

EnviroRad Services Pty. Ltd.

Naturally Occurring Radioactive Materials (NORM) in Australian Industries - Review of Current Inventories and Future Generation

Malcolm B. Cooper

A Report prepared for the Radiation Health and Safety Advisory Council

ERS-006

December 2003

Table of Contents

1	Introduction and Scope.....	1
2	Approach	2
3	Mining and Mineral Processing Industries.....	3
	3.1 Mineral Sand Production.....	3
	3.2 Downstream Processing of Mineral Sands.....	6
	3.2.1 Titanium Pigment Production.....	6
	3.2.2 Zircon Refining.....	7
	3.3 Aluminium Production	8
	3.4 Copper Production.....	10
	3.5 Tin/Tantalum Production.....	11
	3.6 Iron and Steel Production	12
4	Industrial Minerals and Uses.....	14
	4.1 Phosphate Fertilizer Production	14
	4.2 Ceramics and Building Materials	17
	4.3 Sandblasting	19
5	Fuel Production and Use	20
	5.1 Oil and Gas Production	20
	5.2 Coal and Coal Combustion.....	22
6	Other Potential Sources.....	25
	6.1 Drinking Water Purification.....	25
7	Summary and Conclusions.....	27
8	References	34

1 Introduction and Scope

Enhanced levels of naturally-occurring radionuclides may be associated with certain natural materials, minerals and other resources. Exploitation of these resources and production of consumer items may lead to further enhancement of the radioactivity in the products, by-products, residues or waste arising from the industrial process. A potential outcome is an increase in occupational and public exposures to radiation.

This area is of particular importance in Australia because of the major mining and mineral processing activities, and the large-scale production and use of fossil fuels in this country.

The scope of this report is limited to the quantification of naturally-occurring radioactive materials (NORM) in various industries in Australia. The report encompasses a range of industries and materials in which enhanced levels of NORM may be present in the raw materials for the process, in products, by-products or waste streams.

The following areas are covered by this report:

- Mining and mineral processing, including the mineral sand industry, alumina production, tantalum mining, tin smelting, copper production.
- Down stream processing of heavy minerals, including titanium pigment production, and zirconium products
- Fossil fuels use, including oil and gas production, coal-fired power stations.
- Metal smelting industries, including tin smelting, pig iron production.
- Ceramics and building materials.
- Water treatment and purification.

For each of the industries examined, the report provides a brief description of the industry itself and the processes involved, types of waste materials generated, and an overview of the origin and nature of the radioactivity associated with the raw materials, products and the waste. Using available sources of information and data, the quantities of waste, and the radionuclide content typical of each case are presented in order to gain an appreciation of the extent of NORM occurrence in Australian industries.

Where information or data was not readily available from local sources, published information is drawn from overseas experience where relevant to the Australian situation. The report also highlights those areas of importance where the overall information is deficient.

2 Approach

The approach taken in compiling the report has been to draw upon information and publications provided by the following organisations and individuals:

- Minerals Council of Australia
- Australasian Institute of Mining and Metallurgy
- Western Australia Chamber of Mines
- Western Australia Department of Health
- Western Australia Department of Industry and Resources
- Queensland Department of Health
- Individual companies involved in the various industries
- Private consultants involved in the various areas of interest
- CSIRO Division of Minerals
- Australian Nuclear Science and Technology Organisation
- Water Services Association of Australia

The information provided in the report relies heavily on documents published in the public domain or from available reports on relevant internet web sites. Specific references used are listed in Section 6. Generally, it was found that there is a paucity of publications of Australian studies of NORM in the open literature, and therefore, overseas publications and compilations of data were the main available source of information for certain aspects.

The detail that could be included in the report is further limited in a number of key areas. Critical Australian data on radionuclide concentrations and waste quantities could not be provided by some individuals approached because it comprised part of a confidential contract with a specific company, or included in confidential reports to regulatory authorities. Individual companies have not been identified by agreement.

3 Mining and Mineral Processing Industries

3.1 Mineral Sand Production

Background

Mineral sands constitute ores with heavy minerals having densities in excess of 3. The heavy minerals of major commercial importance are the titanium bearing minerals, namely ilmenite, leucoxene and rutile, zirconium bearing – zircon, and rare earth bearing – monazite and xenotime.

Australia is a major producer of heavy minerals, supplying more than 50% of the global demand for rutile and synthetic rutile and more than 60% of the demand for zircon. In 2000-01 the production of ilmenite and rutile concentrate was approximately 2 million tonnes and 390 thousand tonnes of zircon were produced [1]. Mineral sand deposits are mined on the east and west coasts of Australia. Major new deposits are being developed in the Murray-Darling basin.

The heavy minerals extracted from mineral sands have many applications. Ilmenite and rutile are used to produce titanium dioxide pigments for the paint, paper and plastics industry, and for the production of titanium metal. The major uses of zircon, and zirconia and zirconium products are in the ceramics industry, as a refractory material in the steel industry, in the foundry industry and for abrasive materials.

Rare earths extracted from monazite are used for phosphors in the electronics industry, production of magnets, as catalysts, and in metallurgical applications.

Processes

Mining of mineral sand ores uses either a dry operation or dredging of the slurried ore. Extraction of the various heavy minerals takes place in two main stages. The primary step is the production of a heavy mineral concentrate using a wet gravity separation. The concentrate constitutes between 5 and 10% of the original ore. Individual minerals are then separated in a dry process that utilizes a sequence of electrostatic and magnetic steps to produce the various mineral products.

Ilmenite, which comprises the main mineral constituent, may also be upgraded to synthetic rutile as part of the production. This operation involves chemical treatment of ilmenite to remove iron oxides and produce a high percentage titanium oxide feed material for subsequent production of titanium pigment.

Waste Production

Apart from the mining overburden, primary processing of the ore at the mine site produces waste materials in the form of oversize material, sand tailings and clay fines. These materials are returned to the mined out pit for disposal, after drying if necessary. Where dredging is used for mining, waste slurries are discharged into the dredging pond for disposal.

Waste material from the mineral sand processing plant arises from the secondary separation of the heavy minerals from the concentrate produced during the primary separation of the ore and from the plant in which synthetic rutile is produced. The secondary separation waste consists of oversize solids, tailings, clay fines, dust and other particulates collected from stack discharges.

Because of the current market conditions, monazite concentrate is not usually marketed but returned to the mine site for blending with mine sand tailings and disposed of into the mine pit. The synthetic rutile plant produces either solid or slurried waste in various forms:

- Inert solids, iron oxides;
- Slurries and oversize solids from the product drying kilns;
- Neutralised acid effluent solids; and
- Non-magnetic fines.

This waste material is collected from the processing either as dry solids, or slurries that have to be dried prior to disposal. The waste is disposed of in dedicated landfill sites. Some material may be recycled or used as road base, as is the case of the kiln discharge oversize, and, in the case of the neutralised acid effluent solids, as fertiliser in the agriculture industry.

Radioactivity

Typical activity concentrations for uranium and thorium in products and waste arising from mineral sand mining and processing are given in Table 1. Apart from those heavy minerals that contain uranium and/or thorium within the mineral structure, the radioactivity levels in waste material depends mainly on the monazite content of the original ore, which can vary considerably depending on the location of the ore body. Monazite is phosphate mineral consisting of rare earth elements and thorium (about 6%) and uranium (< 1%).

