2.2

Development of a methodology for assessing occupational exposure at workplaces where materials are processed which contain enhanced levels of natural radionuclides

S.F. Mobbs, J.S. Penfold

National Radiological Protection Board
United Kingdom

J-P Degrange

CEPN
France

DEVELOPMENT OF A METHODOLOGY FOR ASSESSING OCCUPATIONAL EXPOSURE AT WORKPLACES WHERE MATERIALS ARE PROCESSED WHICH CONTAIN ENHANCED LEVELS OF NATURAL RADIONUCLIDES

J-P Degrange[1], JSS Penfold[2] and SF Mobbs[2]

ABSTRACT

The revised Basic Safety Standards provide a regulatory control system for the protection of workers and the public from sources of ionising radiation. In the special case of occupational exposure of workers to natural radiation sources, competent national authorities may determine which work activities require controls. However there is a need for the harmonisation of approaches in the EU. A study was performed by NRPB and CEPN for the European Commission to establish reference levels for the regulatory control of workplaces involved in the processing of materials containing enhanced natural radionuclides.

This paper describes the assessment methodology that was developed for the study and the doses that were calculated. The reference levels are described in another paper. The first step was to identify the relevant industries, the materials containing enhanced levels of natural radionuclides and their activity concentrations. The next step was to establish exposure scenarios reflecting the working conditions and to use these to estimate doses to workers in industries. Both normal and unlikely sets of assumptions were studied.

INTRODUCTION

Certain minerals contain significant levels of naturally occurring radionuclides which may be enhanced during processing. These materials, their by-products and the end products may expose both workers and members of the public. This paper describes a methodology for the assessment of such doses, developed as part of a study for the EC to generate reference levels for the regulatory control of workplaces [1].

Firstly, the industries where enhanced levels of natural radionuclides are present were reviewed. The aim of this review was to gain information so that suitable exposure scenarios could be established for workers in the different industries (reflecting the working conditions and practices in those industries). However, in most cases there were insufficient data on the working practices so that it was necessary to develop generic exposure scenarios. These scenarios were modified with the material specific data where available and used to assess radiation doses[AAA] to workers.

[1] CEPN, Route de Panorama BP 48, 92263 Fontenay aux Roses Cedex FRANCE

[2] NRPB, Chilton, Didcot, Oxfordshire OX11 ORQ, UNITED KINGDOM

Unless otherwise indicated the word "dose" refers to the individual effective dose as defined in ICRP publication 60 [2]. The only exception is skin dose which refers to the equivalent dose to areas of the skin.

REVIEW OF INDUSTRIES

Approach

The purpose of this review was to identify the following items for each industry:

- the quantities of material used or produced,
- the range of concentrations of radionuclides in these materials, and
- details of processes used and typical working procedures.

Three types of materials were considered separately.

Mineral ores

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.

By-products and residues

Processing may concentrate the radionuclides in by-products or residues. This can occur by means of mass separation (for example in processing certain mineral sands), other physical phenomena (*eg.* the 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 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 ores, particularly those by-products with high activity concentrations.

Products

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}.

These three types of materials were identified for the most significant industries within the EU. These industries were picked both on the identified radiological hazards within the industry and its scale and economic significance. This gave a total of seven industries:

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

The phosphate industry

Mining and milling of phosphate ore

Most of the phosphate ore used is in the form of calcium phosphates $Ca_3(PO_4)_2$ (phosphorites) and apatite ($3Ca_3(PO_4)_2.CaF_2$). Phosphorites have a typical activity concentration of natural uranium of 1.5 Bq g^{-1}. Radionuclides in the Th-232 decay chain are typically present with activity concentration of between one and two orders of magnitude less. Some Russian deposits of apatite contain much less

uranium (usually several tenths of Bq g^{-1}) but roughly the same concentration of Th-232 and its progeny.

Phosphate ore wet process

The wet process produces phosphoric acid (H_3PO_4) by reaction with sulphuric acid, phosphogypsum ($CaSO_4$) being formed as a by product. Alternatively, this process produces superphosphate (a combination of phosphoric acid and phosphogypsum). 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.

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). Hence phosphogypsum derived from Central Florida rocks contains Ra-226 and its progeny at concentrations of around 0.9 to 1.3 Bq g^{-1}.

