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Technologically enhanced naturally occurring radioactive materials

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11.1 Introduction

Radioactive elements ^{238}U and ^{232}Th and ^{40}K have been in the earth's crust since the formation of the planet. Natural radionuclides are composed of primordial radioactive elements in the crust at very low concentrations. Naturally occurring radioactive substances (NORM) are composed of radioactive substances brought to the surface in various concentrations for various natural reasons. If the increase in radioactivity concentrations results from human activities, technologically developed naturally occurring radioactive materials (TENORM) will generate. Therefore NORM and TENORM usually consist of decay products such as radium and radon. TENORM, resulting from human activities that intensify radioactivity, increases human and environmental risks. The main reason for this is that there are at least 400 minerals in nature containing high concentrations of natural radionuclides from the uranium and thorium decay series (Michalik, 2007). Most of the materials considered TENORM could have very low radioactivity almost at the background level. However, some have a relatively high concentration of radioactivity, which can result in high exposure. NORM and Technically Enhanced NORM (TENORM) dispersion in soil, groundwater, and surface water cause various contamination problems. TENORM sources and potential effects differ from site to site depending on the risk to which they are associated (Abdel Rahman et al., 2014a). Uranium-238, commonly found in rocks, soil, and the environment, decays to form radium-226 with a half-life of 1600 years. Radium-226 then decays to form the radon-222 gas with a half-life of 3.8 days. Radiological risks from TENORM are caused by the presence of natural radioisotopes and decay products. The

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main radioisotopes that commonly cause dose exposure are uranium, thorium, and potassium. In particular, radium and its decay product radon are the most important radioisotopes in terms of radiological risk. A usual natural background level of radium-226 in soil is about 0.04 Bq/g. The potential risks should be evaluated by characterizing TENORM by considering the potential risks specific to the location. First, TENORM's radioactivity levels should be compared with the exemption concentrations of TENORM emissions and the level of dose exposed due to TENORM should be compared with an average worldwide exposure of 0.07 mSv/y and within the recommended level of exposure 1 mSv/y for the public (IAEA, 1996). If the dose is 1 mSv per year or less when exposed to TENORM, the general criterion for exemption is considered to be met. Research on industrial activities involving TENORM indicates that the dose received by a member of the public living near a facility is generally no more than a few microsieverts per year, exceptionally up to about 100 μSv/y (UNSCEAR, 2000), and is consequently only a small fraction of the dose that could be received by a worker. Therefore a decision on exemption can generally be made by considering only the doses received by workers (International Atomic Energy Agency, 2006). The National Council on Radiation Protection and Measurements (NCRP) Report No. 116 (NCRP, 1993) contains recommendations on limitation of exposure of workers and the public to ionizing radiation. For human-made sources, the recommended annual dose limits for individual members of the public are 1 mSv (100 mrem) for continuous exposures and 5 mSv (500 mrem) for infrequent exposures. Exposures of the public should be justified (no exposures without expectation of benefit) and should be "as low as reasonably achievable" (ALARA). It is also recommended that if a single site could potentially expose members of the public to more than 25% of the dose limit, the operator should ensure that the annual dose from all human-made sources does not exceed 1 mSv (100 mrem). The International Commission on Radiological Protection Publication 60 (ICRP, 1991) contains recommendations on limitation of exposure to ionizing radiation for both workers and the public. The International Atomic Energy Agency (IAEA) guidance on radiation protection of the public is contained in the basic safety standards (IAEA, 1996). Those standards include two provisions that are applicable to TENORM. The standards encourage the regulation of some exposures to TENORM as practices with their being subjected to the annual dose limit of 1 mSv (100 mrem) from all sources combined. IAEA's standards include recommendations for the exemption from regulatory control of TENORM-containing

low-activity concentrations and low total activities, as indicated in the statements on the "Requirements for Practices." The exemption levels for naturally occurring radionuclides were developed on the basis of the following considerations:

- The annual effective dose for individual members of the public from the exempted practice or source should not exceed about 10 μSv (1 mrem).
- The annual collective effective dose from the exempted practice or source should not exceed about 1 person-Sv (100 person-rem).
- A series of bounding exposure scenarios for use and disposal are assumed.
- The application of exemption to natural sources, where these are not excluded, is limited to the incorporation of naturally occurring radionuclides into consumer products, their use as a radioactive source, or for their elemental properties.

The first two considerations are taken from previous IAEA recommendations on exemption principles (IAEA, 2003a). The last consideration indicates that the exemption levels for naturally occurring radionuclides apply only to intentional and beneficial uses of these radionuclides and therefore do not apply to residual radioactive materials or other wastes containing TENORM.

