



Australian Government

**Australian Radiation Protection
and Nuclear Safety Agency**

SAFETY GUIDE

Management of Naturally Occurring Radioactive Material (NORM)

RADIATION PROTECTION SERIES No. 15

Radiation Protection Series

The ***Radiation Protection Series*** is published by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) to promote practices which protect human health and the environment from the possible harmful effects of radiation. ARPANSA is assisted in this task by the Radiation Health and Safety Advisory Council, which reviews the publication program for the ***Series*** and endorses documents for publication, and by the Radiation Health Committee, which oversees the preparation of draft documents and recommends publication.

There are four categories of publication in the ***Series***:

Radiation Protection Standards set fundamental requirements for safety. They are regulatory in style and may be referenced by regulatory instruments in State, Territory or Commonwealth jurisdictions. They may contain key procedural requirements regarded as essential for best international practice in radiation protection, and fundamental quantitative requirements, such as exposure limits.

Codes of Practice are also regulatory in style and may be referenced by regulations or conditions of licence. They contain practice-specific requirements that must be satisfied to ensure an acceptable level of safety and security in dealings involving exposure to radiation. Requirements are expressed in 'must' statements.

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In many cases, for practical convenience, regulatory and guidance documents which are related to each other may be published together. A **Code of Practice** and a corresponding **Safety Guide** may be published within a single set of covers.

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Radiation Protection Series Publication No. 15

August 2008

This publication was approved by the Radiation Health Committee on
17 July 2008 and on 8 August 2008 the
Radiation Health and Safety Advisory Council advised the CEO
to adopt the Safety Guide

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The mission of ARPANSA is to protect the health and safety of people, and to protect the environment, from the harmful effects of radiation.

Published by the Chief Executive Officer of ARPANSA in August 2008

Foreword

Naturally occurring radioactive materials (NORM) are ubiquitous in the environment. NORM is widespread in sands, clays, soils and rocks, and many ores and minerals, commodities, products, by-products, recycled residues, and devices used by humans. Although the concentration of NORM in most natural substances is low, any operation in which material is extracted from the earth and processed can potentially concentrate NORM in product, by-product or waste (residue) streams. The generation of products, by-products, residues and wastes containing NORM has potential to lead to exposures to both workers and members of the public, along with environmental impacts.

In 2004, the Radiation Health and Safety Advisory Council released a discussion paper on the management of NORM in Australia. After consultation, including at the *National Conference on Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing* in April 2005, Council forwarded advice on NORM to me as the CEO of ARPANSA.

Following Council's advice, ARPANSA commenced a process of review and assessment of NORM management in various industries. This *Safety Guide*, was developed to provide national guidance on the management of NORM and a methodology for assessment of the need for a regulatory approach in specific situations involving NORM.

The *Safety Guide* takes account of recently developed international guidance on NORM management. It recognises that regulation will not always be the appropriate approach for dealing with NORM, and describes a graded approach to regulation for those cases where a regulatory approach is assessed as being necessary. It includes three detailed Annexes for the oil and gas, bauxite and phosphate industries. It is intended to prepare Annexes on other NORM-related industries in future.

A working group, including industry, regulator and ARPANSA representatives, developed a draft of the *Safety Guide*, which was released for public comment from 2 May 2008 until 13 June 2008. Thirteen public submissions were received and reviewed. The Radiation Health Committee approved the final draft at its meeting of 16-17 July 2008. The Radiation Health and Safety Advisory Council advised me to adopt the *Safety Guide* at its meeting of 8 August 2008.

A resource page on NORM issues has also been developed on the ARPANSA web site (www.arpansa.gov.au/aboutus/committees/norm.cfm). In consultation with a NORM stakeholder group that includes government and industry representatives, ARPANSA will develop this web page further over time.

It is expected that the *Safety Guide* and web page will be of particular assistance to industries and regulators considering the need for appropriate radiation protection measures and/or a regulatory approach in those situations where NORM is present in an industry. ARPANSA will continue to monitor international developments on NORM management and will work with relevant industries to prepare additional Annexes for this *Safety Guide*, and to develop the web page into a resource on radiation protection and NORM.

A handwritten signature in black ink, appearing to read 'John Loy', with a stylized flourish at the end.

John Loy PSM
CEO of ARPANSA

27 August 2008

Contents

Radiation
Protection
Series
No. 15

Foreword	i
1. Introduction.....	1
1.1 CITATION	1
1.2 BACKGROUND	1
1.3 PURPOSE.....	6
1.4 SCOPE.....	6
1.5 STRUCTURE.....	7
1.6 RELATIONSHIP TO OTHER RADIATION PROTECTION SERIES PUBLICATIONS	7
2. Some Industries where Radiation Protection issues may arise in dealing with NORM.....	9
2.1 OIL & GAS INDUSTRY.....	9
2.1.1 Downstream processing of oil and gas	10
2.2 BAUXITE/ALUMINIUM INDUSTRY.....	10
2.3 PHOSPHATE INDUSTRY	11
2.4 METAL EXTRACTION AND PROCESSING.....	12
2.4.1 Copper	12
2.4.2 Tin/Tantalum.....	13
2.5 COAL EXTRACTION AND ELECTRICITY GENERATION.....	14
2.6 IRON AND STEEL PRODUCTION	15
2.7 MINERAL SANDS AND RARE EARTHS	15
2.8 DOWNSTREAM PROCESSING OF MINERAL SANDS	17
2.8.1 Titanium dioxide pigment production	17
2.8.2 Zircon and zirconia production	18
2.9 SCRAP METAL RECYCLING	18
2.10 WATER TREATMENT	19
2.11 THE BUILDING INDUSTRY.....	20
2.12 UNDERGROUND MINING AND TUNNELLING	20
2.13 GEOTHERMAL ENERGY GENERATION	20
3. Radiological Issues in NORM Management	21
3.1 GENERAL	21
3.2 EXPOSURE PATHWAYS	21
3.2.1 Internal exposures.....	21
3.2.2 External exposures.....	23
3.3 MINERAL EXTRACTION	24
3.3.1 Open pit mines	25
3.3.2 Underground operations and work places	25
3.3.3 Dredging for mineral extraction	26
3.3.4 Liquid/gas extraction from wells.....	26
3.4 MINERAL AND DOWNSTREAM PROCESSING	26
3.4.1 Dust.....	26
3.4.2 Material handling.....	26
3.4.3 Radon.....	27

Safety Guide
Management of Naturally Occurring Radioactive Material (NORM)

3.5	TRANSPORT OF BULK COMMODITIES, RESIDUES AND WASTES.....	27
3.5.1	Dust (loading and unloading)	27
3.5.2	External exposures during transport	28
3.5.3	Transport accidents	28
3.6	USE OF PRODUCTS.....	28
3.7	MANAGEMENT OF RESIDUES.....	29
3.7.1	Storage/Disposal	29
3.7.2	Utilisation of NORM residues	30
3.7.3	Optimisation - use of the ALARA principle	30
3.8	MANAGEMENT OF WASTES	31
3.8.1	Storage	31
3.8.2	Near surface burial	31
3.8.3	Other disposal options.....	32
3.9	PUBLIC PERCEPTION.....	32
3.10	SUMMARY	32
4.	Regulatory Issues in NORM Management	33
4.1	INTERNATIONAL DEVELOPMENTS IN NORM MANAGEMENT	33
4.2	CURRENT REGULATORY FRAMEWORKS IN AUSTRALIA.....	33
4.3	ASSESSING THE NEED TO REGULATE NORM.....	35
4.3.1	Application of Exclusion and Exemption to NORM.....	35
4.3.2	First stage of assessment - identification of operations involving NORM	36
4.3.3	Second stage of assessment – consideration of other materials....	37
4.3.4	Other work situations	39
4.4	GRADED APPROACH TO REGULATION	40
4.4.1	Notification	40
4.4.2	Screening assessment	40
4.4.3	Unconditional exemption.....	42
4.4.4	Conditional exemption (registration)	42
4.4.5	Licensing	43
4.4.6	NORM management plan.....	43
4.5	DOSE AND IMPACT ASSESSMENT	44
4.5.1	The iterative improvement approach to dose and impact assessment	44
4.5.2	Monitoring Programs	44
4.6	MANAGEMENT OF NORM WASTES AND RESIDUES	44
4.6.1	Wastes	45
4.6.2	Residues	45
4.6.3	Products	46
4.7	TRANSPORT.....	46
4.8	SITE REMEDIATION AND CLOSE-OUT REQUIREMENTS	46
4.9	ASSESSING THE IMPACT OF REGULATORY PROPOSALS	47
5.	Operational issues – the NORM Management Plan	49
5.1	INTRODUCTION	49
5.2	IDENTIFICATION OF POTENTIAL SOURCES OF HEALTH IMPACT ON WORKERS, MEMBERS OF THE PUBLIC AND THE ENVIRONMENT	49
5.3	MANAGEMENT OF THE HEALTH IMPACT ON WORKERS, MEMBERS OF THE PUBLIC AND THE ENVIRONMENT.....	49

5.3.1	Control/mitigation procedures.....	49
5.3.2	Monitoring programs.....	52
5.3.3	Dose and safety assessment.....	53
5.3.4	The iterative improvement approach.....	54
5.3.5	The use of computer models.....	55
5.4	REMEDIATION AND CLOSE-OUT REQUIREMENTS FOR OPERATIONAL SITES.....	56
5.5	NON-RADIOLOGICAL ISSUES.....	56
6.	Remediation of legacy sites.....	57
7.	Summary.....	58
	References.....	60
	Bibliography.....	65
	Glossary.....	76
Annex 1	Management of NORM in the Oil & Gas Production Industry.....	78
A1.1	Introduction.....	78
A1.2	Raw materials.....	78
A1.3	Processing steps.....	78
A1.4	Waste streams.....	81
A1.5	Operational Issues.....	82
A1.6	Environment Protection.....	88
A1.7	NORM issues in downstream processing.....	89
Annex 2	Management of NORM in the Bauxite/Aluminium Industry.....	91
A2.1	Brief description of industry.....	91
A2.2	Mineral processing steps.....	94
A2.3	Types of NORM residues resulting from mineral processing.....	95
A2.4	Management strategies for each type of residue.....	97
Annex 3	Management of NORM in the Phosphate Industry.....	102
A3.1	Brief Description of the Phosphate Industry.....	102
A3.2	Sources of Phosphate Rock.....	102
A3.3	Phosphate Processing.....	103
A3.4	The Origin of Phosphate NORM.....	105
A3.5	Occupational NORM Exposure.....	106
A3.6	Management of Waste and Residue.....	107
A3.7	Public Health.....	107
	ARPANSA Radiation Protection Series Publications.....	109
	Regulatory Authorities.....	111
	Contributors to Drafting and Review.....	112
	Index.....	113

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1. Introduction

1.1 CITATION

This Safety Guide may be cited as the Safety Guide for the Management of Naturally Occurring Radioactive Material (NORM) (2008).

1.2 BACKGROUND

Naturally-occurring radioactive material (NORM) is the term used to describe materials containing radionuclides that exist in the natural environment. The radionuclides of interest include long-lived radionuclides such as uranium-238 (^{238}U), uranium-235 (^{235}U) and thorium-232 (^{232}Th) and their radioactive decay products (such as isotopes of radium, radon, polonium, bismuth and lead), and individual long-lived radionuclides such as potassium-40 (^{40}K), rubidium-87 (^{87}Rb) and indium-115 (^{115}In). The parent radionuclides have decay times (half-lives) which are comparable with or larger than the age of the earth, so they have always been present in the earth's crust and within the tissues of all living species. Where materials contain radionuclides from the naturally occurring decay chains (^{238}U , ^{235}U , ^{232}Th), the large number of radionuclides in each chain, and the resulting large range of physical and chemical properties of the individual radionuclides, means that there can be a highly variable degree of secular equilibrium between the individual members of the chains.

The radiological and physical properties and the organs potentially at risk for each of the radionuclides in the ^{238}U decay chain are summarised in Table 1.

Table 1: The important properties of the members of the ^{238}U decay chain

Nuclide	Half-life (Chu et al, 1999)	Form	Principal radiation	Organ(s) potentially at risk
^{238}U	4.468×10^9 a	solid	α	lung, kidney
^{234}Th	24.1 d	solid	β	lung, skeleton, liver, colon
$^{234\text{m}}\text{Pa}$	1.17 min	solid	β	
^{234}U	2.455×10^5 a	solid	α	lung, kidney
^{230}Th	7.538×10^4 a	solid	α, γ	lung, skeleton, liver, colon
^{226}Ra	1.6×10^3 a	solid	α, γ	lung, bone
^{222}Rn	3.82 d	gas	α, γ	lung
^{218}Po	3.10 min	solid	α, γ	liver
^{214}Pb	26.8 min	solid	β, γ	bone
^{214}Bi	19.9 min	solid	β, γ	
^{214}Po	1.643×10^{-6} s	solid	α, γ	liver
^{210}Pb	22.3 a	solid	β, γ	bone
^{210}Bi	5.013 d	solid	β, γ	
^{210}Po	138.4 d	solid	α, γ	liver
^{206}Pb	Stable	solid		

The organ at risk for a particular radionuclide can depend on a number of factors. The organs quoted in Table 1, Table 2, and Table 3 assume that the nuclide is the only radionuclide present. However, if the nuclide of interest

forms inside the body as a result of radioactive decay, its impact can depend on the point where the decay takes place, particularly if the nuclide is short-lived. In some cases, particularly for beta emitting radionuclides such as ^{234m}Pa and the Bi isotopes, the internal dose contribution is negligible compared with the internal dose contributions from other nuclides.

The radiological and physical properties and the organs potentially at risk for each of the radionuclides in the ^{235}U decay chain are summarised in Table 2. The fractional abundance of ^{235}U is very much less than that of ^{238}U , so that in most situations the dose contribution from ^{235}U and its decay products is much smaller than the contribution from ^{238}U and its decay products.

