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Developing a National Level Inventory of NORM Residues and Waste

DEVELOPING A NATIONAL LEVEL INVENTORY OF NORM RESIDUES AND WASTE

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FOREWORD

In numerous industrial sectors not directly related to the nuclear fuel cycle, naturally occurring radionuclides may be present in primary raw materials, by-products, co-products or process residues. These situations necessitate careful consideration to ensure that workers and the public are not subjected to undue exposure to ionizing radiation. A substantial body of literature and technical references addresses the presence of naturally occurring radioactive material (NORM) in various industries, but many IAEA Member States continue to request practical information and strategies for the management of NORM residues and waste. Experience has shown that while legal and regulatory frameworks are essential for controlling exposure, the safe and sustainable management of these materials also depends on the availability of an adequate supporting infrastructure.

To help address this need, the IAEA has established the Holistic Approach to Management of Naturally Occurring Radioactive Material (NORM), a comprehensive framework comprising six interrelated elements: (i) policy and strategy — establishment of national policies and strategic objectives for NORM management; (ii) inventory of NORM residues and waste — systematic identification and documentation of materials containing NORM; (iii) cost estimates for NORM waste disposal — assessment of financial implications to support planning and decision making; (iv) sampling and characterization of NORM residues and waste — provision of accurate data for classification and management; (v) valorization of NORM residues — promotion of reuse and recycling in alignment with circular economy principles; and (vi) decommissioning of NORM related facilities — implementation of safe and sustainable closure of facilities handling NORM.

This publication addresses the second element of the framework, namely the inventory of NORM residues and waste, focusing on the development of a national inventory. Establishing such an inventory is a critical step; it provides the foundation for defining appropriate policies and strategies, supports informed decision making on the management of residues and waste and enables reliable forecasting of arisings that will need attention in the future.

The objective of this publication is to provide specific information and strategies for compiling national inventories of NORM residues and waste arising from various industrial activities, including materials accumulated at legacy sites where safety considerations may not have been adequately addressed.

The methodology presented in this publication facilitates the identification and quantification of NORM residues and waste at the national level, even in cases where prior information on NORM occurrence is limited or absent. The resulting inventory serves as a cornerstone for the development of a practical framework for NORM management. It also supports the application of a graded approach to the regulatory control and oversight of NORM related facilities and activities.

The IAEA is grateful to all those who contributed to the preparation of this publication. The IAEA officer responsible for this publication was H. Monken-Fernandes of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Minerals and various raw materials contain radioisotopes of natural terrestrial origin, commonly known as primordial radionuclides. The radionuclides of greatest relevance from a radiation protection perspective are those belonging to the ^{238}U and ^{232}Th decay series, as well as ^{40}K.

The activity concentrations of these radionuclides in rocks and soils are variable but generally low. However, some minerals and raw materials can contain uranium- and/or thorium-series radionuclides at significantly elevated activity concentrations.

When these materials are further processed or used, for example, during the extraction of metals through physical or chemical operations, the naturally occurring radionuclides may become unevenly distributed among the final products and the various residues generated along the process chain. Consequently, the activity concentrations of radionuclides in certain industrial residues can, in some cases, reach values several orders of magnitude higher than those found in the original mineral or raw material.

In certain mining and mineral processing operations, oil and gas production, and other industrial activities, radionuclides of natural origin can present a non-negligible risk to workers, members of the public, and the environment. This potential risk may require regulatory control if the material meets the definition of Naturally Occurring Radioactive Material (NORM). According to the IAEA Safety Glossary [1], NORM is defined as: "Radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides."

A NORM residue may or may not be classified as waste. In many situations, even when a residue contains natural radionuclides and other hazardous substances, it can still be used beneficially, either directly or after further processing, without posing significant health or environmental risks. When such beneficial use is not viable, or when there is no market demand for the material, it will need to be managed and disposed of safely as waste.

Despite global progress toward safer NORM management, many IAEA Member States still lack comprehensive strategies for addressing NORM residues and wastes. In such situations, the absence of governmental initiatives to support residue valorization or to ensure the availability of disposal routes, when residues are designated as waste, can lead to unintended consequences affecting economics, safety, and overall operational sustainability. This may result in large volumes of waste being accumulated and stored on site with no clear timeframe or pathway for their safe disposal.

Understanding the amounts and types of NORM residues generated across different industrial operations is therefore essential. This knowledge underpins effective planning at various levels of a national NORM management strategy. These aspects are examined in greater detail throughout this publication.

Regarding inventory development, it is important to note that the activity concentrations of NORM residues generated in industrial processes can vary over time, depending on process-related parameters and the characteristics of the input materials. In many cases, only a limited amount of measurement data is available at the initial stage, often originating from campaigns conducted decades ago and therefore not fully representative of the current situation. In some circumstances, information on the radiological properties of NORM residues may be completely absent.

In progressing toward the safe management of NORM, establishing a credible inventory represents an essential first step. Such an inventory helps define the extent of the issue and provides the basis for allocating the necessary resources, financial, human, and infrastructural, to develop an appropriate national policy.

Despite the large body of available literature on NORM-related issues, IAEA Member States have expressed the need for practical guidance on how to develop inventories, including direction on describing the nature and magnitude of NORM-related issues at the national level [2]. The inventory of NORM residues in each country is also a fundamental component of the Holistic Approach to NORM Management [3]. The importance of establishing an accurate NORM inventory has likewise been recognized in the IAEA Safety Guide on NORM residues management [4].

An additional point, not addressed earlier in the text but relevant to inventory development, concerns the analytical capabilities available within a country. In some cases, specialized laboratories capable of performing radiological analyses to determine activity concentrations of radionuclides may not exist, or such capabilities may be limited to universities and research centres. In the latter case, the required volume of analyses might exceed the capacity of these laboratories to meet demand. Furthermore, some samples may present technical challenges, requiring complex analytical procedures. These factors can constrain the development of the inventory and ultimately impact the national capacity to manage NORM residues and wastes. Conducting analyses abroad is an option but can be costly and may significantly increase the overall expense of inventory development. For these reasons, this publication emphasizes that NORM management needs to be approached in a holistic manner.

1.2. OBJECTIVE

This publication aims to provide policymakers, governmental organizations (including regulators), industrial sectors and other stakeholders with specific guidance on how to develop and maintain inventories of the amounts and radiological characteristics of NORM residues and wastes generated in operating industrial facilities, accumulated at legacy sites, and expected to arise in the future from decommissioning or remediation activities. The methodology presented in this publication is intended to support the identification of materials of concern, particularly in situations where little or no information is available and resources for inventory development are limited. It provides a stepwise approach to determine the quantities of materials of primary relevance, recognizing that only a restricted set of resources may be accessible for this purpose. Ultimately, this publication seeks to support the development of comprehensive national policies and strategies that enable effective and sustainable frameworks for managing NORM residues and wastes in IAEA Member States.

1.3. SCOPE

An overview of the industrial sectors of relevance when considering the presence of NORM is provided in [5]. These sectors, which fall within the scope of this publication, include: mining and processing of natural resources other than uranium (such as rare earth elements); the oil and gas industry; production and use of thorium and its compounds; production of niobium, ferroniobium and tantalum; zircon and zirconia industries; manufacture of titanium dioxide pigment; production of iron and steel, tin, copper, aluminium, zinc and lead; and the manufacture of phosphate products, including fertilizers and animal feed. Additional activities addressed in this publication include oil and gas production, fossil fuel combustion, water treatment, and geothermal energy production.

Although the term “legacy sites” is not explicitly defined in the IAEA Safety Glossary, for the purpose of this publication it refers to sites contaminated by past activities that were not regulated to current safety standards or were not regulated at all. Legacy sites associated with the industrial operations listed above may present significant NORM-related concerns and may require dedicated management approaches. Such sites may include former waste disposal areas (such as historical mill tailings deposits) or locations where industrial facilities have ceased operation but were not adequately decommissioned or remediated.

The inventory addressed in this publication focuses on the quantities and radiological characteristics of NORM residues associated with the industrial processes mentioned above, including operational residues, legacy residues, and estimated future arisings from decommissioning and remediation activities.

Although the presence of non-radioactive substances (such as organic compounds and heavy metals) in NORM residues is acknowledged, the scope of this publication is limited to radiological aspects.

1.4. STRUCTURE

This publication is structured into six sections and three appendices. Section 1 provides background information, the objective, and the scope of the report. Section 2 presents an overview of major NORM-residue-generating industrial operations to assist readers who may not be familiar with the processes covered in this publication. Section 3 discusses the strategic importance of developing a NORM inventory, defines its scope, and introduces the proposed framework for building the inventory. Section 4 outlines approaches for calculating the amounts of residues generated in different processes, acknowledging that in some cases, such as in the oil and gas industry, the process may be less straightforward. Section 5 offers a brief overview of compiling information on legacy sites related to NORM, without addressing site characterization approaches in detail. The publication concludes with a summary of key points in Section 6.

The appendices provide templates for compiling the necessary information in the context of oil and gas production. It is to be noted that specific guidance on sampling and radiological/radiochemical analysis will be provided in a separate publication under the ENVIRONET NORM Project.

2. DESCRIPTION OF MAJOR NORM RESIDUE GENERATING OPERATIONS

A significant amount of information on the radiological aspects of various industrial operations with the potential to generate NORM residues and wastes is available in the literature. The IAEA has produced comprehensive reviews on operations related to oil and gas [6], phosphates [7], rare earths from thorium-containing minerals [8], zircon and zirconia [9], and titanium dioxide and related industries [10]. Readers of this publication are referred to these references for more detailed information on the radiological aspects of these operations.

In this section, the objective is to provide an overview focused on the NORM-containing residues arising from the operations mentioned above. For this purpose, the industrial processes are grouped into two main categories: one comprising metallic and non-metallic ores as well as water treatment, and another encompassing operations related to energy production, such as the oil and gas industry, coal combustion, and geothermal processes.

2.1. METALLIC AND NON-METALLIC MINERAL PROCESSING

A naturally occurring material with a unique atomic structure, and distinct chemical and physical characteristics is considered a mineral. A solid aggregate of minerals is known as a rock. According to their origins and formation processes, rocks can be divided into three primary categories: sedimentary, igneous, and metamorphic[1]. Ore is a naturally occurring substance from which one or more economically valuable minerals can be extracted[2]. Typically, minerals, especially metals, are mined first in ore form, then refined later. Man made minerals are not regarded as true minerals. However, from a processing perspective, they behave similarly to virgin minerals and are treated accordingly, particularly in recycling processes.

An industrial mineral is a rock, a mineral or any other naturally occurring material that has economic value. The data to be gathered at this stage includes the identification and location of the sites, the operating companies, the associated mining steps, and any known onsite studies related to overall product and residue/waste management. The operations performed at a mine site to exploit and utilize an ore deposit can be divided into three main steps:

- Access to the ore deposit (clearance, and galleries producing barren waste);
- In situ ore extraction and selection; and
- Ore processing.

Each mining step has the potential to generate residues, typically with different physical and chemical properties (Fig. 1). The quantities produced depend on the mining method and the characteristics of the raw material. Likewise, the chemical composition of the residues is influenced by the type of ore, its geological setting, and the processing techniques applied.

Mineral processing operations can be broadly divided into two types: dry and wet. Dry processing takes place without the use of water, whereas wet processing encompasses all operations in which water is required. In general, wet processing offers higher efficiency, allows for more compact installations, and eliminates dust generation.

[1] British Geological Survey, Discovering Geology: Rocks and Minerals, https://www.bgs.ac.uk/discovering-geology/rocks-and-minerals/
[2] https://www.usgs.gov/communications-and-publishing/news/earthword-ore

Mineral processing involves handling three main categories of Run of Mine (ROM) materials. These materials are extracted, broken into pieces, and removed from their original location. They may be used directly or subjected to simple or more complex processing. The classifications are [11]:

- Rocks: Granites, marble, limestone, building stones, sand, coal, and clays;
- Industrial minerals: Quartz, diamond, gemstones, fluorite, apatite, zircon, garnet, vermiculite, barite, and wollastonite;
- The metalliferous deposits: Gold, platinum, chromite, chalcopyrite, sphalerite, galena, bauxite, hematite, and magnetite.

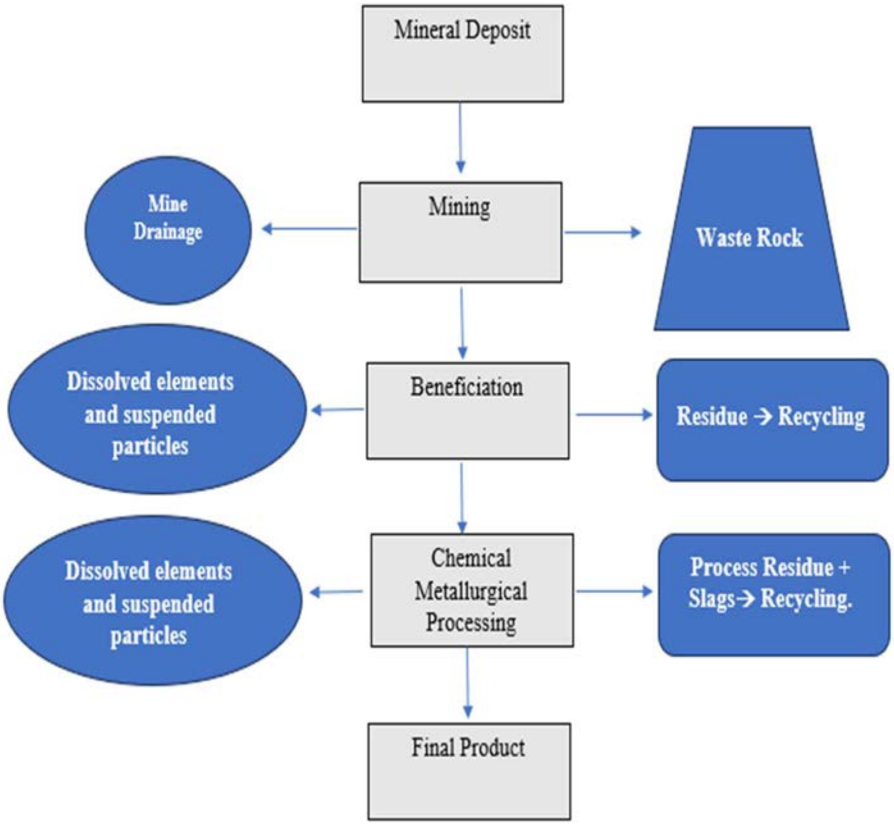


FIG. 1. Schematic flowsheet of a hypothetical mineral processing operation.

In general, the initial stage of mineral processing consists of reducing the size of ores to enable the separation of valuable minerals from the host rock. The typical liberation size ranges from approximately 100 to 10 µm. Crushing and grinding, used in various combinations, are required to achieve effective size reduction in rocks and minerals.

The next stage involves washing, which is a basic enrichment process used to improve the quality of rock and mineral fractions from sand size and upwards. The objective of this step is to remove surface impurities such as clays, dust, organic matter, and salts.

Once minerals have been liberated through size reduction, they can be separated from one another. Various separation methods, such as gravimetric separation, flotation, magnetic separation, and leaching, may be applied to recover individual minerals based on their specific physical and chemical properties.

Following the enrichment process, two principal outputs are generated: a valuable product (the concentrate) and a non-valuable product (the tailings). Tailings are generally not immediately suitable for sale or disposal due to their water content, particle size distribution, or chemical composition. However, their characteristics may be improved through various upgrading methods. Treatment processes such as sedimentation, mechanical dewatering, drying, calcining or sintering, as well as the recovery of process water, can render these materials suitable for disposal. It is important to note that the designation of certain streams as “non-value products” (wastes) is increasingly being reconsidered, particularly within the framework of the circular economy. A comprehensive inventory will therefore be essential in determining whether some of the residues possess potential economic value, for example because of their uranium content.

Finally, the handling of dry material involves loading, unloading, transportation, storage, and feeding operations. The handling of wet material, commonly referred to as slurry handling, requires the use of hoses and slurry pumps for transportation, pumps for feeding, and slurry agitation systems for storage. Mineral processing operations face numerous challenges in process control due to the variability of ore properties, material transport delays, and nonlinear system responses. These factors may become significant constraints when conducting inventory assessments.

2.1.1. Types of residues generated in mining and mineral processing

The main types of mining residues, in addition to topsoil and overburden, can be classified into the following categories:

- Waste rock (mine rock piles);
- Tailings (processing waste);
- Drainage that needs treatment and can produce slurry enriched in radionuclides and heavy metals;
- Filters to collect materials from gaseous emissions.

Unused extraction materials, that are classified as waste rock due to high transportation costs, are typically disposed of near the main mining centre unless they can be repurposed for a beneficial use. The quantity of mining waste that can be accommodated at a site varies considerably and is influenced by the selectivity of the mining method. In most cases, open-pit mines and quarries generate substantially larger volumes of mining waste compared to underground mines.

The primary form of waste rock is produced during surface stripping, also referred to as barren rock stripping, carried out to expose shallow ore bodies. These rocks have undergone varying degrees of weathering but become fresher with increasing depth, reflecting the geological characteristics of the surrounding formations. Their composition generally resembles that of the local rock mass. The largest quantity of barren rock, by weight, is generated through stripping in open-pit operations. In underground mines, this type of waste rock arises from the excavation of passages such as shafts and crosscuts.

Mill waste is commonly referred to as tailings, discharges, or effluents. These materials are generated through the various mineral upgrading methods used to meet production demands. The physicochemical properties of mill tailings depend on the conditions under which the minerals were originally formed, and therefore tailings can exhibit a wide range of characteristics. The volume and diversity of these wastes tend to increase with the growing demand for raw materials and the adoption of more complex upgrading techniques.

Mill wastes are produced at every stage of the mineral recovery and upgrading process within the same operational chain and may be present in solid, liquid, or gaseous forms. They represent the final residues from which valuable elements have already been removed.

2.2. WATER TREATMENT

Radionuclides from the natural decay chains of ^{238}U, ^{235}U, and ^{232}Th are present in trace quantities in all rocks. When groundwater interacts with these rocks, a small proportion of the radionuclides can dissolve into the water. The resulting activity concentrations depend strongly on the rock type and its chemical composition. Median (Med) and maximum (Max) values of the activity concentrations of commonly occurring natural radionuclides in untreated groundwater, expressed in millibecquerel per litre and categorized by aquifer rock type, are presented in Table 1. It can be observed that the dominant radionuclide in terms of activity concentration varies with the host rock and the geochemical characteristics of the groundwater. For example, in gneisses and granites, ^{226}Ra activity concentrations may exceed those of uranium, whereas uranium tends to dominate in limestone or sandstone aquifers.

2.2.1. Types of residues from water treatment processing

To comply with regulatory requirements or in response to safety assessment protocols, groundwater may need to be treated to drinking water quality standards. Even when the treatment process is not specifically designed to remove radionuclides, these species can accumulate in certain residues to levels that require proper disposal, depending on their activity concentrations. It is worth noting that surface waters generally contain lower concentrations of natural radionuclides than groundwater; therefore, residues with elevated radionuclide contents are more likely to arise during the treatment of groundwater. The process of eliminating radionuclides from water is not straightforward. Ion exchange, reverse osmosis, activated alumina, coagulation/filtration, lime softening, electrodialysis/electrodialysis reversal, and preformed hydrous manganese oxide filtration are among the treatment methods to be considered. Below is a description of the main techniques used for water treatment and considerations regarding the residues they generate. Since the quantities produced may not be negligible, a national inventory of NORM residues needs to pay close attention to these situations, as appropriate disposal options will be required if these residues are classified as waste.

