

Radiological protection against exposure to naturally occurring radioactive material

P. P. Haridasan, M. Harikumar, P. M. Ravi¹, R. M. Tripathi¹

HPU, IREL, Udyogamandal, Eranakulam, Kerala, ¹Health Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai, Maharashtra, India

ABSTRACT

A large effort is under way at a national and international level to assess exposure to the naturally occurring radioactive material (NORM) and to develop strategies to address existing situations that give rise to exposures. The new International Basic Safety Standards (the BSS) published by the IAEA in 2014 provides requirements reflecting the concept of planned, existing, and emergency exposure situations. This concept is yet to be incorporated in the national standards. Exposure to natural sources, in general, is subject to the requirements for existing exposure situations with some exceptions to be considered as planned exposure situations. Several radiation protection challenges exist for controlling exposures to NORM including concerns on regulatory approaches, diverse nature of the industries, and classification as either existing exposure situations or planned exposure situations, optimization using reference levels or dose constraints, and management of NORM residues and wastes. A review of the current situation on radiological protection applicable to NORM is outlined.

KEYWORDS: Industries, NORM, radiation exposure, thorium, uranium

INTRODUCTION

Almost all minerals and raw materials contain radionuclides of natural origin mainly, the ²³⁸U and ²³²Th decay series radionuclides. Radionuclides in the ²³⁵U decay series are less important for exposures, except for ²²⁷Ac, which can contribute significantly to inhalation exposure. Since natural potassium contains 0.0117% ⁴⁰K, this radionuclide is also found. The levels of other natural radionuclides in minerals and raw materials, that is, ⁸⁷Rb, ¹³⁸La, ¹⁴⁷Sm, and ¹⁷⁶Lu, are not normally of concern for radiation protection. In normal rocks and soil, the activity concentrations of radionuclides in the ²³⁸U and ²³²Th decay series and of ⁴⁰K are variable but generally low. The average concentrations are 0.033 Bq/g for ²³⁸U, 0.045 Bq/g

for ²³²Th and 0.412 Bq/g for ⁴⁰K.^[1] However, certain minerals contain these 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 radionuclide concentrations in materials arising from the process may be significantly higher than those in the original mineral or raw material. During chemical processes, selective mobilization of radionuclides can disrupt the original decay chain equilibrium that existed in the ore. Such items of natural raw materials, ores, minerals, process residues, and wastes containing elevated concentrations of natural radionuclides fall within the definition of naturally occurring radioactive material (NORM). Any mining operation or other industrial activity involving a mineral or raw material has the potential to increase the effective dose received by individuals from natural sources, as a result of exposure to radionuclides of natural origin contained

Address for correspondence:

Dr. P. P. Haridasan, Health Physics Division Bhabha Atomic Research Centre, Trombay, Mumbai, Maharashtra, India.
E-mail: haripadmam@gmail.com

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in or released from such material. Where this increase in dose is significant, radiation protection measures may be needed to protect workers or members of the public. The presence of radionuclides at elevated activity concentrations is an important factor in determining which radiation protection requirements are applicable in terms of the safety standards.^[2] The paper provides a review of the radiological protection applicable in situations involving NORM including sources, criteria for regulation, and industrial sectors of concern.

SOURCES OF EXPOSURE

There are common mechanisms for the mobilization and concentration of radionuclides in the processes and thus for the creation of particular scenarios involving enhanced exposure. Characterization of processes on this basis can be useful for the identification of the process steps most likely to require attention within a particular industry sector. Four main types of process can be identified:

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

The main concern in the mining and exploitation of ore is occupational exposure arising from elevated concentrations of radionuclides in the ore and from the enhancement of the exposure potential due to the nature of the mining process. In ore, the radionuclides in each of the uranium and thorium series are likely to be in secular equilibrium. Therefore, the knowledge of the uranium and thorium ore grades is required to characterize the radioactive properties of the material. There is limited opportunity for radionuclide mobilization and disruption of equilibrium. Gamma doses received by workers depend on their proximity to bulk quantities of material. Other important factors affecting occupational exposure may be the geological formation (e.g., sedimentary or igneous rock, mineral sand), the mining method (surface or underground, dry or wet), and the ore comminution method (dry or wet crushing, grinding). Atmospheric and liquid effluent releases from mining operations may result in public exposures.

