

# **Naturally-Occurring Radioactive Material (NORM) in Australia: Issues for Discussion**

**prepared by the**

**Radiation Health & Safety Advisory Council  
for the CEO of ARPANSA**

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This version has been updated to remove any factual errors and include additional data provided in submissions received during the public consultation process. It is not an attempt to respond to all issues raised in the submissions. Other issues raised were considered by Council in finalising its advice to the CEO of ARPANSA.



# TABLE OF CONTENTS

<b>EXECUTIVE SUMMARY .....</b>	<b>5</b>
<b>1. INTRODUCTION.....</b>	<b>7</b>
<b>2. WHAT IS NORM?.....</b>	<b>7</b>
<b>3. WHAT IS DIFFERENT ABOUT NORM?.....</b>	<b>8</b>
OCCURRENCE.....	8
NATURAL BACKGROUND RADIONUCLIDE CONCENTRATIONS AND RADIATION LEVELS .....	8
POTENTIAL ISSUES .....	9
<b>4. INDUSTRIES WITH NORM RADIATION .....</b>	<b>9</b>
<b>5. HOW MUCH NORM WASTE DOES AUSTRALIA GENERATE?.....</b>	<b>11</b>
<b>6. NORM IN COMMODITIES.....</b>	<b>13</b>
PHYSICAL AND CHEMICAL FORM ISSUES .....	13
<b>7. INTERNATIONAL RADIATION PROTECTION GUIDELINES &amp; REGULATORY ISSUES .....</b>	<b>14</b>
PRINCIPLES OF RADIATION PROTECTION.....	14
CURRENT INTERNATIONAL REGULATIONS AND GUIDELINES .....	15
EXEMPTION DEFINITIONS AND EXCLUSIONS .....	16
<b>8. TRADE ISSUES.....</b>	<b>16</b>
<b>9. AUSTRALIAN RADIATION PROTECTION REGULATIONS AND GUIDELINES.....</b>	<b>17</b>
CURRENT REGULATORY REQUIREMENTS.....	17
INDUSTRY GUIDES .....	18
OPTIONS FOR ESTABLISHING NORM MANAGEMENT CRITERIA.....	18
<b>10. ISSUES AND OPTIONS FOR DEALING WITH NORM WASTE .....</b>	<b>19</b>
ISSUES FOR MANAGING NORM WASTE.....	19
OPTIONS FOR DISPOSAL OF NORM WASTE .....	20
DISPOSAL APPROACHES BY AUSTRALIAN JURISDICTIONS.....	21
<b>11. ISSUES FOR DISCUSSION .....</b>	<b>23</b>
<b>12. CONSULTATION AND ACKNOWLEDGEMENTS.....</b>	<b>24</b>
ORGANISATION .....	24
<b>13. GLOSSARY &amp; ABBREVIATIONS .....</b>	<b>24</b>
<b>14. REFERENCES.....</b>	<b>25</b>
<b>APPENDIX INDUSTRY PROCESSES.....</b>	<b>28</b>
MINERAL SANDS PRODUCTION .....	28
DOWNSTREAM PROCESSING OF MINERAL SANDS PRODUCTS.....	28
BAUXITE PROCESSING (ALUMINIUM PRODUCTION) .....	29
COPPER PRODUCTION.....	30
TIN/TANTALUM PRODUCTION .....	31
IRON AND STEEL PRODUCTION.....	31
PHOSPHATE ORE PROCESSING.....	32
BUILDING MATERIALS AND CERAMICS .....	33
SANDBLASTING .....	34
OIL & GAS PRODUCTION.....	34
COAL BURNING.....	35
WASTE FROM DRINKING WATER PURIFICATION .....	36



## EXECUTIVE SUMMARY

This discussion paper has been developed by the Radiation Health & Safety Advisory Council (RHSAC) following a request from the CEO of ARPANSA to identify and examine options for dealing with issues involving naturally- occurring radioactive material (NORM) in Australia. It does not aim to provide solutions but seeks comment from interested parties on a number of matters related to NORM. These include development of national guidance to enable a uniform approach to establishing criteria for regulation of NORM.

NORM is distributed throughout the earth's crust in water, rocks, minerals and soils. Most NORM contains radionuclides from the so-called "primordial" decay chains resulting from the decay of uranium-238 ( $^{238}\text{U}$ ), uranium-235 ( $^{235}\text{U}$ ) and thorium-232 ( $^{232}\text{Th}$ ), and other long-lived radionuclides such as potassium-40 ( $^{40}\text{K}$ ). In the majority of situations, the naturally occurring radionuclide concentrations are not high enough to pose problems for the environment or human health, but in those situations where the radionuclide concentrations are significantly higher than the average level, human health may be affected.

Unlike the man-made radionuclides, which do not normally exist in appreciable concentrations for any length of time in the natural environment, NORM is widely distributed, and gives rise to a natural radiation background that varies by approximately two orders of magnitude over the Earth, and even more if localised mineral deposits are taken into account. This means every living species is exposed to this radiation, and in most situations this exposure is not amenable to control. There appears to be no scientific evidence relating general variations in natural background radiation to health effects.

The widespread occurrence of NORM means that many of the ores and minerals (e.g. coal, oil and gas, iron ore, bauxite, phosphate rock), commodities (e.g. water, building materials, fertiliser), products (e.g. ceramics), and devices (e.g. welding rods, gas mantles and electronic components) used by humans can contain NORM.

Activities such as mineral processing, coal burning (e.g. for electricity generation) and water treatment can modify the NORM concentrations in the products, by-products and wastes (residues) generated by these activities. In some situations, specific radionuclides can become separated from the original radionuclide mixture, e.g. volatilisation of polonium and lead isotopes when coal is burnt to generate electricity and the separation of radium and uranium during the processing of phosphate ore to produce fertiliser and phosphogypsum.

In some industries the management of possible NORM exposures is already being addressed. In the oil and gas industry for example radiation protection measures are implemented for staff undertaking maintenance on norm contaminated equipment. However, in industries where NORM has not been recognised as a potential issue, occupational and public health matters may not be adequately addressed. Public health issues may also arise from the use of products containing NORM or from the inappropriate disposal of NORM bearing wastes.

Current and historical options for disposing of NORM wastes and residues on-site include landfill, down-hole disposal, near-surface disposal, land contouring, and disposal into mine tailings dams. Off-site options include dilution in industrial waste disposal facilities, land farming by ploughing in over a gazetted disposal area, incorporation into concrete for building construction or road base, and incorporation into other building materials such as bricks or plasterboard. In some cases, a lack of awareness of NORM issues in the past has led to the creation of contaminated sites for which no

individual or organisation is legally accountable. The remediation of these sites will require careful consideration.

In the nuclear power industry, stringent design and operational controls are applied to reduce radiation exposures and the probability of accidents. In most NORM industries the potential for this type of serious accident does not exist, hence any proposed precautions in NORM industries may need to be based only on control of radiation exposures.

Despite the widespread occurrence of NORM, and notwithstanding the development of guidance material in some countries and by international authorities, there is no systematic international approach to regulating NORM in commodities and products, or for the management of NORM wastes.

Similarly, in Australia, there is no uniform regulatory approach to NORM issues. Each State and Territory and the Commonwealth Government has a regulatory system for radiation protection, including the use of radioactive materials. In each jurisdiction the regulations include exemption limits for the activity and activity concentration of radioactive material to be regulated. While all jurisdictions have regulations that deal with radioactive wastes in general, there is no uniform approach to regulation of NORM wastes and residues, and no national guidance on the management of these wastes. ARPANSA's role is to provide national guidance on the management of materials containing NORM, and promote the development of a uniform approach to the regulation of these materials.

Developing Australia's requirements for regulatory controls over NORM in isolation from the international community could lead to trade difficulties for Australian mineral producers and processors. Council understands there are significant concerns arising from differences in regulatory regimes between countries engaged in international trade, and differences between jurisdictional requirements within Australia.

Council also notes that information on NORM in some Australian industries is either dated or not available, and would like to be informed of additional sources of data.

**Council seeks comment from interested parties on NORM issues in Australia, in particular on whether there is a need to:**

- Develop national guidance on exclusion, exemption and clearance for natural radioactive materials, to enable a uniform approach to establishing criteria that may be used to regulate NORM in all jurisdictions. The guidance would take the existence and variability of the natural background into consideration, and also allow for the wide range of scenarios that can lead to exposure to ionizing radiation from materials containing NORM.
- Develop national guidance on strategies and criteria for the treatment and disposal of NORM arising from various process waste streams, including by landfill or land spreading.
- Develop guidance for remedial action at sites contaminated by historical NORM waste generation, including reviewing the 1984 NHMRC statement "Guidelines for Remedial Action in Areas where Residues from Mineral Sand Mining and Processing have been Deposited" to ascertain whether the information is still relevant and, if necessary, re-publish up to date guidance within the Radiation Protection Series.
- Develop a strategy for raising awareness of NORM issues, both in relevant industries and with the public generally.