Table 1. Typical Quantities and Activity Concentrations in Products and Waste from Mineral Sand Mining and Processing [2,3]

Stage of Operation	Material	Typical quantity ^a (kt.y ⁻¹)	Thorium ^b (Bq.kg ⁻¹)	Uranium ^b (Bq.kg ⁻¹)
Mining and Primary Separation	Ore	-	20 – 280	30 - 120
	Heavy mineral concentrate	500	300 – 3000	<100 - 800
	Sand tailings	6,000	< 200	<100
	Oversize	700	< 200	<100
Processing plant - secondary separation	Ilmenite	300	200 – 2000	<100 - 400
	Leucoxene	10	300 – 3000	200 - 600
	Rutile	30	<200 – 1400	<100 - 300
	Zircon	60	600 – 1200	1000 - 4000
	Monazite concentrate	10	40000 – 250000	6000 -30000
	Oversize	6	300 – 8000	600 -2000
	Tailings	70	800 – 24000	100 - 12000
	Clay slimes	1	~ 2400	~ 400
	Mill dust and stack particulates	2	1000 –20000	100 - 6000
	Processing plant - synthetic rutile	Synthetic rutile	210	<200 – 1500
Iron oxide and other inert solids		120	< 400	< 300
Neutralised and non magnetic solids		95	200 – 7000	100 - 1200
Kiln solids		40	100 – 1200	<100 - 600

Note: a. Quantities relate to a typical mine or processing plant
b. Radioactive equilibrium of the respective U and Th series is likely to be maintained throughout processing

3.2 Downstream Processing of Mineral Sands

3.2.1 Titanium Pigment Production

Background

Processing of rutile and synthetic rutile from ilmenite is used to produce titanium dioxide pigments for use in the manufacture of paint, plastics, paper, ink, ceramics and many other products. Pigment production currently takes place at two locations in Western Australia. Australia's annual production of titanium pigment was approximately 185 kilotonnes in 2001-02 [1].

Processes

Titanium oxide is extracted from rutile and synthetic rutile using either a chloride process or by sulphuric acid extraction [4]. The chloride process has become the preferred technology because of the lesser environmental consequences arising from the disposal of waste effluents. In this process, the rutile is reacted at high temperatures with chlorine gas, leading to the formation of titanium tetrachloride as a gas. The tetrachloride is condensed, purified and converted to titanium oxide. The raw titanium pigment is purified and finished by surface coating with other oxides to form the various products.

Waste Production

Waste solid slurries, including waste ore, arise from the chlorination and condensation stages of the process. These solids are neutralised, washed and separated from the liquids. The solid waste is slurried for transport and dried in ponds before final disposal of as landfill. Liquid effluent is treated and discharged to the ocean. Solids from the effluent treatment are also disposed of in a landfill. Typical quantities of waste from a pigment plant are given in Table 2.

Radioactivity

Traces of uranium and thorium and radioactive progeny are present in the original rutile and synthetic rutile minerals. The radionuclides will follow the solid waste stream in the process. Titanium oxide pigments do not have detectable levels of radioactivity. Typical radionuclide concentrations in the solid waste are given in Table 2.

Table 2. Typical Quantities and Radionuclide Concentrations in Titanium Dioxide Pigment Production [2]

Material	Typical quantity^a (kt.y⁻¹)	Thorium-232^b (Bq.kg⁻¹)	Uranium-232^b (Bq.kg⁻¹)
Titanium dioxide pigment	95	Not detectable	Not detectable
Neutralised residue slurry	100	1200 (wet)	350 (wet)
Solid waste from liquid effluent treatment	100	800 - 1400 (dry)	300 - 500 (dry)

Note: a. Quantities relate to typical processing plant
 b. Based on mass concentrations of U and Th, however, radioactive equilibrium of the respective U and Th series may not be maintained throughout processing

3.2.2 Zircon Refining

Background

Zirconium is an abundant element present in zircon mineral as the silicate and as the oxide in baddleyite ore. Zircon is the raw material in the manufacture of steel refractory materials, in glazes, glasses and ceramics, and in the manufacturing of dielectric materials and in special alloys. Zircon is milled to produce zircon flour or powdered zircon, and also refined to produce zirconia, which is the oxide form. Fused zirconia is used in the ceramics and glazes. Zirconia and zircon are also the raw materials for zirconium metal manufacture. This is not carried out at Australia plants.

Processes

Zirconium oxide (zirconia) is produced by high temperature fusion of zircon to separate the silica. Zirconium metal manufacture involves a chlorination process to convert the oxide to zirconium chloride, which is then reduced to the metal.

Refractory bricks for steel and glass furnaces are made by fusing zircon sand with alumina and sodium carbonate.

Waste Production

Dry milling or fusion of zircon produces dusts that are collected by filters in the plant. Accumulation of residues can also occur in off-gas systems and pipework. Relatively small quantities of waste, of the order of several hundred tonnes, are produced annually in a typical zircon processing plant.

Disposal of used refractory bricks made from zircon may also be a waste issue.

Radioactivity

The zircon mineral contains trace amounts of uranium and thorium within the mineral structure. Typical activities of uranium and thorium in Australian zircons are in the ranges 1000 - 4000 Bq/kg and 200 - 1000 Bq/g, respectively [2]. Radioactive equilibrium will exist between the radionuclides within their respective decay series. Because zircon is used directly in the manufacture of refractory materials and glazes, the products will contain similar amounts of radioactivity [6]. Higher concentrations may be found in zirconia.

In the fusion of zircon, the more volatile radionuclides, for example ^{210}Pb and ^{210}Po , may accumulate in dust and fumes within the plant. The main radiological issue is occupational exposure to these radionuclides in airborne dusts in the processing plant.

3.3 Aluminium Production

Background

The main mineral source of aluminium is bauxite, which contains 30 to 50% hydrated aluminium oxide. Bauxite is mined on a large scale in Australia, which is the world's largest producer of bauxite (~40%) with a current annual production of about 55 million tonnes [1]. The main deposits of bauxite in Australia are in the north-western region of Western Australia.

Bauxite is refined to produce alumina (anhydrous aluminium oxide) at refineries in Western Australia and Queensland. The current annual production of alumina in Australia is approximately 16 million tonnes with most of the production (~80%) being exported [1]. The remainder of the alumina is smelted at plants in several Australian states to produce aluminium ingots for fabrication into a range of industrial and domestic products. Approximately 1.8 million tonnes of ingots are produced locally [1].

Processes

The process to refine bauxite and produce alumina is termed the Bayer process [4]. There are five basic steps, namely:

- i. Bauxite washing and grinding
- ii. Bauxite digestion in caustic soda at high temperature and pressure.
- iii. Separation and washing of solid residues
- iv. Crystallisation of hydrated alumina
- v. Calcining at about 1000°C to remove water and produce anhydrous alumina.

The main raw materials for this process, apart from bauxite, are caustic soda and lime.

The production of aluminium metal involves electrolysis of the alumina in a mixture of fluoride salts, contained in carbon cells. The electrolysis takes place at around 970°C and the aluminium is removed from the production cells as the molten metal, allowed to solidify and cast as ingots. Other aluminium products for special applications, such as powders and pastes, are produced from the molten metal.

Waste Production

The main solid residues from the alumina production are the undissolved bauxite residues containing iron, silica and titanium removed from the digestion step of the process. These residues, termed "red mud", are produced in large quantities with between 1 and 6 tonnes of red mud produced per tonne of alumina depending on the grade of bauxite [4]. Based on this ratio, it is estimated that there is an annual generation in excess of 20 million tonnes of red mud and other solid waste from alumina production in Australia.

The main liquid residues arise from the washing of solid waste and from the settling ponds are recycled as process water.

Disposal of red mud and other solid residues commonly takes place by spreading in layers over a large area to allow the material to dry, followed by rehabilitation of the land, which involves the waste with sand and re-vegetating the surface. Leachates from the disposal areas are collected and returned to production and as process water.

Alumina smelting does not produce substantial quantities of solid waste. The main residues are the fluoride-containing gases that are removed from the vapour discharges by scrubbing in an extraction system to remove in excess of 99% of the fluoride.

Radioactivity

The original bauxite ores can contain significant levels of natural radioactivity due to both uranium (^{238}U) and thorium (^{232}Th) and respective decay products. Some of the radioactivity may be associated with trace quantities of other minerals, such as ilmenite or monazite. Levels of ^{238}U and ^{232}Th can range from 10-9000 Bq.kg⁻¹ and 35-1400 Bq.kg⁻¹ [5], respectively, depending on the source of the bauxite ore. Virtually the entire amount of radioactivity is transferred to the solid waste, and little, if none, of the uranium or thorium is present in the alumina. Moreover, there is a threefold increase in the radionuclide content of red mud compared to the original bauxite mineral. Reported concentrations for natural radionuclides in red mud from Western Australian sources are given in Table 3.