Phosphate ore thermal process

In the thermal process the phosphate ore is crushed, mixed with silica (SiO_2 gravel) and coke, and heated to 1500°C in an electric furnace, to produce phosphorus. The elemental phosphorus is often converted into phosphoric acid, using nitric acid, for later use in the manufacture of artificial fertilisers. Fused calcium silicate slag ($CaSiO_2$) and ferro-phosphorous are produced as waste and by-products.

Most of the uranium (and associated decay products) originally contained in the phosphate ore are retained in the slag, giving U-238 and Th-230 concentrations of between 1 and 2.7 Bq g^{-1}. Because of the high temperature of process about 95% of the relatively volatile radionuclides are released to the process air, giving typical concentrations of 50 to 500 Bq g^{-1} of Pb-210 and Po-210 in some electrostatically precipitated dusts.

Fertilisers

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. Activities of U-238 vary from around 0.3 to 3 Bq g^{-1}. U-234 and Th-230 are present at about the same activity, however Ra-226 and Pb-210 are typically between 30 % and 60 % of the U-238 activity (0.2 to 1 Bq g^{-1}). Th-228, Ra-228 (and presumably Th-232) are present with activity between 0.008 and 0.04 Bq g^{-1}.

Processing of metal ores

Tin

Cassiterite or tinstone (SnO_2) is the most important ore. Sulphide ores are also of commercial significance. The ore concentrate is mixed with charcoal and heated to 1000-1200°C. The tin is then remelted in a second furnace for further purification.

The main radiological hazards are the smelting slag and the volatilised Po-210 which collects in dust precipitators. Typical activity concentrations of tin ore and slag in the UK were 1 Bq g^{-1} of U-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 Th-232 chain. Concentrations of volatilised Po-210 of up to 200 Bq g^{-1} have been found in collected fume of one UK plant.

Niobium

Niobium is found together with other elements in ores such as tantalite Ta_2O_6(Fe,Mn), columbite Nb_2O_6Fe, fergusonite (Nb,Ta)O_4(Y,Er,Ce).$Nb_2O_7Ca_2$, samarskite, pyrochlore $(Na,Ca,Ce)_2$ Nb_2O_6F, koppite and loparite. 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. Ferro-niobium may be also produced using a process involving a high temperature exothermic reaction between pyrochlore and aluminium powder.

Pyrochlore usually has a high activity concentration of both U-238 and Th-232 decay series radionuclides. Reported activity concentrations range from 7 to 80 Bq g^{-1} of Th-232 and 6 to 10 Bq g^{-1} of U-238.

Other metals

The extraction of many metals may give rise to radiological hazards, however few radiological data are available. Any large scale process which involves smelting metals at high temperatures may give rise to volatilised Pb and Po which can lead to radiological hazards to workers if it collects in flue precipitates or if workers are able to inhale it directly. These hazards were assessed generically, although they may be found in the production of copper and iron. 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.

Zircon sands and refractory materials

The most common ores of zirconium are Zircon ($ZrSiO_4$) and Baddeleyite (ZrO_2), and most of the commercially useful deposits of zircon are in beach sands. Typically the sand is pre-processed in very large quantities by gravimetric and electromagnetic sorting to separate the zircon sands from the other mineral sands, which include monazite and bastnaesite. An important use of zircon sands is in the manufacture of refractory components. These are made by mixing zircon sand with alumina and sodium carbonate and smelting at high temperature. Such blocks or components are finished by grinding and polishing.

A wide range of activity concentrations are reported for zircon sand, from 0.4 Bq g^{-1} to 40 Bq g^{-1} of Th-232, and 0.2 to 74 Bq g^{-1} of U-238.

Manufacture of rare earths

The most important sources of rare earth elements are monazite $(Ce,La,Nd,Th)PO_4$ and bastnaesite $(Ce,La,...)(CO_3)F$. 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.

