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Waste Generation and Disposal:

Awareness, Management, and Disposal Guidance for Solid Waste Containing Technologically Enhanced Naturally Occurring Radioactive Material (TENORM)

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Radiation Task Force
Materials Management Subcommittee

Association of State and Territorial Solid Waste Management Officials
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I. EXECUTIVE SUMMARY/ INTRODUCTION

Natural radioactivity is present in trace amounts in the earth's crust and waters. Numerous industrial processes that utilize or come in contact with natural raw materials, such as water, soils, rock or reused feedstocks from other waste streams, may generate Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). The resulting wastes that contain TENORM can present health and safety hazards to humans and the environment if they are not handled and disposed of properly. Currently the inadvertent generation and disposal of only a few TENORM waste streams are federally regulated, and the applicable State laws and regulations governing how TENORM is generated, handled, and disposed vary.

As knowledge of TENORM increases and waste streams are studied in greater detail for TENORM content, industrial processors and landfill operators are becoming more aware of potential disposal issues. This increased awareness of TENORM, combined with emerging methods of fossil fuel production, is expected to result in an increase in the national volume of TENORM waste requiring management. Wastes historically accepted for disposal or beneficial use may now be rejected due to their TENORM content. In the absence of clearly established criteria for free release and disposal, the TENORM waste disposal options range from landfill disposal, which may create a future public health burden due to unacceptable doses to future members of the public from high-activity TENORM waste, to low-level radioactive waste disposal, which may be overly restrictive and costly for low-activity TENORM waste.

The intent of this guidance document is to increase awareness regarding TENORM waste generation, as well as the regulatory and radiological complexities surrounding appropriate and protective TENORM waste management methods. Included in this guidance document are tools to aid industry and landfill operators in discussing, handling, assessing the associated risks, and disposing of TENORM waste, with the goal of minimizing current and future impacts on human health and the environment. Although this guidance is primarily directed toward regulators, solid waste managers, and disposal facility operators, the resources and information provided may be applicable to other industries. For example, those who encounter TENORM in their operation, such as metal recyclers, may find the referenced tools useful when considering the beneficial use of TENORM waste.

II. TENORM AND TENORM WASTE GENERATORS

Radioactive material is found naturally in water, soils and rock. When this type of radioactive material is found in its original location and in its natural concentration distributions (including ore bodies) it is referred to as Naturally Occurring Radioactive Material (NORM). Many industrial processes use or come in contact with natural raw materials that contain NORM such as ore, water, soil, rock, oil and natural gas. When industrial processes separate or concentrate the NORM found in these raw materials and expel this radioactive material in their waste streams, the resulting concentrated NORM is referred to as Technologically Enhanced Naturally Occurring Radioactive Material (TENORM). The U.S. Environmental Protection Agency (EPA), as well as some States, define TENORM to include NORM that has been processed or moved by human activity causing an increase in the potential for exposure to humans relative to the radioactive materials' original location or natural state. So, even if the NORM has not been concentrated, it is still considered TENORM by the EPA and some States if the potential for human exposure has been increased by any human activity.[1] The NORM decay chains of uranium-238 and thorium-232 and their decay products, called daughter products or progeny, are the primary radionuclides associated with TENORM waste. The primary risk drivers of the uranium-238 series are: radium-226 and radon-222 (radon); the primary risk drivers of the thorium-232 series are: radium-228 and thorium-228. Research is ongoing which indicates lead-210 and polonium-210, which are part of the uranium-238 series, may also pose exposure threats to oil and gas workers. Potassium-40 (K-40) may also be present, but is not considered a health hazard because the human body regulates the amount of potassium retained. Higher concentrations of TENORM in waste leads to greater potential for adverse impacts on human health and the environment.

TENORM waste generation is commonly associated with specific industries and practices. Examples include conventional uranium mining and mining overburden, phosphate waste, coal waste, petroleum production scale and sludge, drinking water treatment sludge, mineral mining/overburden and processing/extraction, mineral processors and geothermal wastes. Table 1, adapted from the ASTSWMO publication, *Incidental TENORM: A Guidance for State Solid Waste Managers, 2011*, provides a listing of common industry generators of TENORM waste. Additional industry specific information can be found in the identified Appendix C.

Table 1. Common Industry Generators of TENORM Waste

Industry Sectors	**TENORM Location**	**Predominate TENORM Nuclides***	**Appendix**
Building materials	Certain construction materials (e.g., gypsum) and stone (e.g., granite), refractory brick	Ra-226, U, Th, K-40	
Chemical industry and use	Potassium compounds, cooling tower, and component scales	Ra-226, K-40	
Coal combustion for energy generation	Bottom and fly ash	Ra-226, U, Th	C1
Decorative or optical glass	Slag and coating residuals	U, Th	
Drinking water treatment	Sludge and ion exchange resins	Ra-226, Ra-228, U, Th	
Geothermal energy generation	Brine residuals and scale	Ra-226, U, Th	

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[1] This also includes the potential for increased environmental mobility. An example is drill cuttings from shale formations. Uranium in the reduced environment is found in the +4 valence state, which is insoluble. Once the uranium is brought to the surface and exposed to the outside air, it quickly oxidizes to the more mobile +6 valence state. That change in mobility can increase the potential for human exposure.

Metal casting, grinding or sand-blasting	Foundry sands or casting molds, grinding or shot with zircons	U, Th	
Metal mining	Waste overburden	U, Th	
Metal ore processing	Slag and sludges	U, Th	
Metal welding and fabrication	Metal alloys and products	Th	
Mineral Processors	Variety of industries including paint manufacturing, and titanium producers	Ra-226, Th, U	
Oil and gas production	Process brine water treatment sludge, scale in equipment, storage tank bottom sludge, gas refining separation process	Ra-226, Ra-228, U, Th-228, Pb-210, Po-210	C2
Paper and pulp production	Scale and sludge	Ra-226, U, Th, K-40	C3
Phosphate fertilizer and phosphorus production	Waste phosphogypsum, scale, residuals, slag	Ra-226, U	C4
Stone cutting and polishing	Certain base rock (e.g., granite) with high U/Th series	U, Th	
Uranium mining - Conventional	Waste overburden or low grade ore	U, Th	
Wastewater treatment	Sludge	Ra-226, Ra-228, U, Th	C5

* U refers to the uranium-238 decay series; Th refers to the thorium-232 decay series.

The following discussions identify issues surrounding TENORM disposal and underscore the need for awareness on behalf of generators, disposal facilities, and regulators in the construct of appropriate disposal guidelines.

III. TENORM WASTE AND WASTE MANAGEMENT OPTIONS

The oil and gas production industries are historically known as the major generators of TENORM waste. This includes the processing and treatment of natural gas and the contamination of gas sweeteners. Drinking water and wastewater treatment facilities may also generate high concentration TENORM waste. Industries that generate or use large volumes of ore, such as phosphate fertilizer and phosphorus production facilities, mining operations, and mineral processors, tend to generate large volumes of low concentration TENORM waste.

The standard management options for TENORM waste are disposal and beneficial use. The current disposal facilities or practices being utilized by industry for TENORM waste include, but are not limited to:

- RCRA Subtitle C Hazardous Waste Disposal Facility;
- RCRA Subtitle D Landfill – Part 257 (non-municipal landfill);
- RCRA Subtitle D Landfill – Part 258[2] (municipal solid waste landfill);
- Low-Level Radioactive Waste Sites;
- Mixing/blending, where permitted;
- Deep well injection; and
- Encapsulation at the well site (solidification and burial at well site).

This guidance recognizes that the waste streams of some TENORM generating industries may contain components that are valuable or beneficial for other industries, though these beneficial waste streams may also contain TENORM. Solid waste program managers and site owners must be aware of the TENORM component of these beneficial waste streams and understand how these beneficial waste streams may have the potential to adversely impact human health and the environment if not managed properly.

Some examples of potential beneficial uses of waste materials from TENORM generating industries that may contain TENORM include:

- Liquids for irrigation and dust suppression;
- Aggregates for road construction;
- Fly ash for concrete and cement production;
- Land application; and
- Processing for recovery of petroleum or other useful constituents from the waste.[3]

It is expected that the volumes of high activity TENORM waste generated will increase in the future due a number of developments, such as the expansion of fracking technology, including the exploration and production of gas from the various formation. The revised definition of TENORM that includes the movement (physical relocation) of NORM, if it is more widely adopted, may also create an increased volume of low activity TENORM waste that was previously classified as NORM.

Determining the appropriate management option for this expected increased volume of both high and low concentration TENORM waste may prove to be complicated due to the lack of federal standards, the varying State regulatory approaches, and the lack of a clear understanding of the potential adverse impacts on human health and the environment from TENORM.

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[2] This category may also include monofills, facilities designed for one specific waste stream such as alum sludge from water treatment.

[3] An additional source of information regarding the beneficial use of oil and gas waste streams is the ASTSWMO Beneficial Use Task Force publication, *Oil and Gas Exploration and Production Waste Management Survey Report* (March 2015).

All waste streams, including those containing TENORM, should be characterized to also ensure that no characteristic or listed hazardous wastes, or other hazardous substances, are present that could preclude disposal in Subtitle D facilities.[4]

IV. LACK OF FEDERAL TENORM STANDARDS

The Nuclear Regulatory Commission (NRC) is the federal agency responsible for regulating certain types of radioactive material under the Atomic Energy Act. Through the NRC's Agreement State Program, the NRC relinquishes its regulatory authority to the NRC approved State. This State then becomes known as an Agreement State and thus becomes the regulatory authority for the types of radioactive material regulated by the NRC. States which have not become Agreement States are known as NRC States. However, all States have the authority to expand their regulatory scope by developing, implementing, and enforcing laws and State regulations for TENORM waste management.

Due to the lack of federal standards, some States have adopted their own regulations, standards and/or guidance that may be inconsistent from State to State.

The Conference of Radiation Control Program Directors (CRCPD) has published and is currently reviewing updated draft template regulations for the possession and use of TENORM, as well as an implementation guide. These suggested regulations are meant to be a template for States, in an effort to implement a consistent nation-wide protective regulatory framework. A summary of the status of States' adoption of TENORM regulations can be found in the ASTSWMO publication, *State Regulations and Policies for Control of Naturally-Occurring and Accelerator Produced Radioactive Materials (NARM) and Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), 2014*.

A number of statutes grant the U.S. Environmental Protection Agency (EPA) authority to protect the public health and environment from the adverse effects of exposure to ionizing radiation from TENORM wastes. These statutes include:

- Clean Air Act (CAA);
- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA);
- Toxic Substances Control Act (TSCA);
- Resource Conservation and Recovery Act (RCRA), which amended and superseded the Solid Waste Disposal Act (SWDA); and
- Safe Drinking Water Act (SDWA).

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[4] Unlike uranium mill tailings for which a single law addresses both the radioactive and hazardous constituents, TENORM may be subject to or managed under TSCA, RCRA and CERCLA and may contain co-mingled TENORM and hazardous constituents.

EPA has not promulgated regulations specifically designed to govern the cleanup or disposal of TENORM wastes under RCRA, the federal statute governing most aspects of waste management. However, as indicated in the enumerated Acts above, many federal laws do regulate certain aspects of TENORM generation or management. However, not all waste forms generated from these industries are regulated and not all TENORM-generating industries are addressed. Under many of these statutes, States also have a role in the implementation of these requirements, e.g., through a "delegated" or authorized regulatory program.

Where federal regulatory gaps exist, the States may choose to promulgate their own TENORM regulations and guidelines; in addition, under most EPA statutes, States are allowed to be more stringent irrespective of any federal gaps. However, as these wastes are not generally in the regulatory oversight of State radiation control program managers and radiation is generally not in the forefront of solid waste program managers' expertise, TENORM wastes are often unregulated.

Consequently, many generators are not required to dispose of this material in a specific manner. TENORM waste generators currently dispose of this waste by numerous methods or repurpose the wastes for some type of beneficial use. The end recipient of the TENORM may not be aware of the radiological content and resulting radiological concerns of this material, thereby overlooking factors that impact workers, the public, and the environment. The gaps in current federal standards also means disposal facilities may not be implementing worker radiological protection measures or performing site specific dose assessments to determine the future impacts to public health and the environment from TENORM waste disposal. The overall absence of uniform standards for the regulatory oversight of TENORM generators, users, and disposal facilities increases the potential for inconsistently applied worker protection measures, potential public exposure, transportation issues, and possible environmental contamination issues.

V. <u>TENORM MANAGEMENT ISSUES</u>

As the recognition of TENORM in industrial wastes increases, and the definition of TENORM changes to include physically relocated NORM, the volume of TENORM wastes may increase. Many States are forced to address the current and increasing volumes of TENORM waste by exploring multiple disposal options including deep well injection, RCRA Subtitle D landfills, up to low-level radioactive waste disposal as a result of local disposal prohibitions at these facilities. Some TENORM wastes may be redirected for beneficial use such as land application.

This document primarily addresses the identification and management of bulk TENORM material. A long-standing question exists if the same amounts of regulatory oversight and exposure control are necessary for small quantities of TENORM. Additionally, many TENORM-producing facilities may also generate contaminated equipment, piping, pumps, filters, tanks, or other appurtenances that require decontamination or increased controls for disposal and handling. There exists wide variation in what States have determined to be an acceptable release criterion for this equipment. As some States do not regulate TENORM, equipment contaminated with TENORM may not have any technical criteria for release. Other States have adopted release limits ranging from a dose rate screening level, to concentration-based exemptions, up to a dose-based limit. The American National Standards Institute (ANSI) in partnership with the Health Physics Society (HPS) developed release criteria based on a conservative dose to the public. ANSI/HPS N13.12-1999, "Surface and Volume Radioactivity Standards for Clearance" proposed derived screening levels for TENORM radionuclides to facilitate clearance as well as provided discussion on implementation. As a consensus standard, this may prove an appropriate and useful tool for waste and radioactive material program managers to assist in decision making. Finally, with regard to small quantities of low concentration TENORM waste, the exposure and environmental concerns discussed in this paper may not exist to the individual generators. However, in aggregate, the acceptance of small quantities of low concentration wastes is believed to generate the type of exposure and handling concerns discussed here. As this paper generally applies to generators and regulators of bulk material, the need to implement increased controls for small quantities, giving consideration to the amount of dose mitigated for the regulatory footprint required, is best left to the discretion of the individual States.

