

**Safety Reports Series**

**No. 49**

**Assessing the Need for  
Radiation Protection  
Measures in Work  
Involving Minerals and  
Raw Materials**



**IAEA**

International Atomic Energy Agency

ASSESSING THE NEED FOR  
RADIATION PROTECTION  
MEASURES IN WORK  
INVOLVING MINERALS  
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SAFETY REPORTS SERIES No. 49

ASSESSING THE NEED FOR  
RADIATION PROTECTION  
MEASURES IN WORK  
INVOLVING MINERALS  
AND RAW MATERIALS

INTERNATIONAL ATOMIC ENERGY AGENCY  
VIENNA, 2006

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## FOREWORD

The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Safety Series No. 115) specify requirements to be fulfilled in all activities involving exposure to radiation, including radiation from natural sources. The Safety Guides on Occupational Radiation Protection in the Mining and Processing of Raw Materials (IAEA Safety Standards Series No. RS-G-1.6) and Management of Radioactive Waste from the Mining and Milling of Ores (IAEA Safety Standards Series No. WS-G-1.2) recommend actions for meeting these requirements in the mining and mineral processing industry including, in the former publication, explicit actions for meeting the requirements concerning exposure to radon in the workplace.

In the case of exposure to radionuclides of natural origin other than radon, considerably more regulatory discretion is required in assessing the need for radiation protection measures. The activity concentrations of radionuclides of natural origin in commercially exploited minerals are in most cases similar to those in normal rocks and soil and are not generally of regulatory concern, but there are instances where significantly higher values are found. Furthermore, the mobilization of these radionuclides during mineral processing operations can result in significant increases in activity concentration.

The Safety Guide on Application of the Concepts of Exclusion, Exemption and Clearance (IAEA Safety Standards Series No. RS-G-1.7) provides values of activity concentration for radionuclides of natural origin below which it is usually unnecessary to regulate. Where these values are exceeded, the regulatory body needs to determine whether control measures for radiation protection are warranted and, if so, to ensure that the application of such measures is commensurate with the characteristics of the operation and the exposures involved. This Safety Report provides information on the relevant industrial activities, materials and expected exposure levels, with the aim of facilitating this regulatory decision making process.

This Safety Report was drafted and finalized in two consultants meetings, held during the period 2003–2005. Particular acknowledgement is paid to the contributions made to the preparation of this Safety Report by G.P. de Beer, A. Faanhof, A. Melbourne, P.M.B. Pillai, P.V. Shaw and J. van der Steen. The IAEA officer responsible for this report was D.G. Wymer of the Division of Radiation, Transport and Waste Safety.

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# 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  $^{238}\text{U}$  and  $^{232}\text{Th}$  decay series (see Appendix I for details) and  $^{40}\text{K}$  are the main radionuclides of interest.<sup>1</sup> 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 and selective mobilization of radionuclides can disrupt the original decay chain equilibrium. As a result, radionuclide concentrations in materials arising from a process may exceed those in the original mineral or raw material, sometimes by orders of magnitude.

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 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. This can occur in two types of situation:

- (1) Where the radionuclide concentration in any material associated with the process is significantly higher than in normal rocks and soil, whether as a result of the process or not, protective measures may need to be considered with regard to:
  - (a) External exposure to radiation (primarily gamma radiation) emitted by the material;

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

- (b) Intake of material (primarily through inhalation of radionuclides in dust);
- (c) Inhalation of radon (and sometimes thoron) released from the material into the air<sup>2</sup>.

Material that is designated as being subject to regulatory control in this regard is referred to as naturally occurring radioactive material (NORM).

- (2) Where the radionuclide concentrations in the materials associated with the process are not significantly higher than in normal soil, measures may still be needed to protect workers against exposure to radon if the workplace conditions are conducive to the buildup of radon gas in the air – in underground mines, for instance, radon may become concentrated in the mine atmosphere due to emanation from the rock or from water entering the workings.

A key question is “at what level of activity concentration does it become necessary to regulate?” 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. Similarly, for those industrial activities identified as requiring some form of regulation, the imposition of the most stringent level of control, irrespective of the nature and likelihood of the radiological hazard, would not be consistent with the optimization of protection. Decisions therefore have to be made on what to regulate and how. The IAEA safety standards (the Standards) provide the basis on which to make such decisions [1–4]. This Safety Report provides information on the relevant industrial activities, materials and expected exposure levels, in support of this decision making process.

## 1.2. OBJECTIVE

In view of the very large number of work activities worldwide involving minerals and raw materials, most of which are unlikely to require measures for radiation protection, the Standards recommend that the regulatory body “should first undertake an investigation of these situations to determine the

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<sup>2</sup> In this report, the use of the terms ‘radon’ and ‘thoron’ is generally taken to include not only the parent radionuclides <sup>222</sup>Rn and <sup>220</sup>Rn, respectively, but also their short lived progeny. However, the terms ‘radon concentration’ and ‘thoron concentration’ refer to the concentrations in air of the parent radionuclides alone.

extent of the exposures” [3]. This process could consume large amounts of time and resources if not conducted in a systematic manner. The objective of this Safety Report is to provide information to assist Member States in identifying (a) industrial activities that may require some form of regulatory supervision or control and (b) for such activities, the most appropriate regulatory approach.

This Safety Report is aimed primarily at regulatory bodies and other national authorities involved in the application of the Standards to work activities involving exposure to natural sources, including the development of suitable regulations and regulatory approaches. The Safety Report will also be of interest to operators, workers and their representatives — as well as to health, safety and environmental professionals — in the industrial sectors concerned.

### 1.3. SCOPE

This Safety Report identifies the industry sectors and process materials most likely to need regulatory consideration and provides further information to assist regulatory bodies in assessing the need for radiation protection measures. This information includes a description and radiological characterization of the relevant industrial processes, activity concentration levels for the various types of material involved and broad estimates of the effective doses that might be received. This information is intended to serve as a prioritization tool to bring greater focus to the assessment process. The Safety Report also provides information on practical techniques for determining radionuclide activity concentrations, where such measurements are required as part of the assessment process. The report concludes with an example of how all the information provided might be used by regulatory bodies.

Exposure to radon is covered in the Safety Report, but not in great detail, since this has been dealt with at some length in the Safety Guides on Occupational Radiation Protection [3] and Occupational Radiation Protection in the Mining and Processing of Raw Materials [4], and in the Safety Report on Radiation Protection against Radon in Workplaces other than Mines [5].

The scope of this Safety Report does not include remediation of past practices involving NORM, although it may be of some interest to those involved in such activities. Information on the remediation of residues from uranium mining and processing operations (applicable in principle to other NORM residues) can be found in Refs [6, 7].

Material associated with the mining and processing of uranium ores is, in the strictest sense, NORM. However, because such activities are part of the nuclear fuel cycle, they are automatically subject to licensing and are not

discussed further in this Safety Report. Guidance on such activities is given elsewhere [4, 8]. The production and use of radiation sources containing radionuclides of natural origin are also not within the scope of this Safety Report — such sources are treated in the same way as sources containing radionuclides of artificial origin.

This Safety Report is intended to cover only the first steps in the application of the Standards to industrial activities involving NORM, namely, the identification of relevant activities and the considerations involved in determining the most appropriate regulatory approach. Detailed information on radiation protection and management of radioactive waste in specific industry sectors is provided in other Safety Reports [9–13].

#### 1.4. STRUCTURE

Following this introductory section, Section 2 provides a summary of the Standards as they apply to work involving minerals and raw materials, with particular emphasis on the scope of application of the Standards and the so-called ‘graded approach’ to regulation. Section 3 describes the industrial activities for which radiation protection measures are most likely to be required — such activities are identified on the basis of industry sectors, materials involved and worker exposures. Knowledge of radionuclide activity concentrations is important in the preliminary investigation of work activities involving minerals and raw materials and information on practical techniques for determining the concentrations of the main radionuclides of interest is given in Section 4. Finally, Section 5 contains an example of how the information provided in this Safety Report might be used in assessing the need for radiation protection measures. Three appendices provide information on radionuclides in the uranium and thorium decay series, on the characterization of industrial processes in terms of how they lead to enhanced levels of exposure and on the estimation of dose received by a mineral processing worker exposed to gamma radiation and to dust.

## **2. APPLICATION OF THE STANDARDS TO WORK INVOLVING MINERALS AND RAW MATERIALS**

### **2.1. EXCLUDED EXPOSURES**

Paragraph 1.4 of Ref. [1] states that “Any exposure whose magnitude or likelihood is essentially unamenable to control through the requirements of the Standards is deemed to be excluded from the Standards”. Examples of excluded exposure given in the Standards are “exposure from  $^{40}\text{K}$  in the body, from cosmic radiation at the surface of the earth and from unmodified concentrations of radionuclides in most raw materials” (Ref. [1], footnote 2). Although all of these examples relate to exposure to natural sources, there is no explicit requirement to limit the concept of exclusion to such exposure.

### **2.2. APPLICABILITY OF REQUIREMENTS**

#### **2.2.1. Practice or intervention?**

Paragraph 2.5 of Ref. [1] states that “Exposure to natural sources shall normally be considered as a chronic exposure situation and, if necessary, shall be subject to the requirements for intervention”. However, there are some human activities giving rise to exposure to natural sources that have the characteristics of practices and for which the intervention approach may therefore be inappropriate. If the exposure is amenable to control, it may be necessary to exercise such control in accordance with the requirements for practices. In terms of the Standards, the following work activities involving exposure to natural sources are subject to such requirements (Ref. [1], para. 2.1):

- (a) The production and use of radiation sources involving radionuclides of natural origin;
- (b) The mining and processing of radioactive ore as part of the nuclear fuel cycle;
- (c) Any other work activity involving exposure to natural sources specified by the regulatory body as requiring control.

This Safety Report deals specifically with the activities referred to in (c) above.

The Standards also specify the following exposures to natural sources as being automatically subject to the requirements for practices, unless such

exposures are excluded or the practice or source is exempted (Ref. [1], para. 2.5):

- (a) Certain exposures of workers to radon (see Section 2.2.3 for details);
- (b) Public exposures delivered by effluent discharges or the disposal of radioactive waste arising from a practice involving natural sources.

### **2.2.2. Material containing radionuclides of natural origin**

The following values of activity concentration are specified in the Standards as being values below which it is usually unnecessary to regulate [2], irrespective of the quantity of material or whether it is in its natural state or has been subject to some form of processing:<sup>3,4</sup>

- (a) 1 Bq/g for uranium and thorium series radionuclides;<sup>5</sup>
- (b) 10 Bq/g for <sup>40</sup>K.

These values were derived on the basis of the concept of exclusion, i.e. non-amenability to control, and were selected by considering the upper end of the worldwide distribution of activity concentrations in soil [14]. They do not apply to radon in air, material in transport in accordance with the IAEA Transport Regulations [15], discharges from authorized practices, or NORM residues in the environment.

Work activities involving material in which either of the above activity concentration values is exceeded would, by implication, need to be considered by the regulatory body. In terms of the graded approach to regulation, however, the regulatory body may decide that the optimum regulatory option is not to apply regulatory requirements (see Section 2.3.2).

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<sup>3</sup> The use of building materials with activity concentrations below these values may need some regulatory consideration (Ref. [2], para. 5.1) — further guidance on this topic is being developed.