## 1. INTRODUCTION

In April 2003 the CEO of ARPANSA requested that Council prepare a discussion paper covering a range of naturally-occurring radioactive material (NORM) and technologically enhanced naturally-occurring radioactive material (TENORM) issues. These included the industries affected, an estimate of NORM waste generated, the current regulatory position, NORM in commodities, and options for dealing with NORM waste. This followed Council's advice to the CEO in September 2002 wherein it recommended

***Recommendation 1:** ARPANSA should coordinate the development of national guidance on handling and disposal of waste from Naturally Occurring Radioactive Material (NORM) and Technologically Enhanced Naturally Occurring Radioactive Material (TENORM).*

The purpose of this paper is to identify and examine options for dealing with issues involving NORM in Australia, rather than provide solutions. In preparing this paper Council consulted various parties involved with NORM. While necessarily examining approaches to NORM internationally, the paper concentrates on those issues relevant to Australia.

A consultant was also engaged to gather specific information on quantities of NORM within Australia.

At the conclusion of the report Council notes issues on which further discussion may be required, including the development of national guidance material and raising the awareness of NORM issues within industries affected and with the general public.

## 2. WHAT IS NORM?

Naturally-occurring radioactive material (NORM) is the term used to describe materials that contain radionuclides that exist in the natural environment. Long-lived radioactive elements of interest include uranium, thorium and potassium, and any of their radioactive decay products, such as radium and radon. These elements have always been present in the earth's crust and within the tissues of all living species.

NORM is found in a wide variety of bulk commodities, process wastes and commercial items, sands, clays and soils, rocks, coal, groundwater, oil and gas, metal ores and non-metal minerals, including fertiliser raw materials such as rock phosphate and apatite. Metal ores that have been found to be associated with NORM include tin, tantalum, and niobium ores, rare earths, and some copper and gold occurrences. Although the concentration of NORM in most natural substances is low almost any operation in which any material is extracted from the earth and processed can concentrate NORM.

While most of the NORM issues centre around very large volumes of low activity waste from industrial processes, some of the material is put to commercial use and could be better described as a commodity than a waste. In summary, NORM can be found in bulk commodities, commercial items and process wastes.

Artificially concentrated NORM is sometimes called TENORM, an acronym for 'technologically enhanced naturally occurring radioactive material'. Council considers that this additional term is

superfluous and unhelpful, and throughout this paper the term NORM is used to include TENORM. This is consistent with the terminology used in International Commission on Radiological Protection Publication 82 (ICRP, 2000).

### 3. WHAT IS DIFFERENT ABOUT NORM?

#### OCCURRENCE

Unlike the anthropogenic radionuclides, which do not normally exist in appreciable concentrations for any length of time in the natural environment, NORM is widely distributed, and gives rise to a natural radiation background that varies by approximately two orders of magnitude over the Earth, and even more if localised mineral deposits are taken into account. This means every living species is exposed to this radiation, and in most situations this exposure is not amenable to control. There appears to be no scientific evidence relating general variations in this natural background to health effects.

Materials containing NORM can contain single radionuclides (e.g.  $^{40}\text{K}$ ), or radionuclides from the naturally occurring decay chains ( $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{232}\text{Th}$ ). In these decay chains, because of the large number of radionuclides in each chain, and the resulting large range of physical and chemical properties of the individual radionuclides, there is a highly variable degree of equilibrium between the individual members of the chains.

In general, increasing exposure to radionuclides will increase the radiation dose to humans. However, in the case of potassium-40 ( $^{40}\text{K}$ ), the concentration in the human body is controlled within narrow limits by homeostatic processes. Therefore, even if the environmental level of  $^{40}\text{K}$  varies naturally or is changed as a result of human activities, the dose delivered from  $^{40}\text{K}$  inside the body remains approximately constant.

#### NATURAL BACKGROUND RADIONUCLIDE CONCENTRATIONS AND RADIATION LEVELS

The world-wide average activity concentrations of some of the naturally occurring radionuclides in the undisturbed environment, including a number of very long-lived singly occurring radionuclides such as potassium-40 ( $^{40}\text{K}$ ), rubidium-87 ( $^{87}\text{Rb}$ ) and indium-115 ( $^{115}\text{In}$ ) are given in Eisenbud (1987). The primordial decay series result from the decay of uranium-238 ( $^{238}\text{U}$ ), thorium-232 ( $^{232}\text{Th}$ ) and uranium-235 ( $^{235}\text{U}$ ). For the two most important primordial decay series the average concentrations are given below:

$$^{238}\text{U}: 30\text{-}50 \text{ Bq kg}^{-1}$$

$$^{232}\text{Th}: 40\text{-}60 \text{ Bq kg}^{-1}$$

The presence of these radionuclides in the environment gives rise to natural background radiation. In Australia, the average annual dose received from this natural background radiation by an adult is approximately 1.5-2 millisievert (mSv), comprising approximately 0.3 mSv due to terrestrial gamma radiation, approximately 0.3 mSv due to cosmic radiation (at sea-level), approximately 0.2-0.25 mSv due to beta and gamma radiation from  $^{40}\text{K}$  inside the body, and approximately 0.6-1.1 mSv due to inhalation of radon ( $^{222}\text{Rn}$ ) and its radioactive decay products. In some parts of the world the annual dose received from natural background radiation exceeds 100 mSv, and in one known case 200 mSv. The local variability in annual background doses can be of the order of 0.5 mSv over distances of a few kilometres. As an example of the variability in natural background radiation levels, the dose from terrestrial gamma radiation in parts of the Darling Ranges east of

Perth is approximately three times the average value for Australia quoted above. Some of the potential ramifications of this variability will be discussed later in this paper.

## **POTENTIAL ISSUES**

### ***Effects of Processing***

Processing of materials containing NORM can lead to the production of both products (commodities) and wastes. In some cases the original mixture or concentration of radionuclides is changed in the products and/or the wastes as a result of the processing. This can complicate the process of assessing the effects of NORM.

Some examples are given in Section 4 of this report and in the attached Appendix.

### ***General Public and Industry Awareness of NORM***

Another issue with NORM is one of awareness. Many industries, particularly the mining industries (other than uranium and mineral sand mining), may have operated until recently without realising that their operations could give rise to NORM in wastes and/or products. Similarly, the general public may also be largely unaware of natural background radiation, and that NORM occurs in a variety of everyday products. For example, materials containing NORM are commonly used in road building, landfill, building materials and other applications. Council considers that raising the awareness of both industries and the public, while keeping potential risks in context, is an important part of any NORM management strategy.

### ***Application of Radiation Protection Requirements***

In the nuclear power industry, the potential consequences of a serious accident can be catastrophic in the short term and highly deleterious to human health and the environment in the long term. Therefore, stringent design and operational controls are applied, not only to reduce radiation exposures, but to reduce the probability of accidents. In most NORM industries the potential for this type of serious accident does not exist, hence any proposed precautions in NORM industries may need to be based only on control of radiation exposures.

## **4. INDUSTRIES WITH NORM RADIATION**

This section provides a brief outline of the main industries in which NORM is handled and NORM wastes are produced in Australia. Descriptions of industry processes and waste streams are contained in the Appendix to this report, and additional details, including tables of quantities and activities are provided in the accompanying report by Dr. M.B. Cooper (2003), *Naturally Occurring Radioactive Materials (NORM) in Australian Industries – Review of Current Inventories and Future Generation*, which was commissioned by Council.

- ***Extraction of minerals*** is undertaken by conventional underground or open pit mining techniques or acid leaching. Mineral processing can involve dry techniques including electrostatic or magnetic separation, or wet techniques such as acid or alkaline leaching and flotation, or smelting. All of these processes can affect the concentrations of radionuclides in both waste and product streams.
- ***Mineral sands production*** (including ilmenite, leucoxene, rutile, zircon, monazite and xenotime) leads to several waste materials from primary processing of the ore. Some of these waste materials are returned to the mined out pit for disposal. In downstream processing there is a potential for dust levels to increase and for inhalation of radioactive

material to be an issue. Ventilation, local dust extraction, and respiratory protective equipment may be necessary to keep exposures low.

- In **alumina production**, the main solid residues are undissolved bauxite residues containing iron, silica and titanium. These residues, termed "red mud", are produced in large quantities. Disposal of these residues commonly takes place by spreading in layers over a large area to allow the material to dry prior to rehabilitation by covering the waste with sand and revegetating the surface. Alumina smelting does not produce substantial quantities of solid waste.

Liquid residues arising from the washing of solid residues, and from settling ponds, are recycled as process water. Leachates from the disposal areas are collected and returned to production as process water.

Virtually all the radioactivity is transferred to the solid residues, and little, if any, of the radioactivity is present in the alumina.