For the most important naturally occurring radionuclides other than radon, the recommended exemption levels are as follows:

- For natural uranium or thorium, an activity concentration of 1 Bq/g and a total activity of 1000 Bq.
- For 226 Ra, an activity concentration of 10 Bq/g and a total activity of 10000 Bq.
- For 228 Ra, an activity concentration of 10 Bq/g and a total activity of 100000 Bq.
- For 210Pb, an activity concentration of 10 Bq/g and a total activity of 10000 Bq.

The physical, chemical, and radiological characteristics of TENORM vary from one industrial process to another and even from one site to another. Effective measures should be taken to protect people and the environment from unnecessary exposure to TENORM-induced radiation. Technologically developed naturally occurring radioactive materials are generated from concentrated or exposed media as a result of human activities such as production, mineral extraction, or water treatment. The mining and mineral processing, oil and gas extraction, the fertilizer industries and the use of fossil fuels have the potential to produce large amounts of residues or waste, resulting in TENORM. For

example, various dose scenarios for exposure to NORM have been identified in dose assessments for activities related to the processing and use of phosphates in Cuba, and it has been stated that doses less than 0.3–2.7 mSv/y and 17 μSv/y for employees. In oil extraction activities, associated doses for oil industry workers range from 0.3 to 1.3 mSv/y. In the refractory brick factory, it was reported that workers are exposed to doses between 0.08–0.2 mSv/y (Zerquera et al., 2006). If these residues and wastes are not managed properly and safely, TENORM will be created in large areas, causing unnecessary natural radiation exposure to the public. For this reason, it has become important to determine the TENORM production sites and take necessary measures. Studies should be carried out in three stages to identify risks and take additional measures. These are the identification of TENORM-producing industries, their potential exposures, and characterization of TENORM. An exemption level of 10,000 Bq/kg for TENORM waste is recommended in the IAEA safety standards (IAEA, 2003b; Gesell and Prichard, 1975).

11.2 Technologically enhanced naturally occurring radioactive materials industries and main sources

Radionuclides of natural origin are present in most material, the most common being the radionuclides of the uranium and thorium series and ^{40}K. TENORM is produced by many industries in various types and quantities. Due to the different types of TENORM, potential radiation exposure risks must be assessed site-specific depending on the conditions. The main sources of TENORM wastes include oil production, gas production processes, mining and mineral processing, and various industrial activities and water treatment. The major industrial sectors that generate TENORM are as follows;

Mining and mineral processing
Bauxite and alumina production
Oil and gas production
Coal combustion residuals
Water treatment
Fertilizer and fertilizer production

In these industries various processes containing natural minerals that contain natural radioisotopes lead to the formation of TENORM. TENORM resulting from these residues leads to scale accumulation on the inner surfaces of the process equipment.



Figure 11.1 TENORM scrap waste.

These residues accumulate with the pressure and temperature changes occurring in production pipes, wells, valves, pumps, separators, water treatment vessels, gas treatment vessels, and oil storage tanks. A typical metal scrap waste as TENORM is presented in Fig. 11.1.

11.2.1 Mining and mineral processing

Mining is a mechanical process in which mineral ores or coal are extracted from the earth's crust. During the processing of mineral ores and fossil fuels containing uranium and thorium series elements, these radionuclides can be found as residues, which leads to greater exposure of the public to natural radiation (UNSCEAR, 1988; Baxter, 1996). Uranium mining and processing wastes are not included in this chapter because they are a component of the nuclear fuel cycle. TENORM sources in mining activities are generally rare earth-rich monazite sands, phosphate rocks, gold, lead, silver, copper, tin, tantalum, and niobium associated with uranium and thorium (Paschoa and Godoy, 2002). The iron and steel industry produces a large number of different types of waste. The radiological risk in the iron and steel industry is mainly due to ^{210}Pb and ^{210}Po radionuclides. Both radionuclides are enriched by thermal processes in the iron and steel industry (Khater and Bakr, 2011).

In oil and gas production, the natural radioisotope decay products ^{226}Ra, ^{228}Ra migrate from the reservoir rock and

appear in the water produced with oil and gas. Radionuclide activity concentrations in various thermal processes are given in Table 11.1 (IAEA, 2013).

During the smelting of natural raw materials at high temperatures radioisotopes in the materials cause the formation of TENORM as furnace slag, ash, or dust. Typical radionuclide activity concentrations in smelting are given in Table 11.2 (IAEA, 2013).