TABLE 1. MEDIAN AND MAXIMUM CONCENTRATIONS OF NATURAL RADIONUCLIDES IN GROUNDWATER SAMPLES IN GERMANY in mBq/L [12]

Aquifer Rock Type	^{238}U		^{226}Ra		^{210}Pb		^{210}Po		^{228}Ra	
	Med	Max	Med	Max	Med	Max	Med	Max	Med	Max
Basalt	< 0.7	5.7	1.0	2.8	1.9	20	0.99	5.6	< 0.8	5.4
Gneiss	1.2	53	12	98	9.5	70	2.0	19	11	29
Granite	1.2	53	12	98	9.5	70	2.0	19	11	29
Limestone	6.0	210	5.9	160	3.2	23	1.3	18	5.4	110
Sand	3.6	120	7.1	36	2.1	18	1.3	19	6.7	46
Shale	1.1	97	2.6	27	2.1	19	1.8	9.4	3.7	26
Sandstone	17	590	12	380	3.6	31	2.9	630	9.3	210
Other Rocks	2.5	620	8.0	300	4.1	270	2.0	410	7.5	130

2.2.1.1. Ion exchange

Ion exchange treatment involves passing water through a resin containing exchangeable ions. Stronger binding ions in the resin replace weaker binding ions in the water, thereby removing them from the treated stream. Two main types of ion exchange are used: cation exchange and anion exchange. In anion exchange, pollutants such as uranium are replaced with chloride, while in cation exchange, radium and other cationic species are typically substituted with sodium or potassium. For systems requiring the removal of both uranium and radium, mixed-bed resins containing layers of cation and anion exchange media are employed. Ion exchange is also effective for removing photon-emitting and beta-emitting radionuclides.

Depending on factors such as resin type, pH, and the presence of competing ions, ion exchange can remove up to 99% of these contaminants. Regeneration of ion exchange resins generally involves backwashing, brining, and rinsing. The method is versatile, with anion exchange targeting contaminants such as alkalinity, nitrate, and arsenic, while cation exchange removes hardness-causing minerals.

For the process to operate effectively, contaminants need to be in the appropriate ionic form and bind more strongly to the resin than the ions being displaced. Competing ions, such as sulphate and hardness-causing ions, can reduce the resin bed's capacity to target specific radionuclides. Fouling of the resin is another concern, as particulates and metals (e.g. iron and manganese) in the water can clog the resin or precipitate, thereby blocking exchange sites. Pre-treatment, including filtration, helps reduce fouling and extend the resin's lifespan, although it may also capture radionuclides, creating an additional disposal consideration. Anion exchange may lower water alkalinity, which can require subsequent adjustment by adding carbonate or caustic substances.

Although resins can be regenerated, this process generates waste solutions containing elevated levels of removed contaminants and regenerant salts. Residuals from ion exchange, such as brine, backwash, rinse water, and spent resins, can require disposal through different approaches, including direct discharge, discharge to sewer systems, wastewater treatment, or underground injection. Spent resins are typically disposed of in suitable landfills, and in some cases, plant sludges and wastewater are applied to land or used for spray irrigation, depending on local regulations. If radionuclides become highly concentrated in the brine or resin, special handling and disposal procedures may be needed. Alternatively, some systems use disposable media and operate the resin to exhaustion rather than regenerating it, particularly where liquid residual disposal is not feasible.

2.2.1.2. Reverse osmosis

Reverse osmosis is a membrane-based separation process driven by pressure. Water is pushed through a membrane with tiny pores under pressures of approximately 100 to 150 psi, preventing larger molecules from passing through and excluding a significant portion of the water along with these molecules. The treated water is collected on the opposite side of the membrane.

This process has proven effective for removing uranium, radium, gross alpha and beta particles, photon emitters, and various other contaminants such as arsenic, nitrates, and microbes, with removal rates reaching up to 99%. Reverse osmosis systems are often automated and compact, making them suitable for small-scale applications.

Residuals generated by reverse osmosis include liquid concentrate and spent membranes. Liquid waste disposal options can involve direct discharge, sewer system discharge, treatment plant disposal, or underground injection. Used membranes are disposed of in appropriate landfill facilities. The radionuclide concentration in the liquid waste may influence the selection of disposal options due to the potentially high levels of concentrated contaminants removed during treatment, depending on the performance of the unit.

2.2.1.3. Activated alumina

Activated alumina uses a porous, granular aluminium medium to adsorb ions from solutions. This medium can be regenerated through a series of washes or replaced once it becomes fully saturated. Depending on the pH and the concentration of competing ions, activated alumina can remove up to 99% of contaminants. It is also effective in eliminating ions such as arsenate, fluoride, sulphate, and selenate. Compared to other adsorption methods, activated alumina is less affected by total dissolved solids (TDS) and sulphate.

Residuals from the treatment process may include backwash water, caustic regeneration and rinse water, acid-neutralization water, and spent media. Liquid waste is typically routed to a wastewater treatment plant or disposed of in an underground injection control well, since direct discharge is often restricted due to elevated levels of dissolved solids and radionuclides. While regeneration can reduce operating costs, smaller systems may opt to dispose of exhausted media to avoid handling caustic and acidic solutions. Appropriate disposal arrangements are also needed for media that has not been regenerated prior to removal.

2.2.1.4. Coagulation/filtration

Coagulation followed by filtration is widely used in large-scale water treatment systems for removing particulates and turbidity from surface waters. The process involves introducing a coagulant, typically iron or aluminium salts combined with polymeric substances, into the incoming water. Coagulation promotes the aggregation of fine particles into larger flocs, which are subsequently removed through filtration, often using sand, anthracite coal, or a mixture of both.

Residuals from the coagulation and filtration process include backwash water, sludge, and spent filtration media. Liquid waste disposal options can include routing the effluent to a wastewater treatment plant, disposal through underground injection wells, or direct discharge when radionuclide concentrations and total dissolved solids are reduced to acceptable levels through blending. Spent filtration media, once no longer effective, are generally routed to appropriately designated landfills.

2.2.1.5. Preformed hydrous manganese oxide (HMO) filtration

The preformed Hydrous Manganese Oxide (HMO) filtration method is an effective approach for removing radium from water. The process involves adding preformed manganese oxide to the water, where it binds to radium and is subsequently removed through filtration. Removal efficiencies can reach up to 90%, and the method is particularly suitable for systems equipped with existing filtration units that can incorporate HMO with minimal modification. In addition to radium, preformed HMO filtration is also effective in removing arsenic. Proper dosing of HMO is an important operational consideration. Excessive dosing can increase head loss or clog the filtration media, whereas insufficient dosing reduces removal efficiency, requiring careful control by operators.

Residuals generated from the process include backwash water, sludge, and spent filtration media. Liquid waste may be routed to wastewater treatment facilities, disposed of through underground injection wells, or discharged directly when radionuclide concentrations and dissolved solids are sufficiently reduced through blending. Spent filtration media are typically disposed of in an appropriate landfill class.

2.2.1.6. Lime softening

Lime softening involves adding quicklime or hydrated lime to increase the pH and induce calcium precipitation. In a subsequent enhanced softening step, the pH is raised further, typically to at least 10.6, to also precipitate magnesium. Under suitable operating conditions, lime softening can reduce the concentrations of radium and uranium in water. Traditional single-stage softening can remove approximately 50-80% of radium, while enhanced lime softening can achieve up to 90% removal of both uranium and radium and can also reduce iron, manganese, and arsenic levels. Effective uranium removal requires a pH above 10.6 and sufficient magnesium in the water, either naturally present or added.

Enhanced lime softening can be more resource-intensive than conventional softening, as it requires tighter operational control and a good understanding of water chemistry. Although package plants exist, additional operator training may be necessary in facilities where softening processes are not already in place. Because softening reduces hardness and alkalinity, the treated water may exhibit increased corrosivity. To protect the distribution system, corrosion-inhibiting agents may need to be added to the final treated water.

Sludge, backwash water, and outdated or ineffective media are examples of treatment residues generated by lime softening. Disposal options can be influenced by the radionuclide content of these materials. In general, water softening facilities are not permitted to discharge liquid or solid waste directly into water bodies. When radionuclides are removed during treatment, the disposal process can become more complex. In some cases, sludge disposal programmes allow softened sludge to be applied to land. Sludge and spent media are to be disposed of in an appropriately designated landfill class.

2.2.1.7. Single use disposable media/resin

Single-use or disposable treatment media and resins are increasingly employed for the removal of uranium and radium, driven by stricter restrictions on wastewater discharges from conventional cation and anion exchange processes. For uranium removal, a strong base anion resin is typically used, whereas proprietary media, often incorporating materials such as barium sulphate, are widely applied for radium removal. Radium removal relies on complexation mechanisms similar to the barium-sulphate co-precipitation processes used in mining operations.

These systems are generally designed in a manner similar to ion exchange units, operating with empty bed contact times of approximately 1.5 minutes, and functioning in either downflow or upflow configurations. They may operate with single or multiple vessels, and some installations employ parallel vessels on staggered cycles to produce blended treated water, thereby reducing fluctuations in effluent quality. This feature is particularly relevant for anion-exchange media, which may cause significant reductions in alkalinity and pH during the early phase of their operational cycle.

A key advantage of disposable media systems is their ability to avoid on-site generation of wastewater containing concentrated radionuclides, thereby eliminating the challenges associated with managing such effluents. However, their operating costs are generally higher than those associated with conventional ion exchange systems. As a result, disposable media may be particularly useful in situations where regulatory restrictions prevent wastewater discharge or where sewer access is not available.

Despite these benefits, disposable media systems also present certain limitations. Elevated concentrations of iron and manganese in the feed water can diminish media efficiency, and sediment accumulation over the operational lifespan of the media bed can further impair performance. For radium-specific applications, even trace levels of iron can markedly reduce media longevity. Pretreatment steps, such as iron sequestration or sediment filtration, may mitigate some of these issues. Nonetheless, because these systems are not typically backwashed, sediments tend to accumulate within the media bed over time.

Certain radium-selective media can reach retention levels above 370 Bq·g^{-1}, though periodic cleaning may be required to maintain performance The gamma radiation emitted by media containing accumulated radium at the time of replacement can add complexity to disposal activities, particularly because disposal requirements and acceptance criteria may evolve over time.

Once the media is exhausted, it is removed from the vessel, repackaged for transport, and required to pass a paint-filter test. The material is then stored and transferred to a licensed NORM disposal facility. Regulatory approval is generally needed for both the system design and the associated disposal plan.

2.2.1.8. Additional treatment options

Ion exchange membranes are used in electrodialysis and electrodialysis reversal (ED/EDR) to remove ionic impurities. Contaminants are separated by applying an electric potential across alternating cation and anion exchange membranes, and periodic reversal of the voltage cleans the membrane surfaces. This technique is effective for removing radium and can also lower concentrations of other ionic constituents such as hardness-forming minerals, uranium, arsenic, nitrate, and perchlorate. ED/EDR systems are generally highly automated and operate with routine maintenance and monitoring. For small-scale applications that address multiple contaminants, ED/EDR can represent a viable option, although it is often more costly than other radionuclide treatment methods. In addition to substantial capital costs, expenditures associated with disposal and acid-washing procedures for radionuclide removal contribute to higher operational costs. Elevated concentrations of radionuclides and other contaminants also tend to accumulate in the reject stream and within the membranes.

Residual waste from radionuclide treatment technologies can be either liquid or solid. Examples of liquid residuals include brine, backwash water, reject water, acid-neutralization water, caustic regenerant, and rinse water. Discharging liquid waste into a sewer system is the most common disposal route. Some facilities may also use underground injection wells, conduct on-site wastewater treatment, transport wastewater to an external treatment facility, or release treated effluent directly into a water body, depending on regulatory permissions and waste characteristics. Certain treatment systems are designed to minimize the volume of liquid waste, which can be advantageous where disposal options are limited.

Solid residuals include spent or ineffective filter media and sludges generated from processes such as coagulation/filtration, ion exchange, preformed hydrous manganese oxide filtration, and lime softening. These materials are typically disposed of in licensed landfills; however, if radionuclide activity concentrations exceed applicable acceptance limits, disposal at specialized facilities may be required. The selection of appropriate disposal options for both liquid and solid residuals depends on several factors, including contamination levels, relevant national and local regulatory requirements, available disposal infrastructure, transportation considerations, and overall cost.

2.3. ENERGY INDUSTRY

As for mineral processing operations (Section 2.1), this section begins by outlining general concepts relevant to the following discussion of energy-generating processes.

2.3.1. Oil and gas

The oil and gas sector has three key areas:

- Upstream;
- Midstream;
- Downstream.

The upstream sector focuses on locating natural gas and crude oil deposits in subsurface or subsea formations and includes activities such as drilling exploratory wells and extracting resources from established ones. The midstream sector involves the transportation, storage, and preliminary processing of these resources. Because oil and gas reserves are often distant from refineries, transportation systems such as pipelines, tanker ships, and trucks are used to move the materials to refining facilities. Storage depots and intermediate processing units may also operate within this sector. The downstream sector is responsible for processing the raw materials extracted during the upstream phase, including refining crude oil and purifying natural gas, followed by marketing and distributing the final products, such as gasoline, diesel, jet fuel, lubricants, kerosene, heating oil, LPG, asphalt, and various petrochemicals, to consumers and end users.

Within the upstream sector, a typical oil and gas operating cycle consists of several phases, each designed to achieve specific objectives through the use of specialized technologies. These phases include the assessment of areas and basins, the identification of prospects following discovery, the development of the oil field, the production phase, and, finally, decommissioning of the facility. These stages are broadly comparable to those found in mining and other resource extraction processes, although adapted to the specific characteristics and technical requirements of oil and gas operations.

Crude oil refers to hydrocarbon mixtures located in underground reservoirs that remain in liquid form under standard atmospheric conditions. Natural gas consists of gaseous hydrocarbon mixtures, predominantly methane, under standard temperature and pressure. Hydrocarbon reservoirs, which rely on porous and permeable host rocks for storage, can occur hundreds of metres below the surface, accumulating within sedimentary basins when suitable geological conditions are present.

Crude oil processing may include:

- Separation of gas from oil;
- Separation of water from oil;
- Desalting to reduce saline content;
- Desulphurization to remove hydrogen sulphide;
- Stabilization to ensure compliance with required specifications.

Gas processing may include:

- Phase separation;
- Dehydration to remove water, using systems such as refrigeration, adsorption, or absorption;
- Condensate removal through refrigeration and adsorption;
- Desulphurization and decarbonation to eliminate hydrogen sulphide and carbon dioxide when present at unacceptable levels.

The end of a field's operational life is reached when production is no longer economically viable. At this stage, wells are required to be plugged and abandoned (P&A). The fundamental principles of P&A are similar for both onshore and offshore wells. The methods and materials used are designed to ensure long-term zonal isolation, even as downhole conditions evolve over time. The aim of all planning and analysis operations is to accomplish the following:

- Isolate and protect all fresh and near freshwater zones;
- Isolate and protect all future commercial zones;
- Prevent leaks in perpetuity from or into the well;
- Remove surface equipment and cut pipe to a mandated level below the surface.

The traditional abandonment procedure begins with a well-killing operation, during which the produced fluids are either removed from the wellbore or displaced back into the formation. These fluids are replaced with dense drilling fluids to control any existing formation pressures. The 'Christmas tree'[3] is then removed and substituted with a blowout preventer, which provides pressure control during subsequent operations, including the removal of the production tubing.

Cement is pumped through the open perforations and squeezed into the formation to seal all productive layers and prevent fluid migration. Depending on the well configuration, various cement plugs and wireline-deployed plugs are placed at specific depths in the liner and production casing, aligned with the top of the cement behind the production casing. The production casing is then severed and raised above the cement top, and a cement plug is installed over the remaining casing stub to isolate the annulus and any potentially open formations beneath the intermediate casing shoe. A dedicated publication addressing the decommissioning of oil and gas facilities is currently under development within the ENVIRONET NORM Project.

2.3.1.1. Oil and gas platforms

Once a commercially viable well is confirmed, operations transition from exploration and drilling to the production phase. There is a production platform suitable for virtually every type of offshore setting.

A fixed platform (FP) consists of a steel jacket structure supported by piles driven into the seabed, with a deck on top that accommodates crew quarters, a drilling rig, and production facilities. Fixed platforms are generally considered economically viable in water depths of up to approximately 500 m.

A compliant tower (CT) is composed of a slender, flexible tower and a piled foundation, capable of supporting a standard deck for drilling and production activities. Unlike fixed platforms, compliant towers are designed to absorb large lateral forces by allowing substantial lateral deflection and are typically used in water depths ranging from 300 to 600 m.

A Tension Leg Platform (TLP) is a floating structure anchored in place by vertical, tensioned tendons attached to pile-secured templates or foundations on the seabed. The continuously taut tendons enable TLPs to operate across a broad range of water depths while considerably

[3] In petroleum and natural gas extraction, a Christmas tree is an assembly of valves, casing spools, and fittings used to regulate the flow of pipes in an oil well, gas well, water injection well, water disposal well, gas injection well, condensate well, and other types of well.

reducing vertical motion. Large TLPs have been successfully installed in water depths approaching 1,200 m.

A Mini Tension Leg Platform (Mini TLP) is a cost-efficient floating platform designed for the development of smaller deep-water reserves that would not be economically feasible using conventional deep-water production systems. It can also function as a utility, satellite, or early-production hub for larger deep-water fields. The first Mini TLP was installed in the Gulf of Mexico in 1998.

The SPAR Platform (SPAR) is a floating offshore structure composed of a topside deck supported by a single large-diameter vertical cylindrical hull. It includes a conventional fixed-platform topside, three types of risers (production, drilling, and export), and a hull that is held in place by a taut catenary mooring system consisting of six to twenty lines anchored to the seabed. SPAR platforms are currently in operation at water depths of up to approximately 900 m, and technological advancements may enable future installations at depths approaching 2,300 m.

The Floating Production, Storage and Offloading (FPSO) system consists of a semi-submersible unit equipped with drilling and production facilities. It can be maintained in position using wire-rope and chain moorings or by dynamic positioning systems employing rotating thrusters. Production fluids are transported from subsea wells to the platform via risers designed to accommodate platform motion. FPSO units are suitable for applications in very deep-water environments.

The Subsea System (SS) can range from a single subsea well connected to a nearby platform, FPSO, or TLP to a complex network of multiple wells linked to a manifold and pipeline system leading to a distant production facility. These systems are currently deployed in water depths exceeding 1500 m.

A Floating Production, Storage and Offloading system consists of a large tanker-type vessel that is anchored to the seabed. It is designed to process and store production from nearby subsea wells and to periodically transfer the stored oil to a shuttle tanker. The shuttle tanker then transports the oil to an onshore facility for further processing. FPSOs are suitable for marginally economic fields in remote deep-water locations where pipeline infrastructure is not available.

2.3.1.2. Offshore pipelines

Offshore pipelines are critical components of offshore oil and natural gas production systems. These pipelines, laid on the ocean floor, transport hydrocarbons from subsea wells to offshore platforms and subsequently carry oil or gas from the platforms to onshore facilities for processing and distribution.

There are three types of classifications for pipelines:

- Infield Pipelines: These pipelines transport fluids within the field and are often referred to as flowlines or feeder lines. They carry a mixture of oil, gas, and water from subsea wells to a manifold or directly to the processing platform. Some infield lines also transport treated water from the platform to injection wells for disposal.
- Export Pipelines: Export pipelines move processed oil or gas from offshore platforms to the coast. A pipeline carrying both oil and gas is classified as a multi-phase pipeline. while those transporting only oil or only gas, are classified as single-phase pipelines.

— Transmission pipelines: Transmission pipelines transport oil or gas between two coastal locations, similar to how tankers move oil for trade.

2.3.1.3. NORM waste in oil and gas operations

Figure 2 illustrates areas where NORM can be accumulated in an oil and gas production facility. Radioactive scale often forms inside oil and gas pipelines and associated equipment. Accumulation in the production tubing, wellheads, separators, dehydrators, and overboard pump can be significant. For the purposes of this report, it is useful to provide readers who are not familiar with the specific components of an oil and gas production facility with an overview of their functions.

A separator is a container in the shape of a cylinder or sphere that is utilized to divide oil, gas, and water from the fluid flow generated by a well[4]. They may be horizontal or vertical in configuration. They are generally classified as two-phase separators (oil and gas) or three-phase separators (oil, water, and gas), the latter often referred to as free-water knockouts. They can also be grouped according to their operating pressure.

The primary separation mechanism is gravity segregation, whereby the heavier fluid settles while lighter fluids rise to the top. The extent of gas-liquid separation achieved within the vessel depends on factors such as the operating pressure, the residence time of the fluid mixture, and the flow characteristics. Turbulent flow promotes the release of entrained gas bubbles more effectively than laminar flow.