- In **copper production**, wastes containing NORM arise in tailings from the flotation stage and furnace slags from the smelting stage. In tin and tantalum production, dry and wet separation stages produce a tailings slurry that is further treated and disposed of in a tailings dam close to the mine site. Tantalum products also contain low levels of NORM. Iron and steel production wastes include blast furnace slags, and dusts and fumes from the sinter plant, and off gas cleaning in the blast furnace operation.
- In **phosphate ore processing**, NORM is found in tailings from fertiliser production that are normally used as backfill at the mine site, and also in fertiliser product at levels which do not cause any significant increase in the uranium and thorium levels in soil treated with fertiliser. In phosphoric acid production, the majority of the NORM is left in the phosphogypsum, which can be stockpiled on site or disposed of as landfill. Phosphogypsum may also be used in fertiliser, soil conditioner, building material (eg plasterboard, cement aggregate), and in road construction.
- **Heavy minerals**, eg garnet, commonly used as sand-blasting abrasives may be contaminated with uranium and thorium due to the presence of other heavy minerals such as ilmenite, zircon and monazite.
- In the **oil and gas industry**, NORM, particularly radium isotopes, is present in production water, sands and oily sludges. Radium precipitates out on equipment surfaces resulting in sludges and hard scales. Disposal of sludge is by on-shore landfill or dumping at sea direct from the production platform. Equipment with NORM scales is either cleaned for re-use or stored awaiting approval for scrap metal smelting, disposal or other recycling options.
- When **coal** is burned in power production, fly ash containing the more volatile radionuclides, such as polonium-210 and lead-210, is produced along with bottom ash and slag containing the more refractory elements, such as uranium and thorium. The radionuclide concentrations in the ash are generally enhanced compared with those in the original coal. Disposal practice for fly ash is to slurry the ash and transfer to a settling pond, after which it is disposed of in a landfill at the power station site. Approximately 30% of the bottom and fly ash is sold for industrial uses such as cement-extender in concrete, in road making, or in mine site remediation. Another recent study has proposed the conditional use of coal combustion products in agriculture (ADAA submission, 2004).

- NORM contamination can also arise in the solid waste from *drinking water treatment* plants, particularly where the water supply comes from groundwater. Other than in Perth, groundwater is not widely used for major public supply systems in Australia, and based on previous studies of radionuclide concentrations, it is unlikely that drinking water treatment will generate significant levels of NORM contamination.

## 5. HOW MUCH NORM WASTE DOES AUSTRALIA GENERATE?

Council commissioned a consultant to prepare a report on the quantities of NORM waste generated in Australia. This report provides detail on the particular radionuclides, activities and quantities of NORM wastes produced by a range of industries.

The search for information has highlighted the lack of published data on radionuclide content of materials and/or solid wastes for many industrial processes. One exception to this is the mineral sand industry because of the potential for significant occupational radiation exposures due to the high concentrations of radionuclides in certain heavy minerals. In other cases, where specific studies on behalf of a company or industry have been undertaken under contract, access to relevant data may be restricted.

It was not possible to obtain detailed information on historical arisings of NORM wastes from particular industries except by inference from current annual production levels and knowledge of the operating life of the industry. A more detailed survey would be required to identify significant NORM contamination from past practices and activities.

Table 1 below, taken from Dr Cooper's report, gives an overview of the quantities and activities of NORM produced annually.

**Table 1: Quantities and Activity Concentrations of Wastes, Residues and Products Containing NORM<sup>1</sup>**

Radionuclide content (Bq kg <sup>-1</sup> ) <sup>2</sup>	Quantity produced annually		
	Small (< 1 kt)	Moderate (1 kt – 100 kt)	Large (> 100 kt)
0 – 1000 <sup>3</sup>	Oil (sands and sludge) Oil (hard scales and films)	Oversize from secondary mineral sands separation	Titanium dioxide pigment, neutralised titanium slurries & solids from effluent treatment Mineral sands tailings Phosphogypsum Heavy minerals (concentrate, ilmenite, rutile, zircon) & synthetic rutile Red mud Superphosphate & phosphate rock Bottom ash & fly ash - coal Building materials & building/demolition waste Ores (eg coal, bauxite, iron ore) & virgin excavated natural material (VENM) Water treatment sludge
1000 – 5000	Oil (sands and sludge) Oil (hard scales and films)	Oversize from secondary mineral sands separation Dust from secondary mineral sands separation Phosphoric acid	Heavy minerals (concentrate, ilmenite, rutile, zircon) Solids from effluent treatment (titanium dioxide pigment production) Red mud Superphosphate & phosphate rock
5000 – 20000	Oil (sands and sludge) Oil (hard scales and films)	Dust from secondary mineral sands separation. Tantalum concentrate	Tails from secondary mineral sands separation
> 20000	Oil (hard scales and films)	Tantalum concentrate Monazite concentrate	Tails from secondary mineral sands separation

<sup>1</sup> This table is intended to provide a summary of typical radionuclide concentration in different kinds of wastes, residues and products and the quantities produced. It is not intended to indicate a categorisation system for regulation.

<sup>2</sup> Activity concentration ranges are for individual radionuclides, for example U-238, Th-232, Ra-226.

<sup>3</sup> UNSCEAR 2000 Annex B, *Exposures from Natural Radiation Sources*, indicates that typical mean background levels for soils and rocks range from 30-50 Bq.kg<sup>-1</sup>. The UNSCEAR 2000 Report to the General Assembly also states that “The level of natural exposure varies around the globe, usually by a factor of about 3. At many locations, however, typical levels of natural radiation exposure exceed the average levels by a factor of 10, and sometimes even by a factor of 100”.

## 6. NORM IN COMMODITIES

NORM occurs in a range of commodities derived from natural materials. These include granite and basalt, which are widely used as building materials, plasterboard or soil conditioner containing phosphogypsum, thoriated gas mantles, thoriated tungsten welding rods, luminous paint on clocks and dials, static eliminators, refractory bricks, ceramics, sandblasting grit, magnesium-thorium alloy (used in the aircraft industry), uranium glass, depleted uranium in armour-piercing ammunition, uranium ballast in aircraft and yachts, and titanium dioxide pigment.

Commodities containing NORM are in some instances imported into Australia. For example, phosphogypsum is imported from China and Indonesia for use in plasterboard.

A waste can become a commodity, depending on demand and economic factors, or on regulatory definitions, which can vary between jurisdictions. Red mud from bauxite processing is generally regarded as a waste, but in some circumstances it has been used for improving the water retention properties of sandy soils (Cooper et al, 1995).

In the case of bulk NORM materials, exposures generally involve a small number of people, but the exposure levels can be significant. For example, bulk quantities of zircon containing up to 5,000-10,000 Bq kg<sup>-1</sup> of <sup>238</sup>U and <sup>232</sup>Th can potentially give rise to significant external doses, if no precautions are taken. However, in the case of products containing NORM, the number of people exposed may be large, but the quantities of NORM are generally small. For example, when zircon is used in tile glaze, the layer of glaze is usually approximately 0.3 mm thick, with exposure time (eg in a bathroom) generally less than one hour per day. The resulting doses are of the order of a few tens of microsieverts per year (O'Brien et al, 1998).

NORM, usually in the form of radium isotopes, can be found in mineral water and underground water used for drinking. The Australian Drinking Water Guidelines (NHMRC/ARMCANZ, 2001) recommend acceptable activity concentrations for radium and other radionuclides in drinking water because prolonged exposure may pose a hazard. Similarly, activity concentration limits for radium and other radionuclides in bottled water are set via the Australia New Zealand Food Standards Code (FSANZ, 2000), as amended.

### PHYSICAL AND CHEMICAL FORM ISSUES

There is a wide range of physical and chemical properties of both individual radionuclides within each of the naturally occurring decay chains, and the materials comprising commodities. These differences can significantly influence environmental pathways and exposures.

For example:

- Radon (<sup>222</sup>Rn) is a gas, so it can be exhaled from the material into the atmosphere and then dispersed.
- Radium (Ra) isotopes are much more soluble than uranium (U) isotopes in the natural environment. This can result in selective dissolution of Ra in surface water and ground water.
- Polonium-210 (<sup>210</sup>Po) is volatile at smelter temperatures. This can result in the release of <sup>210</sup>Po to the atmosphere.
- Uranium-238 (<sup>238</sup>U) has a half-life of 4.5 billion years

- Polonium-214 ( $^{214}\text{Po}$ ) has a half-life of 164 microseconds
- The large differences in the energy emitted as a result of radioactive decay of different radionuclides means that the radiological impact of different radionuclides is highly variable.
- Most of the anthropogenic radionuclides emit beta/gamma radiation, but many NORM radionuclides emit alpha particles, which pose a much greater potential radiological hazard if the radionuclides are inhaled or ingested.
- Chemical toxicity issues also arise, particularly with the very long-lived radionuclides (e.g. uranium in the kidney).
- Fertiliser, which contains uranium, is specifically chosen to enhance uptake by plants because of its solubility, whereas zircon tile glaze (also containing uranium) is highly insoluble.

In some circumstances, commodities containing NORM pose an inhalation risk. Examples of this are

- *thoriated tungsten welding rods.*  
Welding with thoriated tungsten welding rods can produce very fine particles containing thorium which are readily suspended in air and inhaled. Grinding of the welding rods to produce a fine point prior to each use also produces dust. Therefore adequate ventilation is required when working with these welding rods.
- *thoriated mantles in gas lamps.*  
Thorium gas mantles are used because of the intense white light they produce. However, these mantles are easily broken to produce a fine powder which is readily suspended in air. The use of mantles containing cerium or yttrium rather than thorium has been encouraged in recent years, but thorium mantles are still widely available.
- *exhalation of radon from phosphogypsum plasterboard.*  
This can be reduced by the use of covering materials such as paint and cardboard. (O'Brien et al, 1995).

In other cases the potential risk is from external exposure (eg zircon-glazed tiles).

The physical and chemical forms of the materials containing the radionuclides are important as they affect the mobility of radionuclides in the environment and the relative impact of different exposure pathways.