Natural radionuclide concentrations in mines are presented in Table 11.3 based on data from Polish mining activities (Skowronek et al., 2005). Some radium concentrations are above 50 Bq/kg for the earth's crust. This level is specified by UNSCEAR.

High activity concentrations of some terrestrial naturally occurring radionuclides such as ^{226}Ra and ^{232}Th were found in

Table 11.1 Radionuclide activity concentrations in various thermal and chemical processes.

Industrial process	Radionuclide	Radioactivity concentration (Bq/g)	
		Minimum	Maximum
Oil and gas	^{226}Ra	0.1	15000
Phosphoric acid	^{226}Ra	0.03	4000
Titanium dioxide	^{226}Ra	<1	1600
Zircon	^{226}Ra	–	>5000
Coal-fired steam generator	^{210}Pb	–	>100
Coal mining	^{226}Ra and ^{228}Ra	–	200

Table 11.2 Typical radionuclide activity concentrations in various smelting and thermal processes.

Mineral smelting/thermal process	Radionuclide	Radioactivity concentration (Bq/g)	
		Minimum	Maximum
Niobium	^{232}Th	20	120
Tin	^{232}Th	0.07	15
Copper	^{226}Ra	0.4	2
Phosphorus	^{238}U	0.5	1.9

Table 11.3 Maximum concentrations of radionuclides in polish mining industries.

Product activity (Bq/kg)	^{226}Ra	^{228}Ra	^{40}K
Hard coal	159	123	785
Coal waste rock	122	106	1797
Underground scales	204127	83785	14815
Copper ore	75	20	466
Copper waste rock	53	43	676
Copper scales	1340	68	1108
Copper slag	530	183	1459
Zinc ore	21	17	65
Zinc waste rock	40	17	194
Scales	76	61	---

Table 11.4 TENORM types and activities in the Netherlands.

Industry	Waste/residue	Activity concentration (Bq/g)
Oil and Gas production	sludge	Up to 25 ^{226}Ra/^{228}Ra Up to 250 Pb/Po
Phosphorus production	Slag	1 ^{238}U
Phosphoric Acid production	phosphogypsium	0.5 ^{226}Ra
Steel production	Slag	0.15 ^{238}U 0.15 ^{232}Th
Coal combustion	Fly ash	0.050.2 ^{238}U 0.060.3 ^{232}Th

industrial waste samples of bauxite, alumina, and aluminum slag waste (Abbady and El-Arabi, 2006). TENORM in the aluminum industry is formed in red mud and sand samples, which are the residues of the Bayer process in the aluminum industry (Valeria et al., 2011).

The most important residues and waste streams from TENORM industries in the Netherlands are summarized in Table 11.4 (Van Der Steen, 2006).

Naturally occurring radioactive materials such as ^{238}U series, ^{232}Th series, and ^{40}K and their decay products occurring during



Figure 11.2 Residual accumulation in a pipe.

mining and production of phosphate rocks can be concentrated in various places and contain high radioactivity. Therefore radiological effects from TENORM may be important in some phosphate production plants (Khater and AL-Sewaidan, 2008).

In the phosphate industry, since phosphate ore naturally contains uranium, radioactive residues accumulate in the screens, pipes, storage tanks, mixers, and valves of phosphate plants. A typical residue accumulation in a pipe is presented in Fig. 11.2.

Since the phosphoric acid waste treatment plants contain ^{226}Ra radioisotopes, the wastes emerge as TENORM. During physical and chemical processes, especially leaching and purification processes are effective in TENORM radioactivity concentration (El Afifi et al., 2010). There are three main processes in the phosphate industry: wet processing, thermal processing, and fertilizer production. Phosphogypsum generates as a byproduct of wet processing, and slag waste comes out during the thermal processing stage.

11.2.2 Oil and gas production

TENORM in petroleum production is caused by the precipitation of alkaline earth metals such as sulfate, carbonates, and

silicates in drill pipes or other metal surfaces. Researchers have reported seeing radioactive scales accumulated in tubes used in some operations in the oil industry as a source of occupational hazards (Kolb and Wojcik, 1985; Heaton and Lambley, 1995). It has been reported that activity concentrations in offshore oil production facilities are at 3×10^2 kBq/kg (Kvasnicka, 1996; Paschao and MacDowell, 1996). Pressurized water mixed with sand and chemicals is injected into rock formations for oil and natural gas production through drilling and rock fracturing processes. During this process, cracks are formed that move the underground radioactive material from its natural environment. These natural radioactive elements come into contact with liquids and equipment that come to the surface during production. Materials contaminated in this way become TENORM, which creates occupational health risks in the oil and gas well fields. The solid scale, mud, and water produced are typical deposits contaminated with natural radionuclides and range between 3700 and 168 kBq/kg for solid scale and mud, respectively. The TENORM generated from oil and gas production facilities: Drill bits and pipes, mud, water, filtration equipment, contaminated parts. Sludge from the petroleum industry, which is formed as waste on the surface during oil and gas production, is an important source of ^{226}Ra around the facility. Disposal of contaminated oil pipes and materials around such facilities poses a serious internal and external radiation hazard for employees.