<sup>4</sup> In the case of occupational exposure, where there are elevated gamma radiation dose rates due to the presence of natural radioactive substances in the ground and building materials that make up the workplace, an approach similar to that for radon in workplaces could be used (see Section 2.2.3), with a guideline action level for intervention through remedial action in this case being a gamma dose rate of 0.5 µSv/h or some multiple thereof (Ref. [3], para. 2.29).

<sup>5</sup> The value applies individually to each radionuclide.

The above mentioned activity concentration values may also be used to determine whether NORM can be released (without restriction) from regulatory control (Ref. [2], para. 5.3).

### **2.2.3. Radon**

Exposure to radon is normally considered as a chronic exposure situation and subject, if necessary, to the requirements for intervention.<sup>6</sup> The Standards require that an action level for intervention through remedial action be determined using an approach based on optimization of protection. Guideline action levels are specified in terms of the annual average activity concentration of <sup>222</sup>Rn in air: 200–600 Bq/m<sup>3</sup> in dwellings and 1000 Bq/m<sup>3</sup> in workplaces (Ref. [1], Schedule VI).

For workplaces, the Standards recommend (Ref. [3], para. 2.20) that the regulatory body identify or determine, by means of a survey or otherwise, those workplaces with radon concentrations above the action level. Consideration should then be given to whether such concentrations can reasonably be reduced to below the action level. Where sufficient reduction in concentrations cannot reasonably be achieved, the requirements for practices should be applied<sup>7</sup>. In such circumstances, the numerical value of the action level takes on a conceptually different significance — instead of being used as the basis for a decision on intervention, it is used “as the basis for a decision to consider the exposures to be arising from a practice” (Ref. [3], para. 2.20).

## **2.3. GRADED APPROACH TO REGULATION**

### **2.3.1. Introduction**

A graded approach to regulation is one of the key principles embodied in the Standards, which state that the application of the requirements for practices “shall be commensurate with the characteristics of the practice or source and with the magnitude and likelihood of the exposures” (Ref. [1], para. 2.8). For

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<sup>6</sup> This is the case for most workplaces, where exposure of workers to radon is incidental to their work. Where the exposure is not incidental to the work, for instance in the mining and processing of uranium ore and thorium ore, such exposure (other than exposure whose magnitude or likelihood is essentially unamenable to control) is automatically subject to the requirements for practices.

<sup>7</sup> Unless the exposure is excluded or the practice or source is exempted.



situations involving exposure to NORM, it implies that the regulatory body will go beyond just establishing that the activity concentration values in Section 2.2.2 are exceeded; it will consider particular types of operation, process and material in more detail, including some form of exposure or dose assessment in order to determine the optimum regulatory approach.

The graded approach applies to all sources of radiation subject to regulation. However, it is particularly relevant to operations involving exposure to natural sources, because the exposures are generally (but not always) moderate, with little or no likelihood of extreme radiological consequences from accidents and because occupational health and safety (OHS) measures already in place to control other (non-radiological) hazards in the workplace may well provide some protection against radiological hazards as well.

### **2.3.2. Exemption**

The first, most basic, level in the graded approach is where the regulatory body decides that the optimum regulatory option is, in fact, not to impose regulatory requirements. The mechanism for giving effect to such a decision could take the form of an exemption. Although the decision is in principle based on optimization, the following numerical guidance expressed in terms of effective dose is given in the Standards:

- (a) With regard to the activity concentration levels in materials below which it is usually unnecessary to regulate (1 Bq/g for uranium and thorium series radionuclides and 10 Bq/g for  $^{40}\text{K}$  (see Section 2.2.2)) the Standards state that “Doses to individuals as a consequence of these activity concentrations would be unlikely to exceed about 1 mSv in a year, excluding the contribution from the emanation of radon, which is dealt with separately in the BSS” (Ref. [2], para. 3.3). The corollary of this is that it would usually be unnecessary to regulate any activity involving exposure to NORM if the effective dose received by a worker or member of the public does not exceed about 1 mSv in a year.
- (b) The International Commission on Radiological Protection (ICRP) recommends, for materials containing uranium and thorium series radionuclides, that “regulatory agencies choose activity concentrations of parent nuclides within the range 1–10 Bq/g to determine whether the exposures from these materials should be regarded as occupational”, noting that such concentrations “will lead to an effective dose of about 1–2 mSv in a year” [16]. This recommendation is reflected in the Safety Guide on Occupational Radiation Protection [3] and implies that if the

effective dose received by a worker from exposure to gamma radiation and to dust does not exceed 1–2 mSv in a year it would be unnecessary to regulate that exposure.

Experience with industrial activities involving exposure to NORM indicates that the dose received by a member of the public living near the industrial facility concerned is generally no more than a few microsieverts per year (exceptionally of the order of 100  $\mu\text{Sv/a}$  — see, for instance, Ref. [14], Annex B, para. 188) and is consequently only a small fraction of the dose that could be received by a worker. Therefore, a decision not to impose regulatory requirements (i.e. a decision to exempt the practice or source) can generally be made on the basis of the worker dose not exceeding 1–2 mSv in a year, secure in the knowledge that under such circumstances the dose received by a member of the public living nearby is likely to be lower by at least an order of magnitude. This approach greatly facilitates the decision making process because it avoids the practical problems involved in making reliable assessments of doses to members of the public at small increments above background levels.

The soundness of any decision as to whether or not to impose regulatory requirements, made on the basis of the doses received by workers, depends on how realistically such doses are estimated. This implies, for instance, that due account is taken of the effect (and effectiveness) of existing OHS controls, e.g. ventilation systems, personal protective equipment (see Section 2.3.4.2).

### **2.3.3. Notification**

Where the regulatory body decides that there is a need to apply regulatory requirements to a particular type of operation or process, the next level in the graded approach is the requirement for the legal person to submit a formal notification to the regulatory body (Ref. [1], para. 2.10). Notification alone could be sufficient where exposures are unlikely to exceed a small fraction, specified by the regulatory body, of the relevant limits. In practical terms, this is similar to exemption, but with the important difference that the regulatory body is kept informed of all such operations or processes. Again, the existence of more general OHS measures would be an important factor in deciding whether notification alone was the optimum regulatory option.

## **2.3.4. Authorization**

### *2.3.4.1. Registration and licensing*

Where the nature of the hazard is such that further obligations beyond notification need to be placed on the legal person, the Standards require that person to apply to the regulatory body for an authorization. In accordance with the graded approach to regulation, the authorization may take the form of either a registration or a licence, the difference being essentially in the level of stringency of regulation (Ref. [1], para. 2.11). Registration, which typically places only limited obligations on the legal person, may provide a sufficient level of control in many operations involving significant, but nevertheless moderate, exposures to NORM and/or radon. In situations where optimized protection can only be achieved through the enforcement of specific exposure control measures, licensing may be the more appropriate form of authorization. Licensing represents the highest level in the graded approach to regulation and the need for licensing of operations giving rise to exposure to NORM will probably be largely limited to operations involving significant quantities of material with very high radionuclide activity concentrations.

### *2.3.4.2. Control measures*

A detailed account of the control measures that may be appropriate for authorized practices involving work with minerals and raw materials is given in Refs [4, 8]. In terms of the graded approach to regulation, the nature and extent of such measures will be commensurate with the type of practice and the levels of exposure, but will generally entail the establishment of some form of radiation protection programme with suitable provisions for monitoring and dose assessment at a more detailed level than in the initial assessment referred to in Section 2.3.1.

The main types of exposure arising from work with NORM are external exposure to gamma radiation and internal exposure to inhaled dust and radon. While specific radiological measures in the workplace such as control of occupancy time or even shielding may sometimes be appropriate to minimize external exposure to NORM, exposure to dust is likely to be controlled already in many workplaces through general OHS regulations. Control of the air quality for the purpose of minimizing dust levels may also help to reduce radon concentrations. Therefore, the extent to which existing OHS control measures are effective in minimizing workers' radiation exposure is something that the regulatory body would first need to establish before deciding to impose additional control measures for purely radiological reasons.

In some workplaces, existing OHS control measures alone may provide sufficient protection against radiological hazards. In other workplaces, additional control measures specifically for radiation protection purposes may become necessary as a result of applying the Standards. Many industrial facilities will have commenced operation long before the requirements for such control measures were introduced, but have, nevertheless, succeeded in modifying their operations accordingly. In a limited number of cases, difficulties have arisen in achieving compliance with the occupational dose limit of 20 mSv/a. This is particularly the case with exposure to radon in some underground mines where the necessary improvements to ventilation systems cannot always be reasonably achieved. The Standards provide various ways of dealing with this situation. Firstly, they provide some flexibility by allowing five-year averaging of doses received by workers when verifying compliance with the dose limit (Ref. [1], para. II-5). Secondly, the Standards recommend that “In mines where there are areas with high levels of radiation exposure, where no other practicable means of control are available, job rotation may be considered in order to restrict the exposure of individual workers” (Ref. [4], para. 5.42). Finally, provision is made for the approval by the regulatory body, in special circumstances, of “a temporary change in a dose limitation requirement of the Standards”, subject to specific conditions (Ref. [1], paras I.50–I.54).

### **3. INDUSTRIAL ACTIVITIES MOST LIKELY TO REQUIRE REGULATORY CONSIDERATION**

#### **3.1. INDUSTRY SECTORS**

A considerable body of knowledge and experience has already been built up concerning operations involving minerals and raw materials (in addition to uranium ores) that may lead to a significant increase in exposure to natural sources. Reviews of such activities can be found, for instance, in Refs [17–20]. The following industry sectors have been identified, roughly in descending order of priority, as being the most likely to require some form of regulatory consideration:

- (1) Extraction of rare earth elements;
- (2) Production and use of thorium and its compounds;
- (3) Production of niobium and ferro-niobium;

- (4) Mining of ores other than uranium ore;
- (5) Production of oil and gas;
- (6) Manufacture of titanium dioxide pigments;
- (7) The phosphate industry;
- (8) The zircon and zirconia industries;
- (9) Production of tin, copper, aluminium, zinc, lead, and iron and steel;
- (10) Combustion of coal;
- (11) Water treatment.

Each of these industry sectors and the relevant radiological considerations are discussed briefly below.

### **3.1.1. 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. They are extracted from monazite, bastnaesite, xenotime and rare earth bearing clays using chemical processes. These minerals contain concentrations of  $^{232}\text{Th}$  ranging from a few becquerels per gram to several hundred [21]. The mineral sands are separated by gravimetric, magnetic and electrostatic processes. The monazite and other rare earth mineral fractions are processed by acid/alkali digestion. The processes can give rise to radiological hazards from the inhalation of dust and thoron and from external gamma radiation and are likely to require measures to control external and internal radiation exposures. In the mining, mineral separation and chemical processing of monazite for the extraction of rare earths, available data suggest that the average dose received by a worker is in the range of 1–8 mSv/a [22], with higher exposures being possible where controls are inadequate. Thorium-232 activity concentrations of the order of 10 Bq/g have been reported for cerium concentrates used in glass manufacture [17]. Residues and liquid and gaseous effluents from the extraction process contain  $^{232}\text{Th}$  and/or  $^{228}\text{Ra}$  in concentrations significantly exceeding those in the input raw materials, ranging from tens to thousands of becquerels per gram [21]. The removal, treatment and disposal of these residues, as well as the discharge of liquid effluents containing high concentrations of  $^{228}\text{Ra}$ , need to be managed under regulatory control.