Table 2: The important properties of the members of the ^{235}U decay chain

Nuclide	Half-life (Chu et al, 1999)	Form	Principal radiation	Organ(s) potentially at risk
^{235}U	7.038×10^8 a	solid	α, β, γ	lung, kidney
^{231}Th	25.52 h	solid	β, γ	lung, skeleton, liver, colon
^{231}Pa	3.276×10^4 a	solid	α, γ	
^{227}Ac	21.77 a	solid	β, γ	lung, liver, bone surface
^{227}Th	18.72 d	solid	β, γ	lung, skeleton, liver, colon
^{223}Ra	11.435 d	solid	α, γ	bone
^{219}Rn	3.96 s	gas	α, γ	lung
^{215}Po	1.781×10^{-3} s	solid	α, γ	liver
^{211}Pb	36.1 min	solid	β, γ	bone
^{211}Bi	2.14 min	solid	β, γ	lung
^{211}Po	0.516 s	solid	α, γ	liver
^{207}Tl	4.77 min	solid	β, γ	
^{207}Pb	Stable	solid		

The radiological and physical properties and the organs potentially at risk for each of the radionuclides in the ^{232}Th decay chain are summarised in Table 3.

Table 3: The important properties of the members of the ^{232}Th decay chain

Nuclide	Half-life (Chu et al, 1999)	Form	Principal radiation	Organ(s) potentially at risk
^{232}Th	1.41×10^{10} a	solid	α , β , γ	lung, skeleton, liver, colon
^{228}Ra	5.75 a	solid	β	lung, bone
^{228}Ac	6.15 h	solid	β , γ	
^{228}Th	1.91 a	solid	α	lung, skeleton, liver, colon
^{224}Ra	3.66 d	solid	α , γ	lung, bone
^{220}Rn	55.6 s	gas	α	lung
^{216}Po	0.145 s	solid	α	liver
^{212}Pb	10.6 h	solid	β , γ	bone
^{212}Bi	60.6 min	solid	α , β , γ	
^{212}Po (64%)	2.99×10^{-7} s	solid	α , β , γ	liver
^{208}Pb	Stable	solid	β , γ	bone
^{208}Tl (36%)	3.053 min	solid	β , γ	
^{208}Pb	Stable	solid		

The physical and chemical properties of the radionuclides can have a strong influence on their environmental behaviour and resulting exposure pathways. For example, the isotopes of lead and polonium are volatile at temperatures commonly encountered in smelters, blast furnaces and power station furnaces. This means that these processes can release lead and polonium isotopes to the atmosphere.

The radiological and physical properties and organs potentially at risk for some single naturally occurring radionuclides are summarised in Table 4.

Table 4: The important properties of some single natural radionuclides

Nuclide	Half-life	Form	Principal radiation	Organ(s) potentially at risk
^{40}K	1.277×10^9 a	solid	β , γ	all – low risk
^{87}Rb	4.75×10^{10} a	solid	β	all – low risk
^{115}In	4.41×10^{14} a	solid	β , γ	bone marrow

The concentration of potassium (and hence ^{40}K) in the human body is governed by homeostatic processes, and tends to remain approximately constant.

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.

The world-wide average activity concentrations of some of the naturally occurring radionuclides in the undisturbed environment are given in Eisenbud (1987). More recent information is given in UNSCEAR reports

(UNSCEAR, 2000). For the two most important naturally occurring decay series the average concentrations are given below:

^{238}U : 0.03-0.05 Bq g⁻¹

^{232}Th : 0.04-0.06 Bq g⁻¹

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 (from the decay of radionuclides in soils and rocks), and approximately 0.6 - 1.1 mSv due to inhalation of radon (^{222}Rn) and its radioactive decay products. In addition, natural background includes a contribution of approximately 0.3 mSv due to cosmic radiation (at sea-level), and approximately 0.2 - 0.25 mSv due to beta and gamma radiation from ^{40}K inside the body. 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.

The widespread occurrence of NORM means that sands, clays, soils and rocks, and many ores and minerals (e.g. coal, oil and gas, bauxite, phosphate rock, ores containing tin, tantalum, niobium, rare earths, and some copper and gold deposits), commodities (e.g. water, building materials, fertiliser), products (e.g. ceramics, glazes, uranium glass), by-products (e.g. phosphogypsum), residues with potential for future use (e.g. fly ash from coal burning, red mud from alumina production and slags from mineral processing), and devices used by humans (e.g. welding rods, gas mantles and electronic components) can contain NORM. 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 in product, by-product, residue or waste streams. There is also potential for this to occur in down-stream processing (see Sections 2.8 and 3.4). In some situations, specific radionuclides can become separated from the original radionuclide mixture (e.g. volatilisation of polonium and lead isotopes in mineral smelters or coal-burning power stations, and the separation of radium and uranium during the processing of phosphate ore to produce fertiliser and phosphogypsum).

In general, this Safety Guide deals with those situations where the radionuclides present in materials have little or no commercial value. This means that uranium and thorium ores and concentrates, sealed radium sources, etc., are not covered by this document. Uranium ores are mined specifically for their radionuclide content, and radium sources and similar devices are designed to exploit the radioactive properties of the incorporated radionuclides. Although mineral sands are not mined for their radionuclide content in Australia, the extraction and processing of mineral sands are subject to the *Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing* (ARPANSA 2005a), referred to as 'the Mining Code', due to the radionuclide activities involved. Waste rock, process tailings, and products containing elevated concentrations of naturally occurring radionuclides are covered by this NORM Safety Guide.

4 The generation of products, by-products, residues and wastes containing NORM has the potential to lead to both exposures to workers and members

of the public, and to environmental impacts. This means that consideration has to be given to the management and disposal of these materials. Current and historical methods 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 approaches to re-use or disposal 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.

An important issue with NORM is one of awareness. In some industries the management of possible NORM exposures is already being addressed. 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.

Raising the awareness of both industries and the public, while keeping potential risks in context, is an important part of any NORM management strategy.

In most NORM industries the potential for a catastrophic radiological 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 residues and 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 materials. ARPANSA's role is to promote uniformity of radiation protection policy and practices across the jurisdictions of the Commonwealth, States and Territories in a manner consistent with international best practice, and to provide advice on radiation protection and related issues.

With these considerations in mind, the Radiation Health and Safety Advisory Council, established under the ARPANS Act 1998, released a discussion paper in 2003 on the management of NORM in Australia. Following public consultation on the discussion paper, Council revised the discussion paper (RHSAC, 2005a) and finalised its advice to the CEO of ARPANSA in September 2005 (RHSAC, 2005b). In responding to this advice, the CEO

agreed ‘that it was timely to address management of NORM and for Australia to move ahead in a structured way to achieve nationally uniform outcomes’ (ARPANSA, 2005b).

Accordingly, ARPANSA is developing national guidance on the management of materials containing NORM, and on a uniform approach to consideration of when regulation might be appropriate.

1.3 PURPOSE

The purpose of this Safety Guide is to assist regulators and industries in which radionuclide concentrations in NORM may be enhanced, in managing NORM and assessing the need for radiation protection measures, including regulation. The approach is based on the framework for management of NORM arising from the *National Directory for Radiation Protection* (ARPANSA, 2004), and the Mining Code. This Safety Guide also gives advice on the type of radiation protection measures that may be required.

1.4 SCOPE

This Safety Guide describes the broad regulatory decision-making framework of exclusion and exemption established by the National Directory for Radiation Protection and the regulatory framework of the Mining Code, giving broad guidance about how relevant decisions should be made to apply these frameworks. A series of Annexes addresses the application of this guidance to specific industries in which NORM may be a potential issue. The Annexes developed for this edition are: the oil & gas industry, the bauxite/aluminium industry and the phosphate industry. Other Annexes will be published in the future.

This Safety Guide deals primarily with NORM in materials associated with mineral extraction and processing (for example ores, bulk wastes, residues and products), where the radionuclide content of the materials does not have any commercial value. In addition, there are some industries such as water treatment and metal recycling, and some products, such as uranium glass, where consideration of NORM issues may arise.

It does not deal with uranium and mineral sands mining and processing as these operations are subject to an existing regulatory framework, which incorporates the ARPANSA Mining Code. It also does not deal with radioactive sources, but does discuss the potential problems associated with the loss and dispersal of a radioactive source containing naturally occurring radionuclides.

While mineral sands extraction and primary processing are not included in this Safety Guide, the products, residues and wastes arising from downstream processing of mineral sands (such as ilmenite and zircon) are included, because although these materials contain radionuclides, they are not specifically produced or generated for their radionuclide content.

This NORM Safety Guide is intended to supplement the Mining Code and Mining Safety Guide, and in particular provide guidance on situations where an assessment of the need for regulation or radiation protection measures is an important consideration.

1.5 STRUCTURE

This Safety Guide is structured as follows:

Section 2 describes industries where radiation protection issues could arise due to the concentration of NORM involved in residues, wastes, by-products or products associated with those industries. Further detail on each of the industries is provided in Annexes. The first edition of this Safety Guide includes Annexes on oil and gas, bauxite and phosphate industries. Annexes for the remaining industries will be considered in future.

Section 3 describes the radiological issues in NORM management and the pathways for exposures to occur within the different stages of the processes of each industry, including mineral extraction, mineral processing, the use of products and by-products containing NORM, the management of residues containing NORM, and the management of wastes containing NORM. Again further detail is provided in the Annexes.

Section 4 describes approaches to regulation of NORM-related industries, both internationally and in Australia. It discusses approaches to exclusion and exemption that might apply to NORM-related industries, a graded approach to regulation and a methodology for assessment of whether regulation is required in NORM-related industries. Monitoring programs and transport issues are also discussed.

Section 5 provides a summary of some of the key operational issues. The important potential exposure pathways are discussed, together with mitigation techniques for minimising doses to workers. Monitoring programs and transport issues are also discussed.

Section 7 contains a discussion of remediation strategies and methodologies for contaminated sites resulting from past operations (legacy sites).

Section 7 provides a summary and discussion of the key elements of NORM management.

The Annexes, in addition to expanding on the information in Sections 2 and 3 above, give information on the activity concentrations of NORM in specific industries and on approaches to NORM management in those industries.

1.6 RELATIONSHIP TO OTHER RADIATION PROTECTION SERIES PUBLICATIONS

Readers of this Safety Guide may find it useful to examine other related publications in the Radiation Protection Series, including:

RPS 1 (ARPANSA, 2002), which presents the overall radiation protection system and occupational and public doses limits;

RPS 2 (ARPANSA, 2008), which describes the requirements for transport of radioactive material including NORM;

RPS 6 (ARPANSA, 2004), the National Directory for Radiation Protection (NDRP), which provides an overall framework for uniformity including specific regulatory elements, and of particular relevance to NORM:

- exemption and exclusion provisions, and
- provisions covering the disposal of low level radioactive waste by the user (in preparation).

RPS 9 (ARPANSA, 2005a), which describes the requirements for radiation protection and radioactive waste management in mining and mineral processing, and could be used by regulators to apply to some NORM industries.

2. Some Industries where Radiation Protection issues may arise in dealing with NORM

This section covers industries which generate products, wastes and residues containing NORM (for example industries involved in the extraction and processing of mineral ores), and industries which use NORM products and residues (for example the building industry).

The material in this section is based on international experience and recommendations (IAEA, 2003a; IAEA, 2006a), and a report (Cooper, 2005) which summarised production of NORM products, residues and wastes in Australia. In particular IAEA Technical Reports Series No. 419 (IAEA, 2003a) contains considerable information on the typical radionuclide concentrations found (world-wide) in many minerals and wastes produced by mineral processing.

2.1 OIL & GAS INDUSTRY

Oil and gas reservoirs consist of beds of permeable sandy sedimentary rock, with the oil and/or gas occurring in the interstitial spaces between the grains of sand. Commonly the oil and gas occurs in a layer which is on top of a layer of interstitial water. During oil and gas production, reservoir pressure drives the oil and gas towards wells drilled into the formation; as the reservoir is depleted of oil and gas, water is produced as well – this is referred to as ‘produced formation water’. Water may be injected into the formation from outlying injection wells in order to maintain reservoir pressure.

The formation sands contain uranium in the range of proportions typical of sedimentary rock, and while the uranium remains in place, two of its decay products are able to leave the sand grains and enter the interstitial fluids:

- Radon can emanate from the sand into the oil, water or gas – radon is soluble in hydrocarbons and less so in water;
- Depending on the chemistry of the formation water, radium can be dissolved from the sand and be held in solution in the formation water. The solubility of radium increases as the temperature and pressure increases and as the pH decreases. The common presence of H₂S and CO₂ dissolved in the formation water assists with lowering the pH.

Oil and gas production operations carry out varying amounts of processing of the produced fluids, depending on the circumstances of each operation. The separation of the produced formation water from the other liquids is essential; the water is typically returned to the ocean (in the case of an offshore field) or reinjected into the formation (for either an offshore or onshore field). Gases (methane, ethane, propane and butane) are often separated from the liquid hydrocarbons and may undergo further processing to remove contaminants (e.g. H₂S) and to separate the component gases. The fate of the radium and radon brought to the surface with the produced fluids diverge:

- The radium largely follows the water stream; as the pressures and temperatures are reduced, the solubility of radium is reduced and it precipitates out into process equipment. Commonly, these precipitates accompany non-NORM solids that have been produced with the oil and gas.
- The radon follows the gas streams; as it undergoes radioactive decay its decay products, being solids, typically filter or impact out at choke points and other process circumstances that interrupt or disturb the flow, such as bends in piping, piping 'T' pieces, control valves, orifice plates, strainers, pump impellers, etc. These deposits may, depending on the local fluid flow conditions, occur as NORM metals plated out inside items of processing equipment or may occur as finely divided dusts that settle in low flow areas.

Oil and gas processing takes place within enclosed equipment; thus occupational exposure to NORM typically takes place:

- as a result of gamma radiation from deposits inside equipment exposing workers outside the equipment; or
- as a result of disturbing NORM deposits during maintenance work on equipment when taken offline.

There is considerable additional information on NORM in the oil and gas industry in Safety Report Series No. 34 (IAEA, 2003b).

2.1.1 Downstream processing of oil and gas

NORM arising from oil and gas production can also be an issue in downstream processing. Most commonly this occurs during the subsequent processing of ethane (e.g. in petrochemical plants using ethane as a feedstock) and involves radon and its decay products. Radium may also be a minor issue during the refining of crude oil, where the highest boiling point fractions left after distillation processes may contain low activity concentrations of radium.