Majority of naturally occurring radioactive materials are produced in the form of waste, with the increase in the number of oil and gas production facilities. The average activities of both radionuclides exceed the 10,000 Bq/kg exemption level recommended by the IAEA safety standards. This means that TENORM wastes from the oil industry can produce radiation exposure levels that require attention and constant monitoring during routine processes in this industry. This exposure is mostly caused by ^{226}Ra radionuclide and external gamma radiation from their progeny (Bou-Rabee et al., 2009).

Drilling mud that comes to the surface during the rock-breaking method, which is widely used in natural gas production, is collected in waste pools. Waste pools are widely used in traditional natural gas extraction areas. The main purpose of the waste pools is to hold the required amount of water and drilling mud for hydraulic breakage. These waste pools contain TENORM, which includes natural underground radioisotopes and its decay products.

11.2.3 Coal combustion

Coal and coal types (lignite, anthracite) are widely used as fuel to generate heat in energy production and industrial applications. The coal contains natural radioisotopes and as a result of coal combustion, radioactive substances mostly accumulate in fly ash, bottom ash, and boiler slag. The fly ash, bottom ash, and boiler slag formed as a result of the combustion process become approximately 10%–20% TENORM. As a result of the combustion of coal, residues containing concentrated naturally occurring radiation materials, also called TENORM, are formed. The most common radionuclides found in coal combustion residues and their decay products are uranium, thorium, potassium, and radium.

As a result of the burning of coal, three main wastes are formed:

- Fly ash consists of small particles (typically 10–100 μ in diameter) that can be transported by hot flue gases. It is the most common type of waste resulting from coal burning.
- The lower ash contains large particles that cannot be carried by the hot flue gases and is collected at the bottom of the combustion boiler.
- Boiler ash forms the slag remaining in the boiler as it forms a melt under intense combustion heat.

Depending on the carbon content of the coal, approximately 10% of its original volume remains ash after combustion. This remaining ash contains on average 74% fly ash, 20% bottom ash, and 6% boiler slag (Dinis et al., 2014).

11.2.4 Water treatment

There are natural radioactive elements in waters with varying concentrations. After purification in water treatment plants, radioisotopes are concentrated in purification resins and sludge. Radioactivity of waters is depend on the characteristics of surrounding geological formation. Technologically enhanced naturally occurring radioactive materials are generated as a result of active treatment of drinking water containing uranium (according to the new WHO recommendations for U content in drinking water) and the accumulation of radioisotopes on filter sands in mineral waters or drinking water facilities for a long time.

Water supplied from surface watersheds and groundwater sources must be purified from ^{238}U, ^{232}Th, ^{226}Ra, ^{222}Rn, and ^{210}Po radioisotopes before use. Surface water treatment

processes include sedimentation, coagulation, flocculation, and filtration, while groundwater cation exchange is purified using methods similar to reverse osmosis, activated charcoal. or surface water treatment. The waste products produced as a result of treatment include sediments and sludge, filtration media, exhausted ion exchange resin, backwash, and wastewater. High residual radionuclide concentrations have been identified in these waste products. These should also be handled and controlled as TENORM waste (Kleinschmidt and Akber, 2008; UNSCEAR, 2000).

Among the constituents of TENORM deposits in the liquid phase are (1) contaminated water extracted from mines; (2) "produced water," which contains the mixture of rock formation water and injection water during oil and gas production; (3) excess water from the heaps such as waste dams and phosphogypsum waste heaps; (4) used process water, including water separated from the slurry streams, washing water, flotation water, used leaching solutions and gas washing water; (5) water from the equipment's decontamination; and (6) spent solvents.

Such aqueous wastes generally occur in very large quantities. Oil production plants produce 40,000 m^3/d wastewater. Gas production facilities produce much less at 1.5–30 m^3/d. Radionuclide activity concentrations in wastewater vary over a wide range. For example, ^{226}Ra concentrations produced in oil and gas plants range from 0.002 to 1200 Bq/L (IAEA, 2013).