A dehydrator is a device used to remove moisture from a material. The material may include produced fluids such as crude oil, natural gas, or natural gas liquids (NGLs). Fluid dehydration is important to minimize corrosion and avoid the accumulation of free water in low points of pipelines. In the case of natural gas, dehydration also prevents hydrate formation and enables compliance with pipeline specifications.

A gas or oil reservoir is generally characterized as a reducing environment, which results in both Th and U being present in the +IV oxidation state. Under these conditions, they remain in the solid rock phase and do not dissolve into the aqueous or oily phases. In contrast, Ra isotopes behave differently. They are produced by α-decay from their immediate progenitors and can be released from the rock–fluid interface into well fluids through the α-recoil process. Radium also exhibits a strong preference for the aqueous phase, leading to naturally elevated concentrations in formation water. Consequently, during production, Ra tends to follow the produced water stream. As a member of the alkaline earth group, Ra shares chemical characteristics with barium (Ba), strontium (Sr), calcium (Ca), and magnesium (Mg), all of which commonly form sulphate or carbonate deposits. These deposits may occur as hard scale inside installations or be generated at the surface [13].

In gas or oil fields, ^{210}Pb may also become incorporated into any deposits that form. In such deposits, ^{210}Pb activity concentrations are often substantially higher than those of ^{226}Ra, indicating the presence of a distinct and independent mechanism for Pb transport. Under certain conditions, natural radionuclides may precipitate or accumulate inside production or treatment installations as scale or sludge [14]. Changes in operating conditions that can lead to the formation of NORM in oil and gas production include [13]:

[4] https://glossary.slb.com/en/terms/s/separator

— Temperature and pressure variations;
— Varying flow (transition between laminar and turbulent)
— Gas expansion due to a pipeline diameter change;
— pH variation (increase in sulphate concentration due to injection of fluids rich in sulphates, or mixture of different produced waters);
— Presence of seed crystals on the inner surface of the equipment and rough surfaces, (for example, in sour gas wells, the presence of NORM scale is enhanced by the presence of gypsum).

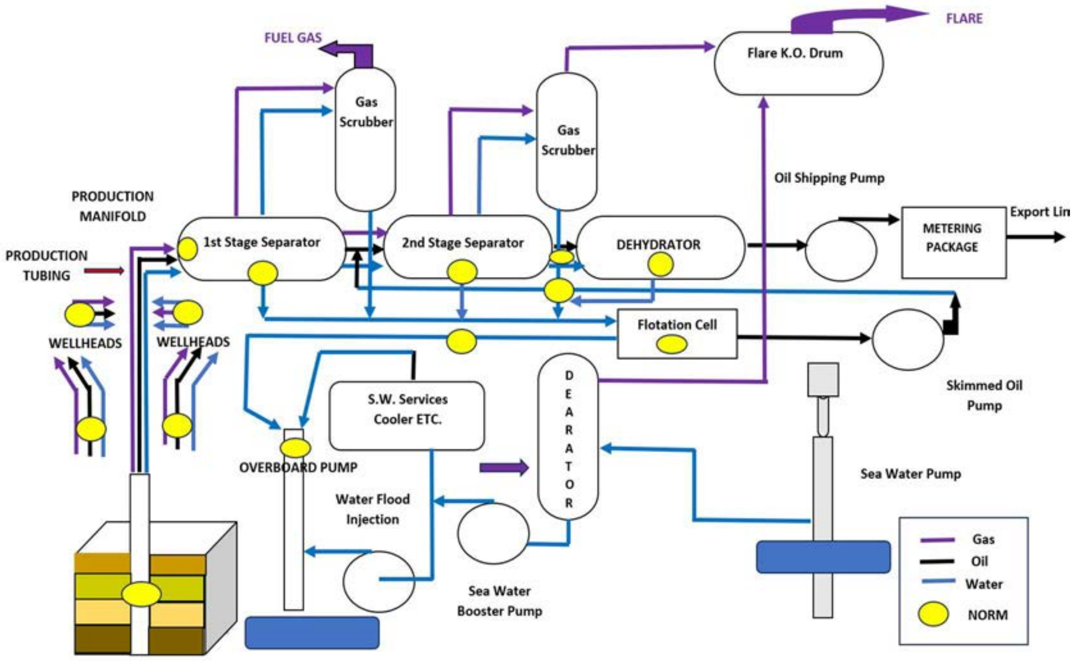


FIG. 2. Schematic of where NORM can occur in the offshore E&P Environment.

The main types of scale encountered in oil and gas facilities are sulphate scales, such as $BaSO_4$, and carbonate scales, such as $CaCO_3$. Several routine oil field operations can lead to the formation of NORM-bearing scale. One common mechanism is the mixing of seawater, which contains elevated sulphate concentrations, with formation water, which is typically rich in brine. Variations in temperature, pressure, and the acidity of the formation water during its flow to the surface can also contribute to scale accumulation.

The above-described phenomenon significantly impacts oil and gas production, as it reduces the capacity of pipelines to transport hydrocarbons. It is important to note that scales are rarely homogeneous, so the activity concentrations of natural radionuclides vary within these deposits. Very thin films of ^{210}Pb may form on the inner surfaces of gas transmission lines, associated with relatively high ^{222}Rn concentrations in natural gas and prolonged operation of the lines.

An inventory for oil and gas production is not a straightforward task, as the generation of NORM waste in these operations does not follow the predictable patterns typically observed in mineral processing. Some empirical estimates exist. For example, an annual scale generation rate of approximately 100 t per oil well in the USA has been suggested. However, the rate at which scale accumulates in oil and gas facilities varies considerably and often increases with the age of the installation. It is also estimated that approximately 230,000 t of sludge are produced each year in oil and gas production facilities in the USA. This sludge generally consists of oily, loose material containing silica compounds and, in some cases, substantial amounts of barium. When dried, the activity concentrations of radionuclides such as ^{226}Ra, ^{210}Po, ^{210}Pb and ^{228}Ra tend to increase [14].

Taking these considerations into account, the inventory in the OIL AND GAS industry involves accounting for both existing or accumulated material and approximations of the amounts expected to be generated in the future. It is also relevant to note that particular attention is directed toward the quantities of NORM waste that may arise during the decommissioning of OIL AND GAS platforms. Until 2011, approximately four tonnes of radioactive waste (scale, sludge, and sediments) with activity concentrations of 10 $Bq \cdot g^{-1}$ or more had been identified in each offshore installation decommissioned in Norway [15]. The report also estimates that the Norwegian and British sectors of the continental shelf would generate 96 and 271 tonnes of NORM, respectively, during the period from 2010 to 2020. In addition, the report highlights that corrosion products and other deposits containing radioactive substances in process equipment can be difficult to distinguish from visually similar materials that do not contain radioactive substances during onshore cleaning. Consequently, the actual quantities of waste requiring NORM-specific treatment may be considerably higher than initially calculated.

2.3.2. Combustion of fossil fuel

Heat energy is released when the combustible components of fuel combine with oxygen in a rapid chemical reaction known as combustion. When air is used as the oxygen source, flammable components such as carbon, sulphur, hydrogen, and others react with oxygen to form their corresponding oxides. Air contains approximately 21% oxygen by volume and 23.2% by weight. Although nitrogen constitutes about 79% of the air by volume, it does not participate in the combustion process; instead, it carries the heat generated during combustion to the steam boiler stack. According to combustion theory, complete oxidation of the combustible components of the fuel requires an adequate supply of air. This required amount of air is commonly referred to as the stoichiometric requirement.

2.3.2.1. Combustion of coal

Various techniques are used for coal combustion. In general, combustion refers to a rapid, high-temperature chemical reaction in which oxygen interacts with the carbon, hydrogen, and sulphur present in coal. This process typically occurs in four main stages:

- Formation of coal-oxygen complexes, releasing heat;
- Breakdown of these complexes, producing CO_2 and H_2O along with carboxyl (COOH), carbonyl (C=O), and phenolic OH groups, generating additional heat;
- Decomposition of these groups, yielding CO, CO_2, H_2, H_2O, and hydrocarbons such as ethane, ethylene, and propylene;
- Breakdown of aliphatic structures (organic compounds with open carbon chains, not aromatic rings) to form CO, CO_2, and H_2O.

At lower temperatures, the first stage of combustion proceeds more rapidly. During this phase, oxygen molecules diffuse into the pore structure of the coal and adhere to internal surfaces through physical adsorption. As an oxide layer gradually forms on the coal surface due to air exposure, it partially obstructs oxygen diffusion, leading to a progressive reduction in the oxidation rate. The reactions between coal and oxygen are exothermic.

As the temperature increases, the reaction rate accelerates, and coal eventually reaches its ignition temperature, approximately 175 °C, at which visible flames appear. The interval from the onset of oxidation to the point of ignition is referred to as the incubation period.

The ignition point is the temperature a combustible material has to reach to react with oxygen and ignite. For complete combustion to occur, sufficient time is allowed to ensure that the temperature of the gases remains above this threshold before cooling begins.

2.3.2.2. Wastes from coal fired power plants

Coal-fired power generation produces the second-largest industrial waste stream in the United States after mine wastes, generating approximately 110 million tonnes of coal ash, formally known as coal combustion residuals (CCR), each year [16]. Coal naturally contains trace amounts of radionuclides, as well as elements such as mercury, cadmium, and arsenic. Analysis of approximately 2,000 coal samples from the Western United States and 300 samples from the Illinois Basin indicated uranium concentrations typically ranging from just under 1 part per million (ppm) to 4 ppm, with values exceeding 20 ppm being uncommon. Thorium concentrations generally fall within a similar range, and occurrences above 20 ppm are considered rare [17]. During combustion, most uranium, thorium, and their decay products are released from the coal matrix and partition between the gas phase and the solid combustion byproducts.

Three main waste streams are reported [18]:

- Fly ash is a light coloured, fine particle waste that resembles a powder. It represents the majority of the wastes generated from coal combustion;
- Bottom ash consists of coarser and heavier particles than fly ash and resembles a mixture of sand and small stones. It accounts for slightly more than 10% of coal combustion wastes;
- Boiler slag is produced when bottom ash melts under the high temperatures of combustion. It has a gravel-like appearance and represents approximately 2% of the total coal combustion waste.

Approximately 99% of fly ash is captured by filtration systems, while about 1% may escape into the atmosphere. More than half of the fly ash, bottom ash, and boiler slag generated is repurposed in applications such as concrete production, blended cement, structural fills, embankments, blasting grit, and roofing granules[5].

Historically, coal ash has been managed by disposal in landfills or by mixing the ash with water to create a slurry that is pumped into surface impoundments located near power plants. These impoundments allow the solid ash to settle, after which clarified water is discharged under regulatory permits. Over several decades, large volumes of coal ash slurry have accumulated in such facilities. The collapse of a dike on 22 December 2008, which released approximately 4 million cubic metres of coal ash into the Emory River in Tennessee, demonstrated the environmental risks associated with this approach[6]. This is a typical example where beneficial use of residues can represent a better and safer approach than disposing these materials as waste.

[5] https://www.documentcloud.org/documents/21149977-coal-ash-production-and-use

[6] It was the largest industrial spill in United States history.

This incident underscores the importance of exploring alternatives to traditional coal ash disposal. Over time, markets for the beneficial reuse of coal ash have emerged, supported by private sector investments aimed at enhancing coal ash processing and recovering valuable by-products from legacy deposits. Despite these developments, concerns persist regarding the declining availability of coal ash as coal-based electricity generation decreases and coal combustion residuals units continue to close. Consequently, there is an ongoing need for long-term storage solutions to manage existing coal ash inventories. Such storage facilities may present lower environmental risks compared to conventional disposal approaches currently in place.

2.3.3. Geothermal energy production

Geothermal energy is heat derived from within the subsurface of the Earth, transported to the surface by circulating water or steam. Radionuclides present in the subsurface may also be brought to the surface along with these fluids. Geothermal energy is a renewable resource and, compared with other renewable technologies, is distinctive in that it can provide continuous base-load electricity generation while also being suitable for replacing fossil fuel-based heating systems.

2.3.3.1. Basics of geothermal energy

There are various geothermal technologies for direct uses, including district heating, geothermal heat pumps and greenhouse heating, as well as technologies for electricity generation. Electricity production generally requires high-temperature geothermal resources, typically above 150 °C. Binary cycle systems are an exception, as they can generate electricity at temperatures as low as 70 °C. Medium- to low-temperature resources (below 150 °C) are generally suited for industrial processes and heating applications.

Most countries that generate electricity from geothermal resources (see Table 2) are located in high-temperature regions along the boundaries of tectonic plates, such as the Pacific Ring of Fire, which is often associated with volcanic activity. However, an increasing number of countries outside these regions are also developing geothermal electricity production. For example, Türkiye relies primarily on lower-temperature geothermal resources.

TABLE 2. TOP 10 GEOTHERMAL COUNTRIES IN THE YEAR 2021[7]

Country	Production (GWh)
USA	3722
Indonesia	2276
Philippines	1918
Türkiye	1710
New Zealand	1037
Mexico	963
Italy	944
Kenya	861
Iceland	754
Japan	603
Others	1067

2.3.3.2. Geothermal energy plants

Geothermal power plants are typically constructed near geothermal reservoirs, generally at depths of 1.5–3 km below the earth's surface. Currently, there are roughly 400 geothermal power plants worldwide, most of which operate as flash steam systems [19]. There are three basic types of geothermal power plants:

— Dry steam plants: Utilize steam directly from geothermal reservoirs to rotate generator turbines;
— Flash steam plants: Extract high-pressure hot water from deep underground and convert it into steam to power turbines. After cooling, the steam condenses back into water, which is reinjected into the ground for reuse;
— Binary cycle power plants: Transfer heat from geothermal hot water to a secondary liquid with a lower boiling point, which vaporizes and drives the turbine to generate electricity.

2.3.3.3. NORM waste in geothermal energy production

Geothermal activities also generate waste materials, including solid waste. Waste may arise during exploration, production, maintenance, laboratory analysis, and power generation. The primary solid wastes include drill cuttings, scale from cooling water systems, scale produced during maintenance operations, domestic waste, and hazardous solid waste associated with

[7] https://www.thinkgeoenergy.com/geothermal/

machinery and heavy equipment maintenance. Additional waste streams may include silica sludge, organic waste, and other by-products [20].

Radioactive elements of concern in geothermal energy production may dissolve in subsurface water and be transported with the groundwater flow into the geothermal plant. These radionuclides are subsequently brought to the surface along with the extracted water. Radionuclides commonly detected in geothermal source water include ^{226}Ra, ^{222}Rn, ^{210}Pb, ^{228}Ra, and ^{224}Ra. Once at the surface, these radionuclides may enter the environment or accumulate within equipment and waste streams. Their concentrations vary according to the radionuclide content of the subsoil [20].

NORM residues can also arise during the exploration phase of geothermal operations. When deep water is pumped from the subsurface for energy production, natural radionuclides dissolved in the water reach the surface. The radionuclide content and activity concentrations of these residues are often significantly higher than the natural background levels of soils and rocks. In addition to scale deposits, elevated concentrations of NORM may appear in other residues accumulated within geothermal facilities, including defective plant components, filter materials, sludge, and protective clothing.

Residues with enhanced radionuclide content arise primarily from the use of deep geothermal waters with high salinity (up to 300 g of dissolved salts per litre of water). Such conditions have been documented, for example, in the North German Basin and the Upper Rhine Valley. In contrast, deep waters extracted from regions such as the alpine uplands typically exhibit salinity levels below 1 g/l. Conversely, near-surface geothermal systems used for applications such as residential heat pumps do not generate residues with elevated radionuclide content [21].

Depending on the water composition and operational conditions within the plant, dissolved constituents may precipitate and form deposits on internal components. These accumulated residues can be released when equipment is opened, particularly during:

- Periodic maintenance of the plant requiring the geothermal water to be drained;
- Periodic replacement of the filter elements;
- Periodic removal of scaling if scaling reactions occur.

The locations and conditions under which scaling occurs depend largely on the configuration of the plant. In general, scale can accumulate on any component that remains in contact with deep geothermal water. Variations in pressure and temperature are the primary drivers of precipitation. The resulting deposits consist of poorly soluble carbonate and sulphate salts, or metallic scale containing base metals such as lead. The radionuclides most frequently encountered include:

- ^{210}Pb in the case of metallic precipitates;
- ^{226}Ra and ^{228}Ra, in the other types of scale deposits.

Several hundred becquerels per gram can also be observed in certain scale deposits. Measurements of liquid and solid residues produced during the exploration phase of wells in the Netherlands have shown that formation water contains elevated levels of ^{226}Ra and ^{228}Ra, along with high concentrations of chlorine. This combination creates specific challenges for the storage, handling, and treatment of large quantities of liquid and solid NORM residues during the exploration phase [22]. In the Minerals and Hazardous Waste (including NORM)

Repository in the Netherlands, the maximum measured activity concentrations of NORM are presented in Table 3.

TABLE 3. MAXIMAL ACTIVITY CONCENTRATION PER NUCLIDE FOR WASTE ORIGINATED FROM GEOTHERMAL INDUSTRIES

Nuclide	[$Bq \cdot g^{-1}$]
^{226}Ra	3.0
^{210}Pb	1000
^{210}Po	1000
^{228}Ra	3.0
^{228}Th	3.0

Geothermal energy production has been classified among the industries handling NORM in the New Basic Safety Standards (2013/59/Euratom) due to the occurrence of radionuclides during the exploration phase and in waste streams. A clearance or exemption threshold for naturally occurring radionuclides in solid materials, under conditions of secular equilibrium with their decay products, is set at 1 $Bq \cdot g^{-1}$. This threshold applies to radionuclides in the ^{238}U decay series, including ^{226}Ra, ^{222}Rn, ^{210}Po, and ^{210}Pb [23].

3. THE NORM RESIDUES AND WASTES INVENTORY

It is not uncommon for a country to establish regulatory requirements for NORM management without a comprehensive understanding of the prevailing national situation. An essential initial step is to examine the list of sectors identified in [4] and to evaluate their relevance within the national context. This involves determining whether each sector is present in the country and whether it involves NORM in amounts that warrant attention. While certain polymetallic ore deposits contain uranium at concentrations that are economically viable for production, most metal ores worldwide do not present significant NORM-related concerns [24].

It is a well-established principle that, before attempting to address a problem, it is necessary to determine whether the problem exists and, if so, to understand its magnitude. Clear knowledge of this information forms the basis for all subsequent actions related to NORM management at the national level.

When scoping NORM-related industries in a country, an initial literature review is essential. This review involves consulting various information sources on NORM issues relevant to each industrial sector in order to understand operational processes, materials of interest, and any aspects that may require further attention.

In business, inventory refers to the items, goods, merchandise, and materials held by an organization for sale in the market to generate profit. In this context, the purpose of inventory is to create a buffer between production and sales, maintain a steady flow of goods, and ensure that products are available when customers place orders. Achieving this objective requires careful inventory management and, when appropriate, the adoption of an adequate inventory system.

The drivers for developing an inventory at various stages of policy formulation are summarized in Table 4. Within the scope of radioactive waste safety, the term inventory is defined as [4]:

> "The total amount of radioactive material, radioactive sources or radioactive waste within a certain specified area or intended to be managed in a certain specified way (or a breakdown of the characteristics of the material or waste within that total amount, for example the total activity of each radionuclide present)".

In practical terms, the inventory is a structured database containing information on existing radioactive waste as well as waste expected to arise in the future. The inventory evolves over time and requires periodic updates. For example, in France, the national radioactive waste inventory is updated every three years [25].

TABLE 4. DRIVERS AND OUTPUT OF INVENTORY BUILDING IN DIFFERENT STAGES OF POLICY DEVELOPMENT

Purpose	Intended Output
Justifying policy action	Order of magnitude to verify that the problem exists and has to be addressed.
Planning of service and investment needs	Order of magnitude of main residue groups in the country. Rough geographical breakdown of NORM residues quantities. Grouping of waste types by main valorization or disposal options.
Fulfilling monitoring and reporting obligations. Informing the national Policy and Strategy	Annual volume of generated NORM residues; activity concentration/total activity; breakdown per management route.

