic fracturing wastewaters. Because most sludge disposal is accomplished by either land application or landfill disposal, the environmental impact (given sample results) can be evaluated via RESRAD or similar models. Special attention should be given to those facilities that utilize alternative disposal techniques, such as public distribution<sup>6</sup> (USEPA 2012) where the regulatory controls that mitigate radium accumulation do not exist.

Although IAEA reported studies that have been conducted on the discharge of produced water into coastal and offshore areas of the Gulf of Mexico (IAEA 2003), little data were available. Moreover, because TENORM in oil and gas is not specifically regulated on a federal level, implementation of monitoring requirements for radium into NPDES permits is left to the discretion of the states. Given the variable fraction of radium that may be discharged and the lack of environmental impact data on radium deposition into navigable water bodies, regulating bodies should consider analyzing for radium where hydraulic fracturing wastewaters are being treated.

Aside from the licensed discharge limit of 2.2 Bq/L (60 pCi/L), the *Clean Water Act* (CWA 1972) establishes an annual average surface water quality standard of:

- combined Ra-226 and Ra-228 of 0.185 Bq/L (5 pCi/L) (general use); and
- 0.14 Bq/L (3.75 pCi/L) for most other waters (such as public and food processing water supplies).

Although federal regulations do not specifically identify a NPDES discharge concentration limit for Ra-226 or Ra-228, the provision that no NDPES discharge shall cause an exceedance of any water quality standard, such as those outlined in this section, indirectly restricts effluents. Therefore, although a licensee may conceivably discharge an effluent up to 2.2 Bq/L (60 pCi/L) combined radium, the resulting impact to the surface water (and groundwater)

process. Class A biosolids also may be sold in large box stores as fertilizer or potting soil. For additional information on Class A biosolids, see

<sup>&</sup>lt;sup>6</sup> Some wastewater treatment facilities are permitted to distribute dried sludge to the public (to individuals who may use sludge for gardens, top soil, backfill, etc.). USEPA refers to this as "exceptional quality" or Class A biosolids and allows the process. Class A biosolids also may be sold in large box stores as fertilizer or potting

http://water.epa.gov/polwaste/wastewater/treatment/biosolids/genqa.cfm (USEPA 2015).

may not cause an exceedance of the applicable standard, as low as 0.14 Bq/L (3.75 pCi/L). Moreover, depending on the interpretation of the state and federal regulating bodies, non-degradation standards may limit the impact on surface and groundwater to no deviation from background concentrations. Therefore, the nexus between licensed discharges and the allowable impact, if any, upon applicable groundwater standards should be clearly defined in any regulatory efforts.

# Landfill Disposal

Landfill disposal of dry, solid wastes may include items such as drill cuttings, any dewatered sludges or sediments produced from the treatment of drilling fluids or produced waters, and scale or scale contaminated equipment. Landfill disposal of these could be problematic from the standpoint of:

- radon sequestration<sup>7</sup> (USEPA 2013);
- leaching of TENORM into the groundwater; and
- external exposure.

Based upon the analyses in Appendix C-2, as well as the data reviewed, the E-42 Task Force believes that if landfill disposal is afforded, the municipal solid waste landfill requirements for 10 feet of uncontaminated clean overburden should be employed with specific prohibitions against utilization of TENORM in this cap.

Furthermore, additional concerns that need to be addressed for landfill disposal are:

- erosion rate of the cap;
- monitoring of leachate for mobilization of radium;
- monitoring of groundwater in the event of lining failure;
- the manner in which TENORM is deposited into lifts;
- plume emission of radon from gas collection systems; and
- post-closure time frames.

ANL identified radon emanation from gas collection systems as the principle concern with landfill burial of TENORM (ANL 1992; ANL 1996).

Finally, the magnitude of all of these exposure avenues is proportional to the source term afforded to landfills. Several states have already implemented or

<sup>&</sup>lt;sup>7</sup> Many landfills have methane capture and venting systems that will also capture radon.

are considering a total source term limitation on landfills to place bounding numbers on the exposure models.

Appendix C-2 quotes the conclusions of an Argonne National Laboratory study (ANL 1999). Though this Report does not necessarily adopt the assumptions and models employed in the ANL 1999 study, the ANL report is highlighted. It provides a path forward for establishing dose-based and/or risk-based standards for the disposition of TENORM. This is as opposed to establishing an explicit concentration limit for disposal of TENORM in landfills, such as the 0.185 Bq/L (5 pCi/g) limit above background on the disposal of Ra-226 in landfills, which is being adopted by many states at the time of the preparation of this Report. Additionally, new models should be developed to assess the mobility and TEDE impact from the disposal of natural gas waste streams containing high concentrations of Pb-210 and Po-210.

## **Deep Well Injection**

Data from the 1995 API survey report that deep well injection is the preferred disposal method for upwards of 90% of produced water (API 1997). Moreover, the reference materials utilized commonly refer to deep well injection as having the lowest likelihood of radiological exposure to the public. For the purposes of analyzing the environmental impact, deep well injection includes:

- recycling produced waters for enhanced recovery;
- slurrying of drilling waste for disposal or use in plugs;
- injection into formations; or
- injection into abandoned wells or caverns.

Although no data exist to indicate that recent technological developments in oil and gas recovery would increase the risk of groundwater contamination, it is worth noting that the groundwater monitoring regulations in place may not detect all incidents of contamination. This is due to the fact that the *Clean Water Act* (CWA 1972) mandates radiological monitoring for community water supplies after the treatment process. In addition to municipalities being able to go onto reduced monitoring schedules, facilities serving groundwater that do not meet the community water supply definition are typically not required to monitor for radionuclides. These include non-transient non-community (NTNC) and transient non-community (TNC) supplies. These would be small (less than 25 connections) communities, residences, farms, ranches, industrial facilities, or schools with their own water supplies. In areas where deep well injection is in proximity to a groundwater bearing formation, it may be prudent to determine which monitoring requirements apply and how often monitoring is required.

#### Site Considerations

The previous sections have attempted to provide the radiological concentrations and volumes associated with TENORM waste streams in the oil and gas industry (i.e., the source term). Based on the concentrations and volumes involved, there is a high likelihood that areas where waste has been allowed to accumulate or has been disposed of without regard to TENORM contamination, unrestricted use of sites may not be permissible.

Unrestricted use, as defined by the USNRC, sets the threshold of 0.25 mSv (25 mrem) TEDE per year to the average member of the critical group. Under USEPA Superfund approach, a site would need to be under 0.12 mSv/yr (12 mrem/yr) to meet a risk level of  $3 \times 10^{-4}$  based on the current guidance. Although the dose limit deemed permissible varies by state and federal agency, the capability to exceed even the upper end of public dose constraints of 1 mSv/yr (100 mrem/yr) is present. For example, API and IAEA have recognized the potential for elevated exposures to TENORM during routine well work in Mississippi. Tubing scale contaminated soil on sites beyond 37 Bq/g (1,000 pCi/g) and exhibited dose rates in excess of 0.02 mSv/hr (2 mrem/hr) (IAEA 2003).

Therefore, an assessment of sites to be released to the general public should be performed first to determine the extent to which environmental deposition has encroached upon a particular state's dose limit. Considerations that should be evaluated to determine the extent of the environmental impact should include the following:

- use of legally defensible laboratory data and data quality objectives;
- spills from work-over operations or tank and pit overflows, keeping in mind that often smaller spills are not required to be reported;
- scale-contaminated piping left in the soil and not removed;
- idle or abandoned wells or open boreholes that create a direct avenue for groundwater contamination;
- legacy contamination prior to TENORM oversight and regulation;
- removal and processing of piping and equipment;
- shallow site burial of TENORM wastes and reserve pits and sediment ponds;
- radium accumulation in soil due to unrestricted land application; and
- storage areas used for pipe and equipment.

With respect to removal and processing of piping and equipment, many states can attest to the presence of contaminated piping arriving at scrap iron facilities due to the sounding of radiation monitoring alarms. In an effort to alleviate rejected loads and avoid accidental smelting, an assessment of the equipment being sent for scrap should be performed. Additionally, the fate of the scale being removed should be monitored. An important note regarding the screening of equipment prior to removal is the degree of secular equilibrium in the contamination. Although the rapid movement of oil and gas through the conveyances of a production site may result in a lack of secular equilibrium between radionuclides and their progeny, by the time a site is being abandoned, equilibrium will likely be met within a period of a month. (The thorium series may take longer.) As a result, the gamma emissions from progeny will contribute to higher ambient dose rates that need to be accounted for. Surveys and release of equipment should account for this in-growth, especially if states allow screening equipment and sites for release based upon gamma emission. Although the Marcellus shale characteristically has a 3:1 Ra-226: Ra-228 ratio, formations with elevated Ra-228 concentrations may not follow the old rules of thumb that exist for Ra-226 and a correlated dose rate. If the concentration of Ra-228 is present in a higher ratio than Ra-226, there is a lower incidence of gamma emission per unit volume. Therefore, the combined radium concentration could be much higher than environmental deposition may afford, and an observable gamma emission rate would not be as readily detectable as it would be with a higher Ra-226 concentration. This is especially true when the contaminants of concern are alpha/beta emitters (Po-210 and Pb-210) where the gamma survey will not detect their presence.

Shallow site burial of TENORM wastes and reserve pits and sediment ponds present additional concerns. Many on-shore sites discharge produced water into lagoons or ponds. Water is allowed to drain and the solids are allowed to sediment out. USEPA reported sediments in these pits and ponds range from 10 to 40.7 Bq/g (270 to 1,100 pCi/g).

An additional concern is the use of these sedimentation or reserve pits as the final disposal site once they are dewatered and covered with dirt. API survey results from 1997 indicate over two-thirds of remaining drilling waste solids are disposed of by burying them onsite in the reserve pit. IAEA estimated that 30,000 such contaminated waste pits and bottom sediment sites exist in coastal Louisiana alone (IAEA 2003).

Storage areas used for pipe and equipment may have contaminated soil that is of concern. Louisiana Department of Environmental Quality Nuclear Energy Division reported Ra-226 concentrations up to 322 Bq/g (8,700 pCi/g) in soil contaminated with scale at pipe storage areas (USOSHA 1989).

Finally, additional environmental concerns arise when many or all of the disposal options discussed in this section are prohibited. Regulatory oversight can effectively manage the disposal of TENORM waste and ensure environmental impact and consequently, the dose to the public is kept within a state's limits. However, as disposal options become limited within a particular region, the wastes are often shipped to different areas. The additional transport

by trucks and barges presents new environmental hazards that need to be addressed. Note that the U.S. Coast Guard is considering regulations concerning barge traffic containing shale gas extraction wastewaters. Also, consideration should be given to the less reputable individuals and companies that may elect to irresponsibly dispose of TENORM when the disposal options available are either too costly or prohibited all together.

#### **Potential Radon Concerns**

The E-42 Task Force has held numerous discussions regarding trigger levels defining the concentration and quantity of Ra-226 and other radionuclides that can be disposed at a landfill of any kind. One of the options discussed was permitting the disposal of such material if it can be demonstrated that the potential exposures to members of the public will not exceed 0.25 mSv/yr (25 mrem/yr) for a period of 1,000 years following closure of the landfill. Some states include radon and some states do not include radon in these calculations. In addition, the E-42 Task Force believes that a level of assurance should be provided that the disposal of TENORM at a landfill is unlikely to result in the contamination of potable groundwater resources in excess of the drinking water standards for a period of 1,000 years following closure of the landfill. In making these determinations, credit for engineering and institutional controls should be given for no more than 100 years following closure of the landfill. The E-42 Task Force believes that it is essential that these issues be addressed by CRCPD and other standard-setting bodies.

In keeping with USEPA guidance (USEPA 2006, Table 5-1), workers at TENORM facilities and waste disposal facilities and members of the public who might be exposed to material in the landfill following closure of the facility should not experience chronic exposures to indoor radon in excess of 0.148 Bq/L (4 pCi/L) from all sources with consideration given to the degree to which short-lived radon progeny are close to achieving equilibrium.

With respect to radon exposures to members of the public following closure of the landfill, consideration should also be given to the possibility that members of the public might take up residence in the vicinity of the landfill up to 1,000 years after closure of the landfill. In theory, models can be used to demonstrate that these radon limits will not be exceeded for a period of 1,000 years following closure of the landfill. However, such models are highly uncertain, and it is preferable to establish requirements that structures that may be established on or near the landfill in the future must be designed to be radon resistant and that measurements are made following construction that demonstrate that the 0.148 Bq/L (4 pCi/L) guidance has been achieved.

However, such a regulatory strategy will be difficult to implement, given that we are concerned with time periods far into the future and the closure for *Resource Conservation and Recovery Act* (RCRA) (RCRA 1976) landfills is 30 years. In

light of this concern, consideration should be given to establishing limits on TENORM disposal such that the radon flux from soil surface is limited. This strategy for the management of radon exposures has precedent with the uranium mill tailings standards and has merit because radon flux can be modeled more reliably than the radon concentration inside structures that might or might not be established at a site far into the future. In addition, consideration should be given to establishing requirements that structures built on or near locations with elevated levels of Ra-226 in soil be required to meet radon resistant structural requirements.

#### Special Challenges Associated with Regulation of Radon Exposures

The E-42 Task Force recognizes the special challenges associated with regulating radon exposures with respect to the management and disposal of TENORM containing Ra-226. There are two factors that establish these challenges.

First, naturally occurring radon levels in homes are typically on the order of about 1 to a few Bq/L (pCi/L) (USEPA 1993),<sup>8</sup> and the annual effective dose associated with this level of exposure is about 2 mSv/yr (200 mrem/yr) (NCRP 2009).<sup>9</sup>

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommends a radon dose conversion factor of 9 nSv Bq<sup>-1</sup> h<sup>-1</sup> m<sup>3</sup> (0.033 mrem/hr per pCi/L) for the purpose of evaluating the effective dose from radon inhalation for miners (UNSCEAR 2006, Section VIII of Annex E). UNSCEAR states that "Although there are major uncertainties in extrapolating the risks of exposure to radon from the miner studies in order to assess the risk of radon in the home, there is nevertheless remarkably good agreement between the risk factors derived from the miner studies and from the pooled residential case control studies." (UNSCEAR 2006, Par. 533.)

<sup>&</sup>lt;sup>8</sup> Table 5-1 of *Technical Report on Technologically Enhanced Naturally Occurring Radioactive Material from Uranium Mining Volume 1: Mining and Reclamation Background*, was previously published on-line and printed as Vol. 1 of USEPA 402-R-05-007, January 2006, updated June 2007, and printed April 2008 as USEPA 402-R-08-005. It states that the average exposure to radon in the U.S. is 2.0 mSv/yr (200 mrem/yr), ranging from 0.3 to 8.0 mSv/yr (30 to 800 mrem/yr) effective dose. Also see USEPA's Map of Radon in Homes (USEPA 1993).

<sup>&</sup>lt;sup>9</sup> NCRP indicates that the average effective dose in the United States from naturally occurring radon and thoron is 2.28 mSv/yr (228 mrem/yr), the vast majority of which is from radon and its short-lived progeny (NCRP 2009, Fig. 1.1)

Hence, the main difference between the doses (and associated health risks) to miners (or other occupational exposures) and residents of homes are the duration of exposure.

Assuming 2,000 hours per year, occupational exposures, and the annual normalized dose is  $0.033 \ge 2,000 = 0.66 \text{ mSv/yr}$  (66 mrem/yr) per Bq/L (pCi/L) and for residential exposure it is  $0.033 \ge 7884$  (USEPA 1989), this would result in 2.6 mSv/yr (60 mrem/yr per Bq/L (pCi/L) effective dose.

The implications are that relatively low indoor concentrations of indoor radon (i.e., 1 to a few Bq/L (pCi/L) are associated with relatively high effective doses. *ICRP Publication 115* also provides a relationship between effective dose and radon concentration of 5.7 nanosievert (nSv) per becquerel-hours per cubic meter (Bqh/m<sup>3</sup>) [or 1.6 mSv per millijoule-hours per cubic meter (mJh/m<sup>3</sup>)] (ICRP 2010, Annex B.).

Assuming an inhalation rate of  $1.2 \text{ m}^3/\text{hr}$ , this converts to 6.8 nSv/Bq or  $6.8 \times 10^{-9}$  sievert (Sv) per Bq. *ICRP Publication 115* indicates a distribution of radon dose conversion factors ranging from 1.6 to 6.0 mSv per millijoule-hour per cubic meter (mJh/m<sup>3</sup>) (ICRP 2010, Annex B.).

Specifically, the dose conversion factors in Table B.1 of *ICRP Publication 115* range from  $6.8 \times 10^{-9}$  to  $2.6 \times 10^{-8}$  Sv/Bq (ICRP 2010, Table B.1.). Assuming an indoor occupancy factor for adults of 948 minutes per day (USEPA 2011c, Table 16-1), the annual effective dose per pCi/L of radon indoors ranges from 174 to 664 mrem/yr per pCi/L (0.047 to 0.18 Sv/yr per Bq/L).

Secondly, typical Ra-226 concentration occurring naturally in soil has been reported to range from less than 0.037 Bq/g (1 pCi/g) to approximately 0.067 Bq/g (1.8 pCi/g) dry weight. For example, 0.0222 Bq/g (0.6 pCi/g) dry weight<sup>10</sup> was reported by NCRP (NCRP 1984, Table 4-1.).

In addition, *NCRP Report No 94* reports typical levels of U-238 in soil of 0.0666 Bq/g (1.8 pCi/g) (NCRP 1987, Table 4.3). It can be assumed that Ra-226 is present in soil in approximate equilibrium with U-238. (Sextro et al. 1987, Table 1).

 $<sup>^{10}</sup>$  It should be noted that the average Ra-226 concentration in soil in different regions of the country and different geological settings can be highly variable. For example, unpublished data from a soil sampling survey conducted in 102 counties in Illinois revealed an average Ra-226 plus Ra-228 concentration (dry weight) of 0.07733 Bq/g (2.08 pCi/g) for agricultural soils and (0.07474 Bg/g) 2.02 pCi/g for non-agricultural soil.

On this basis, it appears that the effective dose to individuals can be well in excess of 1 to 2 mSv/yr (100 to over 200 mrem/yr) due to naturally occurring levels of Ra-226 in soil. As that concentration of Ra-226 in soil increases (such as might occur as a result of the management or mismanagement of TENORM), indoor exposures to radon and its progeny would be expected to increase proportionally.

However, it is important to acknowledge that a vast body of literature demonstrates that this relationship among real homes varies by orders of magnitude depending on a myriad of factors related to the structure of the home such as:

- cracks in the foundation;
- construction on slab or with basement;
- air turnover rate;
- time of year;
- basement versus upper floor occupancy;
- weather conditions; and
- local geology and the characteristics of the soil, which are perhaps most important (George and Hinchliffe 1987; USEPA 1993).

It is for this reason that none of the dose-based standards for the protection of workers or members of the public include explicit consideration of radon exposures, and USEPA guidelines limiting indoor exposures to radon have been established based on a prescribed concentration limit of 0.148 Bq/L (4 pCi/L), as opposed to a dose-based or risk-based standard.