11.3 Management of technologically enhanced naturally occurring radioactive materials

Waste management options depend on both technical and nontechnical factors. The most important technical factors include the suitability of the land used in the disposal programs for NORM-containing residues, the availability of the land, NORM wastes, climate, geology, water, disposal site, environment, volume of the material, the state of the physical material, and the current and future production rate of the material. Nontechnical factors include national policies and the legal framework; socioeconomic aspects; implementation and management resources (human, technical, and financial); cultural aspects; and the public's perception of risk on public reuse facilities and the effectiveness of proposed disposal

facilities. Generally, hazards associated with TENORM radiological contaminants occur through three mechanisms: direct exposure to external radiation; radiation exposure due to inhalation of pollutants; and radiation exposure due to ingestion of radioactive pollutants. The worldwide average dose rate values range from 18 to 93 ηGy/h and the population-weighted average absorbed dose rate is approximately 60 ηGy/h (UNSCEAR, 1993). The acceptable total absorbed dose rate due to gamma radiations by occupational radiation dose and absorbed by the staff operators surrounded by materials containing radionuclides of ^{226}Ra, ^{232}Th and ^{40}K should not exceed the average world value of 0.055 μgy/h (UNSCEAR, 1993). Besides, doses to members of the public from intake of radionuclides from radioactive materials are described by the International Commission on Radiological Protection (ICRP, 1996). TENORM waste management principles are the same as traditional waste management principles. Factors such as the availability of appropriate technology, cost, and public acceptance are all considerations when choosing the right TENORM waste management method (Kunze et al., 2007).

11.3.1 Technologically enhanced naturally occurring radioactive materials generation

Controlling of the generation of radioactive waste covers avoiding the occurrence of TENORM and minimizing its formation. If there is another method or technology to reduce TENORM generation, it must first be evaluated and implemented. The main principles of radioactive waste management are the most obvious and effective ways of minimizing the amount of TENORM resulting from waste minimization, recycling of NORM residues, or use as byproducts. Another method of reducing the amount of TENORM is by using additives, inhibitors, and chemical or physical decontamination processes or by changing the industrial process. Such waste reduction techniques can be applied to both existing operations and new operations. Another important way to minimize TENORM formation is to take advantage of the cleaning mechanism as much as possible so that residues can be disposed of as normal industrial waste instead of TENORM waste. Volume reduction can be applied by compaction or decontamination operations. For example, surfactants can be used as extracting agent for the removal of radium radionuclides from TENORM sludge waste in the petroleum industry.

11.3.2 Technologically enhanced naturally occurring radioactive materials management

The development and implementation of a TENORM management strategy can be accomplished in three stages: (1) Identification, characterization, and evaluation of existing situations involving the production of TENORM in the past, present, or future, including old sites contaminated with TENORM; (2) Evaluation of TENORM management options and selection of the optimum option for both current and future TENORM waste; and (3) Application of the optimum option for each TENORM stream. The basic TENORM management stages are given in Fig. 11.3.

Pretreatment of waste is an important stage of waste management and is the first step in waste management after waste generation. In the pretreatment phase, TENORM collects in a certain area, and physical or chemical separation is performed, and then decontamination is applied. Pretreatment can facilitate the minimization of waste by providing a significant part of TENORM to be cleaned. Pretreatment of TENORM waste allows the selection

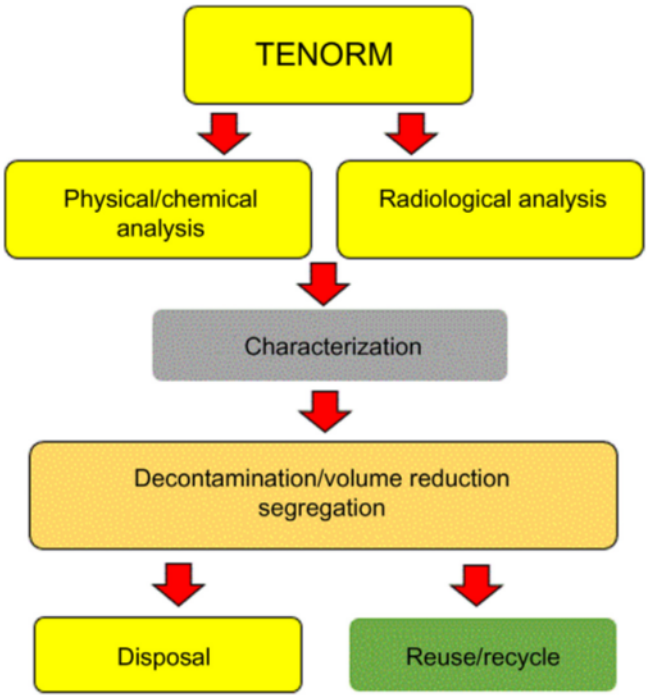

Figure 11.3 TENORM management stages.