Monazite concentrates typically have a much higher activity concentration than bastnaesite concentrates as they include a Th PO_4 constituent. In the monazite concentrate, radionuclides in the Th-232 decay chain are reported to have activities of 8 to 3000 Bq g^{-1}, whilst radionuclides in the U-238 decay chain are reported to have activity concentrations ranging from 6 to 40 Bq g^{-1}. 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 Ra-228 and 450 Bq g^{-1} of Ra-226. A second by-product with a typical activity concentration of about 20 Bq g^{-1} Ra-228 and 3 Bq g^{-1} Ra-226 can also occur.

Manufacture and use of thorium compounds

Minerals with high concentrations of thorium oxide include monazite, thorite and thorianite. Thorium is obtained from them by first concentrating minerals, 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 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.

The activity concentration of thoriated tungsten welding electrodes have been variously reported but is around 100 Bq g^{-1} of Th-232 and Th-228. Gas mantles typically contain about 1000 Bq of Th-232 and Th-228 each. Special alloys such as those used in jets engines may have an activity of about 70 Bq g^{-1}.

Titanium dioxide pigment industry

The most significant raw materials containing titanium are rutile (TiO_2) and ilmenite ($FeO.TiO_2$), which contains monazite as an impurity. Tailings from bauxite and copper ore processing may also be sources of titanium. Rutile, and sometimes ilmenite concentrate is crushed and mixed with coal. Titanium tetrachloride $TiCl_4$ is obtained by chlorination in shaft furnaces. The $TiCl_4$ is then reduced to titanium sponge which is melted and remelted in a vacuum arc furnace.

The ore activity concentration of both U-238 and Th-232 decay chain members may range from 0.07 to 9 Bq g^{-1}. Also, during the processing of ilmenite for the production of TiO_2 pigments, a radium containing precipitate occurs. Activity concentrations of such precipitates have been reported as around 400 Bq g^{-1} Ra-226 .

Oil and gas extraction industry

In many oil and gas exploration platforms the build-up of scale in pipework and vessels constitutes a significant radiological hazard. Typically the scale 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 drops. The material is either a barium/strontium sulphate ($Ba/SrSO_4$) or calcium carbonate ($CaCO_4$) precipitate. The chemical similarity of radium and barium leads to them selectively co-precipitating in the scale, which leads to a concentration of radium isotopes.

The main radiation protection problems associated with the scales are irradiation of staff in areas where scale is deposited and internal contamination by those staff removing the scale. Therefore during removal processes areas of scale are copiously wetted, and workers are equipped with a high standard of respiratory protection and other protective measures.

The activity concentration is strongly dependent on site specific parameters such as the pressure and temperature variations in the facility. The activity concentration has been reported as being less than 1 to around 1000 Bq g^{-1} of Ra-226 , with typically rather less Ra-228 (depending on the age of the scale). 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 concentration is around 1 to 10 Bq g^{-1}.

DEVELOPMENT OF METHODOLOGY

Introduction

The review of industries showed that more than one material per industry can contain radionuclides, for example the ore, by-products and products may all have different radiological characteristics. It was decided to develop one scenario or exposure situation per material. This approach avoids complications in relating radionuclide concentrations in by-products and finished products to those in feedstock.

Parameter values for the scenarios and pathways were based on known working practices and material characteristics where possible. Two different situations were considered: normal and unlikely, giving information on the range of results for different conditions.

Activity concentration ranges

The activity concentrations used in the calculations were taken from the review of industries. The range of activity concentrations for each industry is summarised in Table 1. The values for each material are given in reference [1]. In many cases the natural radionuclide decay chains were in secular equilibrium in materials. The exceptions were:

- Where volatilised Pb and/or Po have condensed on fume precipitate. This occurs during high temperature furnacing. These radionuclides may also be missing from products or by-products.
- Barium sulphate residues contain enhanced concentrations of Ra-226, Ra-228 and their short lived progeny (because of chemical similarity).
- Thoriated tungsten welding electrodes contain only isotopes of thorium and their short lived progeny.
- Phosphogypsum often contains slightly enhanced levels of radium isotopes due to processing.
- Fertilisers contain varying amounts of radionuclides and enhanced K-40, depending upon type.

Choice of exposure situations, pathways and data

Situations were identified in which a worker receives the highest exposure from each material. The following five pathways were considered.