## **7. INTERNATIONAL RADIATION PROTECTION GUIDELINES & REGULATORY ISSUES**

### **PRINCIPLES OF RADIATION PROTECTION**

The International Commission on Radiological Protection (ICRP) believes that any exposure to ionizing radiation may be potentially harmful to health, and advocates three fundamental principles for managing radiation exposures:

- ***Justification***

No activity involving ionizing radiation for any purpose can be justified unless it is possible to demonstrate that it will lead to a positive net benefit.

- ***Optimization***

The magnitude of individual exposures, the number of people exposed and the likelihood of incurring exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account (the ALARA principle).

- ***Limitation***

No individual is to be exposed to a radiation risk that is judged to be unacceptable in any normal circumstances.

The ICRP recognizes that everyone is subject to a significant background radiation exposure. However, even smaller-than-background doses from occupational practices are unjustifiable if there is no associated benefit, or they can be readily avoided. The situation with NORM is complicated by the fact that NORM is a major contributor to background radiation, and natural background levels are highly variable.

A further issue in interpreting the ICRP principles is that people can have different perceptions on what is acceptable or reasonably achievable. Discussion of these issues will help to determine what is acceptable and reasonable for Australia.

## **CURRENT INTERNATIONAL REGULATIONS AND GUIDELINES**

In the United Kingdom, the current regulatory controls, the Ionising Radiation Regulations 1999 (UKIRR, 1999), do not specifically address NORM.

A joint set of recommendations has been developed by the Nordic countries Denmark, Finland, Iceland, Norway and Sweden (RPA, 2000). These recommendations cover radon in air in dwellings and workplaces, natural radioactivity in drinking water, and exposure from gamma radiation in building materials.

In Canada, guidelines have been developed for the management of NORM, covering material management, radiation protection, waste management and transport. The guidelines (CanNORM, 2000) include Derived Working Limits for the workplace.

In the USA, there are variations in approaches to management of NORM between jurisdictions. The US EPA has published guidelines on NORM which, at the request of Congress, were evaluated by the National Academy of Science (NAS). The NAS review was reported to Congress with the EPA's response (EPA, 2000). The NAS Committee found that there were differences in NORM guidelines among federal, state and other agencies. The Committee found that these differences in guidelines represented differences in risk management policies, rather than differences in the technical evaluation of NORM.

The ICRP has published guidelines on the disposal of long-lived solid radioactive waste, which are applicable to NORM (ICRP, 1998).

The International Atomic Energy Agency (IAEA) has produced a range of publications, including Technical Reports and Safety Series documents, related to remediation and characterisation of contaminated sites. Most of these publications are not specific to NORM issues.

In summary, it appears that there is no systematic approach to regulating NORM.

## **EXEMPTION DEFINITIONS AND EXCLUSIONS**

One of the difficulties in considering NORM issues is that they must always be put in the context of natural background radiation levels. The fact that natural background levels vary considerably throughout the world further complicates the issue, as material can have activity concentrations comparable with local natural background levels in one area but quite different from the natural background levels in other areas. This makes it difficult for regulators to define the level at which regulatory action is required.

The IAEA has, until recently, focussed mainly on the anthropogenic radionuclides resulting from nuclear weapons testing and the nuclear fuel cycle. Uranium mine wastes have been included, but other forms of NORM have not been specifically discussed in IAEA publications. The IAEA recommendations on exemption limits for example, have been based on the assumption of zero background and on moderate quantities of material, which is appropriate for the anthropogenic radionuclides, but causes some problems with wastes from the nuclear fuel cycle, and may not be appropriate for NORM, where bulk quantities of materials have to be considered.

## **8. TRADE ISSUES**

Developing Australian requirements for regulatory controls with regard to NORM in isolation from the international community could lead to difficulties in trade for Australian mineral producers and processors.

Council is aware the mining industry has a concern regarding regulation of NORM, including the potential effects of a draft IAEA Safety Guide (DS161 - *Application of the Concepts of Exclusion, Exemption and Clearance*), which proposes exemption levels for bulk materials including those containing NORM.

Industry is also concerned that there is a trend towards lowering the levels at which regulations apply, and that international recommendations should not be adopted without consultation with industry. Council understands that another significant issue for NORM producers arises from differences in regulatory regimes between countries engaged in international trade, and differences between jurisdictions within Australia.

Council notes that:

- exports of minerals and processed material containing NORM are an important component of Australian overseas trade (over \$1 billion per annum);
- the industry is concerned that the exemption levels proposed in the IAEA draft (DS161) are lower than those currently regulated under the Transport Code (ARPANSA, 2001);
- the proposed exemption levels could lead to material currently not regulated being defined as radioactive material;
- difficulties in shipping some minerals have already been encountered, particularly denial of service by shippers for materials labelled as “radioactive”.

## 9. AUSTRALIAN RADIATION PROTECTION REGULATIONS AND GUIDELINES

### CURRENT REGULATORY REQUIREMENTS

Each State and Territory and the Commonwealth Government has a regulatory system for radiation protection, including the use of radioactive materials. In each jurisdiction the regulations include exemption limits on, for example, the total activity and activity concentration of radioactive material to be regulated. However, there is no uniform regulatory approach to NORM issues within Australia. For example, across different jurisdictions there is a wide range of exemption levels. What is exempt in one jurisdiction may be regulated in another.

Table 2 below shows the activity levels used as part of the exemption criteria in each jurisdiction. In some jurisdictions, there are additional exemption provisions, such as limits on activity concentration or definitions of ‘mineral substances’. The inconsistency in what is regulated is an important matter that is to be addressed via the National Directory for Radiation Protection, which is being developed by ARPANSA via the Radiation Health Committee to establish a uniform regulatory framework for radiation protection in Australia, and agreed regulatory elements for adoption in all jurisdictions.

These variations in regulatory definitions also introduce difficulties when transporting NORM commodities across national or jurisdictional boundaries.

**Table 2. Comparison of Activity Exemption Levels**

NUCLIDE	HALF LIFE	IAEA BSS	AUSTRALIAN JURISDICTION								
			ACT	ARPANSA	NSW	NT	QLD	SA	TAS <sup>4</sup>	VIC	WA
		Total MBq	MBq	MBq	MBq	MBq	MBq	MBq	MBq	MBq	MBq
K-40	1.28 × 10 <sup>9</sup> y	1		1			1				
Th-nat (inc. Th-232)	1.4 × 10 <sup>10</sup> y	0.001	4	0.001	40		0.001	5		4	4
Th-232 series											
Th-232	1.4 × 10 <sup>10</sup> y		4		40			5			
Ra-228	5.75 y	0.1	0.004	0.1	0.04		0.1	0.005			
Ac-228	6.13 h	1	0.04	1	0.4		1	0.05			
Th-228	1.91 d	0.01	0.004	0.01	0.04		0.01	0.005			
Ra-224	3.66 d	0.1	0.04	0.1	0.4		0.1	0.05			
Rn-220	55.6 s	10		10	4		10	0.5			
Pb-212	10.6 h	0.1	0.04	0.1	0.4		0.1	0.05			
Bi-212	60.55 m	0.1	0.4	0.1	4		0.1	0.5			
U-nat		0.001	4	0.001	40		0.001	5		4	4
U-238 series											
U-238	4.47 × 10 <sup>9</sup> y	0.01	4	0.01	40		0.01	5			
Th-234	24.1 d	0.1	0.04	0.1	0.4	3.7	0.1	0.05			
U-234	2.44 × 10 <sup>5</sup> y	0.01	0.004	0.01	0.04		0.01	0.005			
Th-230	7.70 × 10 <sup>4</sup> y	0.01	0.004	0.01	0.04		0.01	0.005			
Ra-226	1.60 × 10 <sup>3</sup> y	0.01	0.004	0.01	0.04	0.037	0.01	0.005		0.0004	0.0004
Rn-222	3.8235 d	100	0.4	100	4		100	0.5			
Pb-210	22.3 y	0.01	0.004	0.01	0.04	0.037	0.01	0.005			
Bi-210	5.01 d	1	0.04	1	0.4		1	0.05		0.04	0.04
Po-210	138 d	0.01	0.004	0.01	0.04	0.037	0.01	0.005		0.004	0.004

<sup>4</sup> The Tasmanian regulations exempt a natural material with concentration less than 31 Bq/g, but do not have an activity limit. Exemptions for individual radionuclides are based on 1/2000<sup>th</sup> of the most restrictive Annual Limit on Intake (ALI) for that radionuclide. As ALI are based on ingestion/inhalation pathways only, the limits are very restrictive when compared with systems that take into account a range of exposure scenarios.

The offshore storage and disposal of NORM produced during the normal operation of offshore petroleum production facilities in Commonwealth waters is regulated by the *Petroleum (Submerged Lands) Act 1967* through the *Petroleum (Submerged Lands) (Management of Environment) Regulations 1999*, the *Petroleum (Submerged Lands) (Management of Safety on Offshore Facilities) Regulations 1996*, and the *Petroleum (Submerged Lands) (Occupational Health and Safety) Regulations 1993*. In addition to the requirements of the *Petroleum (Submerged Lands) Act*, the *Environment Protection and Biodiversity Conservation Act 1999* may also require proponents to consider the possible impacts on the disposal of NORM on matters of national environmental significance.