Under the Basel Convention [26], a national waste inventory is a comprehensive compilation of data on hazardous waste within a country. It includes information on the types and quantities of hazardous waste generated, as well as how these wastes are managed. Such national inventories play an important role in tracking the transboundary movements of hazardous wastes and in ensuring that these movements take place in accordance with the regulations established under the Basel Convention. Although classified as NORM, NORM waste may also fall under the category of hazardous waste and therefore be subject to the Convention.

Within the context of this publication, the national inventory of NORM residues is primarily a tool for national authorities to assess the generation and management of NORM residues in the country. Its purpose is to support environmentally sound management practices and contribute to progress towards sustainability and circularity as reflected in national policy. In addition, the inventory provides valuable information to residues producers and managers, encouraging them to identify market opportunities and develop innovative approaches for sustainable management.

3.1. THE STRATEGIC IMPORTANCE OF HAVING A NORM INVENTORY

A national inventory of NORM residues provides comprehensive and up-to-date information on the generation and management of these materials within the country. The drivers for establishing an inventory may differ, and the scope and level of detail required will vary according to the stage of development of the national policy and strategy.

At an initial stage, the primary purpose of the inventory may be to determine whether NORM issues exist nationally. In such cases, the information included may consist of broad estimates of the quantities of major NORM residue streams, acknowledging that these values may be associated with substantial statistical uncertainties.

At more advanced stages, the inventory may support planning for service needs, infrastructure development, and investment decisions. Ultimately, a mature national inventory is expected to contain a detailed breakdown of NORM residues generated and managed in the country, including information by facility, waste stream, and management route.

Regardless of the stage of policy development, the national inventory remains a fundamental tool, as it provides valuable statistical data on the generation and management of residues. This information enables policymakers to assess the effectiveness of strategic actions and to anticipate future changes and trends that require attention [27]. Overall, the national inventory is used by a wide range of stakeholders, including:

- Government departments and agencies that develop waste management strategies and regulate the operation of NORM related industries;
- Supply chain organizations, who are critical in the circular economy (as they are responsible for the sourcing, moving, and transforming materials that enter the global economy each year) and can incorporate NORM residues in place of or along raw materials;
- Individuals who are tasked with the formulation of waste planning and are responsible for making sure waste management facilities fulfil both local and national requirements;
- Researchers and academics who develop innovative technologies and processes for the management of NORM waste or the use of the residues for beneficial purposes;
- Members of the public who want to remain informed on how NORM residues are managed in the country.

3.2. DEFINING THE SCOPE OF THE INVENTORY

In brief, the basic information on NORM residues/wastes will include the following data:

- Description of residue/waste;
- Process and facility in which residue/waste have been generated;
- Residue/waste classification;
- Volumes of existing residues;
- Estimates of residues/wastes to arise in the future;
- Activity concentration of relevant radionuclides;
- Management routes (disposal/incineration/valorization);
- Imports and exports.

Collecting such information is vital for establishing a transparent and traceable system that protects public health and the environment, complies with legal requirements, and supports effective planning for residues management. Moreover, it enables authorities and residues/waste management organizations to monitor the lifecycle of NORM, from generation to final disposal or valorization, and to make informed decisions that enhance policies and infrastructure.

A brief description of each of the above-listed items is provided in the following subsections.

3.2.1. Description of residue or waste

A detailed description of the relevant residue or waste streams, including their physical and chemical characteristics, is essential for accurate identification and classification. This information enables proper handling, treatment, and determination of viable options for use (in the case of residues) or disposal (in the case of wastes). Furthermore, comprehensive descriptions help identify valuable components within residues, supporting efficient recovery and recycling.

3.2.2. Generating facility or process

It is essential to develop a clear understanding of the industries associated with the generation of specific types of NORM residues and wastes, as well as the processes in which these materials arise.

Different NORM-related industrial sectors may produce similar residues, which can often be treated or valorized using comparable methods. Capturing this information in the inventory enables the dissemination of good practices in NORM management across multiple sectors.

For example, NORM-contaminated sediments and sludge are common in many mining operations. Likewise, scrap metal containing NORM scale is a frequent residue in activities ranging from oil and gas production to phosphate fertilizer manufacturing.

3.2.3. Residue or waste classification

The decision to classify NORM residues or wastes as radioactive waste is a national legal or regulatory matter and may have different implications depending on the country's regulatory framework. For example, the disposal of radioactive waste typically requires the use of a licensed facility, which is often operated by a governmental or nationally authorized organization.

In the USA, one of the first countries to regulate NORM, these materials are not regulated by the federal government (i.e., the NRC or EPA) under the Atomic Energy Act or the Low-Level Radioactive Waste Policy Act, unless the material is specifically designated as nuclear source material, byproduct material, or special nuclear material [28]. Instead, each state establishes its own regulations for the handling and disposal of NORM waste, and these wastes are generally not classified as radioactive waste. In Europe, the classification of NORM varies among countries [29]. The decision often depends on national inventories and legal frameworks. In practice, arguments against classifying NORM waste as radioactive waste do not necessarily lead to simplified management; on the contrary, classification decisions can have substantial implications for management approaches and regulatory oversight.

The IAEA [30] proposes six different classes for radioactive waste:

1. Exempt waste;
2. Very short-lived waste (VSLW);
3. Very low-level waste (VLLW);
4. Low level waste (LLW);
5. Intermediate level waste (ILW);
6. High level waste (HLW).

If NORM is regarded as radioactive waste, most NORM waste falls under categories 1, 3, and 4, with small amounts possibly reaching category 5.

Several countries permit the disposal of NORM waste with activity concentrations below 10 $Bq\cdot g^{-1}$ at designated and controlled landfills, together with other types of industrial waste. These classification categories are also relevant for valorization: NORM residues in the range of 1–10 $Bq\cdot g^{-1}$ are generally more suitable for reuse or valorization, including potential marketing as consumer products.

Chemical classification is also an important consideration. For instance, hazardous waste requires specialized management and is subject to specific regulatory controls. This classification determines whether a residue can be disposed of, valorized, or even used directly in the economy without further processing. For most NORM residues, the concentration of hazardous substances, rather than radionuclides, represents the main barrier to valorization or direct use.

3.2.4. Existing and predicted residue and waste amounts

Once the industries responsible for generating NORM residues and wastes have been identified, two different situations need to be considered, when applicable:

- Amounts currently being generated and predictions of future amounts;
- Historical residues/waste stored or disposed of on site.

In the case of mining and ore processing, residues and wastes are generally disposed of near the locations where they originate. This is due to the enormous volumes involved, which make transportation economically and logistically impractical. A key constraint in these cases is that information on the radiological composition of such materials may not be available prior to inventory development, requiring characterization to be performed [31]. For residues and wastes expected to be generated in the future, projections can be made based on current operational data and production trends.

In the case of the oil and gas industry, scales are generally stored in drums, making the calculation of the existing amounts relatively straightforward. Predictions regarding future quantities, however, rely on existing operational data and empirical estimates. For oil fields that have not yet exhibited scale-related NORM issues, estimating future amounts may be more complex. Where radiological characterization of scales has not been performed, sampling and analysis will be required to establish their activity concentrations and support reliable inventory development.

3.2.5. Activity concentration of relevant radionuclides

Information on the quantities of residues and wastes generated, or accumulated over a defined period, needs to be complemented by radiological characterization. Knowledge of the material's chemical characteristics is equally important and is frequently easier to obtain. However, radiological characterization is unlikely to be available in many cases, if not in the majority, prior to inventory development.

In some countries, capabilities for conducting radiological analysis may not even be available outside universities and research centres. Furthermore, many industries may not even be aware that radionuclides of natural origin are present in the raw materials they process. In some cases, operators may also be unaware that the presence of radioactive species in their processes could pose undue risks to workers and the public. As a result, the initial phase of inventory development may not include information on the radiological composition of residues or wastes. Acquiring this data, as will be discussed later, will therefore become the objective of a second phase of the inventory, which may involve collecting samples and analysing them for relevant parameters.

Several analytical techniques are available for the quantification of radionuclide activity concentrations in NORM residues and wastes. These include radiometric methods, such as alpha, beta, and gamma spectrometry, as well as other analytical techniques, including mass spectrometry. When selecting the most suitable technique, it is important to understand the capabilities and limitations of each method [32]. Key factors to consider include selectivity, sensitivity, and the range of measurable activity concentrations. The various techniques differ in their operational complexity and associated costs.

In brief, gamma spectrometry enables the simultaneous detection of multiple radionuclides and generally requires relatively short counting times. It is also comparatively cost-effective. However, low-energy gamma emitters such as ^{238}U and ^{210}Pb may require detectors with enhanced resolution or specialized configurations. Alpha spectrometry, on the other hand, is suitable for measuring very low activity concentrations but requires complex sample preparation involving radiochemical extraction, making it time-consuming and costly. Proportional counting provides information on total alpha and beta activity but does not identify individual radionuclides. Sample preparation is relatively simple, and counting times are short, making this an inexpensive technique. Similar to proportional counting, liquid scintillation counting measures alpha and beta activity without radionuclide identification. Samples must be dissolved in a suitable solution before analysis.

Other analytical techniques include X-ray fluorescence spectrometry (XRF), which is well suited for the rapid determination of elemental uranium and thorium concentrations in solid samples, and inductively coupled plasma mass spectrometry (ICP-MS), which is highly effective for determining total uranium and thorium content.

The selection of an appropriate analytical technique needs to consider the intended purpose of the measurements and be fit for that purpose. In the context of NORM residues and wastes, the basic analytical infrastructure typically includes X-ray fluorescence (XRF) and gamma spectrometry using high-purity germanium (HPGe) radiation detectors. These techniques are complementary and may be applied in combination, when appropriate, together with gross alpha and beta counting for routine measurements. As a general guideline, more advanced radiochemical techniques are often required for baseline surveys, characterization of liquid effluent discharges from NORM-related facilities, and the assessment of materials from industrial processes in which radionuclides such as ^{210}Pb and ^{210}Po are of particular concern. A number of publications describing measurement techniques can be found in Refs [31,32].

3.2.6. Management routes, imports, and exports

Information on how and where waste is disposed of or recovered is essential for evaluating environmental impacts and assessing the effectiveness of residue management practices. It also facilitates the identification of good practices within a given sector or for specific types of residues, which can subsequently be promoted across other facilities or industries. Additionally, where imports or exports of NORM waste are permitted, records of transboundary movements are to be collected. Monitoring the cross-border transfer of NORM waste is important for demonstrating compliance with international regulations and for reducing the risk of illegal disposal practices.

3.3. FRAMEWORK TO BUILD AN INVENTORY

A schematic step-by-step flow diagram illustrating the development of a national inventory of NORM is presented in Fig. 3. The framework is structured into three main phases. Prior to the implementation of these phases, a preliminary step involves the designation, by the Government or the relevant regulatory authority, of an responsible for the development and coordination of the inventory. In Ref. [4], it is stated that:

> "The government should coordinate the establishment of an appropriate national inventory of significant NORM residues arising from new and existing NORM activities. Where possible, residues identified from past practices (i.e. those that need to be considered as part of the national strategy for residue management) should also be included in the inventory".

In the paragraph above, the term 'coordinate' does not explicitly specify whether the collection of information and the development of the inventory is to be carried out directly by a governmental organization. As a result, it leaves open the possibility that these tasks may be undertaken by a private entity on behalf of the Government. It is also to be noted that the inventory described in [4] is primarily intended to support regulatory functions. In the context of this publication, it is acknowledged that the information collected through the national inventory will indeed contribute to regulatory decision-making and compliance; however, its principal purpose is broader. The national inventory is conceived as a strategic tool to inform, support, and guide national policies and strategies for the management of NORM residues and wastes.

The designated organization, or a pool of organizations (under a well-established coordinated scheme), will oversee the collection of the necessary information on the existing NORM residues in the country, including those at legacy sites, as well as a forecast of expected future residue generation.

The capability of the organization(s) responsible for building the inventory plays a key role in the overall process. This entity needs to have appropriate background, experience, and skills for this task. It also needs to have access to a broad range of information sources including license databases, and previous studies (which may not always be publicly available), to serve as a starting point for inventory development. Collaboration with companies generating residues and wastes is of paramount importance. Furthermore, the fact that the inventory builder operates under a formal mandate from the government significantly contributes to the success of this activity.

Different organizations may be involved in the production and maintenance of the NORM residues inventory. While most of the work during the initial phase will fall on the organization designated to lead the process, in the longer term, other actors will play increasingly important roles. Residue producers and managers will provide information on a regular basis, and the regulatory body will oversee NORM-related facilities, ensuring that characterization processes and reported results are reliable. Figure 4 schematically represents the governance structure for NORM residue inventory development, highlighting the roles and responsibilities of the different actors involved.

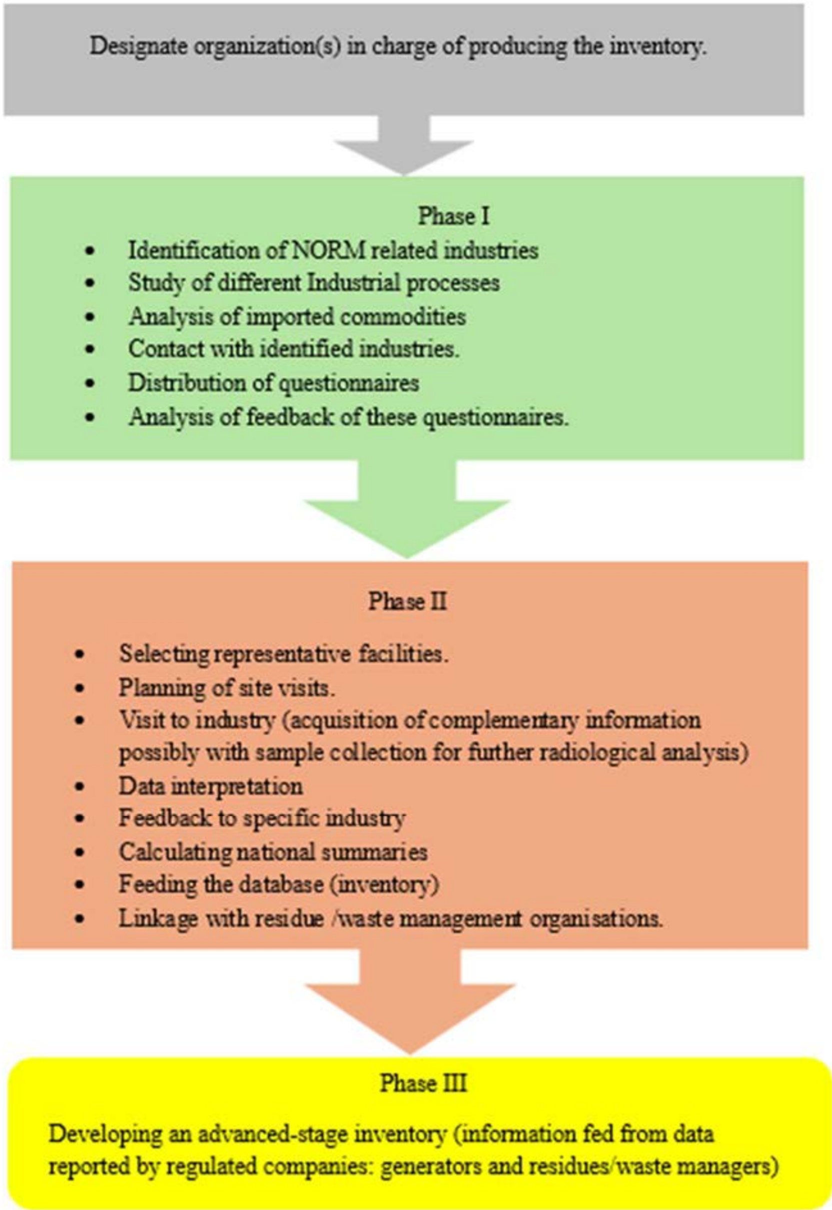


FIG. 3. General approach to the construction of an inventory for NORM residue.

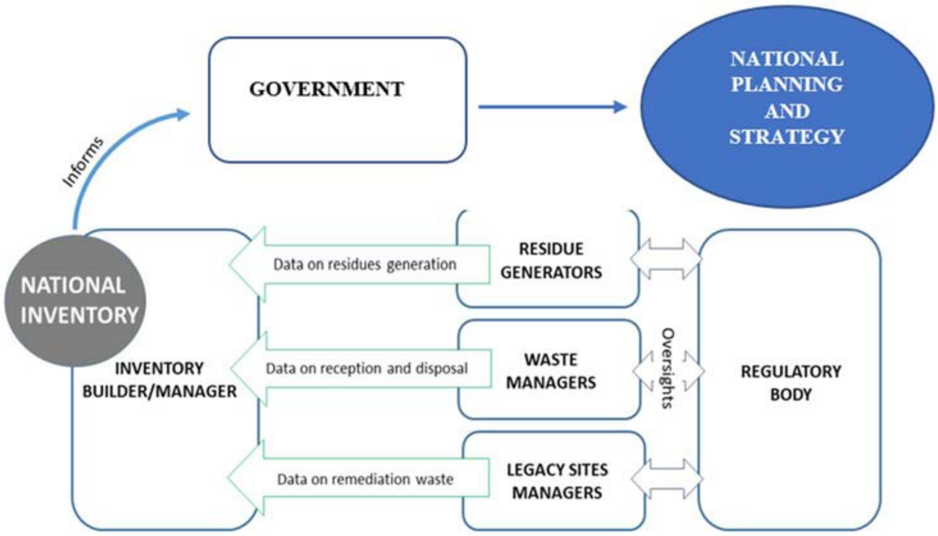


FIG. 4. Roles and responsibilities in inventory building and maintenance.

3.3.1. Phase I: Laying the groundwork; initiating the inventory

This phase consists primarily of office work and planning. The first step is to identify, at the national level, the NORM related industries and legacy sites. The task essentially involves research using databases, national registries (e.g. public registry of commerce, national mining agency), and is to be carried out by the organization designated to develop the inventory. To compile the information, the following steps are recommended:

- Identify facilities within each of the relevant industrial sectors and compile data on their ownership and geographic location;
- Establish a framework and prepare and distribute inventory forms, designed to collect the following information:
  a. Operational flow sheet of the identified industries and activities (NORM generating facilities);
  b. Based on the analysis of the operational flowsheet, data on existing and future volumes of the potentially relevant residues/waste streams from each of the identified facilities;
  c. Data on the physical state (solid, liquid, or solid–liquid mixture) and chemical composition of the relevant residue/waste streams;
  d. Data on the current management route for each relevant residue/waste stream.
  e. Data on radiological characterization of the relevant residues/waste streams (if any);
- Any other relevant information;
- Analyse the collected data and structure it within the inventory database.

Further details on how to implement each of these steps are provided in the following subsections.

3.3.1.1. Identification of NORM related industries and legacy sites

The list of industrial activities as reported in [4] serves as a useful starting point for identifying potential NORM related facilities and activities within the country. However, the association of an individual operation with NORM needs to be confirmed through a site-specific assessment, as the presence of natural radionuclides in raw materials can vary significantly across different geological settings. The steps described so far correspond to the first stage in establishing the inventory. It is possible that some industries initially considered may ultimately prove not to be associated with NORM in a particular country.

For the identification of individual facilities within each relevant sector, legally operating industrial installations must typically be registered in national databases, such as business registries, chambers of commerce, or governmental authorization systems. Depending on the size and complexity of the country, locating and compiling this information can be a time-consuming and challenging task.

An example of how to identify facilities that might warrant further investigation is provided in Ref. [33]. Brazilian mining is an extremely relevant segment for the country's economy representing almost 5% of its Gross Domestic Product (GDP) [34]. The sector supplies products to various industries, including steel, fertilizers, petrochemicals, and metallurgy. Therefore, to provide a comprehensive overview of the mining industry, a national mining map was developed [33].

The database linked to this map is structured into the following categories:

- Industrial minerals: limestone, phosphate, talc, agalmatolite, kaolin, phyllite, asbestos, feldspar, vermiculite;
- Energetic minerals: coal and uranium;
- Metallic minerals: iron, gold, bauxite, copper, manganese, nickel, cassiterite, chromite, niobium, zinc, lithium, tungsten, vanadium;
- Ramp-up projects: gold, iron, phosphate, copper, potassium, zinc/lead, coal, ilmenite, nickel, rare earth elements, bauxite, copper/gold, diamond, lithium, manganese, nickel/cobalt and zinc.

