

European Commission

RADIATION PROTECTION 95

**Reference levels
for workplaces
processing materials with
enhanced levels of naturally
occurring radionuclides**

**A guide to assist implementation
of Title VII of the European Basic
Safety Standards Directive (BSS)
concerning natural radiation sources**

This document has been prepared for use within the Commission. It does not necessarily represent the Commission's official position.

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FOREWORD

The new Basic Safety Standards for the health protection of the general public and workers against the dangers of ionising radiation (Directive 96/29/EURATOM, OJ L-159) have integrated *work activities* involving the presence of natural radiation sources into the scope of the Directive. The requirements are laid down in Title VII of the Directive. Guidance on the implementation of Title VII has been produced by the Group of Experts established under Article 31 of the Euratom Treaty and published as *Radiation Protection 88*. This will assist Member States in transposing the Directive by May 2000.

Among the work activities which are within the scope of Title VII are in particular those *involving operations with and storage of materials, not usually regarded as radioactive but which contain naturally occurring radionuclides, causing a significant increase in the exposure of workers* (Article 40.2b). Examples of industrial processes which may be of concern are given in Section 3 of Radiation Protection 88, together with recommended measures to control the exposure of workers. These recommendations are given with reference to ranges of annual exposure of workers. In order to use this in practice for the identification of industries which are of concern there is a need to translate such annual exposures into measurable reference levels in terms of activity concentration of the feed material or of enhanced activity concentration of materials at different stages of the process.

This task was the subject of a contract with NRPB and CEPN (National Radiological Protection Board, UK, and Centre d'Etude sur l'Evaluation de la Protection dans le domaine Nucléaire, France, contract 95-ET-009). The report which resulted from this work was discussed by a working party of the Article 31 Group of Experts. Parts of the contract report were incorporated in the form of guidance which was submitted to the plenary Article 31 Group of Experts at its meeting in Lisbon on 8-9 June 1998. The experts approved the approach outlined by the working party and recommended that it be published.

This document is intended to offer guidance to national authorities and the Commission hopes that it will serve this purpose. Ensuring compliance with the Basic Safety Standards remains a Member State responsibility.

S. KAISER

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1. Introduction

1. Title VII of the revised Basic Safety Standards Directive (96/29/Euratom)¹ sets out a separate, flexible control regime for protecting workers and members of the public from exposure to natural radiation sources arising from work activities. This separate treatment recognises the special problems that need addressing when the source of exposure has not been artificially generated but is of natural origin. It also recognises that the controls can only act on significant increases in exposure that arise from the work activity, and not on the natural level of radiation itself.

2. One of the work activities with natural radiation sources identified in Title VII is the processing of naturally occurring radioactive materials (NORM). The Basic Safety Standards Directive draws a distinction between NORM processed for their "radioactive, fissile or fertile properties" and NORM processed for other purposes. In the former case the process is subject to the full control regime for practices set out in Titles III, IV, V, VI and VIII. Only in the latter case is the process subject to the more flexible Title VII regime.

3. The purpose of this Guide is to provide advice on work activities where the processing of NORM is subject to the Title VII regime. These processes provide a major challenge for radiation protection. The existence of the radiation risk is incidental to the process and the concentration of natural radionuclides can occur at one or more stages during it. This may happen, for instance, during chemical separation, metallurgical smelting or physical screening. Indeed in some cases the undertakings themselves are not aware of the risk. Therefore simple means of identifying and categorising such industries are needed. Then their managements can be made aware of the potential risks and decisions can be made whether they need to make a more detailed radiological assessment of the processes for which they are responsible.

4. The Title VII regime leaves Member States to decide which work activities are to be subject to national control, and nothing in this Guide is intended to interfere with that flexibility. Rather the Guide provides assistance to Member States - and consequently to relevant industries operating in their territories - in identifying many of the processes where the potential exists for significant radiation exposure of workers. It then offers a simple technique for screening and categorising these industries based on radiation dose criteria. Where the categorisation suggests a significant potential dose, professional advice and site specific characterisation will probably then be needed.

5. The screening and categorisation procedures set out in this Guide are only applicable to the exposure of workers in industries subject to the Title VII regime. They cannot be applied to the more complex, though equally important, aspect of exposure of members of the public arising from these industries.

¹ Council Directive of 13 May 1996 laying down basic safety standards for the health protection of the general public and workers against the dangers of ionizing radiation (OJ L 159)

6. This Guide is based on a research contract for the EU (95-ET-009)² undertaken by NRPB and CEPN. It aims to provide a simplified explanation of their methods and enable ready use to be made of their calculations and conclusions. Readers wanting a fuller explanation about particular numerical values or methods used, or conclusions reached in this Guide should refer to the full Report.

2. Review of relevant industries

7. This section summarises the most significant industries in Europe where processing of NORM can cause increased exposure of workers. The industries use raw materials containing naturally occurring uranium-238 and thorium-232 and their decay products. Processing of these materials may lead to the selective concentration of certain radionuclides in by-products, residues or product streams, because of their chemical or physical properties.

8. The most significant industries within the EU, based on the radiological risk and economic significance, are:

- the phosphate industry;
- processing of metal ores;
- zircon sands and refractory materials;
- manufacture of rare earths;
- manufacture and use of thorium compounds;
- the titanium dioxide pigment industry; and
- oil and gas extraction.

More details of these industries and their processes appear in Appendix 1. The list above is not in any order of significance, nor intended to be comprehensive. Other industries, such as the handling and reuse of fly-ash, may also give rise to a radiological risk under some circumstances.

9. Within these industries three distinct types of materials can be identified:

Mineral Ores

10. Ores can contain activity concentrations of several, even tens of Bq g⁻¹ of naturally occurring radionuclides, often concentrated by the same natural process that concentrates the elements in which the ore is rich. Such ores are typically extracted and processed in very large quantities. The physical characteristics may range from a beach sand to a dense rock. It is more common nowadays for such ores to be imported into the EU from developing countries.

² Establishment of Reference Levels for Regulatory Control of Workplaces where materials are processed which contain enhanced levels of naturally-occurring radionuclides, J.S.S Penfold, J.-P. Degrange, S.F. Mobbs and T. Schneider, Radiation Protection 107, 1999

By-products and residues

11. Processing may concentrate the radionuclides in by-products and residues. This can occur by means of mass separation (for example in processing certain mineral sands), other physical phenomena (eg volatilisation of lead and polonium in high temperature furnaces) or by chemical reactions (eg the precipitation of radium containing scales in the oil and gas industry). The activity concentration of the by-products, scales or residues may be as high as several hundred Bq g⁻¹ of certain radionuclides. The quantities of such material are often smaller than the ores, particularly those by-products with high activity concentrations.

Products

12. In some cases products intentionally contain high levels of naturally radioactive elements such as thorium, although not for the radiological properties of the elements. An example of such a use is the use of thorium in welding electrodes, where it aids arc ignition and stability. The activity concentration of such materials may be quite high, perhaps several hundreds of Bq g⁻¹.

3. Approach

13. In order to establish the significant industries and the techniques for categorising their processes, it was necessary to identify the pathways by which workers could receive a significant radiation dose, and develop a set of typical exposure situations. The purpose of this was to allow the generation of a relationship between the activity of radionuclides in the input materials and the doses that those working in the processes might be expected to receive.

14. The pathways identified were:

- external irradiation;
- inhalation of dust;
- inhalation of radon³.
- ingestion of dirt and dust; and
- skin contamination;

However, skin contamination was found not to be a significant source of exposure in any of the exposure situations, because of the relatively low specific activity found in NORM. Therefore it is not referred to further in this Guide.

15. Three typical exposure situations were developed, based on observations of the processes concerned. These situations were:

³ Radon is a natural radioactive gas that arises from the decay of radionuclides found in NORM.

(a) **Stockpiles of materials: exposure of a warehouse operative;**
A worker is exposed to the material whilst working in a warehouse containing a very large quantity of it. The worker spends most of the working period in the warehouse, close to the material, breathing and picking up dust generated from loading and unloading the material.

(b) **Residues and scales: exposure of a worker removing residues;**
The worker is exposed when removing residues, ie cleaning pipes or vessels. The worker performs this operation infrequently (perhaps a day a week or an hour or so a day), but is exposed to high concentrations of dust in the removal process. The quantity of material present is usually between a few kilograms and a few tonnes. Any quantity of residues larger than this could be treated as a stockpile. Some respiratory protection has been assumed in the normal set of assumptions. It is assumed that pipes and vessels are cleaned before cutting.

(c) **Process material in vessels and pipes: exposure of a general worker;**
Workers are quite likely to be 'incidentally' exposed to materials in pipes and vessels for a significant fraction of their working year. However, the only exposure pathway is by external irradiation, and there is some shielding from the pipe or vessel walls.

16. These pathways and exposure situations were then used to calculate doses received from input material of a defined level of activity. This was done in two different ways, using normal assumptions and unlikely assumptions about how the worker might be exposed. These calculations can then be reversed to lead from a defined dose level to an activity in the input material. Appendix 2 presents further information on the parameter values used in each exposure situation under normal and unlikely assumptions.