of suitable methods for different types of TENORM. The main treatment methods are volume reduction, radionuclide removal, and composition replacement. Volume reduction is consistent with the "concentrate and containment" approach, one of the radioactive waste management principles. This process facilitates the transportation and treatment of waste due to volume reduction but increases the concentration of radionuclide.

Generally, volume reduction techniques for solid TENORM include combustion and compression. The volume reduction process in liquid wastes can be carried out using techniques such as radionuclide removal, evaporation, filtration, or ion exchange. Certain chemical species may need to be precipitated or agglomerated to remove radionuclide in the composition of a liquid waste stream. As a result of the treatment of liquid waste streams, these processes cause various secondary and higher activity waste outputs that need to be managed, such as dirty filters, used resins and sludge. Dilution of radioactivity is also among the methods used. For this, it is mixed with nonradioactive material and dilutes the radionuclide content, thereby reducing the concentration of activity. For some TENORM waste dilution with another nonradioactive material can be an option to avoid other much costlier and difficult disposal options.

The conditioning of radioactive waste, which is an important stage of radioactive waste management, involves processes that turn the material into a form suitable for handling, transport, storage, and disposal. Conditioning stage is usually accomplished by immobilizing the material against environmental influences, placing it in safe containers and packaging it as a secondary barrier. Matrix materials such as cement, bitumen, and polymer are commonly used for immobilization of liquid-form TENORM. Depending on the nature and concentrations of the radionuclides in TENORM taken into solid form, they are stored in different types of containers. Various containers are designed according to their radiation protection levels. Treatment and conditioning should be carried out in conjunction with each other in accordance with the principles of waste management. Conditioning is not used for solid-form TENORM waste because the material is generally suitable for the necessary physical processing.

TENORM storage may be required at any stage of waste management. For example, large quantities of TENORM from mines and phosphogypsum from phosphate plants should be stored in the areas where they are produced, because transporting them off-site is very expensive and destructive and may bring additional health, safety, and environmental risks.

11.3.3 Technologically enhanced naturally occurring radioactive materials recycling

Separation or cleaning of radioactive parts is generally a convenient solution for TENORM recycling. In addition other methods are available for recycling. Certain conditions must be appropriate for this to be implemented economically. For example, metal parts that have been cleaned or separated from radioactive parts can easily be recycled. However, a costly pyrometallurgical process technology may be required to clean a contaminated metal.

Decontamination ensures that radiological contamination is removed from the surfaces of the facilities and equipment by various chemical and physical techniques, thus achieving the following objectives.

- Reducing radiation exposure
- Enabling reuse of facilities and equipment
- Reducing the amount of material (equipment, construction, and related debris) requiring expensive disposal
- Restoring a site or facility to productive use
- Removing contaminants prior to return to use, further treatment, modifications, protective storage, or longer-term management and disposal
- Reducing the amount of residual radioactivity to protect public and worker health and safety and the environment

An operation for restoring a site for further use is presented in Fig. 11.4.



Figure 11.4 Restoring operations at a site for further use.

In the decontamination process, treatment of surface contamination includes activities that remove or stabilize the material on the surface. These may include the various washing or abrasive technologies that remove the contaminant from the surface. From an environmental protection standpoint, treatment may include: stabilization (e.g., fixation), thermal treatment, dehalogenation, soil washing, etc. This method typically does not include waste capping in place by itself. The stabilization technology reduces the mobility of the contaminant, for the most part it does not do so by treating the actual contaminated media (US EPA, 2006).