It provides details on the operating company, which facilitates direct contact with the mining operator. Additional information includes the main ore, type of mine, location (city and state), production run of mine (ROM) in tonne year, mine classification and the estimated value of the operation.

Other examples of useful databases that can be used to obtain relevant information are provided in Ref. [35]. For EU countries, the selection of industrial activities potentially associated with NORM can initially be based on Annex VI of the 2013/59/EURATOM Directive [36].

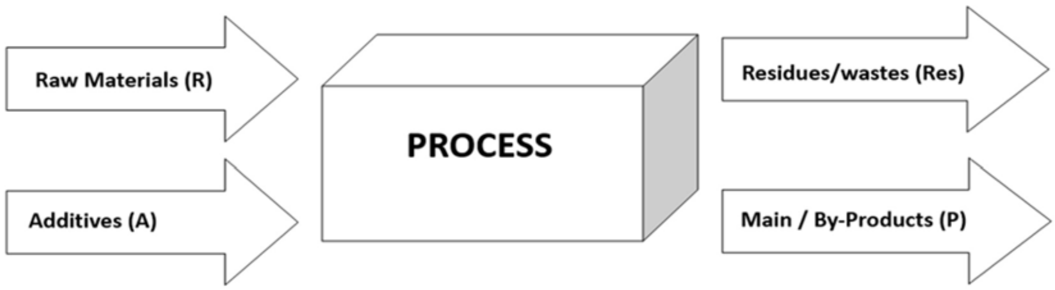
3.3.1.2. Study of different industrial processes and analysis of operational flow sheet of the industry

Once the operations and facilities potentially associated with NORM have been identified, the organization responsible for the inventory needs to analyse the industrial process under investigation to identify the materials or equipment that are likely to exhibit enhanced radionuclide activity concentrations. A generic description of the processes of interest was provided in the previous section focusing on the most relevant industrial sectors, including processing of minerals, water treatment, coal combustion, oil/gas operations and fertilizer production.

The operational flowsheet of each process is an essential tool for this analysis. It provides a step-by-step representation of the processes and sub-processes involved, in sequential order. It enables the identification of points within the process where residues are generated, where radionuclide accumulation may occur, and where sampling or characterization efforts may need to be focused.

Initially, the primary interest lies in understanding the materials entering and leaving the process (i.e. inputs and outputs). In subsequent steps, more detailed characteristics of the process can be explored vis à vis the establishment of the inventory. When examining a flowsheet for inventory purposes, it is essential to determine the amounts of materials entering the system (as raw materials) and leaving it (in the form of residues and wastes). When information on the activity concentration of the inputs and outputs is already available, the analysis becomes straightforward. However, it is important to emphasize that in NORM related industries, the presence of radionuclides is usually unintended (in other words, the radioactive properties of the material are not relevant for the sake of that process). Consequently, unless regulatory requirements exist, data on the radiological properties of materials in the process are likely to be absent. Nevertheless, a substantial body of scientific literature exists on the fractionation of natural radionuclides across various industrial processes. These serve as a good basis for an initial appraisal of these industries.

In simple terms, for any given process, the amount of raw material (and other inputs) entering the process multiplied by the activity concentration of the individual radionuclides in the raw material (inputs) will give the total input activity of radionuclides. The total output activity, accounting for residues and products, is calculated in the same way as for the materials entering the process. A schematic representation is shown in Fig. 5.



Mass Balance (for the whole process)	Activity Balance (for a specific radionuclide (i), assuming no radioactive decay during the considered time interval Δt
$\sum M_R + M_A = M_{Res} = M_P$	$\sum A_{R,i} + A_{A,i} = \sum A_{Res,i} + A_{P,i}$
Unit Kg [entering/leaving during time interval Δt]	Unit Bq [entering/leaving during time interval Δt]

FIG. 5. Example of a simplified industrial process including the mass balance and the activity balance for a specific long-lived radionuclide present in the incoming raw materials and/or additives.

In certain industries, raw materials may not be sourced domestically but imported from diverse regions, resulting in variations in composition and radiological characteristics. The geochemical properties of the ore exert a significant influence on the composition of the resulting residues. Consequently, extrapolations based on limited data can introduce substantial errors if such potential variability is not adequately considered.

3.3.1.3. Contact with identified industries

At this stage, industries potentially related to NORM in the country would have been identified and localized geographically (if not exhaustively, then at least to a significant extent, including the principal producers). The next step involves contacting individual facilities to communicate the purpose of the inventory, encourage their participation, validate the information collected in previous steps, and obtain additional data.

In countries lacking a regulatory framework for NORM management, researchers and even regulatory authorities frequently report challenges in securing cooperation from companies. Such reluctance often stems from concerns about protecting proprietary information or avoiding disclosure of details that could negatively impact the company's valuation. Furthermore, it has been observed that companies may fear that sharing operational information could lead to the imposition of additional regulatory requirements, potentially resulting in undesirable economic consequences.

These situations can often be addressed on a case-by-case basis; however, engaging with business associations rather than individual companies can be a more effective strategy.

Conversely, some companies may recognize the advantages of adopting a national approach to the management of NORM residues and wastes. For instance, the oil and gas sector, which generates scales and sludges containing naturally occurring radionuclides, would benefit from the establishment of disposal routes for such materials, particularly given that no beneficial use has yet been identified for these wastes.

Likewise, if the government recognizes that many of the residues stored at production facilities could be repurposed for beneficial use, thereby creating business opportunities for companies and delivering societal benefits, dedicated policies can be introduced to promote the valorization of these materials. Such measures would contribute to sustainability and foster economic growth. In summary, demonstrating the benefits of information sharing is essential to encourage industry cooperation.

Eventually, regulatory requirements will be established, compelling industries to provide the necessary data. However, it is in their best interest to share information proactively, prior to the adoption of regulations, so that the country-specific context can be considered during the regulatory development process. This approach *will enhance the likelihood* that regulations are effective, practical, and impose the minimum possible burden on stakeholders.

3.3.1.4. Distribution of questionnaires

Establishing an organized system for data collection is essential to harmonize the information received from different industries and, in doing so, create the conditions for a more efficient process of data consolidation. The specific information to be collected through the questionnaires is described in the following section. It is important that questionnaires are tailored to each industry so that potential NORM residue and waste streams are pre-identified prior to distribution.

When the number of facilities is large, it may be advantageous to develop a dedicated web platform where companies can upload their data directly and attach supporting materials such as technical drawings and maps, while ensuring confidentiality and data protection.

3.3.1.5. Analysis of the feedback to the questionnaires

With the provided information, a careful analysis of the data needs to be made. Validating the submitted data and assessing its accuracy can be challenging and gaps are likely to be identified, particularly where radiological characterization data are unavailable, as noted previously

Based on the questionnaire results, the organization responsible for the inventory needs to determine whether site visits are necessary and define the specific objectives of such visits. Key considerations include whether samples will be collected, which materials should be sampled, and how to ensure that the samples are representative. Additionally, decisions must be made regarding the analytical methods to be employed and the facilities where the collected samples will be analysed.

At this stage, the consolidated information may be organized into a database, potentially linked to a Geographic Information System (GIS), to visually represent the geographic distribution of the identified industries. Relevant information to be uploaded is as follows:

- The first level of information will include the facility contact and administrative details and other relevant information such as annual physical production;
- The second level of information will include information on the annual amounts of generated residues and released effluents, current management strategies, activity concentrations of the relevant radionuclides in residues and effluents (if available) and the associated mass balance;
- The inventory can be expanded to include a third level of information that would contain other sorts of related information that will be of interest from the perspective of safety considerations [37]. Such data could include records of dose levels in different working areas (if available); estimates of radiological impact assessment of the discharges in the environment (air and water bodies); any information from radiological monitoring programs.

In practice, companies are generally able to provide the first level of information and part of the second level. However, radiological data may be unavailable for many facilities, particularly in countries where routine characterization is not yet established.

3.3.1.6. Final considerations

The processing of raw materials inevitably results in the generation of various forms of residues and wastes, including potential releases to the atmosphere (gaseous emissions and aerosols) and to aquatic bodies (rivers, lakes, marine environments, and groundwater). To prevent environmental contamination arising from industrial activities, discharges may be subjected to controls. This publication does not deal with such situations; instead, it focuses on solid residues that are generated and eventually stored or disposed within the premises of a given facility. Depending on site-specific conditions and residue characteristics, these materials may be repurposed for beneficial use or transferred to an authorized facility for disposal.

With respect to disposal, one critical aspect to consider is the leaching potential of the material and the nature of contaminants that may be present in the leachate, particularly naturally occurring radionuclides. While such information is unlikely to be available during Phase I of the inventory at the facility level, these studies can be undertaken on a broader scale in subsequent phases.

Assessing the likelihood of contaminant leachability provides valuable insight into the potential mobilization of radionuclides and other contaminants under different management scenarios, thereby informing safe and sustainable disposal practices.

3.3.2. Phase II: Developing the early-stage inventory

With the information collected during Phase I, an initial overview of the main industrial sectors involving NORM within the country becomes available, along with a preliminary estimate of the quantities of residues requiring management. However, significant gaps in the data are expected and may vary across industries.

Phase II focuses on addressing these gaps by selecting representative facilities for detailed investigation. For these facilities, site visits will be conducted to collect samples for laboratory analysis and perform field measurements. To ensure consistency and reliability, the organization responsible for the inventory will need to develop industry-specific standardized protocols for sampling and radiometric analysis.

The following subsections describe:

- How to select representative facilities;
- How to conduct site visits and, finally;
- How to build the early-stage inventory based on the results obtained in Phase I and by means of activities (i) and (ii) above.

The resulting early-stage inventory will be shared with policymakers and other stakeholders involved in strategy development, including waste management organizations, to support planning and decision-making. A simplified version, typically excluding facility-specific details and presenting aggregated data by sector or waste stream, can also be made publicly available to promote awareness, ensure transparency, and build trust in support of the national policy and strategy for NORM residue management.

3.3.2.1. Selecting representative facilities

Prioritizing the industrial facilities for detailed investigation is a critical step, as it is generally impractical to address all installations simultaneously during this initial stage. The number of facilities selected will largely depend on the financial and human resources available to the organization responsible for developing the inventory. In general, the inclusion of a greater number of facilities will improve the accuracy and reliability of inventory estimates. As a minimum requirement, at least one facility has to be selected from each NORM-related industrial sector operating within the country.

The selection criteria may vary across sectors. When considering the production of a given commodity, for example, fertilizer, if more than one industry operates in the sector, it may be appropriate to prioritize the analysis of one representative facility and then make careful extrapolations to the others. This needs to be done with the understanding that differences in ore type and operational processes can provide important insights into the characteristics of the sector as a whole. In mining and mineral processing industries, the mineralogical composition of the ore can serve as an indicator of the likelihood of natural radionuclides being present in residues and wastes. For instance, potassium occurs in various mineral forms in the Earth's crust, including sylvite (KCl), carnallite ($KMgCl_3 \cdot 6H_2O$), langbeinite ($K_2Mg_2(SO_4)_3$), polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$), and potassium feldspathic minerals such as orthoclase. Thorium may appear as a trace element in phosphates, oxides, and silicates, including monazite ($(Ce,La,Nd,Th)PO_4$), thorianite (ThO_2), and thorite ($ThSiO_4$). Uranium can occur in accessory minerals such as brannerite ($(U,Ca,Ce)(Ti,Fe)_2O_6$), carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 2H_2O$), uraninite ($UO_2$), uranophane ($Ca(UO_2)_2(Si_2O_3 \cdot 5H_2O)$), apatite ($Ca_5(PO_4)_3(OH,F,Cl)$), sphene ($CaTiOSiO_5$), pitchblende ($U_2O_5 \cdot UO_3$), and zircon ($ZrSiO_4$) [38]. Considering the list of industries typically associated with NORM and the mineralogical composition of the ores processed in each operation can provide valuable clues about which facilities are more likely to generate residues containing natural radionuclides. This analysis is particularly relevant when no information is available regarding activity concentrations of radionuclides in raw materials (ROM) or in residues and wastes.

Caution is needed when extrapolating results from one facility to another within the same commodity sector, as specific mineral processing characteristics can lead to significant differences in radionuclide partitioning among residues and wastes [39].

Another approach is to prioritize facilities based on factors such as production scale, proximity to major urban centres, or other criteria deemed relevant. The complexity of this task will depend on the size of the country, the geographical distribution of industries, accessibility, and the diversity of industrial activities. In general terms, the following prioritization criteria can be considered for selecting representative facilities across sectors:

- Volume of annual production (prioritizing the main producers), or annual volume of potential NORM residues produced;
- If available from phase I, activity concentration of radionuclides in the residue/waste streams, or as a surrogate, data on heavy metal concentration that show a strong positive correlation with naturally occurring radionuclides such as Pb, Hg, Zn or As);
- Information on previous incidents from specific facilities e.g. whether there have been detections of radioactive material from radiation portal monitors in ports or smelters;
- Urgency. Facilities transferring large amounts of NORM residues per year to offsite managers can be prioritized over facilities where the residues and waste are stored or disposed on site, in order to acquire reliable estimates that would be needed for assessing infrastructure needs at the national level.

3.3.2.2. Visit to the industry

The primary purpose of the site visit is to obtain radiological data for the main residue and waste streams and to verify the accuracy of the information provided by the facility during Phase I. Additionally, the visit helps identify any relevant residue(s) type(s) that may not have been previously reported. Beyond data collection, the site visit offers an excellent opportunity to engage with facility staff, explain the objectives of the inventory in greater detail, capture industry expectations, and clarify outstanding issues. This interaction strengthens engagement and mutual trust, emphasizing that the process aims to achieve objectives of shared benefit. The site visit may start with an opening meeting where the objectives of the inventory project are clearly communicated, and any remaining questions from the previous phase are addressed. It is essential to clarify the scope of the visit from the outset and stress that the visit is neither an audit nor an inspection; its sole purpose is to collect relevant data for the inventory. Facility representatives may seek clarification regarding potential implications of the visit, particularly concerning confidentiality and data disclosure, and these concerns needs to be addressed transparently. Points to be addressed during the visit can include:

- Description and listing of master data for the operational processes (flowchart), including all data fields and attributes with confirmation of all the residue/waste streams;
- Validation of the shared information with the team (eventually composed by subject matter experts);
- Making sure that there have been no significant changes in the process recently;
- Sampling of operational residues and, when applicable, temporal storage or disposal sites, for subsequent radiological analysis;
- In situ measurements, including ambient gamma dose rate; surface contaminations; an in-situ gamma spectrometry.

The visit concludes with a final meeting during which the main observations are presented, outstanding issues are addressed, and a mutual commitment is established regarding full disclosure of the data to be obtained. It is also essential to agree, preferably from the outset, on which information may be made public, and which needs to remain confidential due to commercial sensitivity. Once the data set has been compiled, interpreted and subjected to quality control procedures, the information will be uploaded in a dedicated database.

3.3.2.3. Data interpretation

When interpreting results obtained from the site visits, it is important to recognize that these visits provide only a snapshot of the radiological situation at the facility; they do not constitute a continuous monitoring program. Consequently, temporal variability in the activity concentrations of natural radionuclides in residues and waste streams is not captured during this phase and would require dedicated monitoring to be addressed.

It is also essential to distinguish between the process of data acquisition for the purpose of building a residue/waste inventory and a full-scope radiological risk assessment of industrial operations. The latter would require additional measurements and methodologies beyond those applied in Phase II. For example, Ref. [40] reports an assessment of worker exposure to natural radionuclides in various mining and processing operations in Brazil. Internal contamination was evaluated using indirect methods, including the analysis of uranium, thorium, and polonium concentrations in excreta samples, complemented by measurements of thorium and uranium in air samples. Polonium was determined in urine samples as a screening tool to indicate radon exposure. In addition, some workers were equipped with personal air samplers fitted with cyclones (cut-off diameter: 2.5 μm) during an 8-hour working period to assess inhalation exposure.

For the sake of environmental impact assessment, it will be necessary to couple release data (liquid and aerial effluents) with dose assessment models, at least at a screening level. Additionally, evidence of groundwater contamination resulting from seepage from waste piles and dams needs to be investigated. These impacts may occur in the present or manifest only in the future. In such cases, understanding the source term is of critical importance, as mechanisms triggering the release of radionuclides and other pollutants may be initiated over time. An example of such a screening approach applied to a uranium mining and milling facility in Brazil is presented in Ref. [37].

3.3.2.4. Feedback to specific industry

The results of the surveys and site visits are to be shared with the respective facility. This feedback enables the industry to address specific issues, gain a clearer understanding of residue/waste streams of concern and orientate its actions toward implementing appropriate management practices.

It is not uncommon for industry operators to be unaware of potential radiological issues associated with their operations. In many cases, facilities may have commenced operations decades ago without conducting a comprehensive environmental impact assessment. Consequently, certain mitigative measures, such as lining the ground beneath areas designated for residue or waste placement, may not have been implemented.

Providing feedback also serves an 'educational' purpose, helping industry operators understand radiological risks associated with NORM, radiation protection principles, and internationally recognized good practices. This approach maximizes the benefits of interaction between the inventory developer and the industry while fostering mutual confidence and trust, as previously emphasized.

3.3.2.5. Calculating national summaries

Depending on the scale of industrial activities involving NORM within a country, this step may require considerable time and effort to be completed. It can be regarded as a dynamic process, requiring periodic updates as new data become available.

Results obtained from the site visits will be incorporated into the database, not only to document facility-specific information but also to support the development of sector-wide estimates. These estimates enable the calculation of residue and waste volumes, as well as activity concentrations, at the national level. For example, site visit data may indicate that a significant portion of sludges generated at oil extraction sites qualifies as NORM, with an average activity concentration represented by a specific value in $Bq \cdot g^{-1}$. Such estimates, following appropriate statistical analysis, can then be applied as multipliers to fill gaps in Phase I data, thereby improving the completeness of the national inventory.

It is important to note that estimates produced during Phase I will be subject to large uncertainties and therefore need be considered semi-quantitative. All assumptions made during the calculation of national summaries must be clearly documented in a technical report describing the methodology used to develop the inventory.

The consolidation of the inventory will aggregate the amounts of residues and wastes across different industries and geographical regions. This geographic dimension is particularly important in countries with large territorial areas, as it influences transportation costs when disposal sites are located far from points of generation. It may also determine the need for multiple disposal facilities to optimize logistics and reduce costs. Furthermore, the inventory can classify NORM wastes into ranges of activity concentration, which is essential for defining appropriate management strategies.

Ultimately, the inventory will serve as a critical planning tool for the waste management supply chain, enabling stakeholders to anticipate infrastructure needs and make timely investments to avoid capacity shortfalls [41].

This process will also encourage waste producers and management organizations to provide high-quality data on current and future NORM waste arisings. When residues are not classified as waste because they have potential for beneficial use, the inventory will support economic decisions based on a market-driven supply-and-demand approach.

3.3.2.6. Linkage with residue/waste management organization.

As already mentioned, the development and maintenance of the NORM residue/waste inventory may be assigned to different entities, such as the regulatory authority, the national radioactive waste management organization (where one exists), or another designated body tasked with this specific role.

Regardless of the responsible entity, the inventory serves as a strategic planning tool and provides essential input for the formulation of policies, strategies, and regulations at the national level. Therefore, it needs to be made accessible to all relevant stakeholders.

3.3.3. Phase III: Developing the advanced stage inventory

Phase II of the inventory provides the foundation for establishing a national policy and strategy for NORM residue management and for developing rational, balanced regulations that are feasible to implement. However, it must be emphasized that Phase II remains semi-quantitative in nature, as it is subject to potentially significant uncertainties.

In the long term, and depending on applicable regulatory requirements, accurate data for inventory development will need to be provided regularly by each regulated facility. This information should be based on a characterization programme previously approved by the regulatory body, as part of the facility's NORM residue management programme. On the other hand, NORM residue managers may also be required to provide information on the volumes of residues they valorize, import or export, or dispose of each year.