Generators may seek to stabilize the waste form of TENORM in order to decrease the likelihood of dispersion during transport or placement in a landfill. While any modifications to the waste form must still meet the waste acceptance criteria of the accepting facility and the regulating body, the carrier material utilized to stabilize the waste form may in fact lower the concentration of the TENORM waste. Individual States should assess whether they will allow averaging of the radionuclide concentrations over any carrier material. If a container or contaminated item is being assessed, the State may likewise have to determine if the weight of the container or item can be used to effectively dilute the TENORM concentrations present. While stabilizing waste forms may be beneficial to reduce exposure to workers, it may be appropriate to assess the viability of these disposals on the basis of total activity. Since much of the projected impact to the environment is assessed on the basis of total source term, it may be acceptable to screen acceptance of such materials on the basis of concentration – but total afforded activity in a disposal facility (or repurposed area) should also be reviewed by the program managers.

Challenges with Determining Appropriate Management Options

While the focus of this paper is on TENORM, it is important to note that landfills and recycling facilities may encounter radioactive materials aside from TENORM. While TENORM is often an inadvertent contaminant already present in waste streams, these other radioactive materials are generally distinct and only enter the waste stream when they fail to be detected. Examples include: human/animal nuclear medicine medical treatment waste (bedding, sanitary products, cat litter); general public waste (items, e.g., radium painted clocks and gauges; laboratory kit chemicals; smoke detectors); and inappropriately discarded industrial sources.

The cost to remediate contamination or recover these sources can be substantial. Therefore, many disposal facilities install gamma radiation monitors to detect the presence of radioactive materials, including TENORM. Determining the source of an alarm and the appropriate actions to be taken can be confusing if the disposal facility operators are not knowledgeable about radioactive materials or the origin of the waste stream. Section VI.B, *Alarming Radiation Monitors*, provides suggested actions a facility operator can take when responding to an alarming radiation monitor.

Determining the appropriate management option for wastes containing TENORM requires the TENORM generator to have an understanding of the radionuclides, radioactive activities in the waste, and the waste form. When the TENORM waste contains elevated levels of uranium series radionuclides, the primary radiological concerns are external radiation exposure to the workers from radium-226 and bismuth-214, and internal exposure from the generation of the radon-222 gas (radon). This scenario requires protocols for managing this waste in a manner that reduces the accumulation of radon gas and reduces worker radiation exposure. Upon landfill closure, a specific cover thickness may be required to allow the radon to decay prior to reaching the ambient air surface above the cover. This potential requirement may also be met by disposing of the radium waste at a minimum distance below the ground surface. In either case, it is recommended that the development of enclosed structures over closed waste disposal units be restricted unless allowed by approved closure plans and dose modeling shows there is not a potential for radon gas to accumulate in structures. Additionally, elevated concentrations of the long-lived radon progeny, Pb-210 and Po-210, can present an inhalation or ingestion hazard to maintenance and disposal workers and should be characterized. As mentioned previously, solidification of wastes to decrease the dispersion potential during transport and placement is also an option. When the TENORM waste contains elevated levels of thorium-232, the primary radiological concern is the external radiation exposure to workers from radium-228 progeny and thorium-228. This scenario requires protocols on managing this waste in a manner that reduces worker radiation exposure.

Since the physical and chemical form of the accepted waste and the design of the disposal facility will affect TENORM mobility, it is recommended that both be considered in order to reduce leaching through the soils that could cause future impacts to the groundwater. Intermediate treatment, such as solidification or stabilization, may be required for more soluble forms of TENORM prior to disposal. The Radiation Task Force recommends that disposal facilities accepting TENORM waste perform a site specific dose assessment to ensure the facility's operating and closure requirements are protective of human health and the environment during operations and into the future after the disposal unit is closed. Generic modeling may also be used, as discussed later in this guidance. Section VI.A, *TENORM Radiation Basics*, provides TENORM specific radiological information including basic radiation terminology and units, sources of background radiation, and TENORM radiation risks.

Disposal Facilities

Low-level radioactive waste sites are facilities that are specifically licensed by the NRC to accept low-level radioactive waste, as defined by the NRC. There are currently only four low-level radioactive waste sites in the United States.

These facilities have specific waste acceptance criteria that require the waste to be packaged in a protective manner, employ stringent engineering and procedural controls to protect workers and handle/manage waste, engage in comprehensive environmental monitoring programs, perform extensive site specific performance assessments to determine the radiological impacts to future generations of humans, and are required to meet closure regulations that reduce human contact with the disposed waste.

Though TENORM is not considered low-level radioactive waste by the NRC, two of the four low-level radioactive waste sites accept TENORM waste. Disposal of waste in a low-level radioactive waste site is costly, and diffuse TENORM waste does not typically present the same degree of worker hazard as low-level radioactive waste, thus does not typically require the same degree of packaging requirements and worker protection as required for low-level radioactive waste. This may not be the case for concentrated TENORM that can be found in some filters, spent resins and similar waste streams. Treating TENORM waste in the same manner as low-level radioactive waste may be cost prohibitive to many industries, and may not return an increased level of public protection as compared to other disposal facility options. Careful consideration should be made when evaluating the physical, chemical, and radiological components of TENORM wastes prior to disposal.

Facilities that are permitted under RCRA Subtitle C are authorized to manage hazardous waste. The specific management operations (treatment, storage, and/or disposal) allowed at the facility are specified in the facility's permit. These facility permits include specific waste acceptance criteria that specify exactly what wastes are and are not accepted, as well as requirements to implement a worker protection program, engage in environmental monitoring, and meet closure regulations. These facilities, if authorized, could accept certain concentrations and cumulative activities of TENORM. If a RCRA Subtitle C facility is considering accepting TENORM waste, this guidance offers the following recommendations:

- Implement TENORM training and communications tools at appropriate levels of detail for workers, managers and stakeholders;
- Have appropriate and adequate survey and analytical capabilities to check incoming loads;
- Develop engineering controls and procedures for handling and managing TENORM waste;
- Expand the occupational and environmental monitoring program to include TENORM; and
- Perform a site specific dose assessment to determine the total activity the site can accept and still meet public dose limits to a receptor throughout the applicable post-closure period assuming realistic scenarios and pathways. Generic modeling efforts have been performed by the Department of Energy's Argonne National Laboratory. However, the assumptions in that model may not be applicable in all scenarios in every State. Acceptance of Ra-226 may require additional closure cover depth to mitigate future radon concerns.

Disposal facilities that are permitted by States to accept non-hazardous solid waste have waste acceptance criteria that specify exactly what wastes are and are not accepted, engage in environmental monitoring (including leachate monitoring), are designed to limit groundwater impacts, and have closure requirements including post-closure monitoring.

If authorized in their permits, these non-hazardous waste disposal facilities can accept certain concentrations and cumulative activities of TENORM. Due to a lack of industry awareness and lack of uniform TENORM standards, some non-hazardous waste disposal facilities may currently be unknowingly accepting TENORM waste. If a non-hazardous waste disposal facility is considering accepting TENORM waste, this guidance offers the following recommendations.

In addition to the guidance for hazardous waste facilities, these non-hazardous waste facilities should also consider the following:

- Consult with the State radiation program to assess the need to expand the environmental monitoring program to include TENORM;
- Since these facilities typically accept bulk waste and do not have comprehensive worker protection programs, it is recommended that dust suppression methods be implemented if dispersible bulk material is accepted. TENORM should not be used as daily cover; rather, it should be buried immediately upon emplacement in the cell to avoid wind dispersion.

It is recommended that disposal facilities considering accepting TENORM waste assess their current disposal practices to ensure workers and the public are protected during disposal operations, and review their closure and post-closure plans, as applicable, to ensure the public and the environment are protected after disposal unit closure. Section VI.C, *Disposal Facility Considerations for Accepting TENORM Waste*, provides a summary of specific waste acceptance criteria recommended that the disposal facility consider imposing when accepting TENORM waste for disposal. Section VI.D provides guidance on handling and managing TENORM waste, and Section VI.E provides guidance on developing a TENORM radiation protection program.

Lack of Generator Requirements to Characterize TENORM Waste

In order for the disposal facility to adequately model and/or implement TENORM control measures when disposing of TENORM, it is recommended that the generator be required to characterize the TENORM component of the waste stream and provide this information to the disposal facility. Components of this waste stream characterization may include the concentration and total activity of each specific radionuclide in the TENORM waste, volume, physical form of the waste, and applicable chemical characteristics such as pH. This waste characterization information is needed to ensure the facility is accepting waste within its regulatory authority (e.g., not accepting characteristic or listed hazardous wastes), workers and the public are protected during disposal operations, and the facility stays within the criteria used for its site specific dose assessment and closure plans.

Need for Disposal Facility Site Specific Dose Assessment

Site specific dose assessments are a critical tool for ensuring workers and the public are protected during the operational phase of the facility, and in determining the future radiological impacts on human health and the environment from the disposal of TENORM waste.

Simple radiation physics principles can be used to perform operational phase dose assessments. Computer models, such as ResRad, are also used to perform the more complicated closure assessments. Dose assessments incorporate facility and site specific information, in conjunction with the concentration and mobility of each TENORM radionuclide disposed at the facility, to determine the radionuclide leaching rate and the resulting concentration of these radionuclides in the environment, e.g., groundwater, air, vegetation.

These assessments then determine the maximum dose to an individual from pathways including ingestion, inhalation, drinking water and radon, over a specified period of time (e.g., 500, 1,000, 10,000 years). Facility closure information is also critical in this assessment, for example: is the facility installing a cover, what is the depth of the cover, will erosion controls be implemented, will inhabited structures on the closed disposal unit be prohibited, will future human residences be allowed, will farming and grazing be allowed?

Many of the TENORM parent radionuclides have long half-lives and will continue to be present long after post-closure periods or custodial duties of disposal or repurposing facilities are concluded. Computer models like those discussed above enable assessment of future dose to the public via release pathways to the environment. One example is the migration of radium to groundwater. Pathway analysis should be conservative and consider events likely to occur over these long half-lives, for example, liner failure. Another pathway of potential concern is methane collection and creating point source releases of radon. This underscores the need for total source term assessment and model-assisted decision making. While RESRAD and RESRAD-OFFSITE are popular with radiation program managers, solid waste program managers may also choose to evaluate infiltration models such as HELP, UNSAT-H. For groundwater flow, MODFLOW may be preferable. In complex terrain, AERMOD may be preferred over RESRAD. EPA also provides online calculators. Unfortunately, models are merely educated predictions and may over or underestimate the hazard. For these reasons, liable parties need to be involved in the decision-making process and ensure they understand the environmental and economic liabilities involved. Discussions on the “ownership” of waste, establishment of baseline environmental TENORM concentrations, financial assurance, and longer-term monitoring would ideally occur early in the permitting phase. Finally, these stakeholder conversations should involve public outreach and education. The hazards that exist with low-level radioactive waste are not the same as those with TENORM.

Solid Waste Facility Capacity

As landfill managers become increasingly aware of issues surrounding the disposal of radioactive materials, more facilities are using radiation monitors to scan incoming trucks for radiation. In addition to screening for radioactive sources and medical waste, TENORM waste streams are being identified. In some cases, these TENORM wastes had previously been accepted as solid waste without regard to the elevated levels of TENORM. The ability to identify the presence of TENORM does not now necessitate that the waste be disposed as a mixed waste or low-level radioactive waste. TENORM waste stands to be both a commodity to RCRA landfill operators as well as a threat to low-level radioactive waste site capacity. Diversion of low activity TENORM waste to a low-level radioactive waste site, rather than quantifying the actual risk associated with conventional disposal, potentially reduces low-level radioactive waste site disposal capacity that should remain available for higher activity wastes or those that are statutorily defined as low-level radioactive waste. It may not be in the best interests of public dose protection to consume the limited space with wastes that can be safely accommodated elsewhere. Many States have already passed policies or regulations to maintain RCRA Subtitle D disposal as a viable option for TENORM waste. Conversely, space at these RCRA Subtitle D facilities should be managed, both to prohibit a facility from becoming a de facto TENORM disposal facility and to prevent the accumulation of large source terms that threaten groundwater and/or increase radon emissions. For example, it may be beneficial to limit the amount of TENORM in a particular cell to keep radon emissions down and to also keep a landfill from turning into a de facto TENORM disposal facility only.

Reduction in Available Management Options

Historically, many wastes have been disposed or beneficially used without regard to the TENORM content. Often this was due to the fact that the TENORM was unknown to the generator and/or the recipient of the waste. As knowledge of TENORM in waste streams increases, some of these disposal and beneficial use options may become prohibited. It is recommended that an evaluation of how these waste streams should be managed, stored, and disposed be conducted to quantify the risks, or lack thereof, associated with each TENORM-generating industry's operations. Conducting a proper characterization of the potential exposure to humans, assessing the mobility of TENORM in the environment, and effectively communicating this information to stakeholders may help ensure appropriate disposal and beneficial use pathways for TENORM wastes remain available.

VI. TOOLS FOR DISPOSAL FACILITIES ACCEPTING TENORM

A. TENORM Radiation Basics

A discussion on TENORM radiation basics is provided to orient the reader on radiation exposure, dose, and how these manifest themselves into a long-term waste management strategy. Air, water, and soil contain naturally occurring radioactive material (NORM). The presence of NORM gives rise to "natural background radiation" and is a component of our annual exposure to radioactive materials. The National Council on Radiation Protection and Measurements (NCRP) Report No. 160, "Ionizing Radiation Exposure of the Population of the United States," estimates the annual exposure to humans, from all sources, results in a dose of 620 millirem (mrem), with half derived from background radiation and radon. Medical radiation doses comprise the bulk of the remaining annual exposure.