The regulatory situation is complicated by the fact that possible exposures to workers and members of the public from NORM can vary considerably for the same material, depending on the exposure conditions. Most NORM commodities are transported in bulk, but in many cases, eg plasterboard, glazes, sand-blasting grit, the NORM is present in products only in small quantities. This means that a range of possible exposure scenarios must be considered when assessing the effects of NORM on the environment and on human health.

While all jurisdictions have regulations that deal with radioactive wastes and residues in general, and environmental regulations that deal with dust emissions, there is no uniform approach on regulation of NORM wastes and residues, and no national guidance on the management of these wastes and residues.

Another issue is the existence of sites that are contaminated as a result of historical operations. In these situations, where the original operator may not exist or may have no clear legal obligations, the assignment of responsibility for any necessary remedial action may present difficulties.

## **INDUSTRY GUIDES**

Council has been made aware that there are a number of guidelines on NORM management within specific industries. For example, Smith (1992) has reported on NORM in the USA petroleum industry, and Australian Petroleum Production and Exploration Association Limited has published guidelines for the oil industry (APPEA, 2002). The APPEA Guideline provides guidance on NORM monitoring, management of occupational radiation exposures and decision-making regarding NORM waste disposal. APPEA recommended a similar approach to that used in the uranium mining and milling and heavy mineral sands industries.

## **OPTIONS FOR ESTABLISHING NORM MANAGEMENT CRITERIA**

### ***Application of ALARA***

There are substantial variations in natural background levels, and wide ranges in the radionuclide concentrations in existing products, commodities and wastes containing NORM. Therefore, establishing limits may be less effective than optimisation when dealing with NORM. Optimisation, which involves application of the ALARA principle, requires consideration of a range of factors, including social and economic impacts, of any NORM management strategy.

### ***Risk-based assessment***

In principle the risk-based assessment approach is the most desirable, but the wide range of situations in which exposures to NORM can occur make it difficult to develop a single, standard approach. In many of these situations, particularly where relatively small quantities of NORM are involved, it is possible to make an assessment of potential risks by analogy with the natural background occurrence of NORM (for example, fertiliser spreading, radon exhalation and/or emission of gamma radiation from granite slabs or clay bricks). Estimation of NORM dose/risk as

a fraction or multiple of the natural background dose/risk is another possible approach. The process of risk assessment depends on the hazard and can be simple or detailed.

### ***Activity concentrations vs other approaches***

The simplest approach is to use activity concentration as the basis for any required action. As already pointed out, this may not be satisfactory due to the wide variations in the amounts of NORM to which workers, the public and the environment can be exposed in different situations involving the same material.

## **10. ISSUES AND OPTIONS FOR DEALING WITH NORM WASTE**

### **ISSUES FOR MANAGING NORM WASTE**

The major issues for managing NORM waste include:

- ***Accepted guidelines*** - There are no clear, widely accepted guidelines setting exclusion, exemption and clearance levels for NORM waste. Options for establishing such criteria include constraints on activity concentration, risk or dose. Variation in the background radiation levels can complicate this decision-making process.
- ***Methods of disposal*** - There is no clear national or international agreement on acceptable methods of disposal of NORM waste. There are various options for disposal of NORM waste, each of which has advantages and disadvantages.
- ***Measurement*** - Pipe geometry can affect the capacity of the oil and gas industry to assess whether the level of radioactivity in scale inside pipes, pumps, valves and other equipment requires remedial action.
- ***Environment*** - The effects of ionizing radiation on non-human species have only recently received attention from the scientific community. The traditional approach was to assume that if humans were protected then all other species were automatically protected. As a first step in evaluating the effects of ionizing radiation on other species, ICRP has published guidelines on assessing these effects (ICRP, 2002).
- ***Occupational health*** - Management of materials containing NORM can lead to occupational health issues. In some industries these issues are already being addressed; for example, in the oil and gas industry radiation protection measures are implemented for staff undertaking maintenance on NORM contaminated equipment. In industries where NORM has not been recognised as a potential issue, occupational health matters may not be adequately addressed.
- ***Public health*** - The use of products containing NORM, or the disposal of NORM bearing wastes may give rise to public health issues. For example, there is potential for issues to arise in industries where awareness is low and no NORM management procedures are implemented. With some NORM-containing products, such as thorium gas mantles, warnings must be provided to reduce the potential for inhalation of the fine dust that can result from damaged mantles, and manufacturers are encouraged to produce non-radioactive alternatives, where possible.
- ***Contaminated sites*** - In 1985 the NHMRC published a statement "Guidelines for Remedial Action in Areas where Residues from Mineral Sand Mining and Processing have been

Deposited” (NHMRC, 1985). Council notes that the NHMRC statement was published some 19 years ago. Since that time radiation protection standards have changed considerably. There has been very little published in Australia on criteria for clean up of sites contaminated with radioactive material. Internationally, the IAEA has published some documents on this subject and others are in preparation (Falck, 2001). ICRP (1998) has also published recommendations on the disposal of long-lived solid radioactive waste, which are relevant to remediation of contaminated sites. Council considers that there may be a requirement for the development of appropriate guidance on remediation criteria for sites contaminated with radioactive materials, including review of the 1985 NHMRC statement. This should take account of the IAEA, ICRP and other relevant guidelines.

## OPTIONS FOR DISPOSAL OF NORM WASTE

Current (and historical) options for disposing of NORM wastes include disposal into on-site landfill, down-hole disposal into old oil wells that are subsequently plugged with concrete, near-surface disposal on mine site or oil well leases, dilution in industrial waste disposal facilities, 'Land farming' (dilution by ploughing in over a gazetted disposal area), incorporation into concrete for building construction or road base, dilution and burial in on-site land contouring, disposal into mined out underground mine stopes being backfilled with cemented fill, and disposal into mine tailings dams. Cassels and Waite (2001) have discussed disposal of NORM wastes from petroleum exploration in the Northern Territory by ocean-floor dumping. Veil et al (1998) have discussed disposal of NORM contaminated oil-field wastes in salt caverns.

### *Assessment of Exposure Pathways for Different Disposal Options*

There are five groups of pathways that can lead to exposure of humans. These are:

- external,
- suspension or re-suspension of dust particles,
- radon exhalation,
- transport by surface (including ocean) water, and
- transport by ground water.

Table 3 below is a guide as to which pathways may be relevant for different NORM disposal methods.

**Table 3. Disposal Options**

Disposal option	External	Dust	Radon	Surface water	Ground water
Land-fill	Yes	Yes	Yes	Yes	Yes
Down-hole	No	No	No	No	Yes
Near-surface	No	No	Possibly	No	Yes
Dilution in industrial waste disposal facilities.	Possibly	Possibly	Possibly	Possibly	Yes
'Land farming'	Yes	Yes	Yes	Yes	Yes
Incorporation into concrete	Yes	No	Yes	No	No
Dilution and burial in on-site land contouring	Yes	Yes	Yes	Yes	Yes
Mine back-filling	No	No	Yes	No	Yes
Tailings dams	Yes	Possibly	Possibly	Yes	Yes

## **“Concentrate and Contain” vs “Dilute and Disperse”**

Two general approaches to radioactive waste management are to “Concentrate and Contain” and to “Dilute and Disperse”. The concentrate and contain approach involves concentrating the radionuclides in the material into a smaller volume which can then be contained in an appropriate radioactive waste management facility. The dilute and disperse approach is to mix the waste with uncontaminated material until the radionuclide concentration reaches a level where it can be released directly to the environment without any adverse impacts. Both approaches have advantages and disadvantages, and the issue of which is more appropriate for NORM contaminated materials may become increasingly important as awareness of NORM issues grows.

For example, while ocean dumping has been traditionally seen by some as an example of “dilute and disperse”, recent evidence from North Sea sites suggests that some material settles to the sea bottom, rather than dispersing. It is also known that small marine creatures and plants can concentrate heavy metals, either dissolved in water as organic compounds or absorbed on to seabed sediments, thus introducing these contaminants into the food chain. Examples of this type of problem are the Minimata episode, when hundreds of Japanese died from the effects of years of eating seafood contaminated by methyl mercury compounds, and data from Wales, Ireland and the west coast of England on the concentration of ruthenium-106 and technetium-99 in seaweed and marine creatures. As a result, the Irish government has sought redress against the UK under the Law of the Sea for allowing liquid radioactive waste from Sellafield to flow into the Irish Sea. The Western Isles Council has asked the Scottish Environmental Protection Agency to carry out comprehensive tests to reassure farmers that the traditional practice of using seaweed to fertilise crops is safe. The Norwegian RPA testing (Brown et al, 1998) has found Tc-99 levels ranging from 0.1 to 7 Bq/m<sup>3</sup> in the North Sea and adjoining waters, and levels up to 42 Bq/kg wet weight in lobster. NRPA has measured Tc-99 levels as high as 510 Bq/kg (dry weight) in seaweed. This is approaching the European Union limit for food of 600 Bq/kg.

It should also be noted that ocean dispersal does not inevitably lead to biological concentration. The NRPA (2001) notes that levels of Cs-137 in its ocean waters range from 3 to 23 Bq/m<sup>3</sup>, but the levels in fish are below 1 Bq/kg, while the levels in lobsters and mussels are below 0.4 Bq/kg.