The organization responsible for maintaining the inventory will be in charge of validating the information provided by each facility/company, cross checking the data from residue producers and managers and performing other quality control checks.

Ideally, the national inventory will have to be updated regularly. Statistics on residues generation (accounting for ongoing industrial activities and waste coming from the remediation of contaminated sites) and on management routes provide very valuable information in terms of the policy and strategy established by the Government. For example, such statistics provide the basis for assessing infrastructure capacity; monitoring progress towards the relevant indicators and targets; identifying trends, etc. Some considerations on aggregating data to produce relevant statistical outputs are given in the following section.

3.3.3.1. Aggregating data

Producing statistical outputs requires systematic data processing, with the final stage involving the calculation of aggregates.

After appropriate data treatment (conversion of units; validation, etc.), the data collected is processed to generate statistical outputs on the volumes of NORM residues. These summaries may be grouped by stream, activity concentration range, or management route, depending on the objectives of the analysis.

Most of the aggregates calculated will be sums and means (or any other percentile of the distribution of input data):

- Sum typically refers to the total amount of a given continuous variable (such as volume);
- Mean refers to the arithmetic mean of the individual values.

In both cases, calculating aggregates is straightforward, however, data gaps and missing values have to be properly addressed to ensure sound outputs:

For sums, missing values can be replaced through imputation, for example, using estimates validated by statistical analysis of historical data. When imputation is applied, the contribution of estimated values to the final total must be assessed, and threshold rules may be established to determine whether the final estimate is reliable.

For obtaining means, missing values may be: i) ignored, which reduces precision but can be acceptable when data are normally distributed and missing values occur randomly; or ii) replaced by imputation, using statistically derived estimates to maintain representativeness.

Data aggregation is a common task performed by many international organizations. The Food and Agriculture Organization of The United Nations (FAO), for instance, makes the following technical recommendations regarding this process [42], which are highly relevant to managing and producing estimates for the inventory of NORM residues:

- Collaboration between statisticians and subject matter experts is encouraged to design data aggregation strategies based on robust methodologies. The goals, methods, and assumptions involved have to be explicitly defined and documented;
- Careful monitoring is essential during the implementation of the aggregation process in the selected software to prevent errors. The process needs to undergo thorough testing to ensure accuracy and reproducibility;
- Aggregated data should include relevant contextual information, such as units of measurement and reference periods, to facilitate accurate interpretation.
- Users have to be informed when aggregates are derived solely from reported data, excluding missing values. They also need to be made aware of how this approach might impact the accuracy of the final statistical outputs;
- If data imputation is used to address gaps for aggregation purposes, the assumptions underlying the imputation process have to be transparently communicated. Additionally, the extent of missing data and the potential influence of imputed values on the final results need to be assessed and shared with users.

3.3.3.2. Updating of the inventory database

As highlighted in international best practices for waste inventory record-keeping systems for the management and disposal of radioactive waste [43], the NORM residue inventory database is not a self-sustaining entity once initially implemented. Over its lifetime, updates and modifications will be necessary to maintain functionality and relevance. These changes may arise due to:

— Problems are encountered (glitches or “bugs”);
— Inventory users may request enhancements or improvements;
— Additional data set items may be specified, or existing items may be removed, and
— Technological changes (e.g., hardware/software changes) may force the reengineering of the database hosting the inventory.

4. CALCULATING THE AMOUNTS OF RESIDUES

This section provides examples of how an inventory of NORM residues can be developed for a given facility. It is emphasized that a thorough understanding of the industrial process is essential, including knowledge of where NORM is likely to occur and how to obtain reasonable estimates of the quantities generated. As these estimates will inevitably carry a degree of uncertainty, this must be carefully considered when interpreting the results and making decisions based on them.

4.1. METALLIC AND NON-METALLIC MINERAL PROCESSING

In developing an inventory, an analysis of material distribution when process streams split and combine is highly beneficial. Such analysis is an integral component of mineral processing studies and provides essential information for designing and evaluating flow sheets, as well as for operational assessments of processing plants.

The fundamental principle governing material accounting in any processing plant or unit operation is mass conservation, expressed as:

$$\text{Mass In} = \text{Mass Out} \tag{1}$$

Accordingly, the material balance is based on the principle of conservation of matter:

$$\text{Input-Output} = \text{Accumulation} \tag{2}$$

For a continuous system[8] operating at steady state, accumulation is zero, and therefore:

$$\text{Input} = \text{Output} \tag{3}$$

In mineral processing operations, a single input of feed (ore) typically yields a concentrate containing most of the valuable metal and a tailing composed primarily of gangue minerals. Thus:

$$\text{Tonnes of feed } (M_F) = \text{Tonnes of concentrate } (M_C) + \text{Tonnes of tailings } (M_T) \tag{4}$$

Let f, c, and t represent the fractions of the metal in the feed, concentrate, and tailings, respectively. Then:

$$f\,M_F = c\,M_C + t\,M_T \tag{5}$$

Combining equations (4) and (5), the ratio of feed mass to concentrate mass is:

$$\frac{M_F}{M_C} = \frac{c - t}{f - t} \tag{6}$$

[8] This is a key difference between conducting an inventory in a mining industry with a continuous process and in oil and gas operations in which the residues are not generated in the same fashion e.g. the accumulation of scales in pipes and tubing.

The plant recovery R, expressed as a percentage, is then given by:

$$R = \frac{M_C\, c}{M_F\, f} \times 100 \quad (7)$$

In industries related to NORM, the objective is not to evaluate the efficiency of the production process in generating the intended product(s). Instead, the focus lies in understanding how natural radionuclides fractionate across the various residue streams including both the activity concentrations within the residues and the quantities of these residues generated. The mass balance calculation provides an estimation of the consistency of the information being evaluated and helps identify whether any significant amounts are unaccounted for.

The quantities of residues generated by a given industry, along with their associated activity concentrations of natural radionuclides, inform the management options required from a radiological protection perspective. For instance, if further assessment shows that certain residues have to be relocated from their current storage areas, the operational requirements and available management options for doing so will need to be identified. This decision-making process involves safety considerations, including the evaluation of radionuclide mobility within the residues and their potential to migrate through environmental pathways and reach receptors. Conversely, some residues may be suitable for beneficial use. In such cases, accurate knowledge of the quantities produced, combined with detailed radiological characterization, constitutes critical information for developing a business case and assessing the economic feasibility of valorizing these materials.

The analysis of data obtained through surveys, supplemented by information collected during on-site visits, enables more accurate estimations. However, in the absence of such detailed information, an alternative approach involves calculations based on the quantities of ore extracted from mines in different regions. This method utilizes ore grade data and the correlation between run-of-mine ore and commercial concentrate to predict the amount of waste generated throughout the mining operation. The crucial requirement for applying this approach is having knowledge of the radiological composition of the ore.

The total radionuclide activity entering the process is based on the quantity of run-of-mine processed and the activity concentrations of the natural radionuclides present in this feed material. This activity is then apportioned between the final product and the various solid, liquid, and gaseous residues discharged from the system, as depicted in Fig. 1.

4.1.1. Fractionation of radionuclides in non-ferrous mineral processing

Industrial processing characteristics vary significantly across sectors. In this subsection, three representative examples are presented: niobium production, rare earth processing, and the fertilizer industry.

4.1.1.1. Example: fractionation of radionuclides during niobium processing

Tables 5 and 6 illustrate radionuclide distribution in two niobium (Nb) processing plants [39]. In this investigation, samples of run-of-mine material and residues from two distinct operational processes were collected and analysed for radionuclides belonging to the ^{238}U and ^{232}Th decay series.

Sampling was carried out by the facility operator in accordance with the established quality assurance and quality control procedures. The collected material consisted primarily of composite samples representing one full day of operation. It is important to note that these samples were taken from active process streams, not from residues already deposited on site. Quantifying the radionuclide content of deposited residues requires a separate assessment, applying a different methodological approach. After sampling, the materials were transported to the laboratory, where they underwent chemical digestion followed by radiological analysis. A detailed discussion of sampling strategies and analytical protocols lies beyond the scope of this publication. However, for the sake of the objectives of this publication (i.e. inventory construction), some observations are worth mentioning.

TABLE 5. ACTIVITY CONCENTRATION IN DIFFERENT MATERIALS OF Nb PROCESSING INDUSTRY I.

Operational Step	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{228}Ra	t/h
ROM ($Bq \cdot g^{-1}$)	*0.9*	0.8	1.3	*6.4*	5.2	145
Total Activity (Bq)	1.1×10^{12}	1.0×10^{12}	1.7×10^{12}	8.1×10^{12}	6.6×10^{12}	
Magnetic Separation Residue ($Bq \cdot g^{-1}$)	1.1	0.3	0.7	0.9	0.8	22
Total Activity (Bq)	2.1×10^{11}	5.8×10^{10}	1.4×10^{11}	1.7×10^{11}	1.5×10^{11}	
Washing Residue ($Bq \cdot g^{-1}$)	1.3	1.4	2.0	9.0	5.3	17.3
Total Activity (Bq)	2.0×10^{11}	2.1×10^{11}	3.0×10^{11}	1.4×10^{12}	8.0×10^{11}	
Flotation Residue ($Bq \cdot g^{-1}$)	0.8	1.0	2.4	3.1	1.4	*89.7*
Total Activity (Bq)	6.3×10^{11}	7.9×10^{11}	1.9×10^{12}	2.4×10^{12}	1.1×10^{12}	
Barium Sulphate (barite) ($Bq \cdot g^{-1}$)	0.04	*26*	7.4	0.04	*197*	0.6
Total Activity (Bq)	2.1×10^{8}	*1.4×10^{11}*	3.9×10^{10}	2.1×10^{8}	*1.0×10^{12}*	
Aluminothermic Slags ($Bq \cdot g^{-1}$)	*23*	3.3	2.4	*118*	20	3.0
Total Activity (Bq)	*6.0×10^{11}*	8.7×10^{10}	6.3×10^{10}	*3.1×10^{12}*	5.4×10^{11}	
∑ All Fraction	1.6×10^{12}	1.3×10^{12}	2.4×10^{12}	7.1×10^{12}	3.6×10^{12}	
Total Activity Rom)/ ∑ Activity in all Fractions	1.44	1.26	1.47	0.87	0.55	132.6

Note: Italicized values indicate radionuclide concentrations or operational parameters of particular significance as discussed in the text.

TABLE 6. ACTIVITY CONCENTRATION IN DIFFERENT MATERIALS OF Nb PROCESSING INDUSTRY II.

Operational Step	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{228}Ra	tonne/a
ROM (Bq·g^{-1})	*4.5*	3.4	8.0	*0.9*	2.0	65
Total Activity (Bq)	2.6 × 10^{12}	1.9 × 10^{12}	4.6 × 10^{12}	5.1 × 10^{11}	1.1 × 10^{11}	
Magnetic Separation Residue (Bq·g^{-1})	0.8	0.9	1.7	0.3	0.3	13
Total Activity (Bq)	9.1 × 10^{10}	1.0 × 10^{11}	1.9 × 10^{11}	3.4 × 10^{10}	3.4 × 10^{10}	
Washing Residue (Bq·g^{-1})	6.7	6.9	6.2	1.7	3.0	17.3
Total Activity (Bq)	1.7 × 10^{11}	1.8 × 10^{11}	1.6 × 10^{11}	4.4 × 10^{10}	7.8 × 10^{10}	
Flotation Residue (Bq·g^{-1})	5.0	3.4	7.5	1.0	1.8	43
Total Activity (Bq)	1.8 × 10^{12}	1.2 × 10^{12}	2.8 × 10^{12}	3.7 × 10^{11}	6.8 × 10^{11}	
Aluminothermic Slags (Bq·g^{-1})	*35*	5.0	0.4	17	*6.4*	0.82
Total Activity (Bq)	2.5 × 10^{11}	3.6 × 10^{10}	2.8 × 10^{9}	1.2 × 10^{11}	4.6 × 10^{10}	
Total ∑ All Fraction	4.9 × 10^{12}	3.5 × 10^{12}	7.7 × 10^{12}	1.1 × 10^{12}	1.9 × 10^{12}	74.1
(Total Activity ROM)/ ∑ All Fraction	1.94	1.83	1.70	2.13	1.73	

Note: Italicized values indicate radionuclide concentrations or operational parameters of particular significance as discussed in the text.

In Industry I, the activity concentration of ^{232}Th exceeds that of ^{238}U. Among the residue streams, the material originating from the flotation step exhibits the highest mass compared to other residues generated during processing. The ratio between the total mass entering the process (145 tonne/h) and the combined mass of all residue streams is 0.91, which appears to be within an acceptable range.

In the barite stream, the most significant radionuclides are the two radium isotopes, with activity concentrations up to three to four orders of magnitude higher than other radionuclides in the decay series. In contrast, the metallurgical slags primarily contain ^{238}U and ^{232}Th. Although the masses of residues associated with barium sulphate and metallurgical slags are relatively small compared to other streams, their total activities are of the same order of magnitude.

A pronounced disequilibrium is observed following acid leaching of the concentrate with sulfuric acid, which generates the barium sulphate residue. The potential dissolution of this residue poses an environmental risk, particularly to groundwater, and therefore requires careful management. Conversely, despite the elevated activity concentrations of ^{238}U and ^{232}Th in the slags, their refractory nature significantly limits radionuclide mobility.

The amount of ^{238}U associated with the flotation residues is approximately 50 t/a, a value similar to that observed for the residues from the metallurgical process. In principle, extracting uranium from the slags is more complex than recovering it from the flotation residue. However, recent studies on the recovery of uranium oxide from aluminothermic slags generated during the metallurgical processing of columbite have demonstrated that recovery efficiencies above 80% can be achieved for uranium oxide at pH < 1.5 and processing times exceeding eight hours. These findings indicate that the residues produced during niobium processing may represent a viable secondary source of uranium.

In Industry I, the activity concentration of ^{232}Th was approximately six times higher than that of ^{238}U, whereas the reverse was observed in the run-of-mine material of Industry II, where uranium activity concentration was nearly five times greater than thorium. In Industry I, one residue stream consists of barium sulphate, exhibiting activity concentrations as high as 197 $Bq \cdot g^{-1}$ for ^{228}Ra and 26 $Bq \cdot g^{-1}$ for ^{226}Ra. This residue type is absent in Industry II.

In Industry II, where barium sulphate is not present, the residue of primary concern with respect to natural radionuclide activity concentrations is the metallurgical slag, which contains ^{238}U and ^{232}Th at activity concentrations of approximately 35 $Bq \cdot g^{-1}$ and 17 $Bq \cdot g^{-1}$, respectively.

From an economic perspective, approximately 1.88×10^{12} Bq of ^{238}U are generated annually in Industry II within the flotation residue stream. This corresponds to an estimated 150 tU per year. At a (spot price)[9] of USD 88 per kilogram of uranium, the potential revenue from selling this material would amount to approximately USD 13 million [44]. It must be emphasized, however, that this figure represents only a preliminary estimate, as significant capital investment would be required to establish the necessary infrastructure, in addition to ongoing operational costs. Nevertheless, such inventory data provide valuable insights for assessing the feasibility of residue valorization.

The IAEA has published a report on the inventory of uranium resources in mine wastes [45], with the objective of promoting the evaluation of complete uranium extraction from these materials. This initiative also aims to establish a framework for integrating resource recovery with environmental and remediation strategies to achieve a zero-waste approach. The methodology proposed in this study aligns with the principles outlined in Ref. [45] but focuses specifically on non-uranium mining and processing operations.

The residues generated by both industries are significant not only in the context of uranium recovery. In Industry I, as previously noted, one of the residues is barite. The barite concentration process utilizes waste material from the niobium concentration stage [46]. Part of the final waste from the flotation stage is thickened in hydro cyclones, followed by conditioning and direct flotation of barite in flotation columns. The resulting product, containing more than 85% $BaSO_4$, is dewatered and subsequently marketed as barite concentrate. However, the presence of radium isotopes in these residues may raise radiological concerns depending on the intended application of the material, and this issue must be carefully addressed.

Regarding Industry I, a route for producing magnetite from residues of pyrochlore processing is also under evaluation. The magnetic residue is generated through magnetic separation, after which the magnetic fraction is sent to a cycloning stage to reduce contaminants. Material containing more than 60% Fe is then dewatered for subsequent commercialization [46].

[9] https://www.cameco.com/invest/markets/uranium-price

Although natural radionuclides are present in this residue, the observed activity concentrations appear to be sufficiently low to avoid raising additional radiological concerns. However, this aspect needs to be addressed.

For slags, it is important to note that these materials, originating in this case from tin smelters, may contain not only thorium and uranium but also valuable elements such as Ti, Ta, Zr, Hf, and rare earth elements [46]. Consequently, slags represent a significant potential resource for the mineral processing industry. Conventional leaching methods for uranium recovery from slags are often ineffective due to uranium's association with refractory phases, particularly silicon and titanium. An alternative approach involves breaking down these refractory phases through fusion techniques, thereby enhancing the economic viability of recovery. This process employs a fusing agent to liberate uranium, enabling subsequent extraction with a mild lixiviant. Potassium hydrogen sulphate ($KHSO_4$) can serve as the fusing agent, while sulfuric acid is used for leaching. With comprehensive radiological characterization of the various residues and accurate quantification of residue generation across streams, a robust assessment of the feasibility of valorizing these materials can be undertaken.

4.1.1.2. Example: fractionation of radionuclides during REE processing

The separation of radionuclides during rare earth element (REE) production, as illustrated in Figure 6, has been the subject of extensive research due to the need for effective management of radioactive nuclides [47]. A patented process originally developed for actinide extraction from radioactive waste has been adapted for REE ores. Under optimized conditions, solubilization yields reached 90–95% for thorium and 60–75% for uranium in sulfuric and nitric acid media. The principal minerals serving as sources for rare earth production include:

- Bastnasite, a fluorocarbonate mineral, $(Ce,La,Y)(CO_3)F$, typically found in carbonatites and associated igneous rocks, with a rare earth oxide (REO) content of 58–75% by mass;
- Monazite, a phosphate mineral, $(Ce,La,Nd,Y,Th)PO_4$, occurring in heavy mineral sands, vein-type deposits in granite, and low-grade tin ores from Southeast Asia, containing 35–78% REO by mass;
- Rare earth bearing clay, an ion-adsorption ore formed through lateritic weathering of igneous rocks, with a REO content of 0.05–4% by mass;
- Xenotime, a phosphate mineral, YPO_4, typically associated with monazite in heavy mineral sands and tin ores, featuring REO of 54–65% by mass.

Circa 70% of China's total rare earth production originates from the Bayan Obo deposit site, making it the largest rare earth source in the world [48]. A mixture of two types of rare earth minerals, bastnasite and monazite, is present. Following ore beneficiation, the resulting concentrate typically contains RE oxides in the range of 50–60 % $_{\text{(wet weight)}}$, ThO_2 in the range of 0.18–0.3% $_{\text{(wet weight)}}$ and U_3O_8 at less than 0.001% $_{\text{(wet weight)}}$. This concentrate is subsequently processed for rare earth production. The primary processing route, applied to approximately 90% of the concentrates, involves digestion with H_2SO_4 at temperatures exceeding 500 °C, as shown in Fig. 6.