Dose is a measurement of the radiation energy absorbed by the body. The unit of absorbed dose is the rem, a measure of radiation dose which takes into account the amount of energy absorbed by the body from the radionuclide and its effectiveness in causing detrimental biological effects. Typically, much smaller units are used in environmental exposures, such as the millirem (mrem). The System International (SI) unit is the Sievert (Sv). One mrem equals 0.01 mSv.

Dose is subdivided into internal dose (from radioactive materials that enter the body and irradiates surrounding cells), and external dose (from radioactive sources outside the body that deliver dose, e.g., cosmic rays). The total dose is determined by summing external dose with internal dose. Internal dose is determined from summing the dose from all potential internal pathways through which radiation can affect the body, including inhalation and ingestion. Internal dose cannot be directly measured; dose modeling is typically required to calculate the internal dose. Hand-held survey instruments used at solid waste facilities to measure exposure rate usually read out in microRoentgen (µR) per hour. This measurement can typically be thought of as the measurement for external dose.

TENORM is produced from the enhancement or relocation of NORM. TENORM can create a potential for radiation dose to humans and can increase their annual radiation dose. The following table provides a context of doses from a range of sources:

Luggage x-ray inspection	0.002 mrem/year
Use of gas lantern mantles while camping	0.003 mrem/year
Have a smoke detector	0.008 mrem/year
Have porcelain crowns	0.070 mrem/year
Cross country flight	5.0 mrem
Chest x-ray	10 mrem
Nuclear medical procedure	14 mrem and up
Mammography x-ray	40 mrem
Public Dose Limit (NRC)	**100 mrem/year above background**
CT Scans (head)	200 mrem
Radiation Worker Dose Limit (NRC)	**5000 mrem/year**
X-ray (Upper GI)	600 mrem
CT Scan (Whole Body)	1000 mrem
CT Scan (Cardiac)	2000 mrem

The table is a combination of data from the NRC http://www.nrc.gov/about-nrc/radiation/around-us/calculator.html and Radiology Info.org (produced by American College of Radiology and Radiological Society of North America) http://www.radiologyinfo.org/en/info.cfm?pg=safety-xray. EPA also has a dose calculator: https://www.epa.gov/radiation/calculate-your-radiation-dose.

Often, conversations about radioactive materials lead to discussions of illness, physical responses to exposure, and immediate health effects from large doses of radiation. It is important to realize the context in which TENORM fits when discussing these doses. The thresholds for manifestation of tissue effects from an acute radiation dose is provided by EPA as approximately 50,000 millirem (mrem). Note, this dose must be received in a very short period of time. As a protective measure against both tissue effects and stochastic (probabilistic) effects, radiation workers (such as those at a nuclear power plant) are limited to as low as is reasonably achievable (ALARA) below 5,000 mrem in a year. According to the Non-Destructive Testing (NDT) Resource Center, "Stochastic effects are those that occur by chance and consist primarily of cancer and genetic effects. Stochastic effects often show up years after exposure. As the dose to an individual increases, the probability that cancer or a genetic effect will occur also increases. However, at no time, even for high doses, is it certain that cancer or genetic damage will result. Similarly, for stochastic effects, there is no threshold dose below which it is relatively certain that an adverse effect cannot occur."

Although there is variation among domestic and international regulatory bodies, the commonly accepted limit for public dose is 100 mrem in a year above background, exclusive of radon (for example, this limit is adopted by both NRC and the International Commission on Radiological Protection). This is far beneath the level at which health effects are observed. When a load of TENORM-contaminated material arrives at a landfill, the potential for a slight dose to a worker exists, however, dose rates associated with TENORM are normally well beneath 2.0 mrem in any one hour (the public dose rate limit). The potential for a large, acute dose is therefore not a possibility with commonly seen TENORM.

The conservative premise for radiation protection is that there is no completely safe level of exposure and even long-term, low-level exposures can increase the life-time risk (probability) for cancer. Therefore, regulatory authorities are examining the means by which the long-term exposure pathways created by TENORM disposal can be effectively mitigated. Although the half-lives of TENORM radionuclides vary from tens of billions of years to microseconds, natural radioactive decay will generally not alleviate the dose concern before consideration for controls is necessary. Specifically, high concentrations of TENORM in the soil may give rise to high indoor radon concentrations, surface or groundwater contamination, or particles that can be inhaled. All of these pathways increase the risk for dose to the public. Therefore, disposal of TENORM needs to consider the exposure pathways the TENORM may create both in the short and long-term. Mobility of radionuclides in leachate, failure of liners, radon emanation, and future intrusion all need to be considered for proper long-term care and public dose abatement. Advanced modeling tools are available to assess both short and long-term doses, thereby facilitating the evaluation of TENORM disposal. Examples of dose modeling, specific to evaluation of TENORM disposals, are provided in Sections VI.F, *Performing Site Specific Dose Assessments for TENORM Disposal in Landfills*, and VII, *Dose Assessments and Disposal Case Studies*.

In the operational phase of the disposal facility, external dose is frequently reduced through the use of time, distance, and shielding. Increasing distance from the radioactive material reduces dose; decreasing the time one is near the radioactive material decreases dose; and using shielding, such as concrete blocks or daily cover, reduces dose. Sections VI.C, *Disposal Facility Considerations for Accepting TENORM Waste*, and D, *Handling and Managing TENORM Waste*, discuss considerations to reduce worker doses in the operational phase of the disposal facility.

The amount of TENORM in a material is generally measured in either units of total activity (e.g., picocuries, pCi, or Becquerels, Bq), or concentration (pCi/g, Bq/g). A very large volume of low concentration waste can contain a large amount of activity (e.g., millicuries, picocuries), whereas a small volume of high concentration waste can also contain a large amount of activity.

Activity is independent of the radionuclide, thus the activities of all radionuclides present can be added together to determine the total activity present. Dose, as described above, is radionuclide dependent since dose takes into account the biological impacts from each radionuclide. Due to dose being nuclide dependent, there is not a simple conversion from activity to dose.

Screening of wastes is often conducted by measuring the gamma exposure rates from the material in units of microroentgen per hour (µR/h) or dose rates in microrem per hour (µrem/h) using hand-held detectors. Surface contaminated objects are usually screened using hand-held detectors reading in units of counts per minute calibrated to disintegrations per minute (dpm)/100 cm^2. Neither exposure rate nor surface activity levels can relate directly to pCi/g without prior knowledge of the waste stream.

B. Alarming Radiation Monitors

Radioactive materials can inadvertently enter the general waste stream. As mentioned previously, these waste streams are typically in a solid form. Examples include human/animal nuclear medicine medical waste (bedding, sanitary products, cat litter) that should normally not be disposed of until adequate decay has occurred. Exempt consumer products such as laboratory chemical kits and smoke detectors may also cause radiation alarms. These items also have prescribed disposal and recycling methods – which may not always be followed. Perhaps of primary importance are the large industrial sources that should never be discarded into the waste or recycling streams. Many disposal facilities and metal recyclers install radiation monitors to detect for the presence of these radioactive materials. However, determining the source of the alarm and the appropriate actions to be taken can be confusing if the disposal facility is not knowledgeable on radioactive materials or the origin of the waste stream.

Although there are always exceptions, radiation alarms at landfill facilities are most commonly from medical waste that was hastily or improperly discarded. Since medical wastes are not sent to metal recycling facilities, radiation alarms at metal recycling facilities are more likely to be due to TENORM, or the errant licensed radioactive source.

EPA provides online resources for responding to radiation alarms at scrap metal processing and demolition sites. A sample flow chart for responding to radiation alarms is provided in Appendix B, *Radiation Alarm Flow Chart*. The following guidance is provided as a general set of steps that a disposal facility or metal recycling facility manager could implement when responding to a radiation alarm:

As requirements and resources vary by State, facilities should check with their State radiation control and solid waste program managers to ensure the facility's response is in compliance with all local and State regulations. Facilities without radiation detection equipment should be aware of the waste streams that are potentially contaminated and should be aware of the resources available to them to facilitate proper disposal.

Verify the Alarm

- Run the load past the monitor to verify the alarm.
    - A radiation alarm may not always be immediately reproducible due to shielding, load shifts, and low intensity sources. If subsequent passes through the portal monitor fail to reproduce an alarm, the following actions are recommended to be taken prior to dismissing the alarm:
        - Survey the vehicle with a hand-held survey instrument.
        - If elevated readings are not obtained, the load may be accepted. After acceptance, the EPA recommends emptying the load and resurveying the load without the truck walls and other material providing shielding.
- If the load does alarm, the source of the alarm will need to be investigated.

Determine the Source of the Alarm

- Have the driver exit the vehicle and survey the driver. If the driver has undergone a recent nuclear medicine or medical isotope procedure, a detectable level of medical isotope will remain in the body. The duration of time the medical isotope is detectable is dependent on the medical isotope used:
    - Technetium-99m (Tc-99m): should not be detectable 3 to 4 days after a test.
    - Fluorine-18 (F-18): should not be detectable 1 day after a test.
    - Thallium-201 (Tl-201): can remain detectable up to 30 days.
    - Iodine-131 (I-131): can remain detectable as long as three months after treatment.
- If the driver presents with elevated radiation readings, survey the cab of the vehicle.
    - If the cab of the vehicle is contaminated, stop and contact your State radiation control program manager.
    - If the cab of the vehicle is not contaminated, run the load past the monitors with a new driver to confirm the driver is the source of the alarm. If the load does not alarm, the driver is the source of the alarm, and the load may be accepted.
- If the driver does not present with elevated radiation readings, the driver is not the source of the alarm, and the load will need to be investigated.

Load is Source of Alarm

If the load is confirmed to be the source of the alarm:

- If you have a survey meter, survey the load from the external surface of the vehicle to get a more exact measurement, and, if possible, identify the general area of the load where elevated readings are located (e.g., driver's side, lower rear). Do not open the truck or interact with the waste until the source of the alarm has been identified.
- If you have a portable gamma spectrometry unit, attempt to identify the radionuclide(s) from the external surface of the vehicle. Do not open the truck or interact with the waste until the source of the alarm has been identified.
- If your facility is authorized to accept this type of radioactive material, supporting documentation is present to verify the load meets your facility's waste acceptance criteria, and all applicable local and State regulations are met, the load may be processed.
- If the load does not meet your facility's waste acceptance criteria or your facility is not authorized to accept this type of radioactive material, the following actions are recommended:
    - Isolate and secure the load from workers and the public.
    - Contact your State radiation control program manager. A list of State radiation control program managers can be found on the CRCPD website (http://www.crcpd.org).
    - Provide your State radiation control official the survey meter and gamma spectrometry information. Some States support gamma spectrometry and may release loads remotely once an acceptable spectrum has been emailed to the radiation control program staff.
    - If the radionuclide(s) is/are not identified, the State radiation control manager may require you to contract a radioactive waste broker/consultant for assistance in identifying the radionuclide(s).

Load Not Initially Accepted

If the load is not initially accepted and the radionuclide(s) are identified (contact your State solid waste program manager for State-specific regulations regarding storing and dumping of loads):

- If the radionuclide(s) are short-lived (e.g., medical waste) the State radiation control manager may allow you to isolate and secure the load until background levels are reached.
- If the radionuclide(s) are long-lived (e.g., TENORM) the State radiation control manager may allow you to:
    - Isolate and secure the load at your facility until the load can be dumped, sorted and the source of elevated readings isolated by the State radiation control manager and/or a radioactive waste broker/consultant.
    - Once the radioactive source has been removed, run the vehicle past the monitor to see if the vehicle is contaminated. If contamination is found contact your State radiation control program manager. The State radiation control manager may require a radioactive consultant/decommissioning service to decontaminate the

vehicle. Confirmatory monitor runs are recommended to be performed to confirm the contamination has been removed.

Load Rejected

The facility may elect to reject the load. The State radiation control manager may require the facility to return an unacceptable load regardless of the radioactive information known.

- If rejecting the load, a U.S. Department of Transportation (DOT) Special Permit 10656 or 11406 is likely required to return the load to the hauler or generator. Information regarding DOT Special Permits can be found on the CRCPD website.
- The radiation control program will issue the permits once the facility completes all the information.
- The load should not go back on the road without the proper paperwork or it may be in violation of DOT regulations. Drivers who are on the clock or companies that need the truck for other loads may resist keeping the load locked down until the special permit is issued. Demurrage costs for rejected rail cars can be very high.
- The State landfill permitting agency should be notified when a disposal facility rejects a load.

C. Disposal Facility Considerations for Accepting TENORM Waste

It is recommended that a disposal facility review numerous aspects of their current facility design, waste acceptance criteria, disposal practices, and worker protection program when considering expanding their waste acceptance criteria to accept TENORM waste. Since landfill permits are granted by local authorities, the stakeholder process can be daunting. The facility should be prepared to explain and defend the decision to accept TENORM to local stakeholders. The following is a partial list of topics for consideration, specific guidance on operational handling and managing of TENORM waste is provided in Section VI.D:

- Form and Disposal Packaging of TENORM Waste

  It is recommended that the disposal facility's current site design, disposal practices, and worker protection program be reviewed when determining the acceptable form and packaging requirements of the waste. Design and Operations plans will need to be updated with appropriate standard operating procedures. It is recommended that facilities that do not have lined disposal cells with leachate collection and recovery systems consider limited acceptance of wastes containing TENORM to minimize leaching through the soils that could cause future impacts to the groundwater. To limit radionuclide mobility, neither TENORM nor the surrounding waste should be overly acidic or basic (neutral pH). This is due to the fact that leachate that comes in contact with TENORM may act to mobilize the radionuclides. Consideration may be given to limiting the emplacement of TENORM away from putrescible waste to limit the amount of mobilizing leachate the TENORM may come in contact with. Alternatively, the facility may choose to consider monocells/monofills if there will be enough material to warrant the construction costs. It is recommended that facilities that accept bulk dispersible waste assess the potential for the spread of contamination and worker inhalation during the offload process and implement dust suppression methods and worker protection controls as necessary. A radiation (or health physics) consultant can aid in determining appropriate worker protection controls.