The main physical mineral separation processes are gravity concentration, magnetic and electrostatic separation, and flotation. While these processes may alter radionuclide concentrations, they are unlikely to change the equilibrium conditions. In dry separation circuits, in mineral sands operations, the alpha activity concentration in airborne dust is influenced strongly by the monazite content of the feed material, since the

mechanical properties of monazite cause this mineral to become preferentially concentrated in the dust. As monazite is relatively rich in thorium, the total alpha activity concentration in the dust can be an order of the magnitude or so higher than in the feed material. Wet physical processes can sometimes cause precipitation of radionuclides on the walls of process equipment. In oil and gas extraction, for instance, precipitation of radionuclides in some instances at very high concentrations occurs in the scaling of pipes and valves when formation water is subject to temperature and pressure changes as it is brought to the surface with the oil or gas.

Chemical extraction is, in general, a chemical leaching process and may be applied *in situ* or to crushed or milled ore in extraction plants. Leaching processes with strong acids or alkalis normally results in significant extraction of radionuclides. Leach solutions can be subjected to various subsequent wet chemical processes in order to concentrate or extract various elements; these include solvent extraction, ion exchange and the recovery of metal by means of electrochemical processes. During these processes, dissolved radionuclides can precipitate in tanks or form scales on equipment walls, or can "plate out" on specific surfaces such as rubber and filter media. These precipitates, scales, and resins are mostly enhanced in specific radionuclides and to levels that depend more on chemical conditions than on the original ore grade. Precipitates and scales especially may contain relatively high radionuclide concentrations, resulting in the possibility of significant occupational exposure to external gamma radiation and to intake of radionuclides by inhalation. Exposure due to ingestion is less likely to be of concern, especially if normal industrial hygiene measures are in place. Sulfate compounds of radium and lead may be of particular interest during leaching with sulfuric acid. Radionuclide specific analyzes are essential during radiological assessments in chemical extraction plants.

Thermal processes include a variety of melting and reduction processes employed to produce or refine metals, including the recycling of scrap metal, and sometimes also to separate minerals from each other. Residues are left as slag, which is often used or further processed into products, but which may also be treated as a waste. Thermal processes also include roasting and calcination to extract or refine minerals or to produce stabilized products, ceramics, or building materials. Finally, thermal processes may also involve the combustion of minerals in the form of fossil fuels such as coal and peat for power generation, giving rise to residues in the form of ash, slag and scale. During any thermal process, exposure of plant workers to furnace fume and dust can be the main concern. Owing to

very dry conditions, airborne dust generation is likely to be significant. The heating process is also likely to volatilize radionuclides with low boiling points (i.e., ^{210}Pb and ^{210}Po). These condense again in scrubbers, filters and stacks, posing mainly an inhalation risk during maintenance operations within these areas. Non volatilized radionuclides tend to migrate to slag, ash or scale, giving rise to a possible risk due to gamma radiation or airborne dust during disposal or use as a by-product.

CRITERIA FOR REGULATION

Exposure that is unamenable to control such as ^{40}K in the body; exposure to cosmic radiation at the earth's surface; public exposure to radon outdoors etc., are excluded entirely from the regulatory safety standards. Exposure to natural sources is normally subject to the requirements for existing exposure situations. However, if the activity concentrations are significantly elevated above background levels, regulatory control in accordance with the requirements for planned exposure situations may need to be considered. In an existing exposure situation, the exposure is not regulated as a practice but, where necessary, may be controlled instead by remedial or protective actions, provided that such actions are undertaken only when they are justified and that their duration, nature, and extent are determined by an optimization process to achieve the maximum net benefit. When an industrial activity is more appropriate to control as a practice, a key question arises at what level of activity concentration does it become appropriate to regulate as planned exposure situation? It is important to appreciate that the selection of activity concentrations that are so low as to invoke widespread regulatory consideration, in circumstances where this is unlikely to achieve any worthwhile improvement in protection, would not be an optimum use of regulatory resources.^[3] Consequently, the following activity concentration criteria are specified in the safety standards:^[2]

- 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 radioactive material (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 radioactive material (NORM), the industrial activity is regarded as a practice and the requirements for planned exposure situations apply.