2.2 BAUXITE/ALUMINIUM INDUSTRY

Bauxite ores can sometimes contain elevated concentrations of uranium and thorium and their decay products. Production of aluminium from bauxite is carried out in two stages. In the first stage, bauxite is refined to produce alumina (anhydrous aluminium oxide), using the Bayer process, which consists of five basic steps:

- (a) bauxite washing and grinding;
- (b) bauxite digestion in caustic soda at high temperature and pressure;
- (c) separation and washing of solid residues;
- (d) precipitation of hydrated alumina;
- (e) calcining at about 1000°C to remove water and produce anhydrous alumina.

In the second stage, aluminium metal is produced by electrolysis of the alumina in a mixture of fluoride salts, contained in carbon cells.

Production of alumina, generates a *solid residue stream* comprising a *mud residue* component (also designated *red mud*) and a sand residue component (see Annex 2). The mud residue component preferentially carries the trace radionuclides transferred from the bauxite to the solid residue stream. Typically, 0.3 to 0.5 tonne of mud residue is produced per tonne of bauxite. Some of the radioactivity in the original bauxite may be associated with trace quantities of other minerals, such as ilmenite or monazite. As the radionuclides in the original bauxite ore transfer mainly to the mud residue, there is (approximately) a two-fold to three-fold increase in the radionuclide content of the mud residue compared to the original bauxite ore.

Very large volumes of red mud are generated, generally with elevated (above background) but still relatively low uranium and thorium concentrations.

Liquid residues, which arise from the washing of solid waste and from settling ponds, are recycled as process water.

Alumina smelting does not produce substantial quantities of solid waste.

Disposal of mud residue and sand residue commonly takes place by spreading in layers over a large area to allow the material to dry, followed by remediation of the land, which involves mixing the waste with sand and re-vegetating the surface. Mud residue has also been used as a soil conditioner (Summers et al, 1993; Cooper et al, 1995) because of its ability to enhance the water retention of very dry, sandy soils.

2.3 PHOSPHATE INDUSTRY

Natural phosphates contain a wide range of radionuclide concentrations. Most phosphates contain elevated levels of uranium and radium, but some phosphates can contain elevated levels of thorium. When phosphate ore is processed the uranium isotopes tend to remain with the fertiliser (product), while the radium isotopes tend to remain with the by-product phosphogypsum.

Very large volumes of phosphogypsum can be generated, generally containing low concentrations of radium up to approximately 10-15 times natural background levels.

Phosphogypsum has the same chemical properties as natural gypsum.

Phosphate ore can be combined with sulphuric or phosphoric acid to produce different kinds of fertilisers (characterised by the phosphorus content of the fertiliser) for agricultural use. Normal superphosphate is produced by adding sulphuric acid to phosphate rock to form soluble monocalcium phosphate and phosphoric acid. Phosphoric acid is used in the manufacture of higher grades of superphosphate and ammonium phosphates, and is also used as a raw material for phosphate chemicals used extensively in detergents, deflocculants, animal feeds and for corrosion treatment of metal.

Phosphoric acid itself is produced by treating rock phosphate with excess sulphuric acid. Unless the acid is to be used for fertiliser production, purification of the phosphoric acid is carried out by solvent extraction.

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

The major solid waste resulting from fertiliser and phosphoric acid production is calcium sulphate (phosphogypsum). Approximately 4-5 tonnes of phosphogypsum are produced per tonne of acid, so that very large volumes of phosphogypsum are produced in Australia. In addition, small quantities of scales are deposited in process pipes, filtration tanks and filter parts. Phosphogypsum is stockpiled on site or used as landfill along with the scale and filter materials. Phosphogypsum is also used as fertiliser and soil conditioner, building materials (e.g. plasterboard), cement aggregate, and in road construction.

When phosphate rock is treated with sulphuric acid to produce phosphoric acid, the uranium and thorium series radionuclides become partitioned in the product or residue. Most of the ^{226}Ra is left in the phosphogypsum, while most of the ^{232}Th and ^{238}U remain in the fertiliser at approximately 150% of their concentrations in the original phosphate rock. Typical radionuclide activity concentrations in the residue/waste streams range from 5-15 times natural background levels in the phosphogypsum, with the ^{238}U activity concentrations typically an order of magnitude lower than the activity concentrations of ^{226}Ra and subsequent decay products. The ^{232}Th activity concentrations in phosphogypsum are typically less than 0.01 Bq.g^{-1} . Radionuclide concentrations in scale are highly variable, ranging from near zero to 100 times the natural background level.

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 ^{226}Ra relative to ^{238}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 and consequently individual doses from their use are not enhanced above normal background.

2.4 METAL EXTRACTION AND PROCESSING

2.4.1 Copper

Copper metal is widely used in electrical installations and the electronics industry. In Australia the major proportion of copper comes from sulphide deposits (e.g. Olympic Dam and Mt Isa). These deposits are typically copper iron sulphides and may contain, or be associated with, other metals, including gold, silver (both in most deposits), lead, zinc (both for example at Mt Isa) and sometimes uranium (as at Olympic Dam). The sulphides must generally be concentrated before being passed to the smelting stage for subsequent metal recovery by pyrometallurgical and electrometallurgical processing.

Some near surface oxidised deposits contain copper that is recovered by leaching, solvent extraction and electrowinning. For this type of deposit, other metals are generally not present in economic quantities and are not recovered by this technique.

After extraction and milling of the sulphide ores, the copper minerals are separated by flotation to produce a concentrate with a copper content of approximately 30%, depending on the mineralogy and the efficiency of the flotation process. As noted above, uranium (and to a lesser extent, thorium series) radionuclides may be present in significant quantities in the original copper mineralisation. While most of these radionuclides remain in the flotation tailings, some will be transferred to the copper concentrate.

The concentrate is smelted to remove some of the volatile impurities to a fume, and some of the iron and other impurities to a slag. The copper-iron-sulphur matte produced by smelting is further processed to an impure blister copper, and can be further smelted again to produce anodes which are used to electro-refine the copper to high purity for industrial use. Partitioning of ^{238}U series radionuclides in the copper concentrate occurs during this smelting process.

Typically ^{238}U , ^{226}Ra (and some ^{210}Pb) in the copper concentrate is transferred to the slag with little passing through to the blister copper. ^{210}Pb and ^{210}Po are vaporised at the smelting stage and may accumulate in dusts collected from off-gases although significant quantities can remain in the blister and final anode copper.

The waste 'slimes' resulting from electro-refining the copper anodes, may contain remaining uranium series radionuclides (particularly ^{210}Pb and ^{210}Po). This slime is further processed for separate recovery of high purity metals (e.g. gold and silver) and ^{210}Pb and ^{210}Po are vaporised and will accumulate in off-gas.

Unless uranium series radionuclides are separated during processing, they will remain in the tailings from the flotation stage or will be present in the copper concentrate and partition to the slag, dusts and other products of copper smelting.

In the case of the Olympic Dam mine both the copper concentrate and the flotation tailings are leached to dissolve uranium which is subsequently recovered by a solvent extraction technique.

The main waste materials arising from the copper separation and refining processes are tailings from the flotation stage and furnace slags from the smelting stage.

2.4.2 Tin/Tantalum

Tantalum mineralisation is sometimes associated with tin-bearing minerals. Tantalum is used in the electronics industry as a major constituent of capacitors. Processing of the minerals takes place at plants at the respective mine sites.

Tantalum can be present in pegmatite ore in several possible mineral forms (as complexes with iron, manganese, calcium or antimony). The average grade of tantalum varies with the location of the ore body but ranges from 0.04 to 0.1%. The tantalum ore bodies also contain low grade (< 0.1%) tin mineralisation, either complexed with the tantalum mineral, or as the tin-

bearing mineral, cassiterite. Other major constituents of the ore include sulphide minerals and traces of ilmenite and zircon may also be present.

The primary ore goes through a crushing stage, followed by a series of dry and wet gravity, dry screening and magnetic stages, to produce high-grade tin and tantalum concentrates. Tantalum is normally supplied as high grade concentrates or glass. In some cases flotation and leaching are necessary to remove sulphides and trace quantities of uranium and thorium impurities in the concentrates. Smelting of the concentrates may be required to produce tin metal and tantalum glass.

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

Activities of uranium and thorium in the primary tantalum/tin ore are less than 0.06 Bq g⁻¹ and 0.005 Bq g⁻¹, respectively. However, the levels of uranium and thorium in the tantalum products range from 7.5 Bq g⁻¹ to 75 Bq g⁻¹.

2.5 COAL EXTRACTION AND ELECTRICITY GENERATION

Approximately 85% of Australia's electricity requirements is generated by coal-fired power plants, with the balance generated by oil and gas plants, or hydroelectricity. Over 100 million tonnes of coal is consumed annually in Australia to produce electricity. Extraction of coal is done by excavation, either in open pits or in underground mines. Approximately 50% of coal used in Australia for power generation comprises bituminous and sub-bituminous coals (also known as hard or black coal). The remainder is lignite, or brown coal.

In a typical coal-fired power plant, coal is pulverised, mixed with hot air, and burnt in a boiler to produce steam. The steam is used to drive a turbine, which in turn drives an electrical generator. The combustion of the coal produces a mixture of heavy, refractory material (bottom ash, slag), and a mixture of hot gases and fine particulate residues (fly ash) which is passed to a gas handling system to separate the fly ash before discharge of the cleaned gas to the stack. Flue gases are scrubbed to remove other volatile contaminants prior to discharge to the atmosphere. The bottom ash and slag settles at the bottom of the boiler.

A typical coal contains 5 to 30% inert mineral material that remains as ash after burning; the ash content of lignite and brown coal is lower than that of black coal.

Most of the solid waste from a typical coal fired power station is fly ash, Current management practice for the disposal of fly ash is to slurry the ash, transfer it to a settling pond, and then dispose of the ash in a landfill, usually at the site of the power station. Bottom and fly ash are also used as cement-extender in concrete, for road making and other applications, such as mine site remediation.

Coal contains trace amounts of ⁴⁰K and ²³⁸U, ²³⁵U and ²³²Th series radionuclides. These radionuclides are associated with elements in the coal

itself, such as sulphides, or occur within the minerals making up the coal formation. Radionuclide concentrations in coal are generally lower than the average radionuclide concentrations in soils and depend on the type of coal and the location of the mine (Cooper, 2005). Most of the radionuclides in the original coal tend to remain with the ash (with an enhancement factor of approximately 3-20), and the various radionuclides are partitioned between the different forms of ash. The more volatile radionuclides, such as ^{210}Po and ^{210}Pb , tend to accumulate in the fly ash and in the stack emissions, whereas the more refractory elements, such as uranium and thorium, accumulate in the bottom ash and slag (Cooper, 2005).

2.6 IRON AND STEEL PRODUCTION

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

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

Production of sinter generates waste dust in the off-gases. Most of this dust is removed from the gas stream by dry electrostatic precipitators. In the blast furnace the main wastes are the blast furnace slags and the dusts and fumes collected from the off gas cleaning in the blast furnace operation. The slag is stored on site, or used as road base or in cement or concrete applications.

Iron ores scavenge radionuclides and heavy metals, because of their similar geochemical properties. There are also trace levels of uranium in the other raw materials for iron-making, namely coke, and limestone. The main accumulation of radioactivity in the sinter plant is due to ^{210}Pb and ^{210}Po in the dust collected from the gas cleaning systems. The concentrations of ^{210}Pb and ^{210}Po become further enhanced because of recycling of the dust through the sinter plant in order to reduce dust emissions. Blast furnace slag will contain low levels of long-lived radionuclides from the uranium and thorium series. The ^{210}Pb and ^{210}Po levels in dust collected from the blast furnace off-gases are generally lower than those from the sinter plant.

2.7 MINERAL SANDS AND RARE EARTHS

Mineral sands constitute ores with heavy minerals having densities in excess of 3 g cm^{-3} . The heavy minerals of major commercial importance are the titanium bearing minerals (ilmenite, leucosene and rutile), the zirconium bearing mineral zircon, and rare earth bearing minerals (monazite and xenotime).

While this Safety Guide does not address extraction of mineral sands, an understanding of the extraction processes is helpful in considering the issues associated with downstream processing. Extraction of mineral sand ores is carried out by dry operation or dredging of the slurried ore. Separation of the various heavy minerals takes place in two main stages. The primary step is the production of a heavy mineral concentrate using a wet gravity separation process. The concentrate constitutes between 5 and 10% of the original ore. Individual minerals are then separated in a dry process that utilises a sequence of electrostatic and magnetic steps to produce the various mineral products.

The heavy minerals extracted from mineral sands have a wide range of applications. Ilmenite and rutile are used to produce titanium dioxide pigments for the paint, paper and plastics industry, and for the production of titanium metal. The major uses of zircon, zirconia and zirconium products are in the ceramics industry, as refractory materials 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 (Cooper, 2005).

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

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

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

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 from one ore body to another. Monazite is a phosphate mineral consisting of rare earth elements and thorium (about 6%) and uranium (< 1%).

Currently (in Australia), monazite concentrate is not usually marketed but is returned to the mine site for blending with mine sand tailings and disposed of into the mine pit. Synthetic rutile plants produce either solid or slurried waste in various forms, including:

- inert solids, iron oxides;
- slurries and oversize solids from the product drying kilns;

- neutralised acid effluent solids; and
- non-magnetic fines.

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

Typical activity concentrations for uranium and thorium in products and waste arising from mineral sand mining and processing (WACME, 2000; Hewson & Upton, 1996) are summarised in Cooper (2005). There is considerable variability between the different materials resulting from processing, and between the ores from different locations.

2.8 DOWNSTREAM PROCESSING OF MINERAL SANDS

2.8.1 Titanium dioxide pigment production

Rutile and synthetic rutile (from ilmenite) are processed to produce titanium dioxide pigments for use in the manufacture of paint, plastics, paper, ink, ceramics and many other products. Titanium oxide is extracted from rutile and synthetic rutile using either a chloride process or by sulphuric acid extraction.

Waste solids and slurries, including waste ore, arise from the chlorination and condensation stages of the process. The solids are neutralised, washed and separated from the liquids. The solid waste is slurried for transport and dried in ponds before final disposal as landfill. Solids from the effluent treatment are also disposed to landfill.

The original rutile and synthetic rutile minerals contain trace quantities of uranium and thorium and their radioactive decay products. These radionuclides tend to follow the solid waste stream during processing. Titanium oxide pigments do not have detectable levels of radioactivity. Typical radionuclide concentrations in the solid waste are given in Table 5.