- Determine Life-Time Site Activity Limit for Each Radionuclide that Will Be Accepted
  For the protection of the workers and the public during the operational and closure phases, it is recommended that disposal facilities determine both which TENORM radionuclides will be accepted and their associated life-time site activity limits. These limits ensure the facility remains within its site specific dose assessment inputs, and ensure the operational practices and closure plans will be adequate for the waste accepted. The site specific dose assessment can be used to aid in determining the life-time site activity limit for each radionuclide. For operational ease, activity limits per year or load, or concentration limits for each radionuclide may be derived from the life-time site activity limit. It is recommended that the facility track the received activities on an annual basis as a percentage of all waste accepted to ensure they will not exceed these values.

- Require Generator Characterization of the TENORM Waste
  At a minimum, it is recommended that this characterization include the concentration and total activity of each specific radionuclide in the TENORM waste, waste volume, the physical form of the waste, and applicable chemical characteristics such as pH. This waste characterization information is needed to ensure the disposal facility is accepting waste within its waste acceptance criteria, the workers and the public are protected during disposal operations, and the facility stays within the criteria used for its site specific dose assessment and closure plans. The waste should also be characterized for characteristic or listed hazardous wastes to ensure the landfill does not accept material outside its permitted authorizations. For operational ease, some facilities may develop generic disposal profiles that would allow generators to dispose without providing a detailed characterization. In this situation, the recommendation is that facilities consider obtaining the information necessary to ensure the facilities' life-time site activity limits are not being exceeded, e.g., provide volume disposed when a generic concentration profile is being used.

- Environmental Monitoring
  It is recommended that disposal facilities that accept large quantities of radium-226 assess the radon potential and implement a radon monitoring program as needed. The site specific dose assessment can be used to aid in determining the need for radon monitoring based on the modeled radon emissions from disposed radium-226. It is also recommended that facilities that have a leachate collection and recovery system analyze the leachate for TENORM radionuclides. If the facility does not have a leachate collection and recovery system, or if the leachate results exceed screening levels, the recommendation is that groundwater monitoring wells be installed and the samples analyzed for TENORM radionuclides. Therefore, baseline environmental data on NORM concentrations in monitoring wells may also be beneficial. There is the additional recommendation that air monitoring be considered if large volumes of dispersible bulk waste are accepted. A radiation (or health physics) consultant can aid in determining the screening levels, and need for radon and air monitoring.

- Closure Requirements
  It is recommended that disposal facilities that have a high life-time site activity limit for radium-226 consider final closure impacts, such as cover thickness, to reduce the escape of radon gas. Upon closure a specific cover thickness may be required to allow the radon to decay prior to reaching the ambient air surface above the cover. This potential requirement may also be met by disposing of the radium waste at a minimum distance below the ground surface. The use of models such as ResRad and RADON can aid in the determination of the thickness of the radon barrier cover. Radon may also present an exposure concern when discharged from methane recovery systems. Large source terms of radium may result in radon point source discharges or substantial radon progeny accumulation in recovery systems.

  Durable institutional controls may be desirable to document the presence of TENORM on the site out into the future. Landfill footprints are increasingly being utilized post-closure for other projects, such as solar farms. Durable institutional controls may be effective in maintaining safety and reducing liability in future years.

D. Handling and Managing TENORM Waste

Regardless of the TENORM waste acceptance authority of the disposal facility, it is recommended that protocols on how to handle and manage TENORM waste receipt and disposal be developed and implemented. This section highlights TENORM waste, though these practices are acceptable for all radioactive materials encountered at a disposal facility. Specific guidance on developing a TENORM radiation protection program is provided in Section VI.E. It is recommended that disposal facilities that accept TENORM waste contract the services of a radiation (or health physics) consultant to aid in developing site specific protocols for handling and managing TENORM waste.

It is recommended that protocols for handling and managing TENORM waste include, at a minimum, the following topics:

> ***As requirements and resources vary by State, facilities should check with their State radiation control and solid waste program managers to ensure the facility's protocols for isolation and securing TENORM waste is in compliance with all local and State regulations.***

- Isolating and Storing Waste
  When TENORM waste is either awaiting the assessment of an alarm or in storage awaiting disposal, it is recommended that the waste be isolated to reduce worker and public exposure. Workers in disposal facilities are considered members of the public, unless specifically trained as Radiation Workers. The NRC external exposure rate and annual radiation dose limits for members of the public are 2 mR in any one hour with a total of 100 mrem/year, from all pathways. The annual radiation dose is calculated by adding the external dose (exposure rate in mR/hr multiplied by the number of hours at that exposure rate) to the internal dose (estimated through calculation or

measurement). It is recommended that these limits be taken into account when determining storage locations.

The concept of reducing doses to As Low As is Reasonably Achievable (ALARA) through the use of time, distance, and shielding, accounting for financial and practical considerations, is recommended to be included in the storage protocols. In particular, facilities that receive high activity radium-226, radium-228 or thorium-228 TENORM wastes are encouraged to consider storage practices that reduce the direct exposure rate and the worker's annual cumulative radiation dose. Examples of exposure reducing storage practices include the use of concrete block shielding; having storage areas that are a distance away from worker locations; and minimizing the amount of time the waste remains above ground. It is recommended that wastes that contain radium-226 be stored outdoors, or in vented structures, to reduce the trapping of the progeny radon gas.

The storage of TENORM waste is not encouraged. The recommendation is that TENORM waste be promptly disposed. If waste must be stored, it is recommended that the storage location take into account leaching or runoff to avoid possible surface water, groundwater or soil impacts. Dust suppression methods may need to be adopted to avoid windblown contamination. Extended storage is discouraged.

- <u>Securing Waste</u>
  The recommendation is that when TENORM waste is either awaiting the assessment of an alarm, or in storage awaiting disposal, the waste be secured in a fashion that prohibits both inadvertent and deliberate access. Particular recommendations are to store the waste in a restricted area, or an area to which the public does not have reasonable access, and identify it through appropriate markings and postings to deter workers from accessing the waste.

- <u>Disposal Practices</u>
  It is recommended that facilities that accept high activity radium-226, radium-228 or thorium-228 TENORM waste loads consider disposal practices that reduce worker radiation exposure. Examples of exposure-reducing disposal practices include promptly disposing of waste, then placing additional soil, waste, or shielding material over the high activity waste; reducing the time workers are near the high activity waste during disposal; and increasing the distance between the worker and the high activity waste during disposal. Heavy equipment with enclosed cabs is preferred. They can be fitted with HEPA filters to mitigate particulate inhalation by the operator. The use of TENORM containing wastes as daily cover is not consistent with ALARA practices and is not advised.

- <u>Special Consideration for Dispersible Bulk TENORM Waste</u>
  It is recommended that prior to disposal, dispersible bulk TENORM waste capable of being ingested, inhaled, or absorbed be isolated to reduce the likelihood of internal

exposure and to control the spread of contamination. It is further recommended that: waste disposal practices limit dusting of dispersible TENORM waste during disposal operations and employ dust suppression methods when bulk disposal of TENORM is practiced; any disposed dispersible or loose TENORM waste be promptly covered; and the need for worker Personal Protective Equipment (PPE) be assessed. A radiation (or health physics) consultant can aid in determining appropriate worker protection controls.

- Universal Worker Practices
  It is recommended that direct contact with TENORM waste be minimized unless appropriate PPE is utilized. It is further recommended that practices that could cause an internal exposure, e.g., eating, smoking, drinking, applying cosmetics, applying bug spray, etc., while in the vicinity of the waste be prohibited.

E. TENORM Radiation Protection Program

It is recommended that, regardless of the TENORM waste acceptance authority of the disposal facility, protocols on how to protect workers during receipt and, if applicable, disposal be developed and implemented. The recommendation is that the TENORM radiation protection program be commensurate with the facility's overall disposal program. Disposal facilities that have predetermined waste acceptance criteria that result in a protective standard for workers and the environment may not require some of the program components identified below. A radiation (or health physics) consultant can aid in developing a site specific TENORM radiation protection program. This section highlights TENORM waste, though these practices are acceptable for all radioactive materials encountered at a disposal facility.

It is recommended that a site specific documented TENORM radiation protection program include, as applicable, the following components:

- PPE
  The disposal facility's PPE requirements are recommended to be based on the waste acceptance criteria (allowable TENORM radionuclides and activities, allowable waste form, and applicable packaging requirements), and disposal practices (bulk disposal or package placement). If disposal practices require the worker to contact un-containerized waste or remain in close proximity to un-containerized waste, coveralls may be required due to the potential for the spread of contamination and contact with the worker's skin. It is recommended that facilities that accept dispersible bulk TENORM waste require workers to don coveralls, and, in extreme circumstances, respiratory protection. Depending on the waste acceptance criteria and likelihood of inhalation or ingestion, simply standing upwind is generally a sufficiently protective action. An additional recommendation is to implement dust suppression techniques when offloading dispersible bulk TENORM waste.

- Surveys
  It is strongly recommended that the disposal facility have radiation survey meters. All instrumentation must be calibrated annually, and should undergo a documented response check each day of use. At a minimum, these would include a dose rate meter and a surface contamination meter; a portable gamma spectrometry unit is encouraged to aid in the specific identification of radionuclides in the waste. It is also recommended that the TENORM radiation protection program include: a survey assessment of the incoming waste to ensure it is within the facility's waste acceptance criteria; facility disposal unit exposure surveys to ensure the work areas are within allowable dose limits; facility radiological contamination surveys to ensure there is no spread of TENORM; and worker personal contamination surveys to ensure the worker did not become contaminated. A documented records management/quality assurance program is highly recommended. Although a dosimetry program is generally not required for TENORM wastes, a facility may want to consider a passive area dosimeter to document long-term exposure to gamma radiation is adequately controlled. A radiation (or health physics) consultant can provide training on how to properly use radiation survey instruments and on how to conduct a proper radiation survey.

- TENORM Awareness Level Training
  It is recommended that the disposal facility develop site specific training that covers: a basic review of radiation types and the units used to quantify radiation; what TENORM is and the human health risks associated with TENORM; the principles of reducing dose through the use of time, distance, and shielding and the concept of As Low As Reasonably Achievable (ALARA); the facility's waste acceptance criteria, and packaging and disposal requirements; how workers are being protected through the use of PPE, engineering controls (ECs), and protocols; and how to perform personnel contamination surveys, and facility exposure and contamination surveys. There may be worker right to know requirements in the form of postings, notifications, etc. Check with the local permitting authority. If the State radiation control authority requires a radiation safety officer or other higher level of training for management of personnel, additional levels of training may be required.

F. Performing Site Specific Dose Assessments for TENORM Disposal in Landfills

Site specific dose assessments are a critical tool in ensuring workers and the public are protected during the operational phase and in determining the future radiological impacts on human health and the environment from the disposal of TENORM waste during the closure phase of the disposal facility. Site specific dose assessments can be used to determine the total activity the site can accept, as well as ensure the planned closure controls are protective. Simple radiation physics principles can be used to perform operational phase dose assessments. New facilities should conduct a baseline survey of soils, surface and groundwater prior to construction of the facility as this data is valuable for closure. Computer models are typically used to perform more complicated closure assessments. Dose assessments are predicated on choosing an appropriate scenario with respect to which pathways will be utilized. It is recommended that disposal facilities contract the services of a radiation (or health physics) consultant to aid in performing site specific dose assessment. A list of radiation (or health physics) consultants can be found on the CRCPD web site at http://www.crcpd.org/.

Some common radiological dose assessment computer models are:

- ResRad – A free computer model developed by Argonne National Laboratory and commonly used by regulators for compliance with onsite radiological limits.
- ResRad Offsite – A free computer model developed by Argonne National Laboratory and commonly used by regulators for compliance with offsite radiological limits, including air emissions and drinking water from leachate releases.
- Microshield – Used to evaluate shipping container shielding effectiveness.
- Commercial Programs are also available though not typically utilized by regulators.

Site specific radiological dose assessments require the input of many model parameters. The ResRad codes provide defaults values for many of these parameters. Some parameters will be fixed as a result of the RCRA design criteria (modeling liners and liner failure requires someone expert in the model). Other parameters, such as: dose limit, dose coefficients, meteorological data (wind rose), assessment time period, intake pathways, future land use, terms of occupancy for a future resident, modeling the average member of the exposed public or the maximally exposed member, and expectations for food derivation from the site, have not been federally standardized. Depending on climate and location, many landfills now employ evapo-transpiration caps rather than highly engineered caps. Site specific geotechnical and geochemical and hydrological parameters are necessary to conduct realistic offsite evaluations. Overly conservative assumptions may result in unrealistic results. In lieu of federal requirements, your State radiation control manager should be contacted for guidance on what site specific inputs are required.[5] The Interagency Steering Committee on Radiation Standards (ISCORS) issued the technical document *ISCORS Assessment of Radioactivity in Sewage Sludge: Modeling to Assess Radiation Doses* that provides technical information on the ResRad code and input parameters. EPA also has an Exposure Factors Handbook that may be of help: https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252.

Some critical model parameters to consider are identified below:

Dose Limits

There are no federal dose standards for the operational or post closure phases of TENORM facilities. Currently, facilities under NRC jurisdiction must restrict dose from the licensed activity offsite. However, this is just from a site, and is above background. Contact your radiation control program manager regarding the requirements (State-specific dose constraints and considerations for including radon as a component of modeling):

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[5] Note that more site-specific information is needed to run ResRad or ResRad-OFFSITE in probabilistic mode, in order to adequately define parameter distributions.