Hence, notwithstanding any dose-based standard adopted by state authorities for the protection of workers or members of the public related to TENORM exposures, the E-42 Task Force recommends that careful consideration be given to indoor radon exposures when establishing acceptable limits of Ra-226 associated with site cleanup and the disposition of both liquid and solid TENORM waste.

## TENORM Training of Workers and Health and Safety Personnel in the Oil and Gas Industry

The current CRCPD SSRCR requirements for radiological training of workers associated with TENORM facilities and non-TENORM radiological facilities are essentially the same.

*SSRCR Part N* states that "each person subject to a specific or general license under *Part N* shall conduct operations such that protection of workers is in compliance with the standards for radiation protection set out in Parts D and J of these regulations." (CRCPD 2004, sec. N.6.)

SSRCR Part J specifies radiological training requirements for all individuals at licensed or registered facilities "who in the course of employment are likely to receive in a year an occupational dose in excess of 1 mSv (100 mrem)," and goes on to specify general areas to be covered by the training and instruction (CRCPD 2000, sec. J.12).

*SSRCR Part N* issues a general license to all persons who possess, use, transfer, distribute, or dispose of TENORM (without regard to quantity) who:

- are not required to be specifically licensed in accordance with section N.20 of *SSRCR Part N*; or
- are not exempted by section N.4 of *SSRCR Part N* (CRCPD 2004, sec. N.10).

Two important exemptions in section N.4 (N.4.a and N.4.f) apply to radium (Ra-226 plus Ra-228) concentrations less than 185 Bq/kg (5 pCi/g) or when the state makes a determination that the reasonably maximally exposed individual will not receive a public dose with a TEDE of more than 1 mSv (100 mrem) in one year from all licensed or registered sources of radiation, including TENORM.

In both SSRCR Part N and SSRCR Part J:

- the training requirements apply to licensed facilities, including those generally licensed;
- the requirements apply to persons who are likely to receive an occupational dose in a year in excess of 1 mSv (100 mrem); and
- a basic requirement of the training is that it be commensurate with potential radiological health protection problems present in the workplace.

*IAEA Safety Series Report No. 34* provides an overview of training with respect to radiation, including NORM and TENORM, in the oil and gas industry (IAEA 2003, sec.7 and App. III).

General training of workers in the oil and gas industry with regard to TENORM should be implemented in accordance to ensure worker protection and awareness training.

The following are recommendations regarding training.

- TENORM awareness training (1-2 hours) should be included as part of the health and safety training program (10-30 hours) required for TENORM workers in general.
- For facilities where exposures could exceed 1 mSv/yr (100 mrem/yr), additional training in radiation protection should be provided. Also, under these circumstances, access to health physics consultation and oversight is recommended.

• A more comprehensive training and radiation oversight program is recommended at sites where exposures could approach the radiation exposure limit for occupational dose, such as that required by *SSRCR Part J, Notices, Instructions and Reports to Workers; Inspections* (CRCPD 2003), which is equivalent to USNRC limits in *10 CFR Part 19.* Such a program should be tailored to TENORM activities.

#### Training Recommended for Workers

Training for all workers should address the following topics.

- Fundamentals of Radiation Safety including:
  - introduction to NORM and TENORM;
  - characteristics of alpha, beta, and gamma radiation;
  - units of radiation dose and quantity of radioactivity associated with TENORM;
  - hazards of exposure to the different kinds of radiation;
  - o levels of radiation from TENORM sources of radiation; and
  - methods of controlling radiation dose through time, distance, and shielding.

Radiation Detection Instruments including:

- use, operation, and limitations of radiation survey instruments for alpha, beta, and gamma radiation;
- o survey techniques including ambient and frisking methods;
- use of personnel monitoring equipment ((film badge, thermoluminescent dosimeter (TLD), and optically stimulated luminescence dosimeter OSL) and/or personnel air sampler); and
- $\circ~$  surveying and sampling for NORM and TENORM.
- Proper Use of Personnel Protective Equipment (PPE) including:
  - different types of PPE;
  - donning of PPE;
  - removal of PPE;
  - o decontamination techniques; and
  - use of respiratory protection equipment, as needed.
- Posting and Labeling TENORM areas.
- Containerization, storage and disposal of TENORM wastes.
- Requirements of pertinent state and federal regulations.

• Topics and discussions of assigned activities during normal and abnormal situations involving exposure to TENORM which can reasonably be expected to occur during work activities.

The extent of these instructions must be commensurate with potential radiological health protection problems present in the work place. The responsible party should provide a 1-4-hour TENORM refresher training for employees at intervals not to exceed 12 months and when there is a significant change to radiation protection policies, procedures, or regulations. The training program at each TENORM facility should be approved by the relevant state authority.

For those facilities performing routine operations where exposures could exceed 1 mSv/yr (100 mrem/yr), training should be site-specific and give the workers an insight into:

- the radioactive material associated with NORM and TENORM;
- radiation effects; and
- risks associated with their facility.

This should contain, at a minimum, policies and procedures for each facility, including the ALARA program and management policy to maintain all personnel exposure within the site dose guidelines.

If TENORM exposures are at the high end of the graded approach (i.e., above 1 mSv/yr (100 mrem/yr), a Radiation Safety Officer (RSO), who has completed a higher level of training, typically a one week radiation safety training course, should be placed in charge of the program. The RSO should supervise each training program, with trainers working under RSO supervision. Each trainer should have attended the worker training and have at least two years of radiation safety experience.

The following are recommendations for the duration and frequency of TENORM training for workers and RSOs based on job functions and duties:

- General Awareness training 1 to 4 hours
- Worker training (job specific) 4 to 8 hours
- Annual refresher training 1 to 4 hours
- RSO training 40 hours (typically a one week course)
- RSO annual refresher training related to TENORM remediation 8 hours

# Recommended Training for Instructors

Instructors of TENORM courses, other than the RSO, must have adequate and commensurate experience in field operations associated with TENORM activities at oil and gas well operations/facilities. The field experience work needs to

include sufficient time in radiation protection and use of radiation detection equipment.

# TENORM DATABASE

In order to understand the nature and extent of the hazards to workers, the public, and the environment associated with TENORM in the oil and gas industry, it is necessary to have a comprehensive database characterizing the amount and composition of TENORM associated with the oil and gas industry. A national database needs to be assembled and managed as a clearinghouse for researchers, regulators, and the oil and gas industry. This database should ensure consistently high-quality data characterizing the radiochemical composition of the myriad types of TENORM as described in this Report. In its *Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, Progress Report* (USEPA 2012), USEPA summarizes the status of the developing TENORM database as follows:

Data from multiple sources have been obtained for review and analysis. Many of the data come directly from the oil and gas industry and states with high levels of oil and gas activity. Information on the chemicals and practices used in hydraulic fracturing has been collected from nine companies that hydraulically fractured a total of 24,925 wells between September 2009 and October 2010. Additional data on chemicals and water use for hydraulic fracturing are being pulled from over 12,000 well-specific chemical disclosures in FracFocus, a national hydraulic fracturing chemical registry operated by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission. Well construction and hydraulic fracturing records provided by well operators are being reviewed for 333 oil and gas wells across the United States; data within these records are being scrutinized to assess the effectiveness of current well construction practices at containing gases and liquids before, during, and after hydraulic fracturing.

In addition, the USEPA is reviewing scientific literature relevant to the research questions posed in this study. A Federal Register notice was published on November 9, 2012, requesting relevant, peer-reviewed data and published reports, including information on advances in industry practices and technologies. This body of literature will be synthesized with results from the other research projects to create a report of results. (USEPA 2012)

Unfortunately, FracFocus does not currently address TENORM. In addition, a consistent complaint experienced by the E-42 Task Force members is the poor quality of data. Either incomplete datasets, missing quality assurance/quality control (QA/QC), lack of methods provided, etc., plagued many of the reports. Any database compiled should have a minimum set of qualifying criteria that

ensures the data going in are of sufficient quality and of a scientific format that does not generate questions regarding data validity.

# RECOMMENDATIONS

The E-42 Task Force is making the following recommendations to the CRCPD Executive Board for further action and study:

# **Definition of TENORM**

Various standard-setting bodies use different definitions of TENORM. Some use a narrow definition, limiting it to material where naturally occurring radionuclides have been concentrated. Others employ a broader definition, which includes the relocation of naturally occurring radionuclides such that there is an increase in the potential for environmental mobility and/or for workers or members of the public to experience radiation exposures that they would not have received if the material had not been relocated. The current *SSRCR Part N* definition uses the narrow definition (CRCPD 2004).

The E-42 Task Force recommends:

- reconsideration of the current CRCPD definition of TENORM regarding the activities encompassed by the broader definition inasmuch as the broader definition appears to have become more widely used in recent years; and
- that *SSRCR Part N* be reviewed to ensure it is clear that byproduct material as described in the *Energy Policy Act of 2005* (USEPA 2005) is excluded from the definition of TENORM because these materials are regulated by USNRC.

## Acceptance Criteria

The E-42 Task Force recommends the current acceptance criteria (trigger levels) in *SSRCR Part N* (CRCPD 2004) be reviewed for adequacy<sup>11</sup> and that

<sup>11</sup> For example, see acceptance criteria in:

- N.4a, N.7b, et al 0.185 Bq/g (5 pCi/g);
- N.4g 0.370 Bq/g (10 pCi/g);
- N.7f (50 uR/hr); and
- acceptance criteria for surface contamination in N.7g and App A. (CRCPD 2004).

consideration be given to developing additional acceptance criteria to address radionuclides other than radium (e.g., Pb-210 and Pb-210 disposal criteria in particular).

The reason for this recommendation is that the acceptance criteria that are currently in *SSRCR Part N* either do not result in a consistent dose and/or a consistent regulatory approach to that currently in place for *Atomic Energy Act* (AEA 1954) materials as addressed in other SSRCR Parts.

The E-42 Task Force is especially concerned with the exemption standard of 0.185 Bq/g (5 pCi/g) of radium above background due to its extensive usage as an exemption criterion in *SSRCR Part N* (CRCPD 2004). This standard needs to be revisited because, depending on the conditions under which NORM and TENORM are produced, handled, and disposed, the doses and potential health risks to workers and members of the public can vary significantly.

The E-42 Task Force further recommends that CRCPD:

- partner with NCRP in the investigation and evaluation of these issues for future development of action levels; and
- employ the ICRP system of radiation protection, including justification, optimization, and limitation, in the development of action levels.

# Quantification and Characterization of Pb-210, Po-210 and Radon

The extent and quantification of Pb-210 and Po-210 contamination and exposure to radon in the oil and natural gas industry should be further evaluated and necessary worker protection standards be implemented. Due to the characteristics of these contaminants, the historically relied upon gamma screening methods will not be sufficient and analytical methods must be employed to determine the protective and appropriate disposition.

There is a direct pathway for worker internal exposure that may occur during maintenance of values, pipes, filters and equipment.

# Training

Training requirements specified in *SSRCR Part N* (CRCPD 2004) for TENORM workers are identical to those for *Atomic Energy Act* (AEA 1954) radioactive materials workers inasmuch as Section N.6 requires compliance with *SSRCR Part J* (CRCPD 2000).

The E-42 Task Force recommends augmenting those training requirements for oil and gas TENORM workers. The E-42 Task Force has prepared a set of proposed minimum training requirements for oil and gas industry TENORM workers, as well as for persons providing such training, that it believes would meet the need for the augmented training. (See "TENORM Training of Workers and Health and Safety Personnel in the Oil and Gas Industry" in this Report).

#### **Radiation Exposures Baselines**

The E-42 Task Force recommends that CRCPD establish a Working Group to work with stakeholders in the development of a radiation exposure baseline for oil and gas workers exposed to TENORM in the conventional oil and gas industry. The baseline would allow for a comparison of TENORM exposures of oil and gas workers during unconventional drilling, including fracking, in the future. Such an analysis will provide insight into the degree to which unconventional drilling may increase the potential for elevated radiation exposures from TENORM.

## **Consolidated Guidance**

CRCPD should develop the equivalent of a USNRC *NUREG*-1556 series type of document, giving consolidated guidance of a non-licensing nature, for use at facilities that require a TENORM permit.

## Incorporation of TENORM Assessment into Oil and Gas Permitting

The E-42 Task Force recommends that the oil and gas industry develop and incorporate best management practices and/or guidance. These should address the need for applications for oil and gas facilities and other supporting facilities, such as produced water treatment facilities, to include, as part of the overall licensing and permitting process, evaluations of the degree to which TENORM might be produced and/or handled at the facility. The applications should also address the potential doses that might be experienced by workers and members of the public, and the types, quantities and characteristics of TENORM waste that might be associated with such facilities. The level of detail of the evaluations should be commensurate with the potential magnitude of the anticipated impacts.

## Use of Existing Regulatory Programs

The E-42 Task Force recommends that existing processes for permitting oil and gas operations be amended to include an assessment of TENORM impacts. Where applicable and available, these existing regulatory programs should be utilized to limit the impact TENORM disposals may have on the environment.

Two such areas identified by the E-42 Task Force are:

- land application of solids; and
- discharge of liquid effluents containing TENORM.

The distribution of TENORM without incorporation or consideration as to the resulting radium buildup easily may exceed the public dose limit and should be approached with sufficient oversight to minimize a significant increase. Existing USEPA Part 503 Biosolids Program permits and state or federal NPDES discharge permits should include TENORM parameters. In this manner, many of the constraints that may serve to mobilize radium or expedite groundwater contamination are given bounding constraints by virtue of existing land application site requirements, application restrictions, and liquid discharge requirements.

The E-42 Task Force believes this would also address the lack of effluent restrictions in *SSRCR Part N* and the *E-36 Implementation Guide* and the current exemption limit of 0.37Bq/g (10 pCi/g), which does not account for buildup of radium in soil.

#### **State Regulations**

The E-42 Task Force recommends that CRCPD collect and maintain a compendium of state regulations and guidelines pertaining to the management and disposition of TENORM associated with the oil and gas industry.

#### **TENORM** Database

The E-42 Task Force recommends compiling and maintaining a database of the concentrations and volumes of TENORM. This database should include the radiation fields associated with or in the vicinity of facilities, equipment, residue, and waste related to the production, possession, distribution, use, transfer, receipt, disposal, and management of TENORM associated with the oil and gas industry in geographical and geological locations throughout the United States.

Some of these recommendations are similar to recommendations made by *E-36 Task Force Implementation Guidance* (CRCPD 2003). The E-42 Task Force continues to support the recommendations made by the E-36 Task Force in conjunction with the recommendations made in this section of the E-42 Task Force Report.

# APPENDICIES

# APPENDIX A

# REFERENCE MATERIAL FOR FACILITIES, SYSTEMS AND COMPONENTS IN THE OIL AND GAS INDUSTRY IMPACTED BY TENORM

CRCPD *E-4 Report* (CRPCD 1994) provides an overview of the literature describing the accumulation of TENORM in piping in the oil and gas industry. However, since the publication of that report, our understanding of TENORM issues in the oil and gas industry has greatly increased. The following references provide more information on the oil and gas industry facilities, systems, and components where TENORM is a potential issue.

API 2010. Water Management Associated with Hydraulic Fracturing, Guidance Document HF2. Washington, D.C.: American Petroleum Institute (API), 2010. This document provides an excellent overview of water management associated with hydraulic fracturing, but only limited information on NORM.

GWPC 2009. *Modern Shale Gas-Development in the United States: A Primer*. Tulsa, Oklahoma: Groundwater Protection Council (GWPC) and ALL Consulting, 2009.

IAEA 2003. Safety Reports Series No. 34: Radiation Protection and the Management of Radioactive Waste in the Oil and Gas Industry ANL/EAD-2. Vienna, Austria: International Atomic Energy Agency (IAEA), 2003. This report could be used as a roadmap for characterizing TENORM issues associated with each of the sectors that comprise the oil and gas industry. The report provides a good description of the industry, and Section 5 addresses NORM and where and why NORM accumulates in various pieces of equipment. Figures 22–24 and Table II provide an excellent overview of where and why different NORM radionuclides accumulate in oil and gas equipment.

IOGCC 1994. Understanding the Basics of Naturally Occurring Radioactive Material (NORM) in the Oil and Gas Industry. Oklahoma City, Oklahoma: NORM Subcommittee of the Interstate Oil and Gas Compact Commission (IOGCC) Environmental and Safety Committee, IOGCC, 1994. This document contains useful material describing where TENORM is an issue in the oil and gas industry.

NYSDEC 2011. Revised draft Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program, Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs. Albany, New York: New York State Department of Environmental Conservation (NYSDEC), Division of Mineral Resources, Bureau of Oil & Gas Regulation, 2011.

USDOE 2013. Modern Shale Gas Development in the United States: An Update, DOC0000080. Washington, D.C.: National Energy Technology Laboratory, U.S. Department of Energy (USDOE), 2013.

USEPA 2000. USEPA Office of Compliance Sector Notebook Project – Profile of the Oil and Gas Industry, USEPA/310-R-99-006. Washington, D.C.: USEPA, 2000. This report could be used as a roadmap for characterizing TENORM issues associated with each of the sectors that comprise the oil and gas industry.

USEPA 2011b. Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, USEPA/600/R-11/122. Washington, D.C.: USEPA, 2011. Although this report does not address TENORM specifically, it can be used as a roadmap for characterizing TENORM issues associated with hydraulic fracturing.

USGAO 2012. Oil and Gas – Information on Shale Resources, Development, and Environmental and Public Health Risks. Washington, D.C.: United States Government Accountability Office (USGAO), 2012.

# APPENDIX B

# CURRENT TENORM STANDARDS, GUIDELINES, AND STATE REGULATIONS

Appendix B summarizes the complex array of standards, guidelines, and state regulations that have been published that might be useful in establishing health and safety criteria pertaining to TENORM. Such criteria should be established in order to address issues that are unique to TENORM in the oil and gas industry, within the overarching regulatory philosophy of justification, optimization, and limitations on individual risk as recommended by ICRP. One of the issues that the E-42 Task Force is addressing is the definition of TENORM. For the purpose of this Report, the definition of TENORM, as provided in *SSRCR Part N* (CRCPD 2004) is used, as follows:

Technologically Enhanced Naturally Occurring Radioactive Material (TENORM) means naturally occurring radioactive material whose radionuclide concentrations are increased by or as a result of past or present human practices. TENORM does not include background radiation or the natural radioactivity of rocks or soils. TENORM does not include source material and byproduct material as both are defined in the *Atomic Energy Act of 1954*, as amended (AEA 42 USC §2011 et seq.) and relevant regulations implemented by the USNRC (CRCPD 2004).

However, the definition is expanded to include material that may not have been reconcentrated with respect to the concentrations in the original formation, if they are elevated naturally and are relocated so that there is an increased potential for environmental mobility and/or they are more accessible to workers and the public, because they also can be considered a source of TENORM. The E-42 Task Force recognizes that this expanded definition must be applied carefully since there are conditions where trivial concentrations and quantities of both NORM and TENORM can be produced and/or relocated in a manner that is inconsequential.