4. Classification system for regulatory control

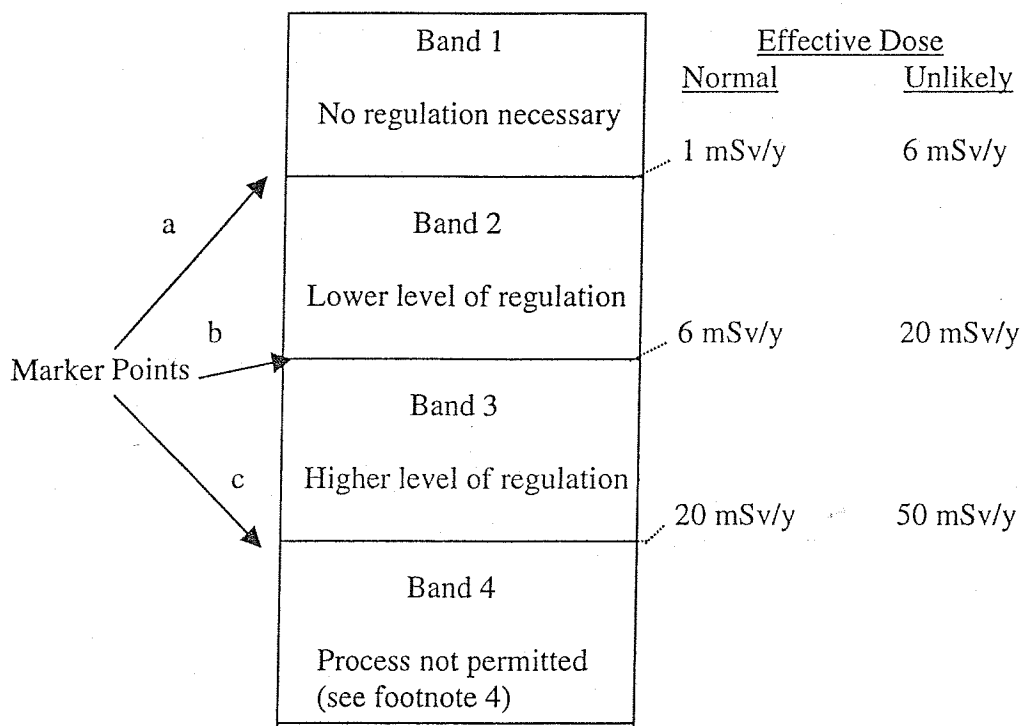
17. One of the difficulties of processing materials containing NORM is that there is no obvious relationship between activity level in the input material and the extent of the measures needed to control the radiation risk. One way to establish such a relationship is by placing processes into one of a small number 'control bands'. Each band suggests a level of regulatory control commensurate with the radiation exposures workers may receive in the process.

18. For this Guide four control bands have been chosen, as follows:

- Band 1 no need to consider regulation;
- Band 2 lower level of regulation should be applied;
- Band 3 higher level of regulation should be applied;
- Band 4 process should not be permitted without a full individual assessment⁴.

⁴ This means that a thorough review of the working practices is necessary to make a detailed assessment of doses. If these prove to exceed the worker dose limit as set out in the BSS Directive, then the process must cease.

19. This four band system requires three marker points to separate the bands. Given this relates to a radiation risk, it is obviously appropriate for these points to be related to radiation doses that workers could receive. The doses chosen are 1, 6 and 20 mSv per year under normal assumptions about exposure, and 6, 20 and 50 mSv per year under unlikely assumptions about exposure. These doses have been chosen because they align with dose levels used for the control of practices in the Basic Safety Standards Directive. This scheme is presented graphically below.



5. Screening levels

20. Materials containing NORM usually have a mixture of different radionuclides, all capable of making some degree of contribution to worker exposure. Therefore, it was necessary to introduce some method of simplification to allow ready use of the calculated information. For a specific material, there is usually a fairly constant radionuclide composition. So a reasonable simplification for screening purposes is to assume a fixed radionuclide composition and characterise the activity of the input material on the basis of its single most significant nuclide.

21. Each of the chosen doses in paragraph 19 can be converted, using the exposure pathways and situations, to the activity of the input material on the basis of its most significant nuclide (para 16). This leaves two activity figures for each of the marker points separating adjacent control bands, one based on the normal assumptions of exposure, the other on the unlikely assumptions. The lower of these two activity figures is then used as the screening level. Each material has three screening levels, one for each marker point,

separating the four control bands set out in paragraph 18. Appendix 3 sets out for each input material, the most significant nuclide (or nuclide segment) and the three screening levels.

6. Reference levels

22. The derivation of the screening levels requires the simplifying assumption that for a particular input material the radionuclide composition is the same in different samples. Where a more detailed analysis is available of the radionuclide composition of the material, a more accurate calculation can be made of the dose likely to arise from the different exposure situations. Appendix 4 sets out three Tables (a to c). Each Table relates to a different marker point, and sets out the appropriate activity level in the input material of all the common radionuclides. These activity levels are known as 'reference levels'. The classification of the material proceeds by summing the ratios of activity concentrations to reference levels. With knowledge of the radionuclide composition of the actual material and applying the sum-ratios to each Table in turn, the input material can be placed in a control band. This method is likely to be more accurate than relying only on the screening levels.

7. Use of screening levels and reference levels

23. The management of one of the industries referred to in paragraph 8 should initially be able to establish the activity of the most significant nuclide in their input material, for instance from their supplier. By using the screening levels in Appendix 3, their input material can be located relative to the marker points, and their process placed in a regulatory control band. This provides a first estimate of the classification of their process.

24. If their process falls well within the band requiring no regulatory control (Band 1), then it will not be necessary to make any further assessment. In any other case, this initial assessment should be followed up with an analysis of the radionuclide composition of the input material. This will allow a more precise classification of the process, using the reference levels set out in Appendix 4. This is particularly important where the use of the screening levels indicates the process is close to one of the marker points.

25. Appendix 5 offers a worked example, concerning zircon sands and refractory products, showing how to utilise the information on the activity of the material to place the process in a control band using the screening and reference levels.

8. Controlling worker exposure

26. If the use of the screening and reference levels has placed the process in Band 1, then it follows that no further action is necessary. However, if the process is placed in a higher control band, then either:

- the appropriate control measures should be adopted, or
- the process should receive individual assessment, prior to deciding the control measures to adopt.

27. This individual assessment of the process could consist of the following approaches:

- (a) conducting a detailed dose assessment, utilising the services of someone with radiation protection expertise to assess likely exposure routes on a site and process specific basis, and the worker dose arising therefrom; and/or
- (b) checking the validity of the assumptions set out in Appendix 2 against actual working conditions. For instance, actual exposure times may be very different in practice from the assumptions used to derive the screening and reference levels.

28. Once the process has been clearly placed in a control band, then the control measures needed are usually relatively simple, and common-sense precautions should be taken to avoid all unnecessary exposures. The important routes of exposure are normally from external irradiation, inhalation of dust and inhalation of radon. Appropriate control measures may include limitation of time in certain areas, attention to the arrangements for storage of bulk material, ventilation and dust control. In some cases radon gas may present a problem and so might surface contamination. It should also be remembered that sometimes the highest doses do not arise when the plant is operating normally, but rather during maintenance.

29. For Band 2 situations, it would be appropriate to consider whether doses could be effectively reduced, and whether there is a possibility of doses increasing over time or as a result of an accident. But if doses are low and cannot be effectively reduced further, and there is no realistic potential for accidents, then few further protection measures are likely to be required, other than ensuring that doses do not increase.

30. For Band 3 situations, dose reduction also needs to be considered, but it is likely that more detailed precautions will be required. For instance, it may be appropriate to establish controlled areas. Once control measures are in place, assessments should continue to be made of the doses workers are actually receiving.

31. For Band 4 situations, a thorough review of working practices is necessary to make a detailed assessment of doses, and action should be taken to reduce them. If, despite these further actions, doses to workers still exceed the dose limits set out in the Basic Safety Standards Directive, then the process must cease.

APPENDIX I SIGNIFICANT EU INDUSTRIES USING NORM

1. The phosphate industry

The phosphate rock is the starting material¹ for the production of all phosphate products and is the main source of phosphorus for fertilisers. The phosphate processing operations can be divided into the mining and milling of phosphate ore and the manufacture of phosphate products by either the wet or the thermal process. The wet process produces superphosphate and phosphoric acid by reaction with sulphuric acid, phosphogypsum (CaSO_4) being formed as a by-product. An alternative wet process, developed in France, uses hydrochloric acid. Fertilisers are produced from these processes. The thermal process produces elemental phosphorus P, which is in turn used for the production of high grade phosphoric acid, phosphate-based detergents ($\text{Na}_4\text{P}_2\text{O}_7$, $\text{Na}_5\text{P}_3\text{O}_{10}$) and organic chemicals. Fused calcium silicate slag (CaSiO_3) and ferro-phosphorous are produced as waste and by-products.

1.1. Mining and milling of phosphate ore

a) Ore processing

In the period 1990 to 1994, phosphate ore importation has ranged from 7.3 to 11.8 million t, with the largest country of origin being Morocco (40% in 1994)². According to reference 5, 80 % of the phosphate ore used is in the form of calcium phosphates (phosphorites) which are very old marine deposits. These materials are often calcined prior to dispatch. This involves heating the damp, sifted phosphate to about 950°C to eliminate the calcium carbonate (CaCO_3) and decomposed organic matter.

b) Activity concentration of materials

Calcium phosphates or phosphorites have a typical activity concentration of natural uranium of 1.5 Bq g^{-1} , the decay chains being in secular equilibrium. Radionuclides in the thorium-232 decay chain are typically present with activity concentration of between one and two orders of magnitude less. Some Russian deposits of apatite ($3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaF}_2$) contain much less uranium (usually several tenths of Bq g^{-1}) but roughly the same concentration of thorium-232 and its progeny. There is no significant enhancement in mining and milling processes.

1 UNSCEAR 1993, Sources and effects of Ionizing Radiation, New York, UN, Report to the General Assembly, with annexes, 1993.

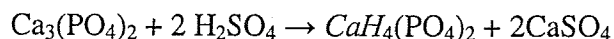
2 Despres, A, and Reutord, P. Rejets de substances radioactives par les industries non nucléaires. Document presented to the French delegation of the RAD group of OSPARCOM

1.2. Phosphate ore wet process

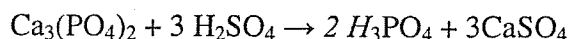
a) Ore processing

No specific data were identified for the quantities of phosphate ore used in the wet process.