- 100 mrem/yr above background total effective dose equivalent from all pathways, during operations, public dose limit (10 CFR Part 20, Subpart D);
- ALARA below 25 mrem/yr total effective dose equivalent, for unrestricted release, from all pathways, after closure (10 CFR Part 20, Subpart E);
- 25 mrem/yr, restricted release with institutional controls, agreed upon pathways, after closure;
- 100 mrem/yr, restricted release with institutional control failure, agreed upon pathways, after closure;
- "A few millirem" dose from disposing of licensed material in an unlicensed facility under 10 CFR 20.2002.

The EPA has numerous limits including:

- 10 mrem/yr from particulate air emissions (i.e., exclusive of radon);
- 4 mrem/yr from drinking water;
- The CERCLA derived dose limit of 12 mrem/yr is generally consistent with the CERCLA acceptable risk range of 10^{-4} to 10^{-6} life-time risk.

Individual States may have adopted more or less restrictive dose limits. Contact your radiation control program manager for requirements or guidance on what dose limits apply to your facility prior to performing an assessment.

Dose Projection Time Periods

There is no standard for the length of time post closure in which models assess impacts for TENORM facilities. EPA regulations require that the post-closure care period for each hazardous waste management unit subject to the requirements of 40 CFR 264/265.117 through 264/265.120 must begin after completion of closure of the unit and continue for 30 years after that date. Still, the regulations' identification of a default 30-year post-closure care period does not reflect a determination by EPA that 30 years of post-closure care is necessarily sufficient to eliminate potential threats to human health and the environment in all cases. Nor is the full 30-year period always necessary. These facilities may petition individual States to reduce the 30-year post-closure assessment period if all post-closure requirements are achieved. If conditions warrant, post-closure assessments could be extended well past 30 years at individual facilities. Post-closure RCRA assessments include ground water and gas monitoring, as well as an assessment of the integrity of the final cover. Facilities under NRC jurisdiction must perform assessments for 1,000 years (uranium mills and proposed compliance period for low-level radioactive waste sites) to 10,000 years (proposed performance period for low-level radioactive waste sites) after closure. Individual States may adopt more restrictive time limits. Contact your radiation control program manager for requirements or guidance on what assessment period applies to your facility.

Radiological Inputs

- Radionuclides present
- Radionuclide concentrations
- Radionuclide solubility (Class F, M, S)
- Dose coefficient library[6]

Facility Specific Inputs

- Thickness of waste
- Area of waste
- Thickness of cover layers
- Density of cover layers
- Erosion rate
- Depth to groundwater
- Groundwater flow direction and velocity
- Water table drop rate
- Water infiltration rate
- Underlying soil layers permeability, porosity, conductivity (liners usually not counted or use tight clay permeability to represent)
- Distribution coefficient (Kd) of the radionuclides (chemical form may alter mobility)
- Radon emanation coefficient (chemical form may alter mobility)
- Watershed drainage area

Occupancy times

- Time spent outside
- Time spent inside (in a residence or commercial facility that is built on-site after closure for all controls fail scenario)
- Slab on grade or basement (if radon is included in the model)

Pathways

There are no federal standards for what pathways must be included when performing a post-closure assessment of a TENORM facility. Facilities under NRC jurisdiction must include all applicable pathways. The EPA has guidelines for indoor radon concentrations in air, so the EPA CERCLA assessment would include all applicable pathways including radon. The radon pathway in ResRad assumes a habituated structure over the disposal cell. Results will vary widely if one model utilizes a house with a basement dug into the cap and another uses a slab on grade construction. Additionally, a review of the data available indicates a poor correlation of soil concentration to indoor radon concentration. Although radium in the soil is certainly causative, differences in soil porosity, foundation integrity, and air turnover can dominate the factors leading to indoor air concentration. For example, naturally occurring radium concentrations may lead to high indoor air concentrations in a tightly sealed home. Therefore, modeling experts disagree on the protectiveness of incorporating radon into such a model without

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[6] RESRAD allows for different dose coefficient libraries to be used, e.g., ICRP 26/30, ICRP 60, FGR13…

knowledge of the future buildings. Contact your radiation control program manager regarding the requirements for radon modeling. The groundwater pathway in ResRad assumes a well within the boundaries of the disposal cell. It is recommended that excluding a pathway from the assessment be supported by a deed restriction on the property or other legally binding agreement that ensures that pathway will not be activated after closure. Also, some areas may have specific geologic or hydrogeologic features that could justify eliminating some pathways. Contact your radiation control program manager for requirements or guidance on what scenarios/pathways must be included in your assessment.

Engineering and Institutional Control Inclusion and Failures

Assessments can be performed for numerous scenarios including assuming all engineering/institutional controls (EC/ICs) are active and in place, and assuming the EC/ICs fail. The NRC requires additional assessments assuming all EC/ICs fail. These can also be described as bounding scenarios and realistic scenarios. Defining the receptor is also crucial – i.e., the reasonably maximally exposed individual or the average member of the critical group, etc. Contact your radiation control program manager or the applicable environmental department for requirements or guidance on the inclusion of ECs and ICs, as well as how to define the receptor.

Sensitivity Analysis

The ResRad code allows for a sensitivity analysis of any input parameter. The sensitivity analysis is a powerful tool to determine the impacts of a particular input parameter on the resulting dose. The performance of sensitivity analyses is recommended to ensure critical parameters are identified and resources are focused to get the most accurate data. If sufficient resources are available, ResRad can be run in probabilistic mode, which may help to reduce uncertainty. Contact your radiation control program manager for requirements or guidance on the inclusion of a sensitivity analysis in your assessment.

VII. DOSE ASSESSMENTS AND DISPOSAL CASE STUDIES

Site specific dose assessments are a critical tool in ensuring workers and the public are protected during the operational phase and in determining the future radiological impacts on human health and the environment from the disposal of TENORM waste. Simple radiation physics principles can be used to perform worker operational phase dose assessments. Computer models, such as ResRad, are used to perform more complicated public, environmental and closure assessments. Section VI.F provides guidance on performing dose assessments. Many regulatory agencies and States have performed site specific dose assessments and presented these assessments as case study documents or reports. The following list provides a partial listing of TENORM assessments that have been performed:

- The State of North Dakota and Argonne National Laboratory performed comprehensive dose assessments for numerous scenarios of oil and gas production, including well site operations, improperly managed waste, transportation, and disposal. These studies can be found on the North Dakota TENORM website.

- The State of Michigan issued a white paper on TENORM Disposal, *Michigan TENORM Disposal Advisory Panel White Paper*, 2014-2015.
- The State of Michigan, in concert with Argonne National Laboratory, conducted a study on landfill disposal of TENORM, *An Assessment of the Disposal of Petroleum Industry NORM in Nonhazardous Landfills*, September 1999, DOE/BC/W-31-109-ENG-38-8.
- Argonne National Laboratory issued a report addressing the characterization of contaminated facilities, *The Application of Adaptive Sampling and Analysis Program Techniques to NORM Sites*, October 1999, DOE/BC/W-31-109-ENG-38-9.
- Argonne National Laboratory issued a petroleum industry specific dose assessment report, *Radiological Dose Assessment Related to Management of Naturally Occurring Radioactive Materials Generated by the Petroleum Industry*, September 1996, ANL/EAD-2.
- The Colorado Department of Public Health and Environment discussed numerous risk assessments that had been submitted over the years in their *2007 Interim Policy and Guidance Pending Rulemaking for Control and Disposition of Technologically-Enhanced Naturally Occurring Radioactive Materials in Colorado.*
- The Interagency Steering Committee on Radiation Standards' (ISCORS) Sewage Sludge Subcommittee produced three reports: a survey of radionuclides in sewage sludge; modeling parameters for assessing the dose from disposal of sewage sludge; and recommendations on the management of radioactive materials in sewage sludge for various disposal methods.
- Zircon sands have a variety of uses and may end up in a waste stream. Appendix D provides an example dose assessment of zircon waste after disposal at a landfill. In addition, an assessment of the operational phase is also provided, demonstrating that public exposures are not exceeded.
- Fly ash from coal fired power plants has been used since 2013 at select gold/silver mines in Nevada as a binder (along with Portland Cement) in the batching process for cemented tailings paste used as backfill in underground workings. Testing of paste samples using ASTM C1308(08) showed that the paste process effectively immobilized constituents from the tailings and fly ash. This process produced the following benefits:
    - Protection of groundwater through immobilization of COCs, sealing of the exposed underground rock wall, and neutralization of potential acid rock drainage;
    - Reduction of tailings volume disposed of in the conventional tailings impoundment at the mine;
    - Reduction of fly ash volume required to be disposed of in the ash landfill at the power plant.

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Conference of Radiation Control Program Directors*, 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)*.

Environmental Protection Agency, *Diffuse Norm Wastes - Waste Characterization and Preliminary Risk Assessment*, RAE-9232/1-2, May 1993.

International Atomic Energy Agency, *Technical Series Report No 419, Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation*, December 2003.

Interagency Steering Committee on Radiation Standards, *ISCORS Assessment of Radioactivity in Sewage Sludge: Modeling to Assess Radiation Doses*, NUREG-1783; EPA 832-R-03-002A; DOE/EH-0670, February 2005.

National Council on Radiation Protection and Measurements (NCRP), No. 160*, Ionizing Radiation Exposure of the Population of the United States*, 2009.

Non-Destructive Testing Resource Center website: https://www.nde-ed.org/EducationResources/CommunityCollege/RadiationSafety/biological/stochastic/stochastic.htm

APPENDIX A
SELECT RADIATION DEFINITIONS

ALARA

“As Low As is Reasonably Achievable" is an approach used to manage and control exposures (both individual and collective to the work force and to the general public) and releases of radioactive material to the environment so that the levels are as low as is reasonably achievable taking into account social, technical, economic, practical, and public policy considerations.

Byproduct Material

Byproduct material is defined by the U.S. Nuclear Regulatory Commission (NRC) as: (1) Any radioactive material (except special nuclear material) yielded in, or made radioactive by, exposure to the radiation incident to the process of producing or using special nuclear material; (2)(i) Any discrete source of radium-226 that is produced, extracted, or converted after extraction, before, on, or after August 8, 2005, for use for a commercial, medical, or research activity; or (ii) Any material that: (A) Has been made radioactive by use of a particle accelerator; and (B) Is produced, extracted, or converted after extraction, before, on, or after August 8, 2005, for use for a commercial, medical, or research activity; and (3) Any discrete source of naturally occurring radioactive material, other than source material, that: (i) The NRC, in consultation with the Administrator of the Environmental Protection Agency, the Secretary of Energy, the Secretary of Homeland Security, and the head of any other appropriate Federal agency, determines would pose a threat similar to the threat posed by a discrete source of radium-226 to the public health and safety or the common defense and security; and (ii) Before, on, or after August 8, 2005, is extracted or converted after extraction for use in a commercial, medical, or research activity. Note that NRC defines byproduct material slightly different in 10 CFR 40.4 as the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content, including discrete surface wastes resulting from uranium solution extraction processes. Underground ore bodies depleted by such solution extraction operations do not constitute "byproduct material" within this definition.

Conventional Uranium Mining

Where uranium ore is removed from deep underground shafts or shallow open pits, conventional uranium mining is regulated by the Office of Surface Mining, the U.S. Department of the Interior, and the individual States where the mines are located.

Committed effective dose equivalent (CEDE)

As defined in Title 10, Section 20.1003, of the Code of Federal Regulations (10 CFR 20.1003), the CEDE ($H_{E,50}$) is the sum of the products of the committed dose equivalents for each of the body organs or tissues that are irradiated multiplied by the weighting factors (WT) applicable to each of those organs or tissues ($H_{E,50} = \Sigma W_T H_{T.50}$).

High-Level Radioactive Waste
High-level radioactive waste are wastes that contain (1) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (2) other highly radioactive material that the NRC, consistent with existing law, determines by rule requires permanent isolation.

In Situ Uranium Recovery
Where uranium ore is removed by in situ leach recovery, where the uranium ore is chemically altered underground before being pumped to the surface for further processing. In situ uranium mining is regulated by the U.S. Nuclear Regulatory Commission (NRC).

Low-Level Radioactive Waste
A general term for a wide range of items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation. A variety of industries, hospitals and medical institutions, educational and research institutions, private or government laboratories, and nuclear fuel cycle facilities generate low-level radioactive waste as part of their day-to-day use of radioactive materials. Some examples include radioactively contaminated protective shoe covers and clothing; cleaning rags, mops, filters, and reactor water treatment residues; equipment and tools; medical tubes, swabs, and hypodermic syringes; and carcasses and tissues from laboratory animals. The radioactivity in these wastes can range from just above natural background levels to much higher levels, such as seen in parts from inside the reactor vessel in a nuclear power plant. Low-level waste is typically stored onsite by licensees, either until it has decayed away and can be disposed of as ordinary trash, or until the accumulated amount becomes large enough to warrant shipment to a low-level waste disposal site. For further information, see Low-Level Waste. NRC link:
https://www.nrc.gov/reading-rm/basic-ref/glossary/low-level-radioactive-waste-llw.html

Source Material
Source material is defined as: (1) Uranium or thorium, or any combination thereof, in any physical or chemical form or (2) Ores that contain by weight one-twentieth of one percent (0.05%) or more of: (i) Uranium, (ii) Thorium, or (iii) Any combination thereof. Source material does not include special nuclear material.

Special Nuclear Material
Special nuclear material is defined as: (1) Plutonium, uranium-233, uranium enriched in the isotope 233 or in the isotope 235, and any other material which the NRC determines to be special nuclear material, but does not include source material; or (2) Any material artificially enriched by any of the foregoing but does not include source material.