### **3.1.2. Production and use of thorium and its compounds**

Thorium concentrate, containing up to 20% 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). Small quantities of thorium are used in many other products such as lamp starters, airport runway lights, radiation detectors and fuel cell elements. The materials involved in the various production processes tend to contain high concentrations of thorium (or  $^{228}\text{Ra}$ ) and can give rise to radiation hazards that may require specific radiation protection measures, principally to protect against exposure to external gamma (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. Experience has indicated that effective doses received by workers in the production of thorium compounds, principally from external radiation and inhalation of thoron, have generally varied from 6 to 15 mSv/a, although doses could exceed 20 mSv/a. Effective doses received by workers in manufacturing processes involving moderate quantities of thorium containing material are generally lower — often less than 1 mSv/a but sometimes reaching 10 mSv/a or more. Solid wastes and effluents generated in industrial processes involving thorium may need to be monitored and controlled.

### **3.1.3. 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  $^{232}\text{Th}$  at an activity concentration approaching 100 Bq/g and similar concentrations have been found in ferro-niobium slag [23]. Furthermore, the use of high temperatures generates precipitator dust containing  $^{210}\text{Pb}$  and  $^{210}\text{Po}$  at concentrations of 100–500 Bq/g [17]. 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  $^{238}\text{U}$  (~300 Bq/g),  $^{232}\text{Th}$  (~100 Bq/g) and  $^{226}\text{Ra}$  (~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.

### 3.1.4. 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). The influence of parent radionuclide activity concentrations in the ore, although discernible, tends to be masked by these other factors and is, therefore, of limited use in predicting radon concentrations. This is illustrated in Fig. 1, which gives examples of radon concentrations in three types of mining operation. Figure 1 shows how the radon action level can be exceeded even in the mining of ores with radionuclide concentrations not significantly exceeding

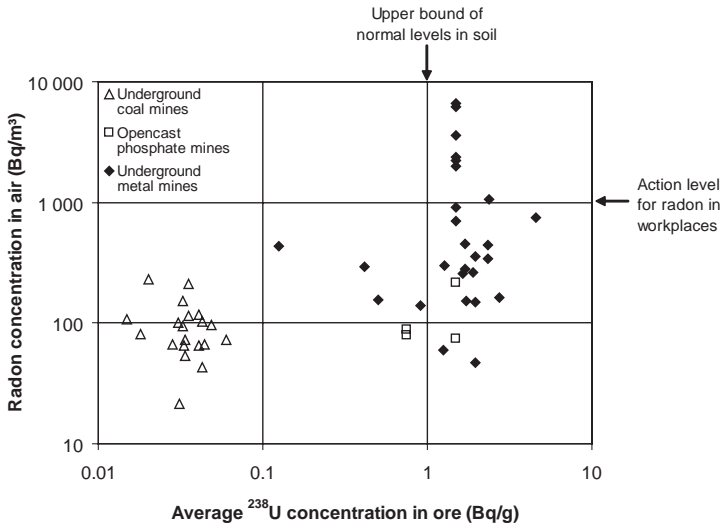


FIG. 1. Examples of radon concentrations in mining operations (from Ref. [24]).

those in normal soil. 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 (see Section 3.1.11) and tourist caves.

In some mines, fissure water entering the workings may contain unusually high concentrations of  $^{226}\text{Ra}$ , 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. In addition, the discharge of this water can lead to significant environmental contamination [20].

### **3.1.5. Production of oil and gas**

The water contained in oil and gas formations contains  $^{228}\text{Ra}$ ,  $^{226}\text{Ra}$  and  $^{224}\text{Ra}$  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  $^{210}\text{Pb}$  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  $^{226}\text{Ra}$ ). 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. Individuals working close to heavily scaled pipes and vessels may also need to be subject to radiation protection measures. Further details are given in Ref. [9].

### **3.1.6. Manufacture of titanium dioxide pigments**

The principal raw materials for titanium dioxide production are ilmenite and rutile — the activity concentrations of  $^{238}\text{U}$  and  $^{232}\text{Th}$  series radionuclides in these minerals are typically less than 2 Bq/g. Production from ilmenite often involves the use of intermediate or upgraded feedstocks such as synthetic rutile and slag. Ilmenite and rutile are obtained from so-called heavy mineral sands that also contain minerals such as monazite, zircon, 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, particularly if these have a significant monazite component (>5%) with its characteristically high concentrations of  $^{232}\text{Th}$  series radionuclides.

Various thermal and/or hydrometallurgical processes are used for the production of titanium dioxide pigments, throughout which the radionuclide activity concentrations generally remain moderate. Regulatory attention is most likely required in the cases of exposure of workers to radium rich scale, which has activity concentrations of  $^{228}\text{Ra}$  and  $^{226}\text{Ra}$  ranging from <1 to 1600 Bq/g, and the management of some of the many different waste streams. The process waste from the pigment industry results in wastes containing  $^{228}\text{Ra}$  at concentrations of up to a few becquerels per gram.

### **3.1.7. The phosphate industry**

Phosphate rock is mined on a large scale as a source material for fertilizers and other phosphorus containing products. The radionuclide content of the ore is generally less than 3 Bq/g. The phosphate rock is processed in one of two ways:

- (1) Most phosphate rock is treated with acid and, depending on the detailed process, this produces phosphoric acid (most of which is used 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 the following:
  - (a) The production of phosphoric acid generates large quantities of phosphogypsum containing radium at a concentration similar to that in the original rock [19]. Environmental protection issues arise from the disposal of phosphogypsum in 'stacks' or by discharge into surface water bodies — in the case of the latter, radiological 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. Phosphogypsum plasterboard is reported to have  $^{226}\text{Ra}$  activity concentrations ranging from insignificant levels, as found in natural gypsum, up to 0.7 Bq/g [19].
  - (b) Radium bearing scales and sediments are formed inside the process equipment. The radionuclide concentrations in these materials vary from values similar to those in the original rock up to 1000 times greater [25]. Exposure to external gamma radiation and/or to inhaled

dust might need to be considered during maintenance and decommissioning.

- (2) 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. During the process,  $^{210}\text{Pb}$  becomes concentrated in the precipitator dust by up to a thousand times [26]. The exposure of workers to this dust, as well as the disposal of the material, needs to be controlled. 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.

### **3.1.8. The zircon and zirconia industries**

Zircon (zirconium silicate) is recovered from heavy mineral sands. The radiological hazards associated with its separation from the other heavy mineral sand components are essentially the same as for the separation of ilmenite and rutile and are described in Section 3.1.6. Zircon sand typically has a  $^{238}\text{U}$  activity concentration of 2–4 Bq/g. Higher values can be found, but such material is not widely exploited on a commercial scale. 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 less than 5  $\mu\text{m}$ . Modern zircon milling operations maintain a high standard of dust control, not just for 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  $^{210}\text{Pb}$  and  $^{210}\text{Po}$  in the feed material end up in the silica fume, which is removed by a fume collection system. Activity concentrations of particulate matter in silica fume are reported to be up to 200 Bq/g for  $^{210}\text{Pb}$  and 600 Bq/g for  $^{210}\text{Po}$  [19]. The exposure of workers to silica fume needs to be controlled by respiratory protection, which is required in any case because of the presence of silica.

Zirconia is also manufactured by chemical processing of zircon sand and the control of effluent discharges may need to be considered.

### **3.1.9. Production of tin, copper, aluminium, zinc, lead, and iron and steel**

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  $^{210}\text{Pb}$  and/or  $^{210}\text{Po}$  in the precipitator dust of up to 200 Bq/g [23], but doses received by workers are not usually a significant source of concern. Radionuclides may become moderately concentrated in the slag — concentrations range from less than 1 to more than 10 Bq/g — 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. In the past, tin slag was also used in the manufacture of insulation ‘wool’ (mineral wool) that was incorporated into various industrial facilities, the decommissioning of which led to the wool being detected as a radioactive material after finding its way to metal recycling facilities [27]. It is reported that, in the absence of controls, this wool could give rise to significant doses to workers engaged in decommissioning activities.

### **3.1.10. Combustion of coal**

The combustion of coal to produce heat and electricity results in the generation of fly ash (much of which is separated from the flue gases and collected) and the heavier bottom ash or slag. The concentrations of radionuclides in the ash tend to be significantly higher than in the coal, but do not generally exceed 1 Bq/g. Volatile radionuclides such as  $^{210}\text{Pb}$  and  $^{210}\text{Po}$  can be expected to accumulate in the fly ash, as well as on the inner surfaces of burner kettles where  $^{210}\text{Pb}$  concentrations  $>100$  Bq/g in the deposited scales have been reported [28]. Flue gas desulphurization results in additional residues in the form of sludges and gypsum, but the radionuclide concentrations in these residues tend to be lower than in the ash. 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.

### 3.1.11. Water treatment

Water treatment is practised on a wide scale to remove contaminants. Such processes often remove radionuclides of natural origin and these can therefore accumulate in water treatment wastes such as ion exchange resins. The activity concentrations in such wastes are usually only moderately elevated, but can reach more than 10 Bq/g in the treatment of groundwater. This 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 [19]. In underground water treatment facilities, radon may accumulate to concentrations well in excess of the action level for workplaces.

## 3.2. MATERIALS

The activity concentration values specified in Section 2.2.2 (1 Bq/g for uranium and thorium series radionuclides, 10 Bq/g for  $^{40}\text{K}$ ), below which it is usually unnecessary to regulate, provide a simple and effective way of narrowing down the range of materials that might need regulatory consideration. A preliminary list of such materials is shown in Table 1, based on information gathered from industry experts and on data from other studies such as those sponsored by the European Commission [17, 18].<sup>8</sup> While the list of materials in Table 1 is not necessarily exhaustive, it probably captures the majority of materials that need to be considered. Already, this makes the problem of deciding what to regulate considerably more manageable.

## 3.3. ACTIVITY CONCENTRATION AS AN INDICATOR OF DOSE FROM EXPOSURE TO GAMMA RADIATION AND TO DUST

Some of the industry sectors identified in Section 3.1 as being likely to require regulatory consideration and possible control involve the exploitation of minerals with significantly elevated radionuclide concentrations, e.g. the extraction of rare earth elements from minerals such as monazite, or of

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<sup>8</sup> Materials involved in the mining, extraction and use of uranium are automatically subject to the requirements for practices and are not included in Table 1. For some materials, reports of activity concentrations falling significantly outside the ranges given in Table 1 may be found in the literature, but these are not considered to be typical of materials used in current industrial processes.