Burial (and possibly landfill) is an example of “contain”, because of the low rate of migration of radionuclides in soil. This option also has to be treated cautiously, because radionuclides that can dissolve readily in groundwater can disperse quickly and find their way into the food chain. The Near Surface Disposal Code (NHMRC, 1993) specifies low rainfall areas with deep water tables as desirable for near surface disposal of low-level waste, to minimise dispersion.

## **DISPOSAL APPROACHES BY AUSTRALIAN JURISDICTIONS**

### ***New South Wales***

In NSW, a radioactive waste is a hazardous waste if the activity concentration is greater than 100,000 Bq kg<sup>-1</sup> and the total activity exceeds either 40kBq, 400kBq, 4 MBq, or 40 MBq, depending on the radiotoxicity classification in Schedule 1 of the *Radiation Control Regulation 1993*. The consequence of becoming captured as a hazardous waste under the *Protection of the Environment Operations Act (Waste) Regulation 1996* is severe, as there is no approved final in-state disposal site.

### ***Queensland***

Under the *Radiation Safety Regulation 1999*, the disposal of radioactive material into the air, water or sewerage system is allowed without the approval of the regulatory authority provided that the concentration of the radionuclide is not more than the concentration stated in the regulations. The disposal of a mineral substance, other than into the air, water or sewerage system, may occur, without the approval of the regulatory authority, if:

- (a) the gross alpha and gross beta concentrations in the leachate is less than 10 times the concentration stated in the NHMRC and ARMCANZ 'Australian Drinking Water Guidelines'; and
- (b) the concentration of the material is less than 10 times the IAEA Exemption levels.

For all other disposal into the environment, a person must apply to the regulatory authority for an approval to dispose of the radioactive material. In this case, the applicant will be asked to demonstrate that no person in the critical group will receive in excess of 300microsieverts in a year as a consequence of the disposal.

***South Australia***

Unrestricted disposal of materials containing radionuclide concentrations under 35,000 Bq kg<sup>-1</sup> is allowed. Wastes containing radionuclide concentrations over 35,000 Bq kg<sup>-1</sup> may be disposed of by burial if exemption is granted, based on dose estimates. Approval was granted in the past for disposal of wastes from an old radium refinery and uranium pilot operations, into the tailings dam of the former uranium mine at Radium Hill.

***Victoria***

Victoria allows disposal on the basis of modelling scenarios that demonstrate that doses to members of the public will be 0.01 mSv per year or less. A NORM waste disposal facility is being planned at Dutson Downs, near Sale.

***Western Australia***

Unrestricted disposal is allowed for radionuclide concentrations under 30,000 Bq kg<sup>-1</sup>, or (for mine sites) for modelling scenarios which predict doses to workers under 1 mSv per year and doses to members of the public under 0.5 mSv per year. The W.A. Dept. of Housing and Works operates an Intractable Wastes Disposal Facility at Mt Walton (100 km NW of Kalgoorlie), which accepts radioactive wastes including from industry and sealed sources from hospitals, but is legally prevented from accepting wastes produced outside W.A.

## 11. ISSUES FOR DISCUSSION

NORM is widely distributed throughout a range of industries and situations. It can occur in process waste streams, bulk commodities and commercial items. Awareness of NORM issues is limited in some industries, which may lead to circumstances where appropriate precautions are not taken.

There is no consistent approach within Australia either in relation to the level of radioactivity at which regulation should commence, or in relation to the management of NORM wastes and commodities. This is similar to overseas experience, where approaches vary in different countries. In particular, there is no national guidance on the use, transport, treatment and disposal of NORM.

**Council seeks comment from interested parties on NORM issues in Australia, in particular on whether there is a need to:**

- Develop national guidance on exclusion, exemption and clearance for natural radioactive materials, to enable a uniform approach to establishing criteria that may be used to regulate NORM in all jurisdictions. The guidance would take the existence and variability of the natural background into consideration, and also allow for the wide range of scenarios that can lead to exposure to ionizing radiation from materials containing NORM.
- Develop national guidance on strategies and criteria for the treatment and disposal of NORM arising from various process waste streams, including by landfill or land spreading.
- Develop guidance for remedial action at sites contaminated by historical NORM waste generation, including reviewing the 1984 NHMRC statement “Guidelines for Remedial Action in Areas where Residues from Mineral Sand Mining and Processing have been Deposited” to ascertain whether the information is still relevant and, if necessary, re-publish up to date guidance within the Radiation Protection Series.
- Develop a strategy for raising awareness of NORM issues, both in relevant industries and with the public generally.

## 12. CONSULTATION AND ACKNOWLEDGEMENTS

In developing this discussion paper, Council received presentations at its meetings from Mr David Hamilton of Esso and Mr Kevin O’Keefe of Sons of Gwalia, to provide industry views of NORM issues, and Mr Mark Sonter of NSW EPA Radiation Control Section, to provide a regulator’s view of NORM issues.

Mr Hamilton and Mr Sonter also participated in discussion with Council and ARPANSA officers (Mr Peter Burns, Dr Richard O’Brien and Ms Sandra Sdraulig).

Dr. Malcolm Cooper was contracted to provide Council with a report on the quantities of NORM waste existing in Australia and the quantities arising annually in various industries.

During the consultation phase, submissions were received from the following 18 organisations:

<b>ORGANISATION</b>
Dept of Business, Industry and Resources Development, NT
Dickson Research Pty Ltd
National Generators Forum
WA Dept of Industry & Resources
Australasian (Iron and Steel) Slag Association Incorporated
Energy Supply Association of Australia
Ash Development Association of Australia
Esso Australia Pty Ltd
Radiological Council of WA
Alcoa World Alumina Australia
Dept of Industry Tourism and Resources
Australian Aluminium Council
Radiation Detection Systems, SA
Dept of Environment & Conservation (NSW)
WMC (Olympic Dam Corporation) Pty Ltd
Australian Nuclear Science & Technology Organisation
Australian Petroleum Production & Exploration Association Limited
Geoscience Australia

## 13. GLOSSARY & ABBREVIATIONS

<b>ALARA</b>	As Low As Reasonably Achievable, economic and social factors being taken into account
<b>APPEA</b>	Australian Petroleum Production and Exploration Association Limited
<b>ARMCANZ</b>	Agricultural and Resource Management Council of Australia and New Zealand
<b>Decay chains</b>	serial chains of radionuclides, each of which undergoes radioactive decay to produce the next member of the chain
<b>IAEA</b>	The International Atomic Energy Agency

<b>ICRP</b>	The International Commission on Radiological Protection
<b><math>\mu</math>Sv</b>	microsievert ( $10^{-6}$ Sievert)
<b>mSv</b>	millisievert ( $10^{-3}$ Sievert)
<b>NAS</b>	National Academy of Sciences (USA)
<b>NHMRC</b>	National Health and Medical Research Council
<b>NORM</b>	Naturally Occurring Radioactive Material
<b>Sievert</b>	the unit of effective dose, i.e. energy absorbed per unit mass of tissue, corrected for radiation type and tissue type (Joule $\text{kg}^{-1}$ )
<b>TENORM</b>	Technologically-Enhanced Naturally Occurring Radioactive Material
<b>USEPA</b>	United States Environmental Protection Agency

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### INDUSTRY PROCESSES

#### MINERAL SANDS PRODUCTION

The mineral sand components of major commercial importance are the titanium bearing minerals (ilmenite, leucosene and rutile), zirconium bearing (zircon), and rare earth bearing minerals (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.

Ilmenite and rutile are used to produce titanium dioxide pigments for the paint, paper and plastics industry, and for the production of titanium metal. Zircon, zirconia and zirconium products are used 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.

Apart from the mining overburden, primary processing of the ore at the mine site produces several waste materials. Some of these materials are returned to the mined out pit for disposal, after drying if necessary. The remaining solid waste is disposed of in dedicated landfill sites, or recycled as road base or fertiliser. Any waste slurries are discharged into a retaining pond for disposal.

At present, monazite concentrate is not usually marketed but is returned to the mine site for blending with mine sand tailings and disposal into the mine pit. Apart from those heavy minerals that contain uranium and/or thorium within the mineral structure, the radioactivity levels in waste material depend mainly on the monazite content of the original ore, which can vary considerably depending on the location of the ore body. Monazite is a mineral consisting of rare earth elements and thorium (about 6%) and uranium (< 1%).

#### DOWNSTREAM PROCESSING OF MINERAL SANDS PRODUCTS

Downstream processing includes rare earth production, zircon smelting etc. Products of downstream processing include sandblasting grit, ceramics, glazes, and foundry industry refractories. The excellent metallurgical properties of zirconium, plus the refractory and other properties of zirconia, make the processing of these materials much more widespread than those mentioned above. Processes include a high temperature treatment, chemical purification, and the manufacture of items such as refractory bricks, nozzles and dielectric materials. The materials are also used in ceramic glazes and in high temperature casting.

When these materials are moved or otherwise manipulated there is a potential for dust levels to increase and for inhalation of radioactive material to be an issue. Control techniques typically include ventilation and local extraction to keep dust levels within manageable proportions. Experience to date indicates that this is not always totally effective, and the use of respiratory protective equipment such as dust masks, respirators or powered face masks is necessary in some cases to keep exposures as low as reasonably achievable.