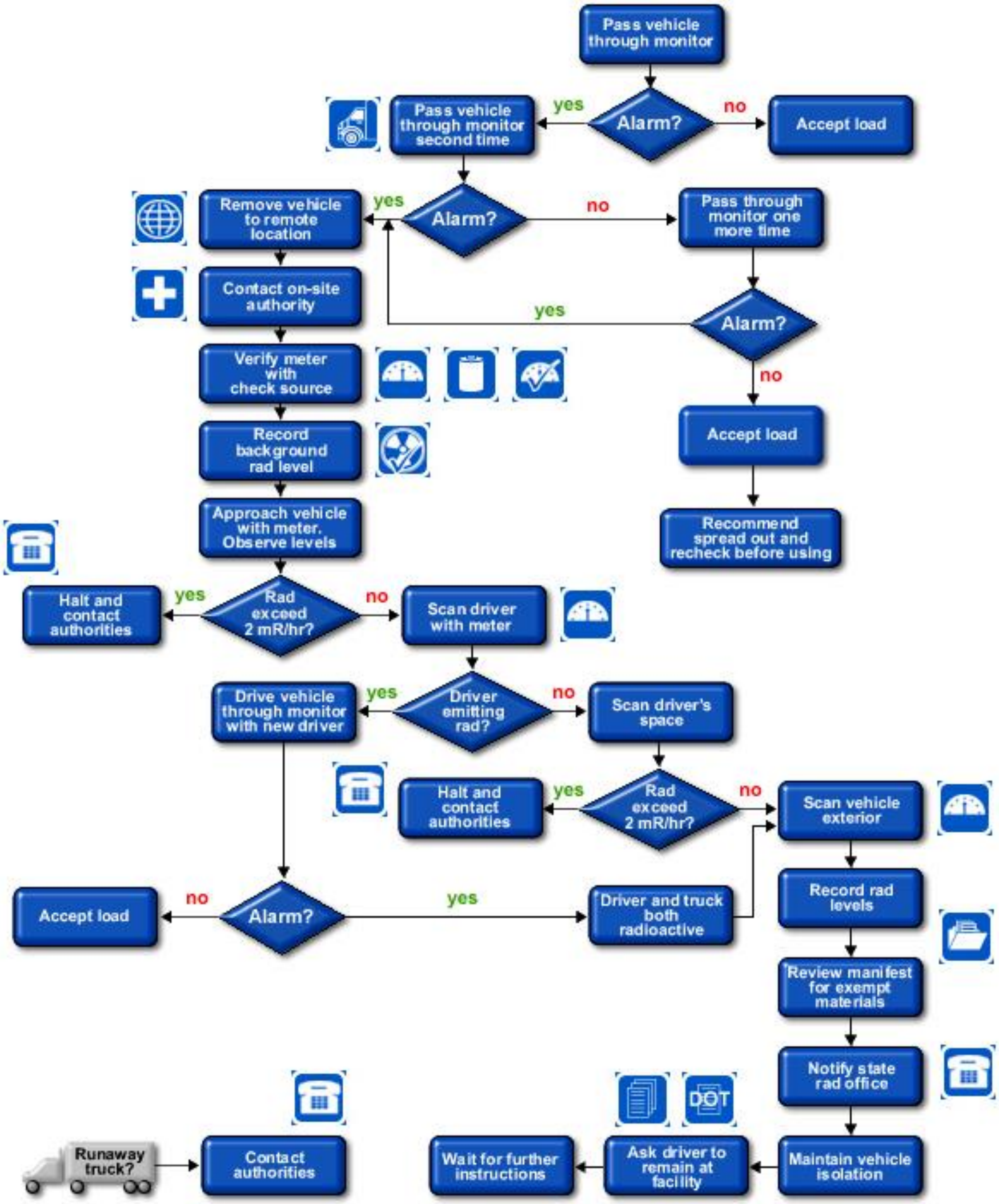
Spent Nuclear Fuel
Spent nuclear fuel is defined as: fuel that has been withdrawn from a nuclear reactor following irradiation, has undergone at least one year's decay since being used as a source of energy in a power reactor, and has not been chemically separated into its constituent elements by

reprocessing. Spent fuel includes the special nuclear material, byproduct material, source material, and other radioactive materials associated with fuel assemblies.

Total Effective Dose Equivalent (TEDE)
The sum of the effective dose equivalent (for external exposures) and the committed effective dose equivalent (for internal exposures).

Transuranic Waste
Transuranic waste are wastes that contain more than 100 nanocuries of alpha-emitting transuranic isotopes per gram of waste with half-lives greater than 20 years, except for (A) high-level radioactive waste, (B) waste that the Secretary of Energy has determined, with concurrence of the Administrator of the Environmental Protection Agency, does not need the degree of isolation required by the disposal regulations, or (C) waste that the Nuclear Regulatory Commission has approved for disposal on a case-by-case basis in accordance with part 61 of title 10 Code of Federal Regulations (CFR).

APPENDIX B
RADIATION ALARM FLOW CHART



Source: EPA Response to Radiation Alarms at Metal Processing Facilities

APPENDIX C1
TENORM WASTE IN COAL COMBUSTION FOR ENERGY GENERATION

How is Coal used?

- Coal is used as a major source of energy to produce electricity.

How is Coal produced?

- Coal is a sedimentary organic rock that contains a lot of carbon.
- Coal can be mined in either open pits or underground mines. Once coal is mined, it is washed, sorted and processed to meet the quality requirements of the customers. Vast amounts of water are used to wash the coal and the process produces a significant amount of waste rock, and drainage water that contains elevated levels of radioactivity.

Where does the NORM Come From?

- Similar to other types of rocks, coal (fossil) contains NORM. It contains U-238, U-234, Th-232, and their radioactive daughter products (example, Ra-226, Ra-228, etc.).
- The quantity of NORM varies depending on the geological formation of the coal. The following table shows the average concentration of radionuclides in USA coal:

NORM in Coal	**U-238 (pCi/g)**	**Th-232 (pCi/g)**	**Ra-226 (pCi/g)**	**Pb-210 (pCi/g)**	**Po-210 (pCi/g)**
USA	0.17 – 1.2	0.10 – 0.57	0.24 – 1.6	0.33 – 2.1	0.09 – 1.4

Source: IAEA, 2003 Technical Reports Series No.419

Where is the TENORM found?

- Mining and combustion of coal for energy generation in coal-fired power plants concentrates the NORM to significant amounts in the waste generated in this process. This Technologically Enhanced NORM is called TENORM.
- TENORM is found in the ash which is the residual waste left behind as a result of coal combustion. The concentration of TENORM in ash depends on the type of geological formation of burnt coal. Two types of ashes, bottom and fly ashes, are produced as a result of coal burning in a coal-fired power plant.
- The bottom ash is found at the bottom of the boiler whereas the fly ash is collected and found from the stack of the power plant.
- Both these two types of ashes contain higher concentration of NORM than the burned coal.
- According to World Nuclear Society:
  - The concentration of uranium and thorium in bottom and fly ashes can reach up to ten (10) times greater than the burnt coal;
  - Fly ash, in general, contains higher concentration of TENORM than the bottom ash;
  - About 1100 metric tons of uranium were recovered from coal ash in the USA in the 1960s and 1970s. This indicates that a huge amount of ashes with high concentration of TENORM are generated as a result of coal combustion power plants.

How much TENORM is in the waste?

- The concentration of TENORM in ashes varies depending on the coal formation.
- The following table shows the average concentrations of radionuclide in fly and bottom ashes in USA:

TENORM Contaminated Waste	U-238 (pCi/g)	Th-232 (pCi/g)	Ra-226 (pCi/g)	Ra-228 (pCi/g)	Total Activity (pCi/g)
Fly Ash	2.6	1.8	3.0	2.6	27
Bottom Ash	0.70	0.51	0.70	0.59	6.9

Source: IAEA, 2003 Technical Reports Series No.419

Where do the TENORM wastes go?

- Coal ash is one of the largest types of industrial waste generated in the United States. According to EPA, nearly 110 million tons of coal ash was generated in 2012.

Disposal Facilities

According to the U.S. Department of Transportation Federal Highway Administration Research and Technology:

- About 70 to 75 percent of fly ash generated is disposed of in landfills or storage lagoons
- Bottom ash is contracted out to ash marketing firms or to local hauling contractors

- Fly ash is disposed in an ash dam as final disposal but the majority of the fly ash is used in building construction

Recyclers

- Coal ash may be used as substitutes for virgin materials in products like concrete or wallboard.

Beneficial Use

- The beneficial use of wastes is managed by State environmental agencies. The relevant State and federal authorities should be consulted to identify all the requirements that would apply to proposed beneficial uses of waste materials. EPA's *Methodology for Evaluating Beneficial Uses of Industrial Non-Hazardous Waste Secondary Materials* and the *Beneficial Use Compendium: A Collection of Resources and Tools to Support Beneficial Use Evaluations* were developed to help evaluate the potential adverse impacts to human health and the environment from the beneficial use of waste materials.
- Under recent EPA regulations (40 CFR 257, subpart D) certain uses of coal ash (coal combustion residuals or CCR) are considered to be "beneficial uses" that are exempt from the waste management requirements.
- To be considered a beneficial use under these regulations, all of the following criteria must be met: (1) The CCR must provide a functional benefit; (2) The CCR must substitute

for the use of a virgin material, conserving natural resources that would otherwise need to be obtained through practices such as extraction; (3) The use of CCRs must meet relevant product specifications, regulatory standards, or design standards when available, and when such standards are not available, CCRs are not used in excess quantities; and (4) When un-encapsulated use of CCRs involves placement on the land of 12,400 tons or more in non-roadway applications, the user must demonstrate and keep records, and provide such documentation upon request, that environmental releases to ground water, surface water, soil and air are comparable to or lower than those from analogous products made without CCRs, or that environmental releases to ground water, surface water, soil and air will be at or below relevant regulatory and health-based benchmarks for human and ecological receptors during use.

- Typical uses of coal ash include:
  - Fly Ash has been used in concrete and blended cement; it can typically be substituted for cement at a rate of 10-40 percent. Fly ash is used as a replacement for Portland cement in concrete applications.
  - Fly ash has also been used for structural fills/embankments, in road base, for snow and ice control and waste stabilization/solidification.
  - Bottom ash has also been used for concrete, blended cement and structural fills/embankments, road base, in snow and ice control, and as an aggregate.

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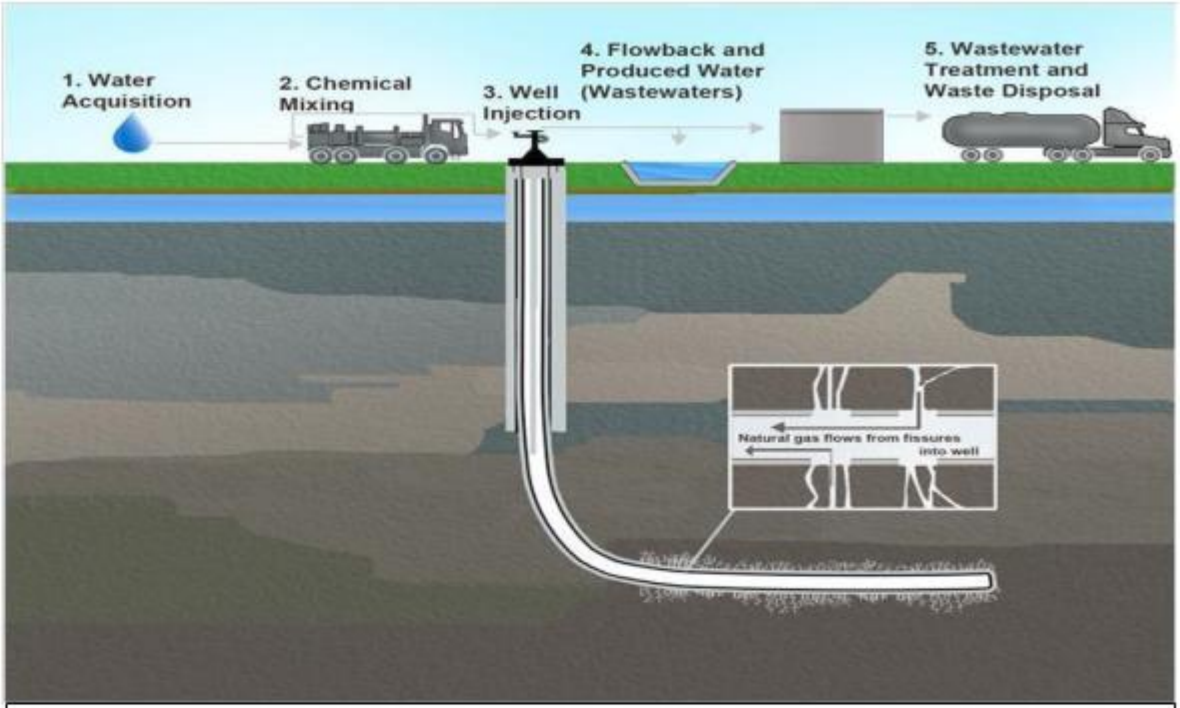
APPENDIX C2
TENORM WASTE IN OIL AND GAS PRODUCTION INDUSTRIES

How is Oil and Gas used?

- Oil and gas fuels cars, heats homes, cooks food, among other uses.

How are Oil and Gas produced?