TABLE 1. MATERIALS TO BE ASSESSED FOR POSSIBLE REGULATORY CONTROL

Category	Material/operation	Radionuclide(s) with highest activity concentration	Typical activity concentration (Bq/g)
Feedstocks	Monazite sand	$^{232}\text{Th}$ series	40–600
	Metal ores, e.g. Nb/Ta, Cu, Au	$^{238}\text{U}$ and $^{232}\text{Th}$ series	Up to 10
	Zircon sand	$^{238}\text{U}$ series	2–4
	Phosphate rock	$^{238}\text{U}$ series	0.03–3
	TiO <sub>2</sub> feedstocks	$^{232}\text{Th}$	0.001–2
	Bauxite	$^{232}\text{Th}$ series	0.035–1.4
Bulk residues	Red mud (alumina production)	$^{238}\text{U}$ , $^{232}\text{Th}$	0.1–3
	Phosphogypsum (H <sub>2</sub> SO <sub>4</sub> process)	$^{226}\text{Ra}$	0.015–3
Slags	Niobium extraction	$^{232}\text{Th}$	20–120
	Tin smelting	$^{232}\text{Th}$	0.07–15
	Copper smelting	$^{226}\text{Ra}$	0.4–2
	Thermal phosphorus production	$^{238}\text{U}$	0.3–2
Scales, sludges and sediments	Scale (oil and gas production)	$^{226}\text{Ra}$	0.1–15 000
	Scale (phosphoric acid production)	$^{226}\text{Ra}$	0.003–4000
	Residue (rare earth extraction)	$^{228}\text{Ra}$	20–3000
	Scale (TiO <sub>2</sub> pigment production)	$^{228}\text{Ra}$ , $^{226}\text{Ra}$	<1–1600
	Scale (rare earth extraction)	$^{226}\text{Ra}$ , $^{228}\text{Th}$	1000
	Sludge (oil and gas production)	$^{226}\text{Ra}$	0.05–800
	Residue (niobium extraction)	$^{228}\text{Ra}$	200–500
	Scale (coal mines with Ra rich inflow water)	$^{226}\text{Ra}$ , $^{228}\text{Ra}$	Up to 200
	Scale (iron smelting)	$^{210}\text{Pb}$ , $^{210}\text{Po}$	Up to 200
	Scale (coal combustion)	$^{210}\text{Pb}$	>100
	Sludge (iron smelting)	$^{210}\text{Pb}$	12–100
	Residue (TiO <sub>2</sub> pigment production)	$^{232}\text{Th}$ , $^{228}\text{Ra}$	<1–20
	Sludge (water treatment)	$^{226}\text{Ra}$	0.1–14

TABLE 1. MATERIALS TO BE ASSESSED FOR POSSIBLE REGULATORY CONTROL (cont.)

Category	Material/operation	Radionuclide(s) with highest activity concentration	Typical activity concentration (Bq/g)
Precipitator dust	Thermal phosphorus production	$^{210}\text{Pb}$	1000
	Fused zirconia production	$^{210}\text{Po}$	600
	Niobium extraction	$^{210}\text{Pb}$ , $^{210}\text{Po}$	100–500
	Metal smelting	$^{210}\text{Pb}$ , $^{210}\text{Po}$	Up to 200
Intermediate products	Thorium compounds	$^{232}\text{Th}$	Up to 2000
	Thorium concentrate	$^{232}\text{Th}$	Up to 800
	Pyrochlore concentrate (niobium extraction)	$^{232}\text{Th}$	80
	Cerium concentrate (glass manufacture)	$^{232}\text{Th}$	10
	Fused zirconia	$^{238}\text{U}$	2–8
Products	Gas mantles	$^{232}\text{Th}$	500–1000
	Thoriated glass	$^{232}\text{Th}$	200–1000
	Thorium containing optical polishing powders	$^{232}\text{Th}$	150
	Thoriated welding electrodes	$^{232}\text{Th}$	30–150
	Thorium alloys	$^{232}\text{Th}$	46–70
	Zirconium containing refractories	$^{238}\text{U}$	1–4
	Phosphate fertilizers	$^{238}\text{U}$	0.4–2
	Technical grade phosphoric acid	$^{238}\text{U}$	0.14–2
Phosphogypsum plasterboard <sup>a</sup>	$^{226}\text{Ra}$	0.004–0.7	

<sup>a</sup> Although this material has an activity concentration of less than 1 Bq/g, it is included because it is a building material (see Section 2.2.2, footnote 3).

niobium from minerals such as pyrochlore. Indeed, any mineral or raw material can be considered a candidate for regulatory attention when it is mined or processed if the radionuclide concentrations are sufficiently elevated. More commonly, however, the raw material (feedstock) contains only moderately elevated or non-elevated radionuclide concentrations. In such cases, any need for regulatory attention is likely to arise more from the mobilization of radio-

nuclides during the extraction or processing of the raw material, leading to the accumulation of these radionuclides at higher concentrations in one or more of the process materials and/or the modification of the exposure pathways to humans. In Appendix II, the main types of industrial process are characterized on this basis and the ways in which they can lead to enhanced levels of exposure are described. Different processes involve different characteristic exposure scenarios. Therefore, when prioritizing work activities in terms of the need for closer regulatory examination, it is important to consider the type of process involved, the way in which it is carried out and the effect this has on exposures.

The effective dose received by a worker is an important factor in determining priorities in any investigation and the only reliable way to assess this dose is through a properly developed monitoring programme conducted in the relevant workplace [4, 29]. However, the dose arising from exposure to gamma radiation and to dust is quite strongly influenced by the radionuclide activity concentration in the material, reflecting the underlying linear relationship between these two parameters. For the purpose of setting priorities, therefore, it is possible to establish a broad indication of dose if there is a reasonable knowledge of the characteristics of the material and the work situation in which the material is used. Such an indication can be used as a prioritization tool to identify, on the basis of activity concentrations in process materials, the types of industrial process that are in greatest need of regulatory attention.

In Appendix III, indicative relationships between annual effective dose and activity concentration are derived for a range of process materials using three generic exposure scenarios:

- (1) Exposure to large quantities of material, e.g. an orebody or a large stockpile of raw material;
- (2) Exposure to small quantities of material such as mineral concentrates, scales and sludges;
- (3) Exposure to material that has been volatilized in high temperature processes, i.e. precipitator dust and furnace fume.

The results are summarized in Table 2, together with rounded activity concentration values that could be used to identify the types of industrial activity most likely to require measures to protect against exposure to gamma radiation and/or to dust. The term 'activity concentration' in Table 2 means the highest individual radionuclide activity concentration in the material concerned. The activity concentration values in the last column of Table 2 represent the levels at which the range of effective doses expected to be received by a worker from gamma radiation and dust starts to extend beyond

about 10% of the occupational dose limit<sup>9</sup> and thus into an area where the need for radiation protection measures becomes more certain. For instance, it can be seen from Table 2 that a worker exposed to a large stockpile of material with an activity concentration of 5 Bq/g would be expected to receive a dose ranging from 0.1 to 2 mSv/a, depending on the type of material involved. Work involving material below the activity concentration values in Table 2 might still require regulatory attention, but the need for measures to protect against gamma radiation and dust would be less likely. The investigation of such work situations would therefore merit a lower priority.

It is important to note that occupational exposure to materials in which <sup>40</sup>K is the dominant radionuclide (fertilizers rich in potassium) can be automatically disregarded from any further consideration. Reference to Appendix III shows that the effective dose per unit activity concentration of <sup>40</sup>K ranges from 0.02 to 0.03 mSv/a per Bq/g and the maximum possible activity concentration is 30.6 Bq/g, this being the activity concentration of

TABLE 2. RELATIONSHIP BETWEEN DOSE AND ACTIVITY CONCENTRATION FOR OCCUPATIONAL EXPOSURE TO GAMMA RADIATION AND TO DUST

Category of material	Broad estimate of annual effective dose per unit activity concentration (mSv/a per Bq/g)		Individual radionuclide activity concentration above which the expected dose may exceed 10% of the dose limit (Bq/g)
	Minimum	Maximum	
Large quantity, e.g. orebody, large stockpile	0.02	0.4	5
Small quantity, e.g. mineral concentrate, scale, sludge	0.008	0.04	50
Volatilized: furnace fume and precipitator dust	0.0006	0.003	500 <sup>a</sup>

<sup>a</sup> This value refers to the activity concentration in the precipitator dust, with exposure to fume having been accounted for by assuming an equivalent dust loading of 1 mg/m<sup>3</sup> at the same activity concentration (i.e. a concentration of 0.5 Bq/m<sup>3</sup> in fume) and an activity median aerodynamic diameter (AMAD) of 1 µm.

<sup>9</sup> The relevant limit is an annual effective dose of 20 mSv averaged over five years (Ref. [1], para. II-5).



$^{40}\text{K}$  in pure potassium.<sup>10</sup> The effective dose received by a worker is therefore always less than 1 mSv/a.

### 3.4. EXPOSURE TO RADON

The radon concentration is the key parameter in identifying workplaces in which the exposure of workers to radon progeny may need to be controlled (see Section 2.2.3). Priority in any investigation of radon levels is usually given to the following types of workplace [5]:

- (a) Underground workplaces such as mines, tunnels and tourist caves, especially those associated with minerals having significantly elevated radionuclide activity concentrations and those known to have an inflow of radium rich water and/or no forced ventilation;
- (b) Above ground workplaces in buildings known to have been constructed from materials having a combination of high porosity and elevated concentrations of  $^{226}\text{Ra}$  such as phosphogypsum, tuff and lightweight concrete made from alum shale;
- (c) Above ground workplaces in radon prone areas identified through a combination of geological considerations and systematic indoor radon surveys (further information on the determination of radon prone areas is given in Ref. [5]);
- (d) Workplaces above or below ground involved with the supply or use of large amounts of groundwater, such as spas and groundwater treatment and distribution facilities.

### 3.5. SHORTLIST OF INDUSTRIAL OPERATIONS BASED ON CURRENT OCCUPATIONAL EXPOSURE DATA

Table 3 lists the types of operation involving minerals and raw materials that have been identified as being likely to warrant regulatory control. The list is based on current knowledge of the effective doses received by workers according to information provided by industry experts and reflects, as far as possible, actual operating experience and measurements. As with Table 1, this list is not exhaustive, but probably captures most of the relevant types of

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<sup>10</sup> The specific activity of  $^{40}\text{K}$ , calculated from its  $1.265 \times 10^9$  year half-life, is  $2.617 \times 10^5$  Bq/g and its natural abundance is 0.0117%.

TABLE 3. TYPES OF OPERATION IDENTIFIED, ON THE BASIS OF WORKER DOSE, AS BEING LIKELY TO REQUIRE REGULATORY CONTROL

Type of operation	Material involved			Worker dose (mSv/a)
	Description	Radionuclide(s) with highest activity concentration	Typical activity concentration (Bq/g)	
Rare earth extraction from monazite	Monazite	<sup>232</sup> Th series	40–600	Average 1–8, could approach or exceed dose limit
	Thorium concentrate	<sup>232</sup> Th	Up to 800	
	Scale	<sup>228</sup> Ra	1000	
	Residue	<sup>228</sup> Ra	20–3000	
Production of thorium compounds	Thorium concentrate	<sup>232</sup> Th	Up to 800	Typically 6–15
	Thorium compounds	<sup>232</sup> Th	Up to 2000	
Manufacture of thorium containing products	Thorium compounds	<sup>232</sup> Th	Up to 2000	<1 to a significant fraction of dose limit
	Products	<sup>232</sup> Th	Up to 1000	
Processing of niobium/tantalum ore	Ore	<sup>232</sup> Th series	1–8	Could reach a significant fraction of dose limit
	Pyrochlore concentrate	<sup>232</sup> Th	80	
	Residue	<sup>228</sup> Ra	200–500	
	Slag	<sup>232</sup> Th	20–120	
Some underground mines and similar workplaces (see Section 3.4(1))	Ore		Up to 10	<1 to a significant fraction of dose limit <sup>a</sup>
	Scales from Ra rich water	<sup>226</sup> Ra, <sup>228</sup> Ra	Up to 200	
Oil and gas production	Scales during removal from pipes/vessels	<sup>226</sup> Ra	0.1–15 000	<1 to a significant fraction of dose limit
TiO <sub>2</sub> pigment production	Scales during removal from pipes/vessels	<sup>228</sup> Ra, <sup>226</sup> Ra	<1–1600	<1–6
Thermal phosphorus production	Fume and precipitator dust	<sup>210</sup> Pb	Up to 1000 <sup>b</sup>	0.2–5 (average ~1)

TABLE 3. TYPES OF OPERATION IDENTIFIED, ON THE BASIS OF WORKER DOSE, AS BEING LIKELY TO REQUIRE REGULATORY CONTROL (cont.)