In the wet process, sulphuric acid H_2SO_4 is used at a 65% concentration to make 18% superphosphate (a combination of phosphoric acid and phosphogypsum), the reaction being:



In addition, phosphates provide the raw material for phosphoric acid (H_3PO_4) manufacture. Sulphuric acid reacts with the phosphate and yields a pulp of orthophosphoric acid and gypsum (which is filtered out) with the following reaction,



The phosphoric acid can be combined with ammonia (NH_3) to make ammonium phosphate, which is the basis of mixed fertilisers. Alternatively the phosphoric acid can be combined with phosphate ore to make triple superphosphates. The reaction with the phosphoric acid yields mono and bicalcium phosphates which are granulated and dried.

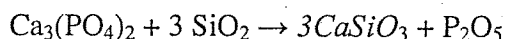
b) Activity concentration of materials

There is evidence to suggest that radium isotopes are more readily retained than other radionuclides in the phosphogypsum (about 80% of the concentration in the ore)². Hence phosphogypsum derived from Central Florida rocks contains radium-226 and its progeny at concentrations of around 0.9 to 1.3 Bq g⁻¹(³).

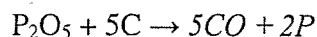
1.3. Phosphate ore thermal process

a) Ore processing

There were no specific data identified for the quantities of phosphate ore used in the thermal process. In this process the phosphate ore is crushed, mixed with silica (SiO_2 gravel) and coke, and heated to 1500°C in an electric furnace. At this temperature phosphorus vapour and carbon monoxide are produced by the following mechanism:



and,



³ Conklin, C. Potential uses of phosphogypsum and associated risks. Background information Document, EPA 402-R92-002, 1992

The phosphorus is condensed and removed as a liquid or solid, and quickly submerged in oil in order to prevent reaction with moisture in the air. The elemental phosphorus is often converted into phosphoric acid, H_3PO_4 , using nitric acid (HNO_3), for later use in the manufacture of artificial fertilisers. As a by-product a large amount of calcium silicate ($CaSiO_3$) slag is produced.

b) *Activity concentration of materials*

Most of the uranium (and associated decay products) originally contained in the phosphate ore is retained in the slag. Because of the high temperature of the process about 95% of the relatively volatile radionuclides are released to the process air⁴, giving typical concentrations of 50 to 500 $Bq\ g^{-1}$ of lead-210 and polonium-210 in dust precipitates. Uranium-238 and thorium-230 were reported to be present in silicates at between 1 and 2.7 $Bq\ g^{-1}$. The matrix of the silicates is such that radon release is inhibited⁴.

1.4. Fertilizers

Fertilizers are produced using the methods described above. In 1993 the total quantity of fertilizers produced in Europe^{**} was 2.2 million t, 42 % being produced in France¹.

The activity concentration of radionuclides in fertilisers varies widely, in part due to the different chemical compositions of fertilisers and also due to the raw material used in their production. It is suggested⁵ that there is a concentration factor of 2 with respect to the phosphate ore. Activities of uranium-238 vary from around 0.3 to 3 $Bq\ g^{-1}$ ⁽⁶⁾. Uranium-234 and thorium-230 are present at about the same activity; however radium-226 and lead-210 are typically between 30 % and 60 % of the uranium-238 activity (0.2 to 1 $Bq\ g^{-1}$). Thorium-228, radium-228 (and presumably thorium-232) are present with activities between 0.008 and 0.04 $Bq\ g^{-1}$ ⁽⁶⁾.

2. Processing of metal ores

2.1. Tin

a) *Ore processing*

In 1987 production and processing of tin amounted to more than 69,000 t⁽⁷⁾ in Europe. In 1993 the main producers of refined tin were the UK (50% of the total) and Spain⁷ (36%). The major use of tin is in alloys with other metals and as a protective coating.

4 Lowe, L M. Radiological implications of naturally-occurring radioactivity in an elemental phosphorus refinery, Proceedings of the Eight International Congress of the International Radiation Protection Association, May 17-22, 1992, Montreal, Canada, 1992

** Where economic data has been associated with "Europe" it includes only the following 12 member states, unless otherwise stated: Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain and the United Kingdom.

5 Scholten, L C, Roelofs, L M M, and van der Steen, J. A survey of potential problems for non-nuclear industries posed by implementation of new EC standards for natural radioactivity. KEMA Nuclear report 40059-NUC 93-5203 (1993).

6 Reichelt A, Röhrer J, Lehmann K-H. Anthropogene stoffe und produkte mit natürlichen radionucliden. Teil 1a. Strahlungseigenschaften von roh- und reststoffen. Litteraturrecherche, TÜV Bayern, 1994

7 Eurostat basic statistics. 32nd. edition, 1995

Cassiterite or tinstone (SnO_2) is the most important ore. In other parts of the world, principally Bolivia and south-east Asia, sulphide ores such as stannite, $\text{Cu}_2\text{FeSnS}_2$, and tealite, PbZnSnS_2 , are also of commercial significance. The ore is washed and separated to produce a 70% tin final concentrate. This concentrate is then mixed with charcoal heated to 1000-1200°C. The tin is remelted in a second furnace for further purification to obtain 99.9% purity tin.

b) Activity concentration of materials

The main hazards are the smelting slag and the volatilised polonium-210 which collects in dust precipitators. Volatilisation of polonium-210 has been found in one UK plant (which ceased operating recently), where concentrations of up to 200 Bq g^{-1} existed in collected fume. Typical activity concentrations in tin ore and slag in the UK were 1 Bq g^{-1} of uranium-238 in both ore and slag, and about 0.3 Bq g^{-1} and 4 Bq g^{-1} in ore and slag respectively for the thorium-232 chain.

2.2. Niobium

a) Ore processing

In 1987 about 30 t of niobium were recovered from ore in Europe, compared to over 3000 t that were imported. Niobium is found together with other elements in ores such as tantalite $\text{Ta}_2\text{O}_6(\text{Fe},\text{Mn})$, columbite $\text{Nb}_2\text{O}_6\text{Fe}$, fergusonite $(\text{Nb},\text{Ta})\text{O}_4(\text{Y},\text{Er},\text{Ce})\cdot\text{Nb}_2\text{O}_7\text{Ca}_2$, samarskite, pyrochlore $(\text{Na}, \text{Ca}, \text{Ce})_2\text{Nb}_2\text{O}_6\text{F}$, koppite and loparite. The largest deposits are located in Australia and Nigeria and extensive deposits have been found in Uganda, Kenya, Tanzania and Canada.

The ore is processed by melting with sodium or potassium hydroxide, dissolving in hydrochloric acid, and processing with chlorine at 750-800°C. The resulting powdered metallic niobium is then further purified by a number of methods. One factory in the UK, which ceased production recently, produced ferro-niobium using a process involving a high temperature exothermic reaction between pyrochlore and aluminium powder. Niobium is widely used in the manufacture of electronic components, chemical engineering (it is resistant to corrosion), in nuclear reactors and in aerospace.

b) Activity concentration of materials

Pyrochlore usually has a high activity concentration of both uranium-238 and thorium-232 decay series radionuclides. Reported activity concentrations^{8,9} range from 7 to 80 Bq g^{-1} of thorium-232 and each member of its decay chain and 6 to 10 Bq g^{-1} of uranium-238 and each member of its decay chain.

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- 8 Harvey, M P, Hipkin, J, Simmonds, J R, Mayall, A, Cabianca, T, Fayers, C, and Haslam, I. Radiological consequences of waste arising with enhanced natural radioactivity content from special metal and ceramic processes. EUR 15613 EN (1994)
- 9 Hipkin, J, and Paynter, R A. Radiation exposures to the workforce from naturally-occurring radioactivity in industrial processes. *Rad. Prot. Dosim.* 36 No.2/4 p 97-100 (1991)

2.3. Other metals

The extraction of many metals may give rise to radiological hazards, but few data are available. Any large scale process which involves smelting metals at high temperatures may give rise to volatilised lead and polonium which can lead to radiological hazards to workers if it collects in flue precipitates or if workers are able to inhale it directly. Such hazards could be found in the production of iron and steel, aluminium, zinc and copper. Lead smelting is a notable exception because the radioactive isotopes of lead are vastly diluted with the stable lead that collects in the precipitates. Other hazards may arise from slightly radioactive slags. Specific radiological data have only been identified for aluminium, copper and zinc.

a) Aluminium

In 1987, production and processing of aluminium amounted to more than 8 thousand tonnes⁷ in Europe. In 1993, the main producers of primary aluminium were Germany (26% of the total) and France (22%). Aluminium is the most abundant metal in the earth's crust where it is found in combination with oxygen, fluorine, silica etc but never in the metallic state. The principal source of aluminium is Bauxite ($(Al,Fe)_2O_3$). Bauxites are the richest form of weathered ores containing up to 55% alumina. Some lateritic ores (containing higher percentages of iron) contain up to 35% Al_2O_3 . The commercial deposits of Bauxite are Gibbsite $Al_2O_3 \cdot 3H_2O$ and Boehmite $Al_2O_3 \cdot H_2O$ and are found in Australia, Guyana, France, Brazil, Ghana, Guinea, Hungary, Jamaica and Surinam. Bauxite is extracted by open-cast mining. Gibbsite is more readily soluble in sodium hydroxide solutions than Boehmite and is therefore preferred for alumina production.

The production of the aluminium metal comprises two basic steps of refining and reduction:

- *Refining (production of alumina from bauxite)*
In the Bayer process, bauxite is digested at high temperature and pressure in a solution of caustic soda. The resulting hydrate is crystallised and calcined to the oxide in a kiln.
- *Reduction (reduction of alumina to aluminium metal)*
In the Hall-Heroult electrolytic process, alumina is reduced using carbon electrodes and cryolite flux.