Table 3. Natural Radioactivity in Bauxite and Solid Residues from Alumina Production in Australia [7]

Radionuclide	Typical Concentration (Bq.kg ⁻¹)	
	Bauxite	Red Mud
Uranium-238 series ^a	120 (10 - 9000)	350 (100 - 3000)
Thorium-232 series ^a	500 (35 - 1400)	1300 (100 - 3000)
Potassium-40 ^a	740 (10 - 600)	150 (10 - 100)

Note: a. Other reported concentration ranges of radioactivity in parentheses (taken from reference 5)

3.4 Copper Production

Background

Copper is a metal of major importance with a range of uses, with the main application being for electrical installations and the electronics industry.

Australia is a major producer of copper with a current annual production of around 870,000 tonnes of primary copper products and 520,000 tonnes of refined copper metal [1]. Australia's largest operations for copper production are at Olympic Dam in South Australia and Mount Isa in Queensland.

Other valuable elements, namely silver, gold and uranium, are often associated with copper mineralisation because of their similar geochemistry.

Processes

After milling the ore, copper is separated by flotation to produce a concentrate with a copper content of about 30%. The concentrates are smelted to remove volatile or less dense impurities. Further purification of the copper melt from the smelter produces a primary form of the metal, known as blister copper. Electro-refining produces higher purity copper.

Other associated gold or uranium minerals are removed at the flotation stage along with the tailings and are subject to additional processing.

Waste Production

The main waste materials arising from the copper separation and refining are the tailings from the flotation stage and the furnace slags from the smelting stage. For example, the operations in 2001 at Mount Isa produced approximately 5 million tonnes of tailings and 200,000 of copper slag from the processing of 9 million tonnes of copper ore and concentrate [8].

Where commercial quantities of uranium are present with other minerals and the copper tailings separated at the flotation stage, additional treatment and processing takes place to isolate the valuable elements. The copper waste streams then will be combined with the other tails arising in the whole operation, as is the case at Olympic Dam.

Radioactivity

Uranium and thorium may be present in significant quantities in the copper mineralisation, especially the former element.

Partitioning of ^{210}Pb and ^{210}Po from uranium occurs into the copper concentrate during the flotation stage. These radionuclides will be vapourised at the smelting stage and may accumulate in dusts collected from off gases. Unless uranium is present in commercial quantities and separated during processing, the uranium will remain in the tailings from the flotation stage or will be present in the copper concentrate and partition to the slag from the copper smelter.

3.5 Tin/Tantalum Production

Background

In some situations tantalum mineralisation is associated with tin-bearing minerals. The main application of tantalum is in the electronics industry as a major constituent of capacitors. Although the worldwide demand for tantalum is relatively small, and linked closely with the fortunes of the high technology sector, Australia supplies in excess of 30% of the world market. Australian production of tantalum comes from mines at two locations, Pilbara and Greenbushes, in Western Australia. Processing of the minerals takes place at plants at the respective mine sites. Typical annual production figures (2002/3) are approximately 2.5 Mt of tantalum ore was processed with an output of 2,500 t of tantalum products [1].

Tantalum is present in pegmatite ore as in several possible mineral forms, as complexes with iron, manganese, calcium or antimony. The average grade of tantalum varies with the location of the ore body but ranges from 0.04 to 0.1%. The tantalum ore bodies also contain low grade (< 0.1%) tin mineralisation, either complexed with the tantalum mineral, or separately as the tin-bearing mineral, cassiterite. Other major constituents of the ore include sulphide minerals and traces of ilmenite and zircon may also be present.

Processing

Tantalum is normally supplied as high grade concentrates or glass. After crushing and grinding the primary ore, processing involves a series of dry and wet gravity, dry screening and magnetic stages to produce high-grade tin and tantalum concentrates. Flotation and leaching may be necessary to remove sulphides and trace quantities of uranium and thorium impurities in the concentrates. In the case of the Greenbushes mine, smelting of the concentrates is carried out to produce tin metal and tantalum glass.

Waste Production

The dry and wet separation stages produce a tailings slurry that is further treated and disposed of in a tailings dam close to the mine sites. Sulphide flotation and acid leaching of concentrates produces further solid and liquid effluents that are also disposed of as tails after treatment.

Radioactivity

The primary tantalum/tin ore contains trace quantities of uranium and thorium associated with the minerals. Activities of uranium and thorium in the ore are less than 60 Bq/kg and less than 5 Bq/kg, respectively. After the initial dry and wet separation some uranium and thorium may remain with the concentrates and are removed by acid leaching. Neutralisation of the leach solutions produces a solid tails containing uranium and thorium. The levels of uranium and thorium in the tantalum products range from 7.5 kBq/kg to 75 kBq/kg.

3.6 Iron and Steel Production

Background

Iron ore consists primarily of iron oxides and is the main source of pig iron for the iron and steel industry. Iron blast furnaces use iron ore to produce molten iron that can be cast into pig iron products to be used as feedstock for steel production.

Processes

The raw materials for steel production are iron ore, coal and limestone. The first stage of the process is sintering in which iron ore, coal or coke, and limestone are prepared into an iron rich porous clinker, called sinter, which is suitable for smelting to iron in the blast furnace. In the second stage, the sinter, is added to the blast furnace with additional iron ore and coke. The iron ore and sinter are reduced and molten iron forms in the bottom of the furnace. The limestone combines with the silica and alumina impurities to form a liquid slag, which is separated from the molten iron. The molten iron is added to the basic oxygen furnace where it is converted into steel, in the third stage of the process.

Waste Production

The main waste materials in the sinter plant in the first stage is dust in the off-gases. The dust is removed from the gas stream by dry electrostatic precipitators. In an Australian sinter plant, a typical production of dust is approximately 1 tonne/hour from a throughput of 1000 tonne of raw materials. Of the dust produced in the off gases, about 10-12 % is released to the atmosphere [9]. In the iron production in the blast furnace the main waste is the blast furnace slags and the dusts and fumes collected from the off gas cleaning in the blast furnace operation. Iron slag is disposed either as landfill or used as road base, or in cement or concrete applications. Dust is normally disposed of as landfill. In a typical steel making plant in the UK, the total mass of slag was approximately 1.6 million tonnes with a total of 60,000 tonnes of dust collected for disposal [10].

Radioactivity

Owing to their geochemical properties, iron ores scavenge radionuclides and heavy metals. There are trace levels of uranium in the main raw materials for iron-making, namely iron ore, coke, and limestone. These are generally very low, of the order of 20 – 30 Bq/kg for iron ore and coke, and 5 Bq/kg for limestone [9].

The main accumulation of radioactivity in the sinter plant is due to ^{210}Pb and ^{210}Po in the dust collected from the gas cleaning systems. Because of the recycling of the waste gases through the sinter plant in order to reduce dust emissions, the concentrations of ^{210}Pb and ^{210}Po become enhanced further. A study of radioactivity in the sinter plant at Port Kembla, NSW, has recently been carried out as part of a broader investigation of natural radioactivity from industrial activities in that region. The results for sinter plant materials are summarized in Table 4.

Table 4. Natural Radionuclides in Sinter Plant Samples from Iron and Steel Production [Reference 9]

Material	Radionuclide concentration (Bq/kg)			
	^{238}U	^{226}Ra	^{210}Pb	^{210}Po
Iron ore	31	42	16	39
Limestone	< 20	14	7	92
Coke	26	26	26	61
Sinter	57	6	5	19
Fugitive dust	30		100	1670
Ductwork dust	< 30	24	18900	15600

The slag from the blast furnace will contain low levels of long-lived radionuclides from the uranium and thorium series but there will only be an enhancement in radioactivity levels above those of the raw materials of the order of a factor of 2-3 [10]. The ^{210}Pb and ^{210}Po levels in dust collected from the off gasses in the blast furnace will generally be lower than those of the sinter plant [10].