When the material is heat treated, this drives off the more volatile radioisotopes of polonium and lead. These tend to deposit in the cooler parts of effluent ducting and in bag houses or precipitators.

Polonium-210 concentrations can exceed 600,000 Bq kg<sup>-1</sup>. These deposits do not give rise to external dose rates but pose a potential inhalation risk. The main issue is disposal. However maintenance of off-gas ductwork can also be an issue because of the potential for exposure to fine dusts containing volatile radionuclides.

### ***Titanium dioxide pigment production***

Rutile and ilmenite are the major sources of titanium dioxide pigment. Australia's annual production of titanium dioxide pigment was approximately 185 kilotonnes in 2001-02. Titanium oxide is extracted from rutile and synthetic rutile using either a chloride process or by sulphuric acid extraction. The chloride process has become the preferred technology because of the lower environmental impacts caused by the disposal of the resulting waste effluents. There was a titanium dioxide pigment production plant in Tasmania; however, this plant closed down several years ago.

Both solid and liquid wastes result from the chlorination and condensation stages of processing. The solid waste is slurried for transport and dried in evaporation ponds before final disposal to landfill. Liquid effluent is treated and discharged to the ocean. Solids from the effluent treatment are also used as landfill.

Traces of uranium and thorium and radioactive progeny are present in the original rutile and synthetic rutile minerals. The radionuclides follow the solid waste stream during processing. Titanium oxide pigments do not contain detectable levels of radioactivity.

### ***Zircon refining***

Zirconium is an abundant element present as silicate in zircon mineral and as oxide in baddleyite ore. Zircon is used in the manufacture of steel refractory materials and dielectric materials, in glazes, glasses and ceramics, and in special alloys.

Zirconium oxide (zirconia) is produced by high temperature fusion of zircon. Zirconium metal manufacture involves a chlorination process to convert zirconia to zirconium chloride, which is then reduced to the metal. Zircon sand is fused with alumina and sodium carbonate to make refractory bricks for steel and glass furnaces.

Dry milling or fusion of zircon produces dusts and fumes 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.

The zircon mineral contains trace amounts of uranium and thorium within the mineral structure. Typical activities of uranium and thorium in Australian zircon are around 4,000 Bq kg<sup>-1</sup> and 1,000 Bq kg<sup>-1</sup> respectively with equilibrium between radionuclides within their respective decay series. Because zircon is used directly in the manufacture of refractory materials and glazes, the products will contain similar concentrations of radioactivity. Higher concentrations may be found in zirconia. In the fusion of zircon the more volatile radionuclides, for example <sup>210</sup>Pb and <sup>210</sup>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.

## **BAUXITE PROCESSING (ALUMINIUM PRODUCTION)**

The main mineral source of aluminium is bauxite, which contains 30 to 50% hydrated aluminium oxide. Australia is the world's largest producer of bauxite (~40%), with a current annual production of about 58 million tonnes in 2003. Australia's five bauxite mines operate at Gove, Boddington, Huntly, Willowdale and Weipa. Bauxite is refined to produce alumina (anhydrous aluminium

oxide). The 2003 annual production of alumina in Australia was approximately 17 million tonnes, with most of the production (~80%) being exported. The remainder of the alumina is smelted to produce aluminium ingots for fabrication into a range of industrial and domestic products. Approximately 1.8 million tonnes of ingots are produced annually in Australia.

The production of aluminium metal involves electrolysis of the alumina in a mixture of fluoride salts, contained in carbon cells.

The main solid residues from the alumina production are 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 0.3 and 2.5 tonnes of red mud produced per tonne of alumina, depending on the grade of bauxite. It is estimated that more than 20 million tonnes of red mud and other solid residues are produced annually from alumina production in Australia. Disposal of these residues commonly takes place by spreading in layers over a large area to allow the material to dry prior to rehabilitation and then covering the residues with sand and revegetating the surface.

The main liquid residues arising from the washing of solid residues, and from settling ponds, are recycled as process water. Leachates from the disposal areas are collected and returned to production 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.

The original bauxite ores can contain significant levels of natural radioactivity due to both uranium ( $^{238}\text{U}$ ) and thorium ( $^{232}\text{Th}$ ) and their decay products. Some of the radioactivity may be associated with trace quantities of other minerals, such as ilmenite or monazite. Levels of  $^{238}\text{U}$  and  $^{232}\text{Th}$  can range from 10-9,000 Bq.kg<sup>-1</sup> and 35-1,400 Bq.kg<sup>-1</sup> respectively, depending on the source of the bauxite ore. Virtually all the radioactivity is transferred to the solid residues, and little, if any, of the uranium or thorium is present in the alumina. There can be a threefold increase in the radionuclide content of red mud compared to the original bauxite mineral. For example, time averaged activity data indicate that total activities for red mud residues are approximately 19,000 Bq.kg<sup>-1</sup> for the Kwinana processing operation, 16,000 Bq.kg<sup>-1</sup> for Pinjarra, and 27,500 Bq.kg<sup>-1</sup> for Wagerup (O'Connor submission on behalf of Alcoa World Aluminium Australia, 2004).

## **COPPER PRODUCTION**

Copper is a metal of major importance, and is mainly used in electrical installations and the electronics industry. Australia is a major producer of copper with a current annual production of around 870,000 tonnes of ore and 520,000 tonnes of refined copper metal. Olympic Dam in South Australia, and Mount Isa, in Queensland, are Australia's largest copper production operations. Other valuable elements, namely silver, gold and uranium are often associated with copper mineralisation because of their similar geochemistry. The copper mineralisation may contain significant quantities of uranium and thorium, especially uranium.

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. In 2001, operations at Mt Isa produced approximately 5,000,000 tonnes of tailings and 200,000 tonnes of copper slag. The Olympic Dam operation presently produces over 200,000 tonnes of copper and over 4,000 tonnes of uranium oxide per annum (ODC submission, 2004). Where commercial quantities of uranium are present (possibly with other minerals) in the copper tailings resulting from the flotation stage,

additional treatment and processing takes place to isolate the valuable elements. The copper waste streams are then combined with the other tails arising from the whole operation, as is the case at Olympic Dam.

Lead-210 ( $^{210}\text{Pb}$ ) and polonium-210 ( $^{210}\text{Po}$ ) (in equilibrium with uranium) 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.

## **TIN/TANTALUM PRODUCTION**

Tantalum mineralisation is sometimes associated with tin-bearing minerals. Tantalum is mainly used in the electronics industry, as a major constituent of capacitors. Australia supplies in excess of 30% of the world market. Processing of the minerals takes place at plants at the mine sites. In 2002-2003 2.5 million tonnes of tantalum ore were processed to produce 2,500 tonnes of tantalum products.

Tantalum is present in pegmatite ore in several possible mineral forms, as complexes with iron, manganese, calcium or antimony. The average grade of tantalum ranges from 0.04 to 0.1%. Other major constituents of the ore include sulphide minerals, and traces of tin, ilmenite and zircon may also be present.

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.

The dry screening and magnetic 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.

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  $60 \text{ Bq kg}^{-1}$  and less than  $5 \text{ Bq kg}^{-1}$ , respectively. After the initial dry and wet separation some uranium and thorium may remain with the concentrates. These radionuclides are removed by acid leaching. Neutralisation of the leach solutions produces a solid tails containing uranium and thorium. The radioactivity levels for uranium and thorium in the tantalum products range from 7,500 to 75,000  $\text{Bq kg}^{-1}$ .

## **IRON AND STEEL PRODUCTION**

Sinter plants and iron blast furnaces use iron ore with coal or coke and limestone to produce molten iron that can be cast into pig iron products for use as feedstock in steel production. Silica and alumina in the ore combine with the limestone to produce a liquid slag. The molten iron product, termed pig iron, is separated and cooled.

The main waste materials in the iron production process are the blast furnace slags and the dusts and fumes collected from the sinter plant and from the off gas cleaning in the blast furnace operation. The ASA advises that approximately 3.1Mt of iron and steel slags were produced in Australasia in 2002. ASA also advised that more than 60% of these iron and steel slag arisings are processed into various finished products and sold into the construction sector. The balance or

surplus is stored on site or used in projects providing some beneficial application (ASA, 2004). Dust is normally disposed of as landfill.

Owing to their geochemical properties, iron ores scavenge radionuclides and heavy metals. There are small concentrations of uranium in each of the feedstocks for iron-making, namely iron ore, coke, and limestone. Because of the volatility of  $^{210}\text{Pb}$  and  $^{210}\text{Po}$ , enhanced concentrations of these radionuclides can occur in the dust collected from the gas cleaning systems.

## **PHOSPHATE ORE PROCESSING**

Phosphate rock is processed to produce fertilisers for agricultural use. Australia's annual production of phosphate rock is approximately 2 million tonnes. Fertilisers are produced in several forms, characterised by their phosphorus content. The production of various forms of phosphate fertilisers requires the acidulation of the phosphate ore with either sulphuric or phosphoric acid.