It should be noted that these activity concentration criteria do not apply to radon, for which separate criteria have been established. As with any exposure to natural sources, exposure to radon is normally subject to the requirements for existing exposure situations.^[2] In terms of the requirements, dose limits do not apply, but the relevant national authority must establish a radon reference level, above which it is not appropriate to plan to allow exposures to occur. The reference level for workplaces should not exceed an activity concentration of 1000 Bq/m^3 . Remedial and/or protective actions may be implemented to reduce exposure to radon provided that such actions are justified and optimized, with special attention being given to situations where the reference level is exceeded. There are two types of situation, however, where exposure to radon in the workplace becomes subject to the requirements for planned exposure situations: The first type of situation is when exposure to other U, Th series radionuclides is already controlled as a planned exposure situation. An example of such a situation would be the underground mining of radioactive ore. The second type of situation is where exposure to other U, Th series radionuclides does not require to be controlled, but where, after remedial action, the radon concentration remains above the reference level. An example of such a situation would be the underground mining of nonradioactive ore where increased ventilation is not possible and/or where radon is released into the workings from radium rich fissure water.

The above regulatory standards are yet to be implemented in the national context. Further, the international standards stipulate the application of a graded approach to regulation exemption; notification; notification and registration; or the highest level notification and licensing commensurate with the nature and magnitude of exposure.

INDUSTRIAL PROCESSES INVOLVING NATURALLY OCCURRING RADIOACTIVE MATERIAL

The following industry sectors have been identified as being the most likely to require some form of regulatory consideration:

- i. Mining and processing of uranium ore;
- ii. Extraction of rare earth elements;
- iii. Production and use of thorium and its compounds;
- iv. Production of niobium and ferro-niobium;
- v. Mining of ores other than uranium ore;
- vi. Production of oil and gas;
- vii. The zircon and zirconia industries;
- viii. Manufacture of titanium dioxide pigment;
- ix. The phosphate industry;

- x. Production of tin, copper, aluminium, zinc, lead, iron and steel;
- xi. Combustion of coal;
- xii. Water treatment.

Each of these industry sectors and the relevant radiological considerations is discussed briefly in the following sections.

Mining and processing of uranium ore

The ^{238}U activity concentrations in most commercially exploited uranium ores range from about 3.5 to 1600 Bq/g. The end product, being essentially a pure uranium compound, has a ^{238}U concentration of the order of 10,000 Bq/g. Given such high activity concentrations, there is obviously a potential for significant worker exposures to gamma, dust and radon, and also a potential for significant public exposure. The possible environmental impacts include the contamination of water bodies as a result of discharges and radionuclide migration from mine residue deposits. The average annual effective dose received by the 12,000 mine workers worldwide is 2 mSv while the corresponding figure for the 3000 ore processing workers worldwide is 1 mSv.^[4] Although these doses are very low, having been progressively reduced over the years, there remains a potential for much higher doses if exposures are not properly controlled, because of the high activity concentrations of the process materials involved. Consequently, these operations are generally licensed by the regulatory bodies.

Uranium tailings are the residue that remains when uranium is chemically extracted from uranium ore using acid or alkaline leaching followed by solvent extraction. The concentrations of ^{230}Th , ^{226}Ra and their decay progeny in uranium tailings remain high. Most uranium ores (and thus uranium tailings) tend to have highly elevated radionuclide activity concentrations, ranging from <10 Bq/g up to values of the order of 1000 Bq/g. There is often an opportunity for recycling the tailings back to the process, since not all the uranium will have been extracted and may also be opportunities to recover other minerals of value such as copper. As with any other type of mine tailings, there are limited options for disposal of uranium tailings because of the very high volumes generated at a facility. The most common approach is to deposit the tailings as slurry in above-ground engineered containments known as tailings dams. There may also be possibilities for backfilling the material into mining voids, either underground or in open pits, although the available volume will generally be much less than the volume of tailings. Uranium tailings disposal facilities have to be highly engineered to ensure that the material is effectively isolated from the surrounding environment. In this regard, physical safety considerations (structural

integrity) and nonradiological environmental hazards such as heavy metals and acidity have to be taken into account as well as radiological hazards. 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. Tailings deposited in open pits may need to be surrounded by a high permeability cover to ensure that the flow of groundwater is diverted around the tailings rather than allowed to pass through. Considerations should also be given from the outset of the uranium mining operation, for closure of the tailings dam on reaching its capacity and further institutional controls.