Type of operation	Material involved			Worker dose (mSv/a)
	Description	Radionuclide(s) with highest activity concentration	Typical activity concentration (Bq/g)	
Fused zirconia production	Fume and precipitator dust	<sup>210</sup> Pb, <sup>210</sup> Po	Up to 600 <sup>b</sup>	0.25–4.5

<sup>a</sup> Measurements in some metal mines indicate an effective dose from gamma radiation and dust of about 0.5 mSv/a per unit <sup>238</sup>U activity concentration (in Bq/g) in the ore [30]. The effective dose from radon is highly variable and difficult to predict, being strongly dependent on ventilation conditions and other factors (see, for instance, Fig. 1).

<sup>b</sup> These values refer to the activity concentration of the precipitator dust.

operation. It shows that there are relatively few types of operation that are likely to need formal regulation.<sup>11</sup> Of course, public exposure also has to be considered but, as explained in Section 2.3.2, this is unlikely to change the situation dramatically. The wide range of doses reflected in Table 3 illustrates the importance of applying the graded approach to regulation.

<sup>11</sup> Similar assessments have been made in the past, such as those made for NORM industries in European countries [17], but these were based on conservative modelling using generic exposure scenarios and involving assumptions that often bore little resemblance to actual work situations. Such studies tended to predict much higher doses. More recent studies, based to a greater extent on facility specific exposure scenarios, predict worker doses more in line with those listed in Table 3 [18].

## 4. PRACTICAL TECHNIQUES FOR DETERMINING RADIONUCLIDE ACTIVITY CONCENTRATIONS

### 4.1. INTRODUCTION

It is clear from Section 3 that the investigation of industrial activities in determining the need for, and extent of, regulatory control of exposure to natural sources is likely to involve the sampling and analysis of various solid materials to determine the activity concentrations of  $^{238}\text{U}$  and  $^{232}\text{Th}$  series radionuclides. These concentrations need to be compared with the activity concentration value of 1 Bq/g, below which it is usually unnecessary to regulate, and with the relevant activity concentration level specified in Table 2 (i.e. 5, 50 or 500 Bq/g, depending on the category of material). The materials requiring sampling and analysis can be encountered in large quantities with moderate or low activity concentrations (e.g. ore, tailings, slag) or in smaller quantities with the possibility of high activity concentrations (e.g. mineral concentrates, scale, sludge, precipitator dust). Accordingly, the sampling method and analysis sensitivity requirements may vary depending on the assessment being made.

The radionuclide activity concentrations to be determined can be identified from Table 1, as follows:

- (a) Uranium series:  $^{238}\text{U}$ ,  $^{226}\text{Ra}$ ,  $^{210}\text{Pb}$  and  $^{210}\text{Po}$ ;
- (b) Thorium series:  $^{232}\text{Th}$ ,  $^{228}\text{Ra}$  and  $^{228}\text{Th}$ .

In most feedstocks, the relevant decay chain can be assumed to be in equilibrium. In such cases, any radionuclide within the chain can be the target of the analysis.

There will also be a need to determine radon concentrations in the workplace air, for comparison with the radon action level. Suitable techniques for the measurement of radon activity concentrations in air are described in Refs [4, 5, 29] and are not discussed further here.

### 4.2. SAMPLING OF MATERIAL

The activity concentration values mentioned in Section 2.2.2 (1 Bq/g) and Table 2 (5, 50 and 500 Bq/g) refer to the average activity concentration in the material concerned. The amount of material giving rise to exposure at any one time could be large and such material could, therefore, exhibit a significant range of activity concentrations. The activity concentration may also vary over

the time periods normally of concern in occupational radiation protection (e.g. one year). To the extent practicable, both of these variations are taken into account when developing a suitable materials sampling strategy.

The number of samples collected for analysis is important for obtaining a reasonable estimate of the average activity concentration — the greater the number of samples collected and analysed, the greater the confidence in the figures that are reported. There is a point, however, where any further gain in accuracy and power to detect trends is outweighed by the time and resources needed to produce the data. The accuracy is also affected by other factors such as the degree to which the samples are representative of the material.

#### 4.3. MEASUREMENT ACCURACY AND QUALITY ASSURANCE

Adequate confidence in the results of analyses is ensured if the samples are analysed at a suitably accredited laboratory and if the level of accuracy of the analytical technique is commensurate with the activity concentration criterion against which the material is being checked. If an accredited laboratory is not available, the analytical techniques can at least be validated against appropriate reference materials. Problems due to cross-contamination between samples and contamination of equipment can be avoided by exercising an appropriate level of care during sampling and at the laboratory.

The distribution of activity concentrations in a material may span an order of magnitude or more. In order not to distort the distribution at the low end, the lower limit of detection (LLD) needs to be sufficiently below the activity level against which the measurements are being compared. For instance, when a material is being compared with the 1 Bq/g activity concentration value, an LLD of 0.1 Bq/g would be appropriate. As the cost of analysis often increases with the sensitivity required, cost effectiveness is clearly an important factor in the choice of analytical method — the analytical capability only needs to be sufficient for comparison with a level of 1, 5, 50 or 500 Bq/g, as appropriate.

#### 4.4. ANALYTICAL TECHNIQUES

Having defined the main radionuclides of interest and the required measurement sensitivity, appropriate analytical protocols can be considered. Analytical techniques for determining activity concentrations of individual radionuclides in solid materials can be time consuming and expensive. The

techniques employed for a particular sample, therefore, need to be chosen judiciously.

For general screening of the total radioactivity it is often adequate to perform gross alpha–beta counting, applying suitable corrections for self-absorption. It is a relatively quick and inexpensive technique for determining the total activities of the alpha emitting and beta emitting radionuclides, from which the ratio of the two can be obtained. On its own, this technique does not give reliable information on individual radionuclides. However, the alpha:beta ratio can provide clues as to the radionuclide composition, which may be useful in deciding upon subsequent analytical steps. Obviously, if the total activity concentration is less than the activity concentration criterion for individual radionuclides, then no further analysis is necessary. Counting times are selected to obtain the required LLD for the materials concerned (i.e. about 10% of the applicable activity concentration level).

For analysis of the individual radionuclides of interest, the following analytical techniques can be applied:

(a) X ray fluorescence (XRF) spectrometry:

The XRF method is widely used to measure the elemental composition of materials and is well suited to the rapid determination of uranium and thorium. There are two types of spectrometer, both of which can be used for this application:

- (i) Wavelength dispersive spectrometers, in which photons are separated by diffraction on an analysing crystal before being detected.
- (ii) Energy dispersive spectrometers, in which the detector allows the determination of the energy of the photon when it is detected. These spectrometers are smaller and cheaper than wavelength dispersive spectrometers and the measurement is faster, but the resolution and detection limit are not as good.

(b) Instrumental neutron activation analysis (INAA):

INAA, a technique involving the irradiation of the sample material with neutrons in a nuclear reactor, is a highly sensitive analytical technique for performing both qualitative and quantitative analyses of major, minor and trace elements in bulk samples. It is well suited to the determination of uranium and thorium.

(c) Inductively coupled plasma atomic emission spectroscopy (ICP-AES):

ICP-AES is used for the chemical analysis of aqueous solutions of rocks and other materials and is suitable for the determination of a wide range of major elements and a limited number of trace elements. Sample preparation involves the digestion of the powdered material with 40 vol. % hydrofluoric acid mixed with either perchloric or nitric acid. Some minerals such as chromite, zircon, rutile and tourmaline will not completely dissolve using this digestion procedure. For samples containing substantial amounts of these minerals, XRF analysis is probably more appropriate.

(d) Inductively coupled plasma mass spectroscopy (ICP-MS):

ICP-MS is used to determine trace elements in aqueous solutions. The technique is well suited to determination of uranium and thorium. The sample preparation procedure is the same as that for ICP-AES.

(e) High energy gamma spectrometry (high purity germanium crystal (HPGe)):

This technique provides a quantification of the important radionuclide  $^{226}\text{Ra}$ , along with  $^{228}\text{Ra}$  and  $^{228}\text{Th}$ . The method can also be used to quantify the  $^{238}\text{U}$  concentration, but with a higher LLD.

(f) Low energy gamma spectrometry (HPGe):

This technique entails a relatively short counting time of 4 h and gives a quantification of  $^{238}\text{U}$  and  $^{210}\text{Pb}$  (as well as  $^{235}\text{U}$ ). It is also possible for the technique to provide a determination of  $^{226}\text{Ra}$  (as well as radionuclides of lesser interest:  $^{227}\text{Ac}$ ,  $^{231}\text{Pa}$  and  $^{230}\text{Th}$ ), but with a higher LLD.

(g) Sample digestion and alpha spectrometry:

This technique is suitable for quantifying the  $^{210}\text{Po}$  concentration. It involves a relatively long counting time.

The application of the above mentioned techniques is summarized in Table 4. The minimum sample size needed is in each case about 10 g. When using techniques (a)–(d), the following conversions from parts per million to becquerels per gram are required:

$$1 \text{ ppm uranium} = 0.012348 \text{ Bq } ^{238}\text{U} \text{ per gram of material};$$

1 ppm thorium = 0.004057 Bq  $^{232}\text{Th}$  per gram of material.

For material associated with most industrial processes, it is adequate to have a basic analytical infrastructure consisting of XRF in combination with a background shielded, thin window HPGe gamma spectrometry system. Only in those processes where  $^{210}\text{Po}$  is of concern will radiochemical techniques in combination with alpha spectrometry be required. Although  $^{40}\text{K}$  is unlikely to be of concern (see Section 3.3), its activity concentration can be determined at no additional cost, especially if both XRF and gamma spectrometry are used for radionuclide analysis. This may be useful when  $^{40}\text{K}$  is present in significant concentrations, since it can be used to deduce information on other radionuclides and to improve the quality assurance of the measurements.

TABLE 4. ANALYTICAL TECHNIQUES FOR DETERMINING RADIONUCLIDE ACTIVITY CONCENTRATIONS

Radionuclide	Suitable technique	Comment
$^{238}\text{U}$ , $^{232}\text{Th}$ (and $^{40}\text{K}$ )	XRF, INAA, ICP-AES, ICP-MS	Sensitivity of 1 ppm uranium or thorium achievable with any of these techniques (equivalent to about 0.01 Bq/g $^{238}\text{U}$ and 0.004 Bq/g $^{232}\text{Th}$ )
$^{226}\text{Ra}$ , $^{228}\text{Ra}$ , $^{228}\text{Th}$ (and $^{40}\text{K}$ )	High energy gamma spectrometry	The presence of uranium may interfere with the direct determination of $^{226}\text{Ra}$ For indirect determination of $^{226}\text{Ra}$ , gas-tight sealing for 3 weeks is needed to ensure equilibrium with progeny ( $^{214}\text{Pb}$ , $^{214}\text{Bi}$ ) LLD of 0.1 Bq/g requires equipment that is well shielded from background radiation High sensitivity (>25%) and high resolution HPGe detectors required Counting times of a few hours per sample are adequate High density materials (>2.5 g/cm <sup>3</sup> ) may need self-absorption corrections
$^{210}\text{Pb}$	Low energy gamma spectrometry	Self-absorption corrections required LLD of 0.1 Bq/g requires equipment that is well shielded from background radiation Counting times of a few hours per sample are adequate
$^{210}\text{Po}$	Sample digestion plus alpha spectrometry	Microwave acid digestion required Validated radiochemical separation techniques required Counting times of a few hours per sample are adequate to achieve an LLD of 0.1 Bq/g



## **5. EXAMPLE OF AN ASSESSMENT PROCEDURE**

The process specific information presented in this report can be of assistance to regulatory bodies in assessing the need for radiation protection measures in work involving minerals and raw materials. The precise assessment procedure will vary, depending on factors such as regulatory preferences and national circumstances. Sections 5.1–5.4 describe an example of an assessment procedure which involves first identifying whether there are relevant industry sectors operating in a Member State and then addressing higher priority issues before allocating resources to assess situations less likely to require radiation protection measures. Table 5 provides a summary of this procedure.