Aluminium production generates useful by-products such as vanadium (1kg per t of Al_2O_3) and gallium (0.1 kg per t of Al_2O_3).

Aluminium is used widely throughout industry and in larger quantities than any other non-ferrous metal. It is alloyed with a variety of other metals and may contain small amounts of other metals for special purposes. The finished products are used in shipbuilding, electrical industry, building industry, and aircraft and automobiles industries. A major application of sheet aluminium is in beverage and food containers. A fine particulate form is employed in paints and in the pyrotechnics industry.

b) Copper

In 1987, production and processing of copper amounted to more than 3,000 t⁽⁷⁾ in Europe. In 1993, the major producers of refined copper were Germany (48% of the total) and

Belgium (23%). Copper is widely distributed in all continents and, although some natural deposits of metallic copper have been found, is generally mined either as sulphide ores, including Covellite (CuS), Chalcocite (Cu_2S), Chalcopyrite (CuFeS_2) and Bornite (Cu_3FeS_3) or as oxides, including Malachite ($\text{Cu}_2\text{CO}_3(\text{OH})_2$), Chrysocolla ($\text{CuSiO}_3 \cdot 2\text{H}_2\text{O}$), and Chalcantite ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$). The copper ore is normally extracted by underground or open-pit mining.

The copper is extracted in different ways depending upon the ore. Native copper, which is remarkably pure, is processed by grinding, washing, melting and casting. The metal is produced from its ores by reduction. Oxides and carbonates can be leached by dilute sulphuric acid and copper may be electrolysed from this solution. Sulphides (0.2 - 5% copper content) are crushed and ground, concentrated by flotation, smelted at 1500°C in a reverberatory furnace with the addition of lime and silica fluxes, and freed from sulphur and iron in a converter. The resulting blister copper, about 98% pure may be further fire-refined to a purity of 99.5%. For electrical use, the copper is further refined to at least 99.9% purity by electrolysis.

Over 75% of copper output is used in the electrical industries. Other applications include water piping, roofing material, kitchenware, chemical and pharmaceutical equipment, and the production of copper alloys. The most widely used non-ferrous alloys are those of copper and zinc (brass), tin (bronze) and nickel (monel metal). Copper metal is also used as a pigment and as a precipitant of selenium.

c) Iron and steel

In 1987, production and processing of iron amounted to more than 148,812 t⁽⁷⁾ in Europe. In 1993, the main pig iron producers were Germany (35% of the total) and France (16%), while the main producers of crude steel were Germany (28% of the total) and Italy (20%). Iron is most widely found in the form of minerals such as oxides, hydrated ores, carbonates, sulphides, silicates, etc. Iron ores are prepared and processed by washing, crushing and screening, by separating the gangue, by calcining, sintering and pelletising, in order to render the ores smeltable and to obtain iron and steel.

The essential feature of iron production is the blast furnace where iron ore is smelted (reduced) to produce pig iron. The furnace is charged from the top with iron ore, coke and limestone. Hot air, frequently enriched with oxygen, is blown in from the bottom, and the carbon monoxide produced from the coke transforms the iron ore into pig iron containing iron, the limestone acting as a flux. The pig iron melts at a temperature of 1600°C and collects at the bottom of the furnace. The furnace is tapped regularly and the iron may then be poured into pigs for later use in foundries, or into ladles where it is transferred still molten, to the steel making plant. The limestone combines with the earth to form slag which may be converted for other uses, in particular for making cement. Alternatively, direct-reduction processes have been developed, where high-grade or upgraded iron ores are directly reduced to sponge iron by extracting the oxygen they contain, thus obtaining a ferrous material which is used to replace scrap.

Pig iron contains large amounts of carbon as well as other impurities, mainly sulphur and phosphorus. The purpose of the steel making is to reduce the carbon content and to oxidise and remove the impurities, in order to convert the iron into a highly elastic metal which can be forged and fabricated. There are three types of steel making furnaces: the open-hearth furnace, the converter, and the electric furnace. In gas- or oil-fired open-hearth

furnaces, which are gradually being replaced by converters, steel is made from pig iron and scrap iron, using pure oxygen. In converters, steel is made by blowing air or oxygen into molten pig iron. In electric furnaces, scrap iron of high quality and pre-reduced sponge-iron pellets are the chief raw materials. Other metallic elements (chromium, tungsten, nickel) may be incorporated to produce alloys (special steels) which respectively prevent rusting, give hardness, and increase strength and corrosion resistance. These alloying constituents may be added either to the blast-furnace charge or to the molten steel (in the furnace or ladle). Steel from the furnace is poured into moulds to form ingots; these are stored in underground ovens where they can be reheated for subsequent processing.

Much dust is generated in the manufacture of iron and steel, in the preparation processes, especially sintering, in front of the blast furnaces and steel furnaces, and in the ingot-making. Dense fumes emitted from the use of oxygen in open-hearth furnaces may especially affect crane drivers.

d) Zinc

Zinc is widely distributed and is found as sulphide (Sphalerite), carbonate, oxide or silicate (Calamine) in combination with other minerals. Sphalerite is the source of 90% of metallic zinc and contains iron and cadmium as impurities. It is almost always accompanied by Galena, the sulphide of lead, and is found occasionally in association with ores containing copper or other base metal sulphides.

Zinc is extracted in the following way. The ore is crushed, ground and then upgraded by flotation to produce zinc concentrates containing 50-60% zinc; every effort being made to separate lead, copper and other minerals as separate concentrates. After roasting, to remove sulphur and improve the physical condition of the concentrates, the product is further refined either by smelting, by electrolytic refining, or distillation. Smelting produces a relatively impure metal suitable for galvanising, spraying, annealing and painting. Electrolytic refining and distillation produce high-grade zinc (more than 99.99% purity) suitable for alloys and diecasting. Zinc oxide is produced by the oxidation of vaporised pure zinc or by the roasting of zinc oxide ore.

On exposure to air, zinc becomes covered with a film of oxide which protects the metal from further oxidation. The resistance to air corrosion forms one of the most common uses of the metal: the protection of steelwork by galvanising. Zinc's ability to protect ferrous metals against corrosion is reinforced by electrolytic action. Being anodic to iron and other structural metals, except aluminium and magnesium, zinc is attacked preferentially. This property is used in many other important applications of zinc, including the use as anodes for cathodic protection of ship's hulls, underground tanks, etc.

Zinc metal is diecast for automobile and electrical equipment industry and for the hardware and toy industries. It is rolled into sheet for the manufacture of roofing, weather stripping, cases for dry batteries, photoengraving plates, etc. Zinc may also be alloyed with copper (brass), nickel, aluminium and magnesium. Finally, zinc metal is used as a pigment in paints, a filler for plastics and rubber, and in cosmetics and pharmaceuticals lotions.

e) Molybdenum

In 1987 around 1300 t of molybdenum was recovered from ore in Europe, compared to over 44000 t that was imported⁶. The rarity of high quality molybdenite ore (MoSO_2) means

that it is not mined in large quantities. The main producers in the world are United States, Canada, Chile and former USSR. Molybdenum trioxide MoO_3 is produced by roasting the sulphide ore. Over 90% of the molybdenum produced is used as an alloying element for iron, steel, and non-ferrous metals.

f) Vanadium

The most important vanadium ores are patronite (V_2S_5) found in Peru and descloizite ($\text{VO}_4(\text{PbOH})(\text{Pb,Zn})$) found in South Africa. Other ores that are used include vanadinite, roscoelite and carnotite. Crude petroleum may also contain small amounts of vanadium and flue-gas deposits from oil-fired furnaces can contain over 50% vanadium pentoxide.

Extraction from patronite involves roasting with coal. The resulting slag is granulated in water, dried and converted to ferro-vanadate in a furnace. Alternatively, the ore is roasted with sodium chloride to produce sodium vanadate which is extracted as a solution in water from which vanadium sulphide is precipitated by treatment with hydrogen sulphide. The sulphide is roasted to the oxide and reduced to the metal with calcium or magnesium in pressure vessels. Only around 40 t of vanadium was recovered from ore in Europe in 1987, compared to over 7000 t that was imported⁷.

The largest use of vanadium is for ferro-vanadium, the most important direct use of which is in high speed steel and tool steel making.

g) Hafnium

Hafnium metal is used in the manufacture of electrodes and light bulb filaments. It has also been used as cladding on tantalum for rocket engine parts which must operate at very high temperatures. It is found with zirconium at a relative abundance of about 2 %. Because of their similar properties the technique for hafnium recovery from ore is identical to that for zirconium extraction. It is then separated using differences in physical properties such as solubility or volatility.

h) Zirconium

Relatively little recovery of zirconium metal occurs in Europe. In 1987 all of the 136 t of zirconium used in Europe was imported⁷.

3. Zircon sands and refractory materials

a) *Ore processing*

Most of the commercially useful deposits of zircon are in beach sands, found in Australia, India, Ukraine, Malaysia, and United States. Baddeleyite has been found in commercially useful deposits in Brazil, Sweden, India and Italy. Typically the sand is pre-processed in very large quantities by gravimetric and electromagnetic sorting to separate the mineral sands, which include monazite and bastnasite. As this is a potentially dusty process dust control measures are often used. The dust levels may mean that there are significant radiation hazards from inhalation as well as the external irradiation from large mounds of material. The "raw" sands generally have a granular size of 100 to 200 μm , which may

reduced to around $2 \mu\text{m}$ for use in ceramics and paint applications by milling to a flour¹⁰. Zircon is used in fine ceramics where it acts as an opacifier in glazes and enamels and also as an additive in special glass.