Extraction of rare earth elements

Rare earth elements are used in the electronics, illumination and glass making industries, in the manufacture of magnets, superconductors and ceramics, and as chemical catalysts and alloying agents in metallurgy. Chemical processes are used to extract rare earths from the thorium-bearing minerals monazite, bastnäsite and xenotime, as well as from rare earth bearing clays, and to subsequently separate and purify them into commercial products. The ^{232}Th activity concentrations in the various process materials vary over a wide range:^[5,6]

- a. Monazite concentrate: 6–400 Bq/g;
- b. Bastnäsite concentrate: 0.15–7.8 Bq/g;
- c. Xenotime concentrate: 13–200 Bq/g;
- d. Rare earth clays: <1 Bq/g;
- e. Process residues: 0.2–1000 Bq/g (up to 5000 Bq/g ^{228}Ra).

Monazite and xenotime are usually obtained from heavy-mineral sands and are separated by gravimetric, magnetic and electrostatic processes. The monazite and other rare earth mineral fractions are processed by acid or alkali digestion. The processes can give rise to radiological hazards from the inhalation of dust and thoron/progeny and from external gamma radiation and are likely to require measures to control external and internal radiation exposures. In the mining and separation of monazite and its chemical processing for the extraction of rare earth, the occupational exposure can vary in the range 0.3–10 mSv/a. In all cases, higher doses are possible if exposures are not adequately controlled. Although purified rare earth products have very low activity concentrations, ^{232}Th activity concentrations of the order of 10 Bq/g have been reported for low purity cerium concentrates used in glass manufacture. Residues and liquid and gaseous effluents from the extraction process contain ^{232}Th and/or ^{228}Ra in concentrations and the removal, treatment and disposal of these residues, as well as the discharge of liquid effluents containing high concentrations of ^{228}Ra , need to be managed under regulatory control.

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 times of tailings per year. The activity concentrations of ^{232}Th are typically in the range 1–20 Bq/g. If there is no intention of extracting monazite, 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. 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. At sites where dry mining operations are carried out, the tailings are usually mixed with other low activity residues, returned to the mining void and covered with nonradioactive sand or overburden.

Production and use of thorium and its compounds

Thorium concentrate, containing up to 20% or more thorium, is obtained from the chemical processing of monazite and other thorium rich minerals. It is digested with nitric acid, concentrated and purified to produce thorium nitrate. This is used for the manufacture of thoriated gas mantles as well as for the production of other thorium compounds such as thorium oxide (used in glass making and catalysts) and thorium fluoride (used for coating lenses and in the glass itself), and for the production of thorium metal (used in magnesium alloys and in welding rods and other forms of tungsten electrodes). The materials involved in the various production processes tend to contain high ^{232}Th activity concentrations:

- a. Thorium concentrate: 500–1000 Bq/g;
- b. Thorium compounds: 2000–2500 Bq/g;
- c. Thorium final products:
 - i. Gas mantles: 500–1000 Bq/g;
 - ii. Thoriated glass: 200–1000 Bq/g;
 - iii. Thorium-containing optical polishing powders: 150 Bq/g;
 - iv. Thoriated welding electrodes: 30–150 Bq/g;
 - v. Thorium alloys: 47–70 Bq/g.

These materials can give rise to radiation hazards that may require specific radiation protection measures, principally to protect against the exposure to external gamma radiation (and, in exceptional cases, beta radiation) and to dust. Exposure to thoron may also

be a significant hazard, particularly in confined spaces such as process vessels, sumps, and storage bins. Annual effective doses received by workers in the production of thorium compounds, have generally varied from 6 to 15 mSv/a. Effective doses received by workers in manufacturing processes involving moderate quantities of thorium-containing material are generally lower often <1 mSv/a but sometimes reaching 10 mSv/a or more. However, because of the high activity concentrations, there is always the potential for higher doses if exposure is not adequately controlled. Solid wastes and effluents generated in industrial processes involving thorium need to be monitored and controlled.