### **5.1. IDENTIFICATION OF INDUSTRY SECTORS**

The list of industry sectors in Section 3.1 provides a good starting point for any investigations conducted in a Member State to assess the need for radiation protection measures in work involving minerals and raw materials. It is usually relatively straightforward for the regulatory body or other relevant national authority to determine which of these industry sectors are operating in the Member State concerned. This information could be obtained, for instance, from a body such as the national geological survey or equivalent institution, or from the government department with responsibility for mining and minerals production.

### **5.2. FIRST LEVEL OF ASSESSMENT**

#### **5.2.1. General**

Once the relevant industry sectors have been identified from the list in Section 3.1, the first priority is to focus, for those particular industry sectors, on the types of operation identified from current knowledge and experience as being the most likely to require regulatory attention (see Table 3). For some types of operation, such as the extraction of rare earths from monazite and the production of thorium containing compounds and products, there will be little doubt that radiation protection measures will be needed and steps can therefore be taken immediately to establish an appropriate system of authorization, taking into account the need for a graded approach to regulation. This will involve placing the usual basic obligations on the legal person, such as the

TABLE 5. SUMMARY OF THE EXAMPLE OF AN ASSESSMENT PROCEDURE

Action	Measurements required	Regulatory implications
<i>Work situations in industry sectors listed in Section 3.1:</i>		
Identification of which of the industry sectors listed in Section 3.1 are operating in the Member State	None	None
First level of assessment: Focus placed on the relevant types of operation listed in Table 3	None, except for radon concentration measurements in underground workplaces such as mines	Graded approach to be applied to regulation (Section 2.3). Where radon action level is exceeded, remedial measures to be applied
Second level of assessment: Focus placed on any other types of operation that involve materials listed in Table 1	Conduct of sampling and analysis to determine activity concentrations (Section 4) and compare with the levels noted in Section 2.2.2	Where activity concentration levels are exceeded, graded approach to regulation (Section 2.3) to be applied, giving priority attention to materials exceeding the activity concentration levels shown in Table 2
<i>Other work situations:</i>		
Focus to be placed on industrial sectors other than those identified in Section 3.1, using Appendix II as an indicator of processes most likely to be of concern	Conduct of sampling and analysis to determine activity concentrations (Section 4) and compare with the levels noted in Section 2.2.2	Where activity concentration levels are exceeded, graded approach to regulation (Section 2.3) to be applied, giving priority attention to materials exceeding the activity concentration levels shown in Table 2
Identification of other workplaces (in addition to underground mines, etc.) where conditions are conducive to buildup of radon [5]	Measurement of radon concentrations and comparison with radon action level noted in Section 2.2.3	Where radon action level is exceeded, remedial measures to be applied

conduct of a radiological assessment (including an exposure assessment for workers and members of the public) and the establishment of a suitable radiation protection programme [3, 4].

### **5.2.2. Underground mines and other workplaces with similar characteristics**

One of the types of operation listed in Table 3 — underground mining — needs special mention because, for this type of operation, the dose received by a worker can vary over a wide range (depending mainly on the contribution of radon). Only in certain mining operations will there be a need for radiation protection measures and these operations will therefore need to be identified. Underground mining operations involving materials exceeding the activity concentration levels given in Table 2 (i.e. ores and large volume wastes with activity concentrations exceeding 5 Bq/g and/or scales and other small volume materials with activity concentrations exceeding 50 Bq/g) can be singled out for attention on the basis that exposures to gamma radiation and to dust will probably need to be controlled. However, exposure to radon is more likely to be the main contributor to doses received by workers and is more difficult to predict. Radon concentrations will need to be measured in order to identify those underground workplaces in which the radon action level is exceeded. To avoid having to survey every workplace in every underground mine, factors such as orebody activity concentration, ventilation characteristics and inflow water quality and quantity (see Section 3.4) can be taken into account when selecting the most appropriate underground workplaces to be included in the survey.

Similar considerations apply to the other underground workplaces described in Section 3.4 where radon exposure may also be the main concern.

### **5.3. SECOND LEVEL OF ASSESSMENT**

Once the relevant high priority situations in Table 3 have been addressed, the focus of attention is turned to the other materials associated with the industry sectors identified in Section 3.1, using the list of materials shown in Table 1 as a starting point. The measurement of activity concentration levels in such materials will identify any additional types of operation for which radiation protection measures might be needed. These are then given the necessary level of attention by the regulatory body to determine whether, in terms of the graded approach to regulation, they can be exempted or whether they have to be subject to notification and, where necessary, authorization. Attention is directed, in the first instance, to any materials for which the relevant activity concentration level in Table 2 is exceeded; an indication of such materials can be established from Table 1. Materials found to have activity concentrations of uranium and thorium series radionuclides not exceeding

1 Bq/g can be eliminated from further consideration unless they are used as building materials.

#### 5.4. OTHER WORK SITUATIONS

Having completed the first and second stage assessments, most of the industrial activities for which radiation protection measures are needed will have been identified. However, there remains the possibility that radiation protection measures will be required for the following additional work situations:

- (a) Processes carried out in industrial sectors other than those described in Section 3.1;
- (b) Workplaces associated with materials in which the activity concentrations are not significantly elevated (in addition to those workplaces referred to in Section 5.2.2), but where radon concentrations in air exceed the action level.

In the case of (a), the approach is to establish, by sampling and measurement, the presence of materials in which the activity concentration of any uranium or thorium series radionuclide exceeds 1 Bq/g, with particular attention being given to the identification of materials for which the activity concentration levels given in Table 2 are also exceeded. Such materials are most likely to be those arising from processes known to lead to enhanced concentrations of radionuclides, such as scale formation in pipes and vessels or the volatilization and subsequent precipitation of radionuclides in high temperature processes. These processes are described in Appendix II.

In the case of radon in workplaces described in (b), information that can assist in identifying workplaces that have high radon concentrations is given in Ref. [5].

## Appendix I

### URANIUM AND THORIUM DECAY SERIES

TABLE 6. URANIUM-238 DECAY SERIES [31]

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

<sup>a</sup> Only major modes of decay are shown.

<sup>b</sup> Only major gamma emissions of interest are shown.

TABLE 7. THORIUM-232 DECAY SERIES [31]

Radionuclide	Half-life	Mode of decay <sup>a</sup>	Gamma energy <sup>b</sup> (keV)
<sup>232</sup> Th	1.405 × 10 <sup>10</sup> a	Alpha	
<sup>228</sup> Ra	5.75 a	Beta	
<sup>228</sup> Ac	6.15 h	Beta	911.204 (25.8%)
<sup>228</sup> Th	1.912 a	Alpha	
<sup>224</sup> Ra	3.66 d	Alpha	240.986 (4.1%)
<sup>220</sup> Rn	55.6 s	Alpha	
<sup>216</sup> Po	0.145 s	Alpha	
<sup>212</sup> Pb	10.64 h	Beta	238.632 (43.6%)
<sup>212</sup> Bi	60.55 min	Beta 64.06% Alpha 35.94%	727.330 (6.67%)
<sup>212</sup> Po	0.299 μs	Alpha	
<sup>208</sup> Tl	3.053 min	Beta	583.191 (84.5%), 2614.533 (99.16%)
<sup>208</sup> Pb	Stable		

<sup>a</sup> Only major modes of decay are shown.

<sup>b</sup> Only major gamma emissions of interest are shown.

## Appendix II

### CHARACTERIZATION OF INDUSTRIAL PROCESSES

Industrial processes involving minerals and raw materials can be characterized according to industry sector (e.g. rare earths extraction, the phosphate industry, industrial uses of thorium), as was done in Section 3.1. In radiological terms, however, the types of material and the processes involved are in many cases common to more than one industry sector. That is, there are common mechanisms for the mobilization and concentration of radionuclides and thus for the creation of particular scenarios involving enhanced exposure. Characterization of processes on this basis can be useful for the identification of:

- (a) The process steps most likely to require attention within a particular industry sector;
- (b) Industry sectors that might otherwise be overlooked when investigating the need for radiation protection measures.

The main processes involved and their radiological implications are described below.

#### II.1. MINING AND COMMINUTION OF ORE

The main concern in the mining and comminution of ore is occupational exposure arising from elevated concentrations of radionuclides in the ore and from enhancement of the exposure potential due to the nature of the mining or comminution process. In ore, the radionuclides in each of the uranium and thorium series are likely to be in secular equilibrium. Therefore, knowledge of the uranium and thorium ore grades may be all that is required to characterize the radioactive properties of the material.

Gamma doses received by workers depend on their proximity to bulk quantities of material rather than on the mobilization of radionuclides; the dose rates can be measured in the workplace or they can be calculated by simulating the orebody or ore piles using typical standardized geometries. 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). These characteristics determine to a large extent the radon exhalation rate and, together with the ventilation conditions, the prevailing radon and airborne radioactive dust concentrations. The different

mechanical properties (and thus propensities for dust generation) of the mineral and matrix fractions of the ore may result in the activity concentration in the dust being different from the average activity concentration in the ore.

Atmospheric and liquid effluent releases from mining and comminution operations may result in public exposures. Generally, these are of lesser importance and may be dealt with as part of the management of residues.

Wet mining and ore comminution operations may cause some dissolution and subsequent precipitation of radionuclides on the walls of process equipment (e.g. when geochemical reactions involving pyritic ores produce slightly acidic water). The radiological impacts will be similar in nature to those arising from wet chemical extraction processes.

## II.2. PHYSICAL MINERAL SEPARATION PROCESSES

Physical mineral separation processes include gravity concentration, magnetic and electrostatic separation processes, and even flotation if this occurs in an environment that is not chemically active. While these processes may alter radionuclide concentrations, they are unlikely to change the equilibrium conditions. Therefore, as with the mining and comminution of ore, knowledge of the uranium and thorium ore grades may be all that is required to characterize the radioactive properties of the feed, product and residue streams.

Again, as in the case of mining and comminution operations, gamma doses received by workers involved in physical separation processes depend more on their proximity to bulk quantities of material than on the mobilization of radionuclides; the dose rates near bulk materials can be measured in the workplace or they can be calculated by simulating material stockpiles and typical process equipment containing smaller or larger amounts of material through typical standardized source geometries. The separation process and ventilation conditions may again influence the prevailing radioactive dust concentration, which is likely to be the dominant pathway in dry circuits but less important in wet operations. 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 magnitude or so higher than in the feed material [32].

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. The radiological impacts are similar to those of scales encountered in wet chemical extraction processes.