4 Industrial Minerals and Uses

4.1 Phosphate Fertilizer Production

Background

Phosphate fertilisers for agricultural use are derived from phosphate rock and are produced in several forms, characterised by the phosphorous content of the fertiliser. Normal superphosphate contains approximately 20% available phosphorous. Higher analysis phosphate fertilisers are triple superphosphate, mono/di-ammonium phosphate, and di-calcium phosphate and generally increasing in use. The production of various forms of phosphate fertilisers requires the acidulation of the phosphate ore with either sulphuric or phosphoric acid.

The Australian market for phosphate fertiliser is about 4 million tonnes of superphosphate [11]. Some 75 per cent of the Australian market for phosphates is supplied by locally manufactured superphosphate with the balance by imports of ammonium phosphates, currently around 1 million tonnes [11]. Local production of superphosphate uses imported ore, mainly from Christmas Island, Jordan, North Africa, and Florida.

The major deposit of phosphate rock in Australia is the Duchess ore body in Queensland. Australia's annual production of phosphate rock was reported to be approximately 2 million tones [11]. Phosphate rock from this mine site is used in an integrated fertiliser plant for the production of ammonium phosphate products, partly to supply the local and export markets.

Another product derived from phosphate rock is phosphoric acid which is an important industrial chemical, not only for fertiliser production, but as a raw material for phosphate chemicals used extensively in detergents, deflocculants, animal feeds and for corrosion treatment of metal. Phosphoric acid used industrially in Australia is now derived from imported material. For economic reasons, local production of phosphoric acid ceased in the early 1990's [4].

Processes

Normal superphosphate is produced by adding sulphuric acid to phosphate rock to form soluble monocalcium phosphate. Phosphoric acid is used as the acidulating agent for higher grades of superphosphate and for ammonium phosphates. Phosphoric acid itself is produced by treating rock phosphate with excess sulphuric acid. Unless the acid is to be used for fertiliser production, purification of the phosphoric acid is carried out by solvent extraction.

Waste Production

Beneficiation of phosphate ore prior to use for fertiliser production can produce clay and sand tailings that would normally be used as backfill material at the mine site.

The major solid waste product from the phosphate industry is the large quantities of calcium sulphate (phosphogypsum) arising in phosphoric acid production. Additional waste arises from small quantities of scales deposited in process pipes and filtration tanks and filter parts. The bulk of phosphogypsum was stockpiled on site or disposed of as landfill along with the scale and filter materials. Other uses of phosphogypsum waste include fertiliser and soil conditioner, building materials, e.g. plasterboard, cement aggregate, and in road construction. Based on data from USA production of phosphoric acid, approximately 4 - 5 tonnes of phosphogypsum are produced per tonne of acid [12]. A typical Australian phosphoric acid plant produced approximately 40,000 tonnes of phosphoric acid annually during the period 1986-90, resulting in an estimated 160 - 200,000 tonnes of phosphogypsum [4]. Overall the annual Australian phosphoric acid production during this period was approximately 100,000 tonnes [4].

Radioactivity

Natural phosphate rock contains traces quantities of uranium and thorium incorporated into the structure of the phosphate-bearing mineral. The uranium content is closely related to the phosphorous content. The typical range of radionuclide concentrations in various sources of phosphate rock in the Australian phosphate industry is given in Table 5. Radioactive equilibrium will exist between uranium and thorium and their respective radioactive progeny in the natural rock.

Table 5. Typical Radionuclide Concentrations in Phosphate Rock Used in the Phosphate Industry in Australia [5]

Source of Phosphate Rock	Uranium concentration (Bq.kg⁻¹)	Thorium concentration (Bq.kg⁻¹)
Australia	15 – 900	5 – 47
Florida	1500 – 1900	16 – 59
Morocco	1500 – 1700	10 – 200
Jordan	1300 – 1850	

During the treatment of phosphate rock with sulphuric acid to form phosphoric acid, radionuclides of the uranium or thorium series become partitioned in the product or waste streams depending on the relative solubilities under acid conditions. In general, about 80% of the ²²⁶Ra, 30% of the ²³²Th, and 14% of the ²³⁸U is left in the phosphogypsum [13]. Uranium and thorium become enriched in the fertiliser to about 150% of their original concentration. Australian data for radionuclide concentrations in phosphogypsum and scale in plant equipment is given in Table 6.

Table 6. Typical radionuclide concentrations for phosphate waste products in Australia [5]

Radionuclide	Concentration (Bq.kg ⁻¹)	
	Phosphogypsum	Scale
Radium-226	280 – 350	3 – 3900
Uranium-238	10 – 24	NA
Lead-210	320 – 440	30 – 1300
Polonium-210	150 – 360	5 – 112
Thorium-232	4 - 7	24 – 189

Radionuclide concentrations in fertiliser products are highly variable, and depend on the radionuclide content of the original ore and the method of production. Table 7 indicates the range of radioactivity levels in various fertiliser products. Fertilisers are generally deficient in ²²⁶Ra relative to ²³⁸U. At normal rates of application of fertiliser products in the agricultural industry there is not a significant increase in the overall uranium and thorium levels in soil and consequently individual doses from their use are not enhanced above normal background.

Table 7. Reported Radionuclide Concentrations in Phosphate Products [5,13-15]

Product	Radionuclide Concentration (Bq.kg ⁻¹)		
	Uranium-238	Radium-226	Thorium-232
Phosphoric acid	1200 - 1500	300	
Normal superphosphate	520 - 1100	110 - 960	15 – 44
Triple superphosphate	800 - 2160	230 - 800	44 – 48
Mono ammonium phosphate	2000	20	63
Di-ammonium phosphate	2300	210	< 15
Di-calcium phosphate		740	< 37
NPK (nitrogen/phosphate/potassium)	440 - 470	210 - 270	< 15
PK (phosphate/potassium)	410	370	< 15

4.2 Ceramics and Building Materials

Background

It is a common practice to use industrial by-products and recycle certain industrial residues and waste as raw materials for the building industry. Concern for potential risks arises where the residues used as raw materials for building products are derived from NORM contaminated waste materials.

The main waste types used in production of building materials are:

- Fly ash from coal burning used in concrete production and brick making - approximately 10% of ash generated in Australia.
- Phosphogypsum from the phosphate industry used as a substitute for natural gypsum in the manufacture of plasterboard.
- Bottom ash from coal burning and furnace slag from metal smelters is used for road construction.

Radioactivity

Building materials can contain uranium and thorium and their radioactive progeny due to their natural occurrence in the raw materials, or if a recycled industrial product, for example zircon in ceramics, or the industrial by-product, such as fly ash and phosphogypsum, has elevated levels of NORM. Generally, the radionuclide concentration in the final material will be lower than that of the original by-product because of the presence of other inert material in the particular building material. Potassium-40 will also be present in some materials because of the stable potassium content of the raw materials used.

There has been a number of investigations of the radionuclide content in Australian building materials [16-20], and levels generally fall in the published ranges for various materials as shown in Table 8.

Table 8. Activity concentrations for natural radionuclides in building materials [5]

Material	Radionuclide Concentration (Bq.kg ⁻¹)		
	Radium-226	Thorium-232	Potassium-40
Concrete	1 - 250	1 – 190	5 – 1570
Clay (red) bricks	9 - 2200	< 1 – 220	180 – 1600
Sand-lime bricks/limestone	6 - 50	1 – 30	5 – 700
Natural building stones	1 - 500	1 – 310	1 – 4000
Natural gypsum	<1 - 70	< 1 – 100	7 – 280
Cement	7 - 180	7 – 240	24 – 850
Tiles (glazed and unglazed)	30 - 200	20 – 200	160 – 1410
Phosphogypsum plasterboard	4 - 700	1 – 53	25 – 120
Blast furnace slag stone and cement	30 - 120	30 – 220	--

4.3 Sandblasting

Background

Heavy minerals, for example garnet, are commonly used as sand blasting abrasives in operations to clean metal surfaces in a range of industries, such as metal foundries, motor engine repairers, oil and gas industry, engineering workshops, and ship dockyards. In the past, other heavy minerals derived from the mineral sand industry, principally ilmenite and zircon, have also been used for sand blasting. Slag and other waste from metal smelting also find use for sand blasting in these industries.