Production of niobium and ferro-niobium

Niobium is used in the electrovacuum, electronics, aerospace and nuclear industries, and for corrosion protection. The production of niobium involves high temperature chemical processing. Pyrochlore is an important source of niobium and contains significantly elevated concentrations of uranium and thorium series radionuclides. Ferro-niobium is produced using a high temperature exothermic reaction between pyrochlore concentrate and aluminium powder. The concentrate typically contains ^{232}Th at an activity concentration of 80 Bq/g and similar concentrations (20–120 Bq/g) have been found in ferro-niobium slag. Furthermore, the use of high temperatures generates precipitator dust containing ^{210}Pb and ^{210}Po at concentrations of 100–500 Bq/g. Consequently, occupational exposure to external gamma radiation and to dust in the production process may be a need to be controlled. Processing of columbite and tantalite ores for the extraction of niobium and tantalum leaves residues containing significant concentrations of ^{238}U (~300 Bq/g), ^{232}Th (~100 Bq/g) and ^{226}Ra (~500 Bq/g). Other residues have ^{228}Ra activity concentrations of 200–500 Bq/g. Residues and wastes generated in these processes may need to be monitored and controlled. In particular, the use of slag might need to be restricted, especially in building materials where it could give rise to high indoor radon or thoron concentrations and gamma radiation.

Mining of ores other than uranium ore

The concentrations of radionuclides of natural origin in most rocks exploited for their mineral content (other than uranium ore) do not significantly exceed those in normal soil. Some hard rock mines may produce ores with higher activity concentrations, ranging up to 10 Bq/g. As the mine environment is conducive to the buildup of radon in the air, particularly in underground mines, exposure of workers to radon is usually the principal cause of concern. The radon concentration is influenced very strongly by factors related to the entry of radon into the air (e.g., porosity of the rock, inflow of radon-containing air and/or water)

and removal of radon from the air (e.g., ventilation conditions underground, atmospheric conditions in open pits). Depending on factors such as the exposure time and the degree of equilibrium between radon and its progeny, the dose received by a worker in such circumstances could approach or even exceed the dose limit. These considerations also apply to workplaces with similar characteristics to those of underground mines, e.g., tunnels, underground water treatment facilities and tourist caves. In some mines, fissure water entering the workings may contain unusually high concentrations of radium, leading to the possibility of significantly increased exposure of workers to radon released from the water, as well as to scales and sediments precipitated in the workings. Scales and sediments may have ^{226}Ra and/or ^{228}Ra activity concentrations of up to 200 Bq/g. Discharge of mine water can lead to significant environmental contamination.

Production of oil and gas

The water contained in oil and gas formations contains ^{228}Ra , ^{226}Ra , and ^{224}Ra dissolved from the reservoir rock, together with their decay progeny. When this water is brought to the surface with the oil and gas, changes in temperature and pressure can lead to the precipitation of radium rich sulphate and carbonate scales on the inner walls of production equipment (e.g., pipes, valves, pumps). The same radium isotopes and their progeny also appear in sludges in separators and skimmer tanks. Lead deposits, containing ^{210}Pb and its progeny, are found in the "wet" parts of gas production installations. The radionuclide activity concentrations are very difficult to predict concentrations range from insignificant levels up to more than 1000 Bq/g (and, exceptionally, to 15,000 Bq/g in the case of ^{226}Ra). Radiation protection considerations arise mainly from the removal of this scale and sludge during maintenance and decommissioning operations (resulting in exposure to external gamma radiation and inhalation of dust) and from the subsequent disposal of such materials as waste, which therefore has to be suitably controlled. Individuals working close to heavily scaled pipes and vessels may also need to be subject to radiation protection measures.^[7,8]

Aqueous residue streams are often generated in very large volumes. Oil production facilities typically generate 2400–40,000 m³/day 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 m³/day. The ^{226}Ra concentrations in produced water generated at oil and gas installations varies from 0.002 to 1200 Bq/L. Large volumes of sludge are generated during oil and gas production. In the USA, it is estimated that 230,000 times of sludge are generated annually in oil and gas production facilities. The sludge

generally consists of oily, loose material often containing silica compounds, but may also contain large amounts of barium. Various treatment and disposal methods are adopted in different countries for the management of sludge and scales.