The annual Australian market for phosphate fertiliser is approximately 4 million tonnes of superphosphate. Some 75 per cent of the Australian market for phosphates is supplied by locally manufactured superphosphate, with the balance supplied by imports of ammonium phosphates. Local production of superphosphate uses ore from Christmas Island and imported ore, mainly from, Jordan, Morocco and USA (Florida). Most of the phosphate fertiliser currently produced in Australia is made at Phosphate Hill as mono-ammonium phosphate and di-ammonium phosphate via phosphoric acid.

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.

Beneficiation of phosphate ore prior to use in fertiliser production can produce clay and sand tailings that are normally used as backfill material at the mine site. The major solid waste/product from the phosphate industry is the large quantity of calcium sulphate (phosphogypsum) arising in phosphoric acid production. Additional waste arises from small quantities of scales deposited in process pipes, filtration tanks and filter parts. The phosphogypsum is stockpiled on site or disposed of as landfill, along with the scale and filter materials. Phosphogypsum can be used in 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. During the period 1986-90, annual production of phosphoric acid and phosphogypsum in Australia were estimated at 100,000 and 400-500,000 tonnes respectively.

Natural phosphate rock contains trace quantities of uranium and thorium incorporated in the structure of the phosphate-bearing mineral. The uranium content is closely related to the phosphorus content. In natural phosphate rock, radioactive equilibrium normally exists between uranium and thorium and their respective radioactive progeny.

**Table 4. Typical Radionuclide Concentrations in Phosphate Rock Used in the Phosphate Industry in Australia**

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

As a result of the treatment of phosphate rock with sulphuric acid, uranium or thorium series radionuclides become partitioned in the product and waste streams depending on the relative solubilities under acid conditions of the compounds containing the radionuclides. For example, approximately 80% of the <sup>226</sup>Ra, 30% of the <sup>232</sup>Th and 14% of the <sup>238</sup>U are left in the phosphogypsum. Uranium and thorium become enriched in the fertiliser to approximately 150% of their original concentration.

Radionuclide concentrations in fertiliser products are highly variable and depend on the radionuclide content of the original ore and the method of production. Fertilisers are generally deficient in <sup>226</sup>Ra relative to <sup>238</sup>U. 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. Therefore individual doses resulting from the use of these products are not enhanced above normal background.

## **BUILDING MATERIALS AND CERAMICS**

Industrial by-products, residues and wastes are widely used as raw materials for the building industry. Recycling of these materials has economic benefits. Concern for potential risks arises where the residues used as raw materials are derived from industries in which NORM contaminated waste is produced.

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

Building materials can contain uranium and thorium and their radioactive progeny due to the natural occurrence of these radionuclides in the raw materials, or where the industrial product, for example zircon in ceramics, or the industrial by-products, such as fly ash and phosphogypsum, contain elevated NORM levels. 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. <sup>40</sup>K will also be present in certain materials because of the stable potassium content of the raw materials used.

There have been several investigations of the radionuclide content of Australian building materials (Beretka et al, 1985; Mathew et al, 1983; Mathew et al, 1984).

## SANDBLASTING

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, the oil and gas industry, engineering workshops, and ship dockyards. Other heavy minerals, principally ilmenite and zircon, derived from the mineral sand industry have also been used for sand blasting. Slag and other waste from metal smelting also find use for sand blasting in these industries. The main waste forms produced are the used sand blasting materials, which may be stockpiled on site awaiting disposal, normally to a landfill.

Garnet used for sandblasting may be contaminated with uranium and thorium and associated radioactive progeny due to the presence of other heavy minerals such as ilmenite, zircon and monazite. An Australian study (Wallace et al, 1987) found garnet sandblasting materials to contain radionuclide concentrations in the range 40,000 to 100,000 Bq.kg<sup>-1</sup> for <sup>232</sup>Th and 15,000 to 30,000 Bq.kg<sup>-1</sup> for <sup>238</sup>U. Ilmenite, containing up to 380 Bq.kg<sup>-1</sup> <sup>232</sup>Th and up to 120 Bq.kg<sup>-1</sup> <sup>238</sup>U, was found to be in widespread use in these industries. Subsequently, some State regulations have limited the uranium and thorium content of sand blasting materials to below 200 Bq.kg<sup>-1</sup>.

## OIL & GAS PRODUCTION

The main NORM issues in the oil and gas industry arise in both on-shore and off-shore production facilities associated with oil and gas reservoirs. 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. The oil/water stream is further treated to remove the geological formation water. For off-shore extraction, this water, also termed production water at this stage, may be treated and discharged to the ocean, or brought on-shore for storage and/or disposal. Sand and oily sludge from the reservoir are also removed during this treatment.

Uranium and thorium compounds are mostly insoluble, and as oil and gas are brought to the surface, remain in the underground reservoir. Radium (Ra) compounds can dissolve preferentially at the high temperatures and pressures encountered in (underground) formation water. When the formation water is brought to the surface with the oil and gas the rapid drop in temperature and pressure causes <sup>226</sup>Ra and <sup>228</sup>Ra to precipitate out, resulting in sludges and hard scales. The highest radium concentrations are found in the hard scales, but the volume of scales is low. In some cases, water is injected into underground reservoirs to maintain reservoir pressure and enhance oil recovery. Chemical incompatibilities between the injected water and the formation water can significantly enhance the volume and activity concentration of NORM scales. In some cases this leads to significant external gamma rates from production equipment. It is noted that this issue does not arise in Victorian oil and gas production because formation water is used for re-injection (Esso submission, 2004).

The oily sludges and sand separated from the oil at an early stage of the process comprise the bulk of the solid waste. The relative amounts of solid waste vary with the production area due to the different geological characteristics of the oil/gas reservoirs.

The annual volume 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 m<sup>3</sup>. Disposal of sludge is by on-shore landfill or dumping at sea direct from off-shore production platforms. 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. It is estimated that 200 tonnes of such equipment is generated annually. On some off-shore platforms, scale removed from pipes and tubulars is ground to a fine powder, slurried with production water and discharged

to the ocean. Another option for tubulars with high activity scales is to dispose of the equipment in a disused well which is then plugged.

Radon gas emanating from the rock formation, or from  $^{226}\text{Ra}$  decay in formation water, is preferentially associated with the natural gas phase and therefore tends to stay with the gas during production stages. Longer-lived decay products of radon (particularly  $^{210}\text{Pb}$ ) can accumulate as thin films and deposits in gas handling equipment and storage tanks. This means that care has to be taken in cleaning or disposing of such equipment.

## COAL BURNING

In 2001-02, Australia was the world's largest exporter of hard coal, with an annual production of approximately 272 million tonnes (Australian Coal Association, 2002), which would have contained approximately  $6.0 \times 10^{12}$  Bq of  $^{238}\text{U}$  (483 tonnes of pure  $^{238}\text{U}$ ). 201 million tonnes of this coal was exported. Approximately 85 % of Australia's electricity requirements are generated by coal-fired power plants. In 2001/02 approximately 120 million tonnes (figures provided by ESAA from Electricity Australia 2003) was consumed to produce electricity. 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.

After burning, coal typically contains 5 to 30% inert mineral material that remains as ash. The ash content of lignite (brown) coals is lower than that of black coal. The fine ash is removed from the hot flue gases (produced from the combustion of the coal) by electrostatic precipitators or fabric filters with efficiencies in excess of 99% (figures provided by ESAA, 2004). Flue gases are also scrubbed to remove other volatile contaminants prior to discharge to the atmosphere. 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. 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 at the site of the power station. The ADAA has advised that in 2003 approximately 13 Mt of coal combustion products were produced in Australasia, of which 4.4 Mt was used in cementitious applications (1.4 Mt), non-cementitious applications (0.5 Mt), and other projects, such as mine site remediation and local haul roads (2.5 Mt). Another recent study has proposed the conditional use of coal combustion products in agriculture (ADAA submission, 2004).

Coal contains traces of naturally occurring radionuclides from the uranium and thorium series and  $^{40}\text{K}$ , either associated with elements in the coal itself, such as sulphides, or in minerals contained in 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.

Swaine (1990) has reviewed a number of studies on the level of radioactivity in coal and emissions from coal-burning power stations. While Swaine concluded that the levels of radioactivity were low, he did not provide quantitative data from the studies he reviewed.

The radionuclide concentrations in the ash are generally enhanced compared to those in the original coal. In addition the 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. Scales containing  $^{226}\text{Ra}$  can also accumulate in coal washeries. These scales are similar to those produced in the oil and gas industry.

## WASTE FROM DRINKING WATER PURIFICATION

Groundwater is not widely used for major public supply systems in Australia, except in Perth where 60% of drinking water is sourced from groundwater supplies. In contrast, approximately 50% of drinking water supplies in both Europe and the USA are from groundwater sources. Some form of treatment for drinking water is undertaken to remove impurities such as iron, nitrates, calcium and organics for supplies in Australian capital cities, as well as in regional centres and some small communities.

Various processes are used to remove impurities from potable water. These processes depend on the nature of the impurities, and include aeration, sand filtration, ion exchange, reverse osmosis, aeration, flocculation and sedimentation, co-precipitation and lime softening, and can remove radium and dissolved uranium contaminants quite efficiently.

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. There do not appear to have been any Australian studies on radionuclide concentrations in sludges, used filter elements, and ion exchange or reverse osmosis cartridges.

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

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

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.