Pathway	Most exposed situation
Inhalation of contaminated dust:	In dusty conditions with little respiratory protection
~~Ingestion of contaminated dirt/dust:~~	~~In dirty and dusty areas with little protective clothing~~
External irradiation:	Close to large amounts of material with little shielding
Skin contamination:	*as ingestion*
Inhalation of ^{222}Rn, ^{220}Rn and progeny:	Enclosed room with large amounts of material and little ventilation

The ingestion and inhalation pathways were modelled by calculating the intake and using ICRP dose coefficients [3]. The skin contamination was modelled using a similar approach to that described in reference [4]. A radon diffusion model was used to predict the radon concentration in warehouses, and ICRP dose coefficients [5] were used to estimate the dose. A method of calculating external doses was developed for the study which incorporated a wide range of exposure geometries, materials and densities. These methods are discussed in more detail in reference [1].

Table 2 summarises the exposure situations used for each material and each industry. Doses and derived levels for each material were assessed for **normal** and **unlikely** sets of parameter value assumptions.

a) *Normal assumptions:* Parameter values have been taken which are towards the conservative end of the normal range. For example a typical ventilation rate of 0.5 air changes per hour has been assumed in most factory situations, which is appropriate for a work space with no forced ventilation.

b) *Unlikely assumptions:* Parameter values that are very unlikely to occur (but are still plausible) have been assumed. For example, the maximum time a worker could spend next to a pipe containing contaminated scale, in a remote area of plant, was assumed to be several hundred hours per year (and not an entire working year).

Accidents have not been explicitly considered although the possible doses from a fire were calculated.

Generic exposure scenarios and parameter values

Exposure from materials for which there were insufficient data available was assessed using an appropriate generic exposure scenario. The three generic exposure scenarios considered are given below. The parameter values used are summarised in Table 3. Special scenarios cover the exposure to products, and also fumes from furnaces.

a) Stockpiles of material- exposure of a warehouse operative: A worker is exposed to the material whilst working in a warehouse containing a very large quantity of the material. The worker spends most of his time in the warehouse, close to the material. Dust is generated from loading or unloading the material.

b) Residues and scales- exposure of a worker removing residues: The worker is exposed when removing residues, *i.e.* 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 a few kg or a few t. A larger quantity of residues could be treated as a stockpile.

c) Process material in vessels and pipes- exposure of general worker: Workers are quite likely to be "incidentally" exposed to material 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.

Method of calculating doses and reference levels

For each material and associated scenario, doses were calculated for a range of values of activity concentrations, under normal and unlikely assumptions, with the following method. The natural decay chains were simplified into a smaller number of key radionuclides and chain segments, where chain segments are nuclides together with their short lived daughters assumed to be in secular equilibrium with them. The effective doses from a key radionuclide or chain segment were calculated separately for each of the five pathways and then summed to give the total corresponding dose. The doses from all key radionuclides and chain segments present were then summed to give the total dose. Skin equivalent doses were also calculated and summed in the same way.

Reference levels and derived levels were calculated by comparing doses with various dose criteria. This is described in reference [1], and discussed in a separate paper for this conference.

RESULTS

Doses

The range of radiation doses from the range of activity concentrations and materials in each industry are presented in Table 4. The results for each material and the most important pathways are detailed in reference [1]. It should be noted that the doses calculated represent model predictions for specific assumptions, and not values of doses actually received. However, by comparing these doses with dose criteria it is possible to comment on the likely classification of the industries.

For the normal assumptions there is a wide range of doses, between a few hundred μSv y^{-1} and a few hundred mSv y^{-1}, depending on the material and the activity concentration considered. All industries could give rise to a dose of more than 1 mSv y^{-1} (the recommended annual dose limit for members of the public) for maximum concentrations, although many materials do not. Typically the materials which give rise to the lowest doses are Pb and Po precipitates and the highest doses arise from materials with

high concentrations of Th-232 and U-238 decay series radionuclides. Finally the equivalent doses to the skin were compared with the dose criteria for skin of 50 mSv y^{-1} for members of the buble and 500 mSv y^{-1} for workers. In virtually all cases the criteria are not exceeded. In the few cases where they were exceeded the corresponding effective dose criterion has also been exceeded.