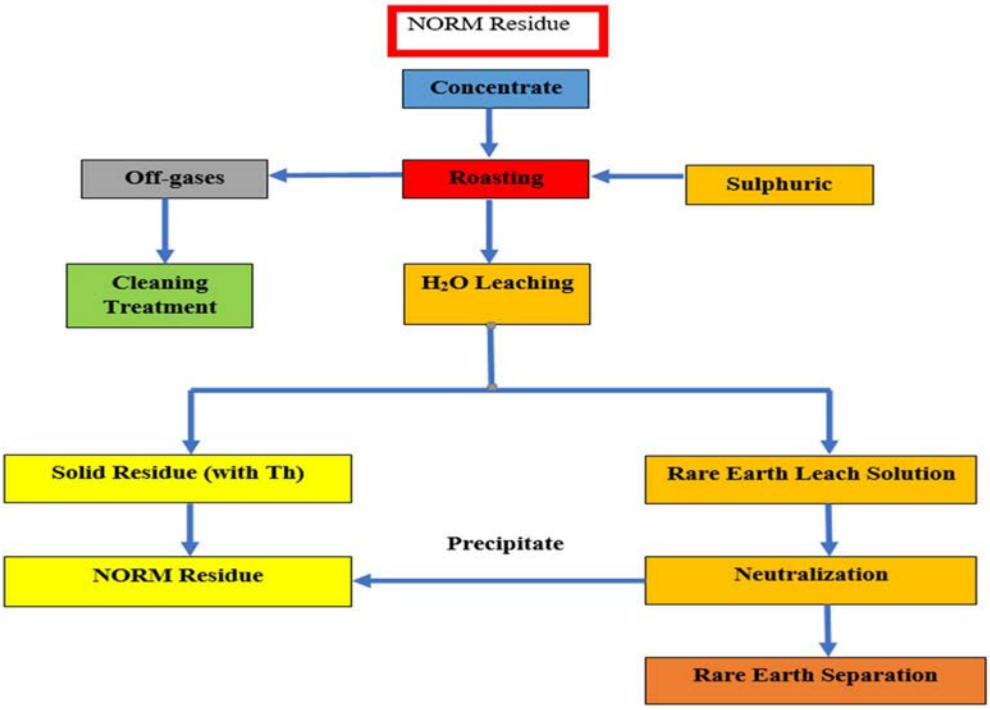


FIG. 6. Generic flowsheet of sulphuric acid decomposition process used for treatment of the Bayan Obo concentrates.

It is reported that thorium remains in the solid residue obtained after washing, whereas its concentration in the sulphuric leaching solution is less than 10 ppm. In the subsequent purification step, which involves precipitation, additional removal of thorium and other impurities from the leach solution occurs [48].

4.1.1.3. Fractionation of radionuclides during phosphate minerals processing

The production of fertilizer from phosphate rock is one of the most extensively studied mineral processing operations. A broad review of various aspects of NORM in the phosphate industry is provided in [7].

Phosphogypsum is the primary waste product generated from the wet-acid process used to produce phosphoric acid. In this process, phosphate rock is dissolved in sulfuric acid to produce a mixture of phosphoric acid and calcium sulphate (phosphogypsum) in the form of a solid–liquid slurry. Phosphogypsum remains as the waste material after filtration separates the desired phosphoric acid component from the mixture. During this process, radionuclides present in the phosphate ore are selectively separated and concentrated. Approximately 80% of ^{226}Ra accumulates in the phosphogypsum, with radium levels in phosphogypsum stacks typically ranging from 0.4 to 1.3 $Bq \cdot g^{-1}$ [49].

Phosphogypsum is used in agriculture to supply calcium and sulphur to nutrient-deficient soils. When applied as a fertilizer, it is evenly distributed across the soil surface, whereas for pH correction or sediment control it is incorporated into the soil. In the USA, phosphogypsum used for agricultural purposes cannot exceed an activity concentration of 0.37 $Bq \cdot g^{-1}$. Each year, approximately 221 000 Mt of phosphogypsum are retrieved from phosphogypsum stacks and applied in agriculture. Phosphogypsum can also be incorporated into Portland cement mixtures for use in road construction.

An equation has been proposed to estimate the amount of phosphogypsum produced per tonne of feed rock:

$$G = \frac{172}{56}\,(C_aO \times 0.98) + IS \quad (8)$$

Where:

G = Phosphogypsum solids (tonnes)
CaO = Weight fraction of Ca in the phosphate rock
IS = Weight fraction of acid insoluble in feed phosphate rock (general unreactive silica around 15%).

Phosphate slag is the primary residue generated from the thermal process used to convert phosphate rock into elemental phosphorus. The production of elemental phosphorus has been steadily decreasing due to reduced demand and increased energy costs associated with this process [49].

Phosphate slag is a vitreous material formed during furnace operations. Owing to its physical characteristics and significant carbonate content, slag exhibits greater resistance to radionuclide leaching compared to phosphogypsum. Nevertheless, activity concentrations of uranium, thorium, and radium in phosphate slag have been reported to reach levels as high as 1.85 $Bq \cdot g^{-1}$ in certain cases [49].

Differences in the radiological characteristics of residues generated from similar mineral processing operations are strongly influenced by the origin of the feed rock. This variability is particularly evident in phosphate fertilizer production. Uranium concentrations in sedimentary phosphate rocks are significantly higher than those in igneous phosphate rocks. In the referenced investigation, uranium content in sedimentary phosphate rocks ranged from 27 to 245 $mg \cdot kg^{-1}$, whereas igneous phosphate rocks from the Russian Kola Peninsula exhibited uranium concentrations between 3 and 3.35 $mg \cdot kg^{-1}$. A case-by-case assessment is therefore required, as these variations directly influence the radiological characteristics of the resulting process residues.

Figure 7 presents a schematic of a phosphate rock processing. In a broad term, most of the ^{238}U and ^{232}Th partition into the phosphoric acid stream, whereas the radium isotopes predominantly associate with the gypsum phase.

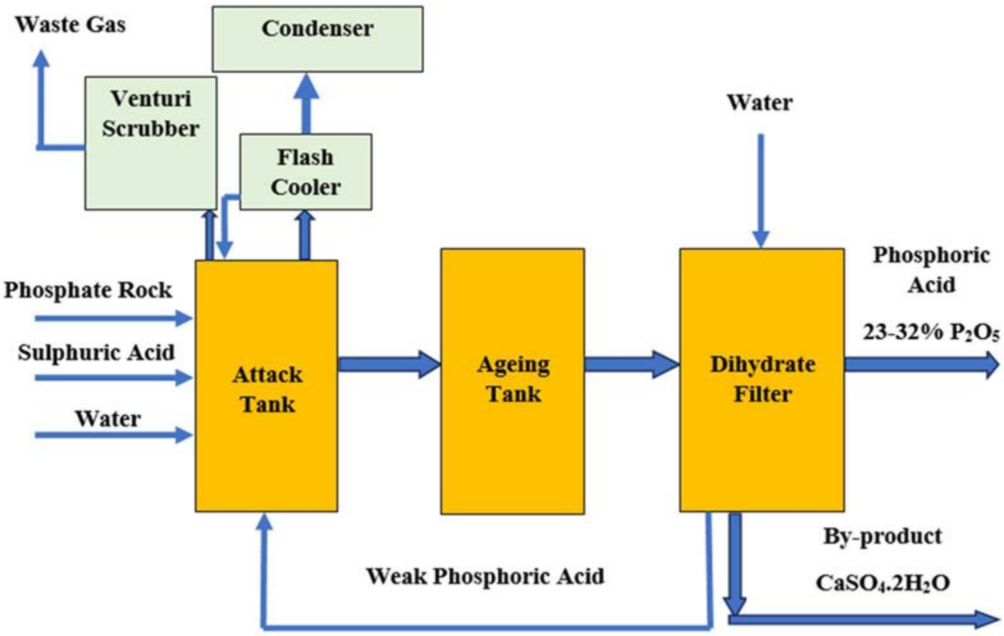


FIG. 7. Generic flowchart of a fertilizer production operational wet process.

4.1.2. Amounts of residues generated by water treatment plants

Activity concentrations of natural radionuclides in residues generated by water treatment plants (WTPs) in Australia are presented in Table 7. The predominant waste streams in WTPs are sludge and sediments, which are closely associated with the type of treatment employed, such as flocculation, settling processes, and bulk filter media including sand and filter coal[10]. According to reported data, coagulated sludge is typically stockpiled on WTP sites. In one case study, approximately 5000 tonnes of alum concentrate were produced annually, and potential reuse applications, such as incorporation into building and construction materials are currently under consideration.

[10] https://www.oilandgasiq.com/drilling-and-development/news/what-are-fixed-platforms

TABLE 7. NATURAL RADIONUCLIDE ACTIVITY CONCENTRATIONS IN SOLID MATERIAL FROM WATER TREATMENT PLANTS (Bq/kg (dry weight))

WTP Residue	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{40}K
Sludge	200	60	80	77	140
Sludge	190	74	90	68	210
Alum Concentrate	70	120	100	78	80
Sludge	140	37	90	46	110
Sludge	130	39	80	50	90
Filter Coal (new)	60	13	10	16	60
Filter Coal (used)	30	16	20	12	< 20
Resin (new)	< 20	< 2	<10	< 8	< 20
Resin (used)	<20	6	110	< 8	60
Sediment (evaporation pond)	230	70	80	60	330
Sediment (evaporation pond)	250	85	110	56	260
Sediment/sludges	130–250	37–85	80–110	46–77	90–260
Filter material/alum concentration	30–70	13–120	10–100	12–78	< 20–80
Ion exchange Resin	< 20	6	110	< 8	60
Australia	11–148	8–21			

Additional information is provided regarding the volume of water treated and the corresponding residue generated during treatment, as summarized in Table 8. Solid residues produced from surface water treatment processes can range from “virtually none” to 46 kg Ml^{-1}. These data can be used to calculate an average solid-residue mass generated per megalitre of surface water treated. An estimated value of approximately 14 kg Ml^{-1} was reported, which appears to be consistent with observations from other countries.

TABLE 8. WASTE PRODUCED FROM METROPOLITAN WTPS

Location	Water Consumption	Solid Waste	
	Ml/year	t/year	kg/Ml
Brisbane – coagulation	250 000	5700	24
Toowoomba	14 400	330	23
Dalby	2600	120	46
Cairns	25 000	0	0
Mackay	13 200	200	15
Sydney	600 000	3730	6
Perth Area	263 000	6500	25
Darwin Area	38 300	0	0
Mean	1 206 500	16 580	14

4.2. OIL AND GAS PRODUCTION

The development of a NORM inventory for oil and gas production presents several sector-specific particularities. In simplified terms, oil and gas NORM inventories are often described as consisting mainly of two material types: scale and sludge. However, this binary classification does not accurately reflect the diversity of NORM-containing materials encountered at production and storage sites. In practice, oil and gas facilities exhibit a wide range of material forms and waste packages. Examples of waste matrices commonly found in the industry include:

- Oily sludge with slop oil appearance;
- Fresh/wet sludge;
- Dry sludge, with a soil like consistency;
- Oily scale, similar look of the sludge but contained within pipes;
- Scale is mainly made of inorganic salts;
- Metallic scale (mainly corrosion products within pipes);
- Contaminated water;
- Ion exchange resins that may be used during wastewater treatment process;
- Filters (cellulose, metallic, mixed, organic such as walnut shell filtering media);
- Contaminated clothing, textiles, plastics, personal protective equipment, and miscellaneous. Burnable and non-burnable.
- Ashes and slag (if an incineration process is involved);
- Grouted matrices (for instance for waste disposal packages);
- Others.

These waste forms may be present in a variety of waste packages, most commonly pipes, drums (with or without overpacks), and metallic scrap. They may also be stored in other types of containers (e.g. big bags, skips), in bulk form (uncontained), such as bottom sediments in evaporation ponds or contaminated soils, or as large individual components such as oil-gas-water separators or Christmas trees, typically arising from dismantling activities.

It is also important to note that the storage conditions of NORM packages can influence the long-term evolution of the waste matrix, particularly with respect to volatile fractions and water content. Changes in moisture content and apparent density can, in turn, affect external gamma dose rate measurements, which are often used as an initial screening or indirect method for estimating activity (Bq).

Matrix properties have a significant influence on radon diffusion and emanation coefficients, and therefore on the equilibrium between ^{226}Ra and ^{228}Ra and their progeny. For ^{228}Ra, it is important to consider the time elapsed since the waste or residue package was generated. With a half-life of 5.75 years (compared with 1600 years for ^{226}Ra), its activity decreases relatively quickly. Consequently, data recorded at the time of package formation may become unreliable after a decade.

Taking these considerations into account, proper inventory development requires first defining, at the company level, as many NORM waste or residue streams as necessary. Standardization of waste packages is also essential. Mixing different waste packages or combining waste forms with differing characteristics has to be avoided. For each identified NORM stream, a specific and well-documented strategy for inventory estimation will be needed.

While the proposed approach may appear straightforward in principle, its practical implementation is considerably more complex. The industry faces several universal challenges that needs to be acknowledged to fully appreciate the scope of the problem and the rationale behind the methodology presented herein. As in other NORM-related sectors, inventory estimation must be supported by field measurements, representative sampling, and laboratory analysis. However, specific difficulties arise in the sampling and in situ characterization of oil and gas (OIL AND GAS) residues, including:

- Common stratification of materials within sludge containers, with oil settling at the top, water in the middle, and the highest activity concentrated in the bottom sediments;
- Variability in contamination levels in scraps, with potential inconsistencies in segregation at the source. A large portion of the scraps are only marginally affected (by weight) or may be entirely uncontaminated.
- It is difficult to assess internal contamination of pipes; visual inspection is not usually valid (visually “clean” pipes may contain significant activity concentrations). There is an inhomogeneous distribution of internal contamination within pipes, and the external dose rate is strongly attenuated by the thick pipe iron walls.

Documented NORM activity concentrations and their spatial distribution exhibit a remarkably wide range, even within the same geographical area or facility. This variability is strongly influenced by geological formations and operational conditions, and activity levels may also fluctuate over the lifetime of a single well. As a result, information from other facilities or from the literature has very limited applicability.

In practice, companies typically operate under guidelines and criteria primarily designed to address health, safety, and environmental (HSE) concerns. Activity levels on the order of a few $Bq \cdot g^{-1}$ often remain undetected by handheld radiation monitors and fall below initial screening thresholds, rendering them effectively "invisible" within standard HSE and radiation protection frameworks. Furthermore, when managing NORM residues, operational procedures are rarely harmonized across different national waste producers. Variations in management flowcharts, screening criteria, and sampling methodologies introduce additional complexity and uncertainty into inventory development.

Considering the heterogeneous distribution of activity within the waste matrix or package, as well as the wide variability of equilibrium factors across different residue forms, establishing a general correlation between dose rate and activity concentration is inherently complex. Moreover, different operators apply different "action levels" (screening criteria) for the preliminary classification of NORM residues. These criteria are often based on dose rate thresholds, such as 0.5 μSv/h, 1 μSv/h, 2.5 μSv/h, 5 μSv/h, or twice the background level. In other cases, classification may rely on contamination probe readings (CPS/CPM, depending on the radiometric instrument) or, less commonly, on predefined system-based classifications that do not require measurements. Such inconsistencies frequently lead to incorrect or non-uniform segregation of NORM waste at the point of origin.

Similar inconsistencies are observed in the application of "release" or clearance criteria for NORM-decontaminated items, as the basis for such decisions is not always transparent. In some cases, equipment deemed decontaminated may still contain residual activity at levels of several $Bq \cdot g^{-1}$. To address these intrinsic challenges, it is advisable to follow several general good practices:

- The inventory needs to be produced with full commitment from waste producers (industry) at highest executive levels, and supported by radioactive waste management organizations, experts, or trained company personnel in this specific field;
- It is recommended to limit the scope of the first inventory, if necessary. Excessive detail may be unnecessary, unachievable, or impractical. For example, the presence of As, Hg, Pb and other heavy metals may influence potential treatment or disposal routes and safety assessments, whereas parameters such as the sludge flash point may not be required at this stage or can be estimated;
- Baseline scenarios are to be agreed with the organization responsible for the inventory. These scenarios document the assumptions used to forecast future NORM waste arisings, based on planned future operations and decommissioning activities of oil and gas facilities;
- The best available information is to be used to develop reasonable estimates and describe the associated uncertainty range. Large uncertainties often arise in long-term predictions, particularly for waste originating from decommissioning, site clean-up, and legacy NORM sites. Despite this, such uncertainties do not represent an obstacle to developing the initial inventory. The inventory evolves and becomes more robust with each update. In certain cases, legacy NORM waste or NORM-contaminated sites with no accountable organization and limited information can remain outside the first inventory cycle and be incorporated in later updates.

Regarding company NORM waste management process, a sequence similar to the one below is typically observed in big producers:

- Initial segregation of NORM waste at the sites of origin;
- Interim storage (in situ buffer) at different decentralized facilities;
- Transport and storage in a centralized storage facility;

— Segregation by type of treatment and available disposal route (if any);
— Final treatment for disposal or clearance.

In this first step, NORM waste is identified, and each item is assigned to a predefined waste stream. This includes waste package preconditioning, labelling, registration, and the collection of basic data.

A good practice is to use a limited number of standardized waste packages, at least within the same organization. Reducing container variability and defining, where possible, a Waste Package Specification helps support and simplify the overall management processes.

Regarding dose-rate measurements, for initial screening these are only useful when the isotopic characteristics of the waste items are known and controlled. Otherwise, NORM pre-classification relies on the established system or process classification, regardless of dose-rate readings. When dose-rate screening is used, it has to be specific to the waste stream and properly justified. Nevertheless, dose-rate measurements remain essential for radiation protection purposes and for potential future data correlations within waste batches.

Similarly, the release or clearance of NORM materials is not expected to rely solely on dose-rate measurements. At the centralized storage facility, the key step for an efficient inventory data-collection process has to be carried out by trained personnel. This step involves the conformation and characterization of waste batches. The inventory needs to be structured around the definition of batches derived from waste streams, with characterization data from selected items extrapolated to represent the entire batch.

A waste batch is defined as a subset of waste items originating from a specific waste stream that share similar characteristics, thereby reducing the inhomogeneity of expected characterization results. The batching process has to be governed by a documented procedure that establishes the criteria for batch definition. For example, a valid batch could be described as: “200 drums containing sludge from Site A, with dose rates below 1 μSv/h, generated within the last five years.” Conversely, a random collection of yellow drums from different operators does not constitute a batch under this definition. From each batch, the parameters required for inventory definition are assessed using a reduced number of selected items or containers. As a minimum, the following information needs to be determined from the sampled items: the ratio of $^{226}Ra/^{228}Ra$, the ratio of $^{226}Ra/^{214}Pb$ or ^{210}Pb, and the mass of the residue (e.g., scale mass per pipe).

It is necessary to develop and justify sampling and sample-preparation procedures for each waste stream. These procedures have to define the quantities, variables, and measurements to be performed in each case. The inventory will be established by extrapolating the characteristics of a limited number of sampled waste packages to the entire batch. Regarding batch size and the number of samples to be collected, statistical methods may be applied depending on the level of uncertainty that can be accepted.

For example, if no initial information on the standard deviation of a parameter within the batch is available (such as the average ^{226}Ra activity of batch items), a conservative formula for determining the number of items to be sampled can be used [24]:

$$n = \frac{Z^2 \times N \times 0.25}{E^2\,(N-1) + Z^2 \times 0.25} \tag{9}$$

where E is the acceptable error, N is the batch size (total number of items), and Z corresponds to the confidence level (typically 1.96 for a 95% confidence level).

Using this formula, for a batch of 500 drums containing sludge, the sampling and characterization activities could be performed on a random selection of 23 drums. This applies when an error of 20% in estimating the selected parameter (e.g., average ^{226}Ra activity of the batch items) is considered acceptable. For the first iteration of a national inventory, such high margins of error may be appropriate. This method is conservative because it assumes no prior information about the standard deviation of the parameters being measured. If the batching configuration is optimized and certain parameters are known to have low variability, a more precise formula can be applied to reduce the number of required samples. Summarizing, an efficient and justified NORM inventory development will benefit from:

- Clear identification of all existing different NORM waste streams for each producer;
- Avoiding the generation of mixed waste in terms of matrix, container type, or isotopic type (by system/origin);
- Standardization of waste packages as much as possible, along with the development of batching criteria and estimate of expected isotopic composition and variability for each stream or batch;
- Sampling and measurements performed on a limited number of items within each batch using documented and accredited methods.

Once the estimates prove consistent over time and across batch types, sampling requirements may be reduced. The release of items from the inventory would likewise be carried out based on batches, established procedures, and documented criteria.

An example of a form for collecting information on generated wastes in an oil and gas operation is provided in the appendix of this publication.

5. INVENTORIES FOR NORM LEGACY SITES

Developing an inventory of NORM materials present in contaminated sites is considerably more complex than compiling an inventory of residues or wastes generated by ongoing or future industrial operations.