Table 5: Typical quantities and radionuclide concentrations in titanium dioxide pigment production (WACME, 2000)

Material	Typical quantity ^a (kt a ⁻¹)	Thorium-232 ^b (Bq g ⁻¹)	Uranium-238 ^b (Bq g ⁻¹)
Titanium dioxide pigment	95	Not detectable	Not detectable
Neutralised residue slurry	100	1.20 (wet)	0.35 (wet)
Solid waste from liquid effluent treatment	100	0.8 – 1.4 (dry)	0.3 – 0.5 (dry)

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

Table 5 is based on mass concentrations of U and Th; however, radioactive equilibrium of the respective U and Th series may not be maintained throughout processing.

2.8.2 Zircon and zirconia production

The element zirconium is widely found in silicate form as the mineral zircon and in oxide form in baddeleyite. Zircon is used as raw material in the manufacture of steel refractory materials, in glazes, glasses and ceramics, in the manufacturing of dielectric materials and in special alloys. Zircon is milled to produce zircon flour or powdered zircon, and also refined or fused to produce zirconia, which is the oxide form. Fused zirconia is used in the production of ceramics and glazes.

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

Refractory bricks for steel and glass furnaces are made by fusing zircon sand with alumina and sodium carbonate. Disposal of used refractory bricks made from zircon may be a waste issue.

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

Zircon mineral contains trace amounts of uranium and thorium incorporated in the mineral structure. Radioactive equilibrium tends to exist between the radionuclides in the natural decay series. Since zircon is used directly in the manufacture of refractory materials and glazes, the products generally contain similar amounts of radioactivity to those in the original zircon. Higher concentrations may be found in zirconia.

Fusion of zircon leads to accumulation of the more volatile radionuclides (for example ^{210}Pb and ^{210}Po) in dust and fumes within the plant. Occupational exposure to these radionuclides in airborne dusts in the processing plant can be a radiological issue.

The International Atomic Agency Safety Report Series No. 51 (IAEA, 2007b) gives a comprehensive discussion of the issues relating to radiation protection and NORM residue management in the zircon and zirconia industries.

2.9 SCRAP METAL RECYCLING

Radioactive sources containing naturally occurring radionuclides do not come within the scope of this Safety Guide. However, if one of these sources becomes lost, it could become part of a scrap metal shipment. When the scrap metal is recycled the source could be broken up and the radionuclides could be dispersed throughout the scrap metal, resulting in wide-spread contamination. The management of this contaminated material is covered by this Safety Guide.

In addition, NORM residues on scrap metal have been known to set off radiation detection alarms at scrap metal treatment facilities.

2.10 WATER TREATMENT

Groundwater is not widely used for major public supply systems in Australia, except in Perth. Some form of treatment for drinking water is undertaken for supplies in all Australian capital cities, except Hobart, as well as regional centres and some small communities.

Impurities (dissolved salts, heavy metals, salinity, and soluble major elements such as calcium and magnesium) are removed from potable water using a variety of processes. These processes, which depend on the nature of the impurities in the water being treated, include aeration to remove iron, sand filtration, ion exchange, reverse osmosis, aeration, flocculation and sedimentation, co-precipitation and lime softening.

In Australia the conventional treatment for surface and ground water supplies is flocculation with alum, followed by removal of the flocculant by sedimentation or filtration (in conjunction with aeration), or sand and mineral filtration. Other treatments include micro-filtration using porous membranes, and reverse osmosis (for some small volume applications).

Residues resulting from water treatment include 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.

Radium isotopes are often present in groundwater, particularly in groundwater with relatively high levels of salinity. The concentration of ^{228}Ra tends to exceed that of ^{226}Ra , reflecting the higher levels of ^{232}Th in the earth's crust compared to that of ^{238}U .

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

Treatments such as aeration, flocculation, reverse osmosis, ion exchange or lime softening tend to remove radium and dissolved uranium contaminants quite efficiently. Therefore the radionuclides concentrate in the wastes. Where large volumes of material are used in water treatment this concentration in the waste is unlikely to pose any significant radiological risk. However, for processes (for example reverse osmosis) where the volume of waste can be much smaller than the volume of treated water, the concentration can be significant and disposal of the wastes may require careful management to avoid unnecessary exposures.

Desalination has been discussed as one option for alleviating water shortages in parts of Australia. This can also concentrate radionuclides and other impurities and contaminants in the waste streams. Since most desalination plants are found on the coast, the liquid wastes are usually pumped into the ocean. However, the effect of these wastes on marine flora and fauna is not well understood.

2.11 THE BUILDING INDUSTRY

The building industry makes use of residues that may contain NORM in some instances:

- fly ash is used as a concrete extender or in lightweight building blocks;
- bottom ash is sometimes used as a concrete extender.

Phosphogypsum is used in plasterboard in many countries, but is not used for this purpose in Australia, because of the availability of abundant cheap supplies of natural gypsum.

The exhalation of radon from building materials can sometimes pose a potential radiological hazard, particularly in poorly ventilated areas (see Section 3.2.1). External exposure may also be a potential problem in some situations because of the effects of geometry (see Section 3.2.2).

Typical concentrations of radionuclides in various building materials are summarised in IAEA Technical Reports Series No. 419 (IAEA, 2003a).

2.12 UNDERGROUND MINING AND TUNNELLING

Underground operations (mining, processing and tunnelling) can result in higher radiation doses to workers than would result from above-ground operations, due to the potential for increased radon concentrations (inhalation) and the 4π geometry (external exposure). These problems are discussed in more detail in Section 3.4.3 (radon) and Section 3.2.2 (external exposures).

2.13 GEOTHERMAL ENERGY GENERATION

Geothermal energy generation is not currently used in Australia, but is being investigated. Using geothermal energy requires drilling deep holes (boreholes) and inserting pipes for pumping high-temperature fluids from the ground. The rocks that contain these high-temperature fluids may also contain minerals, which tend to form a scale inside the pipes and production equipment. As the rocks are also likely to contain radionuclides, such as radium, the mineral scales, production sludges, and waste water could contain enhanced concentrations of NORM. There is limited information available on the potential radiological issues associated with this industry, but it would seem reasonable to assume that any potential issues will be similar in principle to those encountered in the oil and gas extraction and processing industry (see Section 2.1).

3. Radiological Issues in NORM Management

3.1 GENERAL

In the past, most attention has focussed on the uranium and mineral sand mining and processing industries. In uranium mining, in particular, the ore is mined for its radionuclide content. In most industries where NORM is a potential problem, the radionuclides are present in the products and wastes/residues as a contaminant, and the radionuclide concentrations are generally lower than those encountered in the mining and processing of uranium and mineral sands. Therefore the radiological issues involved in NORM management can be quite different from those in uranium and mineral sand mining and processing.

In particular, because many NORM residues are low concentration, high volume materials, there is considerable incentive for producers to utilise these materials where possible. Therefore there is a need for clear guidance on the potential radiological issues involved in the management of NORM, and in particular on assessment of the potential environmental and health impacts of NORM management strategies.

There are several stages in the overall management of materials containing NORM. These will vary for different industries, but include:

- mineral extraction;
- mineral processing;
- the use of products and by-products containing NORM;
- the management of residues containing NORM;
- the management of wastes containing NORM.

Each of these stages involves specific processes that may give rise to radiation exposure, via a range of exposure pathways.

3.2 EXPOSURE PATHWAYS

3.2.1 Internal exposures

Internal exposures can result from the decay of radionuclides within the body. These radionuclides usually enter the body via inhalation, ingestion, and wounds, and by absorption through the skin. The last mechanism is not relevant for the naturally occurring radionuclides discussed in this document. For the naturally occurring radionuclides, the most common modes of entry to the body are via inhalation and ingestion.

Alpha radiation has the greatest effect for internal exposures, because its relatively high energy and low penetrating power means that all the energy of the alpha particle is deposited in a short distance when it passes through tissue.

Doses resulting from internal exposures can therefore depend on the radionuclide concentration(s) in air, food, water or materials being handled, the duration of the exposure, and the rate of intake of material into the body. The dose can also depend on other factors, such as the chemical form of the materials being handled, wind speed, diet, etc.

Inhalation of radon and thoron from materials containing NORM

Radon (^{222}Rn) is produced by the radioactive decay of radium-226, which is present in most rocks, soils and minerals. The radiological risk associated with radon is due to the fact that the half-lives of the radon decay products are comparable with the residence time of air in the lungs. In general, radon levels in open air are not high enough to be a cause for concern. However, under unusual atmospheric conditions such as strong temperature inversions, or in poorly ventilated underground work areas, the radon concentration can increase significantly. Breaking up of rock and soil by blasting and earth-moving operations can also enhance the natural release of radon to the atmosphere.

Thoron (^{220}Rn) is produced by the radioactive decay of radium-224. Thoron has a half-life of 55.6 s. This means that, unless the thoron is produced inside the body or the thoron concentration in the air being breathed is high, thoron dose not normally pose a significant radiological hazard. In those situations where thoron does decay inside the body, since the decay products (with the exception of ^{212}Pb) have half-lives which are short compared with the retention time of air in the respiratory tract they can also pose a radiological hazard.

Inhalation of radon and thoron from building materials

^{226}Ra and ^{224}Ra are present in many building materials (bricks, concrete, stone). In poorly ventilated areas, radon levels can become high enough to be a cause for concern. Normal indoor ventilation rates (1-3 air changes per hour) are usually sufficient to keep indoor radon levels below values which would be of concern. Due to its relatively short half-life (55.6 s), thoron is much less likely to be exhaled from the building materials and enter the indoor air.

Inhalation of dust and fume

Dust is usually raised by wind action, blasting, loading or unloading of solid ores, processed minerals or NORM residues, transport of ore with heavy vehicles and as a result of general earth-moving operations. The presence of naturally occurring radionuclides means that some of these radionuclides will be embedded in or attached to dust particles. If the resuspended dust is inhaled the radionuclides can subsequently decay inside the body.

During the cleaning, maintenance and repair of plant and equipment, there is potential for material (such as scales or dust deposited on surfaces) removed by the cleaning process to become resuspended in air. This material could then be inhaled.

Radon and thoron are the only naturally occurring radionuclides that exist in gaseous form at normal temperatures and pressures. However, polonium and

lead are volatile at temperatures typically encountered in smelters and coal burning power stations. This means that immersion in a cloud of material (fume) containing these radionuclides has to be considered as a potential exposure pathway.

Ingestion of material contaminated with NORM

Surface (landfill) or near surface disposal of NORM wastes/residues can result in leaching of radionuclides from the waste/residue by infiltration of surface water following rainfall or irrigation, or by infiltration of groundwater. The leached radionuclides can enter the groundwater; if this groundwater is subsequently used for irrigation or for watering stock, the leached radionuclides can enter the food chain, and may subsequently be ingested by humans. Estimation of doses from this type of potential exposure pathway is an important part of an environmental impact assessment.

Runoff of surface water can also carry off radionuclides from NORM wastes/residues on the ground surface (landfill). These radionuclides can also enter the food chain and be ingested by humans.

If NORM is being handled, material can be deposited on the skin or on clothing. If sensible hygiene procedures are not followed (washing the hands before eating, changing clothes before eating or going home) some of this material can be ingested.

3.2.2 External exposures

External exposures occur when the radiation source is outside the body. Gamma radiation has the greatest effect on external exposures because of its high penetrating power. Doses from external exposure depend on factors such as the duration of the exposure, proximity to the radiation source, the radionuclide concentration, and the presence of shielding material.

Direct exposure from radionuclides in residues or on equipment or plant surfaces

Humans can be exposed to gamma radiation resulting from the decay of radionuclides in bulk materials (ore, residues) or on equipment or plant surfaces.

Direct exposure from radionuclides on the ground surface

Radionuclides can be deposited on the ground surface as a result of deposition from the atmosphere (for example, material deposited on the ground from a coal-fired power station plume), as the result of the use of materials containing NORM being used as soil conditioner or fertiliser, or as a result of irrigation with water contaminated with elevated concentrations of NORM. Humans can be exposed to the gamma radiation resulting from the radioactive decay of these deposited radionuclides.

Direct exposure from radionuclides in landfill

Residues containing NORM are often utilised as landfill. People accessing the landfill can be exposed to direct radiation from the radionuclides contained

in the landfill material. The duration of exposures and (therefore) the doses received will depend on the subsequent use of the land (recreation, industrial, housing, agriculture, etc.).

Direct exposure from radionuclides in waste rock piles from mining operations

People accessing a waste rock pile can be exposed to direct radiation from the radionuclides contained in the waste. The doses received will depend on the radionuclide concentration in the waste rock and on the time spent on the waste rock pile.

Direct exposure from material deposited on the skin

Material containing radionuclides which is deposited on the skin (dust or fume) can result in external exposure.

Direct exposure from radionuclides in building materials

The occupants of buildings are surrounded by materials which can contain NORM. This situation is referred to as 4π geometry, as distinct from the ground surface or equipment surfaces (2π geometry), and effectively enhances the dose per unit source material by a factor of two. This is compensated for to some extent by the fact that many buildings are not continuously occupied.

This geometric effect is also important in underground operations (see Section 3.3.2).

3.3 MINERAL EXTRACTION

Methods of mineral extraction include extraction of solids by open pit or underground mining, dredging of slurries, and liquid/gas extraction from wells. Each method has specialised techniques for extracting the mineral(s) of interest, and a range of potential risks that have to be understood and managed. Some of these risks arise from the nature of the mineral(s), some arise from the extraction methods used in the specific extraction operation, and some are associated with the environment in which the operation takes place. Figure 1 gives a generic outline of the operations of mineral extraction and processing. The different processing streams (raw mineral, chemicals, water, product, by-product and residue) and their relationship to the overall process are shown. This generic outline applies to all the different types of extraction and processing operations discussed in the following sections, apart from oil and gas production which is discussed in IAEA Safety Report Series No. 34 (IAEA, 2003b).