An important use of zircon sands is in the manufacture of refractory components (used in high temperature furnaces). These are made by mixing zircon sand with alumina and sodium carbonate and smelting at high temperature¹⁰. Such blocks or components are finished by grinding and polishing. The refractory product manufacturing process gives rise to volatilised lead-210 and polonium-210 from smelting and dust from grinding and polishing components, however ventilation is usually good¹⁰. Material is not processed in large quantities so the hazard from external exposure is less significant than other exposure pathways.

b) Activity concentration of materials

A wide range of activity concentrations¹¹ are reported for zircon sand, from 0.4 Bq g^{-1} to 40 Bq g^{-1} of thorium-232, and 0.2 to 74 Bq g^{-1} of uranium-238. In most references the natural decay chains are reported to be in secular equilibrium however one reference⁸ notes some disequilibrium in the natural thorium decay chain.

4. Manufacture of rare earths

a) Ore processing

The most important sources of rare earth elements are monazite $(\text{Ce,La,Nd,Th})\text{PO}_4$ and bastnaesite $(\text{Ce, La, ...})(\text{CO}_3)\text{F}$. Monazite sand typically has a much higher activity concentration as it includes Th PO_4 . As stated previously the monazite ore concentrate is obtained from suitable sands by a gravimetric and electromagnetic sorting. Strong acids or alkaline solutions are then used on the concentrate and lanthanides are precipitated. The bastnaesite ore concentrate is obtained by a wet process in which it is successively washed and separated in water. This concentrate is washed with hydrochloric acid and calcined in order to produce a crude oxide containing 90% of lanthanide oxides.

b) Activity concentration of materials

In the monazite concentrate, radionuclides in the thorium-232 decay chain are reported to have activity concentrations of 8 to 3000 Bq g^{-1} (12,13), whilst radionuclides in the uranium-238 decay chain are reported to have activity concentrations ranging from 6 to 40 Bq g^{-1} (1,13).

During the extraction process isotopes of radium are co-precipitated with barium sulphate to form a radium-bearing by-product (which has an activity concentration of around 3000 Bq g^{-1} of radium-228 and 450 Bq g^{-1} of radium-226). A second by-product with

10 Hewson, G S, and Terry, K W. Retrospective assessment of radioactivity inhaled by mineral sands workers. *Rad. Prot. Dosim.* 4 p 291-8 (1995)

National group for studying the radiological implications of the use of zircon sand. Radiation protection aspects of the use of zircon sand. *Sci. Tot. Env.* 45 p 135-42 (1985)

11 Dalheimer, A, Henrichs, K. Monitoring of workers occupationally exposed to thorium in Germany, *Radiat. Prot. Dosim.* Vol 53, Nos 1-4, p 207-9, 1994

12 Ullman. Enzyklopädie der technischen chemie, band 23. VCH Verlag, Weinheim (1979)

13 Wedepol KH. Handbook of geochemistry. Springer Verlag (1978)

elevated levels of radium also occurs, mainly made up of calcium phosphate and ore residuals. This has a typical activity concentration of about 20 Bq g⁻¹ radium-228 and 3 Bqg⁻¹ radium-226.

5. Manufacture and use of thorium compounds

a) *Ore processing and products*

Thorium oxide occurs in many minerals. Those with high concentrations include monazite (which may contain between 2.5 and 28 % of thorium oxide), thorite and thorianite.

Thorium is obtained by first concentrating minerals (which are sometimes in the form of sand), then decomposing the concentrate with acids to obtain thorium salts. These are the raw materials for the production of metallic thorium. Thorium is used in a number of materials, commonly as an additive. Examples include thoriated tungsten welding electrodes (in which the thorium is added to aid arc ignition and stability) and magnesium-thorium alloys, used in aerospace. Thorium nitrate has been used in the manufacture of gas mantles. The production of such gas mantles used to be a widespread industry but now is much less common in Europe. Reports suggest that one factory still exists in Austria.

b) *Activity concentration of materials*

Reference 14 contains details of the activity of some thorium containing products. The activity concentration of thoriated tungsten welding electrodes had been variously reported but is around 100 Bq g⁻¹ of thorium-232 and thorium-228. Gas mantles typically contain about 1000 Bq of thorium-232 and thorium-228 each. Special alloys such as those used in jets engines may have an activity of about 70 Bq g⁻¹.

6. Titanium dioxide pigment industry

a) *Ore processing*

Titanium dioxide is used in large quantities in Europe. The total quantity in Europe in 1987 was 790,000 t. Of this, however, only 2,000 t was recovered from the ore in Europe, the rest being imported⁷. The most significant raw materials containing titanium are ilmenite (FeO.TiO₂), which contains monazite as an impurity and rutile TiO₂. Tailings from bauxite and copper ore processing may also be sources of titanium.

The following processes are used to recover titanium from ore. Rutile, and sometimes ilmenite concentrate is crushed and mixed with coal. Titanium tetrachloride TiCl₄ is obtained by chlorination in shaft furnaces to form a gas which is condensed and purified. The TiCl₄ is reduced to titanium sponge which is melted and remelted in a vacuum arc furnace. High purity titanium can be obtained by electrolytic refining.

The bulk of titanium metal produced is used in the iron and steel industry, for aircraft and rocket construction, in shipbuilding and in chemical plant construction. Titanium oxide is used in the rubber, ceramics, paint and varnish industries.

b) *Activity concentration of materials*

The radiological hazards from TiO₂ production vary with the type and source of ore. The ore activity concentration of both uranium-238 and thorium-232 decay chain members may range from 0.07 to 9 Bq g⁻¹⁽¹¹⁾. Also, during the processing of ilmenite for the production of TiO₂ pigments a radium containing precipitate occurs. Specific activities of such precipitates have been reported as around 400 Bq g⁻¹ of radium-226¹⁴.

7. Oil and gas extraction industry

a) *Processing and scale buildup*

In many oil and gas exploration platforms the build up of scale in pipework and vessels constitutes a significant radiological hazard. Typically the scale phenomenon occurs with the oil and gas reservoirs formed in the Jurassic era¹⁵. It is a result of mineral impurities and builds up because of the injection of incompatible water into the well, evaporation in gaseous wells, pressure changes and/or temperature drops¹⁶. The material is either a barium/strontium sulphate (Ba/SrSO₄)¹⁷ or calcium carbonate (CaCO₃)¹⁴ precipitate. The chemical similarity of radium and barium leads to it selectively co-precipitating in the scale, which leads to a concentration of radium isotopes. The only other radioactive isotopes in the scale are short-lived progeny of radium-226 and radium-228 parents. However, depending on the age of the scale significant amounts of lead-210 (half life 22.3 years) and thorium-232 (half life 1.4 × 10¹⁰ years) may grow in with their respective parents. The scale consistency is variable. It may be thin and hard, thick and soft, or muddy¹⁶. The scales tend to accumulate most frequently in liquid streams in extraction and collection plant.

b) *Working practices*

The main radiation protection problems associated with the scales are γ-irradiation of staff in areas where scale is deposited and internal contamination by those staff removing the scale¹⁶. Typical removal of scale involves disposing of the affected areas directly or removing the scale with high pressure water jets. In off-shore platforms it may be discharged to sea. In general the oil industry in developed countries takes considerable care when handling scale (either referred to as LSA scale, Low Specific Activity, or NORM, Naturally-occurring Radioactive Material). During removal processes areas of scale are copiously wetted, and workers are equipped with a high standard of respiratory protection and other protective measures. In many cases specialised contractors removing the scale are in close proximity to it for around 30% of time off-shore.

14 UNSCEAR 1988. Sources and effects of Ionizing Radiation, New York, UN, Report to the General Assembly, with annexes, 1988

15 Testa, C. *et al.* Radiation protection and radioactive scales in oil and gas production. *Health Phys* 67 p 34-8 (1994)

16 Testa C. *et al.* Radium, uranium and thorium concentration in low specific activity scales and waters of some oil and gas production plants. *J. Radioanal. Nuc. Chem. Articles*, 170 p 117-24 (1993)

17 Bulletin on management of Naturally Occurring Radioactive Materials (NORM) in oil and gas production. API Bulletin E2, American Petroleum Institute, Washington (1992)

c) *Activity concentration of materials*

The activity concentration has been reported as being less than 1 to around 1000 Bq g⁻¹ of radium-226^{5,18}, with typically rather less radium-228 (depending on the age of the scale). The activity concentration is strongly dependent on site specific parameters such as the pressure and temperature variations in the facility causing this wide range. There is anecdotal evidence that suggests the higher concentrations (> 100 Bq g⁻¹) exist only in relatively small quantities of material (kg), and in large (tonne) quantities the activity concentration is around 1 to 10 Bq g⁻¹.

As both isotopes are precipitated by the same mechanism it is likely that the ratio of radium-226 to radium-228 is close to the relative natural abundance of uranium-238 and thorium-232 parents in the host rock, although the shorter half life of radium-228 (5.75 years) will mean that in older scales its activity will be relatively lower. The short-lived decay products of radium-226 (radon-222, polonium-218, astatine-218, lead-214, bismuth-214 and polonium-214) grow in to 99.6 % of the activity of radium-226 in one month, and so can safely be assumed to be in equilibrium with radium-226 in scale. The short-lived decay product of radium-228 (actinium-228) is in secular equilibrium within a few days.

18 Kolb, W A, and Wojcik, M. Enhanced radioactivity due to natural oil and gas production. Proceedings of the sixth international congress of the International Radiation Protection Association, Berlin. May 7 - 12 (1984)

APPENDIX 2

PARAMETER VALUES USED FOR TYPICAL EXPOSURE SITUATIONS

(a) Exposure from stockpiles

This scenario represents the exposure of a worker to large piles of material in warehouses, where the atmosphere is likely to be dusty. This material could be raw material, by-product or waste material, or finished product.