Waste Production

The main waste form produced is the used sand blasting materials, which may be stockpiled on site awaiting disposal, normally to a landfill.

Radioactivity

Garnet used for sandblasting may be contaminated with trace quantities of uranium and thorium and associated radioactive progeny due to the presence of other heavy minerals such as ilmenite, zircon and monazite. A previous Australian study [21] found that garnet sandblasting materials contain radionuclide concentrations in the range 40 to 100 kBq.kg⁻¹ for ²³²Th and 15 to 30 kBq.kg⁻¹ for ²³⁸U. Ilmenite, containing up to 380 Bq.kg⁻¹ ²³²Th and up to 120 Bq.kg⁻¹ ²³⁸U, was found to be widespread use in these industries. Subsequent State regulations have limited the uranium and thorium content of sand blasting materials to below 200 Bq.kg⁻¹.

5 Fuel Production and Use

5.1 Oil and Gas Production

Background

The main NORM issues in this industry arise with production facilities associated with off-shore oil and gas reservoirs. In Australia the main oil and gas production areas are those off-shore platforms in Bass Strait, and off the coast of the northern and north-western Australia.

Processes

In the process of oil and gas extraction, the oil/gas/water mixture is brought to the surface through well tubing. The mixture then passes through a separator, which removes the gas. With further processing the gas is transported to a gas purification plant where the various gas fractions are separated and purified.

The oil stream is further treated to remove the geological formation water that is extracted with the oil and gas. After separation from the oil, the formation water, also termed production water at this stage, is usually treated and discharged to the ocean. Sand and oily sludge from the reservoir are also removed during this treatment. Solids deposit on the internal surfaces of the oil field extraction and production equipment, such as tubulars, other pipes, heat exchangers and pumps.

Waste Production

In terms of quantity, the oily sludges and sand that are separated from the oil at an early stage of the process comprise the bulk of the solid waste. Scales on equipment are low in volume. The relative amounts of solid waste vary with the production area due to the different geological characteristics of the oil/gas reservoirs.

Hard scales form by precipitation of solids directly from the formation water on to the down-hole tubulars and other wellhead equipment due to changes in temperature, pressure and salinity. These scales typically comprise a mixture of carbonate and sulphate compounds of calcium, strontium and barium.

The volumes of sludge arising from oil and gas production in Australia is relatively small compared to Europe and the USA, and is estimated to amount to about 200 m³ per year [22]. Disposal of sludge is carried out in an on-shore landfill or dumped at sea direct from the production platform. The quantities of hard scales is low with accumulations of 1 – 2 tonnes annually [22, 23].

Currently, in Australia, equipment with NORM scales is either cleaned for re-use within the industry or stored awaiting approval for scrap metal smelting, disposal or other recycling options. On some off-shore platforms, scale has been removed from pipes and tubulars and disposed of in a disused

well which is then plugged, Another option is to ground the scale to a fine powder, slurried with production water and discharged to the ocean.

Radioactivity

Uranium and thorium are present in the oil/gas source rocks. The water associated with the rock formation often contains radium along with chemically similar elements, such as strontium, barium and calcium due to their greater solubility than uranium and thorium under saline conditions.

Radium isotopes, ^{226}Ra and ^{228}Ra are co-precipitated with barium and strontium salts from the formation water during the extraction and separation of the oil and gas. This process results in enhanced radium concentrations in both sludges and scales in pipes and other production equipment. Table 9 presents some typical activities for radium levels in various oil and gas production waste, as reported for local and overseas production facilities. The highest radium concentrations are found in the hard scales, which constitute of a relatively small volume compared to the sand and sludges.

Radon gas emanating from the rock formation or from ^{226}Ra decay in formation water is preferentially associated with the natural gas phase and therefore follows through the gas production stages. Longer-lived decay products of radon, such as ^{210}Pb , can accumulate as very thin films and deposits in gas handling equipment and storage tanks.

Unless cleaned for disposal or reuse in the industry, NORM contaminated equipment, mainly tubulars and pipes from the production, is currently stored awaiting a suitable off-site option, either for recycling or scrap metal for smelting. It is estimated that 200 tonnes of such equipment is generated annually.

Table 9. Typical Activity Levels in Waste Products from the Oil and Gas Industry [5,13,22-24]

Waste Material	Radionuclide Concentrations (Bq.kg^{-1})				
	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{228}Ra
Sand/sludges	< 10	100 - 10000	20 - 1000	< 10	50 – 4000
Hard scales	< 10 - 500	100 – 250000	100 - 300000 (gas)	< 10	100 – 100000
Soft scales	< 10 - 50	100 - 25000	20 - 1000	< 10 - 70	50 – 400

5.2 Coal and Coal Combustion

Background

Coal is the main fossil fuel used to generate electricity in Australia. Approximately 85 % of Australia's electricity requirements is generated by coal-fired power plants with the balance by oil and gas plants, or hydroelectricity. A total of 50 million tonnes of coal was consumed in 2000/2001 to produce electricity [25-30]. Coal mining takes place in most Australian states by excavation, either in open pits or in underground mines. Approximately half the quantity of coal used comprises bituminous and sub-bituminous coals (also known as hard or black coal), and approximately half is lignite, or brown coal. Lignite is mainly used in Victorian power stations.

The coal consumption for power stations in various Australian states is shown in Table 10.

Table 10. Annual Consumption of Coal in Australia for Electricity Generation [25-30]

State	Total Power Station Capacity (MW)	Annual Coal Consumption (MT)
New South Wales	10000	16
Victoria	3600	38
Queensland	6920	11
Western Australia	2010	5
South Australia	520	3

Processes

In a typical coal-fired power plant, pulverized coal is burnt in a boiler and the heat is extracted as steam. The finely powdered coal is introduced into the combustion chamber as a mixture of coal and hot air. Steam is used to drive a turbine, which in turn, drives an electrical generator. The fine particulate residues are removed from the hot flue gases from the combustion by electrostatic precipitators with an efficiency in excess of 95%. Flue gases are also scrubbed to remove other volatile contaminants prior to discharge to the atmosphere.

Waste Production

Coal typically contains 5 to 30% inert mineral material that remains as ash after burning. The ash content of lignite (brown) coals is lower than that of black coal.

Fine ash is collected by the electrostatic precipitators and flue gas scrubbers. The heavier, more refractory mineral matter settles at the bottom of the boiler as bottom ash or slag. Most of the waste from a typical coal fired power station is generated as fly ash. Estimates of the annual production of fly ash for Australian coal fired power stations are given in Table 10.

Current management practice for the disposal of fly ash is to slurry the ash and transfer it to a settling pond after which the ash is disposed of in a landfill, usually at the site of the power station. A small percentage (5 – 10 %) of bottom and fly ash is sold for industrial uses such as cement-extender in concrete or for road making.

Radioactivity

Coal contains traces of naturally occurring radioactivity from uranium and thorium series and potassium-40, either associated with elements in the coal itself, such as sulphides, or within the minerals that are part of the coal formation. The radionuclide content of coal is generally below the average radioactivity levels in soils and depends on the type of coal and the location of the mine. The range of NORM concentrations in coal are given in Table 11.

The radionuclide concentrations in the ash material are enhanced significantly compared to the original coal used. In addition, the various radionuclides are partitioned between the various forms of ash. For example, the more volatile radionuclides, such as polonium-210 and lead-210, tend to accumulate in the fly ash and smaller particles in the stack emissions. In contrast, the more refractory elements, such as uranium and thorium, accumulate in the bottom ash and slag. Typical activity concentrations in ash from Australian power stations are given in Table 11.