In case of very low radionuclide activity concentration of any natural material can be used safely as building materials. Those with high activity concentrations from rock residues can be used for the construction of waste sets. Phosphogypsum wastes, in particular, have wide commercial use in agricultural applications such as soil conditioner and soil correction and in construction applications such as drywall, fiber reinforced panels, cement additive (2%–5%), and bedding material in road construction (IAEA, 2013). Due to low-activity concentrations, TENORM reuse from phosphogypsum generally has no significant radiological effects. Therefore it can be used as lining or lining material in garbage storage facilities and marine protection applications. The physical and chemical properties of the metallurgical furnace slag prevent the radionuclides from leaking easily into the environment. Therefore furnace slag can be used as garbage filling material and construction material. However, a risk assessment may be required, especially when used in building construction. It is possible to use kiln slags with relatively low-activity concentrations such as copper smelting, iron and steel melting, scrap metal recycling. and elemental phosphorus production without restrictions in road and dam construction. Kiln slags remaining from iron and steel production can be diluted with low-activity residues such as fly ash and used as cement, concrete, and brick additives.

There are several potential uses for red sludge that occur during the processing of bauxite mineral with the Bayer process. TENORM generation from Bayer process can be used as additives in brick or ceramic production. It can also be used as a soil conditioner and for landfills. Metal components such as pipes, valves, and vessels can often be decontaminated for reuse. Decontamination waste should be disposed of, but in some mineral processing operations, it can now be recycled for the recovery of valuable minerals. In the chlorination of titanium-containing minerals to produce titanium dioxide

pigment, some of the unreacted material in the reactor-bed residue can be returned to the process. Solid-metal chloride residue has applications as a byproduct. It can be added to the cement to form an aggregate for construction applications or it can be processed to be used as a coagulator for water treatment. Water treatment sludge is generally used in brick and concrete production in the range of 1%–2%, although its content is low. Liquid NORM residues are generally recycled to the process that creates them. This management approach can be used for both aqueous residue streams and used solvents.

11.4 Technologically enhanced naturally occurring radioactive materials disposal

Because of their high processing costs, some of the radioactive components in TENORM cannot be economically decontaminated with the current technological possibilities. In this case, direct disposal remains the only option. Appropriate management of secondary radioactive waste is also required, even if decontamination is carried out. All these conditions can be evaluated and direct disposal can be chosen. Radiological risks should be assessed, assuming that an activity concentration of 1 Bq/g for uranium and thorium series radionuclides in a contaminated site is broadly equivalent to an annual dose of 1 mSv. Considering the radiological risks, depending on the radiation level of the site it is decided to decontaminate or secure the site for each site. Factors affecting this decision include whether the area is closed or open, the solubility of the contaminant, and the possibility of groundwater contamination. Disposal areas designed for TENORM storage may eventually become disposal facilities. For this reason, such large quantities of TENORM storages should be designed and managed accordingly. TENORM wastes produced in lower quantities are stored under the cover to protect from rain and snow as they contain loose material that is waiting to be disposed at a more convenient time in the area where it is produced or in another suitable place. However, it is essential to define and plan a suitable disposal site for TENORM formation quantities from the very beginning.

Appropriate disposal in specific sites to be improved includes a dose assessment, radiation protection, and monitoring during the improvement work, coordination of the work carried out by various experts and companies, and a postimprovement survey of the environmental media. The local population should be informed about radiological risks, and wastes resulting from

the improvement work should be disposed of in a hazardous waste storage facility or radioactive waste storage depending on radiological risk. Industrial residues containing radionuclides have been receiving considerable global attention, because of the large amounts of TENORM-containing wastes and the potential long-term risks of long-lived radionuclides.

When TENORM is disposed of it must be in compliance with the disposal facility acceptance criteria. TENORM disposal site can be a landfill or a special surface or a near-surface enclosure. This requires TENORM to be solid, nondispersible, and in passive form. Therefore TENORM may require pretreatment, processing, blending, and/or conditioning. Management options for TENORM waste produced in large quantities are limited due to these criteria. It can be managed by applying one or more of the many methods for TENORM, which occurs in small amounts. A low quantity of TENORM is relatively easy to isolate, immobilize, and transport from the environment and allows mixing (dilution) before disposal.

TENORM disposal is the last step of radioactive waste management where it is placed in a disposal facility with reasonable safety assurance, without the intention of recycling waste, and preferably without relying on long-term surveillance and maintenance. In order to limit the release of radionuclides into the environment in disposal facilities, TENORM is secured by using barriers above, below, and around the area where it is placed. Isolation is provided with a multiple-barrier system by using natural and engineered barriers. Multiple-barrier systems provide greater isolation assurance and help ensure that the release of radionuclides to the environment is at an acceptably low rate. The TENORM matrix material or the metal wall of the container in which it is placed can provide an absolute enclosure for some time as a barrier. As secondary barriers, clay layers can delay the release of radioactive materials into the environment, such as for rock-armored coatings or host rock with high absorption capacity. Barrier systems should be designed according to the disposal option selected and the characteristics of the respective radioactive waste forms. A diagram of the proposed classification scheme for radioactive waste and its method of disposal is shown in Fig. 11.5 (IAEA, 2013).