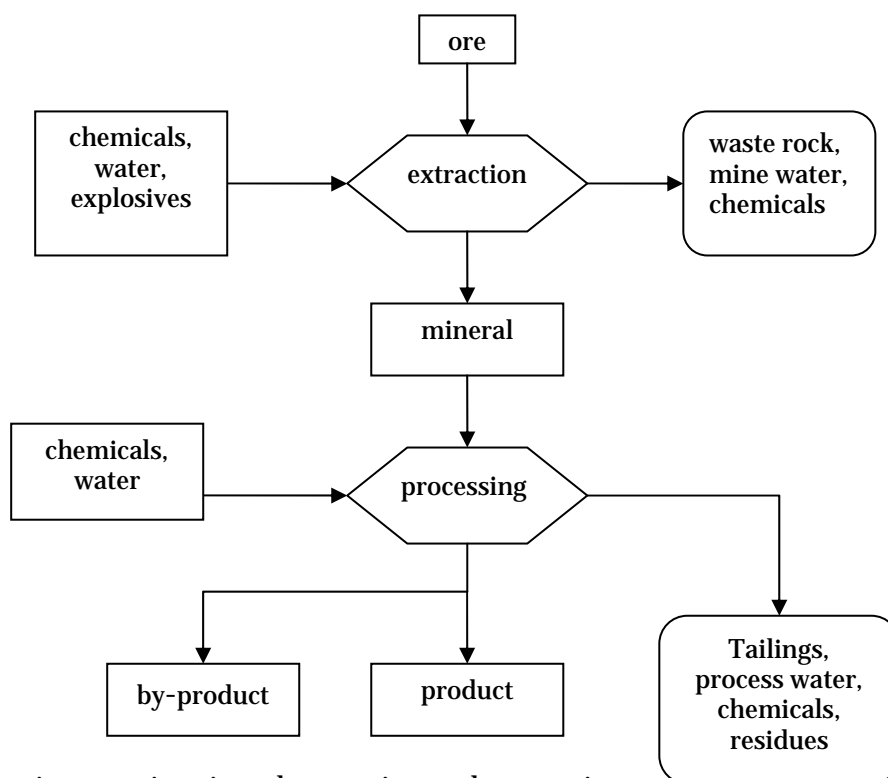


Figure 1: basic stages in mineral extraction and processing

3.3.1 Open pit mines

The potential radiological exposures associated with open pit mining operations arise from the presence of naturally occurring radionuclides in the ore, waste rock and overburden. The main risks are:

- external exposure to gamma radiation emitted by the ore, waste rock and overburden being handled;
- internal exposures resulting from inhalation of dust; and
- inhalation of radon and radon decay products.

Radiological hazards can also depend on the type (solid, liquid or gas) of the material(s) being handled. Where solid materials are being handled the potential risks include external exposure, inhalation of resuspended material, and ingestion of contaminated material which becomes attached to the hands or to clothing. Where liquids are being handled, external exposure and ingestion of contaminated material splashed onto clothing and/or the hands are the most important risks. Where gases are being handled, internal exposure via inhalation is the most important risk.

3.3.2 Underground operations and work places

The potential radiological exposures associated with underground mining operations arise from the presence of naturally occurring radionuclides in the ore, waste rock and country rock. The main risks are:

- inhalation of radon and radon decay products;
- external exposure to gamma radiation emitted by the ore, and waste rock being handled and the surrounding country rock; and
- internal exposures resulting from inhalation of dust.

3.3.3 Dredging for mineral extraction

Dredging operations for mineral extraction are conducted by scraping or digging sediment in lakes and rivers, bringing the material to the surface using bucket chains or similar equipment, and loading into vehicles, such as barges, ships, trains or trucks, for transport. In cases where the concentration plant is located close to the dredge, common practice is to pump the slurry directly to the concentration plant. As the materials are wet the potential for exposure due to inhalation is very low. However, as large volumes of material are being handled there is potential for external exposure and ingestion arising from the splashing of material onto clothing or skin.

3.3.4 Liquid/gas extraction from wells

Extraction of liquids or gases from wells can be accompanied by the build up of radioactive scales on the inside of pipes and pumping equipment, the release of radon, the release of contaminated formation water, and the generation of sludges and oily sands containing radionuclides.

3.4 MINERAL AND DOWNSTREAM PROCESSING

Several operations are involved in the processing of ores and downstream processing of minerals. These include physical or chemical separation of minerals from ore and from each other, or a combination of physical and chemical separation. Each of these operations can lead to the generation of wastes and residues. Each process may result in exposures of workers and discharges of mobile material to the environment. Environmental discharges can impact on the health of members of the public and the environment.

There are a number of pathways which can result in exposures to workers and members of the public. These include generation of dust, handling of material containing NORM, exhalation of radon from materials containing NORM, and cleaning of contaminated equipment.

3.4.1 Dust

In some industries, dry separation techniques are used to separate minerals. Materials can also be transported between different sections of a processing plant in dry form. These procedures have the potential to generate high concentrations of airborne dust containing NORM, which can pose an inhalation risk.

Dust generated in the open air can be dispersed off-site, where it can impact on the environment and members of the public.

3.4.2 Material handling

Handling of materials containing NORM can result in the deposition of contaminated material on the skin or on clothing. For solids the main issues are deposition of dust on clothing and exposed skin. Where liquids are being handled, splashing onto clothing and exposed skin can be an issue. Material deposited on clothing can be transferred to the hands by rubbing. Material on the hands can be inhaled or ingested when eating and/or drinking or if the face is rubbed.

3.4.3 Radon

Radon (^{222}Rn) is a gas, and therefore the main exposure pathway is inhalation. The half-life of radon (approximately 3.8 days) is much longer than the residence time of air in the respiratory tract. However, the short-lived decay products of radon (^{218}Po , ^{214}Pb , ^{214}Bi , ^{214}Po) have half-lives shorter than or comparable with the residence time of air in the respiratory tract. In addition, the radon decay products form as metallic ions and readily attach to any nearby surface. Therefore in most situations the decay products may be the major radiological issue, either from direct inhalation or from inhalation of radon that decays in the respiratory tract with subsequent decay of one or more decay products in the respiratory tract.

3.5 TRANSPORT OF BULK COMMODITIES, RESIDUES AND WASTES

Bulk NORM commodities, residues and wastes can be transported as gases (natural gas, refined gas), liquids (oil), and solids. Therefore requirements for the safe transport of these bulk materials can vary widely.

The transport of radioactive material in Australia is governed by regulations in each jurisdiction that adopt the 'Code of Practice for the Safe Transport of Radioactive Material (2008)' (the Transport Code).

The International Atomic Energy Agency (IAEA) has published a number of documents that are relevant to the transport of radioactive material. These include:

- IAEA Safety Standards Series Safety Guide No. TS-G-1.3 which discusses radiation protection programs for the transport of radioactive material (IAEA, 2007a);
- IAEA Safety Standards Series Safety Guide No. TS-G-1.2 (ST-3) which discusses emergency response to transport accidents (IAEA, 2002a);
- IAEA Safety Standards Series Safety Requirements No. TS-R-1 which contains the 2005 edition of the IAEA Transport Regulations (IAEA, 2005c); and
- IAEA Safety Standards Series Safety Guide No. TS-G-1.1 (ST-2) which contains advisory material on the IAEA Transport Regulations (IAEA, 2002b).

Some of the potential radiological issues arising from the transport of bulk materials are discussed in the following sections.

3.5.1 Dust (loading and unloading)

In the absence of dust control measures, loading and unloading of bulk commodities (for road, rail or sea transport) can generate significant quantities of dust. In some situations this dust could pose an inhalation risk to workers and members of the public.

3.5.2 External exposures during transport

Transport of NORM is unlikely to lead to significant external exposures to members of the public, because of the very short exposure times involved. However, workers such as truck drivers can be exposed for much longer periods. There are two considerations which result in such exposures generally being lower than expected:

- truck drivers are generally enclosed in metal cabs during transport, which provides some shielding from the gamma radiation emanating from the material being transported;
- most of the gamma radiation produced by the radioactive decay of naturally occurring radionuclides is relatively low energy radiation, and a considerable fraction of the radiation released from bulk NORM material is absorbed in the material (self-absorption).

3.5.3 Transport accidents

In the event of an accident in which solid material is spilt from a damaged vehicle or container, the main exposure pathway is likely to be via inhalation of resuspended material (dust).

For transport accidents involving liquids, the main exposure pathways are likely to be external or ingestion from material splashed onto the skin or onto clothing.

For transport accidents involving gases, the main exposure pathways will be via inhalation and external exposure (immersion).

3.6 USE OF PRODUCTS

Products containing NORM are used in a wide variety of situations. These include fertilisers, ceramic pigments and glazes, uranium glass, thoriated welding rods, thorium gas mantles, and Mg-Th alloy in jet engines. In nearly all applications the concentration of radionuclides is low, or the total activity in the material is low (small amount of material used) or the exposure time in any realistic exposure scenario is short. This means that, in many cases, the presence of NORM in these products is of little concern. Some examples are given below.

Ceramic glazes

Although the radionuclide concentrations in ceramic glazes can be quite high (O'Brien et al, 1998), these glazes are usually applied in very thin layers. In homes, ceramic glazes are mostly used in areas (bathrooms, toilets, etc.) where occupancy times are relatively short, and individuals do not spend much time in close proximity to tiled surfaces. Dose estimates indicate that doses to members of the public resulting from the use of ceramic glazes in homes are within acceptable levels. However, these glazes are also used in tiled food stores, ceramic showrooms, older indoor swimming pools, hospitals, meat markets, etc. In these situations the doses received by workers may need to be checked because of the longer occupancy times. Further information is given in the IAEA Safety Report Series No. 51 (IAEA, 2007b).

Thoriated welding rods

Thoriated welding rods are used to conduct heat efficiently to areas where welds are being applied. The major hazard associated with the use of these rods is associated with the grinding necessary to maintain a fine point on the rod. This grinding can result in the suspension of fine particles containing thorium. However, provided good ventilation of work areas is maintained, the rate at which the rods are used is such that the risk of inhalation of thorium is very low.

3.7 MANAGEMENT OF RESIDUES

Processing of NORM materials gives rise to products, wastes and residues. Residues are those materials that have potential for utilisation. The most common ways of dealing with NORM residues are storage in stockpiles and/or tailings dams, utilisation in landfill, roadfill and building materials, and disposal by near-surface burial. The choice of method should be based on the results of an environmental impact assessment. This assessment should consider the nature of the residue, the possible exposure pathways (see the earlier discussion) resulting from each management method, the lifestyle (diet, recreation, etc.) of local residents, and different types of land use.

Strategies for managing NORM residues may be included in a NORM Management Plan (see Section 4.4.6).

3.7.1 Storage/Disposal

Stockpiles

Solid residues are usually stored in stockpiles. The potential exposure pathways associated with a stockpile are inhalation of radon and resuspended dust, direct external exposure, and ingestion of locally grown food which may be contaminated (see earlier).

Tailings dams

Liquid residues, sludges, slurries etc., or small quantities of residues resulting from the final stages of mineral processing are often stored in tailings dams. The important exposure pathways from tailings dams are direct external exposure, ingestion of contaminated water, and ingestion of contaminated food resulting from migration of tailings from the dam via, for example, leaching, leakage, or overflow. A tailings dam may be converted to a disposal site by allowing the liquid to evaporate and covering the tailings with a suitable, clean material such as soil or un-mineralised rock

Near surface burial

Near surface burial is often utilised for disposal of solid residues. This method removes inhalation of resuspended dust as an exposure pathway and reduces doses from direct external exposure, radon inhalation. However, other possible exposure pathways such as leaching to groundwater now have to be considered. In addition, because of the long half-lives of the naturally occurring (parent) radionuclides, the effect of erosion of the cover material over long periods of time has to be taken into consideration.

The large volumes of NORM residues generated in many industries require considerable tracts of land for disposal. This means that another important consideration is the degradation or destruction of habitats of native birds and animals. Consideration also has to be given to the possible habitat degradation or destruction that can occur at the site from which the covering material is obtained (the borrow site).

The cost of the earth moving required for near surface disposal has to be balanced against the reduction in the radiological risk.

3.7.2 Utilisation of NORM residues

In the past, NORM residues have been widely utilised in:

- landfill (phosphogypsum, waste rock, bauxite solid residue, fly ash);
- concrete extender (fly-ash);
- plasterboard (phosphogypsum);
- building materials (phosphogypsum¹, fly ash);
- soil conditioners (phosphogypsum, bauxite mud residue);
- rail ballast (waste rock);
- roadfill (waste rock, fly ash);
- scrap metal recycling (metal slags, bottom ash).

The radiological impacts of many of these uses of NORM residues have been assessed for many different situations, and there is a considerable body of scientific literature available, particularly on the use of NORM residues in landfill, concrete extender, phosphogypsum plasterboard, building materials and roadfill. However, each situation can be subtly different and it is good practice to check each situation before deciding to utilise a NORM residue. If an assessment of the potential radiological impact of these situations is to be carried out, the details of the assessment process should be discussed with the regulator. In the first instance the radiation protection regulator listed in this Safety Guide should be approached. However, other Authorities may also be involved.

3.7.3 Optimisation - use of the ALARA principle

The ALARA principle is defined (ICRP, 2008) as 'the source related process to keep the likelihood of incurring exposures (where these are not certain to be received), the number of people exposed, and the magnitude of individual doses as low as reasonably achievable, taking economic and societal factors into account'. This principle is a statement of the general principle that optimisation should include consideration of all factors, including societal and economic costs. While it can be difficult to implement in some situations, it is an important component of the internationally recommended system of radiation protection, and is particularly relevant to NORM residue management because of the large volumes of material involved and the

¹ Phosphogypsum is used in building materials overseas, but is not used for this purpose in Australia, due to the availability of cheap supplies of natural gypsum.

(generally) low (but not always trivial) levels of radiological risk associated with these materials.

In some cases (as mentioned earlier) an operation can result in exposures to members of the public which approach, and may even exceed, the annual public dose limit. In these situations, if the operation can be clearly shown to be optimised (i.e. doses cannot easily be further reduced without significant expense), and if all stakeholders are prepared to accept the elevated level of risk, application of the ALARA principle would suggest that the operation could be allowed to continue, subject to periodic review.

Another example is the situation where the costs associated with near-surface burial (soil removal, hire of earth-moving equipment, habitat degradation of both the burial site and the borrow site) have to be balanced against the radiological risks associated with other methods of disposal.

3.8 MANAGEMENT OF WASTES

The modern definition of a waste is a material for which there is no foreseeable use. The general approach is therefore to minimise waste production as much as possible and utilise residues as much as possible. This is particularly applicable to NORM and wastes/residues resulting from processing of NORM, where large volumes of material with relatively low concentrations of radionuclides are frequently involved.

