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Management of NORM Residues

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MANAGEMENT OF NORM RESIDUES

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MANAGEMENT OF NORM RESIDUES

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For further information on this publication, please contact:

Waste Technology Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

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FOREWORD

The IAEA attaches great importance to the dissemination of information that can assist Member States in the development, implementation, maintenance and continuous improvement of systems, programmes and activities that support the nuclear fuel cycle and nuclear applications, and that address the legacy of past practices and accidents.

However, radioactive residues are found not only in nuclear fuel cycle activities, but also in a range of other industrial activities, including:

- Mining and milling of metalliferous and non-metallic ores;
- Production of non-nuclear fuels, including coal, oil and gas;
- Extraction and purification of water (e.g. in the generation of geothermal energy, as drinking and industrial process water; in paper and pulp manufacturing processes);
- Production of industrial minerals, including phosphate, clay and building materials;
- Use of radionuclides, such as thorium, for properties other than their radioactivity.

Naturally occurring radioactive material (NORM) may lead to exposures at some stage of these processes and in the use or reuse of products, residues or wastes. Several IAEA publications address NORM issues with a special focus on some of the more relevant industrial operations. This publication attempts to provide guidance on managing residues arising from different NORM type industries, and on pertinent residue management strategies and technologies, to help Member States gain perspectives on the management of NORM residues.

The IAEA is grateful to all contributors to the drafting and review of this report, and wishes to express particular acknowledgement of the contributions made by D. Wymer (South Africa). The IAEA officer responsible for this publication was H. Monken-Fernandes of the Division of Nuclear Fuel Cycle and Waste Management.

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SUMMARY

All minerals and raw materials contain radionuclides of natural origin, of which the most important for the purposes of radiation protection are the radionuclides in the ^{238}U and ^{232}Th decay series and K40. For most human activities involving minerals and raw materials, the levels of exposure to these radionuclides are not significantly greater than normal background levels. Such exposures are generally not of concern for radiation protection. However, certain operations can give rise to significantly enhanced exposures that may need to be controlled by regulation. Material giving rise to these enhanced exposures has become known as naturally occurring radioactive material (NORM). In several processes the activity concentration enhancement will be observed in the generated wastes and/or residues.

Generally speaking recycling of a NORM residue, or its use in other applications rather than disposing of it as waste, is the first consideration. There are many opportunities for recycling NORM residues back to the processes that generated them. Similarly, there are many opportunities for the safe use of NORM residues as by-products. NORM residues should therefore be regarded more as a resource than as waste.

When it is not feasible to recycle a NORM residue the material has to be treated as waste. In this sense it should be subject to the same overall national approach as for radioactive waste as to ensure its management is safe, technically optimal and cost effective. In order to acquire the necessary knowledge and information for establishing a national strategy for NORM waste management, a characterization of the current situation in the country first has to be performed. Subsequent to this step one has to select the optimum NORM waste management option. The development of a strategy for NORM waste management should be guided by the need for keeping the radiation risks as low as reasonably achievable. For each option identified, the risks and benefits need to be evaluated using a multi-parameter analysis technique. When evaluating the various options in terms of risks to health, safety and the environmental the options should be ranked separately for the operational and post-closure period. The process is completed by the implementation of the optimum NORM waste management option. For each NORM waste stream, a NORM waste management plan, based on the selected management option should be developed. It has to be noted that the remediation of legacy sites contaminated with NORM can be a significant source of NORM waste. Therefore, objective of this report is to provide guidance to Member States on good practice in the management of NORM residues, bearing in mind that there is no single approach that applies to all situations.

This report contains five sections, including the introduction. Section 2 describes the occurrence and behaviour of radionuclides of natural origin in mining and mineral processing operations. It identifies the industrial activities for which process material containing these radionuclides may have to be controlled as NORM and describes the various types of NORM residue generated. Section 3 provides a summary of the IAEA Safety Standards and how they apply to industrial activities involving NORM. Section 4 discusses the national approach to the recycling and use of NORM residues as a means of minimizing waste. Some examples of the recycling and use of NORM residues are given. Section 5 addresses the management — as NORM waste — of those NORM residues for which recycling or use as by-products is not feasible It starts with a short review of national radioactive waste policy and strategy objectives and then describes how a strategy is established for the management of NORM waste, including NORM waste from legacy sites. Aspects such as funding and regulatory approach are discussed. Finally, the various options for NORM waste management, including disposal options, are discussed and some examples are given. Details of the main

radionuclides of interest, namely, those in the ^{238}U and ^{232}Th decay chains, are given in an appendix.

1. INTRODUCTION

1.1. BACKGROUND

All minerals and raw materials contain radionuclides of natural, terrestrial origin — these are commonly referred to as primordial radionuclides. The main radionuclides of interest are those from the ^{238}U and ^{232}Th decay series (see Appendix for details) and 40K.[1] The activity concentrations of these radionuclides in normal rocks and soil are variable but generally low. However, certain minerals, including some that are commercially exploited, contain uranium and/or thorium series radionuclides at significantly elevated activity concentrations. Furthermore, during the extraction of minerals from the Earth's crust and subsequent physical and/or chemical processing, the radionuclides may become unevenly distributed between the various materials arising from the process. Selective mobilization of radionuclides can disrupt the original decay chain equilibrium. As a result, radionuclide concentrations in materials arising from a process, including process residues, may exceed those in the original mineral or raw material, sometimes by orders of magnitude.

In some mining and mineral processing operations, radionuclides of natural origin contained in or released from process materials may pose a risk to workers, members of the public or the environment. The risk may be such that some form of control is required, in which case the material falls within the definition of naturally occurring radioactive material (NORM).[2]

NORM associated with industrial activities involving minerals and raw materials can exist in many forms — it can be an ore, a process feedstock, an intermediate product, an end product, a by-product or a process residue. It can be a solid, a liquid or a gas (or a mixture of these). A NORM residue is not necessarily a waste.[3] Paragraph 3.29 of the IAEA Fundamental Safety Principles [1] states that "…the generation of radioactive waste must be kept to the minimum practicable level by means of appropriate design measures and procedures, such as the recycling and reuse of material". Recycling of a NORM residue, or its use in other applications rather than disposing of it as waste, is therefore the first consideration. There are many opportunities for recycling NORM residues back to the processes that generated them. Similarly, there are many opportunities for the safe use of NORM residues as by-products. NORM residues should therefore be regarded more as a resource than as waste.

Regardless of whether a NORM residue is recycled, used as a by-product or disposed of as waste, regulatory attention commensurate with the level of radiological risk is necessary. In addition, many NORM residues contain non-radiological constituents that may be harmful to human health and/or the environment and may have to be controlled under environmental

[1] The levels of other primordial radionuclides in minerals and raw materials, i.e. radionuclides in the ^{235}U decay series, ^{87}Rb, ^{138}La, ^{147}Sm and ^{176}Lu, are not normally of radiological concern. For a material of known uranium concentration, the presence of ^{235}U (and, by implication, its decay progeny) can easily be taken into account, if necessary, on the basis of the abundances of ^{235}U and ^{238}U in natural uranium (0.711% and 99.284% by mass, respectively) — the corresponding $^{235}U/^{238}U$ activity ratio is 0.046.

[2] In terms of the IAEA Safety Glossary, radioactive material is material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity. NORM is a particular form of radioactive material that contains no significant amounts of radionuclides other than naturally occurring radionuclides.

[3] In terms of the IAEA Safety Glossary, a NORM residue is material that remains from a process and comprises or is contaminated by naturally occurring radioactive material (NORM). The definition of NORM waste is narrower — it is a specific type of NORM residue for which no further use is foreseen.

regulations (for instance, in the case of heavy metals) or occupational health and safety regulations (for instance, in the case of airborne silica particles).

1.2. OBJECTIVE

The objective of this report is to provide guidance to Member States on good practice in the management of NORM residues, bearing in mind that there is no single approach that applies to all situations. Although most NORM residues are similar in that they contain radionuclides with very long half-lives, such residues may vary widely in other respects. They are sometimes generated in volumes that are so large that the options for their management are very limited. They exhibit a wide range of chemical compositions and physical states.

Another important aspect of the guidance provided by this report is that the management of NORM residues has to be considered well in advance of the time of their actual generation — from the early planning stages of the operation and at various stages thereafter. Particular consideration has to be given to ways of minimizing the amounts of NORM residues that have to be disposed of as waste by identifying and investigating the possibilities for recycling and use as by-products. Where NORM residues have to be disposed of as waste, the planning of the operation must include a consideration of the ongoing control of radiological (and non-radiological) risks after closure of the facility.

1.3. SCOPE

This report addresses the management aspects of NORM residues, including their disposal as waste, in a wide range of industrial activities involving minerals and raw materials. The report also addresses NORM residues at so-called legacy sites, that is, sites contaminated by past activities that were not regulated to present standards. The mining and extraction of uranium generates NORM residues but these activities are generally excluded from the scope of this document — they are in some respects a special case, in that the IAEA has already produced a range of publications directly addressing the front end of the uranium fuel cycle. Nevertheless, some practices adopted in the uranium industry are mentioned, where they are relevant to other mining and mineral processing industries.

1.4. STRUCTURE

This report contains five sections, including this introduction. Section 2 describes the occurrence and behaviour of radionuclides of natural origin in mining and mineral processing operations. It identifies the industrial activities for which process material containing these radionuclides may have to be controlled as NORM and describes the various types of NORM residue generated. Section 3 provides a summary of the IAEA Safety Standards and how they apply to industrial activities involving NORM. Section 4 discusses the national approach to the recycling and use of NORM residues as a means of minimizing waste. Some examples of the recycling and use of NORM residues are given. Section 5 addresses the management — as NORM waste — of those NORM residues for which recycling or use as by-products is not feasible It starts with a short review of national radioactive waste policy and strategy objectives and then describes how a strategy is established for the management of NORM waste, including NORM waste from legacy sites. Aspects such as funding and regulatory approach are discussed. Finally, the various options for NORM waste management, including disposal options, are discussed and some examples are given. Details of the main radionuclides of interest, namely, those in the ^{238}U and ^{232}Th decay chains, are given in an appendix.

2. INDUSTRIAL ACTIVITIES INVOLVING NORM AND THE GENERATION OF NORM RESIDUES

2.1. OCCURRENCE OF NORM

Some industrial activities involving minerals and raw materials need to be considered for regulation because the feedstocks contain significantly elevated radionuclide concentrations and thus fall within the definition of NORM. In other cases, the radionuclide concentrations in the feedstocks may not be significantly elevated but regulation still needs to be considered because of elevated radionuclide concentrations in the products, intermediate products, by-products or residues. Differences in activity concentration between the feedstocks and the process materials derived from them can be very large, and depend on how the various radionuclides behave during the processes involved.

2.2. RADIONUCLIDE BEHAVIOUR DURING MINING AND MINERAL PROCESSING

The behaviour of radionuclides during mining and mineral processing operations is strongly dependent on the nature of the process. Four main types of process can be identified in this regard:

(i) Mining and comminution of ore; [4]
(ii) Physical mineral separation processes;
(iii) Wet chemical extraction processes;
(iv) Thermal processes for extraction, processing and combustion of minerals.

2.2.1. Mining and comminution of ore

In most ores, the uranium and thorium decay chains are approximately in equilibrium, although equilibrium can be disrupted over time by hydrogeological processes. Mining operations generally result in residues in the form of overburden or rock that is not sufficiently mineralized to be of commercial value.[5] These residues are stockpiled over large areas — at metal mines in the United States of America, for instance, such stockpiles cover areas ranging from less than 1 ha to more than 2000 ha, with an average area of about 50 ha at major mine sites [2]. Some of these residues, and not only those generated by uranium mining, may be sufficiently radioactive to be classified as NORM residues. If the residue contains pyritic material, exposure to air and water (eventually with the participation of bacteria) may lead to the generation of acid drainage. Apart from non-radiological impacts on the environment, this could have radiological implications because of the mobilization of radionuclides, especially uranium isotopes.

During mining and ore comminution operations, there are limited opportunities for radionuclide mobilization, with the result that radionuclide activity concentrations are not significantly modified and approximate equilibrium conditions are usually maintained [3]. The mechanical properties of the various constituents of the ore may differ, resulting in differences in their propensities for dust generation during dry crushing or milling. The composition of airborne dust, and consequently the radionuclide activity concentrations, may therefore differ from those for the corresponding bulk material. Wet mining and comminution

[4] Comminution of ore is the reduction of its particle size by mineral processing techniques such as crushing and grinding (milling).

[5] Mining residues in the form of poorly mineralized rock are commonly referred to in the mining industry as waste rock, even though they are often used as by-products rather than disposed of as waste.

techniques may cause dissolution and subsequent precipitation of radionuclides on equipment surfaces.

2.2.2. Physical mineral separation processes

Physical mineral separation techniques include gravity concentration, magnetic separation, and removal of very fine particles (‘slimes’) by hydrocyclones, electrostatic separation and flotation (in a chemically inactive environment). Radionuclide behaviour is similar in many respects to that during the mining and comminution of ore, in that there are limited opportunities for mobilization of radionuclides and disruption of equilibrium conditions. The radionuclides associated with each constituent mineral of the feedstock remain with that mineral after separation. Depending on the particular mineral, the radionuclide activity concentration of the separated mineral may be significantly higher or lower than that of the feedstock.

As in the case of mining and comminution operations, radionuclide activity concentrations in airborne dust generated by dry separation techniques may differ from those in the ore owing to differences in mechanical properties of the various constituents of the ore. For example, in the dry separation of heavy mineral sands, the thorium rich monazite component, being relatively soft, concentrates preferentially in dust particles, with the result that the concentrations of ^{232}Th and its progeny can be significantly higher in the dust particles than in the bulk material.

Wet physical processes can cause the mobilization of radionuclides and subsequent precipitation on equipment surfaces as a result of abrupt changes in temperature and pressure.

2.2.3. Wet chemical extraction processes

Ores and ore concentrates are usually subjected to some form of acid or alkaline leaching or digestion to extract the minerals of value. Sometimes, chemical leaching is applied directly to the ore in the ground (‘in situ leaching’). Other wet chemical extraction processes include solvent extraction, ion exchange, and electrochemical processing (‘electro winning’). Wet chemical processing generally results in significant mobilization of radionuclides. The residues to which these dissolved radionuclides migrate are often generated in very large amounts. Although these bulk residues generally exhibit only moderate concentrations of radionuclides, they may still be sufficiently radioactive to be classified as NORM residues.