No federal regulations explicitly govern the management and disposal of TENORM associated with the oil and gas industry. However, potentially applicable radiation protection principles have been promulgated:

- under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA);
- in the U.S. Occupational Safety and Health Administration (USOSHA) regulations set forth in *29 CFR 1910.1096*;
- in the USNRC regulations set forth in 10 CFR Part 20;

- in the Clean Water Act (CWA 1972);
- in the Safe Drinking Water Act (SDWA 1974); and
- in the USEPA Superfund and RCRA guidance (RCRA 1976).<sup>12</sup>

In addition, SSRCR Part N, Regulation and Licensing of Technologically *Enhanced Naturally Occurring Radioactive Material (TENORM)* "...establishes radiation protection standards for Technologically Enhanced Naturally Occurring Radioactive Material (TENORM). These standards include the possession, use, processing, manufacture, distribution, transfer, and disposal of TENORM and of products with TENORM." (CRDPD 2004) These CRCPD guidelines are available to states for use in developing state-specific TENORM regulations. Of particular interest to this Report is guidance in *SSRCR Part N* that addresses the disposal of TENORM at permitted landfills and the beneficial use of TENORM (CRCPD 2004).

A vast body of radiation protection regulations and guidance establishes a precedence, or applicable or relevant and appropriate requirements (ARAR). These documents establish a baseline for use in developing and applying criteria for the management, transportation, and disposal of TENORM associated with the oil and gas industry. However, the adoption of these existing overarching criteria and guidelines for use in the oil and gas industry may not always be appropriate. Explicit consideration must be given to optimization issues; the costs and benefits and unintended short- and longterm consequences of adopting any criteria must be taken into consideration. These issues may be:

- unique to the oil and gas industry as a whole;
- unique to the myriad of systems, components, and operations that take place in the oil and gas industry; or
- unique to the varied geographical, demographic, and hydrogeological regions of the country where TENORM is produced, handled, managed, shipped, and disposed.

It is important that the adoption, development, and implementation of criteria does not lose sight of the concepts of exclusion and exemption and the philosophy of a graded approach as described in *ICRP 104* (ICRP 2007).

In addition to the ANSI Standard and CRCPD's E-36 publication (CRCPD 2003), numerous standards-setting bodies have published other standards of good practice pertaining to TENORM, including the following:

<sup>&</sup>lt;sup>12</sup> Note that the National Academy of Sciences (NAS) report to Congress (1999) and USEPA's response to that report address the applicability of RCRA regulations to TENORM.

- Basic Radiation Safety Standards and guidance issued by the National Academy of Sciences (NAS), ICRP, and IAEA dealing with clearance, exemption, exclusion, and intervention of material containing radioactive material
- ISCORS. 2005. ISCORS Assessment of Radioactivity in Sewage Sludge: Modeling to Assess Radiation Dose, ISCORS Technical Report 2004-04, NUREG-1783; USEPA 832-R-03-002; DOE/EH-0670. Washington, D.C.: Interagency Steering Committee on Radiation Standards (ISCORS), 2005.
- NCRP. 1993a. *Limitation of Exposure to Ionizing Radiation, NCRP Report No. 116.* Chapter 16, "Remedial Action Levels for Naturally Occurring Radiation for Members of the Public." Bethesda, Maryland: National Council on Radiation Protection and Measurements (NCRP), 1993.
- NCRP. 1993b. Radiation Protection in the Mineral Extraction Industry, NCRP Report No. 118. Bethesda, Maryland: NCRP, 1993.
- NRC. 1999. Evaluation of Guidelines for Exposure to Technological Naturally Occurring Radioactive Materials. Washington, D.C.: Committee on Evaluation of Guidelines for Exposure to Naturally Occurring Radioactive Material, National Research Council (NRC), 1999.
- CRCPD. 1994. NORM Report #3: Report of the E-4 Committee on NORM Contamination and Decontamination/Decommission, Report 3. Frankfort, Kentucky: CRCPD, 1994.
- IAEA. 2003. Safety Reports Series No. 34: Radiation Protection and the Management of Radioactive Waste in the Oil And Gas Industry ANL/EAD-2. Vienna, Austria: International Atomic Energy Agency (IAEA), 2003.
- CRCPD. 2004. SSRCR Part N Regulation and Licensing of Technologically Enhanced Naturally Occurring Radioactive Material (TENORM). Frankfort, Kentucky: 2004.

## Status of State TENORM Regulations

Unlike special nuclear material, source material, and byproduct material, TENORM falls outside of the regulatory control of the USNRC. USEPA has not promulgated regulations for the management and disposition of TENORM in the oil and gas industry. Therefore, the regulatory burden falls on individual states. CRCPD developed a model standard, *SSRCR Part N* (CRCPD 2004)<sup>13</sup> in an attempt to lead the states to uniform regulation of TENORM. Table B-1 gives the suggested exemption thresholds for waste from *SSRCR Part N*.

	Concentration Threshold Below Which Waste Is Exempt	Dose Threshold Below Which Waste Is Exempt
CRCPD	Any combination of Ra-226	0.5 uSv/hr (50 µR/hr)
Recommendations	and Ra-228 with	including background
in SSRCR Part N	concentrations less than	radiation, at any accessible
(CRCPD 2004)	0.185 Bq/g (5 pCi/g)	location
	[Section N.4(a)]	[Section N.7(f)]

#### Table B-1. Current CRCPD Guidance

Table B-2 summarizes the radiation protection regulations developed by individual states for the management and disposition of TENORM. In addition, the Association of State and Territorial Solid Waste Management Officials (ASTSWMO) published *State Regulations and Policies for Control of Naturally-Occurring and Accelerator Produced Radioactive Materials (NARM) and Technologically Enhanced Naturally-Occurring Radioactive Materials (TENORM)* (ASTSWMO 2014). The summary provided in Table B-2 is provided for information purposes only and should not be used for compliance determination. State regulations in their entirety should be obtained from each individual state. The regulations of most states do not draw a distinction between NORM and TENORM.

State	Concentration or Quantity Threshold Below Which Waste is Exempt	Dose Threshold Below Which Waste is Exempt
Alabama	Concentration of greater than 0.185 Bq/g (5 pCi/g) of combined Ra-226 and Ra-228	Exposure reading of 0.5 uSv/hr (50 µR/hr) background included, at contact with the NORM or NORM-contaminated article

#### Table B-2. Existing State Regulations

<sup>&</sup>lt;sup>13</sup> CRCPD *SSRCR Part N* materials can be downloaded from the following locations: <u>http://www.crcpd.org/SSRCRs/N\_04-04-print.pdf</u> and <u>http://www.crcpd.org/SSRCRs/Implement-Guide-print.pdf</u>.

State	Concentration or Quantity Threshold Below Which Waste is Exempt	Dose Threshold Below Which Waste is Exempt	
Arkansas	Concentrations less than 0.185 Bq/g (5 pCi/g) of Ra-226 and/or Ra-228, 0.05% by weight of uranium or thorium, or 5.55 Bq/g (150 pCi/g) of any other NORM radionuclide, provided that these concentrations are not exceeded at any time	Equipment exposure level does not exceed 0.5 uSv/hr (50 µR/hr) above background radiation at any accessible point	
Georgia	0.185 Bq/g (5 pCi/g) or less of technologically enhanced Ra-226 or Ra-228 in soil or other media, averaged over any 100 square meters and averaged over the first 15 centimeters of soil below the surface, in which the radon emanation rate is equal to or greater than 0.74 Bq (20 pCi) per square meter per second	Radiation level 18 inches from the NORM- contaminated material does not exceed 0.02 mSv/hr (2 mrem/hr)	
Illinois	Sludges and water treatment residuals from the treatment of groundwater are exempt at or below 7.4 Bq/g (200 pCi/g) (dry weight basis) provided disposal is effected through one of two regulated pathways. Sludges beneath 0.111 Bq/g (3 pCi/g) (dry weight basis) are unregulated/not subject to exempt restrictions/requirements	0.10 mSv (10 mrem) per year increase in background exposures due to TENORM	
Louisiana	0.185 Bq/g (5 pCi/g) of Ra-226 or Ra-228 above background or 5.55 Bq/g (150 pCi/g) of another NORM radionuclide	Equipment exposure level does not exceed 0.5 $uSv/hr$ (50 $\mu$ R/hr) above background radiation at any accessible point	
Maine	0.185 Bq/kg (5 pCi/g) excluding natural background	Maximally exposed individual will not receive a total effective dose equivalent of more than 1 mSv (0.1 rem) in one year	

Table B-2. Existing State Regulations

State Concentration on Quantity Date Threshold Polery		
State	Concentration or Quantity Threshold Below Which Waste is	Dose Threshold Below
		Which Waste is Exempt
Mississippi	<b>Exempt</b> 0.185 Bq/g (5 pCi/g) of Ra-226 or Ra-228 above background; or concentrations less than 1.11kBq/kg (30 pCi/g) of technologically enhanced Ra-226 or Ra-228, averaged over any 100 square meters, provided the radon emanation rate does not exceed 740 mBq (20 pCi) per square meter per second, or 5.55 kBq/kg (150 piCi/g) of any other NORM	Equipment exposure level does not exceed 0.25 µSv/hr (25 µR/hr) above background radiation at any accessible point
	radionuclide, provided that these concentrations are not exceeded at any time	
New Jersey	37 kBq (0.1 microcurie)	0.15 mSv/yr (15 mrem/yr) total effective dose equivalent
New Mexico	1.11 Bq/g (30 pCi/g) or less of Ra- 226, above background, or 5.55Bq/g (150 pCi/g) or less of any other NORM radionuclide above background, in soil, in 15- centimeter layers, averaged over 100 square meters	Maximum radiation exposure reading at any accessible point does not exceed 0.5 $\mu$ Sv/hr (50 $\mu$ R/hr) including background
New York Department of Environmental Conservation (NYSDEC)	Any NORM that is processed and concentrated is subject to regulation. TENORM from oil and gas production is not allowed for landfill disposal. (See 6NYCRR Part 380-1.2 (e) and 380-4.2.)	Note: High volume hydraulic fracturing for natural gas has been banned in the State of New York.
Ohio	Concentrations less than 0.185 Bq/g 185 Bq/kg (5 pCi/g) above background	Does not exceed 0.5 µSv/hr (50 µprem/hr) including background

Table B-2. Existing State Regulations

State Concentration or Quantity Dose Threshold Below		
State	Threshold Below Which Waste is	Which Waste is Exempt
		which waste is Exempt
Oregon**	<b>Exempt</b> 185 Bq/kg (5 pCi/g) of radium, 0.05% by weight of uranium or thorium or 5.55 kBq/kg (150 pCi/g) of any other NORM radionuclide provided that these concentrations are not exceeded at any time	Material that may be released to the general environment in groundwater, surface water, air, soil, plants, and animals shall not result in an annual dose above background exceeding an equivalent of 0.25 mSv (25 mrem) to the whole body or 0.75 mSv (75 mrem) to the critical organ of any member of the public
Pennsylvania	No pre-approval required for TENORM waste disposal in RCRA D facilities if the combined radium activity is less than 0.185 Bq/g (5.0 pCi/g), and below 1 cubic meter in volume	
South Carolina	1.11 Bq/g (30 pCi/g) or less of technologically enhanced natural radiation due to Ra-226 or Ra-228 in soil, averaged over any 100 square meters and averaged over the first 15 centimeters of soil below the surface, provided the radon emanation rate is less than 0.74 Bq (20 pCi) per square meter per second, OR 0.185 Bq/g (5 pCi/g) or less of technologically enhanced natural radiation due to Ra-226 or Ra-228 in soil, averaged over any 100 square meters and averaged over the first 15 centimeters of soil below the surface, in which the radon emanation rate is equal to or greater than 0.74 Bq/g (20 pCi) per square meter per second	0.5 μSv/hr (50 μR/hr), including the background radiation level at any accessible point

Table B-2. Existing State Regulations

State	<b>Concentration or Quantity</b>	Dose Threshold Below
	Threshold Below Which Waste is Exempt	Which Waste is Exempt
Texas***	1.11 Bq/g (30 pCi/g) or less of Ra-226 or Ra-228 and also contains 5.55 Bq/g (150 pCi) or less per gram of any other NORM radionuclide in soil, averaged over any 100 square meters and averaged over the first 15 centimeters of soil below the surface	Radiation level 18 inches from the NORM- contaminated material does not exceed 0.02 mSv/hr (2 mrem/hr)
Virginia	0.185 Bq/g , 185 Bq/kg (5 pCi/g) excluding natural background	Maximally exposed individual will receive an annual total effective dose equivalent from the released TENORM in excess of 1 mSv (100 mrem) per year excluding natural background

Table B-2. Existing State Regulations

\*New Jersey recently became an Agreement State<sup>14</sup> and a comprehensive set of TENORM regulations have been adopted.

\*\*Oregon: The possession and use of natural gas and natural gas products as a fuel are exempt from the requirements of these rules. The distribution of natural gas and the manufacturing and distribution of natural gas products are exempt from the specific license requirements of this Division, but are subject to the general license requirements in Oregon Administrative Rules 333-117-0100 and 333-117-0130.

\*\*\*Texas: Applies to oil and gas TENORM only.

As is evident from Table B-2, regulations are inconsistent between states. Concentrations below the indicated thresholds qualify as exempt materials. These wastes may be disposed of in municipal landfills and do not require state licenses. Most states also have provisions in place that prevent the intentional dilution of wastes in order to qualify as exempt material.

In early 2015, the use of high volume hydraulic fracturing was prohibited from moving forward in New York State. This decision was based upon a review by

<sup>&</sup>lt;sup>14</sup> Atomic Energy Act of 1954, as amended, Section 274 provides a statutory basis under which USNRC relinquishes to "Agreement States" portions of its regulatory authority to license and regulate byproduct materials (radioisotopes); source materials (uranium and thorium); and certain quantities of special nuclear materials.

the New York State Department of Environmental Conservation and a public health review by the New York State Department of Health (NYSDEC 2014a; NYSDEC 2014b).

These reviews found potential significant environmental and public health impacts could result from high volume hydraulic fracturing. Further, with the exclusion of sensitive natural, cultural and historic resources, and the increasing number of towns that have enacted bans and moratoria, the potential risks substantially outweigh any potential economic benefits of high volume hydraulic fracturing (NYSDEC 2014b).

Some states regulate TENORM as other radioactive material. A list of those states is shown in Table B-3.

Tuble D 5. States that Regulate TENOIM as other Radioactive Material		
State	Threshold Below Which Waste is	Dose Threshold Below
	Exempt	Which Waste is Exempt
Nevada	0.555 Bq/g (15 pCi/g) Ra-226	N/A
North	0.185 Bq/g (5 pCi/g) total radium	N/A
Dakota		
Tennessee	1.11 Bq/g (30 pCi/g)	Contact dose rate 0.5
		μSv/hr (50 μR/h)
Utah	0.555 Bq/g (15 pCi/g) Ra-226	N/A

 Table B-3. States that Regulate TENORM as Other Radioactive Material

Table B-4 lists the public and occupational exposure limits given in the documents referenced. The E-42 Task Force believes the documents establish a regulatory baseline (potential ARAR) that should help to inform the establishment of health and safety criteria related to TENORM in the oil and gas industry. Many of these criteria are quite complex and must be understood and used within the context to which they apply. In addition, many of these potential ARAR contradict each other, and any proposed regulatory framework must not only reconcile these differences, but recognize the context in which these ARAR were proposed. Hence, their applicability to the different segments of the oil and gas industry must be carefully evaluated. These matters are currently being addressed by the CRCPD Part N Working Group. The E-42 Task Force recommends that many of the technical issues and also the regulatory issues identified and recommended in this Report be taken into consideration by the Part N Working Group.

Target	Criterion	Regulation
Occupationally exposed radiation workers 10 CFR Part 20 UNDER REGULATION	50 mSv/yr 0.05 Sv/year (5,000 mrem/yr)	10 CFR Part 20
Occupationally exposed radiation workers	20 mSv/yr 2,000 mrem/yr	ICRP 103
Occupationally exposed members of the public (non-radiation workers) and members of the public	1 mSv/yr (100 mrem/yr)	10 CFR Part 20; ICRP
Drinking water pathway for members of the public	0.04 mSv/yr (4 mrem/yr)	40 CFR Part 141
Drinking water pathway for members of the public	0.185 Bq/L (5 pCi/L) Ra- 228 plus Ra- 226	40 CFR Part 141
Drinking water pathway for members of the public	30 µg/L of uranium	40 CFR Part 141
General public exposed to non-radon airborne emissions	0.10 mSv/yr (10 mrem/yr)	USEPA National Emissions Standards for Hazardous Air Pollutants
Cleanup criteria under USEPA regulations	0.15 mSv/yr (15 mrem/yr)	USEPA Superfund guidance*
USNRC site decommissioning/ license termination criteria for land and structures	0.25 mSv/yr (25 mrem/yr)	10 CFR Part 20, Subpart E; NCRP Report 129 (1999)
Indoor radon concentration	0.148 Bq/L (4 pCi/L)	USEPA action level for indoor radon for the public
Exempt quantities of radium in solids (above background)	0.111 Bq/g (3 pCi/g)	ANSI Standard administrative release limits
Placarding required for transportation	> 10 Bq/g (270 pCi/g) radium	49 CFR 173.403, 49 CFR 173.436, or values derived according to the instructions in 49 CFR 173.433

Table B-4. Selected Potential Health and Safety Criteria

Target	Criterion	Regulation
Soil cleanup criteria	0.185 Bq/g	USEPA Office of Solid Waste and
Son cleanup cintena	(5  pCi/g) Ra-	Emergency Response Directive
	226,	No. 9295.8-06a
	2,738 Bq/kg	110. 9293.8-00u
	(74  pCi/g)	
	U-238	
Disposal at low-level	0.25 mSv/yr	10 CFR Part 61.41
waste facilities licensed	(25 mrem/yr)	
by the USNRC	for protection of	
	the general	
	public	
Radionuclides in sewage	0.10 mSv/yr	ISCORS Technical Report 2004-4
sludge	(10 mrem/yr)	(2005)
Exposure to TENORM	1-6 mSv/yr	European Commission Report 122
workers	(100–600	(2000)
	mrem/yr),	
	0.518-1.036	
	Bq/L	
	(14–28 pCi/L)	
	radon	
Dose constraint for	0.30 mSv/yr	ICRP Publication 77 (1997)
members of the public	(30 mrem/yr)	
Exemption of wet sludge	5.18 Bq/g	European Commission Report 122
produced by the oil and	(140  pCi/g) for	(2000)
gas industry	uranium and	
	thorium and	
	progeny in	
	equilibrium	
Exempt concentrations	0.185 Bq/g	Suggested State Regulations for
of radium	(5 pCi/g) of any	Control of Radiation (SSRCR) Part
	combination of	N. Regulation and Licensing of
	Ra-226 and Ra-	Technologically Enhanced
	228 above	Naturally Occurring Radioactive
	background	Material (TENORM) (CCRPD 2004)
Water quality protection	State specific	40 CFR Part 131
standards	water quality	
	standards; e.g.	
	0.74 Bq/L	
	(20 pCi/L) Ra-	
	226 and Ra-	
	228 in Illinois	

 Table B-4.
 Selected Potential Health and Safety Criteria

\*Establishment of Cleanup Levels for CERCLA Sites with Radioactive *Contamination*, OSWER No. *9200A-18*, August 22, 1997 (USEPA 1997). This guidance states that remedial actions should generally achieve a level of risk within the 10<sup>-4</sup> to 10<sup>-6</sup> lifetime carcinogenic risk range based on the reasonable maximum exposure for an individua1. The guidance also states that cleanup levels of 0.15 mSv/yr (15 mrem/yr) equates to approximately  $3\times10^{-4}$  increased lifetime risk and has been found to be acceptable to the USEPA. In calculating cleanup levels, one should include exposures from all potential pathways, and through all media (e.g., soil, groundwater, surface water, sediment, air, structures, etc.). Furthermore, the 1997 guidance provides a listing of radiation standards that are likely to be used as ARAR to establish cleanup levels for remedial actions. In addition to these limits, exposures should be maintained as low as is reasonably achievable (ALARA) and many states have adopted or are developing specific TENORM regulations. Note that this guidance has been recently updated by USEPA. USEPA now considers that 0.12 mSv/yr (12 mrem/year) equates to 3 x 10<sup>-4</sup> increase lifetime risk.