Most important exposure pathways

The sensitivity of the dose to parameter values was also investigated, with particular attention to external doses and doses from radon inhalation due to the more complicated models used. In general the most important exposure pathway is that of radon and thoron inhalation from storage in a warehouse. This is because materials are often in form which allows the radon to escape easily, and stored in poorly ventilated spaces that allow radon concentrations to build up. However, the radon concentration may vary substantially as it depends strongly on the ventilation rate, diffusion coefficient and emanating fraction. Nevertheless, even when this is taken into account the total predicted dose is likely to change by less than an order of magnitude. The inhalation of dust pathway is also a major contributor to the total dose where dusty residues are being removed, or dry, fine particles being processed. The external irradiation pathway is important if there are large amounts of material or if the material contains radionuclides which have high yield high energy gamma emissions (eg. Ra-226 in radium scales).

SUMMARY AND CONCLUSIONS

A methodology for assessing the doses to workers in non-nuclear industries has been developed. This has been used to assess the doses in industry and develop reference levels for regulatory control. Results predict that a number of industries could give doses greater than 1 mSv y^{-1} and therefore require some degree of regulation. The corresponding reference levels, described in another paper, will enable regulators to adopt an appropriate level of regulation.

REFERENCES

[1] EC. Establishment of reference levels for regulatory control of workplaces where minerals are processed which contain enhanced levels of natural radionuclides. Report by NRPB and CEPN under contract no 95-ET-009. *To be published*

[2] ICRP. 1990 recommendations of the International Commission on Radiation Protection. ICRP 60. *Ann ICRP*, **21** Nos 1-3 (1991)

[3] ICRP. Dose coefficients for intakes of radionuclides by workers. ICRP 68. *Ann. ICRP* **24** No 4 (1994)

[4] EC. Principles and methods for establishing concentrations and quantities (exemption values) below which reporting is not required under the European directive. Radiation Protection 65. Doc XI-028/93 (1993)

[5] ICRP. Protection against Radon-222 at home and at work. ICRP 65. *Ann. ICRP* **23** No 2 (1993)

Table 1: Ranges of activity concentration used in calculating doses[A]

Industry	Activity concentration, in Bq g^{-1}									
	Th-232		U-238		Ra-226		Pb-210		K-40	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Phosphate industry	$1\ 10^{-2}$	2	$6\ 10^{-3}$	5	$2\ 10^{-2}$	5	$6\ 10^{-3}$	500	1	1
Ferro-niobium	7	80	6	10	6	10	6	500	-	-
Tin smelting	$9\ 10^{-2}$	15	$2\ 10^{-1}$	5.4	$2\ 10^{-1}$	5.4	$2\ 10^{-1}$	5.4[B]	-	-
Zircon & refractory products	$2\ 10^{-1}$	40	$2\ 10^{-1}$	74	$2\ 10^{-1}$	74	$2\ 10^{-1}$	400	-	-
Rare earth extraction	$4\ 10^{-3}$	3000	$4\ 10^{-2}$	500	$4\ 10^{-2}$	500	$4\ 10^{-2}$	500	-	-
Thorium products	27	3600	-	-	$3\ 10^{-2}$	1.5	-	$1.5\ 10^{-1}$	-	-
TiO_2 pigments	$3\ 10^{-2}$	9	$3\ 10^{-2}$	9	$3\ 10^{-2}$	400	$3\ 10^{-2}$	9	-	-
Oil and gas extraction	-	-	-	-	$7\ 10^{-3}$	1100	-	-	-	-
Fertilisers	$8\ 10^{-3}$	$6\ 10^{-2}$	$3\ 10^{-2}$	2.6	$3\ 10^{-3}$	$7.9\ 10^{-1}$	$2\ 10^{-2}$	$9.1\ 10^{-1}$	$4\ 10^{-2}$	9.6

NOTES

A The activity concentrations presented for each radionuclide are the maximum from all materials in each industry

B Po-210 is enhanced to around 200 Bq g^{-1} due to volatilisation, but Pb-210 is unaffected