Radionuclides may also precipitate in scales, sludges, filters, rubber linings and resins, sometimes at concentrations of up to two or three orders of magnitude above those in the feedstock material. Since the chemical behaviour of the various radioelements in the uranium and thorium decay series varies considerably, the radionuclide composition in the process residues is sometimes difficult to predict and radionuclide specific analyses are usually needed to characterize such residues.

2.2.4. Thermal processes for extraction, processing and combustion of minerals

Minerals and raw materials may be subjected to various processes involving high temperatures. These include:

- Metal production by smelting;
- Metal refining using melting or reduction techniques;
- Recycling of scrap metal by melting;
- High temperature separation of minerals;

- Calcining of minerals[6];
- Combustion of fossil fuels.

Low boiling point radionuclides such as 210Pb, 210Po and sometimes Ra isotopes become volatilized, leading to contamination of the air in the surrounding work area and condensation of radionuclides in scrubbers, precipitators, filters and stacks. Furnace dust is generally classified as a NORM residue because these volatile radionuclides, after condensation, are likely to be present at significantly elevated activity concentrations. The non-volatilized radionuclides tend to migrate to residues in the form of furnace slag and ash (usually at moderate concentrations because of the larger amounts of material involved), as well as scale in some cases. The activity concentrations of the non-volatilized radionuclides in ash residues from the combustion of fossil fuels such as coal, lignite and peat are generally too low for these residues to be classified as NORM residues.

2.3. INDUSTRIAL ACTIVITIES INVOLVING NORM

Aside from the mining and extraction of uranium, which is not specifically covered in this report, the following industrial activities (ranked approximately in descending order of radiological significance) have been identified as being likely to require regulatory consideration because of the presence of NORM [4]:

- Extraction of rare earth elements;
- Production and use of thorium and its compounds;
- Production of niobium and ferroniobium;
- Mining of ores other than uranium ore;
- Production of oil and gas;
    - (a) The zircon and zirconia industries;
    - (b) Manufacture of titanium dioxide pigment;
    - (c) The phosphate industry;
    - (d) Production of iron and steel, tin, copper, aluminium, zinc and lead;
    - (e) Combustion of coal;
    - (f) Water treatment.[7]

As explained in Section 2.1, the presence of NORM is often due to it having been generated by the process itself rather than having been introduced as a feedstock. Many mineral feedstocks are not classified as NORM because they do not have significantly elevated radionuclide concentrations. However, the processing of these feedstocks may sometimes generate NORM residues, including small amounts of scale and sediment having activity concentrations two or three orders of magnitude higher. Examples of industrial processes for which this may be the case include the production of oil and gas, the production of titanium dioxide pigment, the production of iron and steel, the combustion of coal and the purification of water.

A general review of the radiological aspects of industrial activities involving NORM is given in IAEA Safety Reports Series No. 49 [4]. More detailed information relating to specific industrial activities is given in several other publications in the IAEA Safety Reports Series [5–9]. The environmental impacts of various industrial activities involving NORM, and measures for their mitigation, are described in Ref. [10]. Regulatory approaches to NORM in

[6] Calcining is a roasting process that decomposes compounds such as hydrates and carbonates and expels volatile material.
[7] Included in this category is the treatment of spent brine in geothermal power production.

certain Member States are discussed in Ref. [11]. A large amount of useful information can also be found in conference proceedings published by the IAEA [12–15].

2.4. GENERATION OF NORM RESIDUES

All of the industrial activities listed in Section 2.3 generate, or have the potential for generating, NORM residues. Different process steps give rise to different types and amounts of NORM residue. Two broad categories of NORM residue can be identified:

(i) Residues with moderate activity concentrations but often generated in large amounts;
(ii) Residues with higher activity concentrations but usually generated in small amounts.

The physical, chemical and radiological characteristics of NORM residues vary from one industrial process to another and, for a given process, even from one site to another. The amounts of residues generated can be very large indeed. For instance, the worldwide generation of phosphogypsum residue from phosphate fertilizer production is 160 million t per year. The nature of many mining and mineral processing operations, including phosphate fertilizer production, is such that, for a given product output, there is little or no prospect of reducing the amounts of residue generated. This is not always the case, however, as can be seen from historical data for waste rock generated at uranium mines in the United States of America [16]:

(a) At the largest open pit uranium mines, the ratio of waste rock to ore peaked in the late 1970s and early 1980s at an average value of about 30:1. As the price of uranium decreased in the early 1980s, only the more efficient open pit operations remained in production, and the waste-to-ore ratios also decreased during that period;
(b) For underground uranium mines, waste-to-ore ratios have generally varied from 20:1 down to 1:1, with an average ratio of about 9:1. Again, the ratio has decreased over the years owing to improved mining efficiency and the selection of more economically exploited deposits. During the 1970s, the typical waste-to-ore ratio decreased from 5:1 to 1:1.

2.5. TYPES OF NORM RESIDUE

2.5.1. Waste rock from mining operations

Despite being commonly referred to in the mining industry as waste rock, residues of this type are not necessarily waste. They often contain low levels of mineralization that may lead to some of them being processed at a future date. These residues are usually generated in bulk quantities and tend to be stockpiled in large heaps at the mine site pending possible future reprocessing or use. Typical waste rock stockpiles are shown in Fig. 1. The radionuclide concentrations may be elevated, but usually only moderately so. For example, waste rock from copper mining has ^{238}U activity concentrations in the range 0.1–2 Bq/g.

2.5.2. Tailings from the dry separation of heavy minerals

Heavy mineral sand recovered from beaches and dunes is a major worldwide source of minerals such as zircon, ilmenite, rutile and monazite. The processing of heavy mineral sand is conducted in two stages — a wet separation process that removes gangue material to produce a heavy mineral concentrate, followed by a sequence of dry separation steps to separate the minerals of interest. Tailings are generated in both stages, but only the tailings from the dry separation process are sufficiently radioactive to be classified as a NORM residue. A typical dry separation plant generates about 70 000 t of tailings per year. The activity concentrations of ^{232}Th are typically in the range 1–20 Bq/g.

One of the constituent minerals of heavy mineral sand is monazite, a source of thorium and rare earth elements. If there is no intention of extracting any of these elements, the monazite fraction has to be treated as a NORM residue, commonly referred to as 'monazite tailings'. It has a typical ^{232}Th activity concentration of 140–250 Bq/g.

FIG. 1. Stockpiles of waste rock at a mine.

2.5.3. Bauxite tailings

Bauxite tailings, commonly known as 'red mud', are generated by the digestion of bauxite in sodium hydroxide, as the first step in the production of aluminium. Generation of red mud worldwide runs to several million tonnes per year. Red mud has a typical ^{232}Th activity concentration of 0.1–3 Bq/g. It contains other constituents of potential concern for environmental protection, such as heavy metals.

2.5.4. Tailings and phosphogypsum from phosphate fertilizer production

Tailings, consisting mainly of sand or clay particles, arise from the wet screening and flotation of phosphate ore to produce a concentrate known as 'phosphate rock'. Worldwide, about 250 million t of tailings are generated per year. The tailings contain radionuclides from the ^{238}U decay series at activity concentrations of 0.01–2 Bq/g. Other constituents such as heavy metals are likely to be more important from an environmental protection point of view.

The digestion of phosphate rock with sulphuric acid generates phosphoric acid and phosphogypsum. Phosphoric acid is used mainly as a feedstock for the production of phosphate fertilizers. Phosphogypsum consists essentially of calcium sulphate, but also contains a variety of heavy metals, fluorides and radionuclides (principally ^{226}Ra and its progeny, at activity concentrations of 0.01–3 Bq/g, depending on the origin and type of the phosphate ore). For every tonne of P_2O_5 produced in the form of phosphoric acid, 4–6 t dry mass of phosphogypsum are produced. The annual production of phosphogypsum worldwide, currently at about 160 million t, could reach 200–250 million t within the next decade or two. On account of its applications in agriculture and construction, phosphogypsum should really be regarded as a co-product of phosphoric acid production rather than a residue. However, because of the large quantities of produced, the seasonal nature of agricultural demand and its under exploitation as a co-product of value, production of phosphogypsum far exceeds demand. As a result, most phosphogypsum is stockpiled as surplus material in large, above ground containment structures known as 'stacks'. A typical phosphogypsum stack is shown in Fig. 2.

FIG. 2. Stockpiling phosphogypsum in a stack (courtesy: Florida Industrial and Phosphate Research Institute, USA).

2.5.5. Scale deposits

Various processes involving minerals and raw materials lead to the deposition of NORM residues in the form of scale on the inside surfaces of process equipment. In the production of oil and gas, ^{226}Ra, ^{228}Ra and their progeny are leached from the reservoir rock into the formation water and thus appear in the water that is co-produced with the oil and gas. Changes in pressure and temperature lead to the precipitation of scale on the inner walls of production tubulars, wellheads, valves, pumps, separators, water treatment vessels, gas treatment vessels and oil storage tanks. Scale typical of that deposited in tubulars is shown in Fig. 3. The scale comprises mainly insoluble sulphates and carbonates of barium, calcium and strontium. Since radium is chemically similar to these elements, ^{226}Ra and ^{228}Ra become incorporated into the scale, sometimes at very high concentrations, together with ^{210}Pb in some instances. Scale deposits can be up to 100 mm thick. Scale formation is sometimes accompanied by the trapping of elemental mercury mobilized from the reservoir rock. Ref. [17] quotes an annual amount of scale generation of approximately 100 t per oil well in the USA, although the rate at which scale is deposited in oil and gas facilities varies over a very wide range, and tends to increase with the age of the facility.

FIG. 3. Scale deposited in an oil and gas production tubular.

The deposition of radioactive scale also occurs in phosphoric acid production, titanium dioxide pigment production, the chemical processing of zircon and coal fired steam generation. Even in mining operations such as coal mining, scale formation can occur if there is an inflow of radium rich water into the workings. In most NORM scale, ^{226}Ra is the predominant radionuclide, although elevated concentrations of ^{228}Ra and ^{210}Pb may also be found, depending on the type of process leading to the scale formation. Activity concentrations are highly variable and difficult to predict. Typical values are shown in Table 1.

TABLE 1. TYPICAL RADIONUCLIDE ACTIVITY CONCENTRATIONS IN SCALE DEPOSITS

Industrial process	Predominant radionuclide	Activity concentration (Bq/g)	
		Minimum	Maximum
Oil and gas production	^{226}Ra	0.1	15 000
Phosphoric acid production	^{226}Ra	0.03	4000
Titanium dioxide production	^{226}Ra	<1	1600
Chemical processing of zircon	^{226}Ra	–	>5000
Coal fired steam generation	^{210}Pb	–	>100
Coal mining, Ra rich inflow water	^{226}Ra, ^{228}Ra	–	200

Scale formation interferes with production by reducing the effective inside dimensions of pipes, valves and other equipment. Therefore, its removal often becomes necessary for operational reasons. Removal of scale may be difficult, and various methods need to be considered, including:

(a) Mechanical removal techniques such as boring and reaming;
(b) Dissolution of the scale by suitable chemicals;
(c) The use of abrasive techniques such as sand blasting or high pressure water jetting;
(d) Melting of scaled components in scrap recycling facilities.

The removal of scale may create new NORM residues in solid or liquid form, depending on the removal method employed.

2.5.6. Sediments and sludge

NORM residues in the form of sediments and sludge are generated in a variety of industrial processes, including rare earths extraction, oil and gas production, the processing of niobium ore, the chlorination of zircon to produce zirconium compounds and zirconium metal, titanium dioxide pigment production, iron and steel production, water treatment and the production of phosphate fertilizers.

Large volumes of sludge are generated during oil and gas production as a result of the precipitation of solids from the produced water due to temperature and pressure changes. In the USA, it is estimated that 230 000 t of sludge are generated annually in oil and gas production facilities [17]. The sludge generally consists of oily, loose material often containing silica compounds, but may also contain large amounts of barium. Dried sludge, with a low oil content, has an appearance similar to that of soil. The main radionuclides of interest are ^{226}Ra, ^{210}Po, ^{210}Pb and ^{228}Ra.

During titanium dioxide pigment production, reactor bed residue generated during the chlorination of titanium bearing minerals contains, among other things, unreacted titanium feedstock and coke. A solid metal chloride residue is also generated as a precipitate during the chlorination process. The radionuclide concentrations are in many cases sufficiently high for these residues to be classified as NORM residues.

When water is treated to remove impurities, the small amounts of radionuclides contained within the raw water are removed and accumulate in sediments and sludge in filters, tanks and pipes, along with non-radioactive constituents such as heavy metals. It is estimated that approximately 260 000 t of NORM residues are generated each year by water treatment facilities in the USA, equivalent to 600 t per treatment plant. Of these residues, filter sludge accounts for 83%, with ion exchange resins and charcoal accounting for the remaining 17% [18].

NORM residues in the form of sediments or sludge arise also from the treatment of spent brine from geothermal power generation. The hot saline fluids from geothermal reservoirs may have a dissolved solids content approaching 30 wt%. One plant in California, USA generates an estimated 54 000 t of residue annually.

Activity concentrations in NORM residues in the form of sediments, precipitates and sludge vary over a wide range, as shown in Table 2.

TABLE 2. TYPICAL RADIONUCLIDE ACTIVITY CONCENTRATIONS
IN SEDIMENTS AND SLUDGE

Industrial process	Predominant radionuclide	Activity concentration (Bq/g)	
		Minimum	Maximum
Rare earths extraction	^{228}Ra	0.6	10 000
Oil and gas production	^{226}Ra, ^{210}Pb	0.05	1300
Niobium extraction	^{226}Ra, ^{228}Ra	200	500
Zircon chlorination	^{226}Ra	0.3	48
Titanium dioxide pigment production	^{232}Th	<0.1	24
Iron smelting	^{210}Pb	12	100
Water treatment	^{226}Ra	0.1	14
Phosphate fertilizer production	^{226}Ra	1.3	4.3

2.5.7. Furnace slag

NORM residues in the form of furnace slag are generated during the high temperature processing of some minerals and raw materials, such as the extraction of niobium from pyrochlore, the smelting of tin and copper and the production of elemental phosphorus by fusion of phosphate rock. Activity concentrations vary over a wide range, but are generally moderate, as shown in Table 3.