### II.3. WET CHEMICAL EXTRACTION PROCESSES

Wet chemical extraction normally starts with a chemical leaching process. This may be applied in situ or to crushed or milled ore in extraction plants. While some leaching processes have little effect on the mobilization of radionuclides (e.g. cyanide leaching of gold), leaching 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 (e.g. solvent extraction, ion exchange, electrowinning<sup>12</sup>). 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. During electrowinning, anode slimes containing enhanced concentrations of radionuclides are sometimes generated from the anode material, while ion exchange resins sometimes retain enhanced radionuclide concentrations even after regeneration. 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. Sulphate compounds of radium and lead may be of particular interest during leaching with sulphuric acid, while a variety of radionuclides may be present in hydroxide precipitates during alkaline leaching. Radionuclide specific analyses are therefore essential during radiological assessments in wet chemical extraction plants.

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<sup>12</sup> Recovery of metal from ore by means of electrochemical processes.

## II.4. THERMAL PROCESSES FOR EXTRACTION, PROCESSING AND COMBUSTION OF MINERALS

Thermal processes include a variety of melting and reduction processes employed to produce or refine metals, including the recycling of scrap metals, 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 calcining<sup>13</sup> 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 the 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. <sup>210</sup>Pb and <sup>210</sup>Po) and, at higher temperatures (in plasma furnaces, for instance), even isotopes of radium. These condense again in scrubbers, filters and stacks, posing mainly an inhalation risk during maintenance operations within these areas. The use of slag will also give rise to exposure of workers and the public that may need to be controlled.

## II.5. RESIDUE MANAGEMENT

Residues include mineral processing tailings, waste rock, scales, sludges and scrap materials. They may be reused or processed into useful products elsewhere or disposed of as waste. Residues are kept in storage areas, impoundments, or burial sites, which may or may not be permanent. The management of mining and mineral processing residues (when designated as waste) is described in Ref. [8]. Tailings impoundments normally also receive the bulk of the water used during mineral processing operations. From here it is recycled through the operations, but some may be released to, or seep into, the environment. In mining and mineral processing operations, tailings impoundments usually constitute the main sources of radon and dust emissions to the environment. The disposal of contaminated equipment and material may also necessitate control measures, including, in many situations, the need for

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<sup>13</sup> A process in which a material is heated to a high temperature without fusing, so that hydrates, carbonates, or other compounds are decomposed and the volatile material expelled.

decontamination using processes such as high pressure water jet cleaning, mechanical cleaning or melting in a suitable facility.

While occupational exposure during the maintenance of residue impoundments may need to be considered, the main concern is the impact on members of the public and the environment. Safety assessments carried out and updated over the life of the mining and mineral processing operation focus on identifying the critical groups of the public and modelling the radiological impacts on those critical groups from aqueous, gaseous (radon) and fugitive dust emissions. For convenience, liquid and gaseous emissions from mining operations may be considered as additional sources in this assessment process.

After closure, tailings impoundments and other management facilities for mining and mineral processing waste may need to be subject to active or passive institutional controls. The need for, and dependence on, such controls will have been minimized as part of the optimization of the design of the facility and the design of any such control programme will be based on the results of the safety assessment [8].

Mineral processing residues are often used, mainly in civil engineering applications. Examples include residues from various thermal processes in the form of slag or ash, and phosphogypsum from the manufacture of phosphoric acid (which, in addition to its use as a component in building materials, is also being considered for wide scale agricultural use as a soil conditioner). Although occupational exposure may need to be considered, the main concern is usually exposure of members of the public, particularly when the material is used in dwellings and public buildings. In these applications, the principal areas of concern are exposures to external gamma radiation and to radon emanations from the material. Apart from the obvious dependence of exposure on radionuclide concentrations in this material, important and influential factors include the degree of dilution with non-radioactive constituents, the characteristics of the material (e.g. porosity, surface coatings), the location within the structure in which the material is used and the characteristics of the structure, including ventilation conditions and the degree of shielding inherent in the design.

## Appendix III

### DOSE PER UNIT ACTIVITY CONCENTRATION RECEIVED BY A MINERAL PROCESSING WORKER EXPOSED TO GAMMA RADIATION AND TO DUST

#### III.1. METHODOLOGY

The materials and exposure scenarios chosen for consideration are based on a selection of those described in Ref. [17] and cover a variety of industry sectors. The exposure scenarios are reported in Ref. [17] as representing work tasks or situations likely to lead to the highest dose from the material concerned.

For exposure to gamma radiation, the following chain segments (defined as those for which the component radionuclides are likely to be in equilibrium) are considered:  $^{226}\text{Ra} \rightarrow ^{214}\text{Po}$ ,  $^{228}\text{Ra} \rightarrow ^{228}\text{Ac}$  and  $^{228}\text{Th} \rightarrow ^{208}\text{Tl}$ , these being the only segments in the uranium and thorium decay series that could contribute significantly to the total gamma dose rate. In the case of potassium rich fertilizers,  $^{40}\text{K}$  is also included in the calculations. The gamma dose coefficient (i.e. the dose rate per unit activity concentration of the head of the chain segment) is taken to be the value reported in Ref. [17], derived using a calculation scheme based on the MicroShield code data library [33]. The gamma dose coefficients for large quantities of material reported in Ref. [17] are derived for large stockpiles of material in mineral processing facilities. However, they could also apply to an orebody in a mine.<sup>14</sup> An overall gamma dose coefficient, defined as the total dose rate per unit activity concentration of the radionuclide with the highest activity concentration, is calculated for each material, assuming the 'indicative' radionuclide compositions reported in Ref. [17].

For dust inhalation, the radionuclides contributing significantly to the total inhalation dose are  $^{238}\text{U}$ ,  $^{234}\text{U}$ ,  $^{230}\text{Th}$ ,  $^{226}\text{Ra}$ ,  $^{210}\text{Pb}$ ,  $^{210}\text{Po}$ ,  $^{227}\text{Ac}$  (from the  $^{235}\text{U}$  decay chain),  $^{232}\text{Th}$ ,  $^{228}\text{Ra}$ ,  $^{228}\text{Th}$  and  $^{224}\text{Ra}$ . For exposure to furnace fume and precipitator dust, the only radionuclides of significance are  $^{210}\text{Pb}$  and  $^{210}\text{Po}$ . Internal exposure to  $^{40}\text{K}$  is excluded from the Standards [1] and is therefore not considered. An overall inhalation dose coefficient (defined as the committed

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<sup>14</sup> In most mining situations, the geometry of an orebody is to some extent similar to that of a large stockpile of material. The gamma dose coefficients would, of course, be higher if the worker were to be completely surrounded by ore at close proximity (so-called '4 $\pi$  geometry'), but such an extreme situation is not typical.

effective dose per unit activity intake of the radionuclide with the highest activity concentration) is calculated from values for individual radionuclides given in the Standards [1], assuming the slowest listed lung absorption class and an AMAD of 5  $\mu\text{m}$  (except for furnace fume, where an AMAD of 1  $\mu\text{m}$  is assumed). The rate of inhalation of dust is assumed to be 1 mg/h, corresponding to a dust concentration of approximately 1 mg/m<sup>3</sup>. This concentration is taken to be representative of the air breathed by a worker even in very dusty workplaces, because it is expected that in such conditions respiratory protection would be used.

Using the above mentioned overall dose coefficients for gamma radiation and dust inhalation, values of total annual effective dose (i.e. the sum of the personal dose equivalent from external gamma radiation and the committed effective dose from inhalation of dust) per unit activity concentration are obtained using the calculation method described in Ref. [1].

### III.2. EXPOSURE TO LARGE QUANTITIES OF MATERIAL

Over a year, a worker is assumed to be exposed to gamma radiation for 400 h, unshielded, at a distance of 1 m from a large volume of material and to inhale dust from the material for 2000 h. The materials considered are:

- (a) Phosphate rock.
- (b) Phosphogypsum by-product.
- (c) Calcium silicate slag from the thermal processing of phosphate rock.
- (d) Pyrochlore feedstock and furnace slag associated with the production of ferro-niobium.
- (e) Zircon sand.
- (f) Sand containing monazite.
- (g) Ilmenite used for titanium dioxide pigment manufacture.
- (h) Tin furnace slag.
- (i) Six types of fertilizer: P superphosphate, NP, triple superphosphate, K, PK and NPK.

The results of the dose calculations are shown in Tables 8–10.

TABLE 8. EXTERNAL GAMMA DOSE COEFFICIENTS FOR LARGE QUANTITIES OF MATERIAL

Material	$^{226}\text{Ra} \rightarrow ^{214}\text{Po}$		$^{228}\text{Ra} \rightarrow ^{228}\text{Ac}$		$^{232}\text{Th} \rightarrow ^{208}\text{Tl}$		$^{40}\text{K}^a$		Overall dose coefficient	
	Relative activity conc. ( $\mu\text{Sv/h per Bq/g}$ )	Dose coeff. ( $\mu\text{Sv/h per Bq/g}$ )	Relative activity conc. ( $\mu\text{Sv/h per Bq/g}$ )	Dose coeff. ( $\mu\text{Sv/h per Bq/g}$ )	Relative activity conc. ( $\mu\text{Sv/h per Bq/g}$ )	Dose coeff. ( $\mu\text{Sv/h per Bq/g}$ )	Relative activity conc. ( $\mu\text{Sv/h per Bq/g}$ )	Dose coeff. ( $\mu\text{Sv/h per Bq/g}$ )	Value ( $\mu\text{Sv/h per Bq/g}$ )	Applicable radionuclide
Phosphate rock	1	0.39	0.2	0.21	0.2	0.37			0.51	$^{238}\text{U}$
Phosphogypsum	1	0.39	0.09	0.21	0.03	0.38			0.42	$^{226}\text{Ra}$
Thermal phosphorus slag	0.7	0.39	0.1	0.21	0.1	0.37			0.33	$^{238}\text{U}$
Fe-Nb feedstock and slag	0.2	0.26	1	0.14	1	0.25			0.44	$^{232}\text{Th}$
Zircon sand	1	0.37	0.1	0.20	0.1	0.35			0.43	$^{238}\text{U}$
Sand containing monazite	0.05	0.26	1	0.14	1	0.24			0.39	$^{232}\text{Th}$
Ilmenite feedstock	0.5	0.39	1	0.21	1	0.37			0.78	$^{232}\text{Th}$
Tin slag	1	0.40	0.7	0.22	0.7	0.38			0.82	$^{238}\text{U}$
P superphosphate fertilizer	0.7	0.41	0.04	0.22	0.04	0.39			0.31	$^{230}\text{Th}$
NP fertilizer	0.1	0.41	0.02	0.22	0.02	0.39			0.05	$^{238}\text{U}$
Triple superphosphate fertilizer	0.3	0.41	0.02	0.22	0.02	0.39			0.14	$^{238}\text{U}$
K fertilizer	0.0005	0.39	0.0009	0.21	0.0009	0.37	1	0.037	0.04	$^{40}\text{K}$
PK fertilizer	0.04	0.39	0.002	0.21	0.002	0.38	1	0.037	0.05	$^{40}\text{K}$
NPK fertilizer	0.05	0.41	0.0003	0.22	0.0003	0.39	1	0.038	0.06	$^{40}\text{K}$

<sup>a</sup> The contribution of  $^{40}\text{K}$  to the gamma dose rate is included only for potassium rich fertilizers. For other materials the contribution is of the order of 1% or less and can be disregarded.