The zircon and zirconia industries

Zircon (zirconium silicate) is recovered from heavy-mineral sands, which also contain minerals such as monazite, ilmenite, rutile, garnet, and xenotime. The mineral sands are separated into their components by gravimetric, magnetic, and electrostatic processes. The separation process could give rise to radiological hazards from dust inhalation as well as from external gamma radiation emanating from large stockpiles of material. Most zircon sand is used as an opacifier in glazes for tiles and sanitary ware. It is also used for foundry sands and mould washes and in the production of refractory materials and zirconia (zirconium oxide). For many of these applications, zircon sand is milled into smaller particles, in some cases down to particle sizes of <5 µm. Modern zircon milling operations maintain a high standard of dust control, not just for occupational health and safety (OHS) reasons but also to avoid the loss of valuable product. Zirconia may be manufactured by melting zircon sand in a very high temperature furnace. Most of the ^{210}Pb and ^{210}Po in the feed material end up in the silica fume, which is removed by a fume collection system. The exposure of workers to silica fume needs to be controlled by respiratory protection. Zirconia is also manufactured by chemical processing of zircon sand and the control of effluent discharges may need to be considered. The activity concentrations in the process materials are as follows:^[9,10]

- Zircon: 2–4 Bq/g ^{238}U ;
- Baddeleyite: 3–13 Bq/g ^{238}U , 0.1–26 Bq/g ^{232}Th ;
- Zirconia from fusion: 1.9–8 Bq/g ^{238}U ;
- Zirconia from chemical processing: 0.001–1 Bq/g ^{226}Ra ;
- SiO_2 residue from zircon fusion: 1.5–6 Bq/g ^{226}Ra , 0–10 Bq/g ^{210}Pb , ^{210}Po ;
- Furnace dust from baddeleyite fusion: 600 Bq/g ^{210}Po ;
- Effluent treatment tank deposit: >5000 Bq/g ^{226}Ra ;
- Chlorination residues: 0.3–48 Bq/g ^{226}Ra .

The annual effective doses received by workers are; in the fusion or chemical processing of zircon or baddeleyite 0.015–5.5 mSv; and all other processes: 0.0003–1 mSv. There is the potential for higher doses if good OHS practices, such as dust control measures, are not adopted.

Manufacture of titanium dioxide pigments

The principal raw materials for titanium dioxide production are ilmenite and rutile. Production from

ilmenite often involves the use of intermediate or upgraded feedstocks such as synthetic rutile and slag. Ilmenite and rutile are obtained from heavy-mineral sands by gravimetric, magnetic and electrostatic processes. The separation process could give rise to radiological hazards from dust inhalation as well as from external gamma radiation from large material stockpiles. Various thermal and/or hydrometallurgical processes are used for the production of titanium dioxide pigments. The activity concentrations in various process materials are as follows:^[11,12]

- a. Ores: 0.001–2 Bq/g ²³²Th;
- b. TiO₂ product, TiCl₄ intermediate product: <0.1 Bq/g;
- c. By-products: <0.01–1 Bq/g ²³²Th;
- d. Scale: <1–1600 Bq/g ²²⁸Ra;
- e. Filter cloths: 2–1000 Bq/g ²²⁸Ra;
- f. Other residues: 0.02–24 Bq/g ²³²Th.

Annual effective doses received by workers are, in practice, very low, ranging from < 0.01 to 1 mSv. However, there is potential for higher doses if good OHS practices not adopted. Public exposure is insignificant, but discharges and disposal of high activity wastes need to be controlled according to good environmental practice. Regulatory attention is required mainly in connection with exposure of workers to radium rich scale and the management of some of the many different waste streams.