Table 2: Materials considered and exposure scenarios used

Industry	Materials assessed by each scenario			
	Stockpile in warehouse	Removal of residues	Exposure from pipes and vats	Special scenario
Phosphate industry	Ore, phosphogypsum, $CaSiO_2$, fertilisers	Phosphogypsum filters, Pb/Po precipitate	Vats of material	Pb/Po fumes
Ferro-niobium	Pyrochlore, slag	Pb/Po precipitate	Vats of material	Pb/Po fumes
Tin smelting	Slag	Po precipitate	-	Po fumes
Zircon & refractory products	Zircon sands	Pb/Po precipitate	-	Refractory products, Pb/Po fumes
Rare earth extraction	Monazite/bastnaesite sand	Radium bearing residues	-	Cerium concentrate for glass
Thorium products	-	-	-	Welding electrodes (store, use), gas mantles, Th glass
TiO_2 pigments	Ilmenite ore	Radium bearing residues	Vats of material	-
Oil and gas extraction	-	Radium bearing residues (sludge and scale)	Radium bearing residues	-
Fertilisers	Fertilisers (K, P, NP, PK, NPK, triple super P)	-	-	-
General metal smelting	-	Pb/Po precipitate	-	Pb/Po fumes

Table 3: Parameter values for generic exposure scenarios

Parameter	Stockpile in warehouse		Removal of scales and residues		Exposure from vessels & pipes	
	Normal	Unlikely	Normal	Unlikely	Normal	Unlikely
Inhalation of dust:						
Time of exposure, h y^{-1}	2000	2000	100	400		
Dust concentration, mg m^{-3}	1	5	10	10	-	-
Protection factor	None	None	0.5	None		
Ingestion of dirt and dust:						
Time of exposure, h y^{-1}	2000	2000	100	400		
Ingestion rate, mg h^{-1}	1.25	3.75	5	5	-	-
Protection factor	None	None	0.5	None		
External exposure:						
Time of exposure, h y^{-1}	400	2000	100	400	400	2000
Distance to source, m	1	1	1	1	1	1
Shielding, mm steel	None	None	None	None	5	5
Radon & Thoron inhalation:						
Time of exposure, h y^{-1}	2000	2000	100	400		
Ventilation rate, h^{-1}	0.5	0.25	0.5	0.25	-	-
Diffusion coefficient, m^2 s^{-1}	$2\ 10^{-6}$	$2\ 10^{-6}$	$2\ 10^{-6}$	$2\ 10^{-6}$		
Emanating fraction	0.2	0.2	0.2	0.2		
Skin contamination:						
Time of exposure, h y^{-1}	2000	2000	100	400		
Depth of contam. on skin, mm	0.1	0.2	0.1	0.2	-	-
Protection factor	None	None	0.5	None		

NOTE

A For radon and thoron calculations the material was assumed to either be in a hemispherical mound or distributed on surfaces. The volume of the room was taken as 4 times the volume of material, with the proviso that the minimum room volume was 100 m^3.

Table 4: Calculated individual doses for various industries

Industry	Effective dose, in mSv y^{-1}			
	Normal assumptions		Unlikely assumptions	
	Minimum activity concentration[A]	Maximum activity concentration[A]	Minimum activity concentration[A]	Maximum activity concentration[A]
Phosphate industry	$1.4\ 10^{-3}$	31	$1.0\ 10^{-2}$	69
Ferro-niobium	$4.7\ 10^{-2}$	$3.2\ 10^{2}$	$1.9\ 10^{-1}$	$6.4\ 10^{2}$
Tin smelting	$7.1\ 10^{-2}$	12	$2.8\ 10^{-1}$	47
Zircon & Refractory products	$1.0\ 10^{-2}$	$2.7\ 10^{2}$	$7.5\ 10^{-2}$	$5.8\ 10^{2}$
Rare earth extraction	$2.3\ 10^{-3}$	$3.5\ 10^{3}$	$1.1\ 10^{-2}$	$9.8\ 10^{3}$
Thorium products	$9.4\ 10^{-2}$	14	1.2	28
TiO_2 pigments	$9.2\ 10^{-3}$	51	$4.6\ 10^{-2}$	$1.2\ 10^{2}$
Oil and gas extraction	$2.4\ 10^{-4}$	29	$1.2\ 10^{-3}$	$2.4\ 10^{2}$
Fertilisers	$1.0\ 10^{-1}$	2.0	$4.8\ 10^{-1}$	5.7

NOTE

A From a range of materials and a range of activity concentrations in the materials