The disposal of TENORM in liquid or gaseous form can be carried out within the permissible limits by discharging into the environment and then dispensing. This approach can also be applied to some solid residues from the TENORM industries. The disposal type should provide a complete, sustainable, acceptable and

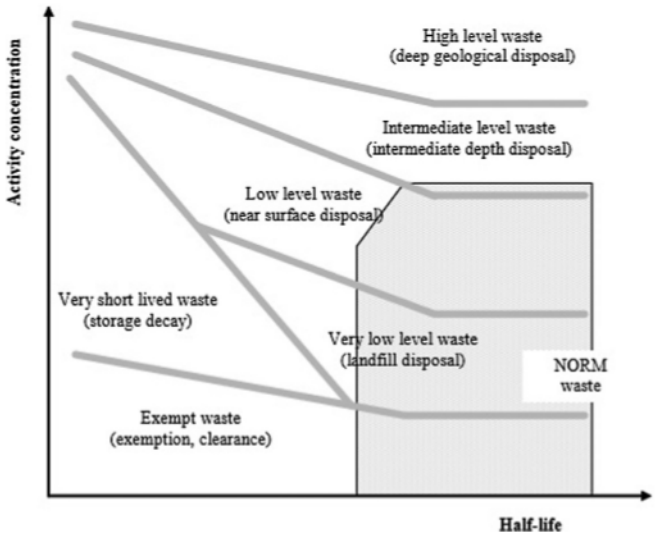

Figure 11.5 Classification scheme for disposal to NORM (IAEA, 2013).

designed a complete solution that can provide long-term security. Risk assessments should be made for each site and dose levels should be calculated for critical groups. Dose assessments of critical groups will define maximum activity concentrations based on intrusion and natural event scenarios. Radioactive pollution prevention measures should be taken into account. These measures include treaties, regulations and standards, and technical methods to control pollution. The risk-informed regulatory process has to be performed regularly, along with the technical methods to control radioactive wastes via site selection criteria, design of radioactive waste disposal facilities, and performance assessment (Abdel Rahman et al., 2014b).

This classification scheme is based on the need to further isolate the biosphere as the TENORM activity concentration increases. TENORM wastes, which usually contain very long half-life radionuclides, are generally classified as low-level waste, very low-level waste, or exempted waste. On this basis, nonexempt NORM wastes can be expected to be disposed on or near the surface in disposal facilities. In practice, the disposal option and related legislation and/or regulations will also be affected by nonradiological components such as chemicals and heavy metals. Basically two general themes should be taken into consideration related to potential environmental contamination by TENORM: implementation of proper methods for reducing the amount of all types of waste being generated and

managing all waste in a manner that protects human health and the environment.

The main principles of TENORM management are similar to the principles of radioactive waste management:

- Radioactive waste should be managed in a way that provides an acceptable level of protection to the environment.
- Radioactive waste should be managed in a way that will not impose undue burdens on future generations.
- Interdependencies among all steps in radioactive waste generation and management should be appropriately taken into account.
- The safety of facilities for radioactive waste management should be appropriately ensured during their lifetime (IAEA, 2003c).

11.5 Conclusion

TENORM presents significant problems for various industries because of its large volumes and widespread occurrence in products, byproducts, and wastes. The physical, chemical, and radiologic properties of TENORM vary widely according to its origin. In terms of radioactivity, ^{226}Ra and its decay products are the radionuclides of primary concern, but other uranium- and thorium-series nuclides should also be considered. TENORM can cause significant adverse effects on human health. When assessing these negative health effects, the magnitude and type of exposure and the threshold and dose-response as well as the toxicological effects should be taken into account. The chemical and physical properties of radionuclides in TENORM greatly affect their environmental mobility and bioavailability. When conducting an exposure assessment for TENORM, bioavailability should take into account factors such as leakage and radon-spread rates. These factors are important for determining appropriate methods in TENORM risk assessments. However, the potential for exposure to TENORM-related but nonradioactive chemical agents should also be considered. Appropriate disposal and rehabilitation strategies of TENORM wastes have to ensure that these wastes do not release radioactive substances into the environment and cause significant environmental harm. A comprehensive radiological and environmental impact assessment is required when choosing disposal facilities. This is necessary to ensure that the effects of radionuclides on groundwater, surface water, and air quality within the disposal facility are within acceptable limits in the long term.

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