The phosphate industry

Phosphate rock is mined on a large scale as a source material for fertilizers, animal feed and other phosphorus containing products. Most phosphate rock is treated with acid (wet process) and depending on the detailed process, this produces phosphoric acid which is used as the input material for the manufacture of fertilizer and a wide variety of other phosphate based products or converts the rock directly to fertilizer. The main areas of possible radiological concern are large quantities of phosphogypsum containing radium at a concentration similar to that in the original rock. Phosphogypsum consists essentially of calcium sulphate, but also contains a variety of heavy metals, fluorides, and radionuclides (principally ²²⁶Ra 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 P₂O₅ produced in the form of phosphoric acid, 4–6 times dry mass of phosphogypsum are produced. The annual production of phosphogypsum worldwide, currently at about 160 million tonnes, could reach 200–250 million tonnes within the next decade or two. Environmental protection issues, mainly related to the heavy metal content, arise from the disposal of phosphogypsum in “stacks” or by discharge into surface water bodies in the case of the latter, environmental protection aspects

have been a cause for concern and such discharges are no longer practised in some countries. Phosphogypsum is also used in building materials and agriculture. In India, a specific regulatory directive exists on the use of phosphogypsum.^[14] Radium bearing scales and sediments formed inside the process equipment also need attention. The radionuclide concentrations in these materials vary from values similar to those in the original rock up to 1000 times greater. Exposure to external gamma radiation and/or to inhaled dust might need to be considered during maintenance and decommissioning.^[13]

Alternatively, some phosphate rock is converted in high temperature furnaces to elemental phosphorus, which is used for the production of high purity phosphoric acid and other phosphorus containing products (thermal process). During the process, ²¹⁰Pb becomes concentrated in the precipitator dust by up to 1000 times. The exposure of workers to this dust, as well as the disposal of the material, needs to be controlled. Because of the short half-lives of ²¹⁰Pb and ²¹⁰Po, decay storage of the furnace dust is carried out. After about 100 years, it will be possible to dispose of the material as nonradioactive waste. The calcium silicate slag contains radionuclides in the upper portion of the uranium decay chain at activity concentrations similar to those in the original ore and as with any other building material containing elevated concentrations of natural radionuclides, the use of this slag as a construction material may need to be restricted to certain applications. The activity concentrations in the various process materials are as follows:

- a. Ore: 0.1–3 Bq/g ²³⁸U;
- b. Process residues:
 - i. Mine tailings: 0.01–2 Bq/g ²³⁸U;
 - ii. Scale: 0.03–4000 Bq/g ²²⁶Ra;
 - iii. Sediment, sludge: 1.3–4.3 Bq/g ²²⁶Ra;
 - iv. Sludge from dicalcium phosphate production: 8–13 Bq/g ²¹⁰Po;
- c. Fertilizer and animal feed products: 0.04–3 Bq/g ²³⁸U;
- d. Phosphogypsum by-product: 0.01–3 Bq/g ²²⁶Ra;
- e. Slag from thermal phosphorus production: 1 Bq/g ²³⁸U;
- f. Furnace dust from thermal phosphorus production: 1000 Bq/g ²¹⁰Pb.

Annual effective doses received by workers are in the range 0.1–0.7 mSv. Tailings from the beneficiation of phosphate ore consist mainly of sand or clay particles. Worldwide, about 250 million tonnes of tailings are generated per year. The tailings contain radionuclides from the ²³⁸U decay series at activity concentrations of 0.01–2 Bq/g. The tailings are usually returned to the mining void. The radiological considerations are minor, owing to the low activity concentrations.

Production of tin, copper, aluminium, zinc, lead, and iron and steel

The radionuclide concentrations in most feedstocks are only moderately higher than normal environmental levels and tend to remain so in the products and waste. The high temperatures used in the smelting and refining processes may lead to concentrations of ^{210}Pb and/or ^{210}Po in the precipitator dust, but doses received by workers are not usually a significant source of concern. Radionuclides may become moderately concentrated in the slag and use of some slag might need to be restricted. Tin slag contains elevated concentrations of radionuclides from both the uranium and the thorium decay series and is sometimes used as a source of niobium and tantalum. The activity concentrations in various process materials are as follows:

- Feedstocks: Usually close to background levels; bauxite 0.035–1.4 Bq/g ^{232}Th ;
- Furnace dust from metal smelting and refining: Up to 200 Bq/g ^{210}Pb , ^{210}Po ;
- Tin slag: 0.07–15 Bq/g ^{232}Th ;
- Copper slag: 0.4–2 Bq/g ^{226}Ra ;
- Sludge from iron smelting: 12–100 Bq/g ^{210}Pb ;
- Red mud (bauxite tailings from aluminium production): 0.1–3 Bq/g ^{238}U , ^{232}Th .