TABLE 3. TYPICAL RADIONUCLIDE ACTIVITY CONCENTRATIONS
IN FURNACE SLAG

Industrial process	Predominant radionuclide	Activity concentration (Bq/g)	
		Minimum	Maximum
Extraction of niobium from pyrochlore	^{232}Th	20	120
Tin smelting	^{232}Th	0.07	15
Copper smelting	^{226}Ra	0.4	2
Thermal phosphorus production	^{238}U	0.5	1.9

2.5.8. Furnace dust

NORM residues in the form of furnace dust are generated by the processing of minerals and raw materials at high temperatures. Most furnace dust is trapped as a condensate in stack filters and electrostatic precipitators and is removed during periodic maintenance operations. Some furnace dust escapes with the stack emissions to the atmosphere, while some may remain within the plant, either contaminating the air in the surrounding workplace or settling out on surfaces, posing a potential inhalation hazard to workers.

The radionuclides of interest in furnace dust are the volatile radionuclides ^{210}Pb and ^{210}Po. Although radium is less volatile than lead and polonium, the presence of radium isotopes may occasionally be of concern.

Radionuclide activity concentrations in furnace dust are shown in Table 4. Despite the relatively high activity concentrations, furnace dust is not very hazardous radiologically because the amounts involved are small and the range of radionuclides involved is limited.

TABLE 4. TYPICAL RADIONUCLIDE ACTIVITY CONCENTRATIONS IN FURNACE DUST

Industrial process	Predominant radionuclide	Activity concentration (Bq/g)	
		Minimum	Maximum
Extraction of niobium from pyrochlore	^{210}Pb, ^{210}Po	100	500
Fusion of baddeleyite	^{210}Po	600	
Thermal phosphorus production	^{210}Po	1000	
Tin smelting	^{210}Pb, ^{210}Po	–	200
Steel smelting	^{210}Pb, ^{210}Po	0.3	47

2.5.9. Liquid NORM residues

Examples of NORM residues in liquid form include:

(a) Contaminated water extracted from mines;
(b) 'Produced water' from oil and gas production, comprising a mixture of formation water and injection water;
(c) Excess water from bulk NORM residue deposits such as tailings dams and phosphogypsum stacks — this water consists of a mixture of recirculated process water and contaminated rainwater;
(d) Used process water, including water separated from slurry streams, wash water, flotation water, spent leach solutions and gas scrubbing water;
(e) Water from decontamination of equipment;
(f) Spent solvents.

Aqueous residue streams are often generated in very large volumes. Oil production facilities typically generate 2400–40 000 m^3/d of produced water, an order of magnitude greater than the amount of oil produced. Gas production facilities generate far less water, typically 1.5–30 m^3/d. Radionuclide activity concentrations vary over a wide range. For instance, the ^{226}Ra concentrations in produced water generated at oil and gas installations varies from 0.002 to 1200 Bq/L.

2.5.10. Gaseous NORM residues

Gaseous residue streams containing radionuclides of natural origin are generated by furnaces, chemical processes and ventilation systems associated with the processing of minerals and raw materials. Radionuclides in the uranium and thorium decay series may be contained in dust particles entrained in the gaseous emission and ^{222}Rn may be contained within the gas itself. Emission standards and environmental regulations usually ensure that the emission of hazardous constituents is kept within acceptable bounds through the use of dust filters, electrostatic precipitators and gas scrubbers. Emission standards are also aimed at ensuring that gaseous emissions are well dispersed into the atmosphere through the use of suitable stack heights. All of these controls serve to limit the release of radionuclides to the environment to very low levels.

Emission controls may themselves generate solid and liquid NORM residues in the form of captured dust particles and contaminated scrubber liquids such as water and sodium hydroxide.

3. THE SAFETY STANDARDS AND THEIR APPLICATION TO NORM

The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation. Requirements for radiation protection and for the safety of radioactive sources are established in the International Basic Safety Standards (BSS) [19]. These requirements are governed by the objectives, concepts and principles of the Fundamental Safety Principles [1].

The adoption of the IAEA safety standards when establishing a national approach to NORM residue management is important not only for ensuring the necessary level of protection and safety but also for achieving a harmonized approach among different countries. This is becoming ever more important because of the increasingly international profile of the mining and mineral processing industry and the growth in international trade in mineral commodities, including NORM products and NORM residues.

3.1. APPLICATION OF THE STANDARDS

The BSS apply to all situations involving radiation exposure that is amenable to control. Exposures deemed not amenable are excluded from the scope of the BSS. Examples of excluded exposures given in the BSS are exposure to ^{40}K in the body and exposure to cosmic radiation at the surface of the Earth. There are several other exposures, especially exposures to natural sources that could be regarded as not being amenable to control. For instance, it is generally accepted that exposures of populations living in high natural background areas are not amenable to control. Therefore, when establishing a legal and regulatory framework, it is essential that the scope of that framework is clearly defined.

3.2. REGULATORY INFRASTRUCTURE

In terms of para. 2.15 of the BSS, it is the responsibility of the government to promulgate legislation that, among other things, establishes and provides for the maintaining of an independent regulatory body with clearly specified functions and responsibilities for the regulation of protection and safety. The body responsible for the regulation of the uranium industry is generally the nuclear regulatory body, since this industry is part of the nuclear fuel cycle. Other activities involving exposure to radionuclides of natural origin are not part of the nuclear fuel cycle. Furthermore, the characteristics of the NORM residues generated are often quite different from those of radioactive waste containing radionuclides of artificial origin. There may be significant differences in activity concentrations and radionuclide properties, necessitating differences in the management approach. There may also be significant differences in the volumes of material that have to be managed. Consequently, depending on national institutional structures, regulatory responsibility for such activities may lie instead with an authority other than the nuclear regulatory body. In some cases, the designated authority may be one that has not been established for the sole purpose of radiation protection. It is important, therefore, that the regulatory regime under which an activity involving NORM is regulated is clearly defined by the government in a national policy statement and/or in the national legal and regulatory framework.

NORM process materials, including residues, may contain other hazardous constituents such as chemicals, hydrocarbons and heavy metals. The control of NORM residues may therefore be of interest to several authorities, each with its own legislative requirements. A NORM residue might satisfy exemption or clearance criteria set by one authority, but may still be subject to regulatory control by another authority. Para. 2.15 of the BSS states that the legislation must provide for coordination between authorities with responsibilities relevant to protection and safety for all exposure situations. Such coordination enables the various authorities to communicate with each other in order to develop and maintain a consistent and harmonized approach to the regulation of industrial activities involving NORM. The need for coordination is illustrated by the following two examples:

(i) Facilities that process groundwater to provide water for drinking purposes may be regulated by an authority that oversees drinking water quality for the public. The professional staff responsible for developing and enforcing the regulations may be water chemists, sanitary engineers and public health specialists. The drinking water quality regulations may include a limitation on the radium content of the public water supply, requiring that the water at drinking water plants be treated to remove radium. Because of this, health physicists, geologists, engineers and environmental specialists working for an authority responsible for radiation protection and radioactive waste management may be called upon to assist in the development of the regulations and to oversee the disposal of radium containing wastes.

(ii) A ceramics manufacturing facility may have to be authorized by a regulatory body responsible for radiation protection because it utilizes zircon flour, an industrial raw material that contains small amounts of uranium. The workers wear respiratory protective equipment to reduce the inhalation of airborne dust — this has a dual purpose, in that it reduces the risk of silicosis and at the same time reduces the dose from inhalation of zircon particles. The applicable regulation or authorization might refer to existing occupational health and safety (OHS) regulations administered by another authority. As a result, both authorities conduct inspections at the same facility, each of them checking on issues specific to its own particular area of concern.

Whatever national approach is decided upon for the regulation of industrial activities involving NORM and for the management of NORM residues, it is preferable to use or modify existing regulatory systems rather than to create new systems.

3.3. TYPES OF EXPOSURE SITUATIONS

For the purpose of establishing practical requirements for protection and safety, the BSS distinguish between three types of exposure situation: planned exposure situations, emergency exposure situations and existing exposure situations. Of these, only planned exposure situations and existing exposure situations are relevant to NORM:

(a) A planned exposure situation is a situation of exposure that arises from the planned operation of a source or from a planned activity that results in an exposure from a source. Since provision for protection and safety can be made before embarking on the activity concerned, the associated exposures and their likelihood of occurrence can be restricted from the outset. The primary means of controlling exposure in planned exposure situations are by good design of facilities, equipment and operating procedures and by training.

(b) An existing exposure situation is a situation of exposure which already exists when a decision on the need for control needs to be taken. Existing exposure situations include situations of exposure to natural background radiation. They also include situations of exposure due to residual radioactive material that derives from past practices that were not subject to regulatory control or that remains after an emergency exposure situation.

While the aim is always to provide a consistent level of protection of human health and the environment, the BSS establish different requirements for different exposure situations. Sometimes, especially when dealing with exposure to natural sources, there may be elements of both planned and existing exposure situations. In such cases, the most appropriate type of exposure situation has been determined in the BSS by taking practical considerations into account. For instance, it would not be considered practical to impose the formal system of regulatory control for practices (a requirement for planned exposure situations) to a member of the public engaged in normal day to day activities, even though such activities might include, for instance, the use (in a planned manner) of fertilizer containing NORM.

Paragraph 3.4 of the BSS states that exposure to natural sources is generally considered to be an existing exposure situation. This means that the exposure, although it might need to be mitigated by protective and/or remedial actions, is not subject to the formal system of regulatory control for practices, as would be the case in a planned exposure situation. However, an exception is made for industrial activities involving NORM, since it is generally more appropriate for such activities to be subject to the formal system of regulatory control for practices. Consequently, the requirements for planned exposure situations apply in much the same way as they would apply to industrial activities involving artificial sources. This is articulated in the BSS by means of activity concentration criteria applied to the each of the process materials involved:

(a) If, in every process material, the activity concentrations of all radionuclides in the ^{238}U and ^{232}Th decay series are 1 Bq/g or less and the activity concentration of ^{40}K is 10 Bq/g or less, the material is not regarded as NORM, the industrial activity is not regarded as a practice and the requirements for *existing exposure situations* apply.

(b) If, in any process material, the activity concentration of any radionuclide in the ^{238}U or ^{232}Th decay series exceeds 1 Bq/g, or if the activity concentration of ^{40}K exceeds 10 Bq/g, that material is regarded as NORM, the industrial activity is regarded as a practice and the requirements for *planned exposure situations* apply.

These same criteria of 1 Bq/g for ^{238}U and ^{232}Th series radionuclides and 10 Bq/g for ^{40}K may also be used as clearance criteria for removal of material from an industrial activity involving NORM (see Section 0). The basis for the choice of these particular activity concentration values is explained in some detail in Ref. [20]. The values are based on practical considerations rather than on any consideration of dose, and represent, to the nearest order of magnitude, the upper bounds of the ranges of activity concentration found in normal rocks and soil. This is illustrated in Fig. 4 for radionuclides in the ^{238}U and ^{232}Th decay series.

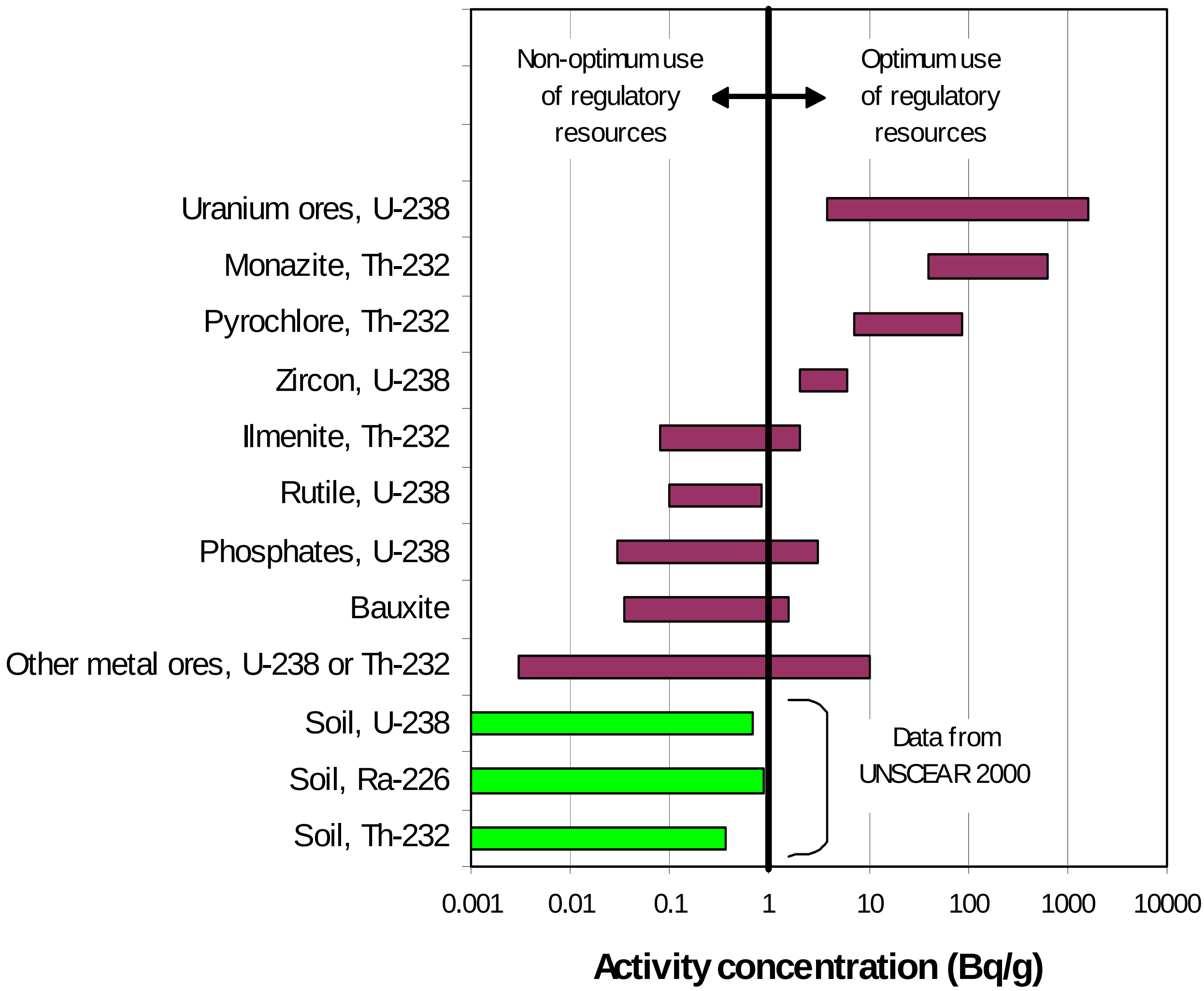

FIG. 4. Radionuclide activity concentrations in some natural materials. The ranges for soil are taken from Ref. [21].