Table 11. Typical Radionuclide Concentrations in Coal and Coal Ash from Australian Power Stations [31]

State	Estimated Annual Ash Production (MT)	Radionuclide Content in Coal (Bq.kg ⁻¹)			Radionuclide Content ^a in Ash (Bq.kg ⁻¹)			
		U-series	Th-series	K-40	Pb-210	U/Ra-226	Th-series	K-40
New South Wales	4.0	8-50	20-70	70-500	130-200 5-10	80-150 80-120	100-200 100-120	500-800 500-700
Victoria	1.0	10	5	20	15	20	15	110
Queensland	3.0	10-20	10-20	10-40	40-100	70-120	50-160	50-400
Western Australia	0.3	5	10	10	45-290 10-30	140-190 45-75	180-200 90-115	90-140 30-90
South Australia	0.3	25	45	30	140 40	120 110	180 120	200 80

Note a. Values given bold text are for bottom ash

6 Other Potential Sources

6.1 Drinking Water Purification

Background

The use of groundwater for major public supply systems in Australia is not a widespread practice except in Perth where 60% of drinking water is sourced from groundwater supplies. In contrast, approximately 50% of the drinking supplies in both Europe and the USA are from groundwater sources.

Some form of treatment for drinking water is undertaken for supplies in all Australian capital cities, except Hobart, as well as regional centres and some small communities. The annual volume of water treated in Australia is approximately 1,500 gigalitres [32].

Processes

Various processes are used to remove impurities from potable water. These processes depend on the nature of impurity but include, aeration to remove iron, sand filtration, ion exchange, reverse osmosis, aeration, flocculation and sedimentation, co-precipitation and lime softening. Essentially, the treatment is used to remove dissolved salts, heavy metals, salinity, and soluble major elements such as calcium and magnesium.

The conventional treatment used in Australia for surface and ground water supplies is flocculation with alum, followed by the removal of the flocculant by sedimentation or filtration, in conjunction with aeration, or sand and mineral filtration. Microfiltration using porous membranes is also performed in some instances. The main purpose of the treatment is to remove iron, nitrates, calcium and organics. Reverse osmosis is used for some small volume applications.

Waste Production

The main residues remaining from water treatment are flocculation sediments, filter sludges, other sand and sludges, spent ion exchange resins and reverse osmosis cartridges. The sediments and sludges are dried and disposed as landfill or by land-spreading. Alum treatment of water is the most common treatment method used in Australia, generates several tonnes of sludge per day in a typical plant [32].

Radioactivity

Radium isotopes are often present in groundwater, particularly those with higher levels of salinity. Concentrations of ^{226}Ra and ^{228}Ra can range up to 1 Bq/L in water for human or agricultural use [31]. The concentration of ^{228}Ra tends to exceed that of ^{226}Ra reflecting the higher levels of ^{232}Th in the earth's crust compared to that of ^{238}U .

Uranium concentrations in groundwater can also be elevated in areas where there are uranium-bearing formations, for example in the Northern Territory. The concentrations of uranium in water will vary depending on the local geology.

Unlike the United States where specific treatment of supplies is recommended to remove radionuclides, treatment of water in Australia is carried out mainly to remove stable impurities. However the processes, such as aeration, flocculation, reverse osmosis, ion exchange or lime softening will remove radium and dissolved uranium contaminants quite efficiently.

From information provided, there have not been any Australian studies on radionuclide concentrations in sludges, used filter elements, and ion exchange or reverse osmosis cartridges from treatment plants. Typical levels, based on the experience in the United States, are presented in Table 12 for different water treatment processes.

Based on data from previous studies of radionuclide concentrations in Australian drinking water supplies, it is unlikely that drinking water treatment will generate significant levels of NORM contamination in solid waste from the treatment plants.

Table 12. Estimated Radionuclide Levels in Water Treatment [5]

Treatment Method	NORM concentration in water (Bq.L ⁻¹)		Waste Volume (kg.day ⁻¹)	Approximate radioactivity (Bq.kg ⁻¹)
	Raw	Finished		
Coagulation/Filtration	1.85	0.37	10	148 (U)
Lime softening	0.93	0.46	22	20.6 (Ra)
Ion Exchange	0.93	0.19	97	7.7 (Ra)
Reverse Osmosis	1.85	0.56	130	11.8 (U)

7 Summary and Conclusions

This study endeavours to provide information on the quantities of materials and wastes arising in various industrial processes that potentially involve NORM. For each of industries or activities, a summary of the scale of the industry and NORM contamination levels in raw materials, products, by-products and waste generated is presented in Table 13. It has not been possible to provide a comprehensive set of data for several of the areas investigated because of time constraints or the lack of readily available data. Those items where data does not exist, or could not be obtained, are indicated by a double asterisk in the Table. In some instances, the radionuclide concentrations are only listed as uranium or thorium concentrations and this may not adequately reflect the activities of their respective progeny because of the partitioning of radioactive elements within the particular process.

Although it was not possible to generate a comprehensive set of data for all the key activities, it should be possible to gauge the relative significance of NORM in major industrial activities both in terms of the quantities of NORM materials and the potential radiological impacts.

The outcome of the study has highlighted the lack of published information on radionuclide content of materials and/or solid waste for the industrial processes in Australia. The exception to this is the mineral sand industry for which there has been considerable work because the high levels of radioactivity in certain heavy minerals and the potential for significant occupational radiation exposures. In some other industries, although there may be a regulatory requirement to provide data to the relevant authority, reports are confidential and not generally available. Also, specific studies of radioactivity in a processing operation have been undertaken under contract on behalf of a company or industry, which also restricts access to useful data.

In order to gauge the historical levels of NORM waste in Australia from past practices, at this stage detail can only be gained by inference based on the current annual production levels and knowledge that the industry has been operating for a certain period of time. To identify significant NORM contamination from past practices or activities in Australia would require a considerably more detailed survey.

In order to assess the relative quantities of NORM produced annually against the respective levels of radioactivity it is useful to group the various materials in terms of small (<1 kt), medium (1-100kt) and large (> 100 kt) quantities produced annually with activity concentrations that are low (< 1000 Bq.kg⁻¹), moderate (1000 – 20000 Bq.kg⁻¹) or high (> 20000 Bq.kg⁻¹). For comparison, soils in Australia typically have uranium and thorium concentrations in the range 10 – 60 Bq.kg⁻¹ [31]. Table 14 presents a summary of the relative quantities and activity concentrations for waste and by-product materials from various industries. From Table 14 it can be seen that the NORM waste that is produced in very large quantities, such as fly ash, alumina “red mud”, and metal smelting slags, and mineral processing tailings, are confined to the group classified as being of low activity. At the high activity end of scale, with the exception of monazite concentrates and tails, only those waste materials, such as oil scales and metal smelting dust, which have a quite low annual production rate fall into this category. It is important to note that monazite waste arise in an industry that is subject

to radiation protection regulations because of the potential for significant occupational exposures in the industry.