# Issues Considered for Recommendations Regarding Standards

The E-42 Task Force considered several issues in making recommendations. These include:

- the need for a single trigger level;
- how to address exposures associated with radon;
- if workers should be identified receiving an occupational radiation dose;
- what level of training is needed; and
- what qualifications are needed for trainers.

These topics are discussed in this appendix.

## Trigger Level

One of the fundamental issues that the CRCPD E-42 Task Force is struggling with is whether to recommend a single trigger level regarding the presence of TENORM at a site that warrants some type of permit issued by the state regulatory authorities. Provided one believes that a trigger level is needed, the issue then becomes whether such a trigger should be prescriptive or performance based. For example:

- A prescriptive trigger might be 0.185 Bq/g (5 pCi/g) of Ra-226 plus Ra-228 above natural background in solids, sludges, and or residue at a site.
- A performance-based trigger could be an annual dose limit, such as 0.25 or 1 mSv/yr (25 or 100 mrem/yr) above natural background (not including radon) that might warrant a TENORM permit.

In exploring this issue, the E-42 Task Force performed a simple default RESRAD calculation to determine the external whole body annual dose associated with varying thickness of soil containing 0.185 Bq/g (5 pCi/g) dry of Ra-226.

Figure B-1 presents the results of these calculations. Keep in mind that this curve is for a reference resident exposure scenario, which may not represent the exposure scenario at a TENORM site, but it is useful as a benchmark in evaluating alternative strategies associated with establishing trigger levels for permitting.

The results indicate that under conditions where the contaminated soil is relatively thick (i.e. about 0.25 meters or greater) and has no clean cover, the external exposures reach their maximum value of about 0.30 mSv/yr (30 mrem/yr). Note that the exposures rapidly decline as the thickness of the contaminated zone decreases. It is also noteworthy that the assumed area of contamination is relatively large (i.e., 10,000 m<sup>2</sup>) and the calculations do not take into consideration surface roughness, which would reduce the actual exposure rate by some small margin, reducing the exposure maximum external rate to close to 0.25 mSv/yr (25 mrem/yr).

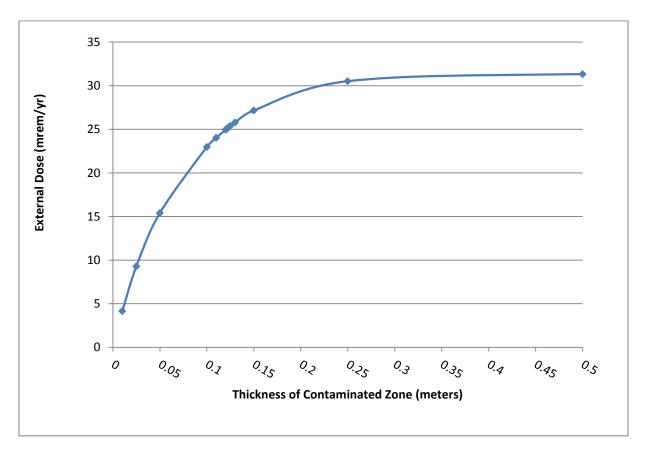


Figure B-1. External Whole Body Annual Dose Associated with 0.185 Bq/g (5 pCi/g) of Ra-226 in Soil in Full Equilibrium with Progeny and Using the Default Parameters Adopted by the RESRAD Code (10,000 m2 area of contamination)

#### Exposures Associated with Radon

A second issue that the E-42 Task Force is dealing with is how to address exposures associated with radon. As discussed elsewhere in this Report, one of the concerns associated with elevated levels of Ra-226 in soil or other solid materials is the production of radon and its potential to be transported by diffusive and advective transport mechanisms into structures located on top of or in the immediate vicinity of soil or other solids containing elevated levels of Ra-226. The relationship between the concentration of Ra-226 in soil and the associated concentration of radon indoors is complex and virtually impossible to predict. However, as a general rule, one can expect about a nominal Bq/L (pCi/L) of radon in air indoors for every Bq/g (pCi/g) of Ra-226 in soil in the immediate vicinity of a structure. Using this relationship, 0.185 Bq/g (5 pCi/g) of Ra-226 in soil might be associated with about 0.185 Bq/L (5 pCi/L) of radon indoors. Again, this relationship might be useful in judging the whether 0.185 Bq/g (5 pCi/g) of Ra-226 in solids above natural background at a site can serve as a useful trigger for determining when a TENORM permit is required at an oil and gas facility.

## Occupational Radiation Dose to Workers

An issue of concern to the E-42 Task Force is whether TENORM workers at a facility should be identified as workers receiving an occupational radiation dose. If so, the question becomes what level of radiation safety training is needed, along with what qualifications of the trainer should be required. These workers may experience occupational radiation exposures. It is the opinion of the E-42 Task Force that all TENORM activities and work should be subject to ALARA and radiation safety training. However, the level of radiation protection, the extent of TENORM training, and the qualifications of the trainer should be commensurate with the levels of exposures the workers might experience. For example, at levels of exposure that are detectable above natural background, it is appropriate to incorporate TENORM exposures into the right-to-know and general health and safety training required for industrial workers.

- The program should be more formal and comprehensive if exposures should exceed 1 mSv/yr (100 mrem/yr).
- In the rare cases where TENORM workers may get relatively higher exposures, an Administrative Level or action level should be considered.
- The current dose limit used by the ICRP is 20 mSv/yr (2,000 mrem/yr) and would be an appropriate annual limit.
- Finally, if worker exposures could approach or exceed 50 mSv/yr (5,000 mrem/yr), radiation controls and training should be comparable to the programs required by USNRC and Agreement State licensees for facilities that have the potential to cause such exposures.

Under all circumstances, TENORM facilities should be required to be designed and operated with due consideration of ALARA principles.

#### **Exposures Related to Shipments of TENORM**

Shipment of TENORM off site is required to meet all U.S. Department of Transportation (USDOT) regulations as set forth in 49 CFR Parts 172 and 173. As a practical matter, placarding of shipments is required if the shipment contains both more than 10 Bq/g and 10 kBq (270 pCi/g and 0.27 microcuries) of Ra-226. (Progeny also is to be included under the sum of fractions rule). Both of these limits must be exceeded in a given shipment before placarding is required. Recent USDOT clarification has underscored that the times 10 reduction for NORM does not apply to TENORM from the oil and gas industry ((*USDOT 49 CFR 173.401(b)(4)))*. The implications of these USDOT requirements are that, if a shipment of waste is placarded for radioactivity, it is unlikely that it will be accepted at a landfill, unless exemptions are approved by the authorized state authorities. Any person who prepares a shipment or shipping papers for Class 7 radioactive material must be properly trained in accordance with these USDOT regulations. The training is valid for a three-year period.

#### Exposures Related to Landfill Disposal of TENORM

The E-42 Task Force has held numerous discussions regarding trigger levels defining the concentration and quantity of Ra-226 and other radionuclides that can be disposed at a landfill of any kind. One of the options discussed was permitting the disposal of such material if it can be demonstrated that the potential exposures to members of the public will not exceed 0.25 mSv/yr (25 mrem/yr) for a period of 1,000 years following closure of the landfill. In addition, the E-42 Task Force believes that a level of assurance should be provided that the disposal of TENORM at a landfill is unlikely to result in the contamination of potable groundwater resources in excess of the drinking water standards for a period of 1,000 years following closure of the landfill. In making these determinations, credit for engineering and institutional controls should be given for no more than 100 years following closure of the landfill. The E-42 Task Force believes that it is essential that these issues be addressed by CRCPD and other standard-setting bodies.

The E-42 Task Force review of current and developing state regulations indicate that many landfills will not accept TENORM at concentrations above 0.185 Bq/g (5 pCi/g) of Ra-226 and Ra-228. (In some cases certain qualifications can relax these acceptance criteria.) The E-42 Task Force believes that the application of the 0.185 Bq/g (5 pCi/g) limit for the disposal of radium as applied to landfills has no scientific basis because of the dilution of the TENORM with other municipal and industrial wastes and the practice of adding fill and cover material that will substantially reduce the average concentration of any TENORM disposed at the facility. In addition, since these facilities are monitored and maintained for extended periods of time, the potential for exposures to both workers and members of the public at the time of disposal

and far into the future is greatly reduced. By adopting a dose-based standard with appropriate monitoring, training of workers, and controls, disposition of TENORM in a landfill under dose-based criteria can be performed in a safe and effective manner.

Workers at landfills receiving TENORM in excess of the trigger levels for permitting should be evaluated with respect to their potential to experience exposures, and a radiation protection plan should be implemented commensurate with that potential. Information available to the E-42 Task Force indicates that, in general, exposures to personnel at landfills has been and will continue to be well below 1 mSv/yr (100 mrem/yr), and simple awareness training would be appropriate at facilities which require a TENORM permit but where the potential for exposures (not including radon) is well below 1 mSv/yr (100 mrem/yr). Exposures to radon should be addressed on a case-by-case basis to determine if indoor exposures could exceed 0.148 Bq/L (4 pCi/L).

Workers at TENORM facilities, waste disposal facilities, and members of the public who might be exposed to material in the landfill following closure of the facility should not experience chronic exposures to indoor radon in excess of 0.148 Bq/L (4 pCi/L) from all sources, with consideration given to the degree to which short-lived radon progeny are close to achieving equilibrium. With respect to radon exposures to members of the public following closure of the landfill, consideration should also be given to the possibility that members of the public might take up residence in the vicinity of the landfill up to 1,000 years after closure of the landfill. In theory, models can be used to demonstrate that these radon limits will not be exceeded for a period of 1,000 years following closure of the landfill. However, such models are based on uncertain future conditions, and it is preferable to establish requirements that structures that may be established on or near the landfill in the future must be designed to be radon resistant and that measurements are made following construction that demonstrate that the 0.148 Bq/L (4 pCi/L) guidance has been achieved. However, such a regulatory strategy will be difficult to implement, given that this concerns time periods far into the future and the closure for RCRA landfills is 30 years. In light of this concern, consideration should be given to establishing limits on TENORM disposal such that the radon flux from soil surface is limited. This strategy for the management of radon exposures has precedent with the uranium mill tailings standards and has merit because radon flux can be modeled more reliably than the radon concentration inside structures that might or might not be established at a site far into the future.

#### Special Challenges Associated with Regulating Radon Exposures

The E-42 Task Force recognizes the special challenges associated with regulating radon exposures with respect to the management and disposal of TENORM containing Ra-226. There are two factors that establish these challenges.

First, naturally occurring radon levels in homes are typically on the order of about 0.037Bq/L to a few Bq/L (1pCi/L to a few pCi/L) (USEPA 2006, Table 5-1)<sup>15</sup>, and the annual effective whole body dose associated with this level of exposure is about 2 mSv/yr (200 mrem/yr) (NCRP 2009, Fig. 1.1.).<sup>16</sup>

Secondly, a typical Ra-226 concentration occurring naturally in soil has been reported to be about 0.0222 Bq/g (0.6 pCi/g) dry weight <sup>17</sup> (NCRP 1984, Table 4-1). In addition, *NCRP Report No. 94* reports typical levels of U-238 in soil of 0.0666 Bq/g (1.8 pCi/g) (NCRP 1987, Table 4.3). It can be assumed that Ra-226 is present in soil in approximate equilibrium with U-238. (See also Sextro et al. 1987, Table 1.)

On this basis, one can calculate a rule of thumb that establishes a general relationship between the concentration of radon in homes and the concentration of large volumes of Ra-226 in the soil in the vicinity of homes of about 0.037 Bq/L (1 pCi/L) of radon indoors per Bq/g (pCi/g) of Ra-226 in soil. However, a vast body of literature demonstrates that this relationship among real homes varies by orders of magnitude depending on a myriad of factors related to the structure of the home such as:

- cracks in the foundation;
- whether the home is constructed on a slab or with a basement;
- air turnover rate;
- time of year;

<sup>16</sup> NCRP indicates that the average effective dose in the United States from naturally occurring radon and thoron is 2.28 mSv/yr (228 mrem/yr); the vast majority of which is from radon and its short-lived progeny (NCRP 2009, Fig. 1.1.).

 $^{17}$  It should be noted that the average Ra-226 concentration in soil in different regions of the country and different geological settings can be highly variable. For example, unpublished data from a soil sampling survey conducted in 102 counties in Illinois revealed an average Ra-226 plus Ra-228 concentration (dry weight) of 0.07733 Bq/g (2.08 pCi/g) for agricultural soils and 0.07474 Bq/g (2.02 pCi/g) for non-agricultural soil.

<sup>&</sup>lt;sup>15</sup> USEPA states that the average exposure to radon in the U.S. is 2 mSv/hr (200 mrem/yr), ranging from 0.3 to 8.0 mSv/yr (30 to 800 mrem/yr) effective dose (USEPA 2006, Table 5-1). Also see *USEPA's Map of Radon in Homes* (USEPA 1993).

- basement versus upper floor occupancy;
- weather conditions; and
- local geology and the characteristics of the soil, which are perhaps the most important factors. (George and Hinchliffe 1987).<sup>18</sup>

It is for this reason that none of the dose-based standards for the protection of workers or members of the public include explicit consideration of radon exposures, and USEPA guidelines limiting indoor exposures to radon have been established based on a prescribed concentration limit of 0.148 Bq/L (4 pCi/L), as opposed to a dose-based or risk-based standard. Hence, notwithstanding any dose-based standard adopted by state authorities for the protection of workers or members of the public related to TENORM exposures, the E-42 Task Force recommends that limits on the acceptable levels of indoor radon concentrations be established in terms of a separate airborne radon dose.

Notwithstanding the dose-based standards adopted to protect workers and members of the public adopted by state authorities, implementation of those standards must establish a relationship between levels of contamination of Ra-226 and other radionuclides in water and solids and radiation dose to individuals who may be exposed to these materials. Hence, fundamental to implementing a given standard is the establishment of standardized protocols for the measurement of radionuclides, especially Ra-226 and Ra-228, in water and solids. Appendix D presents a description of the issues and protocols for measuring the concentration of Ra-226 and Ra-228 in water and solids. It also presents a discussion of the issues, protocols, and equipment used to characterize the external radiation field and doses to penetrating and non-penetrating radiation. Other sections of this Report address methods for relating measured concentrations of radiation and Ra-226 and Ra-228 in the environment and radiation exposures that might be experienced by workers and members of the public exposed to these materials.

<sup>&</sup>lt;sup>18</sup> Also see the USEPA radon home page http://www.epa.gov/radon/ and Map of Radon Zones (USEPA 1993).

# APPENDIX C

# ENVIRONMENTAL IMPACTS OF TENORM: DOSE ASSESSMENTS

## APPENDIX C-1 SOURCE TERM ESTIMATIONS AND CALCULATION OF IMPACT ON BACKGROUND RADIATION

USEPA, USDOE, and API have all performed similar studies in the past (ANL 1992; ANL 1996; API 1989; API 1997). Building upon these previous reports, the following sections attempt to incorporate the most recent data, seemingly reporting higher radionuclide concentrations and much higher volumes of produced waste. This likely is due to development of unconventional hydrocarbon deposits combined with advances in technological capabilities such as horizontal drilling used with high volume hydraulic fracturing. These unconventional deposits include:

- deep gas;
- tight gas;
- gas-containing shales;
- coalbed methane;
- geo-pressurized zones; and
- Arctic and sub-sea hydrates.

Recent studies and publications (and as a consequence, this Report) focus primarily upon the use of horizontal high volume hydraulic fracturing in shale formations. There is little data available on the exploration of other formation types, and the radiological impacts have not yet been widely studied. However, the consensus of the documents reviewed is the need for:

- additional characterization of TENORM content in oil and gas source terms and waste streams, focusing on detailed Quality Assurance/Quality Control (QA/QC) information;
- agreement between sample duplicates; and
- providing information on laboratory data (analytical methods, uncertainties, etc.).

Additional data needs, capable of advancing informed environmental protection decision making, include:

- the time from waste generation to sample analysis;
- the radiological profile of a waste stream throughout a well's life cycle;
- fate of radon; and
- the applications of field-able monitoring methods [such as total dissolved solids (TDS) surrogates].

In the past, the petroleum industry generated around 150,000 cubic meters (260,000 metric tons) of waste including produced water, scales, sludges, and contaminated equipment from conventional drilling. Of that waste, 30% was estimated to contain TENORM (USEPA 2013). USEPA reported that 20% to 100% of the facilities in every state reported some TENORM (USEPA 2013). The volume of TENORM waste generated from unconventional drilling has increased considerably.

The following information was utilized as the basis for volumes, concentrations, and source term estimates referenced in the section of this Report entitled "Disposal Pathways and Environmental Impacts."

### Drill Cuttings

The volume of drill cuttings produced is primarily a function of the depth of the well<sup>19</sup> and the diameter of the wellbore, estimated between 0.2 barrels and 2.0 barrels for each vertical foot drilled. According to 1985 and 1995 surveys by API, annual production of drilling wastes averaged over 253 million barrels (API 1989; API 1997; USEPA 2000).<sup>20</sup> From offshore production in the Gulf of Mexico, estimates from the USEPA assumed that:

- 7,861 barrels of drilling fluids and 2,681 barrels of cuttings are discharged overboard per exploratory well; and
- 5,808 barrels of drilling fluids and 1,628 barrels of cuttings are discharged per development well (USEPA 2000).

Studies on the radioactivity of drill cuttings (rock cuttings) provide varying concentrations of radium. As explained in this appendix, these can also have elevated uranium, thorium, and potassium, primarily based on the level of drilling fluids retained in or on the cuttings. Activity estimates range from 0.24 Bq/g (6.5 pCi/g to 0.024 Bq/g (0. 65 pCi/g) quoted in the *Draft Supplemental Generic Environmental Impact Statement* (NYSDEC 2009).