When NORM residues are used as by-products in the form of fertilizers, soil amendments and construction materials (or components of such), the requirements for existing exposure situations apply, irrespective of the activity concentrations. The reasoning behind this is that these everyday commodities, while used in some industrial activities, are also widely used by individual members of the public. Thus, it would not be appropriate to apply the formal system of regulatory control for practices. In terms of the requirements for existing exposure situations, any restrictions that might need to be placed on these commodities would be imposed by the relevant national authority in the form of simple criteria such as activity concentration limits, in much the same way that levels of other potentially hazardous constituents are controlled.

3.4. REQUIREMENTS FOR PLANNED EXPOSURE SITUATIONS

3.4.1. Graded approach to regulation

For industrial activities subject to the requirements for planned exposure situations, a graded approach to regulation has to be adopted, in accordance with para. 3.6 of the BSS. This means that the application of the requirements for planned exposure situations must be commensurate with the characteristics of the practice or the source within a practice, and with the magnitude and likelihood of the exposures. This is particularly important for industrial activities involving NORM because of:

(a) The economic importance of many NORM industries;
(b) The large volumes of residues that may be generated, and thus the limited options for their management;
(c) The potentially high cost of regulation in relation to the reductions in exposure that can be realistically achieved — in many cases, the exposure levels are already rather low.

In order to determine the optimum regulatory approach, the regulatory body has to go beyond just establishing that the activity concentration criteria in Section 3.3 are exceeded. It must consider, in addition, particular types of operation, process and material in more detail, including an initial assessment of exposure or dose and consideration of the costs of regulation in relation to the benefits achievable. Clearly a detailed understanding of the industrial activity concerned is essential for proper implementation of the graded approach.

As part of the graded approach, the BSS make provision for four levels of regulatory control. These levels (described in Sections 0–0) are, in ascending order of stringency of control:

(i) Exemption;
(ii) Notification;
(iii) Notification plus authorization in the form of registration;
(iv) Notification plus authorization in the form of licensing.

3.4.2. Initial assessment

In determining the optimum regulatory approach, an initial assessment has to be made of the process, the materials involved and the associated exposures. For industrial activities involving NORM, the exposure pathways to workers and members of the public that are most likely to require consideration are those involving external exposure to gamma radiation emitted from process material, internal exposure via the inhalation of radionuclides in dust and, for members of the public, internal exposure via the ingestion of radionuclides (via the food chain). Consideration of internal exposure via the inhalation of ^{222}Rn emitted from process material (leading to exposure to its short lived progeny) may also be necessary during the exploitation of certain minerals. Internal exposure of workers via ingestion is unlikely to require consideration under normal operational circumstances.

The assessment of the effective dose received by an individual involves summing the personal dose equivalent from external exposure to gamma radiation in a specified period and the committed equivalent dose or committed effective dose, as appropriate, from intakes of radionuclides in the same period. The assessment method for industrial activities involving NORM is described in more detail in Ref. [22].

3.4.3. Exemption

The regulatory body may decide that the optimum regulatory option is not to apply regulatory requirements to the legal person responsible for the material. The mechanism for implementing such a decision is the granting of an exemption. As a general criterion, exemption may be granted if either of the following conditions is met [19]:

(a) Radiation risks arising from the practice or a source within a practice are (and are likely to remain) sufficiently low as not to warrant regulatory control; or

(b) Regulatory control of the practice or the source would yield no net benefit, in that no reasonable control measures would achieve a worthwhile return in terms of reduction of individual doses or of health risks.

For exposure to NORM, the general criterion for exemption is deemed to have been met if the dose (as determined in the initial assessment) is of the order of 1 mSv per year or less. The soundness of any decision as to whether or not to impose regulatory requirements, made on the basis of dose, depends on how realistically the dose is estimated. This implies, for instance, that due account should be taken of the effect (and effectiveness) of existing controls that may be in place as a result of other forms of regulation, such as OHS regulation and environmental protection regulation, otherwise the dose may be significantly overestimated. Experience with industrial activities involving NORM indicates that the dose received by a member of the public living near a facility is generally no more than a few microsieverts per year, exceptionally up to about 100 μSv per year [21], and is consequently only a small fraction of the dose that could be received by a worker. Therefore, a decision on exemption can generally be made by considering only the doses received by workers [4].

3.4.4. Notification

Where the regulatory body has determined that exemption is not the optimum option, the minimum requirement is for the legal person to formally submit a notification to the regulatory body of the intention to carry out the practice or to make any modifications that have implications for radiation protection. In this way, the regulatory body remains informed of all such operations and of any important changes. The requirement for notification may be sufficient when the maximum annual effective dose is a small fraction of the applicable dose limit. Again, when deciding whether notification alone is the optimum regulatory option, the regulatory body should take account of other forms of regulation (for instance OHS regulation) that might already be in place and that might be effective in the control of radiation exposure.

3.4.5. Authorization

Where the level of exposure to NORM is such that neither exemption nor notification alone is the optimum regulatory option, certain obligations (additional to the obligation of notification) are placed on the legal person through the granting of an authorization. However, it is a fundamental requirement of the safety standards that practices should only be authorized if they are justified, that is, if the expected benefits to individuals and to society outweigh the harm (including the harmful effects of radiation) resulting from the practice. There are two levels of authorization — registration and licensing:

(i) Registration is the appropriate form of authorization when the legal person needs to meet only limited obligations to ensure that exposed individuals are adequately protected. These obligations would typically involve measures to keep exposures under review and to ensure that the working conditions are such that exposures remain moderate, with little likelihood of doses approaching or exceeding the dose limit.
(ii) Licensing is the appropriate form of authorization when an acceptable level of protection can be ensured only through the enforcement of more stringent exposure control measures. This is the highest level of the graded approach to regulation and its use for practices involving exposure to NORM is likely to be limited to operations involving substantial quantities of material with very high radionuclide activity concentrations.

3.4.6. Clearance

Clearance is the removal of regulatory control from radioactive material or radioactive objects within notified or authorized practices, thus allowing them to be removed from the site without any further restrictions. As a general criterion, approval for clearance may be given if either of the following conditions is met [19]:

(a) Radiation risks arising from the cleared material are (and are likely to remain) sufficiently low as not to warrant regulatory control; or
(b) Continued regulatory control of the material would yield no net benefit, in that no reasonable control measures would achieve a worthwhile return in terms of reduction of individual doses or of health risks.

For material containing radionuclides of natural origin, the general criterion for clearance is deemed to have been met if the activity concentrations of all radionuclides in the ^{238}U and ^{232}Th decay series are 1 Bq/g or less and the activity concentration of ^{40}K is 10 Bq/g or less. These activity concentration criteria are numerically the same as those for determining whether the requirements for planned exposure situations apply (see Section 3.3).

Although these activity concentration criteria are not based specifically on dose considerations, the presence in the public domain of material that has been cleared in accordance with these criteria is not expected to give rise to individual doses exceeding 1 mSv per year. Even in what is considered to be a worst case scenario, in which a large deposit of mineral residue causes contamination of groundwater, it has been conservatively estimated that the annual dose received by a member of the public is unlikely to exceed 0.2 mSv [23].[8]

Clearance, by its very nature, implies that the regulatory body does not exercise any further control over the material concerned, once it has been cleared from a notified or authorized practice. This might suggest that the way is open for cleared material to give rise to doses exceeding 1 mSv per year as a result of it being converted into more highly active material, for instance by chemical processing. In such an event, however, the safety standards would automatically require this to be considered as a new practice and regulated accordingly. Similarly, the use of cleared material to construct residential buildings could, under certain circumstances, result in the residents receiving doses exceeding the applicable reference level (normally 1 mSv per year). However, since this material would be subject to the requirements for existing exposure situations, its use for such purposes would be suitably restricted (see Section 3.5.4).[9]

Material that has been cleared from a notified or authorized facility on account of its low radionuclide content may still give rise to non-radiological risks to humans and the environment as a result of other constituents such as heavy metals. Such material may therefore require ongoing control under the relevant regulations.

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[8] This exposure scenario involved a 2 million m^3 deposit of mineral residue containing radionuclides in the ^{238}U and ^{232}Th decay series, each at an activity concentration of 1 Bq/g (the criterion for clearance). The input parameters for the dose assessment were derived from measured data for a variety of actual NORM residue deposits. The exposed individual was assumed to be living next to the residue deposit and ingesting radionuclides via the contaminated groundwater and food produced on site.

[9] Such restrictions would normally apply irrespective of whether the building material was an industrial residue or sourced directly from the natural environment.

3.4.7. Requirements for authorized practices

One of the fundamental requirements embodied in the safety standards is that protection and safety should be optimized, that is, the magnitude of individual doses, the number of individuals exposed and the likelihood of exposure should be as low as reasonably achievable, economic and social factors being taken into account. In addition, the annual effective doses received by workers and members of the public should not exceed the applicable limits (20 mSv for workers and 1 mSv for members of the public).

Registrants and licensees are responsible for protection and safety. These responsibilities include the performance of an appropriate safety assessment and the establishment and maintenance of a system of protection and safety to protect workers and members of the public against exposure. The radiation protection programme for occupational exposure includes, as appropriate:

(a) The maintenance of organizational, procedural and technical arrangements for the designation of controlled areas and supervised areas, for local rules and for monitoring of the workplace;
(b) The assessment and recording of occupational exposure;
(c) Workers' health surveillance;
(d) Provision of adequate information, instruction and training.

The system of protection and safety must ensure that members of the public are adequately protected against exposure, by means of the following:

(a) Management of radioactive waste and discharges of radioactive material to the environment in accordance with the conditions of the authorization;
(b) Source monitoring and environmental monitoring, the results of which must be recorded and made available.

3.5. REQUIREMENTS FOR EXISTING EXPOSURE SITUATIONS

3.5.1. Identification and evaluation of exposures of concern

The requirements for existing exposure situations apply to:

(a) Most exposures to natural sources (but not, of course, those identified as being not amenable to control and thus excluded from the scope of the legal and regulatory framework);
(b) Exposures to residual radioactive material arising from inadequately controlled past activities (irrespective of whether the radionuclides are of natural or artificial origin) or from a nuclear or radiological emergency.

The government must ensure that these exposures are evaluated in order to identify which existing exposure situations are of concern from the point of view of radiation protection. Once that evaluation has been completed, the government must, for each exposure situation of concern, ensure that responsibilities for radiation protection and any associated remedial or protective actions are assigned, and that appropriate reference levels are established.

3.5.2. Responsibilities

The nature of existing exposure situations and the manner in which they may have to be addressed is such that responsibilities may need to be assigned to various persons or organizations that include, but are not limited to, the regulatory body for nuclear safety and/or radiation protection. This is illustrated by the following examples:

(a) Exposure to radon in air is usually regarded as a public health issue, and the responsible body may well be a public health authority;
(b) Responsibility for dealing with residual radioactive material in the environment, especially if the material is a NORM residue containing chemically hazardous constituents, may be assigned to an environmental protection authority;
(c) Exposure to radionuclides in building materials may be the responsibility of an authority that develops and administers building regulations;
(d) When land contaminated with residual radioactive material is remediated, issues of occupational exposure and radioactive waste management will necessitate the involvement of the regulatory body responsible for nuclear safety and/or radiation protection;
(e) When large scale remediation is to be funded or partly funded by the government, it will be necessary to involve a government financial authority.

In many cases, there will be a need for responsibility to be shared between more than one authority. For instance, the regulatory process for remediation situations involves more than just radiation protection. Other laws and regulations covering such matters as environmental protection, land management and food and drinking water standards are likely to be administered by different government bodies. These other laws and regulations need to be applied as appropriate to create a coherent regulatory approach. It is important that the responsibilities are clearly defined in the legal and regulatory framework and that provision is made for the necessary coordination and cooperation between the responsible persons and organizations. Provision must also be made in the legal and regulatory framework for the involvement of interested parties in decisions regarding the development and implementation of appropriate protection strategies.

3.5.3. Reference levels

A reference level in the context of existing exposure situations is the level of dose or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which optimization of protection and safety would continue to be implemented. The reference level, when expressed in terms of annual effective dose, should normally be set at a value between 1 and 20 mSv, depending on the feasibility of controlling the situation and experience in managing similar situations in the past.

For exposure to radionuclides in commodities such as drinking water, food, animal feed, fertilizers, soil amendments and construction material, the reference level should generally not exceed a value of about 1 mSv. This reference level is of particular significance when considering the use of NORM residues as by-products in agricultural or construction applications.

For exposure to ^{222}Rn in workplaces and homes, the reference level is expressed in terms of annual average activity concentration in air. The value should generally not exceed 1000 Bq/m^3 for workplaces and 300 Bq/m^3 for homes. These values correspond to an annual effective dose of about 10 mSv.

3.5.4. Remedial and protective actions

Remedial actions involve the removal or reduction of the source giving rise to the exposure, such as the decontamination of land and buildings. Protective actions may include restrictions on the use of construction materials, restrictions on the consumption of foodstuffs and restrictions on the use of or access to contaminated land or buildings.

Remedial and protective actions must be undertaken only if they are justified, that is, such actions must yield sufficient benefits to outweigh the costs and other detriments associated with taking them, including detriments in the form of radiation risks. The form, scale and duration of remedial and protective actions must be optimized. The optimization process will result in remedial or protective actions that provide the maximum net benefit. They will not necessarily provide the lowest dose, since dose reduction is only one of several attributes considered in the optimization process. During the optimization process, priority should be given to the reduction of exposures in situations where doses exceed the applicable reference level.

In the case of contaminated land or buildings, the exposure of workers undertaking remedial actions must be controlled in accordance with the relevant requirements for occupational exposure in *planned exposure situations*, even though the work is being undertaken in the context of an existing exposure situation. This may result in the remedial work having to be authorized (as a practice) by the regulatory body.

The implementation of remedial actions ('remediation') does not imply the elimination of all radioactivity or all traces of radioactive material. The optimization process may lead to extensive remediation but not necessarily to the restoration of previous conditions. Preferably, the extent of remediation should be such that there is no need for ongoing control measures after the remediation is complete. In some situations, however, this is not feasible. Post-remediation control measures might take the form of a monitoring and surveillance programme but, for more significant levels of residual contamination, they might involve restrictions on the use of or access to the remediated land or buildings.