Table 13. Summary of NORM in Australian Industries and Materials

Category of NORM I. Raw material II. Product(s) III. Waste/by-product	Scale of mining/production and waste generation in Australia (estimated)	Typical radionuclide concentrations	Waste management or by-product use
MINERAL SAND MINING AND PROCESSING I. Ore II. Heavy minerals III. a. Tails from primary separation b. Oversize from secondary sepn. c. Tails from secondary sepn. d. Dust from secondary sepn. e. Solids from synthetic rutile f. Kiln solids	I. 3.5 Mt.a ⁻¹ II a. 2.5 Mt.a ⁻¹ Concentrate b. 2 Mt.a ⁻¹ Ilmenite/Rutile c. 390 kt.a ⁻¹ Zircon d. 80kt.a ⁻¹ Monazite concentrate e. ** kt.a ⁻¹ Synthetic rutile III a. 30 Mt.a ⁻¹ b. 40 kt.a ⁻¹ c. 400 kt.a ⁻¹ d. 20 kt.a ⁻¹ e. ** kt.a ⁻¹ f. ** kt.a ⁻¹	I. 0.02-0.3 kBq.kg ⁻¹ Th, 0.03-0.12 U II a. 0.3-3 kBq.kg ⁻¹ Th, <0.1-0.8 U b. 0.2-2 kBq.kg ⁻¹ Th, <0.1-0.6 U c. 0.6-1.2 kBq.kg ⁻¹ Th, 1-4 U d. 40-250 kBq.kg ⁻¹ Th, 6-30 U e. <0.2-1.5 kBq.kg ⁻¹ Th, <0.1-0.3U III a. <0.2 kBq.kg ⁻¹ Th, <0.1 U b. 0.3-8 kBq.kg ⁻¹ Th, 0.6-2.0 U c. 0.8-24 kBq.kg ⁻¹ Th, 0.1-12 U d. 1-20 kBq.kg ⁻¹ Th, 0.1-6 U e. <0.2-1.5 kBq.kg ⁻¹ Th, <0.1-0.3 U f. 0.1-1.2 kBq.kg ⁻¹ Th, 0.1-1.2 U	IIIa. Landfill disposal in mined out area IIIb. To IIIf. Dilution with inert solids, then landfill disposal
TITANIUM PIGMENT PRODUCTION I. Rutile/Synthetic rutile II. Titanium pigment III. a. Neutralised slurries b. Solids from effluent treatment c. Liquid effluent	I. as above II. 185 kt.a ⁻¹ titanium pigment III. a. 200 kt.a ⁻¹ b. 200 kt.a ⁻¹ c. **	I. as above II. < 0.01 kBq.kg ⁻¹ Th, <0.01 U III a. 1.2 kBq.kg ⁻¹ Th, 0.35 U b. 0.8-1.4 kBq.kg ⁻¹ Th, 0.3-0.5 U c. < 0.1 kBq.kg Th, < 0.1 U	IIIa. Landfill disposal IIIb. Landfill disposal IIIc. Ocean discharge
ZIRCONIUM AND CERAMICS INDUSTRY I. Zircon II. Zirconia, Refractory materials, ceramics, glazes III. a. Sludge b. Chlorinator residues c. Dust d. Slag	I. as above II. ** III. **	I. as above II. ** III. **	

Note: ** information not currently available to author

Table 13 (cont.) Summary of NORM in Australian Industries and Materials

I. Category of NORM II. Raw material III. Product(s) I. Waste/by-product	Scale of mining/production and waste generation in Australia	Typical radionuclide concentrations	Waste management or by-product use
ALUMINA PRODUCTION I. Bauxite II. Alumina III. Red mud	I. 55 Mt.a ⁻¹ bauxite II. 16 Mt.a ⁻¹ alumina III. > 20 Mt.a ⁻¹ red mud	I. 0.5 kBq.kg Th, 0.12 U, 0.7 ⁴⁰ K II. n.d. Th, n.d. U III. 1.3 kBq.kg ⁻¹ Th, 0.4 U, 0.15 ⁴⁰ K	III. Landspreading
COPPER MINING AND PROCESSING I. Copper ore II. Copper concentrate/refined metal III. a. Tails from flotation b. Dust from smelter c. Slag from smelter	I. 20 Mt.a ⁻¹ II a. 800 kt.a ⁻¹ Primary copper products b. 520 kt.a ⁻¹ refined copper III a. **kt.a ⁻¹ b. **kt.a ⁻¹ c. **kt.a ⁻¹	I. ** II a. ** III a. Bq.kg ⁻¹ Th, Bq.kg ⁻¹ U b. Bq.kg ⁻¹ ²¹⁰ Pb, ²¹⁰ Po c. Bq.kg ⁻¹ Th, Bq.kg ⁻¹ U	IIIa. Disposal in tailings dam with U tails
TANTALUM/TIN MINING AND PROCESSING I. Tantalum ore II. a. Tantalum concentrate b. Tin III. a. Tantalum tails b. Tin slag	I. 2.5 Mt.a ⁻¹ II. a. 2.5 kt.a ⁻¹ b. ** kt.a ⁻¹ III. a. ** kt.a ⁻¹ b. ** kt.a ⁻¹	I. < 10 Bq.kg ⁻¹ Th, < 60 Bq.kg ⁻¹ U. II. a. 7.5 – 75 kBq.kg ⁻¹ , U + Th III. a. ** b. **	IIIa. Landfill disposal
IRON SMELTING I. Iron ore II. Iron (+steel) III. a. Furnace slag b. Dust	I. 200 Mt.a ⁻¹ II. 8 Mt.a ⁻¹ III. a. ** Mt.a ⁻¹ b. ** kt.a ⁻¹	I. 20 – 30 Bq.kg ⁻¹ III. a. b. < 100 kBq.kg ⁻¹ ²¹⁰ Pb and ²¹⁰ Po	III. Landfill disposal of slag and dust

Note: ** information not currently available to author

Table 13 (cont.) Summary of NORM in Australian Industries and Materials

Category of NORM I. Raw material II. Product(s) III. Waste/by-product	Scale of mining/production and waste generation in Australia	Typical radionuclide concentrations	Waste management or by-product use
PHOSPHATE INDUSTRY I. Phosphate rock II. Fertilisers, Phosphoric acid III. a. Phosphogypsum b. Calcium fluoride c. Furnace slag and dust d. Scale	I. 2 Mt.a ⁻¹ (local rock) II. a. 4 Mt.a ⁻¹ superphosphate b. 100 kt.a ⁻¹ acid (< 1993) c. ADP III. a. 250 kt.a ⁻¹ (<1993) b. 90% of ore c. 1% of ore as dust and 85% as slag	I. <0.01-0.2 kBq.kg ⁻¹ Th, <0.1-1.9 U II. a. 0.01-0.06 kBq.kg ⁻¹ Th, 0.5-2.2 U, 0.1-1.0 ²²⁶ Ra (incl. ADP) b. < 0.01 kBq.kg ⁻¹ Th, 1.2-1.5 U, 0.3 ²²⁶ Ra III. a. <0.01 kBq.kg ⁻¹ Th, 0.01-0.02 U, 0.28 - 0.35 ²²⁶ Ra, 0.32-0.44 ²¹⁰ Pb d. <0.01 kBq.kg ⁻¹ Th, 0.01-0.2 U, 0.01-3.9 ²²⁶ Ra, 0.03-1. ²¹⁰ Pb	III a. Stockpiled on site Plasterboard manufacture (10%)
OIL AND GAS PRODUCTION I. Natural oil and gas II. Purified oil and gas III. a. Sands and sludge b. Soft scales c. Hard scales and film	I. ** III a. 200 tonnes b. ** c. 1-2 tonnes	III a. < 0.01 kBq.kg ⁻¹ Th, < 0.01 U, 0.1-10 ²²⁶ Ra, 0.05-4 ²²⁸ Ra, 0.01-1 ²¹⁰ Pb b. <0.01-0.07 Na.kg ⁻¹ Th, < 0.01 U, 0.1-10 ²²⁶ Ra, 0.05-4 ²²⁸ Ra, 0.01-1 ²¹⁰ Pb c. < 0.01 Bq.kg ⁻¹ Th, <0.01-0.5 U, 0.1-100 ²²⁶ Ra, 0.1-40 ²²⁸ Ra, 0.1-300 ²¹⁰ Pb	III a. Landfill Ocean discharge
COAL-FIRED POWER GENERATION I. Coal II. Electrical power III. a. Fly ash b. Bottom ash	I. a. 35 Mt.a ⁻¹ Black coal b. 38 Mt.a ⁻¹ Brown coal III a. 8.6 Mt.a ⁻¹ fly ash b. 1 Mt.a ⁻¹ bottom ash	I a. 0.005-0.05 kBq.kg ⁻¹ Th, 0.01-0.05 U 0.01-0.5 ⁴⁰ K b. 0.005 kBq.kg ⁻¹ Th, 0.01 U, 0.02 ⁴⁰ K II a. 0.02-0.2 kBq.kg ⁻¹ Th, 0.02-0.19 U 0.04-0.3 ²¹⁰ Pb, 0.1-0.8 ⁴⁰ K b. 0.05-0.19 kBq.g ⁻¹ Th, 0.05-0.2 U, 0.005-0.08 ²¹⁰ Pb, 0.04-0.10 ⁴⁰ K	IIIa. Landfill disposal Cement and Brick manufacture IIIb. Landfill disposal Road construction