TABLE 9. INHALATION DOSE COEFFICIENTS FOR LARGE QUANTITIES OF MATERIAL

Material	Relative activity concentration of individual radionuclides (dose coefficients ( $\mu\text{Sv/Bq}$ ) in parentheses)											Overall dose coefficient ( $\mu\text{Sv/Bq}$ )	
	$^{238}\text{U}$ (5.7)	$^{234}\text{U}$ (6.8)	$^{230}\text{Th}$ (7.2)	$^{226}\text{Ra}$ (2.2)	$^{210}\text{Pb}$ (1.1)	$^{210}\text{Po}$ (2.2)	$^{227}\text{Ac}$ (47)	$^{232}\text{Th}$ (12)	$^{228}\text{Ra}$ (1.7)	$^{228}\text{Th}$ (32)	$^{224}\text{Ra}$ (2.4)	Value	Applicable radionuclide
Phosphate rock	1	1	1	1	1	1	0.05	0.2	0.2	0.2	0.2	37	$^{238}\text{U}$
Phosphogypsum	0.3	0.3	0.3	1	0.3	0.3	0.01	0.03	0.09	0.03	0.03	11	$^{226}\text{Ra}$
Thermal phosphorus slag	1	1	1	0.7	0.1	0.07	0.05	0.1	0.1	0.1	0.1	28	$^{238}\text{U}$
Fe-Nb feedstock and slag	0.2	0.2	0.2	0.2	0.2	0.2	0.009	1	1	1	1	54	$^{232}\text{Th}$
Zircon sand	1	1	1	1	1	1	0.05	0.1	0.1	0.1	0.1	32	$^{238}\text{U}$
Sand containing monazite	0.05	0.05	0.05	0.05	0.05	0.05	0.002	1	1	1	1	49	$^{232}\text{Th}$
Ilmenite feedstock	0.5	0.5	0.5	0.5	0.5	0.5	0.02	1	1	1	1	62	$^{232}\text{Th}$
Tin slag	1	1	1	1	1	0.4	0.05	0.7	0.7	0.7	0.7	60	$^{238}\text{U}$
P superphosphate fertilizer	0.9	0.9	1	0.7	0.4	0.4	0.04	0.04	0.04	0.04	0.04	25	$^{230}\text{Th}$
NP fertilizer	1	1	1	0.1	0.1	0.1	0.05	0.02	0.02	0.02	0.02	23	$^{238}\text{U}$
Triple superphosphate fertilizer	1	1	1	0.3	0.5	0.5	0.05	0.02	0.02	0.02	0.02	25	$^{238}\text{U}$
K fertilizer	0.003	0.003	0.02	0.0005	0.002	0.002	0.0001	0.05	0.0009	0.0009	0.0009	1	$^{40}\text{K}$
PK fertilizer	0.08	0.08	0.08	0.04	0.08	0.08	0.004	0.002	0.002	0.002	0.002	2	$^{40}\text{K}$
NPK fertilizer	0.1	0.1	0.1	0.05	0.1	0.1	0.005	0.0003	0.0003	0.0003	0.0003	3	$^{40}\text{K}$

TABLE 10. DOSE RECEIVED BY A WORKER EXPOSED TO GAMMA RADIATION AND TO DUST FROM LARGE QUANTITIES OF MATERIAL

Material	Effective dose per unit activity concentration (mSv/a per Bq/g)			
	Gamma radiation	Dust inhalation	Total (rounded)	Applicable radionuclide
Phosphate rock	0.204	0.074	0.3	<sup>238</sup> U
Phosphogypsum	0.168	0.022	0.2	<sup>226</sup> Ra
Thermal phosphorus slag	0.132	0.058	0.2	<sup>238</sup> U
Fe–Nb feedstock and slag	0.176	0.108	0.3	<sup>232</sup> Th
Zircon sand	0.172	0.064	0.2	<sup>238</sup> U
Sand containing monazite	0.156	0.098	0.3	<sup>232</sup> Th
Ilmenite feedstock	0.312	0.124	0.4	<sup>232</sup> Th
Tin slag	0.328	0.120	0.4	<sup>238</sup> U
P superphosphate fertilizer	0.124	0.048	0.2	<sup>230</sup> Th
NP fertilizer	0.020	0.050	0.07	<sup>238</sup> U
Triple superphosphate fertilizer	0.056	0.046	0.1	<sup>238</sup> U
K fertilizer	0.016	0.002	0.02	<sup>40</sup> K
PK fertilizer	0.020	0.004	0.02	<sup>40</sup> K
NPK fertilizer	0.024	0.006	0.03	<sup>40</sup> K

### III.3. EXPOSURE TO SMALL QUANTITIES OF MATERIAL

A worker is assumed to be exposed to gamma radiation, unshielded, at a distance of 1 m from material normally encountered only in small quantities (~1 m<sup>3</sup>) and to inhale dust from the material. The materials considered are:

- (a) Phosphogypsum cloth filters;
- (b) Zircon containing material used in the production of refractories;
- (c) Rare earth extraction residue;
- (d) Cerium concentrate used in glass manufacture;
- (e) Scale associated with the manufacture of titanium dioxide pigment;
- (f) Scale and sludge associated with the production of oil and gas.



The period of exposure to gamma radiation and to dust is assumed to be 100 h in a year, except for work with cerium concentrate, where the gamma exposure period is assumed to be 400 h, and work involving scale and sludge from the oil and gas industry, where an exposure period of 600 h is assumed for both gamma radiation and dust.<sup>15</sup> The results of the dose calculations are shown in Tables 11–13.

#### III.4. EXPOSURE TO VOLATILIZED MATERIAL

Over a year, a worker is assumed to inhale fume for 600 h while working near a furnace and to inhale precipitator dust for 100 h during cleaning operations. The precipitator dust is assumed to contain the volatile radionuclide <sup>210</sup>Pb (with or without <sup>210</sup>Po at the same activity concentration, depending on the process) and the inhaled fume is assumed to have an equivalent loading of the same dust at 1 mg/m<sup>3</sup> and an AMAD of 1 μm. The results of the dose calculation are shown in Table 14.

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<sup>15</sup> The longer exposure period reflects the tendency for the oil and gas industry to use service providers specializing in the removal of scale and sludge [9].

TABLE 11. EXTERNAL GAMMA DOSE COEFFICIENTS FOR SMALL QUANTITIES OF MATERIAL

Material	$^{226}\text{Ra} \rightarrow ^{214}\text{Po}$		$^{228}\text{Ra} \rightarrow ^{228}\text{Ac}$		$^{228}\text{Th} \rightarrow ^{208}\text{Tl}$		Overall dose coefficient	
	Relative activity conc.	Dose coeff. ( $\mu\text{Sv/h per Bq/g}$ )	Relative activity conc.	Dose coeff. ( $\mu\text{Sv/h per Bq/g}$ )	Relative activity conc.	Dose coeff. ( $\mu\text{Sv/h per Bq/g}$ )		
	Value	Applicable nuclide	Value	Applicable nuclide	Value	Applicable nuclide		
Phosphogypsum cloth filters	1	0.062	0.09	0.033	0.03	0.059	0.067	$^{226}\text{Ra}$
Zircon containing material used in refractories production	1	0.058	0.13	0.031	0.1	0.055	0.068	$^{238}\text{U}$
Rare earth extraction residue	0.1	0.052	1	0.029	1	0.050	0.084	$^{228}\text{Ra}$
Ce concentrate (glass manufacture)	0.05	0.062	1	0.034	1	0.058	0.095	$^{232}\text{Th}$
Scale ( $\text{TiO}_2$ pigment production)	0.3	0.046	1	0.026	1	0.041	0.081	$^{228}\text{Ra}$
Scale/sludge (oil and gas production)	1	0.053	0.1	0.029	0.07	0.052	0.060	$^{226}\text{Ra}$

TABLE 12. INHALATION DOSE COEFFICIENTS FOR SMALL QUANTITIES OF MATERIAL

Material	Relative activity concentration of individual radionuclides (dose coefficients ( $\mu\text{Sv/Bq}$ ) in parentheses)											Overall dose coefficient	
	$^{238}\text{U}$ (5.7)	$^{234}\text{U}$ (6.8)	$^{230}\text{Th}$ (7.2)	$^{226}\text{Ra}$ (2.2)	$^{210}\text{Pb}$ (1.1)	$^{210}\text{Po}$ (2.2)	$^{227}\text{Ac}$ (47)	$^{232}\text{Th}$ (12)	$^{228}\text{Ra}$ (1.7)	$^{228}\text{Th}$ (32)	$^{224}\text{Ra}$ (2.4)		Value ( $\mu\text{Sv/Bq}$ )
Phosphogypsum cloth filters	0.3	0.3	0.3	1	0.3	0.3	0.01	0.03	0.09	0.03	0.03	11	$^{226}\text{Ra}$
Zircon containing material used in refractories production	1	1	1	1	1	1	0.05	0.1	0.1	0.1	0.1	32	$^{238}\text{U}$
Rare earth extraction residue	0	0	0	0.1	0.1	0.1	0	0	1	1	1	37	$^{228}\text{Ra}$
Ce concentrate (glass manufacture)	0.05	0.05	0.05	0.05	0.05	0.05	0.002	1	1	1	1	49	$^{232}\text{Th}$
Scale ( $\text{TiO}_2$ pigment production)	0	0	0	0.3	0.3	0.3	0	0	1	1	1	38	$^{228}\text{Ra}$
Scale/sludge (oil and gas production)	0	0	0	1	1	1	0	0	0.1	0.07	0.07	8	$^{226}\text{Ra}$

TABLE 13. DOSE RECEIVED BY A WORKER EXPOSED TO GAMMA RADIATION AND TO DUST FROM SMALL QUANTITIES OF MATERIAL

Material	Effective dose per unit activity concentration (mSv/a per Bq/g)			
	Gamma radiation	Dust inhalation	Total (rounded)	Applicable radionuclide
Phosphogypsum cloth filters	0.0067	0.0011	0.008	<sup>226</sup> Ra
Zircon containing material used in refractories production	0.0068	0.0032	0.01	<sup>238</sup> U
Rare earth extraction residue	0.0084	0.0037	0.01	<sup>228</sup> Ra
Ce concentrate (glass manufacture)	0.038	0.0049	0.04	<sup>232</sup> Th
Scale (TiO <sub>2</sub> pigment production)	0.0081	0.0038	0.01	<sup>228</sup> Ra
Scale/sludge (oil and gas production)	0.036	0.0048	0.04	<sup>226</sup> Ra

TABLE 14. DOSE RECEIVED BY A WORKER EXPOSED TO FURNACE FUME AND TO PRECIPITATOR DUST

Material	AMAD ( $\mu\text{m}$ )	Inhalation dose coefficient ( $\mu\text{Sv/Bq}$ )			Exposure period (h/a)	Effective dose per unit activity concentration of <sup>210</sup> Pb (mSv/a per Bq/g)	
		<sup>210</sup> Pb	<sup>210</sup> Po	<sup>210</sup> Pb + <sup>210</sup> Po		Dust with Pb only	Dust with Pb + Po
Furnace fume	1	0.89	3.0	3.89	600	0.0005	0.0023
Precipitator dust	5	1.1	2.2	3.3	100	0.0001	0.0003
Total (rounded)						0.0006	0.003

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### **Consultants Meetings**

Vienna, Austria: 22–26 September 2003, 28 November–2 December 2005

**Any mining or minerals processing operation has the potential to increase the radiation dose received by individuals, owing to the fact that all minerals and raw materials contain radionuclides of natural, terrestrial origin. However, only in a limited number of cases does the situation warrant the introduction of radiation protection measures. This Safety Report provides information on the relevant industrial activities, materials and expected exposure levels in order to assist in identifying the activities for which regulatory controls are most likely to be needed and, for such activities, determining the most appropriate regulatory approach.**

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