4. RECYCLING OF NORM RESIDUES AND THEIR USE AS BY-PRODUCTS

4.1. CHANGING ATTITUDES TOWARDS NORM RESIDUES

The opportunities for recycling NORM residues or using them as by-products depend on a variety of factors, including the type of residue, the rate at which it is generated, the location of the facility and, in the case of by-product use, local market conditions. Consequently, the approach to NORM residue management, especially the degree to which NORM residues are recycled or used as by-products, needs to be tailored to the particular industrial activity and its location. Nevertheless, there is an overall trend worldwide towards greater recycling of NORM residues and their use as by-products. This is being driven by sustainability issues such as concerns over the depletion of non-renewable resources, by more stringent environmental protection legislation, by a growing recognition that the amounts of NORM disposed of as waste need to be minimized in order to make their disposal manageable, and sometimes simply by economic considerations, some of which become evident only when the true costs and liabilities of NORM residue disposal as waste are taken into account. Some countries are now making specific provision in their regulatory systems for NORM residue recycling and use [24]. [10]

[10] Recent legislation in the Netherlands identifies the by-product use of NORM residues as the primary target of a NORM residue management system. For application in civil engineering, a specific requirement in Dutch legislation is that the NORM residue is diluted to a level such that it is no longer considered radioactive (in that it does not exceed the relevant 'exemption' level). Thus, dilution in this case is not only a treatment option but also a legal obligation. Only if the options of recycling or use are not feasible can the material be disposed of, and only then is it considered to be waste.

Attention is being focused increasingly on alternative approaches to the management of NORM residues generated in bulk quantities, because the full extent of the problems associated with their storage and eventual disposal is only now being recognized. These problems arise from the large volumes of material involved, the large land areas needed for storage and disposal, structural safety considerations, environmental protection issues such as groundwater contamination and the possibility of financial liabilities that are sufficiently large to threaten the viability of the industrial activity concerned.

4.2. NATIONAL APPROACH

Hazards to human health and the environment associated with NORM residues may arise not only from their radioactivity content but also from non-radioactive constituents such as heavy metals. The national approach to the management of NORM residues should therefore be based on both radiological and non-radiological considerations. In the light of the problems with bulk NORM residues discussed in Section 4.1, special attention needs to be given to identifying management options for these residues that are more acceptable than simply treating them as waste.

From a radiological point of view, the national approach should be in accordance with para. 3.29 of the IAEA Fundamental Safety Principles [1], which states that "……The generation of radioactive waste must be kept to the minimum practicable level by means of appropriate design measures and procedures, such as the recycling and reuse of material". The recycling of NORM residues back to the process that generated them or the use of NORM residues as by-products, rather than their disposal as radioactive waste, should therefore be the primary consideration. This principle should be incorporated into the national approach to NORM residue management. The way in which it is incorporated depends on country specific factors such as the national legal framework, institutional structures and existing national policies and strategies — it may, for instance, be incorporated into the national policy and associated strategy for radioactive waste management (see Section 5) and/or into the national environmental policy and strategy.

It should be implicit in the national approach that when a NORM residue is considered for recycling or use as a by-product, a risk assessment is carried out to demonstrate that such recycling or use is in accordance with the relevant safety criteria described in Section 3. This would include a careful assessment of such things as external exposure to gamma radiation, internal exposure to airborne dust and radon, and the contamination of surface water, groundwater and the food chain due to leaching of radionuclides and/or heavy metals. Because many of the radionuclides involved have very long half-lives, the risk assessment should, where appropriate, include an assessment of risks far into the future.

For some NORM residue by-product applications, the risk assessment may reveal that the residue, if not already diluted with non-radioactive material for technical reasons, should be nevertheless diluted for radiological reasons, either because this is the only acceptable option or because it is the optimum option for protection and safety. For instance, when melting NORM contaminated scrap steel in a furnace to make new steel, it may need to be first diluted with uncontaminated scrap steel. Similarly, the use of slag as a component of construction materials such as cement or bricks may need to involve dilution with other materials such as flyash in order to meet radiological standards for construction materials. Dilution as a means of increasing the amounts of NORM residues that can be used as by-products should not only be permitted in terms of the national approach, but should actually be encouraged.

In order to facilitate the use of NORM residues as by-products and thus to reduce the amounts that have to be disposed of as waste, the national approach should make provision for clearance of NORM residues, that is, their removal from regulatory control, allowing them to be released, without restrictions, from the facility in which they were generated. Accordingly, the criteria for clearance of NORM residues (as set out in Section 0) need to be specified in the relevant legislation or regulations.

4.3. EXAMPLES OF RECYCLING OF NORM RESIDUES AND THEIR USE AS BY-PRODUCTS

Some mining residues in the form of 'waste' rock with low levels of mineralization might be worth reprocessing in the future to extract the residual mineral content, depending on mineral prices and advances in extraction technology. In the meantime, such residues can generally be used safely as construction materials with few, if any, restrictions, since their radionuclide activity concentrations are typically very low. Some applications as construction materials might exist at the mine site itself. For instance, rock residues (including those with significantly elevated activity concentrations) can be used for the construction of tailings embankments.

Phosphogypsum has a wide range of commercial uses, mainly in agricultural applications as a soil conditioner and soil amendment (see Fig. 5), and in construction applications such as plasterboard, fibre reinforced panels, an additive to cement (2–5%) and bedding material in road construction. It also shows great promise as a cover and liner material for conventional landfill disposal facilities and in marine applications such as coastal protection and artificial reefs for oyster production. Because of the low activity concentrations, these uses of phosphogypsum generally have no significant radiological implications.

FIG. 5. Use of phosphogypsum as a soil amendment (courtesy: University of Seville, Spain).

The physical and chemical properties of furnace slag are such that the radionuclide content is not readily leached by environmental media. There are many opportunities for using furnace slag as landfill material and as construction material (or as a component thereof). A risk assessment may indicate the need for certain restrictions, particularly when the slag is used for the construction of buildings. Furnace slag with a moderate activity concentration such as that from copper smelting, iron and steel smelting, scrap metal recycling and elemental phosphorus production can generally be used, without restrictions, in the construction of roads and dams. Furnace slag from the smelting of iron and steel, sometimes after recovering the residual iron content, may be diluted with low activity residue such as flyash and used as a component of cement, concrete and bricks. Zinc smelter slag has in the past been used as an abrasive medium for sandblasting.

Red mud (bauxite tailings) has several potential uses as a by-product, although these are not yet widely exploited. It can be processed to recover metals such as iron and titanium. It can be incorporated into construction materials such as bricks and can be used in the production of catalysts and ceramics. It can also be used as a soil conditioner and for landfill.

Tailings from the dry separation of heavy minerals are often disposed of as waste. However, tailings generated at sites where dredge mining operations are carried out are usually recycled to the dredge mining area such that any residual minerals of value are eventually recovered.

Metal components such as pipes, valves and vessels that become contaminated with scale can often be decontaminated to allow the component to be used again. The scale removed from the components usually has to be disposed of as waste, but in some mineral processing operations it can be reintroduced to the process to recover residual minerals of value. If the metal is decontaminated by recycling as scrap metal, the scale will become diluted into the furnace slag.

In the chlorination of titanium bearing minerals to produce titanium dioxide pigment, some of the unreacted material in the reactor bed residue may be recycled back to the process. The solid metal chloride residue has applications as a by-product. It may be added to cement to form an aggregate for construction applications or processed for use as a coagulant for water treatment.

Water treatment sludge is used occasionally in the production of bricks and concrete, although the content is low, usually in the range 1–2%.

Liquid NORM residues are often recycled back to the process that generated them. This management approach can be used both for aqueous residue streams and for spent solvents.

5. MANAGEMENT OF NORM RESIDUES AS WASTE

When it is not feasible to recycle a NORM residue back to the process or to use it as a by-product, the material has to be treated as radioactive waste. Although in some respects NORM waste may differ significantly from other types of radioactive waste, it should be subject to the same overall national approach so as to ensure that its management is safe, technically optimal and cost effective.

5.1. NATIONAL POLICY FOR RADIOACTIVE WASTE MANAGEMENT

The national approach is normally documented in the form of a national policy statement for the management of radioactive waste (and spent fuel, where appropriate) and associated strategies [25]. The national policy for radioactive waste management should reflect national priorities, circumstances and human and financial resources and should be consistent with other relevant national policies such as those dealing with other hazardous materials. The national approach to NORM waste management should be documented as part of the overall policy for radioactive waste management, rather than as a separate policy statement.

Prime responsibility for establishing the radioactive waste management policy lies with the government. The policy may become codified in the national legislative system. The policy has several elements, of which the following are of particular relevance to NORM waste management:

(a) Safety objectives;
(b) Provision of resources;
(c) Management approach;
(d) Public information and participation;
(e) Roles and responsibilities.

The assurance of radiation protection and safety is a major consideration in the management of radioactive waste and is therefore an important element of national policy. Protection and safety objectives in the national policy should be based on following safety principles [26]:

(i) Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health;
(ii) Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment;
(iii) Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account;
(iv) Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today;
(v) Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations;
(vi) Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions;
(vii) Generation of radioactive waste shall be kept to the minimum practicable;
(viii) Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account;
(ix) The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.

The national policy should be based on the principle that the person or organization that creates the waste is responsible for it and for its safe management. However, the policy should also clarify the responsibilities of the government. These responsibilities include the establishment of a legal and regulatory framework that, among other things, provides for radioactive waste management to be regulated by an independent regulatory body. NORM is not necessarily regulated by the regulatory body responsible for radiation protection and radioactive waste management. It may equally be regulated by another regulatory body such as that responsible for environmental protection. It is important, therefore, that the national policy defines the regulatory regime under which NORM waste is to be managed. Furthermore, the scheme for regulatory control of NORM waste management must be clearly defined in the legal and regulatory framework.

The government may have to take responsibility for the remediation of legacy sites in the form of land and buildings contaminated by accidents or by inadequately regulated past practices. This responsibility must include responsibility for the management of any radioactive waste, including NORM waste, generated during the remediation process. Regardless of how radioactive waste has been generated, the government must ensure that arrangements are implemented for its safe long term management. The national policy should identify the organization(s) responsible for:

(a) Ensuring that radioactive waste is safely managed (normally the registrant or licensee);
(b) The long term management of radioactive waste;
(c) The management of radioactive waste for which no other organization has responsibility.

The national policy also serves as the means for ensuring that the necessary human resources, technical resources and funding are provided for the safe management of radioactive waste, including the provision of institutional controls and monitoring arrangements to ensure the long term safety of radioactive waste storage facilities and repositories after closure.

In formulating a national policy, a knowledge of the existing national situation is needed, including:

(a) The legal and regulatory framework;
(b) Institutional structures;
(c) Applicable international conventions;
(d) An indicative waste inventory;
(e) Availability of resources;
(f) The views and preferences of the major interested parties.

It is also necessary to have knowledge of waste management facilities and available technologies in other countries and of the approaches to radioactive waste management being used, especially in nearby countries which may have similar circumstances.

5.2. STRATEGY FOR NORM WASTE MANAGEMENT

The national goals and requirements set out in the policy are translated into programmes or strategies. These serve as the means for achieving these goals and requirements and therefore take on a more practical and operational form than the policy itself. The strategies may address different types of radioactive waste, one of which would be NORM waste. The strategies specify how the policy will be implemented over all phases of the waste life cycle, define how and when the goals and requirements will be achieved and identify the necessary competencies and how they will be provided. The strategies also serve to enhance public confidence with regard to radioactive waste management. Responsibility for strategy formulation normally lies with the relevant waste owner or waste management agency, which may be either a government or private entity.

The national strategy (or strategies) for NORM waste management should provide a long term plan for addressing issues, needs and problems experienced with NORM waste management within the country. The plan should facilitate the implementation of national policy as it applies to NORM waste management. In the absence of a suitable strategy, there has been a tendency for NORM waste management to be addressed in an uncoordinated and fragmented manner, leading to adverse social, economic, health and environmental impacts.

A NORM waste management strategy should be designed to achieve an integrated ‘cradle to grave’ approach over the entire waste cycle, covering the prevention, generation, collection, storage, transport, pre-disposal treatment and disposal of NORM waste. For any industry, good practice in the management of NORM wastes requires an understanding of:

(a) The industrial activity concerned, particularly the processes leading to the generation of NORM waste, the volumes of wastes generated and the associated radionuclide concentrations;
(b) The radiological hazards associated with the management of the NORM waste generated;
(c) The techniques of risk assessment and safety assessment, including the application of the results to the overall process of NORM waste management.

It is important that steps to establish good practice in the management of NORM waste in accordance with the IAEA safety standards are taken with minimal delay, in order to avoid the creation of further legacy sites that can be complicated and expensive to remediate in future.

A national strategy for the management of NORM waste should include the following aims and objectives:

(a) To establish and maintain a uniform, consistent approach to the management of NORM waste, including its eventual disposal;
(b) To establish radiation protection standards (based on international safety standards) for NORM waste management and a programme for implementing the standards such that individuals (both present and future generations) and the environment are adequately protected;
(c) To define methods and responsibilities for the management, including long term management, of NORM waste generated by authorized facilities;
(d) To establish the process for dealing with legacy sites contaminated by NORM;
(e) To establish appropriate funding mechanisms for NORM waste management, including funding mechanisms for dealing with legacy sites.

To achieve the long term objectives of the strategy, institutional changes and new legislation may have to be introduced and capacity building requirements may need to be addressed and realized. Where possible, legislation, facilities and funding mechanisms that are already in place for the management of other types of radioactive waste should be adapted or expanded to cater for the management of NORM waste rather than establishing entirely new structures. Attention must also be given to raising public awareness on NORM waste management issues and promoting and delivering environmental education. The final phase in the strategy development process should be the formulation of a detailed action plan.

A strategy for NORM waste management may be developed for all types of NORM waste throughout the country. Alternatively, a strategy could be developed for a particular industry sector such as oil and gas production. A strategy may even be developed for a single large company such as a phosphate fertilizer manufacturer.

Strategies for NORM waste management should be subject to continuous review and upgrading as new information becomes available and as understanding of the situation improves. This requires good communication between regulatory bodies, other national authorities, NORM waste management agencies and plant operators, each of which should have a clear understanding of its the role in the overall management process.

5.3. PROCESS FOR DEVELOPING AND IMPLEMENTING A NORM WASTE MANAGEMENT STRATEGY

The development and implementation of a NORM waste strategy extends over three phases:

(i) The identification, characterization and assessment of existing situations involving the generation of NORM waste in the past, present or future, including legacy sites contaminated with NORM;
(ii) The evaluation of NORM waste management options for both existing and future NORM waste and selection of the optimum option;
(iii) The implementation of the optimum option for each NORM waste stream.

The overall process and the steps within each phase are shown in Fig. 6. Each of the three phases is discussed in more detail in Sections 5.3.1–5.3.3.