Note: ** information not currently available to author

Table 13 (cont.). Summary of NORM in Australian Industries and Materials

Category of NORM I. Raw material II. Product(s) III. Waste/by-product	Scale of mining/production and waste generation in Australia	Typical radionuclide concentrations	Waste management or by-product use
WATER TREATMENT I. Surface or bore water II. Purified potable water III. a. Sludge b. Resins and cartridges	I. 1400 GL III. 100 kt.a ⁻¹	I. < 1 Bq.L ⁻¹ ²²⁸ Ra, < 1 Bq.L ⁻¹ ²²⁶ Ra II. ** III. **	IIIa. Landfill disposal or landspreading b. Landfill disposal
BUILDING MATERIALS I. a. Raw materials b. By-product wastes II. Bricks, cement, plasterboard, ceramic tiles	I b. 15 % Phosphogypsum recycled, 10% Fly ash II. **	I. b. As above II. Concrete - 0.001-0.24 kBq.kg ⁻¹ Th, 0.001-0.25 ²²⁶ Ra,.005-1.5 ⁴⁰ K Bricks – 0.001-0.2 kBq.kg ⁻¹ Th, 0.01-2.2 ²²⁶ Ra, 0.01-1.6 ⁴⁰ K Plasterboard - <0.01-0.05 kBq.kg ⁻¹ Th <0.01-0.7 ²²⁶ Ra, 0.025-0.1 ⁴⁰ K Ceramics - 0.02-0.2 kBq.kg ⁻¹ Th, 0.03 - 0.2 ²²⁶ Ra, 0.16-1.4 ⁴⁰ K	

Note: ** information not currently available to author

Table 14. Summary of NORM Materials in Terms of Quantities and Activities

Radionuclide Content (Bq/kg)	Quantity Produced Annually		
	Small (< 1 kt)	Moderate (1 kt - 100 kt)	Large (> 100 kt)
Low (< 1000)	-	Synthetic rut Ceramics Sand blasting materials	Alumina waste (red mud) Coal ash Furnace and metal smelter slags Phosphogypsum Phosphate fertilisers Water treatment sludge? Tantalum tails Copper tailings
Medium (1000 - 20000)	Oil sand/sludge	Tantalum products	Phosphate rock Zircon Ilmenite
High (> 20000)	Zircon dusts Copper smelter dusts Oil scales Iron sinter dusts	Monazite concentrates Monazite tailings	-

8 References

1. Australian Bureau of Agriculture and Resource Economics. Quarterly Report on Australian Commodities, Vol. 10 No. 3, September quarter 2003.
2. Western Australia Chamber of Minerals and Energy. *Best practice in radioactive waste management guidelines in the Western Australian mineral sands industry*, January 2000 revision.
3. Upton, H., and G. Hewson. Radiation Protection in Australia (1996), Vol 14(3).
4. Australasian Institute of Mining and Metallurgy. *Australasian Mining and Metallurgy, The Sir Maurice Mawby Memorial Volume - 2nd Edition*, J.T. Woodcock and J.K. Hamilton Eds., Melbourne, 1993.
5. International Atomic Energy Agency. *The extent of environmental contamination by naturally occurring radioactive material (NORM) and technological options for mitigation*, IAEA draft Technical Report, Vienna, November 2002.
6. Iluka Minerals. *Material Safety Data Sheets*, <http://www.iluka.com.au/>
7. Cooper, M.B., P.C. Clarke, W., Robertson, I.R. McPharlin, and I.R. Jeffrey. *An investigation of radionuclide uptake into food crops grown in soils treated with bauxite mining residues*, J. Radioanal. Nucl. Chemistry (1995), 194(2), 379-387.
8. MIM Holdings Limited. 2001 Environment Report.
9. Brown, S., D. Collier, and P. Kenny. *Radionuclides in the Iron Sinter Plant circuit BHP, Port Kembla*, ANSTO report to Illawarra Radionuclide Investigations Committee, March 2003.
10. Crockett, G.M., K.R. Smith, W.B. Otway and S.F. Mobbs. *Radiological impact on the UK population of industries which use or produce materials containing enhanced levels of naturally occurring radionuclides*, National Radiological Protection Board report, NRPB-W48, Chilton, UK, October 2003.
11. Chemlink. Technical information, <http://www.chemlink.com.au/>
12. United States Environmental Protection Agency. *Diffuse Norm Wastes - Waste Characterisation and Preliminary Risk Assessment*, Draft report, RAE-9232/1-2, April 1993.
13. Hofman, J., R. Leicht, H.J. Wingender, J. Wörner. *Natural radionuclide concentrations in materials processed in the chemical industry and the related radiological impact*, European Commission Report EUR 19264, Brussels, August, 2000.

14. Vandenhove, H., A Bousher, P.H. Jensen, D. Jackson, B. Lambers, T. Zeevaert. *Investigation of a possible basis for a common approach with regard to the restoration of areas affected by lasting radiation exposure as a result of past or old practice or work activity*, European Commission Report 115, September 1999.
15. Schmidt G., C. Kuppers, P. Robinson. *Handling of radium and uranium contaminated waste piles and other wastes from phosphate ore processing*, European Commission Report EUR 15448, Brussels, 1995.
16. Tsurikov, N. *Nick's TENORM notes*, www.eneabba.net/tenorm/
17. Beretka, J., P.J. Mathew, *Natural Radioactivity in Australian building materials, industrial wastes and by-products*, Health Physics (1985), Vol. 48(1), 87-95.
18. O'Brien, R.S., H.Aral, and J.R., Peggie. Radon exhalation rates and gamma doses from ceramic tiles, Health Physics (1998), Vol 75 (6), 630-639.
19. O'Brien, R.S., J.R. Peggie, I.S. Leith. *Estimates of inhalation doses resulting from the possible use of phospho-gypsum plasterboard in Australian homes*, Health Physics (1995), Vol. 68(4), 561-570.
20. Efendi, Z. and P. Jennings. *An assessment of the environmental radiation dose for residents of the Perth metropolitan area*, Radiation Protection in Australia (1994), Vol. 12 (1), 8-12
21. Wallace, B.J., V.A. Leach. *Radiation exposure of sand blasting operators*, Radiation Protection in Australia (1987), Vol 5(3), 63-68.
22. Cassels, B., and A. Waite. *Regulatory management of NORM wastes from petroleum exploration activities in the Northern Territory*, Radiation Protection in Australasia (2001), Vol. 18(1), 16-34.
23. Cobby G., Western Australia Department of Industry and Resources, personal communication.
24. Kvasnicka, J. *Radiation Protection in the Offshore Petroleum Industry*, in Proceedings of the International Congress on Radiation Protection, IRPA 9, International Radiation Protection Association, Vienna, Austria, 1996, Vol.4 621-623.
25. Australian Academy of Technological Sciences and Engineering. *Utilisation of waste from coal-fired power plants*, <http://www.atse.org.au/publications/>
26. Western Australia Government - Office of Energy. *Energy Resources in Western Australia*, <http://www.energy.wa.gov.au>
27. Delta Electricity. *Environment Report 2001/02*, <http://www.de.com.au/Online/>

28. South Australian Office of Energy. <http://www.energy.sa.gov.au/>
29. Hazelwood Power. *Annual Environmental Report July 1999 – 2000*, <http://www.hazelwoodpower.com.au/>
30. Queensland Treasury – Office of Energy. *Electricity Information Sheet*, <http://www.energy.qld.gov.au/electricity/>
31. Australian Radiation Laboratory, unpublished data.
32. Water Services Association of Australia, personal communication.