The choice of an appropriate approach to management and disposal of NORM wastes can depend on factors such as radionuclide concentrations in the waste, the physical form of the waste (solid, liquid or gas) and the chemical form of the waste. Environmental impact can be limited by reducing the mobility of the waste. This can be done by solidification of liquids and/or the use of engineered barriers.

3.8.1 Storage

Except in unusual circumstances, storage of NORM wastes/residues should not be considered as a long term management option, because the very long half-lives of ^{238}U , ^{235}U and ^{232}Th would not lead to significant reduction in exposures over typical storage timeframes. Storage requires the construction of permanent or semi-permanent buildings, with fencing or other means of restricting access, and in some cases (for example in urban areas) may require higher levels of security. An additional disadvantage is that storage is only an interim measure and the cost of ultimately removing the waste and decommissioning the storage facility has to be added to the costs associated with constructing and maintaining the facility.

3.8.2 Near surface burial

The Near Surface Disposal Code (NHRMC, 1993) is applicable to bulk NORM residue disposal. The principles outlined in this code can also be used for small quantities of NORM, particularly in situations with issues of potential transfer of radionuclides into groundwater. As already mentioned, near surface burial reduces the number of potential exposure pathways, but can result in the transfer of radionuclides to groundwater as a result of leaching.

Near surface burial can cause habitat degradation, but in many cases the land may become available for use for recreation, agriculture, residential or industrial purposes. Where necessary the allowable use(s) should be determined on the basis of environmental impact and safety assessments, and if necessary, restrictions should be placed on the use of the land.

3.8.3 Other disposal options

Other disposal options that might be appropriate for NORM wastes are:

- unrestricted disposal to municipal tips or landfill;
- disposal into underground mine cemented backfill;
- injection with some form of encapsulation (such as cement grout) into old oil wells slated for abandonment and plugging;
- disposal into mine waste rock dumps, smelter slag dumps, mine tailings dams or power plant ash ponds.

The last option, however, may only be an interim measure in some cases.

It is clear that the choice of disposal option will depend on the nature of the waste.

3.9 PUBLIC PERCEPTION

Public perception is an issue whenever radioactivity is mentioned. The traditional perception has been 'any exposure to radioactivity is dangerous'. For example, public perception often interprets low levels of exposure as having consequences similar to Chernobyl. Dealing with public perception is an important component of any strategy for management of NORM. It is generally accepted that open communication with and involvement of all stakeholders is an important component of the process of dealing with public concerns (IAEA, 1999a).

Relating the normally low risks associated with NORM exposure to the risks associated with non-radiological public health risks (e.g. from air pollution, travel) may help place NORM exposure in a reasonable context.

Establishing clear and open procedures for optimisation of protection from ionizing radiation in any particular situation is important in dealing with perception issues. The optimisation of protection, including the involvement of stakeholders, is discussed in ICRP Publication 103 (ICRP, 2008).

3.10 SUMMARY

There are many potential exposure scenarios involving NORM, and the dose resulting from a particular exposure scenario can depend on a range of factors. Therefore it is difficult to establish criteria which will apply to all situations. In those cases where the number of potential exposure scenarios is limited (for example, transport of material containing NORM), it is possible to set up simple criteria. However, these criteria may not be applicable in other situations, for example reuse of NORM residues as landfill, where exposures are likely to be of much longer duration.

4. Regulatory Issues in NORM Management

4.1 INTERNATIONAL DEVELOPMENTS IN NORM MANAGEMENT

International interest in NORM issues, including environmental research, development of guidance material and exchange of information, has grown steadily over the past decade. For example, regulatory and management approaches for NORM residues were the subject of meetings held in Vienna in 2002 and 2004 by the IAEA (IAEA, 2006c). There has also been a number of international symposia on NORM, the most recent being the NORM V symposium in Seville in 2007.

There is now a significant and increasing set of international guidance publications on different aspects of NORM management. Some of the important principles within this guidance are:

- Graded approach to regulation

International guidance recommends that regulation be based on a graded approach consistent with the optimisation principle. Hence the stringency of the regulation should be ‘...commensurate with the characteristics of the practice or source and with the magnitude and likelihood of the exposures...’ (IAEA, 1996).

- Scope of regulatory control

There is a consensus that the emphasis of regulatory activity should be on optimisation rather than limitation, and that economic, social and political issues need to be taken into account.

- Stakeholder involvement

Both the IAEA (IAEA, 2007a; IAEA, 2006b) and the ICRP (ICRP, 2008) have emphasised that open communication between stakeholders (operator, regulatory authority, public) is an important component of any regulatory system.

- Risk assessment methodologies

Clear methodologies should be established for assessing risk and demonstrating compliance with licence conditions (IAEA, 2006b). These can include the use of computer models, comparison of measured radionuclide concentrations with reference levels, or comparison of risks with the risks resulting from other activities.

4.2 CURRENT REGULATORY FRAMEWORKS IN AUSTRALIA

All States and Territories and the Commonwealth have regulatory systems governing the management of radioactive materials and sources. In addition, there is other legislation that may be applicable in certain circumstances, including mining, environmental and occupational health and safety legislation. An example is the Environment Protection and Biodiversity

Conservation Act 1999, which aims to protect the environment, particularly matters of National Environmental Significance (Protected matters). It streamlines national environmental assessment and approvals process, protects Australian biodiversity and integrates management of important natural and cultural places.

In providing an agreed national framework for radiation safety, the National Directory for Radiation Protection (NDRP) defines the scope of regulation and exemption levels that will include the management of exposures arising from operations involving NORM, and provide for the protection of the environment from NORM wastes.

The system for assessment of the need for regulation outlined in this Safety Guide is consistent with government actions intended to ensure that regulation is efficient and effective.

The 'Mining Code' applies to the control of occupational and public radiation exposures, and the management of radioactive waste generated at all stages of mining and mineral processing. A 'Mining Safety Guide' accompanies the Code.

Although the Mining Code was primarily developed to apply to the mining and processing of uranium and thorium concentrates and separation of heavy minerals from mineral sands ore, the Code (Clause 2.3.2) notes that:

'The relevant regulatory authority (see Annex A) may direct that this Code be applied, in whole or part, to other mining and mineral processing operations that have the potential to produce significant occupational radiation exposures, or to generate waste having the potential to cause a significant increase in the radiological exposure of members of the public or the environment and which would therefore require specific management. These operations may include:

- (a) the mining and processing of other minerals that adventitiously contain uranium or thorium or their decay products; and*
- (b) processes which lead to the production of waste not usually regarded as radioactive, but which contains naturally occurring radionuclides.'*

This Safety Guide extends the guidance provided in the Mining Safety Guide to operations involving NORM, to provide sufficient flexibility for the operator and regulator to optimise levels of protection in a risk-based manner that also incorporates the fundamental principles outlined above. It is also intended that this Safety Guide will assist both operators and regulators in considering whether a regulatory approach is necessary, and the type of regulatory approach that may be applied, in any particular case.

Where the Regulator directs that the Mining Code is to be applied to operations involving NORM, the extent of application of the Code should be operation specific and should be subject to negotiation between the regulator and operator.

4.3 ASSESSING THE NEED TO REGULATE NORM

An important consideration for regulatory bodies is whether there is a need to regulate activities involving NORM, and at what activity concentration a regulatory approach is necessary. In addition, for many NORM operations, the practices may be optimised to the point where regulation may not lead to an improvement in radiation protection. Invoking a regulatory approach at low activity concentrations, in cases where there is not likely to be improvement in protection, would result in a wide variety of low risk situations being regulated, thereby diverting regulatory resources from dealing with higher risk activities. There would also be a compliance cost to industry for limited benefit in improved protection.

As NORM may be present in tradable commodities, and residues have potential for future use, cross-border issues may arise. It is therefore important to develop a uniform approach to NORM management issues and consideration of regulation across jurisdictions.

The following discussion is intended to assist regulators by giving guidance on assessment of the need for regulation of NORM, and assist industry by describing the process regulators are likely to follow.

4.3.1 Application of Exclusion and Exemption to NORM

The concepts of exclusion and exemption, optimisation of radiation protection and the use of a graded approach to regulation are important considerations in assessing the need for a regulatory approach to NORM.

Exclusion is generally applied to exposures that are not amenable to control. Undisturbed mineral deposits are generally excluded from regulatory control.

For normal exposure situations, it is usually unnecessary to regulate materials with radionuclides of natural origin below 1 Bq g⁻¹. Under these conditions, it can be anticipated that doses to members of the public are unlikely to exceed about 1 mSv a⁻¹ (IAEA, 2004a).

Exposure to a mineral deposit or other natural material may be excluded from the scope of regulatory instruments even if its state has been altered by human activities, when such exposure is deemed to be unamenable to control. However, it is appropriate for the regulatory body to take such exposure into consideration if the individual radionuclide concentration in the material exceeds about 1 Bq g⁻¹. Depending on the outcome of a screening assessment negotiated between the operator and the Authority, the activity concerned may be exempted or be subject to regulatory control.

It is appropriate for the Authority to consider exemptions for practices (generally expected to be dealings involving quantities of naturally occurring radioactive materials) resulting in individual doses up to about 1 mSv per year on the basis of an assessment (to be agreed between the operator and the Authority) that the radiation protection is optimised. Such an exemption may be subject to monitoring and reporting conditions to ensure that the basis for exemption stays in place.

Application of the exemption criterion of approximately 1 mSv to some situations (such as the use of some building materials containing natural radionuclides), will necessitate consideration by the Authority. It may be necessary in such cases to consider some form of regulatory control over exposures from materials due to radionuclides with activity concentrations below those given in Schedule 4 of the National Directory for Radiation Protection (ARPANSA, 2004).

4.3.2 First stage of assessment - identification of operations involving NORM

Section 2 of this Safety Guide gives a range of industry sectors where NORM management measures may need consideration. A regulatory body would start consideration by identifying which relevant industry sectors are operating in its jurisdiction, or by receiving a notification from an industry that it is dealing with NORM in its operations.

Having identified relevant industry sectors, priority should be given to the types of operation known from experience and current knowledge to be most likely to require regulatory measures. The IAEA has identified those types of operation likely to require regulatory control on the basis of worker doses. Table 6 below has been adapted from Table 3 of Safety Report Series 49 (IAEA, 2006a).

Table 6: Types of operation identified, on the basis of worker dose, as being likely to require regulatory control

Type of operation	Material involved			Worker dose (mSv a ⁻¹)
	Description	Radionuclide(s) with highest activity concentration	Typical activity concentration (Bq g ⁻¹)	
Rare earth extraction from monazite	Monazite concentrate Scale Residue	²³² Th series ²³² Th ²²⁸ Ra ²²⁸ Ra	40-600 Up to 800 1000 20-3000	Average 1-8, could approach or exceed dose limit
Production of thorium compounds	Thorium concentrate Thorium compounds	²³² Th ²³² Th	Up to 800 Up to 2000	Typically 6-15
Manufacture of thorium containing products	Thorium compounds Products	²³² Th ²³² Th	Up to 2000 Up to 1000	<1 to a significant fraction of dose limit
Processing of niobium/tantalum ore	Ore Pyrochlore concentrate Residue Slag	²³² Th series ²³² Th ²²⁸ Ra ²³² Th	1-8 80 200-500 20-120	Could reach a significant fraction of dose limit
Some underground mines and similar workplaces	Ore Scales from Ra rich water	²²⁶ Ra, ²²⁸ Ra	Up to 10 Up to 200	<1 to a significant fraction of dose limit ^a
Oil and gas production	Scales during removal from pipes/vessels	²²⁶ Ra	0.1-15000	<1 to a significant fraction of dose limit

Type of operation	Material involved			Worker dose (mSv a ⁻¹)
	Description	Radionuclide(s) with highest activity concentration	Typical activity concentration (Bq g ⁻¹)	
TiO ₂ pigment production	Scales during removal from pipes/vessels	²²⁸ Ra, ²²⁶ Ra	<1-1600	<1-6
Thermal phosphorus production	Fume and precipitator dust	²¹⁰ Pb	Up to 1000 ^b	0.2-5 (average ~ 1)
Fused zirconia production	Fume and precipitator dust	²¹⁰ Pb, ²¹⁰ Po	Up to 600 ^b	0.25-4.5

- ^a Measurements in some metal mines indicate an effective dose from gamma radiation and dust of about 0.5 mSv a⁻¹ per unit ²³⁸U activity concentration (in Bq g⁻¹) in the ore. The effective dose from radon is highly variable and difficult to predict, being strongly dependent on ventilation conditions and other factors.
- ^b These values refer to the activity concentration of the precipitator dust.

IAEA (2006a) notes that ‘...the list is not exhaustive, but probably captures most of the relevant types of operation. It shows that there are relatively few types of operation that are likely to need formal regulation.’

Having evaluated the relevant operations on the basis of experience and/or a screening assessment, the regulator should consider the need for regulation, using a graded approach ‘consistent with the optimisation principle’ (IAEA 2004a). Typically, a graded regulatory approach could include exemption, a requirement for authorisation of the responsible person for the operation, a requirement for a more detailed assessment of the radiation risks (including worker and public doses and environmental impact) and a requirement to develop and implement a NORM management plan.

In addition to worker exposure, public exposure and environmental issues must also be considered in any decision on the need for regulation.

A particular case where additional issues arise is that of underground mining or similar workplaces. In these cases consideration of exposure from radon is required in addition to gamma and dust exposure. Radon concentration will be affected by factors such as orebody activity concentration, ventilation, and inflow water quality and quantity. There are many publications on radon exposure and measurement, including IAEA and ICRP publications (IAEA, 2003d; ICRP, 1994a), so they are not described in detail in this Safety Guide.

4.3.3 Second stage of assessment – consideration of other materials

When the relevant higher priority types of operations above have been assessed, consideration can be given to other materials associated with the industry sectors listed in Section 2 of this Safety Guide. Table 7 below, based on Table 1 of Safety Report Series 49 (IAEA, 2006a), is a useful starting point.