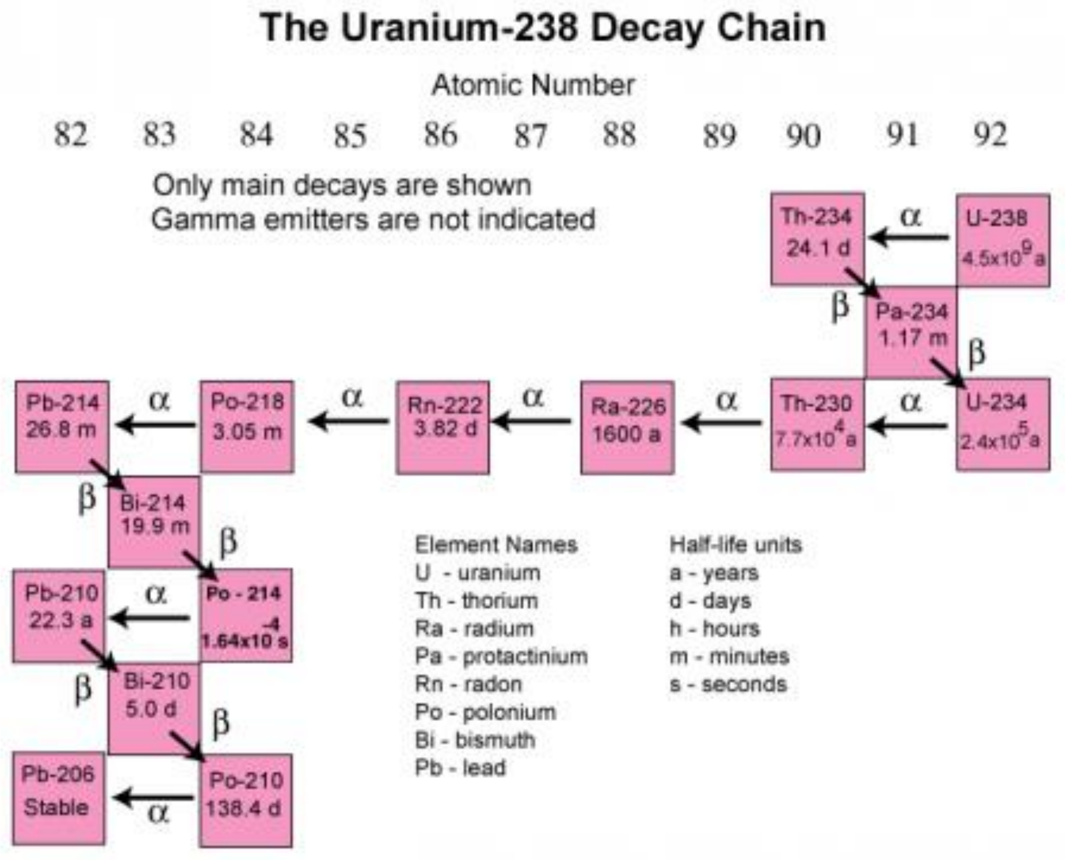
- Oil and natural gas are naturally occurring chemicals that are made up of carbon and hydrogen.
- Oil and gas we use today began as microscopic plants and animals living in the ocean millions of years ago. These microscopic plants and animals absorbed energy from the sun while they were alive and stored it as carbon molecules in their bodies. When they died, they usually sank at the bottom of the sea and were covered by layers of sediments over a million years. Heat and pressure started to rise and as a result, the microorganisms under the layers of the sediments converted to oil and gas depending on the degree of the heat and pressure. The oil and gas formed started to migrate through tiny pores in the rock and moved until trapped by the impermeable layer of rocks and collected there as reservoir. Oil and gas are found in many parts of the earth.
- Oil and gas are produced by two standard methods, typically known as conventional and unconventional production methods.
- Conventional production method is typically used to extract oil (and associated natural gas). In this method, holes are drilled vertically and reach to the reservoir and pump the oil directly from the oil reservoir. Conventional oil drilling is cheaper than unconventional oil drilling.
- Unconventional production methods, called hydraulic fracturing, hydrofracking, or simply fracking technology, are used for both oil and gas production. Note that hydraulic fracturing (enhanced stimulation) has also been used for vertical production from traditional reservoirs for decades. A common divide between conventional and unconventional methods has come to be based on use of both horizontal drilling and fracking of impermeable formations (shale or other tight rocks). Wells are drilled horizontally and chemicals and proppants such as treated water and sand are blasted from horizontally drilled wells into the impermeable formation to allow oil and gas to flow from the fractured shale. Unconventional oil and gas drilling is a much more expensive process than conventional drilling.



http://www2.epa.gov/hfstudy/hydraulic-fracturing-water-cycle

Where does the NORM come from?

- Radioactive materials, such as uranium, thorium, and potassium are found in nature in many types of rock formations.
- These **N**aturally **O**ccurring **R**adioactive **M**aterials, called NORM, are found in normal natural distribution in the formations.
- All minerals, including oil, gas, coal, etc., can contain trace amounts of NORM.
- Oil and gas originate from the breakdown of organic material embedded in sedimentary rocks. Basically, the primordial radionuclides and their progeny are not high in sedimentary rocks but studies indicate that elevated amounts of radionuclides can be found in shale rocks (IAEA 2003 Tech Report 419). Shale formations (the host rock) are now able to be drilled due to the advances in horizontal drilling and enhanced stimulation.
- However, the natural distribution of NORM in the formation can be deposited heterogeneously and be re-disturbed and their concentrations in the environment may be elevated as a result of human interventions, including industrial processes.
- The concentration of the natural radioactive materials can be enhanced technologically, called **T**echnologically **E**nhanced **N**aturally **O**ccurring **R**adioactive **M**aterial (TENORM).
- As a result, when TENORM has been significantly concentrated through large-scale industrial production, occupational and public exposure to radiation can become an issue. Mishandling of the materials (e.g., spills, illegal dumping) can lead to environmental issues.
- Uranium and thorium, and their daughter radionuclides, called progeny, are important from the radiation protection perspective. Their decay chains contain hazardous radioactive materials (e.g., Ra-226, Ra-228 and Rn-220/222).



Source: U.S. Geological Survey (USGS)

Note: The Uranium-238 Decay Chain and Source have been excerpted from the EPA website at https://www.epa.gov/radiation/radioactive-decay

Where is the TENORM found?

- TENORM is found in industrial activities such as thorium and uranium mining/milling; gold, tin mining; water treatment; phosphate fertilizer; coal fire ash; aluminum production, and oil and natural gas production.
- More than 140,000 drums of TENORM waste containing residues with radionuclides greater than 89 pCi/g accumulate in the USA annually from the oil and gas industry.
- During drilling of oil and gas, a mixture of oil, gas, and formation water (brine) is pumped to the surface.
- Depending on the chemical form (uranium has a +4 and a +6 valence state), the solubility of uranium can vary. U and Th are generally not solubilized and stay in formation because of the reduced environment that keeps the U in the +4 state. However, when uranium is oxidized to the +6 valance state, it becomes much more mobile. This can occur when uranium and thorium are brought to the surface in drill cuttings or similar processes. However, radium, their radioactive decay product, is soluble in brine. Isotopes of radium may remain in solution or settle out to form sludge, which accumulates in tanks and pits, or mineral scales, which form inside pipes and drilling equipment.

- Scales are normally found on the inside of piping and tubing; the highest concentrations of radioactivity (TENORM) are in the scale in wellhead piping and in production piping near the wellhead. Concentrations in the scale are as high as tens of thousands of picocuries per gram. Like contaminated scale, sludge contains more Ra-226 than Ra-228.
- Concentrations of Radium-226 in scale are generally higher than those of Ra-228. Like contaminated scale, sludge also contains more Ra-226 than Ra-228.
- Generally, large volumes of scale are found in the following three areas: Water lines associated with separators (separate gas from the oil and water); Heater treaters (divide the oil and water phases); and gas dehydrators, where scale deposits as thick as four inches may accumulate (EPA, last updated on October 29, 2015).

How much TENORM is in the waste?

- The concentration of radionuclides in contaminated materials slightly varies from site to site. Radium-226 (Ra-226) and radium-228 (Ra-228) are the isotopes of primary concern due to their relative solubility in contaminated materials.
- TENORM-contaminated sludge can accumulate inside piping, separators, heater/treaters, storage tanks, and any other equipment where produced water is handled. The following table shows the average concentration of radium, uranium and thorium in contaminated materials:

TENORM Content	**Ra-226 (pCi/g)**	**Ra-228 (pCi/g)**	**Pb-210 (pCi/g)**
Pipe scale	480 pCi/g		5 – 2,000
Sludge	75 pCi/g		3 -35,000
Produced Water	6700 – 9000 pCi/L		1 – 5,000 pCi/L

Additional information on the generation, expected volumes, and concentrations of oil and gas wastes is discussed Appendix C-1 of the June 2015, E-42 Task Force Report, "Review of TENORM in the Oil and Gas Industry", Publication No. CRCPD E-15-2.

Where do the TENORM wastes go?

Disposal Facilities

- TENORM-contaminated scales, sludge, and other solid wastes have been disposed of either through underground injection wells; used to fill abandoned & plugged wells; landfill disposal; or land spreading. The 2007 ASTSWMO Survey on Regulation of Radioactive Materials in Solid Waste Landfills concluded that most of the States' landfill disposal facilities do not accept waste that contains more than 5 pCi/g of combined Ra-226 and Ra-228 above the background. However, since the time of publication, many

States have modified regulations and policies to begin accepting this material. It is good to contact the State's radiological health program for further information before sending waste to landfill facility.

Recyclers

- When the oil and gas industries decommission, most of the contaminated metal equipment, such as pipes, and other metal materials are sent to recyclers for use in making steel products.
- Smelters can cause costly contamination to their facilities from melting commercial sources such as Cs-137. However, the activity in TENORM is generally much less and diffuse. Additionally, the radium partitions mostly into the slag and the melt rather than volatilizing like Cs-137. Nonetheless, due to the cost such an incident can impart upon the steel industry, it has adopted a zero tolerance for radiation in its recycle streams. This has generally resulted in very low alarm set points for rejection at recycling facilities and often results in the identification and rejection of TENORM-contaminated items. To avoid this problem, it is recommended that equipment from the oil and gas industry be screened (surveyed) for TENORM before it is sent to recyclers.

Beneficial Use

- The beneficial use of wastes is managed by State environmental agencies. The relevant State and federal authorities should be consulted to identify all the requirements that would apply to proposed beneficial uses of waste materials. EPA's *Methodology for Evaluating Beneficial Uses of Industrial Non-Hazardous Waste Secondary Materials* and the *Beneficial Use Compendium: A Collection of Resources and Tools to Support Beneficial Use Evaluations* were developed to help evaluate the potential adverse impacts to human health and the environment from the beneficial use of waste materials.
- Produced water (brine) from oil and gas operations which meets applicable release criteria may be used beneficially for purposes such as irrigation, livestock watering, aquifer storage, streamflow augmentation, road deicer or dust suppressant, and municipal and industrial uses.

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APPENDIX C3
TENORM WASTE IN PAPER AND PULP PRODUCTION FACILITIES

How are Pulp and Paper Products used?

- Paper and paper products are used extensively in our daily lives. Pulp and paper industries process wood and wood pulp to produce the paper necessary to support the United States' demand for paper and paper products.

Where does the NORM come from?

- Small quantities of NORM are found naturally in the wood from trees, and in the extensive volume of water used for processing pulp and paper products.

Where is the TENORM found?

- During the lifespan of the processing facility, scale, commonly barite, accumulates inside the pipes, tubes, and vessels. Wherever barium pipe scale accumulates, radium, which is chemically similar and naturally present in the water, will co-deposit in the pipe scale with the barium scale. The concentration of the radium in the pipe scale is enhanced during this process and the pipe scale is now contaminated with TENORM.
- The sludge and waste product pulp found at the bottom of the vessels and tanks attracts and concentrates NORM. The sludge may contain radium, thorium, and uranium TENORM.

Where do the TENORM wastes go?

Disposal Facilities

- The majority of the sludge is disposed in landfills and lagoons.

Recyclers

- When decommissioning a facility, it is recommended that the pipes, tubing, vessels, and tanks be surveyed for the presence of TENORM pipe scale and sludge prior to recycling.

Beneficial Use

- The beneficial use of wastes is managed by State environmental agencies. The relevant State and federal authorities should be consulted to identify all the requirements that would apply to proposed beneficial uses of waste materials. EPA's *Methodology for Evaluating Beneficial Uses of Industrial Non-Hazardous Waste Secondary Materials* and the *Beneficial Use Compendium: A Collection of Resources and Tools to Support Beneficial Use Evaluations* were developed to help evaluate the potential adverse impacts to human health and the environment from the beneficial use of waste materials.
- Paper mill sludge may be land spread for agriculture, composted, used to make bricks, and as a component of landfill caps.
- Paper mill sludge can be incinerated for energy production.

References

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APPENDIX C4
TENORM WASTE IN PHOSPHATE FERTILIZER AND PHOSPHORUS PRODUCTION

How are Phosphate Fertilizer and Phosphorus used?

- Fertilizers are used to amend soil for agricultural purposes.
- Phosphorous based fertilizers enhance plant and crop growth.

Where does the NORM come from?

- Naturally occurring uranium, as well as its progeny, are found in the phosphate rock that is processed to generate phosphorus and phosphate fertilizer.

Where is the TENORM found?

- Most phosphate rock is turned into fertilizer, but prior to being turned into fertilizer it is transformed into either phosphoric acid (through the wet process) or elemental phosphorus (through the thermal process). This processing concentrates NORM in the waste products, transforming them into TENORM.
- The primary waste byproduct of the wet-acid process is phosphogypsum.
- The primary waste byproduct of the thermal process is phosphate slag. Phosphate slag's high carbonate content renders slag to become less susceptible to radionuclide leaching than phosphogypsum.

How much TENORM is in the waste material?

TENORM Contaminated Waste	Ra-226 (pCi/g)	U-238 (pCi/g)	Th-232 (pCi/g)	Pb-210 (pCi/g)	Po-210 (pCi/g)
Phosphogypsum (Florida)	7.3 - 37	0.59 - 12	0.30	9.4 - 50	9.6 – 48
Slag (USA)	11 - 41	12 - 60	0.24 – 1.1	1.5	0.84

Source: IAEA, 2003 Technical Reports Series No.419

Where do the TENORM wastes go?