Pennsylvania has estimated that the Marcellus shale formation contains from 0.1258 to 1.258 Bq/g (3.4 to 34 pCi/g) uranium (PaDEP 1992). However, as the drill cuttings increase in their content of drilling fluids/muds, the higher activity of the fluid will create disposal and exposure problems. Radioactivity in drill cuttings have already tripped radiation monitoring alarms in Pennsylvania. The moisture content of the drill cuttings, which is retained drilling fluid, will

<sup>&</sup>lt;sup>19</sup> A data gap exists and needs to be filled regarding information on the depth of the various shale plays. For example, some like the Utica are very deep (> 10,000 ft), others like the Niobrara in Colorado are only ~4,000 ft.

<sup>&</sup>lt;sup>20</sup> These values pre-date horizontal drilling, which makes them useful as a prior benchmark, but they will need to be updated.

directly dictate the disposal options and environmental consequence thereof. Proper drying and removal of drilling fluids should be a priority for disposal.

One of the radionuclides not explicitly addressed here and elsewhere in this Report is potassium–40 (K-40). This radioisotope could be important as a source of external exposure and also as a radionuclide that could interfere with the measurement of other gamma emitting radionuclides. This is a data gap that needs to be addressed.

### Drilling Fluids and Muds

The chemical composition of drilling fluids varies widely based on the additives employed and the geological region for which they are being tailored. Additionally, the fluid can be water-based, oil-based, or synthetic-based. However, all will generally contain dissolved and suspended contaminants, including naturally occurring trace metals from:

- the formation;
- hydrocarbons;
- hydrogen sulfide;
- natural gas; and
- the soluble components of the uranium and thorium decay chains (radium and its progeny).

Ra-226 is soluble in chloride waters (e.g., brines) and will preferentially dissolve in the drilling fluid under the pressure and temperature conditions below ground. Radioactivity of brine samples varies as reported:

- USGS reported levels above 370 Bq/L (10,000 pCi/L) (USGS 2011);
- NYSDEC (NYS 2009) reported 555 Bq/L (15,000 pCi/L) (CoPhysics 2010); and
- USEPA reported 333Bq/L (9,000 pCi/L) (USEPA 2013).

Therefore, in the studies reviewed, the concentration of the brine water was used for conservative dose estimates and evaluation of disposal options for the drilling fluids. Cursory data from oil production company internet sites yielded an estimated 39,900 gallons of drilling base fluid (non-aqueous) per well.

### Flowback and Produced Waters

Water comprises the largest volume of byproduct material for the oil and gas industry. Reviewed studies indicate its generation at the rate of 15 to 21 billion barrels per year. A distinction should be made between two categories of water, flowback water and produced water.

Flowback is the term for water injected during hydraulic fracturing that returns to the surface. Although initially non-saline (fresh) water, flowback water is

often recycled between well sites and gradually takes on the salinity and chemical and radiological properties of the water within the formation.

Produced water is the term for this formation water, which is also brought to the surface as oil and/or gas is extracted. Due to the extended period of time in which this produced water has been in contact with the underlying geology, it is often very high in salinity and TENORM content. Therefore, produced water is also referred to as brine water. As the productivity of a well declines, the produced water volume increases relative to the oil and gas produced, up to a reported 98% water in some studies.

With little variation, the radionuclides of concern are Ra-226, Ra-228, and their progeny. In addition, Po-210 anomalies have been reported in both low and high pH media. (See the discussion on scale provided later in this appendix.) Uranium and thorium are relatively insoluble and remain in the formation, unlike that of their radium daughters. Therefore, despite the secular equilibrium radium may enjoy in the formation, the soluble radium (predominantly as the Ra<sup>+2</sup> ion) becomes isolated in the removed produced water. Radium chemistry is relatively well understood with Ra<sup>+2</sup> dominating (no less than 77%) the total dissolved radium. RaCl<sup>+</sup> is the second most common form, increasingly present with high salinity and Cl<sup>-</sup>/SO<sub>4-2</sub> ratios. Reports indicate radium may also form strong organic compounds in high salinity, which have not been thoroughly assessed for their fate in disposal models or their differences in bio-availability (USGS 2011).

Finally, IAEA reported high concentrations of lead mobilizing from the formation rock into produced waters, of which a *relatively high* fraction was radioactive Pb-210 (IAEA 2003). This, in combination with the presence of unsupported Po-210, indicative of direct leaching into the produced water from the formation, shows concentrations consistent with secular equilibrium with radium may be exceeded in produced waters. The data in Table C-1-1 represent the ranges of reported radioactivity in produced water in the studies reviewed. For the purposes of modeling environmental impact or disposal scenarios, many studies associate the flowback water with similar radiological characteristics. Dilution with surface water use, the extent to which flowback water is recycled, and other site-specific conditions will determine the accuracy of this assumption. As mentioned in the introduction to this appendix, often the degree of equilibrium or the distinction between Ra-226 and total radium is not made clearly.

Source	Radionuclide Concentration
Produced water from Louisiana	22.4 – 45 Bq/L (605 – 1,215 pCi/L) Ra-
platforms (USOSHA 1989)	226 + Ra-228
Produced water	< Detection – 104 Bq/L (2,800 pCi/L)
(ANL 1992)	Ra-226 + Ra-228
Non-Marcellus shale Produced water	37 Bq/L (1,011 pCi/L) (median) (Ra-
(NYSDEC 1999)	226 + Ra-228)
Produced water	"most sites exceed 70 Bq/L (1,900
(NYS 2009)	pCi/L)" Ra-226 + Ra-228)
Produced water from the Marcellus	0.7 - 104  Bq/L (19 - 2,800  pCi/L) (Ra-
shale (CoPhysics 2010)	226 + Ra-228)
Produced water's upper concentration	333 Bq/L (9,000 pCi/L) (unspecified)
(USEPA 2013)	
Non-Marcellus shale Produced water	< Detection – 248 Bq/L (6,700 pCi/L)
(USGS 2011)	Ra-226 + Ra-228
Marcellus shale, New York Produced	203 Bq/L (5,490 pCi/L) (median) Ra-
water (USGS 2011)	226 + Ra-228*
Marcellus shale, Pennsylvania	
Produced water – (USGS 2011)	226 + Ra-228)*
Produced water	High of 592 Bq/L (16,000 pCi/L) Ra-
(USGS 2011)	226
Produced water	High of 1,184 Bq/L (32,000 pCi/L) Ra-
(IAEA 2003)	226 + Ra-228
Produced water	"a few hundred becquerels per litre"
(IAEA 2003)	Ra-226, Ra-228, Ra-224, Pb-210
(USGS 2011)	59 – 226 Bq/L (1,600–6,100 pCi/L) Ra-
	226 + Ra-228**

Table C-1-1. Ranges of Reported Radioactivity in Produced Water

\*Taking the mean of these values, and multiplying by a conservative value of 3 million gallons per well, results in the production of about 37,000 MBq (1 Ci) of radium per well in many cases, which includes only production and flowback water.

\*\*This range is time based. The 59 Bq/L (1,600 pCi/L) sample was taken during the first week of hydraulic fracturing and the 226 Bq/L (6,100 pCi/L) sample taken at day 20. The increase in radium activity was reported as the equilibration between the injected water (recycled flowback water) and the radium that is present in the reservoir, either adsorbed onto mineral surfaces or dissolved in pore water (produced water).

#### Scale

Concentrations and volumes for scale production were sourced from the USEPA TENORM internet site, and IAEA reference document (IAEA 2003). Both were nearly identical. The average scale concentration of 17.76 Bq/g (480 pCi/g) Ra-226 coincides with the reported ranges from the IAEA. The Louisiana Department of Environmental Quality has also reported the production of scales that contained Ra-226 concentrations up to 37 Bq/g (1,000 pCi/g) (USOSHA 1989). In addition to Ra-226 and Ra-228, the IAEA reports that Pb-210 will

form a thin layer of deposition in production equipment along with stable forms of lead extracted from the formation. The Pb-210 deposits were reported with concentrations exceeding 999 Bq/g (27,000 pCi/g) (IAEA 2003). API found that the highest concentrations of TENORM are in the wellhead piping and nearby production piping. *"Concentrations were as high as tens of thousands of pCi/g."* (USEPA 2013) In addition, sock filters in gas production extraction can have even higher concentrations and pose management and disposal problems. The largest volumes, however, are in water/gas or water/oil separators and gas dehydrators. Although operators may attempt to mitigate scale accumulation through the use of chemical additions, this simply prevents deposition of the sulfate and carbonate scales on equipment and passes it through to the produced water.

### Radon

A good method for the estimation of the concentration of radon gas contributed to a home from an unventilated natural gas source is to start with the average concentration of radon present in gas distribution lines. By focusing on sampled concentrations of natural gas, which are located just prior to the consumer, the variability caused by the extrapolation of the concentration from the source is negated. Concentrations for the consumer endpoint calculated from wellhead values must take into consideration the following:

- wide range in the radon concentration at well heads contributing to production facility (0.185 to 53.65 Bq/L; average of 1.369 Bq/L) (5 to 1,450 pCi/L; average of 37 pCi/L) (USEPA 1973; USGS 2012);
- gas processing in which separation of liquid propane gas reduces radon 30%–75%;
- pipeline transmission time (i.e., decay in transit from wellhead to home);
- radon reductions resulting from comingling, storage, and processing (Anspaugh 2012); and
- storage time and method.

All of these considerations are highly variable and therefore not a good choice for determining an endpoint value, especially when they can be completely avoided by choosing alternative, more consistent sampling locations, i.e., gas distribution lines.

USEPA concluded in 1973 that conventional gas production methods led to an average concentration of radon in natural gas distribution lines of 0.851 Bq/L (23 pCi/L), based on data from the areas of Chicago, New York City, Denver, West Coast, Colorado, Nevada, New Mexico, and Houston.

• The average radon concentration in the gas at the point of use was calculated to be 0.74 Bq/L (20 pCi/L) with a possible variation of 0.37 to 3.7 Bq/L (10 to 100 pCi/L).

- Using the point-of-use concentration and factoring in gas use, dilution, and volume, the average radon contribution in homes from ranges was calculated to be 1.036 E <sup>-4</sup> Bq/L (0.0028 pCi/L).
- This conservatively calculated value is one that would only account for 0.07% of the 0.148 Bq/g (4 pCi/g) guideline recommended by the USEPA in homes in the United States today.

This data indicate that it would take a significant increase in radon concentrations at gas distribution lines to impact the consumers using methane.

Estimates of radon concentrations, previously based upon conventional extraction techniques, may require revisiting in light of recent technological advancements. Empirical testing of wellhead radon concentrations should be combined with an analysis of decreased consumer delivery times (decreased radon decay time due to an increase in facilities). However, current data from a USGS study of Rn-222 content in wells in Pennsylvania (USGS 2012) show a median radon concentration of 1.369 Bq/L (37 pCi/L), the same value as the average concentration of wellheads reported by USEPA (USEPA 1973). A measured concentration of radon in gas distribution lines from Pennsylvania gas sources at Lambertville, New Jersey, was  $0.629 \pm 0.0592$  Bq/L (17.0 ±1.6 pCi/L), a value lower than the average used by the USEPA 0.851 Bq/L (23 pCi/L) to estimate household exposure.

It appears that these new production wells, locations, and gathering techniques have little effect on the concentration of radon to the consumer in comparison to previous production locations and conventional gas production methods. However, it seems prudent to sample wellheads and distributions lines when significant changes in industry occur in order to ensure consumer safety.

A final word on the lead and polonium contamination is warranted as it pertains to workers outside of, or tangential to, the oil and gas industry. Since little data are available and a widespread reliance of releasing equipment for unrestricted use is on the gamma exposure rate, there is a high likelihood that workers performing maintenance on valves, pipelines, railcars, and trucks are exposed to Pb-210 and Po-210. The extent to which this contamination extends into public distribution lines is highly variable based on distance to the consumer and time in transit. Therefore, several companies are currently investigating the contamination potential and regulatory authorities should do the same.

#### Accumulated Sediments (Tank Bottoms/Sludges)

Most oil and gas operations use tanks or pits for the temporary storage of oil, natural gas liquids, and produced water. While stored, small solid particles that are suspended in the liquids can settle out as temperature and pressure change, forming a layer of accumulated sediment with the consistency of sludge or sand. This sediment is likely to contain:

- hydrocarbons;
- any chemical additives employed;
- heavy metals; and
- concentrated chemical contaminants of the contributing geologic formation.

It is difficult to establish an average sludge and accumulated sediment volume on a per well basis due to:

- the variability that exists in frequency in which a site decontaminates equipment;
- how they dispose of contaminated sludges; and
- a facility's produced water handling capabilities.

As stated earlier, uranium and thorium are not highly soluble in the formation water and, therefore, will not accumulate substantially in sludges. However, the high solubility of their radium progeny, Pb-210, and to a lesser extent Po-210, will lead to TENORM concentrations warranting consideration during disposal. Although Ra-226 and Ra-228 have historically been referenced as the radionuclides of concern in scales and sludges, an increasing number of studies point to unsupported Pb-210 contamination. Radioactive lead appears as a high fraction of the isotopic mix of stable leads, in the form of metallic lead, sulfides, oxides and hydroxides. Therefore, although data are insufficient to conclude what individual radionuclide concentrations may be on an average basis, it is a reasonable assumption to expect Pb-210 in excess of secular equilibrium.

Other sources of accumulated sediments include thousands of sock filters that are generated predominantly by gas production every year, which can pose a hazard to workers and are a disposal problem, since they are often disposed of improperly. In addition, condensates from wet wells are valuable and processed for ethane and propane, and represent a potentially significant source of exposure to radon. An example is a new plant being built in Colorado to process condensate into marketable commodities to offset the low gas prices. Both these topics represent data gaps that require further investigation.

## APPENDIX C-2 RESRAD MODEL AND ASSUMPTIONS UTILIZED

Calculations of radiological impact, whether screening or realistic, involve assumptions of not only the concentrations and volumes involved (i.e., source term) but the chemical and physical characteristics that dictate mobility and environmental fate. In short, many modeling scenarios in this section utilized RESRAD 6.5<sup>21</sup> with default parameters, unless otherwise specified. These were chosen because they have been commonly associated with a reasonably realistic set of conservative factors applicable across multiple geographic areas and providing sound bounding numbers. The resulting doses are likely much lower and should be adjusted to the source term and site conditions existing in a particular region. However, it should be noted that since many of the waste forms share common environmental deposition methods, the federal regulations and guidelines that are applicable to these disposal options help to define the variables in modeling. For landfills, these include requirements for:

- cover;
- specified porosity;
- liner; and
- hydrogeological siting.

USEPA Part 503 Biosolids Rule land application regulations define minimum depth to the water table, minimum erodibility, and several other factors that greatly control the dose to the receptor. If the environmental pathways are subject to these related regulations, the modeling scenarios can be greatly simplified. Radon was not incorporated into the derived doses for the reasons previously discussed. However, states may wish to incorporate the radon pathway into these calculations. Should a specific area have restrictions on building codes, mandatory radon mitigation, or other factors that impact the exposure pathways, these also should be utilized to effectively refine the model. Where available, these requirements have been incorporated into modeling scenarios. Recommendations are that assumptions about residency, radon mitigation, land use, and the variables in need of additional research be clearly defined. This should be done so that the dose, and consequently the environmental deposition methods, can be carefully assessed and crafted into adequately protective legislation.

<sup>&</sup>lt;sup>21</sup> RESRAD is a computer model designed to estimate radiation doses and risks from RESidual RADioactive materials and is used for the evaluation of radioactively contaminated sites. https://web.evs.anl.gov/resrad/home2/resrad.cfm

#### Land Application

Some states allow the direct land application (land applying) of water-based drilling fluids. Attempting to put bounding numbers on the environmental impact of land applying these drilling muds, the increase in environmental NORM concentrations, as well as a projected TEDE dose, is provided in the following literature review and scoping calculations using RESRAD.

The following calculations presume a water-based drilling fluid comprised of 8% solids.

- Using the State of Oklahoma as an example, which controls the application rate of drilling mud to 200,000 lbs/acre dry weight (i.e., solids), approximately 298,500 gallons per acre could be applied (OAC 2015a; OAC 2015b).
- If the drilling mud has been allowed to reach equilibrium with the formation water's radium content, 555 Bq/L (15,000 pCi/L) in a 3:1 Ra-226: Ra-228 ratio is a reasonably presumed concentration (utilized by both RWM 2010 and CoPhysics 2010).
- Assuming the density of the sludge is 8.34 lbs/gallon and the soil is 90 pounds per cubic foot with a 12" mixing depth, 5.92x10<sup>8</sup> Bq (16 mCi) per acre would be applied, resulting in a 0.351 Bq/g (9.5 pCi/g) increase in soil radium concentration above background.
- Given average background is around 0.074 Bq/L (2 pCi/g) combined radium (1:1 Ra-226: Ra-228), the annualized dose (RESRAD defaults) would be about 0.69 mSb/yr (69 mrem/yr) from external exposure alone (not to mention additional dose from plant uptake, radon, and a multitude of other pathways, pushing the dose from year one above 1 mSv (100 mrem).

These types of calculations are useful as benchmarks, and are considered to be generally conservative, but it is important to acknowledge uncertainties and variabilities in the physical models and input parameters, which can affect the results of such calculations.

For those drilling wastes receiving treatment at an industrial wastewater or a publicly owned treatment works (POTW) prior to land application, the TENORM content of sludges would be effectively diluted by any additional waste streams contributing solids. Thereafter, incorporation (i.e., tillage) of sludges further dilutes the resulting soil radium concentration. The land application rates of municipal sludges are typically dictated by agronomic requirements and nitrogen/phosphorus loading limits. Therefore, the application rates are much lower (approximately four or five tons per acre), and the radium increases in soil more slowly. With adequately protective ceiling limits, proper management and

selection of sites, sludge sampling, and site tracking, land application of TENORM wastes that have received treatment may be viable.

For example, given the same soil conditions, the same 0.351 Bq/g (9.5 pCi/g)increase in the radium concentration in soil would require 123 years of annual 1.11 Bq/g (30 pCi/g) sludge applications. USDOE studies cite external exposure as the primary concern from land application, comprising 80% of the dose (IAEA 2003). Soil concentrations of 0.185, 1.11, 8.88 Bq/g (5, 30, and 240 pCi/g) were examined and support the assertions that unregulated land applications can easily exceed public dose limits. Therefore, it is recommended that land application of TENORM be conducted under an established regulatory program such as the USEPA 503 Biosolids Rule.<sup>22</sup> Further, it is recommended that radium be included in the site loading/ceiling calculations. In this manner, many of the constraints that may serve to mobilize radium or expedite groundwater contamination are given bounding constraints by virtue of existing land application site requirements and application restrictions. For the purposes of calculating dose and mitigating environmental impact, other uses of solid drilling wastes, such as roadbed construction, landfill cover, and dike stabilization, are essentially analogous to land spreading.