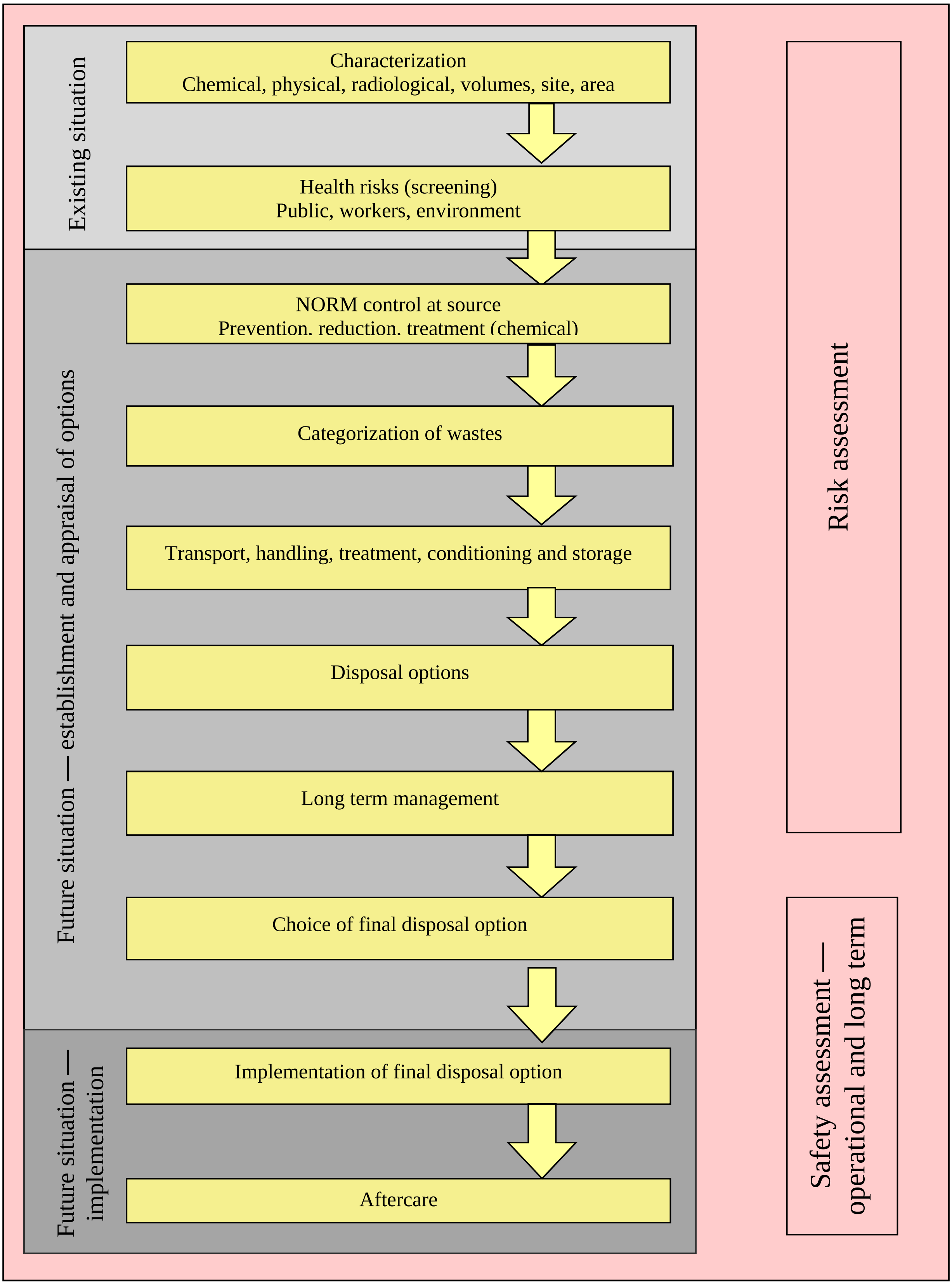

FIG. 6. The process for developing and implementing a NORM management strategy.

5.3.1. Phase 1: Evaluation of the current situation

In order to acquire the necessary knowledge and information for establishing a national strategy for NORM waste management, a characterization of the current situation in the country first has to be performed and the risks to workers, the public and the environment established. Responsibility for performing this evaluation should be assigned to a specific person or organization. The scope of the evaluation should cover all site specific or industry specific waste streams, including historic, current and future waste streams and should categorize these steams to the extent possible to determine, among other things, whether the material is likely to be classified as NORM waste. The characterization of the current situation typically comprises the following steps:

(a) A list of industrial activities potentially generating NORM waste should be established. This could be done in consultation with national or international experts having knowledge and experience of NORM industries, both locally and in other countries, and by extracting information from national databases and industry registers.
(b) The NORM waste expected to be generated by each industrial activity should be identified and characterized to the extent possible. This should include any available information on:
    (i) Existing volumes, annual rates of generation and volumes that will be generated by decommissioning;
    (ii) Chemical composition;
    (iii) Physical state (solid, liquid or solid–liquid mixture);
    (iv) Radionuclide composition, activity concentrations and mobility related parameters such as leaching potential;
    (v) Other (non-radioactive) hazardous constituents and their potential for mobilization;
    (vi) Ownership and geographic location;
    (vii) Existing and future potential for human intrusion and unauthorized use.
(c) NORM waste in the form of residual radioactive material at legacy sites should be identified and, to the extent possible, characterized and quantified by examining old records and geological and mining maps and reports and by interviewing local residents and former workers.
(d) Using the information gathered for both operational and legacy sites, a national inventory of NORM waste should be compiled.
(e) The current legal and regulatory framework should be examined to determine whether any modifications or additions are needed in order to cater for NORM waste management. This examination should also cover:
    (i) The radiological and environmental standards framework for managing radioactive materials and hazardous materials;
    (ii) Other laws and regulations such as those dealing with OHS and environmental protection, both national and international, to determine if they are relevant to NORM waste management.
(f) Strategies being used for NORM waste management in other countries, especially those with similar climatic conditions and social and economic circumstances, should be examined.
(g) An appraisal of existing and planned facilities for managing similar types of radioactive waste should be made.
(h) Details of the funds, funding mechanisms and available expertise to support NORM waste management in the country should be compiled.

(i) The main parties concerned and involved with NORM waste management should be consulted to learn about their expectations and interests.

Using the results of the characterization survey, the associated risks should be assessed using a simple and conservative ‘screening assessment’ that requires a minimum but sufficient amount of data. The results of the screening assessment should indicate to what extent workers, the public and the environment are impacted. Sometimes, a more detailed risk assessment to validate the screening assessment may be required. If the risks are sufficiently low, it may be appropriate in terms of the graded approach to regulation for the waste to be approved for clearance from regulatory control (see Section 3.4.6), in which case it is no longer NORM waste and no further action is necessary from a radiological point of view.

5.3.2. Phase 2: Selection of the optimum NORM waste management option

This second phase of the strategy development and implementation process applies to all NORM waste streams identified in Phase 1 that do not meet the criteria for clearance. It is also applicable when developing a NORM waste management strategy for any new situation involving NORM waste.

The development of a strategy for NORM waste management should be guided by the need for keeping the radiation risks as low as reasonably achievable (ALARA). Since there are usually several ways of mitigating, reducing or controlling the risks associated with the management of a particular NORM waste stream, the need for an optimized approach in the strategy development process entails the consideration of various management options. Attention should be given to all steps in the NORM waste life cycle, starting with waste minimization at source before moving on to pre-disposal steps (pre-treatment, treatment, blending, conditioning and storage) and then to disposal. For each NORM waste stream, all NORM waste management options that are capable of being implemented in accordance with the IAEA safety standards and that are based on established technology (methods, techniques, equipment and processes) should be identified. Consideration might be given to newly developed technology where there is some degree of certainty over its availability, but only if this is not too time consuming or expensive. For instance, a new waste treatment technology might have been developed only on a laboratory scale and would need to be proven in a pilot plant before it could be considered for implementation.

For each option identified, the risks and benefits need to be evaluated using a multi-parameter analysis technique. The chosen parameters should reflect the main objectives of the NORM waste strategy, should take into account the main stakeholder issues and should be fully described and justified. The use of performance parameters (parameters that measure the ability to reduce or avert health, safety and environmental risks) may be helpful when comparing different options. The following parameters are typical of those that need to be taken into account:

(a) The cost–benefit effectiveness over the entire waste life cycle;
(b) Technological considerations, including long term performance and the extent to which the technology is proven and used internationally;
(c) Safety implications:
    (i) Exposures of workers and members of the public (during facility operation) and ALARA considerations;
    (ii) Transport safety;
    (iii) Operational safety;

(d) Social and environmental factors:
   (i) Long term impacts on public safety;
   (ii) Sustainability considerations;
   (iii) Perceived risk and societal acceptability;
   (iv) For legacy sites, the benefit to the community in relation to the 'no action option';
   (v) Environmental impact;
   (vi) Potential for ongoing improvement.

When evaluating the various options in terms of risks to health, safety and the environment, the options should be ranked separately for the operational and the post-closure period. The assessment of long term public health, safety and environmental risks should be based on natural scenarios such as climatic and seismic events and, perhaps more importantly, on human scenarios such as inadvertent intrusion. The assessment of the long term radiological impacts on the environment should take into account the physical, chemical and radiological characteristics of the waste, the disposal site and the surrounding environment, as appropriate. The long term safety of NORM waste disposal facilities should also be assessed against sustainability considerations such as compatibility between the waste and the site conditions, future regulatory scenarios, financial arrangements, reputation of stakeholders and future constraints on safety and long term capacity. If the long term safety of land contaminated by NORM is dependent on land use restrictions, institutional control in the form of long term stewardship will be needed to ensure that these restrictions remain in force. Long term stewardship in the form of monitoring, surveillance and maintenance may also be required for engineered disposal facilities. This implies the need for stable financing arrangements to provide an ongoing source of funding. It should also be recognized that institutional control over a near surface or landfill disposal facility containing NORM waste is highly unlikely to be sustained over periods comparable with the half-lives of the radionuclides concerned. Therefore, a disposal option for which long term safety can be assured without the need for post-closure monitoring or institutional control is clearly the preferred approach.

The need for a supporting infrastructure is a key consideration in the evaluation of different options. Infrastructure includes the necessary trained labour to operate and control the technology and the supporting commercial businesses which provide materials and supplies required by the technology. Infrastructure to deal with the generation of secondary wastes should also be taken into account. Physical resources and systems such as electric power, access roadways, rail access and disposal or storage facilities also form part of the infrastructure. The extent to which a supporting infrastructure is required will affect the cost–benefit effectiveness of the option under consideration.

It is also important to take into account interdependencies among all steps in the NORM waste life cycle, including the planning, design, construction, operation and decommissioning of NORM waste management facilities. Decisions made for one particular step may compromise or eliminate certain alternatives in another step, thus affecting the overall outcome. Account must also be taken of the possible need for characterization, storage and/or transport of NORM waste between and within the various steps.

Another factor that needs to be considered in the evaluation of options is the extent to which an option can be implemented under existing regulations. If new regulations have to be established, this could delay implementation and increase costs.
The results of the evaluation exercise should be presented in a clear manner that facilitates the choice of the optimum option or combination of options. A decision on the option to be adopted should be made after appraisal of the results by the various stakeholders, each of

whom will have a particular interest at stake. Stakeholders may include members of the local community, industry associations and other non-governmental organizations. The views of stakeholders on what constitutes the optimum management option may differ considerably. Nevertheless, all stakeholder views should be taken into account in a transparent and equitable manner, even though this may be a time consuming and complex process.

5.3.3. Phase 3: Implementation of the optimum NORM waste management option

The process is completed by the implementation of the optimum NORM waste management option agreed upon in Phase 2. For each NORM waste stream, a NORM waste management plan, based on the selected management option, should be developed.

For each stage of the NORM waste life cycle, waste acceptance criteria must be established to ensure that health and environmental risk criteria are met.

An appropriate radiological safety assessment and, where necessary, an environmental impact assessment must be performed in order to obtain an authorization from the regulatory body and any other form of approval required from the relevant authority.

Where necessary, post-closure controls at the disposal site have to be established in advance and implemented at the time of closure to ensure long term protection and safety. The final outcome should ensure that the NORM waste ends up in an appropriate form for disposal in an appropriate facility in a compatible environment.

5.4. LEGACY SITES

Many sites contaminated with residual radioactive material, including NORM, are referred to as legacy sites because the person or organization responsible for the contamination is no longer in existence, cannot be located or is financially incapable of remediating the site. Such sites generally become the responsibility of the government.

The remediation of legacy sites contaminated with NORM can be a significant source of NORM waste. The approach adopted for the remediation of such sites is important for NORM waste management because it determines the amounts of NORM waste generated. The process for dealing with legacy sites starts with the identification and preliminary assessment of all legacy sites to determine those for which some form of remedial action is justified, that is, the benefits achieved by remediation outweigh the associated costs and other detriments (see Section 3.5.4). For legacy sites contaminated with NORM, the national strategy for NORM waste management should identify the organization(s) responsible for this assessment process and should specify the criteria (such as reference levels) on which any decisions to remediate should be based. The form, scale and duration of the remedial actions at each site to be remediated must be determined using an optimization approach as described in Section 3.5.4. The NORM waste management strategy must specify the organization(s) responsible for the planning of the remediation programme in this manner and for its subsequent implementation. Finally, the NORM waste management strategy must specify the arrangements and responsibilities for ensuring the availability of sites for storage and/or disposal of NORM waste from the remediation of legacy sites and the long term management of this waste.

5.5. FUNDING OF NORM WASTE MANAGEMENT

In accordance with the well known ‘polluter pays’ principle, the owner or operator of a facility generating waste, including NORM waste, is generally considered to be financially responsible for ensuring that, after cessation of operations, the site is restored to the required condition and all waste is properly and safely managed. It is usual for the relevant authority to require an assurance from the waste generator that it can meet this responsibility, even in the event of unforeseen circumstances such as an accident, bankruptcy or other factors leading to early cessation of operations or other unplanned eventuality. This assurance is usually provided in the form of a bond or bank guarantee that grows with time in line with the growth in the amounts of site contamination and waste. The financial guarantee allows the development of a new industrial facility to proceed while at the same time ensuring that the government does not inherit a financial burden at some time in the future. The financial guarantee also provides an assurance to the public that the environment will be protected without any additional tax burden on society, and serves as an incentive for the company to complete its operations safely and with all its obligations fulfilled.