External exposure

A 100 or 1000 m³ unshielded source represents a large stockpile. The worker is assumed to be 1 m from the source for 400 hours per year under normal assumptions or 2000 hours per year under unlikely assumptions.

Inhalation of dust

The worker is assumed to work for 2000 hours per year without respiratory protection in an inhalable dust concentration of 1 mg m⁻³ under normal assumptions and 5 mg m⁻³ under unlikely assumptions.

Ingestion of dust

Over a 2000 hour year, the worker is assumed to inadvertently ingest 1.25 mg per hour under normal assumptions and 3.75 mg per hour under unlikely assumptions.

Inhalation of radon

Over a 2000 hour year, the worker is assumed to breathe radon exhaled from the stockpile. The warehouse ventilation rate is taken as 0.5 air changes per hour under normal assumptions and 0.25 air changes per hour under unlikely assumptions. The room in which the worker is exposed is assumed to be 4x the material volume or 100 m³, whichever is larger.

(b) Exposure from scales and residues

This scenario represents the exposure of a worker to situations such as the volatilisation of Polonium, or sometimes Lead, in high temperature furnaces, and the collection of radium in pipe scales. The removal process is assumed to be dusty, but protective equipment is more likely to be worn and exposure times shorter.

External exposure

The worker is assumed to be 1 m from an unshielded 1 m³ source for 100 hours per year under normal assumptions or 400 hours per year under unlikely assumptions.

Inhalation of dust

The worker is assumed to work in a dust concentration of 10 mg m⁻³ for 100 hours per year under normal assumptions and 400 hours per year under unlikely assumptions. However, use of respiratory protection is assumed to halve the dust loading actually inhaled under normal assumptions.

Inhalation of fume

The worker is assumed to be exposed without respiratory protection to volatilised polonium or lead, equivalent to a dust concentration of 1 mg m^{-3} , for 100 hours per year under normal assumptions and 400 hours per year under unlikely assumptions.

Ingestion of dust

Under normal assumptions, the worker is assumed to inadvertently ingest 5 mg per hour for a 100 hours per year, but the ingestion rate is halved through use of protective equipment. Under unlikely assumptions, the exposure period is increased to 400 hours per year and no protective equipment is worn.

Inhalation of radon

Under normal assumptions, the worker is assumed to breathe radon exhaled from the residue for 100 hours per year with a ventilation rate of 0.5 air changes per hour. Under unlikely assumptions, the exposure time is increased to 400 hours per year and the ventilation rate reduced to 0.25 air changes per hour.

(c) Exposure from process vessels and pipes

This scenario represents the exposure of a worker to radioactive scale that has built up in process vessels and pipes. As the material is contained, the only exposure is external irradiation. Some shielding arises from the walls of the vessels or pipes, which are assumed to consist of 5 mm thick iron.

External exposure

The worker is assumed to be 1 m from a 100 m^3 source for 400 hours per year under normal assumptions or 2000 hours per year under unlikely assumptions.

Note

1. The parameters set out in this Appendix have been taken directly from the NRPB/CEPN contract report (see paragraph 6), to which readers should refer for an explanation of why particular values have been chosen.
2. Where possible, the above assumptions were modified to reflect the actual exposure conditions in particular industries/processes. Exposure to products was also considered but not on a generic basis, as products do not have 'generic' characteristics.

Appendix 3 : Screening levels

Industry and Material	Indicator Nuclide or Segment	Activity concentration (Bq/g)		
		Marker points		
		a	b	c
Phosphate Industry				
Phosphate ore	U+238	2E-01	1E+00	3E+00
Wet process: phosphogypsum	U+238	1E-01	7E-01	2E+00
Wet process: cloth filters	U+238	4E+00	1E+01	3E+01
Thermal process: CaSiO ₃ slag	U+238	2E+00	8E+00	2E+01
Thermal: Pb/Po precipitate	Pb+210	3E+02	1E+03	2E+03
Thermal: Volatilised Pb/Po	Pb+210	2E+03	1E+04	3E+04
Vats of material	U+238	7E+00	3E+01	7E+01
General fertilizer	U+238	9E-01	5E+00	2E+01
Ferro-niobium				
Pyrochlore feedstock	Th-232	2E-01	1E+00	4E+00
Wastes and slag	Th-232	1E+00	8E+00	2E+01
Vats of material	Th-232	7E+00	3E+01	7E+01
Pb/Po precipitate	Pb+210	3E+02	1E+03	2E+03
Volatilised Pb/Po	Pb+210	2E+03	1E+04	3E+04
Tin smelting				
Tin smelting slag	U+238	8E-01	5E+00	1E+01
Po precipitate	Po-210	4E+02	1E+03	3E+03
Volatilised Po	Po-210	3E+03	1E+04	4E+04
Zircon				
Zircon sands	Th-232	5E-02	3E-01	1E+00
Refractory products	Th-232	2E+00	5E+00	1E+01
Pb/Po precipitate	Pb+210	3E+02	1E+03	2E+03
Volatilised Pb/Po	Pb+210	2E+03	1E+04	3E+04
Rare Earth extraction				
Monazite/bastnasite sand	Th-232	2E+00	1E+01	3E+01
Radium bearing residues	Ra+226	1E+01	5E+01	1E+02
Cerium concentrate for glass	U+238	8E-01	5E+00	1E+01
Thorium products				
W-Th welding electrodes (store)	Th-232	6E+01	3E+02	6E+02
W-Th welding electrodes (grinding)	Th-232	6E+01	2E+02	5E+02
W-Th welding electrodes (use)	Th-232	1E+02	5E+02	1E+03
Thorium Glass	Th-232	6E+03	2E+04	5E+04
Gas Mantle storage	Th-232	3E+02	2E+03	6E+03
Titanium dioxide industry				
Ilmenite feedstock	U+238	2E-01	1E+00	4E+00
Material in vats	Ra+226	6E+00	2E+01	6E+01
Radium bearing scales	Ra+226	7E+00	2E+01	6E+01
Oil & Gas extraction				
Removal of radium scales	Ra+226	3E+01	1E+02	3E+02
Radium scales in pipes	Ra+226	4E+01	2E+02	4E+02
Radium sludge removal	Ra+226	1E+01	5E+01	1E+02
General metal smelting				
Pb/Po precipitate	Pb+210	3E+02	1E+03	2E+03
Volatilised Pb/Po	Pb+210	2E+03	1E+04	3E+04
Fertilisers				
Fertilizers, K	K-40	6E+01	2E+02	6E+02
Fertilizers, P superphosphate	U+238	6E-01	4E+00	1E+01
Fertilizers, NP	U+238	2E+00	1E+01	3E+01
Fertilizers, PK	K-40	8E+00	5E+01	1E+02
Fertilizers, NPK	K-40	8E+00	5E+01	1E+02
Fertilizers, Triple superphosphate	U+238	1E+00	8E+00	2E+01

NOTES:

Screening levels are only intended to indicate the likely level of regulation. To more thoroughly demonstrate the Level of regulation the Reference Levels presented in Appendix 4 should be used. Marker points a to c are defined in paragraph 19. This table has been reproduced from Table 6 of the NRPB/CEPN contract report (see paragraph 6).

Appendix 4(a) Reference Levels – First Marker Point (a)
 (normal assumptions $\leq 1\text{mSv/y}$, unlikely assumptions $\leq 6\text{mSv/y}$)

Industry and Material	Thorium-232 series		Uranium-238 series				Uranium-235 series			K-40	Classified on			
	Th-232	Ra+228	Th-230	U-234	Th-230	Ra+226	Pb+210	Po-210	U+235			Pa-231	Ac+227	
Phosphate Industry														
Phosphate ore	1E+01	1E+01	4E+00	8E+01	7E+01	2E+01	5E-01	3E+02	2E+02	5E+01	6E+00	8E-01	8E+01	U
Wet process: phosphogypsum	1E+01	1E+01	5E+00	8E+01	7E+01	2E+01	1E+00	3E+02	2E+02	5E+01	6E+00	8E-01	8E+01	U
Wet process: cloth filters	3E+01	3E+02	3E+01	2E+02	2E+02	5E+01	2E+01	9E+02	6E+02	2E+02	1E+01	2E+00	3E+03	N
Thermal process: CaSiO ₃ slag	1E+01	1E+01	5E+00	8E+01	7E+01	2E+01	4E+00	3E+02	2E+02	5E+01	6E+00	8E-01	8E+01	U
Thermal: Pb/Po precipitate								1E+03	4E+02					U
Thermal: Volatilised Pb/Po								1E+04	4E+03					U
Vats of material	7E+05	2E+01	1E+01	1E+03	4E+06	4E+05	1E+01	4E+08	2E+06	2E+02	9E+02	7E+01	1E+02	U
General fertilizer	1E+01	1E+01	5E+00	8E+01	7E+01	2E+01	1E+00	3E+02	2E+02	4E+01	6E+00	8E-01	8E+01	U
Ferro-niobium														U
Pyrochlore feedstock	1E+01	2E+01	3E+00	8E+01	7E+01	2E+01	1E-01	3E+02	2E+02	7E+01	6E+00	8E-01	1E+02	U
Wastes and slag	1E+01	2E+01	6E+00	8E+01	7E+01	2E+01	2E+00	3E+02	2E+02	7E+01	6E+00	8E-01	1E+02	U
Vats of material	6E+06	3E+01	1E+01	1E+03	6E+07	4E+06	1E+01	5E+09	3E+06	1E+03	2E+03	1E+02	1E+02	U
Pb/Po precipitate								1E+03	4E+02					U
Volatilised Pb/Po								1E+04	4E+03					U
Tin smelting														U
Tin smelting slag	1E+01	1E+01	5E+00	8E+01	7E+01	2E+01	3E+00	3E+02	2E+02	4E+01	6E+00	8E-01	8E+01	U
Po precipitate														U
Volatilised Po														U
Zircon														U
Zircon sands	7E+00	1E+01	4E+00	4E+01	4E+01	9E+00	1E+00	2E+02	1E+02	4E+01	3E+00	4E-01	8E+01	U
Refractory products	3E+01	3E+02	3E+01	2E+02	2E+02	5E+01	3E+01	9E+02	6E+02	2E+02	1E+01	2E+00	3E+03	N
Pb/Po precipitate								1E+03	4E+02					U
Volatilised Pb/Po								1E+04	4E+03					U
Rare Earth extraction														U
Monazite/bastnasite sand	1E+01	2E+01	6E+00	8E+01	7E+01	2E+01	8E-01	3E+02	2E+02	7E+01	6E+00	8E-01	1E+02	U
Radium bearing residues	3E+02	3E+02					2E+01							U
Cerium concentrate for glass	3E+02	2E+02	7E+01	2E+03	2E+03	4E+02	2E+01	3E+03	4E+03	7E+02	1E+02	2E+01	1E+03	U