There is the potential for workers to receive moderate doses from dust. The use of tin slag may need to be restricted. 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. Several million tonnes of red mud are generated worldwide annually. Red mud has a typical ^{232}Th activity concentration of 0.1–3 Bq/g and contains other constituents of potential concern for environmental protection, such as heavy metals.

Combustion of coal

The combustion of coal to produce heat and electricity generate residues in the form of fly ash (most of which is separated from the flue gases and collected) and the heavier bottom ash or slag. Fly ash contains the volatile radionuclides ^{210}Pb , ^{210}Po . Flue gas desulfurization results in additional residues in the form of sludges and gypsum. The disposal of coal combustion residues might have radiological implications, but these are likely to be of minor significance if the residues are disposed of in reasonably well-engineered landfill sites or surface impoundments. Fly ash and gypsum are used as components of building materials, e.g., as additives to cement and concrete or in lightweight building blocks. The activity concentrations in the final building products are usually too low to be of regulatory concern.

The activity concentrations in various process materials are as follows:

- Coal: Typically at background levels, but sometimes higher up to 0.5–1 Bq/g ^{226}Ra ;
- Fly ash: Typically 0.2 Bq/g, but sometimes higher;
- Bottom ash and slag: 0.1–1.5 Bq/g
- Flue gas desulfurization residues (sludges, gypsum): Lower than ash;
- Scales inside burner kettles: Can exceed 100 Bq/g ^{210}Pb .

There is limited potential for worker exposure, and annual effective doses are not expected to exceed 1 mSv. The bulk storage and disposal of residues have potential environmental impacts, mostly nonradiological, requiring that they be placed in engineered containments. The use of fly ash and gypsum as by-products for construction materials does not usually need to be restricted because of the low activity concentrations and dilution with nonradioactive material. Although the activity levels are low, some of the coal mines have higher radionuclide concentrations and resulting issues with elevated ^{226}Ra concentrations in mine water and radon.

Water treatment

Water treatment processes often remove radionuclides and can accumulate in water treatment sludge in filters, tanks, pipes, sediments and ion exchange resins. The activity concentrations in such wastes are usually only moderately elevated. Activity concentrations of ^{226}Ra are in the range 0.1–14 Bq/g, but the higher values in this range are found only when treating groundwater with elevated radium concentrations. The radionuclide content can have implications for disposal, but the presence of chemically hazardous constituents such as heavy metals may in any case necessitate some form of control. There is limited potential for significant worker exposures. In underground water treatment facilities, however, radon may accumulate to high concentrations, requiring remedial action (ventilation) or protective action (restriction of occupancy times). It is estimated that approximately 260,000 times of NORM residues are generated each year by water treatment facilities in the USA, equivalent to 600 times per treatment plant. Of these residues, filter sludge accounts for 83%, with ion exchange resins and charcoal accounting for the remaining 17%.

CONCLUSIONS

The requirements stipulated in the new international basic safety standards provide greater clarity on the control of exposure to natural sources. However, the standards lead to several radiation protection challenges on exposures to NORM.^[15] Some form of regulation has already been identified for consideration by the industry sector and reasonable knowledge of the radionuclides concentrations in minerals and raw material, processes

involved, likely occupational exposures, residue and waste management is available. The 1 Bq/g criterion for uranium and thorium series radionuclides as a tool for determining which industrial process materials need to be considered for regulation has been widely accepted. There is growing recognition that an industry or process specific approach is needed for ensuring that exposures to NORM are controlled optimal and effectively. Industrial activities involving NORM, and legacy situations from such activities, are very diverse and each has to be addressed by developing “good practice” tailoring to the particular set of circumstances. Application of a graded approach to regulation to control exposures to NORM has also been well recognized. Growing challenges include fixing of an appropriate reference levels in existing exposure situations, implications of conservative modeling for estimating doses in particular public exposures, the need for an evidence-based approach for regulatory decisions and differences in interpretation of the concepts of exclusion, exemption and clearance. The nonstandardized approach in the assessment of worker doses and issues emerging with the new risk estimate to the exposure to radon by the ICRP, pose a great challenge in workplaces. Management of NORM residues and wastes, issues arising by the recycling and use of NORM residues and legacy situations are still major issues across the world.

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