The amount of the financial guarantee needs to be carefully calculated. When planning a new operation involving NORM, the owner or operator should develop a management plan for NORM residues and eventual restoration of the site. This plan should quantify the extent to which the site will become contaminated by NORM and should determine which NORM residues will be disposed of as waste, the amounts of waste involved and how this waste will be managed throughout the life of the facility and beyond. On the basis of this information, the liabilities associated with site restoration and NORM waste management at any time during the life of the facility can be estimated, allowing the amount of financial guarantee to be calculated accordingly. Although the government is usually responsible for any post-closure institutional controls that may be necessary to assure the safe long term management of NORM waste, funding arrangements for this may have to be provided in advance by the waste generator, in which case this would have to be taken into account in calculating the amount of the financial guarantee. The amount of the financial guarantee should be updated on a regular basis and adjusted as necessary.

In the case of legacy sites contaminated with NORM, the national strategy for NORM waste management should establish the funding mechanisms for their remediation, including the management of any NORM waste generated by the remediation process. Although the government usually has to contribute to the cost of remediation, other sources of funding might include the industry sector associated with the contamination, the site developer and the local community. Specific provision for funding of the remediation of legacy sites, including funding of the associated NORM waste management, should be made in the legal and regulatory framework.

5.6. ENTITIES INVOLVED IN NORM WASTE MANAGEMENT

Each of the following entities has a role to play in NORM waste management:

(a) The *NORM waste generator* is responsible for the technical, financial and administrative aspects of NORM waste management during the operation and eventual decommissioning of the facility. The responsibilities of the NORM waste generator include the establishment and implementation of optimization, dose limitation, monitoring, reporting and other programmes and procedures to ensure protection of workers, the public and the environment.

(b) *NORM waste managers* include government institutions and the managers of authorized NORM waste management facilities. NORM waste managers are responsible for the technical and administrative management of facilities for the long term management of NORM waste and for the remediation of legacy sites and the NORM wastes generated.

(c) The *regulatory body* establishes, or contributes to the establishment of, national standards and regulations for NORM waste management. The regulatory body authorizes NORM waste generators (including those engaged in the remediation of legacy sites) and NORM waste management facilities and sets the necessary authorization conditions. The regulatory body monitors the activities of the operator and enforces the conditions of authorization.

(d) *Members of the public* are affected by the implementation of a NORM waste management strategy. They should be involved in the decision making processes related to NORM waste management for new operations, existing operations and legacy sites:
   (i) For a new operation, public involvement should begin at the planning stage. This involvement should continue throughout the operational and post-operational stages. Only in this way can the public be kept fully informed of potential issues and provide input to the decisions made by government, the regulatory body and other national authorities, and operators.
   (ii) For an existing operation, the public should be involved in the decision making process as soon as possible.
   (iii) For a legacy site, the issues can be very complex, as public health and the environment may already have been adversely affected. In such a situation, it is important to make the public aware of possible health issues without causing undue concern. It is also important to communicate the results of realistic assessments of the risks involved, not only for the site as it currently exists but also for the different options that are available for dealing with the site.

5.7. PLANNING FOR NORM WASTE MANAGEMENT

The management of NORM wastes should be planned before the start of operations where possible. The NORM waste management plan should be periodically reviewed and updated as necessary. In this way, many of the potential problems associated with NORM waste management during the life of the operation can be avoided. The planning process should cover the entire life cycle of the waste, from its generation to its eventual disposal.

In situations where an industrial activity involving NORM is already in existence without adequate NORM waste management planning having been done, there is a the need to address any existing problems as well as to prevent, to the extent possible, potential problems in the future. A careful assessment of the operation is necessary to enable the utilization of the available resources to be prioritized, bearing in mind that the available resources may not be entirely adequate. The resources should be allocated in a way that provides the maximum net benefit, both for the present and the future.

The planning process for both new and existing operations should include an assessment of the costs and liabilities involved, including those associated with the eventual restoration of the site to the required condition (see Section 5.5).

Communication with stakeholders is an important part of the planning process. It enables all stakeholders to understand the NORM waste management process and to make an input to decision making where appropriate. In the case of existing operations, communication with stakeholders also allows operators and relevant national authorities to address public concerns and perceptions that have already arisen.

5.8. REGULATORY APPROACH TO NORM WASTE MANAGEMENT

In accordance with the principle of optimization of protection and safety, the regulation of NORM waste management should be based on a graded approach, bearing in mind that the risks associated with NORM waste are often very much lower than those associated with other types of radioactive waste.

The regulatory approach should be consistent with existing legislation and regulations, including other (non-radiological) environmental legislation and regulations. The regulatory approach should also be aimed at encouraging, supporting and monitoring the establishment and maintenance of good management practice. Good communication between the regulatory body, the operator and other stakeholders is very important in this regard.

The regulator should ensure that the operator of any industrial facility that produces NORM waste should have in place a ‘cradle to grave’ plan for the facility that includes an appropriate management strategy for each NORM waste stream.

In order to make efficient use of regulatory resources and to reduce the amount of NORM waste that has to be managed, provision should be made in the legal and regulatory framework for clearance of material that meets the clearance criteria specified in Section 0. These criteria are specified in the form of general, qualitative criteria and also in the form of numerical criteria for automatic clearance without further consideration. While the use of numerical criteria is undoubtedly easier for the regulatory body, it does not allow the regulatory body to take into account the differences in circumstances between one situation and another, such as:

(a) Waste characteristics;
(b) Site characteristics;
(c) Demographics;
(d) Future land use;
(e) Risk of non-compliance with land use restrictions.

These differences can be important, and it may therefore be more appropriate for the regulatory body to consider clearance on a case by case basis using the qualitative criteria given in Section 3.4.6.

5.9. SAFETY ASSESSMENT

The performance of a detailed radiological safety assessment is an important regulatory requirement for NORM waste management. It provides the means for determining, among other things, the doses expected to be received by workers and members of the public arising from all steps in the NORM waste management process. The safety assessment should include a detailed analysis of the relevant exposure pathways from the source to the receptor. Annual effective doses will nearly always have to be assessed well into the future, requiring that a modeling approach be adopted. While a simple modelling procedure may be sufficient in some situations, a more comprehensive procedure using detailed computational models may be necessary in other situations. The level of modelling detail required in the assessment should be mutually agreed upon by the operator and relevant authority. Modelling requires a knowledge of the characteristics of the source and a careful choice of exposure scenarios. Involvement of other stakeholders, including members of the public, in the choice of exposure scenarios increases the likelihood of a realistic and reasonable outcome.

Any assessment of the environmental, health and social impacts (including potential impacts) of NORM waste management should be site specific, and should be based on a careful characterization, by measurement and analysis, of both the site and the waste. The site to be affected (or already affected) by the disposal of NORM waste should be assessed in terms of its physical, chemical, biological, geological and climatological characteristics.

The safety assessment for NORM waste management operations carried out at the waste generating facility would normally be conducted as part of the overall safety assessment for that facility. The overall assessment should include details of the process flow scheme, a mass balance and, if possible, an activity balance, covering process feedstocks, products, by-products, intermediate products and residues, including NORM residues to be disposed of as waste.

5.10. EDUCATION AND TRAINING

Operators engaged in the management of NORM waste should be appropriately educated and trained in accordance with recognized professional standards and should have a good understanding of the NORM management processes involved and the hazards associated with the materials being handled. They should also have a good understanding of the relevant national and local health and safety requirements for managing NORM waste.

5.11. CHARACTERIZATION OF NORM WASTE

Characterization of NORM waste serves various purposes, including:

- Identifying disposal options;
- Identifying opportunities for waste minimization;
- Segregation of materials for purposes of exemption or categorization;
- Making decisions on remediation;
- Determining the potential for future migration of radionuclides from the site;
- Facilitating the acceptance of NORM waste from one management step to another;
- Assuring compliance of waste packages with requirements for storage and disposal;
- Record keeping.

The scope of the characterization should include the following properties of the NORM waste:

- Physical state (solid, liquid or solid–liquid mixture);
- Volume (small, large or bulk);
- Chemical composition, including non-radioactive constituents that could be hazardous to health and/or the environment;
- Radiological properties — radionuclide composition, activity concentrations, potential for mobilization (e.g. leaching).

The sampling strategy for characterization of the material should account for inhomogeneity, which is likely to be particularly evident in bulk NORM waste because of the long time period over which it may have been generated.

5.12. OPTIONS FOR THE MANAGEMENT OF NORM WASTE

When radioactive waste is disposed of, its form (and packaging, where appropriate) must be compatible with the type of disposal facility. In the case of NORM waste, the disposal facility is likely to be a landfill site or an engineered surface or near surface containment. This usually

requires NORM waste to be in a solid, non-dispersible and passive form. This in turn may require that the waste is first subjected to pre-treatment, treatment, blending and/or conditioning.
The management options for NORM waste generated in bulk quantities are limited because of the amounts involved. There is generally a wider range of options available for managing NORM waste generated in relatively small quantities, but the radionuclide activity concentrations may be considerably higher. NORM waste generated in moderate quantities is relatively easy to isolate, immobilize and transport and lends itself to blending (dilution) before disposal.

5.12.1. Waste minimization at source

The most obvious and effective way of minimizing the amounts of NORM waste generated is by recycling NORM residues or using them as by-products, as described in Section 4. Where this is not possible, the amounts of NORM waste generated in an industrial facility can sometimes be reduced by the use of additives, inhibitors and chemical or physical decontamination processes and by modifications to the industrial process itself. Such waste minimization techniques can usually be applied to both existing and new operations.

Another important way to minimize the generation of NORM waste is to make as much use as possible of the regulatory mechanism of clearance, so that residues may be disposed of as normal industrial waste rather than NORM waste.

5.12.2. Pre-treatment

Pre-treatment of waste is the initial step in waste management after waste generation. It consists of, for example, collection, physical or chemical segregation, chemical adjustment and decontamination and may include a period of interim storage. Pre-treatment can facilitate the minimization of NORM waste by providing the opportunity for some of it to be approved for clearance. Pretreatment of NORM waste may also provide the opportunity for segregating the material into different waste streams for which different management options will be applied.

5.12.3. Treatment

Treatment of waste changes its characteristics. The basic treatment methods are volume reduction, radionuclide removal and change of composition. Volume reduction is consistent with the well established ‘concentrate and contain’ approach to radioactive waste management. It makes the waste easier to handle and contain but increases the radionuclide concentration. Volume reduction techniques include incineration and compaction. Radionuclide removal from liquid waste streams may be accomplished using techniques such as evaporation, filtration or ion exchange. A change of composition of a liquid waste stream may be achieved by precipitation or flocculation of particular chemical species. Treatment of liquid waste streams may lead to several types of secondary radioactive waste (possibly with higher activity concentrations) that also have to be managed, such as contaminated filters, spent resins and sludge.

5.12.4. Blending with non-radioactive material

Blending of radioactive material with non-radioactive material dilutes the radionuclide content and thus reduces the activity concentration. Dilution with non-radioactive material is an option that might be considered for some types of NORM waste, as it could open up options for disposal that might otherwise be unattractive or precluded.

5.12.5. Conditioning

Conditioning of radioactive waste involves those operations that transform the material into a form suitable for handling, transportation, storage and disposal. Conditioning is generally carried out by immobilizing the material, placing it into containers and providing additional packaging. For moderately radioactive waste in liquid form, immobilization commonly involves solidification in materials such as cement or bitumen. Containers for immobilized waste range from common 200 L steel drums to engineered thick walled containers, depending on the nature of the radionuclides and their concentrations. In many instances, treatment and conditioning are carried out in conjunction with one another.

Conditioning is not widely used for NORM waste because the material is usually already in the required physical state.

5.12.6. Storage

Storage of NORM waste may need to be considered at any point in its life cycle, either between management steps or within them. Bulk quantities of NORM waste such as mine tailings and phosphogypsum usually have to remain in engineered surface containments at the site at which they were generated because their transport off site is too expensive and disruptive, and could introduce additional health, safety and environmental risks. The engineered containments used for storage may eventually become disposal facilities and therefore have to be designed and managed as such, although opportunities may arise in the meantime for the material to be reprocessed or used as a by-product (see Section 4). NORM waste generated in moderate amounts (but with the possibility of relatively high activity concentrations) is often stored under cover at the site at which it is generated or at another suitable site, pending disposal at a more convenient time, with loose material being contained in drums. However, it is essential that a plan for disposal, including the identification of a suitable disposal site and adequate funding arrangements, is in place from the outset. Otherwise, when the facility ceases operation, closure of the site may not be possible.

Except for furnace dust in which the main radionuclides of interest are 210Pb and 210Po, decay storage is not a viable management option for NORM waste because the radionuclides are very long lived.

5.12.7. Disposal

Disposal is the final step in the radioactive waste life cycle. For most types of radioactive waste, the management approach involves concentration and/or containment, with the waste being placed in a disposal facility with reasonable assurance of safety, without the intention of retrieval and, preferably, without reliance on long term surveillance and maintenance. Safety is in most cases assured by isolation of the waste in the disposal facility using barriers above, below and around the radioactive waste in order to restrict the release of radionuclides into the environment. The barriers can be either natural or engineered and an isolation system can consist of one or more barriers. A system of multiple barriers gives greater assurance of isolation and helps ensure that any release of radionuclides to the environment will occur at an acceptably low rate. Barriers may provide absolute containment for a period of time, as is the case for a metal wall of a container. Alternatively, barriers may retard the release of radioactive materials to the environment, as is the case for clay layers, rock armoured coverings or host rock with a high sorption capability. The barrier system is designed according to the disposal option chosen and the radioactive waste forms involved.

Disposal may also be achieved through the discharge of liquid and gaseous effluent into the environment within authorized limits, with subsequent dispersion. This approach may also be applicable to some solid residues from NORM industries.

The disposal option should provide a complete solution that is practicable, sustainable, acceptable and designed such that long term safety can be assured — this should be demonstrated as part of a site specific dose and risk assessment that in turn forms part of the operational and long term safety assessments. The outcome of the assessments will define maximum activity concentrations (based on intrusion scenarios) and capacity (based on scenarios involving natural phenomena).

A diagram of a proposed classification scheme for radioactive waste and its method of disposal is shown in Fig. 7. Although the vertical axis refers to activity concentration, in some cases the waste may be classified instead according to its total activity content. The classification scheme reflects the general principle that the higher the activity concentration, the greater the need to contain the waste and isolate it from the biosphere. Figure 7 shows how NORM waste might fit into this scheme and thus gives an indication of the types of disposal option that might be appropriate. In terms of the proposed classification scheme, NORM waste, which generally contains radionuclides with very long half-lives, would generally be classified as low level waste, very low level waste or exempt waste. On this basis, non-exempt NORM waste could therefore be expected to be disposed of in surface or near surface disposal facilities. In practice, the choice of disposal option and the applicable legislation and/or regulations will also be influenced by non-radiological constituents such as chemicals and heavy metals.