Industry and Material	Thorium-232 series Th-232 Ra+228 Th+228	Uranium-238 series U+238 U-234 Th-230 Ra+226 Pb+210 Po-210	Uranium-235 series U+235 Pa-231 Ac+227	K-40	Classified on
Thorium products					
W-Th welding electrodes (store)	2E+07 8E+01				U
W-Th welding electrodes (grinding)	1E+02 1E+02	1E+07 2E+02			N
W-Th welding electrodes (use)	3E+02 3E+02	3E+02			U
Thorium Glass	1E+04 1E+04				U
Gas Mantle storage	1E+06 1E+03 7E+02	1E+06 6E+02 2E+05 1E+08			U
Titanium dioxide industry					
Ilmenite feedstock	1E+01 1E+01 4E+00	8E+01 7E+01 2E+01 6E-01 3E+02 2E+02	5E+01 6E+00 8E-01	8E+01	U
Material in vats	1E+06 2E+01 1E+01	1E+03 8E+06 7E+05 1E+01 1E+09 2E+06	3E+02 1E+03 8E+01	1E+02	U
Radium bearing scales	3E+02 3E+01	4E+01			U
Oil & Gas extraction					
Removal of radium scales	3E+02 2E+01	4E+01			U
Radium scales in pipes	1E+02 6E+01	6E+01			U
Radium sludge removal	1E+02 1E+01	2E+01			U
General metal smelting					
Pb/Po precipitate					U
Volatilised Pb/Po					U
Fertilisers					
Fertilizers, K	1E+01 1E+01 5E+00	8E+01 7E+01 2E+01 1E+00 3E+02 2E+02	5E+01 6E+00 8E-01	8E+01	U
Fertilizers, P superphosphate	1E+01 1E+01 5E+00	8E+01 7E+01 2E+01 1E+00 3E+02 2E+02	4E+01 6E+00 8E-01	8E+01	U
Fertilizers, NP	1E+01 1E+01 5E+00	8E+01 7E+01 2E+01 1E+00 3E+02 2E+02	4E+01 6E+00 8E-01	8E+01	U
Fertilizers, PK	1E+01 1E+01 5E+00	8E+01 7E+01 2E+01 1E+00 3E+02 2E+02	5E+01 6E+00 8E-01	8E+01	U
Fertilizers, NPK	1E+01 1E+01 5E+00	8E+01 7E+01 2E+01 1E+00 3E+02 2E+02	4E+01 6E+00 8E-01	8E+01	U
Fertilizers, Triple superphosphate	1E+01 1E+01 5E+00	8E+01 7E+01 2E+01 1E+00 3E+02 2E+02	4E+01 6E+00 8E-01	8E+01	U

NOTES:

- To demonstrate compliance with the classification the activity concentration divided by reference level, summed for all nuclides (segments) present, must be less than or equal to 1, ie: (Activity conc. A/ Reference Level A) + (Activity conc. B/ Reference Level B) + <= 1
- "N" indicates the reference levels were limited by the normal assumptions, "U" indicates they were limited by unlikely assumptions
- This table has been reproduced from Table 7(b) of the NRPB/CEPN contract report (see paragraph 6)

Appendix 4(b) Reference Levels – Second Marker Point (b)
 (normal assumptions ≤ 6 mSv/y, unlikely assumptions ≤ 20 mSv/y)

Industry and Material	Thorium-232 series		Uranium-238 series					Uranium-235 series			K-40	Classified on		
	Th-232	Ra+228 Th+228	U-238	Th-230	Ra+226	Pb+210	Po-210	U+235	Pa-231	Ac+227				
Phosphate Industry														
Phosphate ore	4E+01	4E+01	1E+01	3E+02	2E+02	6E+01	2E+00	1E+03	7E+02	2E+02	2E+01	3E+00	3E+02	U
Wet process: phosphogypsum	4E+01	4E+01	2E+01	3E+02	2E+02	6E+01	5E+00	1E+03	7E+02	2E+02	2E+01	3E+00	3E+02	U
Wet process: cloth filters	1E+02	9E+02	1E+02	7E+02	6E+02	2E+02	7E+01	3E+03	2E+03	7E+02	5E+01	7E+00	8E+03	N
Thermal process: CaSiO3 slag	4E+01	4E+01	2E+01	3E+02	2E+02	6E+01	1E+01	1E+03	7E+02	2E+02	2E+01	3E+00	3E+02	N
Thermal: Pb/Po precipitate								3E+03	1E+03					U
Thermal: Volatilised Pb/Po								4E+04	1E+04					U
Vats of material	2E+06	6E+01	3E+01	3E+03	1E+07	1E+06	3E+01	1E+09	7E+06	7E+02	3E+03	2E+02	4E+02	U
General fertilizer	4E+01	4E+01	2E+01	3E+02	2E+02	6E+01	4E+00	1E+03	7E+02	1E+02	2E+01	3E+00	3E+02	N
Ferro-niobium														U
Pyrochlore feedstock	4E+01	6E+01	1E+01	3E+02	2E+02	6E+01	5E-01	1E+03	7E+02	2E+02	2E+01	3E+00	4E+02	U
Wastes and slag	4E+01	6E+01	2E+01	3E+02	2E+02	6E+01	7E+00	1E+03	7E+02	2E+02	2E+01	3E+00	4E+02	U
Vats of material	2E+07	9E+01	5E+01	4E+03	2E+08	1E+07	5E+01	2E+10	1E+07	4E+03	8E+03	5E+02	4E+02	N
Pb/Po precipitate								3E+03	1E+03					U
Volatilised Pb/Po								4E+04	1E+04					U
Tin smelting														
Tin smelting slag	4E+01	4E+01	2E+01	3E+02	2E+02	6E+01	1E+01	1E+03	7E+02	1E+02	2E+01	3E+00	3E+02	N
Po precipitate														U
Volatilised Po														U
Zircon														
Zircon sands	2E+01	5E+01	1E+01	1E+02	1E+02	3E+01	4E+00	6E+02	4E+02	1E+02	9E+00	1E+00	3E+02	U
Refractory products	1E+02	9E+02	1E+02	7E+02	6E+02	2E+02	1E+02	3E+03	2E+03	7E+02	5E+01	7E+00	8E+03	N
Pb/Po precipitate								3E+03	1E+03					U
Volatilised Pb/Po								4E+04	1E+04					U
Rare Earth extraction														
Monazite/bastnasite sand	4E+01	6E+01	2E+01	3E+02	2E+02	6E+01	3E+00	1E+03	7E+02	2E+02	2E+01	3E+00	3E+02	N
Radium bearing residues		1E+03					8E+01							U
Cerium concentrate for glass	1E+03	6E+02	2E+02	6E+03	6E+03	1E+03	8E+01	1E+04	1E+04	2E+03	5E+02	6E+01	3E+03	U

Industry and Material	Thorium-232 series Th-232 Ra+228 Th+228	Uranium-238 series U-238 Th-234 U-234 Th-230 Ra+226 Pb+210 Po-210	Uranium-235 series U+235 Pa-231 Ac+227	K-40	Classified on
Thorium products					
W-Th welding electrodes (store)	7E+07				N
W-Th welding electrodes (grinding)	4E+02	4E+07 5E+02			N
W-Th welding electrodes (use)	9E+02	1E+03			N
Thorium Glass	5E+04	4E+04			N
Gas Mantle storage	5E+06	3E+03 2E+03	5E+05 4E+08		U
Titanium dioxide industry					
Ilmenite feedstock	4E+01	5E+01 1E+01			U
Material in vats	4E+06	6E+01 3E+01	2E+02 1E+03 7E+02	3E+02	U
Radium bearing scales		1E+03 1E+02	4E+09 7E+06	3E+02	N
Oil & Gas extraction					U
Removal of radium scales	8E+02	5E+01			U
Radium scales in pipes	4E+02	2E+02			U
Radium sludge removal	4E+02	5E+01			U
General metal smelting					
Pb/Po precipitate					U
Volatilised Pb/Po			3E+03 1E+03		U
Fertilisers					
Fertilizers, K	4E+01	5E+01 2E+01			N
Fertilizers, P superphosphate	4E+01	4E+01 2E+01			U
Fertilizers, NP	4E+01	4E+01 2E+01			N
Fertilizers, PK	4E+01	4E+01 2E+01			U
Fertilizers, NPK	4E+01	4E+01 2E+01			U
Fertilizers, Triple superphosphate	4E+01	4E+01 2E+01			U

NOTES:

- To demonstrate compliance with the classification the activity concentration divided by reference level, summed for all nuclides (segments) present, must be less than or equal to 1, ie: (Activity conc. A/ Reference Level A) + (Activity conc. B/ Reference Level B) + ... <= 1
- "N" indicates the reference levels were limited by the normal assumptions, "U" indicates they were limited by unlikely assumptions
- This table has been reproduced from Table 7(c) of the NRPB/CEPN contract report (see paragraph 6)