Table 7: Materials to be assessed for possible regulatory control

Category	Material/operation	Radionuclide(s) with highest activity concentration	Typical activity concentration (Bq g ⁻¹)
Feedstocks	Monazite sand Metal ores, e.g. Nb/Ta, Cu, Au Zircon sand Phosphate rock TiO ₂ feedstocks Bauxite	²³² Th series ²³⁸ U and ²³² Th series ²³⁸ U series ²³⁸ U series ²³² Th ²³² Th series	40–600 Up to 10 2–4 0.03–3 0.001–2 0.035–1.4
Bulk residues	Red mud (alumina production) Phosphogypsum (H ₂ SO ₄ process)	²³⁸ U, ²³² Th ²²⁶ Ra	0.1–3 0.015–3
Slags	Niobium extraction Tin smelting Copper smelting Thermal phosphorus production	²³² Th ²³² Th ²²⁶ Ra ²³⁸ U	20–120 0.07–15 0.4–2 0.3–2
Scales, sludges and sediments	Scale (oil and gas production) Scale (phosphoric acid production) Residue (rare earth extraction) Scale (TiO ₂ pigment production) Scale (rare earth extraction) Sludge (oil and gas production) Residue (niobium extraction) Scale (coal mines with Ra rich inflow water) Scale (iron smelting) Scale (coal combustion) Sludge (iron smelting) Residue (TiO ₂ pigment production) Sludge (water treatment)	²²⁶ Ra ²²⁶ Ra ²²⁸ Ra ²²⁸ Ra, ²²⁶ Ra ²²⁶ Ra, ²²⁸ Th ²²⁶ Ra ²²⁸ Ra ²²⁶ Ra, ²²⁸ Ra ²¹⁰ Pb, ²¹⁰ Po ²¹⁰ Pb ²¹⁰ Pb ²³² Th, ²²⁸ Ra ²²⁶ Ra	0.1–15000 0.003–4000 20–3000 <1–1600 1000 0.05–800 200–500 Up to 200 Up to 200 >100 12–100 <1–20 0.1–14
Precipitator dust	Thermal phosphorus production Fused zirconia production Niobium extraction Metal smelting	²¹⁰ Pb ²¹⁰ Po ²¹⁰ Pb, ²¹⁰ Po ²¹⁰ Pb, ²¹⁰ Po	1000 600 100–500 Up to 200
Intermediate products	Thorium compounds Thorium concentrate Pyrochlore concentrate (niobium extraction) Cerium concentrate (glass manufacture) Fused zirconia	²³² Th ²³² Th ²³² Th ²³² Th ²³⁸ U	Up to 2000 Up to 800 80 10 2–8
Products	Gas mantles Thoriated glass Thorium containing optical polishing powders Thoriated welding electrodes Thorium alloys Zirconium containing refractories Phosphate fertilisers Technical grade phosphoric acid Phosphogypsum plasterboard ^a	²³² Th ²³² Th ²³² Th ²³² Th ²³⁸ U ²³⁸ U ²³⁸ U ²²⁶ Ra	500–1000 200–1000 150 30–150 46–70 1–4 0.4–2 0.14–2 0.004–0.7

^a Although this material has an activity concentration of less than 1 Bq g⁻¹, it is included because it is a building material.

Measurement of the activity concentration levels in these materials may indicate further types of operation where radiation protection measures could be needed. The Regulatory Authority should decide, in accordance with the graded approach to regulation, whether the operations can be exempted, or whether they should be subject to authorisation. A graded approach means

that, where the regulatory authority has determined that regulatory controls are necessary, the regulatory measures should be commensurate with the level of risk associated with the material/operation.

Table 8 (IAEA, 2006a) proposes that initial consideration should be given to materials where activity concentrations could lead to exceeding 10% of the dose limit. Table 8 (IAEA, 2006a) indicates a range of materials for which this could occur.

Table 8: Relationship between dose and activity concentration for occupational exposure to gamma radiation and to dust

Category of material	Broad estimate of annual effective dose per unit activity concentration (mSv a ⁻¹ per Bq g ⁻¹)		Individual radionuclide activity concentration ^b above which the expected dose may exceed 10% of the dose limit (Bq g ⁻¹)
	MINIMUM	MAXIMUM	
Large quantity, e.g. orebody, large stockpile	0.02	0.4	5
Small quantity, e.g. mineral concentrate, scale, sludge	0.008	0.04	50
Volatilised: furnace fume and precipitator dust	0.0006	0.003	500 ^a

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

^b The activity concentrations mean the highest individual radionuclide activity concentration in the material concerned.

Where the materials have activity concentrations of uranium and thorium series radionuclides not exceeding 1 Bq g⁻¹ they are unlikely to require further consideration unless they are used as building materials (see Section 2.11).

A graded approach to regulation of NORM of this type (including consideration of exemption) is important, as exposures arising from NORM operations are generally moderate with little likelihood of extreme radiological consequences from accidents.

4.3.4 Other work situations

It is possible that the following work situations may also require radiation protection measures:

- Processes in industry sectors other than those in Section 2. Here the approach would be to establish, by sampling and measurement, if the activity concentration of uranium or thorium series radionuclides in the materials exceeds 1 Bq g⁻¹, and in particular if the activity concentration levels in Table 8 are exceeded. This can occur in processes that enhance concentration of radionuclides, such as formation of scale in pipes and vessels or the volatilisation and subsequent precipitation of radionuclides in high temperature processes. These are described in Appendix II of Safety Report Series 49 (IAEA, 2006a).

- Workplaces, other than underground mines and workplaces with similar characteristics, where the activity concentrations are not elevated, but the radon concentration in air exceeds the action level of 1000 Bq m⁻³ (ARPANSA, 2002). Information that could assist in identifying workplaces with high radon concentration is given in Safety Report Series No. 33 (IAEA, 2003d).

4.4 GRADED APPROACH TO REGULATION

The graded approach to regulation, which assumes that regulatory effort should be proportional to radiological risk, should commence with the operator notifying the regulator of the existing or proposed operation, or the regulator notifying the operator that an assessment should be carried out. The regulator may require a screening assessment of the potential impact of the operation to be carried out. The details of the assessment should be agreed between the operator and the regulator.

As a result of this screening assessment, the regulator may grant an unconditional exemption or require that a detailed environmental impact assessment and safety assessment be carried out.

Following this more detailed assessment, the regulator may then grant an exemption (possibly with conditions) or require formal (licensed) ongoing management of radiation impacts.

The following sections describe this approach in more detail.

4.4.1 Notification

Most of the industries that have potential to lead to radiological exposures from NORM have been discussed in the earlier sections of this Safety Guide. In these industries, the operator is responsible for notifying the regulator that the operation involves naturally occurring radioactive materials. Typically, the nature of the process materials is reviewed as part of the initial mining and/or processing application, or environmental assessment for a project. The operator should consult the regulator if there is uncertainty as to whether a particular operation may require regulatory attention.

The process of notification provides a record for the Authority of the intended operation and the decision to either exempt the operation where it is clear that exposures and activity concentrations will not exceed the relevant exemption criteria, or to proceed with a screening assessment.

The Regulatory Authority may, on the basis of previous or international experience with a particular type of operation, contact a new or existing industry, and request a screening assessment.

4.4.2 Screening assessment

Upon receiving a notification, the Authority may require an initial screening risk assessment to be made to estimate:

- the magnitude of worker and member of public doses arising from the operation;

- the level of optimisation of radiation protection;
- the long term impact of any residues on the environment in the case of disposal;
- the impact of residues containing NORM or contaminated materials that may be recycled;
- the impact of manufactured items containing NORM.

Where the contact is initiated by the Authority, a screening assessment may also be required.

The screening assessment should be specific to the particular operation and should be negotiated between the operator and regulator. The assessment may be based on existing information relating to the operation, its processes and waste/residue management methods, or be based on an agreed monitoring program to provide more data.

Procedures for carrying out screening assessments have been described by the National Council on Radiological Protection and Measurements (NCRP) (NCRP, 1996). It is important that a screening assessment should be conservative, to ensure that risks are not underestimated.

Possible outcomes of the screening assessment include unconditional exemption, exemption plus periodic review, regulation (possibly including licensing), and/or development of a NORM management plan. This process is shown schematically in Figure 2.

Where a screening assessment indicates that regulation might be required, the form of regulatory control that could be applied to practices involving NORM in minerals is largely outlined in the Code of Practice for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005), RPS 9 (ARPANSA, 2005a).

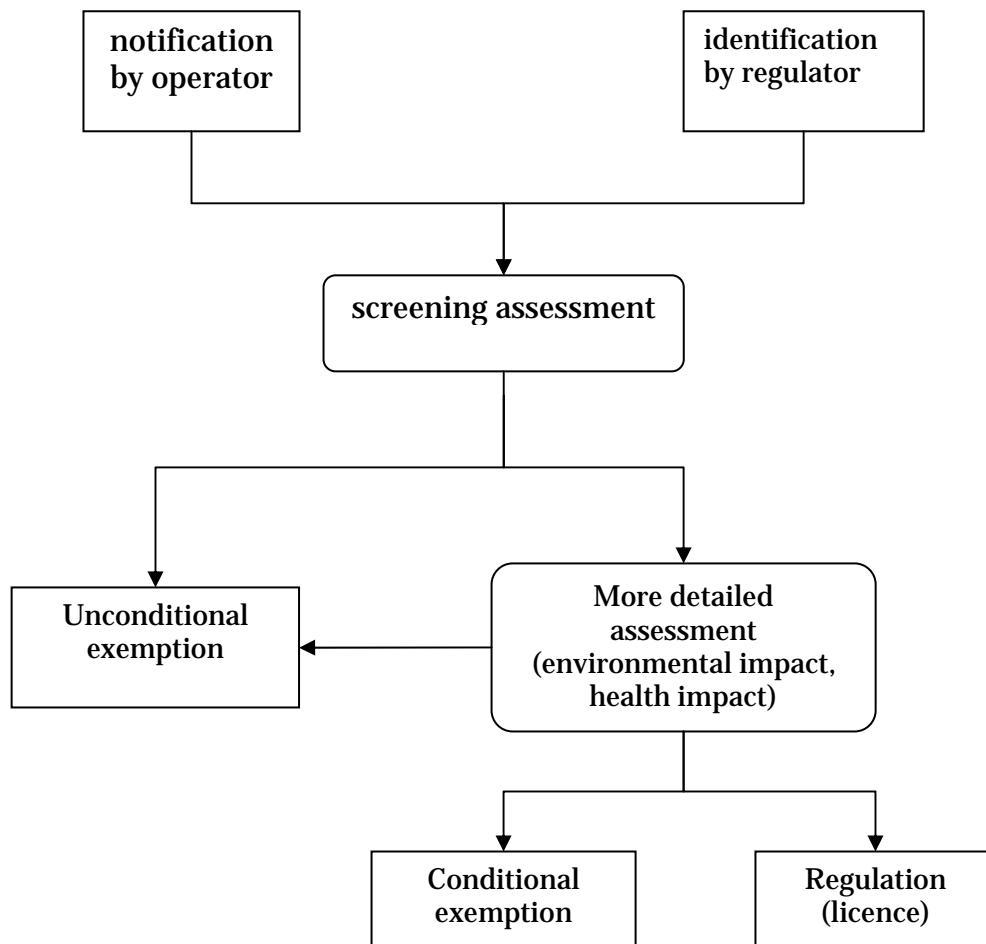


Figure 2: The basic process for management of NORM

4.4.3 Unconditional exemption

Where doses are below the exemption criteria, and any other impacts are considered acceptable, the Authority may exempt the operation from further requirements. This would apply to those cases where it is clear that the potential for significant exposures is negligible (even in situations where there are changes to the process or the materials being handled).

4.4.4 Conditional exemption (registration)

Where the screening assessment confirms that the criteria for unconditional exemption cannot be met, but the doses to the workforce and members of the public are expected to be well below the relevant dose limits, a conditional exemption may be appropriate.

The Authority should maintain a register of operations with ongoing requirements for monitoring and reporting and/or periodic re-assessment being applied as conditions of the exemption.

Periodic monitoring checks should be carried out to verify that the assumptions on which the original assessment was based are still valid. For example, changes in the process or in the nature of the materials being handled could lead to increases in doses to the work force and members of the public, or to increases in the assessed risk to the environment. In these

situations the operator may be required to develop an appropriate NORM management plan (see Section 4.4.6), including provisions for re-assessment.

In the event of significant process change, or where external events have impacted on the operation (flooding, fire, land slippage, subsidence) a new assessment may be required. The operator and regulator should review the situation after a mutually agreed period to check whether exemption is still appropriate.

4.4.5 Licensing

Where an exemption is not granted, regulation may require the operator to hold an appropriate licence or registration. These authorisations would typically assign responsibilities and require a radiation management plan to be implemented. The Authority may apply conditions to any registration or licence issued to define the particular requirements for ongoing monitoring and reporting, and, where appropriate, to specify the frequency of re-assessment of the status of the operation.

The Mining Code, supported by the Mining Safety Guide, establishes a regulatory framework that could be applied to the management of NORM. The Mining Code includes a system of authorisations and approvals and the development of plans for radiation management and radioactive waste management. For operations within the scope of this Safety Guide, where the screening assessment indicates that there is potential for significant exposures to occur, the Authority may require the operator to submit a NORM management plan (see Section 4.4.6). This plan should include provision for monitoring of radionuclide concentrations, and dose assessment where necessary.

4.4.6 NORM management plan

In the case of NORM, the Authority and operator would negotiate a project specific NORM Management Plan (NMP), that consists of a Radiation Management Plan (RMP) and Radioactive Waste Management Plan (RWMP), and other project specific management arrangements as agreed with the Authority, using the guidance from the Mining Safety Guide as a basis. The NORM management plan should include:

- a description of operation/process including a description of where in the process doses may arise;
- a demonstration of compliance with relevant radiation protection standards (see Mining Code and Safety Guide);
- the relevant elements of a radiation management plan (see Mining Code and Safety Guide);
- the relevant elements of a radioactive waste management plan, where applicable (see Mining Code and Safety Guide);
- an assessment of the current or projected use of a material that is regarded as a residue containing NORM and that currently is, or has the potential to be, recycled;
- an assessment of the potential impact of manufactured items containing NORM;

- appropriate monitoring programs;
- the relevant occupational health and safety issues;
- the relevant environmental protection issues;
- the definition of responsibilities for the operator/employer and employees;
- a process of review of the status of the operation in relation to continuing controls.