Historically, many industries operated outside adequate legal or regulatory frameworks for environmental protection, resulting in improper management of generated wastes. Consequently, numerous contaminated sites have emerged worldwide due to waste being discarded, abandoned, or mishandled. These sites include former manufacturing plants, processing facilities, landfills, and mining areas[11].When a potentially contaminated site is identified, a targeted investigation can confirm the presence and extent of contamination. However, various sources of information can assist in assessing the likelihood of contamination. The most challenging aspect remains the identification of sites that may have been impacted in the past and require remediation or inclusion in an inventory. As contamination is more likely to arise in former industrial areas, one way to identify potential legacy sites is to investigate historical industrial activity records, such as those related to mining, oil and gas production, and water treatment industries that are common sources of NORM contamination. Additional resources such as old maps, land-use records, and environmental reports can also serve as valuable tools for identifying potential legacy sites.

Different initiatives can serve as a basis for developing such inventories. The Uranium Mill Tailings Remedial Action (UMTRA) Project is an initiative by the U.S. Department of Energy (DOE) aimed at cleaning up sites contaminated by uranium mill tailings, which are by-products of the uranium concentration process. Another example, also in the USA, is the Superfund Clean-up Process. Sites are identified through various sources, including citizens, state agencies, and EPA Regional Offices. Once identified, these sites are recorded in the Superfund Enterprise Management System (SEMS), the EPA's digital database of locations where hazardous substance releases may have occurred. As part of the Superfund programme, the National Priorities List (NPL) compiles the most serious sites identified for remediation. There are three methods for placing a site on the NPL: Sites that achieve a specific score or higher on the Hazard Ranking System (HRS) qualify for inclusion on the NPL. Each state and territory has the authority to nominate one site for addition to the NPL. If the Agency for Toxic Substances and Disease Registry (ATSDR) issues a public health advisory and additional criteria are satisfied, the site may be listed on the NPL.

In the UK, the Land Affected by Contamination guidance[12] provides principles that support planning decisions for managing land affected by contamination. Information regarding the past uses of a given site is contained in a database called the National Land Use Database, which includes commercial databases, land condition records, and records held by the Environment Agency or the British Geological Survey. Additional information can also be obtained from industry profiles hosted by Contaminated Land: Application in Real Environments (CL: AIRE)[13].

In Canada, the Federal Contaminated Sites Inventory (FCSI) contains details about all identified and potential contaminated sites managed by federal departments, agencies, and consolidated Crown corporations. It also includes non-federal sites for which the Government of Canada has

[11] https://www.epa.gov/superfund/superfund-cleanup-process
[12] https://www.gov.uk/government/collections/land-contamination-technical-guidance
[13] https://www.claire.co.uk/

assumed partial or full financial responsibility. However, the inventory excludes sites where contamination is caused by, and remains under the jurisdiction of, enterprise Crown corporations, private entities, or other levels of government[14].

An example of methods for the inventory of contaminated sites also comes from Sweden [50]. Accounting for these sites is important for taking the necessary steps to characterize these abandoned mining sites and assess the risks they entail, with the aim of solving or mitigating those risks. As a result of this assessment, it may be necessary to relocate some of the residues to a safer location or transfer them to a waste repository. It may also be the case that some residues can be put to beneficial use if the concentrations of natural radionuclides and other contaminants permit. In regard to the objective of this publication, the stepwise approach that can be taken consists of:

- Identification of sites containing mining or processing residues and inclusion in a dedicated inventory;
- Estimation of the quantities of materials present at these sites and determination of the activity concentrations of natural radionuclides;
- Review of historical records from former operators to retrieve any available information;
- Collection of existing data on material composition, or, where such data are unavailable, implementation of sampling and measurement campaigns, particularly relevant for tailings piles.

In most cases, a broader site investigation will be required, often accompanied by an assessment of the potential environmental impacts posed by accumulated residues.

Sampling approaches and protocols for wastes, tailings piles, or tailings in impoundments are well documented in numerous publications. Within the scope of the ENVIRONET NORM Project, specific guidance for sampling and characterization of NORM residues is currently under development. It is important to note that the objective of this inventory is to document the existence of such sites. Detailed guidance on site characterization for remediation purposes falls outside the scope of this publication.

[14] https://www.canada.ca/en/services/environment/pollution-waste-management/contaminated-sites.html

6. CONCLUSION

This publication aims to provide guidance on obtaining information and developing a national-level inventory of NORM residues and wastes generated by various NORM-related industries. The complexity of this task depends largely on the availability and accessibility of relevant information within a given country. Additional challenges arise when numerous NORM-related industries operate across the territory, particularly in countries with large geographical dimensions, where data collection and harmonization become more demanding.

A key point emphasized in this publication is the importance of designating an organization responsible for developing and maintaining the national NORM inventory. Such an entity would ensure proper coordination of efforts and consistency in implementation. Ideally, this organization has to be a relevant regulatory body, or one of the authorities, tasked with managing NORM-related matters in the country. To fulfil its mandate, the organization needs to be provided with adequate funding and institutional support. Strong engagement with industry stakeholders is essential. As noted, some sectors may initially be reluctant to share information. Constructive dialogue is necessary to demonstrate that the outcomes of inventory development also serve the interests of industry. For example, oil and gas operators in certain jurisdictions may lack disposal solutions for NORM waste, forcing them to store residues and retain long-term liabilities, an approach that may not align with their business objectives. Inventory data can help attract investors to conduct feasibility studies for NORM waste treatment and disposal facilities, creating opportunities for sustainable solutions. Policy decisions will also be required regarding the classification of NORM waste—whether as radioactive waste or as hazardous/industrial waste. This distinction is critical because, in some jurisdictions, the disposal of radioactive waste is a governmental responsibility. Engagement with industry associations can further facilitate dialogue and foster collaborative approaches to inventory development and waste management.

Another critical aspect highlighted in this publication is the lack of supporting infrastructure for analysing collected samples. Unlike the nuclear sector, which inherently requires specialized facilities to exploit the radioactive properties of materials, NORM-related industries encounter radioactivity incidentally. Consequently, these industries often lack dedicated infrastructure, such as specialized laboratories for radiological analysis because radiological composition has historically not been a priority. While analytical capacity may exist within universities and research centres, it is necessary to determine whether these institutions should assume responsibility for such work or whether dedicated facilities need to be established to support inventory development.

The methodology proposed in this publication, as part of the IAEA Holistic Approach to NORM Management, is organized into three phases. The first phase consists mainly of office-based work focused on gathering information about industries in the country that may be associated with NORM. During this stage, contacts are made with relevant industries to collect preliminary information. Emphasis is placed on understanding the operational processes of the industries under investigation. Geochemical and geological data can also provide useful guidance when prioritizing which industries will be addressed in the second phase.

The second phase involves site visits, sampling, and the analysis of raw materials and residues. Mass balance plays a central role in determining residue fluxes across different stages of the process and in evaluating the reliability of the obtained results. Particular attention is given to the fractionation of radionuclides in the process and their preferential accumulation in specific residues. This type of assessment is more complex in oil and gas operations, where the formation of scale does not follow a steady pattern. In such cases, new arisings may need to be inferred from past data or comparative analysis.

The third phase consists of entering the collected information into a database and consolidating the inventory. Once the information is available and properly interpreted, it enables informed decision making on strategies for managing these materials, the development of policies, and the establishment of legal and regulatory requirements. It is not uncommon for countries to take decisions related to NORM without a clear understanding of the scale of the issue, or even whether a significant issue exists in the first place. Such an approach is unlikely to serve the best interests of society. In addition to the benefits previously discussed, a national NORM inventory serves as a valuable tool for communication and stakeholder education. Misconceptions and misinformation often lead to unnecessary concern; an inventory provides evidence that authorities are aware of NORM-related issues and possess a clear understanding of their scope.

The inventory also plays a critical role in addressing NORM-contaminated sites, enabling governments to develop strategies for remediation and, where feasible, valorization of accumulated residues.

In line with the Holistic Approach and circular economy principles, valorization needs to be considered whenever concentrations of natural radionuclides and other contaminants permit. However, in many cases, disposal will remain necessary. Here, the inventory becomes essential for determining appropriate disposal options, considering waste volumes, geographic distribution of generation points, and the siting of disposal facilities. These decisions have to balance safety requirements with economic considerations, including transportation costs from generation sites to disposal locations.

APPENDIX I

TEMPLATE REPORT FOR PHASE I

<table>
<tr><td colspan="2">Description of the operational supported by flowsheet indicating Inputs and Outputs to the process.</td></tr>
<tr><td colspan="2">Waste/Residue Stream with radiological characterization of the material (if available)</td></tr>
<tr><td>Residue/waste code (or applicable code):</td><td>Photograph of sample in container/pile/conveyor belt

INSERT IMAGE HERE</td></tr>
<tr><td colspan="2">Physical chemical Characteristics of the residues and wastes</td></tr>
<tr><td colspan="2">Producer Company Data
Industry sector:
Name:
Address:
Contact information:</td></tr>
<tr><td colspan="2">Generating Process: (e.g., decontamination by sand blasting; flocculation, etc.)</td></tr>
<tr><td colspan="2">Treatment and conditioning: (e.g. drying; immobilization, etc.)</td></tr>
<tr><td>Container Type:</td><td>Contact dose rate (μSv/h):

Quote activity range and number of containers surveyed</td></tr>
<tr><td colspan="2">Activity concentration (Bq/kg)</td></tr>
<tr><td>^{238}U series radionuclides
^{238}U:
^{230}Th:
^{226}Ra:
^{210}Pb:
^{210}Po:</td><td>^{232}Th series radionuclides
^{232}Th
^{228}Ra:
^{228}Th:</td></tr>
<tr><td colspan="2">Laboratory: (i.e. identification of the laboratory performing the analysis)</td></tr>
<tr><td colspan="2">Sampling protocol:</td></tr>
</table>

Annual Volume in past calendar year (m^3)			
Estimated Volume for next 2 years (m^3)			
Management route			
☐ Recycling	☐ Recovery	☐ Incineration	☐ Disposal
☐ Export; Destination country:			
Management Company Data		Name: Address:	
PRODUCER COMPANY Signature: Name and Job Title Date		INVENTORY MANAGER Approval: Name and Job Title Date:	

APPENDIX II

TEMPLATE REPORT FOR PHASE II

II.1. ADMINSTRATIVE INFORMATION

- Name of the operating company:
- Address of the facility:
- Permit/License reference code/number:
- Website - Include URL if available online:
- Contact Person
  a) Name:
  b) Phone Number:
  c) E-mail address:

II.2. PRODUCTION INFORMATION

- Description of plant history (construction year, types of production over time, factory expansions, decommissioned facilities, on site disposal sites, etc.);
- Plant layout drawings indicating areas/equipment with potential presence of NORM;
- Annual generation of the different (solid) residue streams over the past three years (attention to be paid to residue/waste streams that present enhanced radionuclide concentrations in relation to the raw materials);
- Authorized discharges to air and water (types and total authorized volumes) and discharge data for the past three years.

II.3. RADIOLOGICAL CHARACTERIZATION DATA

II.3.1. NORM survey report

The report should include information on:

- Graphical representation of measurement results;
- Calibration reports of all monitoring equipment;
- Signature of technician(s) performing the survey.

II.3.2. Operational residues

This section should include radiological characterization data (activity concentration for the relevant radionuclides in the ^{238}U and ^{232}Th decay series) for each residue stream.

All previous information available from the operator should be included in this section, along with characterization results of the samples obtained by the inventory builder during the site visit. In particular, the following information should be included:

- Sampling procedure;
- Description of sampling, indicating number of representative samples obtained, photographs of the samples, and signature of the technician performing sampling;
- Laboratory analysis reports.

II.3.3. Storage areas and disposal sites

When applicable, description of storage areas and disposal sites indicating the operational process from which they were generated along with the following information and supporting documentation (such as calibration and laboratory reports):

- Location of storage facility;
  - a) Total quantity stored (e.g. 1 000 tonnes on 1 January 20xx);
  - b) Description of the material stored (e.g. scales; solid phase liquid phase; in %);
  - c) Mass entering or leaving the process for a given time interval (e.g. 100 kg/year);
  - d) Radionuclides (average and/or range for the) activity concentration to be determined from a representative number of samples taken from a given percentage of containers (e.g., ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra);
  - e) Contact gamma dose rate for each unit (big bags, drums, etc.);
- Location of disposal site;
  - a) Total quantity disposed per cell and time intervals (e.g., cell 1, 1980 to 1986, 10 000 tonnes);
  - b) Description of the material disposed (e.g. red mud: solid phase, liquid phase; in %);
  - c) Description of the material and its state (e.g., solid: humid or dry; liquid; sludge);
  - d) Radionuclides average and/or range for the activity concentration (to be) determined from a representative number of core samples;
  - e) ambient gamma dose rate (e.g. at 1 m height).

APPENDIX III

MANAGEMENT OF NORM WASTE FROM THE OIL AND GAS INDUSTRY IN NORWAY

III.1. BACKGROUND

Integrated radiation protection legislation in Norway encompasses all industries, including those processing NORM. This legislation addresses the management and disposal of radioactive waste (including NORM waste), as well as radioactive discharges.

By 2023, the Norwegian Radiation and Nuclear Safety Authority (DSA) has issued approximately 210 permits related to waste management and pollution, with around 170 of these permits pertaining to NORM-related activities, primarily in the oil and gas sector. Additionally, any industry that might generate radioactive waste or discharges posing an environmental risk is required to map and investigate their waste and emissions to determine if they are relevant vis-à-vis the radiological point of view.

The exemption/clearance levels for NORM in the oil industry in Norway are established by the Norwegian Radiation Protection Authority, as defined below:

— Exemption level: ^{226}Ra + ^{228}Ra +^{210}Pb < 1 Bq·g^{-1};
— Repository level: ^{226}Ra + ^{228}Ra +^{210}Pb < 10 Bq·g^{-1};

III.2. WASTE CLASSIFICATION

According to Norwegian legislation, the following categories apply to NORM waste, in terms of allowed management route:

— Exempt waste: Sum activity < 1 Bq·g^{-1};
— NORM Category 1: Sum activity > 10 Bq·g^{-1};
— NORM Category 2: 1 Bq·g^{-1} < Sum activity < 10 Bq·g^{-1}.

NORM category 1 waste should be sent to specially designed NORM repositories, holding a licence from DSA. More flexible disposal options for NORM category 2 waste are allowed. From the physical point of view, NORM waste from oil production typically has four constituents:

— Heavy oils (tar, wax);
— Produced sand;
— Produced water;
— Scales (that can form an important fraction of the total radioactivity measure in the whole material).

Notwithstanding its radioactive content, the above waste types are also classified as hazardous waste due to the oil content. The activity concentration of waste streams 1 and 2 depends on the amount of scale particles mixed into the sand and oil. Oil and gas sludges from the Norwegian industry have activity concentration typically varying between 0.1 Bq·g^{-1} and about 8.0 Bq·g^{-1}, whereas scale can present values up to several hundreds of Bq·g^{-1}.

A “waste substance number” needs to be assigned to each waste stream generated. Table 9 shows the Waste Substance Numbers, defined by the Norwegian Authorities, relevant for NORM waste from the oil and gas industry. The number is given in the form XXXX Y where XXXX refers to the actual substance and Y to the (specific activity) category. It has been commonly accepted that 3025 is used for NORM sediments and sludges and 3091 is used for NORM produced by descaling processes.

If the waste contains more than 1000 mg/kg Hg the waste substance number to be used is 3081. Sediments and sludges below the exemption limit are usually declared using Waste Substance Number 7022 – oil containing waste.

TABLE 9. WASTE SUBSTANCE CODES USED FOR PETROLEUM INDUSTRY NORM WASTE

Waste	Waste Substance No	Category	EAL No
NORM Sediment <10 $Bq\cdot g^{-1}$	3025 (3081)	2	30 05 02
NORM Sediment >10 $Bq\cdot g^{-1}$	3025 (3081)	1	30 05 02
NORM scale <10 $Bq\cdot g^{-1}$	3091	2	19 02 11
NORM scale >10 $Bq\cdot g^{-1}$	3091	1	19 02 11
Black dust <10 $Bq\cdot g^{-1}$	3025 (3081)	2	30 05 02
Black dust >10 $Bq\cdot g^{-1}$	3025 (3081)	1	30 05 02
Blasting sand	3096	2	12 01 16
K salt	3096	2	12 01 16
Oil containing waste	7022		

III.3. REPORTING OBLIGATIONS

The legislative system implemented by Norway to report NORM related data sets obligations on both waste producers and managers. All hazardous and radioactive waste need to be declared using a web-based application. $Bq\cdot g^{-1}$.

The declaration is made by the waste owner (usually the waste generator) or by a representative appointed by the waste producer. In a first step, the following data are reported: waste products, waste classification, mass, radiological characterization results and “primary waste handler”.

Typically, potential NORM residues are sent from offshore facilities to the so-called primary waste handler, who holds a licence for NORM handling and storage. This party:

- Performs decontamination operations of contaminated pipes and equipment;
- Performs handling and re packing;
- Segregates waste;
- Makes controlled discharges of effluent water (from processing and waste separation);

— Stores waste temporarily, awaiting final disposal;
— Facilitates shipment to final disposal;
— Is responsible for declaration and reporting. Specifically, periodic reports are produced and sent to the waste producer and the competent authorities.

Table 10 shows an example of a monthly report for a producer. The data are to be presented as a excel based flat database, with the reports made using the Pivot table tools.

TABLE 10. EXAMPLE OF A MONTHLY NORM REPORT REGARDING THE NORM STORAGE INVENTORY FOR A WASTE PRODUCER

Status per 31.12.2016					
Row labels	Declaration	Number of Barrels	Activity Concentration ($Bq \cdot g^{-1}$)	Weight (kg)	Total Activity
BP Norge	30006314	202	20.29	55.75	1204.11
Lagret Chemtec	30006314	202	20.29	55.75	1204.11
Ula	30006314	131	30.79	37 717	1195
PO 19263	9802962	16	12.53	4 710	60.10
3025 1	9802962	11	16.03	3023	51.19
3025 2	9802956	5	4.85	1687	8.91
PO 19324	9802957	4	9.40	2671	25.08
3025 1	9802957	11	11.83	778	9.04
3025 2	9802957	1	8.52	1893	16.05
PO 19791	9802829	1	32.16	135	4.34
3025 1	9802829	7	32.16	135	4.34
SAR PO 449486	9802908				
3091 2	9802808				
SAR PO 46251	98022				

In Norway, most oil and gas NORM waste is disposed at Stangeneset NORM Disposal Site located at Sløvåg in Sogn og Fjordane County. This repository opened in October 2008 and can receive NORM waste generated by oil and gas operations in Europe. Containers with NORM drums are received at the quayside and transported unopened to the Storage & Conditioning Tunnel. Typically, the waste is packed in 10 containers with 8 12 drums (220 L). Weight of each drum varies between 300 Kg to 600 kg. The drums are registered, weighed and conditioned (if necessary).

Disposed amounts are reported to the authorities in a yearly report. Table 11 shows an example of a yearly report submitted by the repository to the authorities.

TABLE 11. EXAMPLE OF REPORTING OF YEARLY DISPOSED NORM WASTE AT STANGENESET NORM DISPOSAL SITE.

Row label	Number of barrels	Weight (kg)	Activity Concentration ($Bq \cdot g^{-1}$)	Total Activity
2008	396	184 256	30.03	5467
2009	56	16 036	15.86	890
2010	834	180 345	36.06	6515
2011	955	206 296	40.80	8809
2012	407	99 683	12.09	1155
2013	673	155 827	19.79	3515
2014	730	155 553	19.76	4149
2015	1109	270 511	15.13	4366
2016	640	146 508	19.91	4080
3025 1	103	25 121	28.45	810
3025 2	457	95 366	5.07	468
3091 1	73	24 489	102	2792
3091 2	7	1531	5.53	798
2017	236	72 785	27.83	2097
Total	6676	1 634 307	27.02	45 911

From Table 11 above it can be seen that a total of 6676 barrels have been accumulated in the period of 9 years. That corresponds to 1.6 tonnes of waste with an average activity concentration of 27 $Bq \cdot g^{-1}$ leading to a total activity of 45×10^3 Bq. Overall, Norway's reporting system enables very detailed NORM inventory and facilities systematic updates.

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