Appendix 4 (c) Reference Levels – Third Marker Point (c)
 (normal assumptions <=20 mSv/y, unlikely assumptions <= 50 mSv/y)

Industry and Material	Thorium-232 series		Uranium-238 series					Uranium-235 series			K-40	Classified on			
	Th-232	Ra+228	Th+228	U+238	U-234	Th-230	Ra+226	Pb+210	Po-210	U+235			Pa-231	Ac+227	
Phosphate Industry															
Phosphate ore	1E+02	1E+02	3E+01	6E+02	6E+02	2E+02	4E+00	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02		U
Wet process: phosphogypsum	1E+02	1E+02	4E+01	6E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02		U
Wet process: cloth filters	3E+02	2E+03	3E+02	2E+03	2E+03	4E+02	2E+02	7E+03	5E+03	2E+03	1E+02	2E+01	2E+04		N
Thermal process: CaSiO3 slag	1E+02	1E+02	4E+01	6E+02	6E+02	2E+02	3E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02		N
Thermal: Pb/Po precipitate							8E+03	3E+03	3E+03						U
Thermal: Volatilised Pb/Po							1E+05	4E+04							U
Vats of material	6E+06	2E+02	9E+01	8E+03	3E+07	4E+06	9E+01	4E+09	2E+07	2E+03	7E+03	6E+02	9E+02		N
General fertilizer	1E+02	1E+02	4E+01	6E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02		N
Ferro-niobium															
Pyrochlore feedstock	1E+02	2E+02	2E+01	7E+02	6E+02	2E+02	1E+00	3E+03	2E+03	6E+02	5E+01	7E+00	9E+02		U
Wastes and slag	1E+02	2E+02	5E+01	7E+02	6E+02	2E+02	2E+01	3E+03	2E+03	6E+02	5E+01	7E+00	9E+02		N
Vats of material	5E+07	2E+02	1E+02	1E+04	5E+08	3E+07	1E+02	5E+10	2E+07	9E+03	2E+04	1E+03	1E+03		N
Pb/Po precipitate							8E+03	3E+03							U
Volatilised Pb/Po							1E+05	4E+04							U
Tin smelting															
Tin smelting slag	1E+02	1E+02	4E+01	6E+02	6E+02	2E+02	3E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02		N
Po precipitate															U
Volatilised Po															U
Zircon															
Zircon sands	5E+01	1E+02	3E+01	4E+02	3E+02	8E+01	1E+01	2E+03	9E+02	3E+02	2E+01	3E+00	7E+02		U
Refractory products	3E+02	2E+03	3E+02	2E+03	2E+03	4E+02	2E+02	7E+03	5E+03	2E+03	1E+02	2E+01	2E+04		N
Pb/Po precipitate	3E+02	2E+03	3E+02	1E+03	1E+03	3E+02	6E+02	8E+03	3E+03	1E+03	8E+01	2E+01	3E+04		U
Volatilised Pb/Po							1E+05	4E+04							U
Rare Earth extraction															
Monazite/bastnasite sand	1E+02	2E+02	5E+01	7E+02	6E+02	2E+02	7E+00	3E+03	2E+03	6E+02	5E+01	7E+00	9E+02		N
Radium bearing residues		2E+03				2E+02									U
Cerium concentrate for glass	3E+03	1E+03	6E+02	1E+04	2E+04	4E+03	2E+02	3E+04	3E+04	6E+03	1E+03	2E+02	9E+03		N

Industry and Material	Thorium-232 series Th-232 Ra+228 Th+228		Uranium-238 series U+238 U-234 Th-230 Ra+226 Pb+210 Po-210				Uranium-235 series U+235 Pa-231 Ac+227			K-40	Classified on		
	2E+08 1E+03 2E+03 1E+05 1E+07	9E+03 6E+03 4E+01 2E+02 9E+01 3E+03	7E+02 8E+03 6E+02 7E+07 6E+06 4E+02	U-234 Th-230 Ra+226 Pb+210 Po-210	U+235 Pa-231 Ac+227	U+235 Pa-231 Ac+227	U+235 Pa-231 Ac+227	U+235 Pa-231 Ac+227	U+235 Pa-231 Ac+227				
Thorium products													
W-Th welding electrodes (store)	2E+08	6E+02	1E+08								N		
W-Th welding electrodes (grinding)	1E+03	1E+03	1E+03								N		
W-Th welding electrodes (use)	2E+03	2E+03	2E+03								N		
Thorium Glass	1E+05	9E+04									N		
Gas Mantle storage	1E+07	9E+03	8E+06	5E+03	1E+06	9E+08					U		
Titanium dioxide industry													
Ilmenite feedstock	1E+02	1E+02	7E+02	6E+02	2E+02	5E+00	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02	U
Material in vats	9E+06	2E+02	8E+03	7E+07	6E+06	9E+01	1E+10	2E+07	2E+03	9E+03	6E+02	9E+02	N
Radium bearing scales	3E+03	3E+02				4E+02							U
Oil & Gas extraction													
Removal of radium scales	2E+03	1E+02				3E+02							U
Radium scales in pipes	9E+02	5E+02				5E+02							U
Radium sludge removal	1E+03	1E+02				1E+02							U
General metal smelting													
Pb/Po precipitate													U
Volatilised Pb/Po													U
Fertilisers													
Fertilizers, K	1E+02	1E+02	7E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02	N
Fertilizers, P superphosphate	1E+02	1E+02	6E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02	N
Fertilizers, NP	1E+02	1E+02	6E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02	N
Fertilizers, PK	1E+02	1E+02	7E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02	N
Fertilizers, NPK	1E+02	1E+02	6E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02	N
Fertilizers, Triple superphosphate	1E+02	1E+02	6E+02	6E+02	2E+02	1E+01	3E+03	2E+03	4E+02	5E+01	6E+00	7E+02	N

NOTES:

- To demonstrate compliance with the classification the activity concentration divided by reference level, summed for all nuclides (segments) present, must be less than or equal to 1, ie: (Activity conc. A/ Reference Level A) + (Activity conc. B/ Reference Level B) + ≤ 1
- "N" indicates the reference levels were limited by the normal assumptions, "U" indicates they were limited by unlikely assumptions
- This table has been reproduced from Table 7(d) of the NRPB/CEPN contract report (see paragraph 6)

APPENDIX 5

WORKED EXAMPLE - ZIRCON SANDS & REFRACTORY MATERIALS

Background

A factory handles and processes raw zircon sands and then manufactures refractory products. The latter is done by a smelting process, giving rise to volatilised Pb-210, followed by grinding and polishing, which causes Pb-210 dust. The raw sands have a Th-232 activity of 0.4 Bq g^{-1} , as do the refractory products. The Pb-210 precipitate arising from the process is measured at 100 Bq g^{-1} and the volatilised Pb-210 at 400 Bq g^{-1} .

Screening Levels

Using the information above and the screening levels in Appendix 3:

Material	Indicator Nuclide	Material Activity Bq g^{-1}	Marker Point 1	Marker Point 2	Marker Point 3	Control Band
Zircon Sands	Th-232	0.4	0.05	0.3	1	3
Refractory Prod	Th-232	0.4	2	5	10	1
Pb Precipitate	Pb+210	100	300	1,000	2,000	1
Pb Volatilised	Pb+210	400	2,000	10,000	30,000	1

On this basis, the activity of refractory product processes, and precipitated and volatilised Pb all lie below the first Marker Point. So they fall in the first Control Band "No regulation necessary". However, the activity of the raw sands lies just above the second Marker Point, and so falls in Control Band 3 "Higher level of regulation". It is this part of the process that merits further examination.

Reference Levels

More detailed analysis of the sand provides the following information:

Activity of all members of the Th-232 Chain = 0.4 Bq g^{-1}

Activity of all members of the U-238 Chain = 0.8 Bq g^{-1}

Activity of all members of the U-235 Chain = 0.036 Bq g^{-1}

Marker Point 1

Using the values in Appendix 4(a), to derive the index for the first Marker Point:

Index for Th-232 chain = $0.4/7 + 0.4/10 + 0.4/4 = 0.20$

Index for U-238 chain = $0.8/40 + 0.8/40 + 0.8/9 + 0.8/1 + 0.8/200 + 0.8/100 = 0.94$

Index for U-235 chain = $0.036/40 + 0.036/3 + 0.036/0.4 = 0.10$

Total Index = $0.20 + 0.94 + 0.10 = 1.24$

Since the index is above 1, then the activity of the material is above the first Marker Point.

Marker Point 2

Using the values in Appendix 4(b), to derive the index for the second Marker Point and following the same procedures as for the first Marker point gives:

Index for Th-232 chain = 0.07

Index for U-238 chain = 0.25

Index for U-235 chain = 0.04

Total Index = $0.07 + 0.25 + 0.04 = 0.36$

Since the index is substantially below 1, then the activity of the material is below the second Marker Point.

Control Band

The more detailed analysis of the zircon sands and use of the Reference Points shows that the material activity lies between Marker Points 1 and 2, which means that it falls into Control Band 2 "Lower level of regulation"

Control Measures

Given the nature of the process, the most significant pathway for exposure is going to be the inhalation of dusts and radon. So an important control measure to consider is adequate ventilation of the plant as a whole, and the specific points at which dust is generated.

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This document offers guidance to national authorities in terms of reference levels of activity concentration of naturally occurring radionuclides in materials processed in the industry, in order to identify industries which are of concern for the protection of workers, within the scope of the revised European Union Basic Safety Standards Directive (96/29/Euratom of 13 May 1996), and to establish corresponding levels of regulatory control.