Application of liquid waste streams to the surface (e.g., for dust suppression, road de-icing, or irrigation) can be modeled using similar criteria. Based on the data established in the previous sections, produced water is being modeled with a total radium concentration of 555 Bq/L (15,000 pCi/L). The high total dissolved solids (TDS) in produced water are closely correlated with the level of radioactivity. Several studies reviewed quoted the TDS content of produced water, after reaching equilibrium with the less turbid injection water, in the range of 100,000 mg/L to 250,000 mg/L. The median reported was 200,000 mg/L (USGS 2011).

Assume the application rates are limited, so that excessive runoff does not occur and that crop irrigation would be the most conservative scenario (the largest volume, over the largest area, over a prolonged period of time). The typical number of liters applied per acre was obtained from the USEPA's Irrigation Water Management Guide (as an average across multiple soil and crop types) (USEPA 2003). Albeit highly subjective, this results in 12,356 liters per acre, per irrigation (3:1 Ra-226: Ra-228 isotopic mix). Therefore, 6.99 × 10<sup>6</sup> Bq/acre (1.85 × 10<sup>8</sup> pCi/acre) would be applied, and using  $1.78 \times 10^9$  grams in an acre of soil, the increase in overall radium concentration is 0.0037 Bq/g (0.10 pCi/g) for every period of irrigation.

<sup>&</sup>lt;sup>22</sup> See A Plain English Guide to the USEPA Part 503 Biosolids Rule Title 40 Part 503 Standards For The Use Or Disposal Of Sewage Sludge or Biosolids Rule, http://water.epa.gov/scitech/wastetech/biosolids/503pe\_index.cfm

An acre of soil, with a contaminated zone 12-in thick (all other parameters default), would give rise to an increase of 7.4 X 10  $^{-6}$  Sv/year (0.74 mrem/yr) in dose. This number is approximately linear, so each additional irrigation can be multiplied by 7.4 X 10  $^{-6}$  Sv/year (0.74 mrem) to calculate the resulting increase in annual dose.

Because of the dilution that might occur from tilling TENORM into soil, other scenarios could be more limiting. For example, a road application scenario could be limiting because applications are applied such that the liquid evaporates and leaves behind a concentrated salt like crust layer on the surface.

Finally, the environmental impact of land application to effect the elimination of reserve pits, and/or the direct application of solid production wastes, is highly dependent upon:

- application rate;
- radionuclide concentrations; and
- resulting level of incorporation.

The environmental impact is modeled using the USEPA's average sludge concentration of 2.775 Bq/g (75 pCi/g). As demonstrated in this appendix, land application at agronomic rates with sufficient tillage and maximum ceiling concentrations of soil radium can be accomplished without exceeding a significant fraction of the public dose limit.

However, in the instance of simply spreading the material around a site to effect disposal, it is logical to assume the site would have areas of contamination equal to that of the reserve pit sediment.

Given a two inch layer of this contaminated waste, spread over an acre of ground and using the 3:1 ratio of Ra-226:Ra-228 for Marcellus shales in a 2.775 Bq/g (75 pCi/g) sediment, the first year would yield a 2.29 mSv/yr (229 mrem/yr) dose, falling beneath the public dose limit only after year seven. This dose is driven by external exposure (approximately 90%), with water-independent plant pathways comprising the second largest component.

A sensitivity analysis was performed on the size of the area receiving this two inch layer of contamination from one-half to one-fourth of an acre, and showed only modest decreases in external dose, by roughly 10%. It is only when the contaminated zone drops beneath 30 square meters that the external dose falls beneath the 1 mSv (100 mrem/yr) limit. Thickness of contamination has a large impact, with 1 inch (over a half acre) contributing just over 1 mSv (100 mrem/yr), and 4 inches yielding almost 0.0034 Sv/year (340 mrem/yr).

Therefore, the distribution of accumulated sediments around a site without incorporation or consideration as to the resulting radium buildup of the soil can easily exceed the public dose limit and should be approached with sufficient oversight to minimize a significant increase in the picocuries per gram of total radium. In addition, natural attenuation of TENORM deposited at one location means that the material is relocated. Therefore, when considering the disposition of TENORM, consideration should be given to the redistribution of the TENORM associated with natural attenuation.

#### Intermediate Treatment

Intermediate treatment and disposal via a commercial or municipal wastewater treatment facility has historically accounted for about 15% of the drilling wastes in the oil and gas industry, according to the 1995 API survey (API 1997). Following treatment, the wastes are generally disposed of via one of the four avenues discussed in this appendix.

However, the increased volume of water generated by high volume hydraulic fracturing operations warrants a discussion on the facilities treating them and their resulting impact on the environment. The high levels of TDS in these wastewaters can be corrosive and damaging to facilities not equipped to handle them, the digesters in particular. The Pennsylvania Department of Environmental Protection and the USEPA are both actively studying the impact discharge of these wastewaters may have on the environment (USEPA 2011a).

In addition to treating production waters, the treatment of drilling fluids may generate waste streams containing TENORM. Recovery of drilling fluids is often a priority due to cost, with some companies essentially renting their fluids to the drilling companies. Once the drilling of a well is completed, the fluid is returned, cleaned, and prepared for use in another well. Assuming the industrial treatment facilities recognize the presence of TENORM, the radium can essentially end up in one of three places:

- retained in the drilling fluid and reused;
- solubilized and discharged as an effluent; or
- precipitated out and concentrated in sludge.

Therefore, as stated for municipal and commercial wastewater treatment facilities, the same avenues of deposition exist and monitoring for TENORM content in both produced sludges and permitted discharges should be incorporated.

#### Landfill Disposal

ANL concluded that the disposal of TENORM wastes in *Resource Conservation and Recovery Act Subtitle D* (RCRA 1976) landfills may be acceptable up to 1.85 Bq/g (50 pCi/g) (ANL1992; USDOE 1999). Short-term mitigation of radon and external exposure pathways are effectively obtained through the clay cap. The lengths to which these institutional controls can effectively remain enforced and address long-term drinking water impacts are a matter for regulating authorities to address. The conservative estimates utilized in models should be refined to:

- the liners utilized;
- local hydrogeology;
- depth to the water table;
- form and mobility of radium; and
- the source term landfilled.

Many of the solids disposed of may be processed to lower their radionuclide content. For instance, drill cuttings may have up to 80% of the residual drilling fluids removed, the predominant source of radium contamination, via a shale shaker or separation pit. However, the large volumes disposed of can amass a large inventory of radium in a landfill over time. The progressively increasing volume will generate radon gas, which cannot be effectively controlled with a gas combustion device. There have been no data observed on the gas collection systems that capture methane and the resulting radon progeny that may accumulate in such systems. The multitude of preprocessing options in use, such as mixing with sawdust or oak bark chips, or incineration prior to transfer to a landfill requires each state to assess the unique industrial practices in place. One of these preprocessing options includes solidification. API noted that a mixture of cement, fly ash, lime, or kiln dust is added to drilling wastes to form concrete-like blocks. Although less than 1% of wastes are handled in this fashion, it may serve to immobilize TENORM and other heavy metals. Recent developments have included radon resistant packaging, consistent with the material used for home radon mitigation, which may reduce the radon emanation rate. In an analogous fashion, scale enclosed in pipe joints may require further analysis in modeling to determine if the radon release rate presents a reduced hazard.

Because leachate is collected *in situ* and sent to wastewater treatment facilities, the previously mentioned environmental deposition methods of liquid discharge and sludge handling should be assessed, if TENORM is indeed present in the leachate.

Shallow land burial is not considered in this appendix as sharing similar environmental fate or exposure pathways as landfilling or onsite burial pits. IAEA (2003) discussed disposal of TENORM waste, as has API. Both noted extensive remediation concerns, from both a radiological and chemical contaminant standpoint. Shallow land burial often does not provide the necessary cover to mitigate external exposure, radon flux, vegetative uptake, and loss to erosion, or provide measures to limit migration to groundwater. Additionally, the preventive measures employed at both hazardous and nonhazardous landfills, such as non-permeable liners, hydrogeological assessments, extensive monitoring protocols, and robust regulatory oversight, do not exist for shallow land burial. Therefore, this disposal option is not recommended due to the possibility of exceeding the public dose limit, given the concentrations and volumes discussed in this appendix.

ANL report, *An Assessment of the Disposal of Petroleum Industry NORM in Nonhazardous Landfills*, serves as a useful roadmap for evaluating the doses associated with the disposal of NORM in landfills (ANL 1999). This report was used in part by the Michigan Department of Environmental Quality for establishing guidelines allowing the disposal of material contaminated with Ra-226 and Pb-210 in landfills designed and permitted to receive nonhazardous municipal waste. The study investigates exposures associated with the disposal of 2,000 m<sup>3</sup> of TENORM containing an average of 1.85 Bq/g (50 pCi/g) of Ra-226 and 20 m<sup>3</sup> of waste containing an average Pb-210 of 9.62 Bq/g (260 pCi/g). The exposure scenarios explicitly considered are best summarized by the following material excerpted from the report summary.

For the operational phase worker, the primary exposure pathway evaluated in this study was external irradiation. A second pathway – inhalation of contaminated particulates – also was considered for the worker involved in placing the wastes in the landfill when the wastes were not containerized. For the general public living next to or in the vicinity of the landfill (i.e., within a 50mi radius) during the disposal action, the primary exposure pathway was determined to be inhalation of contaminated particulates; for completeness, the external irradiation, ingestion of contaminated particulates, and ingestion of contaminated foodstuff pathways also were evaluated.

A variety of future land use scenarios – including on-site residential, industrial, and recreational and off-site residential scenarios – were considered. For all of the on-site scenarios, the primary exposure pathways were assumed to be external irradiation and inhalation of indoor and outdoor radon-222. Depending on the scenario, other less likely pathways (e.g., inhalation of contaminated particulates, inadvertent ingestion of contaminated soil, and ingestion of foodstuffs grown on the property) also were considered. For the offsite residential scenario, the only exposure pathways evaluated were ingestion of contaminated groundwater and inhalation of radon. The report concluded the following:

- Potential radiological doses and resultant health risks for workers actively involved in landfill operations would be negligible.
- Potential doses to an individual living adjacent to the landfill during the NORM disposal action and to the general population living within a 50-mi radius would be negligible.
- Potential doses to future industrial and recreational users of the landfill property would be negligible.
- Potential doses to hypothetical future residential users of the landfill property are most sensitive to depth of the NORM waste layer and integrity of the landfill cap. These doses would be negligible on the basis of the assumption that (1) the NORM wastes would be placed at a depth greater than approximately 10 ft below the cap and (2) the landfill cap would not be breached during construction of the home.
- Provided the NORM wastes are placed deeper than approximately 10 ft below the landfill cap, the Michigan policy allowing wastes containing up to 1.85 Bq/g (50 pCi/g) to be disposed of in Type II landfills is protective of human health.
- Increasing the total volume would increase the worker doses linearly and could increase the potential doses to the off-site resident via the groundwater pathway. However, it is estimated that doses for these receptors would be negligible, and increasing the volume probably would not change this overall conclusion. Radiological doses to the future-use receptors would not be affected by increasing the total volume; doses to these receptors are primarily affected by changes in the location of the NORM waste within the landfill.

The report also concludes that "...the results of this assessment indicate that the risk to workers or to the general public associated with the disposal of 20 m<sup>3</sup> of wastes containing an average Pb-210 concentration of 9.62 Bq/g (260 pCi/g) would be negligible." (ANL 1999)

#### **Deepwell Injection**

From a radiological standpoint (chemical constituents aside), the waters are being returned to formations that typically have similar radionuclide concentrations. Studies show 57% to 61% of the produced water is injected back into the producing formation to enhance oil/gas recovery.

The primary environmental concern that surrounds deep well injection is the contamination of a groundwater resource of drinking water. Although the producing formations and injection wells are often much deeper than these drinking water sources, a failed casing may allow TENORM to enter an aquifer.

ANL has performed studies that analyze this exposure pathway and the resulting environmental impact (ANL 1996). This model was performed with SWIFT II<sup>23</sup>, and doses calculated from USEPA drinking water exposure parameters. The source term consisted of 100,000 barrels of TENORM with a Ra-226 concentration of 74 Bq/L (2,000 pCi/L) injected over a period of 4 days. The worst case scenarios (based upon highly improbable scenarios) result in 0.0481 Bq/L (1.3 pCi/L) Ra-226 concentrations approximately 700 years after casing failure. This equates to a (10 mSV/yr) (1 rem/yr) dose when consumed at the rate of 2 liters per day, 390 days per year. USEPA maximum permissible combined radium concentration in drinking water is 0.185 Bg/L (5 pCi/L). ANL reported that doubling the concentration [up to 148 Bq/L (4,000 pCi/L)] doubled the maximum concentrations with no observable effect on arrival time. ANL concluded that much larger concentrations or volumes would likely not contribute to major increases in dose due to the extremely conservative assumptions made. Assuming the linearity of these models is maintained, a loss of contaminated drilling wastes at a concentration of 555 Bg/L (15,000 pCi/L) could give rise to groundwater concentrations in excess of 0.37 Bq/L (10 pCi/L), corresponding to approximately 80 mSv/yr (8 rem/yr).

While certainly within the confines of the public dose limit, a supplement to this Report should be additional modeling, including research into appropriate assumptions about casing failure and TENORM dispersion within geological layers.

The need for review is underscored by the findings of a 2014 USGAO study which indicated Class II injection wells' potential for groundwater contamination may not have been assessed adequately in light of larger injected volumes, over pressuring of targeted geological formations, and potential increased seismic activity. This is especially true for Class II wells that may have been grandfathered into the Underground Injection Control program (USGAO 2014).

<sup>&</sup>lt;sup>23</sup> SWIFT II - Sandia Waste-Isolation Flow and Transport Model is a code developed by Sandia National Laboratories for the USNRC that is used to model radioactive materials' mobility in the environment.

## APPENDIX C-3 SELECT REFERENCES PROVIDING INFORMATION ON TENORM ACCUMULATION

API. 2010. Water Management Associated with Hydraulic Fracturing, Guidance Document HF2. Washington, D.C.: American Petroleum Institute, 2010. This document provides an excellent overview of water management associated with hydraulic fracturing but only limited information on NORM.

GWPC. 2009. *Modern Shale Gas-Development in the United States: A Primer.*, Tulsa, Oklahoma: Groundwater Protection Council (GWPC) and ALL Consulting, 2009.

IAEA. 2003. Safety Reports Series No. 34: Radiation Protection and the Management of Radioactive Waste in the Oil And Gas Industry ANL/EAD-2. Vienna, Austria: International Atomic Energy Agency (IAEA), 2003. This report could be used as a roadmap for characterizing TENORM issues associated with each of the sectors that comprise the oil and gas industry. The report provides a good description of the industry, and Section 5 addresses NORM and where and why NORM accumulates in various pieces of equipment. Figures 22 through 24 and Table II provide an excellent overview of where and why different NORM radionuclides accumulate in oil and gas equipment.

IOGCC. 1994. Understanding the Basics of Naturally Occurring Radioactive Material (NORM) in the Oil and Gas Industry. Oklahoma City, Oklahoma: NORM Subcommittee of the Interstate Oil and Gas Compact Commission (IOGCC) Environmental and Safety Committee, IOGCC, 1994. This document contains useful material describing where TENORM is an issue in the oil and gas industry.

NYSDEC. 1999. An Investigation of Naturally Occurring Radioactive Materials (NORM) in Oil and Gas Wells in New York State. Albany, New York: NYSDEC, Division of Solid and Hazardous Materials, Bureau of Radiation and Hazardous Site Management, 1999.

USAEPA. 2000. USEPA Office of Compliance Sector Notebook Project – Profile of the Oil and Gas Industry, USEPA/310-R-99-006. Washington, D.C.: USEPA, 2000. This document could be used as a roadmap for characterizing TENORM issues associated with each of the sectors that comprise the oil and gas industry.

USEPA. 2011b. *Plan to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, USEPA/600/R-11/122.* Washington, D.C.: USEPA, 2011. Although this document does not address TENORM specifically, it can be

used as a roadmap for characterizing TENORM issues associated with hydraulic fracturing.

USGAO. 2012. Oil and Gas – Information on Shale Resources, Development, and Environmental and Public Health Risks. Washington, D.C.: United States Government Accountability Office (USGAO), 2012.

### APPENDIX D

## RADIOANALYTICAL PROTOCOLS

Appendix D describes the radiochemical protocols developed or approved by USEPA and other scientific entities that have applicability to samples of water, sludge, and solids containing TENORM. Theses protocols are available to laboratories for assaying TENORM. The advantages and limitations of each are described, along with typical limits of detection.

# APPENDIX D - BACKGROUND

The radionuclide of primary interest with respect to TENORM and the oil and gas industry is radium, specifically the alpha-emitting Ra-226. Naturally occurring thorium-232 (Th-232) also gives rise to the beta-emitting Ra-228, whose decay produces Th-228, followed by Ra-224 and Rn-220. However, concentrations of Ra-228 are typically considerably less than Ra-226 in TENORM associated with the oil and gas industry. Because of chemical interactions within the soil, certain members of a decay series will be transported differently through the soil column/ore body. Specifically, while the U-238 and Th-232 decay series may exist in secular equilibrium within the soil, the series' progenitors (U-238 and Th-232) may not be present in ground and surface waters although their progeny (radium radionuclides) are present. Naturally occurring U-238 and Th-232 radionuclides are transformed into a series of other radionuclides as they progress (decay) to stable radionuclides of lead.

The shale formations of interest for oil and gas production are associated with byproducts and wastes with typical Ra-226 concentrations an order of magnitude greater than those of Ra-228, although this does differ geographically and cannot be assumed. However, while considerable variability in the radionuclide content of ore bodies is expected, the main focus for TENORM related to the oil and gas industry is the direct progeny of thorium-230 (Th-230) in the U-238 series, Ra-226. This is due in part to its long half-life of 1,600 years and the fact that it decays directly to Rn-222. With its 3.2-day half-life, Rn-222 quickly produces a series of unstable radionuclides of polonium, bismuth, and lead, all of which are significant with regard to personnel exposure, before ending at stable lead (Pb-206). The degree to which the progeny have accumulated (grown in) must be known or established as part of any analytical protocol.

This can be confusing, in that the two radium radionuclides have different origins (i.e., alpha-emitting Ra-226 is produced by U-238, and beta-emitting Ra-228 is produced by the Th-232)<sup>24</sup>. The chemistry of radium in the environment is the same irrespective of radionuclides, however the concentration of each radioisotope depends on the presence and properties of the series' progenitors, U-238 or Th-232. The issue of secular equilibrium is of particular interest, in that several of the analytical protocols discussed in this appendix are heavily dependent on this parameter. When measuring Ra-226 by the techniques discussed in this appendix, most specifically gamma spectrometry, it is the progeny of radon that are measured, including bismuth-214 (Bi-214) and lead-

<sup>&</sup>lt;sup>24</sup> For the purpose of this report, the contributions of Ra-225 and Ra-223, which originate from U-233 and U-235, respectively, are ignored. Neither of which is deemed to be a significant contributor to TENORM wastes.