- The phosphate extraction industry is concentrated primarily in the southeastern U.S. with Florida, North Carolina, and Tennessee being the largest producing States. Idaho is the primary western production State.
- The phosphogypsum and slag wastes are stored in "stacks" located near the production facilities.
- Phosphogypsum stacks are of considerable size, ranging from 2 to 324 hectares (800 acres) in surface area and 3 to 60 meters in height. [EPA, 2015]
- The majority of the phosphogypsum waste product is located in the State of Florida due to Florida accounting for 90% of the domestic production.
- There are currently about 1 billion tons of phosphogypsum stacked in 24 stacks in Florida and about 30 million new tons are generated each year. [FIPR, 2016]

- The fertilizer industry is aware of the disposal and lack of beneficial use issues involved with phosphate fertilizer production and waste disposal. The industry is actively researching beneficial uses for the vast amounts of phosphogypsum waste that is in stacks.

  Disposal Facilities

  - The method of phosphogypsum disposal is placing the phosphogypsum into stacks on the land near the production facility. EPA regulates radon emissions from these stacks.

  Beneficial Use

  - The phosphate slag can be beneficially used in highway and general construction.
  - Phosphogypsum has limited beneficial uses, but can be land applied as a fertilizer under certain conditions.

How are the TENORM wastes regulated?

- Because of concerns over elevated radionuclide concentrations in phosphogypsum, on June 3, 1992, EPA issued a final rule stating: "Phosphogypsum intended for agricultural use must have a certified average concentration of radium-226 no greater than 10 pCi/g. There is no limitation on the amount of material that can be applied and farmers do not have to maintain certificates or application records." [EPA, 2015]
- The EPA banned the use of phosphogypsum in Portland cement mixtures for use in road construction on June 3, 1992.
- Since 1977, the State of Idaho has banned the use of phosphate slag in the construction of habitable structures; phosphate slag is still used as an aggregate in road construction.
- EPA must approve alternate uses of phosphogypsum (other than agricultural uses for Ra-226 less than 10 pCi/g and indoor research using limited quantities). Information on the process for obtaining approval can be found at https://www.epa.gov/radiation/subpart-r-resources .

References

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International Atomic Energy Agency, Technical Series Report No 419, *Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation*, December 2003.

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U.S. Geological Survey (USGS), USGS Fact Sheet 155-99, *Fertilizers – Sustaining Global Food Supplies*, September 1999.

APPENDIX C5
TENORM WASTE IN SEWAGE TREATMENT PLANTS

How are Sewage Treatment Plants used?

- Publicly Owned Treatment Works (POTW), or sewage treatment plants, are necessary for society in order to treat and manage waste and wastewater.

How is Sewage Sludge produced?

- The product of POTWs is sewage sludge.
- Both POTWs and domestic (septic systems) contribute to producing sewage sludge. Septic tanks are emptied periodically and taken to a POTW or are land applied.
- Some sewage sludge is dried to form a cake, while other POTWs produce liquid sludge that can be applied directly to farm fields.

Where does the NORM come from?

- Radionuclides in ground water, such as radium, uranium and thorium, occur naturally. They are present at least to some extent in almost all rocks and radium, in particular, dissolves more readily into ground water in contact with sands or soils. The acidity of the water, which may be increased by the presence of elevated levels of nitrates associated with agricultural land use, is believed to increase the amount of radium that dissolves into ground water from contact with sands and soils. Different pH levels affect which nuclides will dissolve, for example, some forms of uranium will dissolve in higher pH.

Where is the TENORM found?

- Water that is used by consumers eventually ends up in a POTW or septic tank. If a water treatment system is installed to reduce the amount of radium or uranium in drinking water, backwashing of this system results in concentrated levels of radionuclides. However, even if the water is not treated, some radionuclides, particularly radium, tend to be attracted to the solids, where they eventually end up in sludge.

How much TENORM is in the waste material?

TENORM Contaminated Waste	Ra-226 (pCi/g)	Ra-228 (pCi/g)	Ra-224 (pCi/g)	Th-232 (pCi/g)	U-238 (pCi/g)	U-234 (pCi/g)
POTW sludge	ND – 47	ND-38	ND-12	0.02-1.6	0.18-26	0.18-44
Incineration Ash	ND - 22	0.65 - 30	ND – 4.9	ND – 1.7	0.8 – 74	1.2 - 91

Source: ISCORS national survey

Where do the TENORM wastes go?

Disposal Facilities

- Incinerators
- Landfills
- Land Application for Reclamation

Beneficial Use

- Land application for agricultural use

How are the TENORM wastes regulated?

- Federal and State regulations apply to the amount of radium and uranium that is allowed in drinking water and thus requires treatment to remove.
- Some treatment systems discharge concentrated levels of radionuclides as waste from backwashing and regeneration. Discharge limits for discharges to water, air, and sewage treatment plants are in 10 CFR 20 Appendix B.

References

New Jersey Department of Environmental Radiation, “A South Jersey Homeowner’s Guide to Radioactivity in Drinking Water: Radium”, April, 2004.

Interagency Steering Committee on Radiation Standards, Assessment of Radioactivity in Sewage Sludge: Radiological Survey Results and Analysis, EPA 832-R-03-002, November, 2003.

Interagency Steering Committee on Radiation Standards, Assessment of Radioactivity in Sewage Sludge: Recommendations on Management of Radioactive Materials in Sewage Sludge and Ash at Publicly Owner Treatment Works, EPA 832-R-03-002B, February, 2005.

National Council on Radiation Protection and Measurements, Report No. 160, Ionizing Radiation Exposure of the Population of the United States, March 3, 2009.

APPENDIX D
TENORM IN FLORIDA ZIRCON SAND AND FLOUR

An Assessment of TENORM in Florida Zircon Sand and Flour in a New Jersey Bio-medical Device Manufacturer

NOTE: This example is provided as a reader case study. Other studies (e.g., IAEA) found that there are parts of the process that can yield occupational exposures and also significant groundwater contamination.

I. Introduction

Radium, uranium, and thorium are present in zircon sand. According to the Material Safety Data Sheet, Florida zircon sands contain 110 pCi/g combined uranium and thorium or 0.044% by weight (440 ppm) and radium less than or equal to 120 pCi/g. New Jersey regulations (N.J.A.C. 7:28-4.3(a)5) require licensing of TENORM if a person possesses greater than 5 pCi/g Ra-226 + Ra-228. A New Jersey manufacturer of artificial joints that uses zircon sand and flour requested an exemption from this regulation. The NJ Bureau of Environmental Radiation first required a study to assess worker and landfill worker exposure levels. The results of that study are presented below.

II. Manufacturing Process

The process involves building a ceramic shell over a wax model of the parts to be cast. The shell is developed by dipping the wax model into an aqueous slurry. Zircon sand and flour are received in bags. The flour is dumped into a vat for the wet slurry dipping while the zircon sand is used in the manual rainfall sander between dippings. The dipping and sand application process is repeated until the ceramic shell reaches its desired thickness to withstand the casting process. The shell is de-waxed and the joint is cast inside the shell using CoCrMo Ingots. After the joint is made the ceramic shell which contains the TENORM is “Knocked-out.” This knock-out waste containing diluted zircon flour and sand, colloidal silica, cobalt aluminate, fused silica, carbon, and molochite (alumino-silicate) is collected and disposed of in a landfill.

III. Materials and Methods

The zircon flour, sand and the knock-out waste were analyzed by gamma spectroscopy by a NJ certified laboratory.

External radiation surveys were conducted at various locations in the plant where zircon sand and flour were used as well as background locations outside the facility.

Personal air samples as well as area air samples were taken during the first shift for three days. The personal air samplers were started at the beginning of the shift, collected at the end of the shift and kept in a secured office away from all zircon activity between sampling.

Radon in air was not sampled because of well-documented low exhalation rate for zircon (NUREG 1717). New Jersey has experience with other zircon applications and was aware of the low exhalation rate of zircon.

IV. Results

A. Zircon Sand and Zircon Flour

The average concentrations of the zircon feed material and knock-out waste are presented in Table 1. Based on the literature, U-238 was in considered to be in equilibrium with U-234 and Ra-226, and Th-232 was considered to be in equilibrium with Ra-228.

Table 1: Concentrations from October 2013 sampling (pCi/g)

Material	Ra-226	Ra-228
Zircon Sand (3 samples)	82.1	12.2
Zircon Flour (3 samples)	93.7	12.9
Knock-out Waste (4 samples)	12.1	3.8

B. Direct Gamma External Measurements

The results of the exposure measurements are presented in Table 2.

Table 2: Ambient Exposure Rates Used to Estimate Annual External Dose Equivalent

Location	Ambient Exposure Rate uR/hr
Outside building by dust collector	7.48
Manual dip (middle of work area)	14.20
Manual dip (directly beside dip tank)	20.50
Manual dip (contact with slurry inside tank)	75.60
Automated robot dip (outside cage)	21.10
Exit from shell dry chamber	12.10
Shell room (by wash tanks)	7.10
Knockout	4.57
Kiln furnace (input side)	12.10
Main warehouse corridor in front of zircon storage	10.60
Zircon storage (in contact with zircon)	266
Slurry mixing station in shell room	25.20
Shell room supervisor computer station	6.72
Wax assembly room (by door to shell room)	4.83

C. Personal Air Samplers (PAS)

The results of the filters from the personal air samplers are presented in Table 3.

Table 3: Alpha Spectroscopy Results of PAS filters (pCi/L)

Sample	Th-228 (Th-232)	Th-230 (U-238)	Th-232	U-234 (U-238)	U-235 (U-235)	U-238
1	3.8E-5 $_{MDC}$	6.9E-5$_{MDC}$	1.24E-5$_{MDC}$	1.7E-5±1.2E-5	5.3E-6±8.7E-6	1.4E-5$_{MDC}$
2	5.5E-5$_{MDC}$	7.5E-5$_{MDC}$	2.18E-5$_{MDC}$	1.8E-5$_{MDC}$	1.64E-5$_{MDC}$	1.4E-5$_{MDC}$
3	7.3E-5$_{MDC}$	8.9E-5$_{MDC}$	2.0E-5$_{MDC}$	1.18E-5±8.9E-6	1.13E-5$_{MDC}$	1.41E-5$_{MDC}$
4	4.6E-5$_{MDC}$	7.1E-5$_{MDC}$	1.69E-5$_{MDC}$	2.2E-5±1.2E-5	1.72E-5$_{MDC}$	1.0E-5$_{MDC}$
5	4.4E-5$_{MDC}$	7.4E-5$_{MDC}$	1.41E-5$_{MDC}$	6.4E-5±2.2E-5	1.2E-5$_{MDC}$	1.5E-5±1.2E-5 (same as MDC)
6	-	-	-	-	-	-
7	3.7E-5$_{MDC}$	7.2E-5$_{MDC}$	1.24E-5 ± 9.6E-6			

Worker #6 PAS was not analyzed as this worker was not working directly in the vicinity of the zircon.

Consideration was made of the U-238: Th-232 ratio observed for zircon sand. Ratios were applied to alpha spectroscopy data in order to conservatively yield predicted Th-232 activity concentrations where no thorium isotopes are reported above the MDC.

V. Radiation Exposure Assessment

A. Landfill Worker Exposures

Because the knock-out waste is sent to a landfill for disposal, the Department requested that a dose assessment be performed to ensure that landfill workers were not receiving doses in excess of the public dose limit. Before proceeding to a landfill, the knock-out waste is first sent to a transfer station. An assessment was also performed for the transfer station workers. RESRAD Build was used to determine dose to the transfer station worker and RESRAD 6.5 was used to determine dose to the landfill worker. The results of the transfer station worker were less than 0.1 mrem per year. The results of the landfill worker assessment were 0.6 mrem/y and 0.3 mrem/y for two different landfills.

B. Worker Exposures

Using the exposure measurements and occupancy factors, the Effective Dose Equivalent of workers were determined and shown in Table 4.

Table 4: EDE Derived from Area Survey x Occupancy (corrected for background)

Worker	mrem/y	mSv/yr
Worker #1	1.17	0.0117
Worker #2	±Background*	±Background
Worker #3	6.24	0.0624
Worker #4	6.01	0.0601
Worker #5	1.33	0.0133
Worker #7	1.33	0.0133

*Reported as ± Background to avoid a negative number. Worker #2 estimated EDE is below annual background EDE of 15.83 mrem/y

Using the results of the filter analyses of the PAS and assuming Th-232 concentrations based on the U-238: Th-232 ratios, the Committed Effective Dose Equivalent for each worker was determined as shown in Table 5.

Table 5: CEDE Derived from Alpha Spectroscopy Data

Sample (corresponding Worker)	mSv/y	Mrem/yr
1 (Worker#1)	0.07	7
2 (Worker #2)	0.06	6
3 (Worker#3)	0.05	5
4 (Worker #4)	0.09	9
5 (Worker #5)	0.265	26.5
7 (Worker #7)	0.37	37

Using occupancy factors and ICRP 68 dose conversion factors for inhalation, the total effective dose equivalents were determined as shown in Table 6.

Table 6: TEDE Derived from Area Surveys, Occupancy, Inhalation Dose Conversion Factors (DCFs) and Activity Median Aerodynamic Diameter (AMAD) of 5 µm

Worker	EDE, mrem/y	CEDE, mrem/y	TEDE, mrem/y	TEDE, mSv/yr
Worker #1	1.17	7	8.17	0.08
Worker #2	±Background	6	6	0.06
Worker #3	6.24	5	11.24	0.11
Worker #4	6.01	9	15.01	0.15
Worker #5	1.33	26.5	27.83	0.28
Worker #7	1.33	37	38.33	0.38

VI. Conclusion

This study demonstrated that worker doses and doses from disposition in a landfill of this particular zircon application are below the public dose limit.