For NORM generated in bulk quantities, there may be opportunities for disposing of it in the mining void. In many situations, however, disposal within engineered surface containments may be the only option. As with other types of long lived radioactive waste, the long term safety should be thoroughly assessed and measures for long term stewardship may become necessary. Because the integrity of the containment system may eventually become compromised long before any significant radioactive decay has occurred, the activity concentrations of the radionuclides in the NORM waste may have to be limited to a level at which the assessed risk is deemed to be acceptable for both present and future generations.

Rather than attempting to contain bulk NORM waste, an alternative approach is to disperse it into the surrounding environment. This may be an acceptable disposal option when activity concentrations are only moderately above clearance levels. One example is the use of land spreading or land farming techniques. Land spreading involves a single application while land farming involves repeated applications. Depending on factors such as climatic conditions and characteristics of the NORM waste and of the land to which it is applied, it may be possible for land spreading or land farming to be carried out safely and this may even have a beneficial effect by improving the quality of the soil. A careful radiological and environmental impact assessment for the site concerned is of course essential for ensuring that the impacts on groundwater, surface water and air quality are within acceptable bounds.

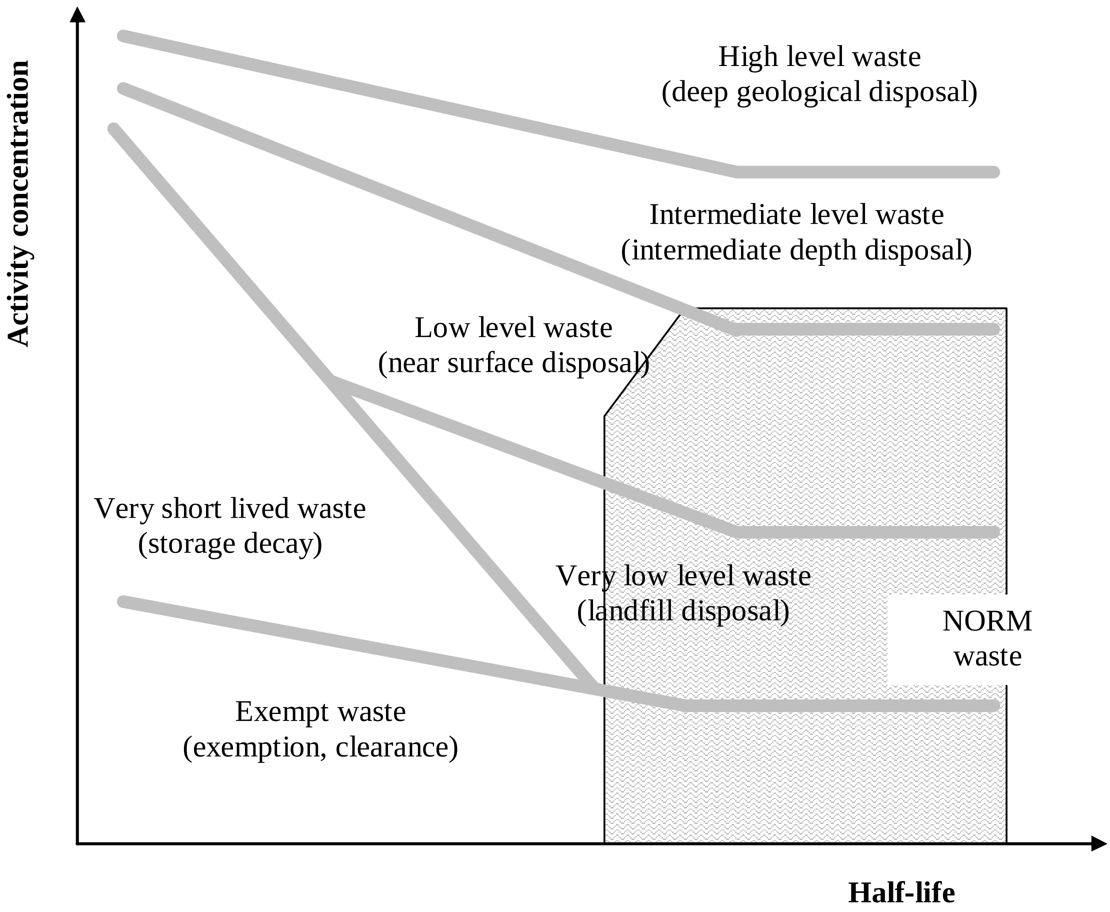

FIG. 7. Classification scheme for radioactive waste — Application to NORM waste.

For NORM waste generated in moderate to reasonably large amounts, disposal options include landfill facilities for industrial or hazardous waste, earthen trenches with suitable natural barrier materials or more highly engineered facilities such as concrete cells or silos. Other disposal options such as boreholes, abandoned oil wells and salt caverns may also be considered. The appropriate type of disposal facility depends on the physical form, chemical characteristics and radionuclide content of the NORM waste concerned. It might be preferable to have a centralized disposal facility rather than having multiple facilities at various locations. The choice depends not only on practical considerations such as site availability but also on the overall national approach to the long term management of radioactive waste, as set out in the national policy statement.

For disposal of NORM waste in an engineered surface containment structure or a landfill site, the long term radiological and non-radiological risks after closure of the facility will depend strongly on whether the land is to be used for residential, agricultural, industrial or recreational purposes, or whether its use is to be prohibited entirely. Post-closure conditions may therefore have to be placed on the disposal site to ensure that it continues to be used in the intended manner. These may include land use restrictions, access control, archiving of records and zoning or permanent marking systems for future generations.

5.13. EXAMPLES OF NORM WASTE MANAGEMENT

5.13.1. Waste rock from mining operations

Waste rock tends to be generated in bulk quantities. Sometimes it is not feasible to use it as a by-product and it has to be disposed of as waste. As with any bulk NORM waste, there are limited options for disposal. It may remain in place as rock piles or, where the opportunity exists, may be backfilled into mining voids such as open pits. The extent of any engineering and/or administrative control measures that might be needed depends on the levels of hazardous constituents, including radionuclides.

5.13.2. Tailings from the dry separation of heavy minerals

Tailings from the dry separation process are usually mixed with other low activity residues, returned to the mining void and covered with non-radioactive sand or overburden. If, in addition, monazite tailings are generated, the high thorium concentration requires that they be blended with (non-radioactive) mine sand tailings to dilute the radionuclide content before disposal in the mine pit.

5.13.3. Bauxite tailings

Bauxite tailings (red mud) are usually disposed of as a slurry (10–30% solids) in large engineered containments that are lined with clay and/or polymeric material (see Fig. 8). Compaction of the tailings is facilitated by drainage systems incorporated in the liner. Other disposal options include disposal in the sea and, after dewatering, dry disposal by land spreading (see Fig. 9). The radioactivity content is only one of several constituents posing a potential risk to the environment.

FIG. 8. Disposal of bauxite tailings in an engineered containment.

FIG. 9. Disposal of dried bauxite tailings by land spreading.

5.13.4. Tailings and phosphogypsum from phosphate fertilizer production

Tailings from the beneficiation of phosphate ore are usually returned to the mining void as a slurry (see Fig. 10). The radiological considerations are minor, owing to the low activity concentrations.

Since the production of phosphogypsum far exceeds demand for agricultural and construction applications, much of it is eventually disposed of as NORM waste. Disposal is usually performed in situ by converting existing large containment structures ('stacks') into permanent disposal facilities, as shown in Fig. 11. Less commonly, phosphogypsum is disposed of by discharging it to water bodies, usually large rivers, river estuaries or the sea.

Stacking of phosphogypsum is carried out by wet deposition (as a slurry) or dry deposition. The safety and environmental issues are similar to those for mine tailings with similar activity concentrations. The radiological issues are insignificant compared with other health, safety and environmental considerations such as structural integrity, heavy metals and acidity.

FIG. 10. Phosphogypsum tailings being returned to the mining void (courtesy: Florida Industrial and Phosphate Research Institute, USA).

FIG. 11. Phosphogypsum stack being converted into a permanent disposal facility (courtesy: Fertiberia, Spain).

5.13.5. Scale deposits

Because of the possibility of close contact with radionuclides at high activity concentrations, outside companies performing scale removal, including scrap melting facilities, may have to be authorized by the regulatory body.

The main options for the disposal of scale after its removal are:

(i) Burial at a site that will remain under institutional control after closure, for instance at a mine site or in engineered earthen trenches or concrete silos;
(ii) Disposal at a hazardous waste disposal facility;
(iii) Disposal at a low/intermediate level radioactive waste disposal facility.

When scaled components are melted as scrap metal, most of the radioactivity in the scale migrates to the slag, leaving the steel essentially free of radioactivity. Blending of scaled components with larger amounts of non-contaminated scrap can reduce activity concentrations and exposures to levels below radiological concern.

The oil and gas industry has some additional options for the disposal of scale:

(i) Discharge as a slurry from offshore rigs into marine waters;
(ii) Injection as a slurry into hydraulically fractured formations;
(iii) Disposal in abandoned wells between concrete plugs.

5.13.6. Sediments and sludge

Depending on the activity concentration, some sediments and sludge have to be treated in a similar manner to high activity scale and disposal in engineered shallow ground burial facilities such as earthen trenches or concrete silos is often the preferred management option. Lower activity sediments and sludge (typically of the order of 10 Bq/g or less) are generally suitable for disposal at landfill facilities for normal industrial waste.

5.13.7. Furnace dust

One disposal option is to dispose of it as industrial waste in a controlled landfill facility. Because of the relatively moderate half-lives of 210Pb (22 years) and 210Po (138 days), another option is to store it for about 100 years, after which it can be disposed of as non-radioactive waste.

5.13.8. Liquid NORM waste

Aqueous waste streams that cannot be recycled are generally treated to remove contaminants and then discharged to the environment in accordance with the authorized discharge limits for the facility concerned. Effluent treatment tends to be driven by the need to remove non-radiological contaminants in order to comply with environmental regulations, but is usually adequate for removing radionuclides as well. Treatment methods generally involve neutralization (using neutralizing agents or mixing acidic and alkaline streams) and solids separation (using settling, precipitation and/or filtration techniques). Up to 90% of radionuclides such as 226Ra can be removed in this manner. Effluent treatment generates solid NORM residues in the form of sludge and filter cake that then have to be disposed of as waste. Under certain circumstances, it may be possible to discharge aqueous residue streams directly into large water bodies such as marine waters, without the need for treatment. This is a widely used option for the management of produced water from offshore oil and gas installations.

In relatively dry climatic conditions, aqueous residue streams may be directed to evaporation and seepage ponds. This is an option commonly used at onshore oil and gas production facilities. It creates the need for subsequent land remediation and management of the contaminated soil. At facilities at which wet deposition of bulk residues (such as mine tailings and phosphogypsum) is carried out, evaporation of aqueous residue streams can take place from the residue ponds, in which case the contaminants simply become part of the bulk solid residue.

Another possibility for aqueous residue streams generated during mining operations is to mix them with solid residues such as sand and to pump the resulting slurry into the mining void. At oil and gas production facilities, the possibility exists for reinjection of the produced water into the reservoir formation.

APPENDIX

RADIONUCLIDES OF NATURAL ORIGIN

TABLE 5. URANIUM-238 DECAY SERIES

	Half-life	Mode of decay[a]	Gamma energy (keV)[b]
^{238}U	4.468×10^9 a	Alpha	
^{234}Th	24.10 d	Beta	63.29 (4.8%), 92.38–92.8 (5.6%)
^{234m}Pa	1.17 min	Beta	1001.03 (0.837%)
^{234}U	245 700 a	Alpha	
^{230}Th	75 380 a	Alpha	
^{226}Ra	1600 a	Alpha	186.211 (3.59%)
^{222}Rn	3.8235 d	Alpha	
^{218}Po	3.10 min	Alpha	
^{214}Pb	26.8 min	Beta	351.932 (37.6%)
^{214}Bi	19.9 min	Beta	609.312 (46.1%), 1764.491 (15.30%)
^{214}Po	164.3 µs	Alpha	
^{210}Pb	22.20 a	Beta	46.539 (4.25%)
^{210}Bi	5.012 d	Beta	
^{210}Po	138.376 d	Alpha	
^{206}Pb	Stable	–	

[a] Only major modes of decay are shown.
[b] Only major gamma emissions of interest are shown.

TABLE 6. THORIUM-232 DECAY SERIES

	Half-life	Mode of decay[a]	Gamma energy (keV)[b]
^{232}Th	1.405×10^{10} a	Alpha	
^{228}Ra	5.75 a	Beta	
^{228}Ac	6.15 h	Beta	911.204 (25.8%), 968.971 (15.8%)
^{228}Th	1.912 a	Alpha	
^{224}Ra	3.66 d	Alpha	240.986 (4.10%)
^{220}Rn	55.6 s	Alpha	
^{216}Po	0.145 s	Alpha	
^{212}Pb	10.64 h	Beta	238.632 (43.6%)
^{212}Bi	60.55 min	Beta 64.06% Alpha 35.94%	727.330 (6.67%)
^{212}Po	0.299 µs	Alpha	
^{208}Tl	3.053 min	Beta	583.191 (84.5%), 2614.533 (99.16%)
^{208}Pb	Stable	–	

[a] Only major modes of decay are shown.
[b] Only major gamma emissions of interest are shown.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Al Masri, M.	Atomic Energy Commission of Syria, Syria
Fischer, H.W.	Division V/7 – Radiation Protection, Austria
Krca, S.	State Office for Radiation Protection, Croatia
Khalaf, S.	Kuwait University, Kuwait
Mannaerts, K.	Federal Agency for Nuclear Control (FANC), Belgium
Miguez, R.	ANDRA, France
Nilsen, M.	Norwegian Radiation Protection Authority (NRPA), Norway
Novikona, E.	Federal Environmental Industrial and Nuclear Supervision Service of Russia, Russian Federation
O'Brien, R.	Australian Radiation Protection & Nuclear Safety Agency (ARPANSA), Australia
Rivas, I.	Ministerio del Poder Popular para la Energia Electrica,Venezuela
Setlow, L.	US Environmental Protection Agency. USA
Soderman, A.L.	Swedish Radiation Safety Authority, Sweden
Tohma, S.	Ministry of Education, Culture, Sports Science and Technology, Japan
Tsurikov, N.	Caltryx Consulting Pty Ltd. Australia
Van der Steen, J.	Consultant, Netherlands
Welberg, J.	COVRA, Netherlands
Wymer, D.	IAEA Consultant, South Africa
Yonehara, H.	National Institute of Radiological Sciences, Japan

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