214 (Pb-214), whose gamma emissions are more easily detected than the emissions from Ra-226.

The basic approach is to quantify the more easily measureable Pb-214 and Bi-214 and equate these with the Ra-226 concentration based on the assumption of secular equilibrium. If the equilibrium is incomplete, these measurements can still be used as long as the degree of equilibrium can be quantified via a known ingrowth period, using well-known decay kinetics. Alternately, the radon emanation technique discussed in this appendix requires a minimum amount of time to allow for sufficient ingrowth of the progeny as part of the analytical protocol. Following that, the progeny are counted with a scintillation detector. The concept of secular equilibrium is fundamentally important to the measurement of all U-238 and Th-232 series radionuclides in TENORM materials, and is particularly pertinent to the quantification of Ra-226.

As mentioned previously, the U-238 and Th-232 that produce Ra-226 and Ra-228 are not routinely observed in ground and surface waters. While their presence in the ground or surface water is expected to be minimal due to their immobility, U-238 and Th-232 may contribute to the gross alpha and beta activity in waters and solids relevant to the production of TENORM. There are well-established radiometric, fluorometric, and phosphorimertic protocols for measuring uranium in soils and waters, while the analytical determination of thorium is limited to a radiometric procedure using alpha spectrometry.

Also of interest for this application of TENORM measurements are Po-210 and Pb-210, both of which are members of the U-238 series and grow in from Ra-226. These radionuclides are not typically measured as often as radium and uranium radionuclides, in part because they present specific measurement challenges. Their contribution can sometimes be inferred by virtue of quantifying their progenitor, i.e., the more easily measureable Ra-226, provided certain assumptions regarding secular equilibrium are appropriate. However, the topic of secular equilibrium, or lack thereof, can become complicated quickly. It is important to keep in mind that both Po-210 and Pb-210 arise from the decay of Rn-222, whose behavior, i.e., solubility, mobility or transport, differs considerably from its solid Ra-226 progenitor by virtue of its gaseous state. Specifically, while a sample may contain easily measureable quantities of Ra-226, its direct progeny gaseous Rn-222 may or may not be present due to changes in temperature, pressure or other environmental conditions.

It is important to consider that any one of four possibilities could exist.

- There are situations when there is secular equilibrium, i.e., the presence of Po-210 and Pb-210 is supported by the presence of Rn-222. In this instance, Rn-222 may be present as well as Po-210 and Pb-210.
- It follows that if Rn-222 is absent, there will not be Po-210 or Pb-210. Therefore, in this instance, there will be no Rn-222, Po-210 or Pb-210.

- Conversely, an environment through which Rn-222 has been moving over time, e.g., a length of enclosed pipe, may have accumulations of Po-210 and Pb-210 but no Rn-222. This occurs as Po-210 and Pb-210 are deposited on the pipe surfaces (become fixed) as the gaseous Rn-222 moves through the area, producing concentrations of unsupported Po-210 and Pb-210. In this case, there would be Po-210 and Pb-210 present, but no Rn-222, even though the Po-210 and Pb-210 were produced by the Rn-222.
- It is also possible to find Rn-222 without Po-210 and Pb-210 in areas where the Rn-222 is produced but somehow purged and the Po-210 and Pb-210 do not accumulate. In this instance, Rn-222 would be present, but not Po-210 and Pb-210.

Quantifying Po-210 and Pb-210 directly in water requires complicated laboratory analytical techniques. Several approaches seek to prepare a single sample to quantify both radionuclides. (See Appendices D-6 and D-8.) Typically, lead and bismuth are separated chemically using stable carriers and/or radioactive tracers and each is assayed separately, allowing for specific temporal considerations. Po-210 is usually measured directly via its energetic alpha emission. Pb-210 is a weak beta emitter that can be determined by measuring the short-lived Bi-210 progeny that has grown in following a specified ingrowth period. Pb-210 may also be quantified in solids via gamma emission.

The proper execution of radiometric techniques for any and all radionuclides listed involves the use of radioactive solutions for instrument calibration as well as routine method performance testing. Spiked samples, as well as for tracers, are discussed in this appendix. These solutions are readily available, usually contain low concentrations of the radionuclides of interest and are exempt from requiring a specific USNRC or state license for laboratory use. Radioactive solutions are an integral part of the operation of a radiochemistry laboratory. The inclusion of the need to use radioactive tracers should not be seen as detrimental to considering a specific method; although, their use may influence a laboratory's choice of method.

Please note that the table and other sections of this Report make reference to the use of radioactive tracers or chemical yield tracers, terms that are synonymous in this Report. Specifically, the tracer is another unstable (radioactive) isotope of the target analyte that is added to the sample quantitatively before processing and is recovered after processing. The tracer behaves identically to the target analyte but is measured independently. The recovery of the tracer represents the recovery of the analyte and allows the correction for losses through processing. For example, when Po-210 is the target analyte, the tracer will be polonium-207 (Po-207), polonium-208 (Po-208), or polonium-209 (Po-209). (See Appendix D-10.) The percent recovery of the Po-

207, Po-208, or Po-209 tracer represents the percent of Po-210 remaining after processing losses.

Table D-1 lists the widely used and approved protocols applicable to the measurement of gross alpha-beta, radium, polonium and lead in water and solids.

Analytical	Medium	Pros/Cons	References
Technique and			
Example Methods			
Gross alpha-beta USEPA Method 900.0	Water, solid	Pros: Low cost; simple analyses; short processing time; 500 mL sample typically adequate	USEPA 1980, USEPA 1984 EMSL 1979
		Cons: Screening only; may not include contributions of all alpha emitters (Po-210); typically under-reports Ra- 228 and Pb-210; limited by solids content for waters (<500 ppm TDS); potentially biased due to heterogeneity for solids (small sample size)	
Gross alpha-high solid samples EERF Method 00- 02	Water	Pros: Co-precipitation method; amenable to high solids water samples (>500 ppm); excellent sensitivity; captures radium and other U and Th alpha emitters; 500 mL sample typically adequate Cons: Longer processing	USEPA 1984
		time; positive values may need further analyses	
Gross radium alpha USEPA Method 903.0	Water	Pros: Co-precipitation method; amenable to high solids water samples (>500 ppm); screens for all radium isotopes (Ra-223, -224, and - 226); 500 mL sample typically adequate	USEPA 1980
		Cons: Longer processing time; positive values may need further processing time; comparable to gross alpha- high solid samples technique	

Table D-1. Radioanalytical Protocols

Analytical	Medium	Pros/Cons	References
Technique and			
<b>Example Methods</b> Ra-226 by gamma spectrometry <sup>25</sup> USEPA Method 901.1 ISO 18589-3 ASTM E181	Solid	Pros: Low cost; short processing time; simple sample preparation; large sample size; can provide information on other natural series radionuclides	USEPA 1984 EMSL 1979 ISO 2007 ASTM 2003
		Cons: Not amenable to water for natural series radionuclides; may be questionable due to incomplete equilibrium for Ra-226 or Ra-228 progeny; may require very large sample volumes or samples with large Ra-226 content to get desirable detection limits	
Ra-226 by radon emanation USEPA Method 903.1	Water, solid	Pros: Ra-226 specific; 1 L sample typically adequate Cons: Potentially biased due to heterogeneity for solids (small sample size); complex processing for waters and more so for solids; requires ingrowth period; more expensive	USEPA 1980 USEPA 1984 EMSL 1979
Ra-228, radiochemical USEPA Method 904.0 EERF Method Ra- 05	Water, solid	Pros: Ra-228 specific; excellent sensitivity; 1 L sample typically adequate Cons: Longer processing time; some procedures assay Ra-228 in conjunction with Ra-226	USEPA 1980 USEPA 1984 EMSL 1979

Table D-1. Radioanalytical Protocols

<sup>&</sup>lt;sup>25</sup> 25 USEPA Method 901.1 is often cited for gamma spectrometry. However, this procedure applies to water samples and must be modified to address specific aspects of solid samples. ISO Method 18589-3 and ASTM E 181-98 more directly address gamma measurements of solid samples.

Analytical	Medium	Pros/Cons	References
Technique and	mourum	1105,0015	References
Example Methods			
Ra-228 by gamma spectrometry USEPA Method 901.1 ISO 18589-3 ASTM E181	Solid	Pros: Low cost; short processing time; simple sample preparation; large sample size; can provide information on other natural series radionuclides Cons: Not amenable to water for natural series radionuclides; may be questionable due to incomplete equilibrium of Ra-228 progeny; may require very large samples volumes to get desirable detection limits	EMSL 1979 ISO 2007 ASTM 2003
Po-210 IAEA AQ/12	Water	Pros: Excellent sensitivity; 1 L sample typically adequate Cons: Requires laboratory processing; alpha spectrometry and use of internal chemical yield tracers (Po-207, Po-208, or Po-209)	EMSL 1979 IAEA 2009
Po-210 EERF Method 00- 03 IAEA AQ/12	Solid	Pros: Excellent sensitivity; allows use of large sample volume Cons: Complex sample preparation; potential volatility of Po-210; requires laboratory processing; alpha spectrometry and use of internal chemical yield (radioactive) tracers (Po-207, Po-208, or Po-209)	EMSL 1979 USEPA 1984 HASL 300
Pb-210	Water	Pros: Excellent sensitivity Cons: Complex sample processing; 21 day growth	EMSL 1979 HASL-300

Analytical Technique and Example Methods	Medium	Pros/Cons	References
		required; may require Atomic Absorption (AA) or Inductively Coupled Plasma (ICP) to correct for chemical recovery	
Pb-210 ISO 18589-3 ASTM E181	Solid	Pros: Data may be obtained concurrently with other photon emitters (Ra-226 or Ra-228) Cons: Low energy of photons may be obscured by higher concentrations of higher energy radionuclides; may require longer counting times or larger samples for	EMSL 1979 USEPA 1984 HASL 300
Gross Alpha-Beta Screening: chemical separation, LSC and gamma spectrometry	Water	desirable detection limits Pros: Provides values for most important alpha and beta emitting natural series radionuclides (uranium and thorium); unaffected by TDS content; 4 L sample typically adequate	USEPA 2014
		Cons: Multi-step, complex process; requires both LSC and gamma spectrometry systems; requires knowledge and/or assumptions regarding degree of secular equilibrium; activity calculations are complicated, especially uncertainty determinations; requires use of radioactive tracers	

# APPENDIX D - 2 QUANTIFYING RA-226 IN WATER

The measurement of Ra-226 is usually the most important aspect of determining the TENORM content of water and solid samples in the oil and gas industry. Since Ra-226 is an alpha emitter, the common practice is to screen a sample using a gross alpha technique. In this context, gross alpha via gas proportional counting should be considered a screening tool for Ra-226. (See the discussion in Appendix D-10.)

The technique consists essentially of evaporating a small, known volume of an acidified water sample to one to two milliliters (mL), transferring it to a counting dish, taking it to dryness, and measuring it for one to two hours in a fixed-base laboratory instrument. Assuming proper execution of the analytical technique, a value of less than 0.185 Bq/L (5 pCi/L) of gross alpha activity allows the interpretation that the content of alpha-emitting Ra-226 in the sample must be less than 0.185 Bq/L (5 pCi/L). However, water samples with high TDS (>500 ppm) precipitate upon drying and can interfere with the assay by attenuating (blocking) the sample's alpha emissions, which produces detection limits typically in the hundreds of Bq/L (pCi/L) and makes the results useless in this context.

Since the main contributor is Ra-226, it is possible to co-precipitate the radium along with most other natural-series potential alpha emitters (i.e., uranium and thorium) using barium sulfate, transfer the residue to a counting dish, and measure it for one to two hours. The sample's TDS content does not interfere, and detection limits of 0.185 Bq/L (5 pCi/L) are easily obtainable. However, this procedure precipitates all radium isotopes, and elevated results for this procedure do not necessarily indicate high Ra-226 concentrations, since they may reflect radium-223 (Ra-223) and/or Ra-224. Such values would require additional analyses. The processing time for this approach is longer than for gross alpha, but it does provide a possible path forward for problematic samples, particularly for high TDS samples. A related procedure, Eastern Environmental Radiation Facility Method 00-02 (EERF 00-02), uses barium sulfate and iron, which essentially precipitates radium and all the actinide elements in the sample, yielding a gross alpha value. (See the discussion in Appendix D-10.)

Gross alpha screening is often referred to as gross alpha-beta screening, in that a value for alpha and beta activity are often reported together. Many of the members of the U-238 and Th-232 series are beta emitters, and the gas proportional counter can measure both alpha and beta emissions simultaneously. There are instances where the gas proportional counter will measure only alpha emissions, by design. The gross beta analysis is more tolerant of a sample's TDS content, due to physical differences in the emissions of the two types of radiation. The gross beta content does not necessarily add value for TENORM samples; however, it can be used to correlate or further support the presence of other natural series radionuclides. Appendix D-10 discusses a novel approach to gross beta determination that USEPA has developed recently.

The definitive method for the determination of Ra-226 is called radon emanation. This technique involves precipitating the radium from an acidified water sample using barium sulfate, dissolving it in a chelating agent (EDTA), transferring it to a sealed glass container, and allowing the radioactive progeny to grow in for a known time, on the order of seven to 14 days. Following the ingrowth, the gas is purged into a scintillation cell. When the alpha emissions of the short-lived progeny polonium-218 (Po-218) and polonium-214 (Po-214) are essentially in equilibrium about four hours, the scintillation cell is counted. Based on the degree of equilibrium calculated from the ingrowth periods, the Ra-226 content is determined. This protocol is specific to Ra-226 and is quite sensitive; detection limits on the order of 0.00185 Bg/L (0.05 pCi/L) are easily obtainable. If a sample's results are elevated, the confidence that they represent actual Ra-226 values is high, assuming proper execution of the technique. While this is the definitive analytical technique for quantifying Ra-226 in water, this approach is costly and time consuming, due to the sample processing and the required ingrowth period.

It must be noted that the prevalence of measuring water samples for U-238 and Th-232 series radionuclides by gamma emission notwithstanding, the approach is not recommended. Due to the low intensity (transition probability) of the gamma lines associated with uranium, thorium, and radium, the effect of small fluctuations attributable to normal background can be exaggerated and produce anomalous results. Even with very large volumes and extended measurement (counting) times, gamma spectrometry should not be used to quantify uranium, thorium, and radium in water samples. Because this technique is quick and appears to provide a great deal of information with a single analysis, it may have a place as a screening tool or in cases where the sample's degree of secular equilibrium is known or can be reasonably estimated.

# **APPENDIX D - 3 QUANTIFYING RA-226 IN SOLIDS**

The Ra-226 content of a solid sample can easily be determined by measuring the gamma emissions from a known mass of sample in a specific configuration (container) for which the measuring instrument has been calibrated, typically called a counting geometry. The measuring instrument is a gamma spectrometer that provides radionuclide-specific data for several members of the U-238 series. One advantage of this technique is that typical sample sizes are on the order of 100 grams (g), allowing for a detection limit of 0.037 to 0.074 Bq/g (1 to 2 pCi/g) with a relatively short measurement period (counting time). For samples where greater sensitivity is desired, larger sample volumes may be required. Larger sample volumes may also provide another analytical option, as discussed in this appendix.

Typically, what this technique actually measures is not Ra-226, but the radioactive progeny that grow in over time, specifically bismuth-214 (Bi-214) and lead-214 (Pb-214), both of which have easily measurable photon (gamma) emissions. These are quantified and the content of their progenitor Ra-226 is inferred based on the known or calculated degree of secular equilibrium. However, when a solid sample is collected, the extent of equilibrium of the members of the uranium decay series within the sample is not known. Additionally, as the material is processed (i.e., handled, heated, or cooled), the more volatile gaseous members of the decay series (radon and polonium) may gas off as explained in Appendix D-1, while the less volatile members (Ra-226, Bi-214, and Pb-214) remain, effectively disrupting the equilibrium. When this occurs, the Bi-214 and Pb-214 that are measured may not be representative of the sample's actual Ra-226 content. In such cases, the sample must be allowed to sit in the sealed counting container for a known time so that the progeny can grow in, which they will as the Rn-222 builds up from decay of the sample's Ra-226 content. When the extent of secular equilibrium is known (i.e., can be calculated on the basis of the time the sample has been in the sealed counting container), the sample can be measured and the Ra-226 content can be inferred accurately. However, the time required for this type of analysis may be problematic, especially when decisions regarding the path forward for material in the field must be made in the field in a relatively short time. If the sample's secular equilibrium is known or can be determined, gamma spectrometry is the method of choice for quantifying Ra-226 in solids.

There are cases where the gamma lines of Ra-226 can be measured directly, as opposed to measuring the Bi-214 and Pb-214 progeny, as discussed in the preceding paragraph. Given a sufficient mass of Ra-226, the photons from the Ra-226 can be measured directly, and the degree of equilibrium is not pertinent. Specifically, a directly measured value for Ra-226 is obtained by assaying either a large sample size of low Ra-226 concentration material or a

smaller sample with a high Ra-226 concentration. This approach has limitations, in part because the Ra-226 gamma emissions are weaker than the Bi-214 and Pb-214 gamma emissions by essentially one order of magnitude. Additionally, Bi-214 and Pb-214 have multiple gamma lines that can help to corroborate the assay values, whereas Ra-226 has a single gamma emission that suffers from interference with another U-238 series radionuclide (U-235). While this approach provides the possibility of a quick turnaround analysis, it is not always appropriate. However, given the logistics of sample collection and TENORM waste disposal, it is worth considering.

# **APPENDIX D - 4 QUANTIFYING RA-228 IN WATER**

Ra-228 is a naturally occurring beta emitter produced by decay of Th-232 and there are several well established analytical methods to quantify it in water. All rely on chemical separation of the radium, using precipitation of a stable barium compound (i.e., barium sulfate) or solvent extraction, both of which isolate and measure the Ra-228 progeny actinium-228 (Ac-228). Typical methods require a 36-hour ingrowth for the accumulation of the 6.2-hour halflife Ac-228, whose beta emission is easier to measure than Ra-228 (5.75 year half-life). The Ac-228 may be separated chemically on stable yttrium (Y)-oxalate and, using a calculated correction for ingrowth (degree of equilibrium between the Ra-228 parent and its Ac-228 progeny), the purified Y-oxalate/Ac-228 is measured using a fixed-base laboratory instrument, typically a gas proportional counter (USEPA 1980). This technique is time consuming, but provides excellent data for water samples and has adequate sensitivity to allow detection limits of 0.037 to 0.074 Bq/g (1 to 2 pCi/L). This procedure is not recommended in cases where there are high concentrations of strontium-90 (Sr-90), an unlikely condition at this time, but formerly a potential factor due to widespread contamination from aboveground nuclear weapons testing.<sup>26</sup> However, there is an Eastern Environmental Radiation Facility (EERF) laboratory procedure (EERF Method Ra-05) that is similar except that it uses solvent extraction to isolate the Ac-228 directly, which would be unaffected by the presence of Sr-90.

<sup>&</sup>lt;sup>26</sup> Above ground nuclear weapons testing produced elevated concentrations of Sr-90 in the biosphere starting in the 1950s. The direct decay progeny of the 28-year half-life Sr-90 is the 64-hour half-life Yttrium-90 (Y-90), which would be carried on the stable Y-oxalate carrier used to carry the Ac-228 precipitate. Accordingly, this procedure is not recommended for samples where Sr-90 concentrations are enhanced relative to current environmental levels. The EERF procedure does not use Y carrier and may be a better choice is some instances for that reason.

# **APPENDIX D - 5 QUANTIFYING RA-228 IN SOLIDS**

In the same manner as described for Ra-226, Ra-228 can easily be quantified in solid samples via gamma counting, with detection limits in the range of 0.037 to 0.074 Bq/g (1 to 2 pCi/g). There are easily measurable photon emissions associated with Ac-228, the direct progeny of Ra-228. Once measured, the content of their progenitor Ra-228 is inferred, based on the calculated degree of secular equilibrium. Due to the decay rate (half-lives) of Ra-228 and Ac-228, equilibrium occurs quickly, much faster than for Ra-226, and the required waiting time is considerably less than for Ra-226.

## **APPENDIX D - 6 QUANTIFYING PO-210 IN WATER**

The determination of Po-210 in water has traditionally been problematic. It has typically involved evaporating very large volumes of water to concentrate expected low-activity concentrations on the order of 0.037 to 0.185 Bg/L (1 to 5 pCi/L). There are other available analytical techniques, all involve chemical separation and deposition of polonium, most involve the use of chemical yield tracers, and few have been used extensively by commercial laboratories. Alternately, polonium can be co-precipitated with manganese oxide (MnO<sub>2</sub>) or iron hydroxide (FeOH<sub>3</sub>). MnO<sub>2</sub> is generally preferable because the iron must be removed later (IAEA 2009). Polonium is then extracted either with solvent or through extraction chromatography and purified. Once purified, polonium in solution will auto-deposit on a silver disk. The disk is then counted in an alpha spectrometer, which allows separation of Po-210 and the tracers, as discussed in this appendix. Disks of aluminum, copper and stainless steel may also be used, although these may reduce the efficiency of the deposition. Once counted, the results are corrected for processing and counting losses and results calculated.

Depending on the time between sample collection and counting, corrections for decay/ingrowth may be required. If the Po-210 is not in equilibrium with its progenitor Pb-210 or the time between separation and counting of the Po-210 is long, the calculations can be complex. Specifically, Po-210 is created by the decay of the 22-year half-life Pb-210, and is decaying simultaneously with a 138-day half-life.

As previously discussed, this technique requires the use of an internal chemical yield tracer, typically polonium-207 (Po-207), polonium-208 (Po-208), or polonium-209 (Po-209). The tracer recovery represents the recovery of the Po-210 and allows the correction for losses through processing, as discussed in Appendix D.1. Po-207, Po-208, and Po-209 all have specific advantages and drawbacks in terms of availability and measurement. Regardless of which tracer is used, the samples must be counted in an alpha spectrometer to discriminate Po-210 from the Po-207, Po-208, or Po-209 tracer. It is worth noting that these procedures were designed to accommodate essentially environmental levels of Po-210, i.e., a maximum concentration on the order of tens of pCi/L or gram of sample. Higher concentrations of Po-210 can be problematic in that the detector can become contaminated due to recoil.<sup>27</sup>

<sup>&</sup>lt;sup>27</sup> When an atom undergoes radioactive decay, the alpha particle takes away energy and momentum. The alpha particle is essentially a helium nucleus minus the orbital electrons; it has much less mass than the nucleus and considerable energy. Since

energy and momentum must be conserved, the heavier nucleus must recoil with a specific energy. When the alpha particle is emitted away from the detector, the nucleus recoils towards the detector. The nucleus can then deposit on the face of the detector, contaminating it with the target radionuclide or its progeny. Generally speaking, the probability of recoil increases with increase in Po-210 concentration and can be a genuine concern for high Po-210 concentration samples measured in an alpha spectrometer.

## **APPENDIX D - 7 QUANTIFYING PO-210 IN SOLIDS**

The determination of Po-210 in solids is similarly problematic. There are no photon emissions from Po-210 that can be easily measured via gamma spectrometry and the determination of Po-210 in solid media is similar to the water procedure discussed in Appendix D, with the exception of preparing the solid. Essentially, solids must be digested in the laboratory with concentrated acids to extract the Po-210, which is then purified and prepared for counting, as described in Appendix D. It is worth noting that Po-210 is more volatile than uranium, thorium, radium or actinium, and heating above 350 C will result in considerable losses. Tracer (Po-207, Po-208, or Po-209) is added to the sample to correct for losses in processing and counting and the losses for solids are typically greater than those for water samples. There are similar analytical methods (EERF 1984) that have minor differences to the IAEA method previously discussed, i.e., the polonium is co-precipitated as hydroxide, redissolved in acid followed by deposition and counting. The EERF procedure also allows for processing a sample for Po-210 and Pb-210 simultaneously, wherein the radionuclides are determined independently by counting the same disk on different instruments. The same considerations regarding equilibrium and counting, as has been described, apply to solid samples.

## **APPENDIX D - 8 QUANTIFYING PB-210 IN WATER**

There are analytical protocols for the determination of Pb-210 in a variety of media (bone, food, urine, feces, blood, air, and water) that involve the extraction of a lead-bismuth bromide complex into an organic solvent (HASL-300). Following purification, the bismuth-210 (Bi-210) progeny are separated, the separation time is noted, and the sample sits for a 2 to 3 week period to allow the ingrowth of Bi-210. Following Bi-210 ingrowth over a specified time period, the sample is counted using gas-flow proportional or liquid scintillation counting. The Pb-210 content is derived based on the actual counting of Bi-210 and corrected for degree of equilibrium, in the same manner as discussed for Ra-228 in water. (See Appendix D.4.) The calculations require considerable laboratory processing time and cannot be shortened for fast turn-around samples.

This procedure relies on a stable lead carrier [typically lead nitrate, Pb(NO<sub>3</sub>)<sub>2</sub>] to determine the losses in processing (chemical yield or recovery). Since measureable levels of stable lead exist in most environmental media, the amount of indigenous lead in the sample and reagents may need to be determined. This is typically performed using atomic absorption (AA) or inductively coupled plasma (ICP) spectrometry, adding to the complications of routine analytical laboratories using this approach.

# **APPENDIX D - 9 QUANTIFYING PB-210 IN SOLIDS**

In the same manner as described for Ra-226 and Ra-228 in these appendices, Pb-210 can be quantified in solid samples via gamma counting. However, the photons that are counted are low in energy, about 46 kiloelectron volts (keV), an area of the gamma spectrum that is not routinely used. Typical gamma systems have calibrations that begin at 59 keV, based on the photons from americium-241 (Am-241) that are in the commercially available gamma calibration solutions. Modern low-energy germanium detectors have sufficient sensitivity to detect 46 keV photons with reasonable efficiency but these are not necessarily in common use at commercial laboratories.

Alternately, the approach outlined for Pb-210 in water can be performed on solid samples once the appropriate sample preparation has occurred. Typical solid media preparations include digestion with concentrated mineral acids typically nitric acid (HNO<sub>3</sub>). This may not be adequate for soils, particularly those containing silicates, which are resistant to most acidic treatment and require the use of hydrofluoric (HF) acid to properly remove them. This presents a considerable challenge for most laboratories because using HF requires specific laboratory safety equipment. However, this approach will work with some soils although it often requires advance information regarding the sample's chemical composition.

# **APPENDIX D - 10 GROSS ALPHA-BETA SCREENING**

Due in part to the increased interest in TENORM related to hydraulic fracturing, USEPA developed and tested an improved method for the Development of Rapid Radiochemical Method for Gross Alpha and Gross Beta Activity in Flowback and Produced Waters in Hydraulic Fracturing Operations, USEPA/600/R-14/107. July 2014. (USEPA 2014). While the title of the method is the determination of Gross Alpha and Gross Beta Activity, in fact what is being quantified are specific alpha and beta emitting radionuclides in the U-238 and Th-232 series whose values are then summed or manipulated numerically to yield composite values. Whereas the typical gross alpha-beta screening is the simplest of techniques, USEPA method for the determination of gross alpha and gross beta activity in flowback and produced waters is a complex, multi-detector, multi-step process that requires information and/or assumptions regarding the degree of secular equilibrium for the U-238 and Th-232 series radionuclides in the sample, as discussed. The goal of this method development was to determine a technically defensible and efficient means to quantify gross alpha and beta activity in flowback and produced water samples, based on the premise that USEPA methods designed for environmental water samples are inadequate.

USEPA Method 900.0 (USEPA 1980) (typical gross alpha/beta screening discussed in Appendix D-2) consists of evaporating a small (about 100 mL) known volume of a water sample, transferring it to a counting dish, taking it to dryness, and counting it for alpha and/or beta emissions in a gas-flow proportional detector. It is appropriate for samples with a TDS content <500 ppm and has historically been the method of choice for gross alpha screening, which relies heavily on quantifying Ra-226 and also other uranium and thorium series alpha emitters. Similarly, the gross beta aspect focuses on Ra-228 and other beta emitters in the uranium and thorium series. However, this method has several notable limitations:

- It is not appropriate for waters with TDS concentrations greater than approximately 500 ppm.
- It under-reports low energy beta emitters such as Ra-228 and Pb-210.
- It is unclear whether it actually captures the alpha emission of Po-210.
- It may miss shorter half-life radionuclides completely, (e.g., Ra-224) and its progeny.

With these limitations in mind, USEPA sought to develop an analytical approach that was more appropriate to flowback and produced waters characteristic of TENORM. Flowback and produced waters typically contain inorganic salts, organic and other compounds, as well as uranium and thorium series radionuclides at concentrations 1,000 to 10,000 times those encountered in typical environmental media. This combination often renders the use of the standard gross alpha-beta screening unusable. The inorganic salts are typically hydroscopic chlorides, i.e., they pick up water from the atmosphere such that the prepared samples will gain weight as they sit awaiting measurement. The samples' moisture can cause erratic counting data and prevent an accurate determination due to interactions within the counting chamber.

The method in Development of Rapid Radiochemical Method for Gross Alpha and Gross Beta Activity in Flowback and Produced Waters in Hydraulic Fracturing Operations, USEPA/600/R-14/107 (USEPA 2014) takes a different approach in that it uses a larger volume (about 300 mL) and combines four different approaches:

- chemical separation using precipitation and anion exchange column;
- liquid scintillation counting (LSC) for alpha emitters;
- gamma spectrometry for beta-gamma emitters; and
- numerical transformation/manipulation of the data.

There has been limited time to review this procedure; however, several aspects are apparent.

- This approach represents a radical departure from the previous approach, which used analytical protocols based on the analysis of drinking waters. As such, it is an excellent step in the right direction. The use of USEPA Method 900.0 is not suited for typical TENORM analyses and acknowledging that directly and adopting a new approach were needed. While this particular procedure may require modifications, it clearly establishes a new direction for TENORM analyses.
- The conceptual basis of the outlined approach is technically sound. However, it requires information regarding a sample's degree of secular equilibrium for both U-238 and Th-232 series radionuclides. It also requires a degree of complexity beyond what most commercial laboratories can currently provide. The calculations are complicated and it is not clear exactly what they represent or how the results they produce relate to specific regulatory criteria or action levels.
- This procedure may not be ready for routine implementation by commercial laboratories. As presented, it is not a "rapid, and economically viable approach" for determining gross alpha activity, as the authors acknowledge (USEPA 2014). It requires multiple analytical instruments, including an LSC and gamma spectrometer, and extensive laboratory processing capabilities.
- Lastly, as written, the procedure may require editing to correct technical aspects, e.g., sample preservation.

# **APPENDIX D - 11 APPROVED LABORATORIES**

There are no laboratory accreditations or approvals specific to the analysis of TENORM. There are state accreditations for the analysis of drinking water and federal approvals relating to specific liquid and solid media.

If a laboratory states that it is approved for the analysis of TENORM, the party procuring the analytical services should inquire regarding the specifics of the approval. Although some of the analytical protocols used to analyze water or solid TENORM are, in fact, equivalent to what would be used for other sample types (i.e., environmental soils, ground or surface waters, or other wastes), approvals related to them do not necessarily mean that a laboratory is familiar with many of the analytical issues specific to TENORM, as discussed in Appendix D in its entirety.

An accreditation from a state or federal agency permits some assumptions regarding the use of specific approved protocols, appropriate sample custody and control, data reduction and documentation, and general data quality or usability. However, because there are no laboratory accreditations for TENORM analyses, the procurer of laboratory analytical services should be aware of the applicability and limitations of all analyses. It is incumbent on the party requesting analytical services to understand the details of the available analytical protocols and the limits of the data the protocols produce.

## ABREVIATIONS AND ACRONYMS

#### AEA – Atomic Energy Act

ALARA - As Low as Reasonably Achievable

- ALI Annual Limit Intake
- ANSI American National Standards Institute
- API American Petroleum Institute

ARAR – Applicable or Relevant and Appropriate Requirements

ASTSWMO – Association of State and Territorial Solid Waste Management Officials

CERCLA – Comprehensive Environmental Response, Compensation and Liability Act

CFR - Code of Federal Regulations

CRCPD - Conference of Radiation Control Program Directors

CWA – Clean Water Act

- CWT Centralized Waste Treatment
- EEFR Eastern Environmental Radiation Facility
- EPA Energy Policy Act

GWPC - Groundwater Protection Council

HVHF – High Volume Hydraulic Fracturing

IAEA - International Atomic Energy Agency

ICRP - International Commission on Radiological Protection

IOGCC – Interstate Oil and Gas Compact Commission

ISCORS - Interagency Steering Committee on Radiation Standards

- NARM Naturally Occurring and Accelerator-Produced Radioactive Materials
- NCRP National Council on Radiation Protection and Measurements
- NPDES National Pollution Discharge Elimination System
- NGL Natural Gas Liquid
- NORM Naturally Occurring Radioactive Material
- NRC National Research Council
- NYSDEC New York State Department of Environmental Conservation
- POTW Publically Owned Treatment Works
- PPE Personnel Protective Equipment
- RCRA Resource Conservation and Recovery Act
- RESRAD -RESRAD (Residual Radiation) computer model
- RSO Radiation Safety Officer
- SDWA Safe Drinking Water Act
- SSRCR Suggested State Regulations for Control of Radiation
- SWIFT II Sandia Waste-Isolation Flow and Transport Model
- TDS Total Dissolved Solids
- TEDE Total Effective Dose Equivalent
- TENORM Technologically Enhanced Naturally Occurring Radioactive Material
- USC United States Code
- USDOT U.S. Department of Transportation
- USEPA U. S. Environmental Protection Agency
- USGAO U.S. Government Accountability Office
- USGS U.S. Geologic Survey

USMSHA – U.S. Mine Safety and Health Administration

- USNRC U. S. Nuclear Regulatory Commission
- USOSHA U.S. Occupational Safety and Health Administration

WL – Working Level

# GLOSSARY

Accumulated Sediments (Tank Bottoms/Sludges): Sediments from tanks or pits used for the temporary storage of oil, natural gas liquids, and produced water that may include hydrocarbons, chemical additives employed, heavy metals, and concentrated chemical contaminants of the contributing geologic formation.

Administrative Level: Action or alert level.

Agreement State: A state to whom USNRC has relinquished portions of its regulatory authority to license and regulate byproduct materials; source materials (uranium and thorium); and certain quantities of special nuclear materials.

Byproduct material: Defined in the *Energy Policy Act of 2005* (USEPA 2005) to include purposely concentrated discrete sources of Ra-226, (referred to as 11e. (3) Byproduct material), which is interpreted by the USNRC also include diffuse Ra-226 that originated from 11e. (3) discrete sources.

Chemical yield tracers: Radioactive tracers.

EDTA: Chelating agent.

Filter cake: The solid mass remaining on a filter after the liquid that contained it has passed through.

Flowback water: Water injected during hydraulic fracturing that returns to the surface, which may be recycled between well sites and gradually takes on the salinity and chemical and radiological properties of the water within the formation.

High volume hydraulic fracturing (also known as, hydrofracking, fracking, hydrofracturing, hydraulic fracturing): An oil and gas well development process that involves injecting water under high pressure into a bedrock formation via the well. It is used to increase oil and/or gas flow to a well from petroleum-bearing rock formations (USGS 2015).

Land Application: Direct land application of water-based drilling fluids.

NARM: Naturally Occurring and Accelerator-Produced Radioactive Materials (NARM) that were excluded from regulation under the *Atomic Energy Act* (AEA 1954) and therefore left to the states to regulate. (That definition is no longer routinely used, as accelerator wastes and discrete sources of Ra-226 are now

regulated under the *Atomic Energy Act* due to changes brought about by the *Energy Policy Act* of 2005.)

NORM: Naturally Occurring Radioactive Material (NORM) has been further divided between NORM in its undisturbed natural state, and TENORM, which is NORM that has undergone some type of technological enhancement, but excludes discrete Ra-226 sources.

Pig: Devices that are inserted into and travel throughout a pipe used for removing deposits and other purposes, such as inspecting pipe interiors.

Produced water: Formation water, which is also brought to the surface as oil and/or gas is extracted and due to the extended period of time in which this produced water has been in contact with the underlying geology, is often very high in salinity and TENORM content.

Public distribution: Distribution of dried sludge to the consumer. Some wastewater treatment facilities are permitted to distribute dried sludge to the public (to individuals who may use sludge for gardens, top soil, backfill, etc.). USEPA refers to this as "exceptional quality" or Class A biosolids and allows the process. Class A biosolids also may be sold in large box stores as fertilizer or potting soil. For additional information on Class A biosolids, see http://water.epa.gov/polwaste/wastewater/treatment/biosolids/genqa.cfm.

Radon emanation: Definitive method for the determination of Ra-226.

RESRAD: A computer model designed to estimate radiation doses and risks from RESidual RADioactive materials, used for evaluation of radioactively contaminated sites.

Play (Shale Play): A play is defined as a set of known or postulated oil and or gas accumulations sharing similar geologic, geographic, and temporal properties, such as source rock, migration pathways, timing, trapping mechanism, and hydrocarbon type (Biewick, L.R.H., G.L. Gunther and C.C. Skinner 2002).

*SWIFT II* - Sandia Waste-Isolation Flow and Transport Model code developed by Sandia National Laboratories for USNRC that is used to model radioactive materials' mobility in the environment).

TENORM: CRCPD and Agreement States that have adopted *SSRCR Part N*, *Regulation and Licensing of Technologically Enhanced Naturally Occurring Radioactive Material* limit the definition of TENORM only to material where the natural concentration of NORM has been enhanced. Trigger level: Action or alert level.

Waste from oil and gas production: Waste, which may have some beneficial reuse, that include produced water, flowback water, drilling fluids and mud, filters, condensate; and accumulated sediments (i.e. tank bottoms or sludges).

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