4.5 DOSE AND IMPACT ASSESSMENT

Dose and impact assessments can be carried out using simple approaches (for example a spreadsheet analysis which makes use of tables of dose coefficients (IAEA, 1996; ICRP, 1990; ICRP, 1994b; ICRP, 1995; ICRP, 1996a; ICRP, 1996b) or by using detailed computer models. Models are available for internal dosimetry calculations (Jarvis et al, 1996; Birchall et al, 2003; Birchall et al, 2006)) and for environmental impact assessments (Yu et al, 1993, Yu et al, 2007). The use of computer models is discussed in more detail in Section 5. The level of detail required in the assessment will be operation specific, and should be agreed by the operator and Authority.

4.5.1 The iterative improvement approach to dose and impact assessment

The number of possible exposure scenarios involving NORM is very large, and there is considerable variation between sites, operations and industries. This makes it difficult to develop 'standard' exposure scenarios which will cover every contingency. Therefore, the international community is placing strong emphasis on the development of iterative improvement methodologies for dose and impact assessment of complex operations.

This approach is designed to build confidence among all stakeholders. The process includes provision for both simple (preliminary) and detailed dose and impact assessments, and regular reviews of the current situation. The process is discussed in more detail in Section 5.3.3.

4.5.2 Monitoring Programs

Monitoring programs are an important component of any environmental impact assessment or safety assessment (IAEA, 2004b; IAEA, 2005a; IAEA, 2006c). There is considerable variation between sites (geology, geography, etc.), operations (extraction, processing, materials used), and industries. This means that it is difficult to design a monitoring program that will be appropriate in all situations. Therefore the monitoring program should be agreed between the operator and the regulator, and should form part of the NORM Management Plan.

4.6 MANAGEMENT OF NORM WASTES AND RESIDUES

Modern international practices in waste management (IAEA, 2006d) encourage the minimisation of waste. In many NORM industries large volumes of material are involved. The storage and/or disposal of these materials can be costly because of the large areas of land required. Therefore

the use of NORM residues is encouraged where feasible. However, this use should be based on a health and environmental impact assessment as agreed by the operator and the Authority as part of a NORM management plan. This assessment should follow the principles discussed earlier, i.e. a simple assessment, followed if necessary by a more detailed assessment, and should include a baseline assessment to ensure that the impact of the storage or disposal operation is assessed correctly.

4.6.1 Wastes

Disposal of NORM waste may require approval of the Authority. Possible disposal options for NORM wastes include:

- tailings dams;
- dilution and dispersal;
- burial.

Guidance on the near-surface burial of NORM waste can be obtained from the Near Surface Disposal Code (NHMRC, 1993). It is likely that an assessment of the health and environmental impact of a proposed waste disposal method will be required.

4.6.2 Residues

Potential utilisation of NORM residues should be notified to the Authority, and assessment of possible health and environmental impacts may be necessary. Where an assessment of doses to members of the public from the utilisation of NORM residues is necessary, it should take into account the following:

- the actual or potential exposure scenario;
- the potential future land use(s) (residential, industrial, agricultural, recreational, other);
- the proposed utilisation;
 - land fill;
 - land spreading;
 - road base, road fill;
 - building materials;
 - concrete extender;
 - plasterboard.

The assessment should consider potential exposure pathways such as inhalation of dust, inhalation of radon, direct external exposure, and the effects of contamination of surface water, ground water and the food chain, and the possibility of recycling of scrap metal containing NORM. The estimated doses to members of the public would generally need to be below 1 mSv, and radiation protection would also have to be optimised. IAEA Safety Report Series No. 21 (IAEA, 2002c) and ICRP publication 103 (ICRP, 2008) provide useful guidance on optimisation.

These assessments usually require the use of computer models. Guidance on the use of these models and on the default parameter values to be used is given in IAEA Safety Reports Series No. 19 (IAEA, 2001), and IAEA Technical Reports Series No.364 (IAEA, 1994) (currently under revision).

4.6.3 Products

The initial discussion between the operator and the Authority should establish whether there is potential for products containing NORM to cause exposures to members of the public. For the case of a new industry or product the Authority may require an impact assessment and/or monitoring (of dose rates, etc.) to be carried out to establish whether there is cause for concern.

4.7 TRANSPORT

The transport of radioactive material is subject to the regulations of the States, Territories and the Commonwealth. These regulations adopt the current ARPANSA Code of Practice for the Safe Transport of Radioactive Material ('the Transport Code') (ARPANSA, 2008), which in turn incorporate the international transport regulations developed by the IAEA (IAEA, 2005c). Activity concentration exemption levels for each radionuclide are listed in the Transport Code. For naturally occurring radionuclides the limit is 1 Bq g⁻¹. In regard to the transport of NORM, the Transport Code also includes a modifying factor that applies to '*natural material and ores containing naturally occurring radionuclides that are either in their natural state, or have been processed only for purposes other than for the extraction of the radionuclides, and that are not intended to be processed for use of these radionuclides*', where the activity concentration of the material does not exceed 10 times the exemption limit (i.e. the modified exemption limit is 10 Bq g⁻¹ for natural materials). This exemption applies to bulk materials or individual items, and is designed so that large quantities of NORM that present a very low radiation hazard do not have to be transported as radioactive material. The exemption is considered to provide an appropriate balance between radiological protection concerns and the practical inconvenience, and associated costs, of regulating large quantities of naturally occurring radioactive material with low activity concentration.

Advice on application of the Transport Code and relevant regulations governing transport of NORM can be obtained from the relevant regulatory authority (see the Regulatory Authorities list following the Annexes in this Safety Guide).

4.8 SITE REMEDIATION AND CLOSE-OUT REQUIREMENTS

The operator and the Regulatory Authority should discuss and establish, as part of the NORM Management Plan, a set of requirements for the release (from control) of an operational site when the operation ceases. In many cases an operator is interested in the 'walk-away' criteria, i.e. the conditions under which the operator would have to carry out no further remediation before abandoning or disposing of the site. The general approach has been summarised by the IAEA (IAEA, 2006c). The possible requirements can include:

- an estimate of potential doses to members of the public;

- consideration of future land use;
- an analysis of any remediation that may be required;
- implementation of an agreed remediation procedure.

The conditions for release of a site from regulatory control should be based on a safety assessment and an environmental impact assessment.

The safety assessment should consider such issues as (for example) the presence of mine shafts, pits, chemicals, rubbish, abandoned equipment and plant.

The environmental impact assessment should produce estimates of the dose contributions from potential exposure pathways such as dust inhalation, radon inhalation, direct external exposure, and the effects of contamination of surface water, ground water and the food chain, taking into consideration different types of future land use, and compare these results with pre-mining/processing conditions. The assessment should also take into consideration the existing variations in natural background levels around the affected area. Typical variations in natural background radiation levels are of the order of 100-300 μSv per year (UNSCEAR, 2000).

If the results of the environmental assessment indicate that doses to members of the public are unlikely to exceed this range, and the safety assessment is acceptable, there is no obvious benefit to be obtained from further remediation (i.e. no further optimisation is practicable), and it should be reasonable to release the site from regulatory control. Where the assessment predicts doses up to approximately 1 mSv, and after review of the assessment, the regulator may decide that release of the site from regulatory control is appropriate and consistent with optimisation having been achieved. At still higher doses a more detailed assessment should be carried out before a regulatory decision is made.

4.9 ASSESSING THE IMPACT OF REGULATORY PROPOSALS

The Best Practice Regulation Handbook (OBPR, 2007) published by the Australian Government states that 'An efficient regulatory system is essential to a well functioning society and economy and depends on having effective processes and institutions for making and administering regulation in all its forms.' To ensure that regulation is efficient and effective (i.e. effective in addressing an identified problem and efficient in terms of maximising the benefits to the community - taking account of the costs), an enhanced regulatory framework has been introduced to improve the analysis applied to regulatory proposals and hence to improve the quality of regulation.

This implies consideration of the case for acting in response to a perceived policy problem at an early stage, including addressing the fundamental question of whether regulatory action is required, or whether the policy objectives can be achieved by alternative measures which would involve lower costs for business and the community.

The Best Practice Regulation Handbook notes that: 'In 2006, the Government endorsed the following six principles of good regulatory process identified by the Taskforce on Reducing Regulatory Burdens on Business.

- Governments should not act to address ‘problems’ until a case for action has been clearly established. This should include establishing the nature of the problem and why actions additional to existing measures are needed, recognising that not all ‘problems’ will justify (additional) government action.
- A range of feasible policy options (including self-regulatory and co-regulatory approaches) need to be identified and their benefits and costs (including compliance costs) assessed within an appropriate framework.
- Only the option that generates the greatest net benefit for the community, taking into account all the impacts, should be adopted.
- Effective guidance should be provided to relevant regulators and regulated parties in order to ensure that the policy intent of the regulation is clear, as well as the expected compliance requirements.
- Mechanisms are needed to ensure that regulation remains relevant and effective over time.
- There needs to be effective consultation with regulated parties at all stages of the regulatory cycle.’

The primary means by which these principles are put into effect is by the preparation of a regulatory impact statement that addresses the costs and benefits of the regulatory proposal and other options for achieving the objective. This should include identifying the affected parties and assessing the costs and benefits to each group. Consultation with stakeholders on regulatory proposals, including the regulatory impact assessment, is also required during their development.

Where proposals, such as Codes and Standards, are national in nature the COAG *Principles and Guidelines for National Standard Setting and Regulatory Action by Ministerial Councils and Standard-setting Bodies* (June 2004) must be followed. The processes for developing the proposals are essentially the same, except that the regulatory impact assessment must address the costs and benefits nationally rather than for a single jurisdiction.

The system for assessment of the need for regulation outlined in this Safety Guide is consistent with government actions intended to ensure that regulation is efficient and effective.

5. Operational issues – the NORM Management Plan

5.1 INTRODUCTION

The major radiological issues to be considered in any operation involving materials containing NORM include:

- identification of potential sources of exposure to workers and members of the public
- identification of potential impacts on the environment;
- management of exposures to workers and members of the public; and
- management of environmental impacts (including management of discharges to the environment)

Guidance on general operational issues is given below, and further detail on operational issues for specific industries is given in the Annex for each industry.

5.2 IDENTIFICATION OF POTENTIAL SOURCES OF HEALTH IMPACT ON WORKERS, MEMBERS OF THE PUBLIC AND THE ENVIRONMENT

The potential sources of exposure to workers and members of the public will depend on the type of operation, the materials being handled, the processes being used, and the potential for discharges to the environment. The identification of these potential sources of exposure should be carried out at the planning stage, to identify the areas of increased risk to workers, the public and the environment and, to enable appropriate control/mitigation measures to be included in the operational NMP if required.

5.3 MANAGEMENT OF THE HEALTH IMPACT ON WORKERS, MEMBERS OF THE PUBLIC AND THE ENVIRONMENT

Once the potential sources of exposure have been identified, the general approach to management of the health impact on workers, members of the public and the environment involves three basic steps; mitigation, monitoring and dose assessment. These steps are described in more detail below.

5.3.1 Control/mitigation procedures

Mitigation is the process of controlling/reducing the potential/identified sources of exposure. Appropriate mitigation procedures should be chosen for each situation, as discussed below.

Radon

The half-life of radon is 3.8 days, whereas typical ventilation rates in buildings are 1-3 air changes per hour. Therefore radon concentrations can be maintained at acceptable levels by provision of adequate ventilation.

In underground work areas, radon can build up because of exhalation of radon from the surrounding rock/soil. In this case provision of adequate ventilation is again the most effective method of controlling the radon concentration in the work-space air. In some circumstances, the ingress of groundwater containing dissolved radon can increase radon concentrations underground, and the control of water ingress can assist with controlling the concentration of radon in air.

Process dust

Machinery used for dry separation of minerals should be enclosed with dedicated dust extraction systems to keep dust levels in air breathed by workers to a minimum. Where materials are transported in dry form, spraying with water or the use of hoods should keep dust levels in work areas at acceptable levels.

Spills of process materials

Bunds and sumps should be installed to contain and retrieve spills of NORM process materials within process plants and transfer points. Work procedures should include regular wash down of bunded areas to dedicated sumps for disposal or recycling of contents.

Material on the skin or on clothing

The radiological risk associated with this pathway can be significantly reduced by following good hygiene procedures, such as washing the face and hands before eating, and removing contaminated clothing before leaving the workplace.

Cleaning of contaminated equipment

Contaminated equipment can be cleaned using sprays, abrasives, and wipes. The cleaning agents need to be disposed of with care, as the radionuclide concentrations in the used cleaning materials can pose a potential radiological risk in some situations. Cleaning operations, particularly where abrasives or wipes are used, can result in the re-suspension of contaminated material, which can lead to inhalation issues.

Some maintenance activities may have similar radiological risks to the cleaning of contaminated equipment, but may not be recognised as 'cleaning'. For example, in the oil and gas production industry, the impellers of pumps in LPG service can acquire coatings of ^{210}Pb , ^{210}Bi and ^{210}Po . Such impellers may need to be rebalanced by grinding off some metal, a process which could lead to significant airborne concentrations of those radionuclides.

Stockpiles

The potential exposure pathways associated with a stockpile are inhalation of radon and resuspended dust, direct external exposure, release of seepage surface or ground water, and ingestion of locally grown food which may be contaminated (see earlier). Exposures can always be reduced by restricting access to stockpiles, the use of water sprays and binding agents to minimise dusting, direction of seepage to disposal ponds or secondary containments.

Tailings dams

External exposure to radionuclides in tailings dams can be minimised by restricting access to such areas.

Leakage or leaching of radionuclides into groundwater can be significantly reduced or delayed by the use of engineered barriers. Clay and HDPE liners have been widely utilised for this purpose.

Overflows resulting from high rainfall events can be contained by the provision of secondary containment barriers (bunds).

Near surface burial of NORM waste

The 'Code of practice for the near surface disposal of radioactive waste in Australia 1992' (NHMRC, 1993) (the Near Surface Disposal Code) sets out the site selection criteria to be checked when planning to dispose of radioactive waste by near surface disposal. The code also states that when the ideal site criteria cannot be met, compensating factors should be incorporated in the design and siting of a near-surface disposal facility.

The IAEA has also published documents (IAEA, 1999b; IAEA, 1999c; IAEA 2003c) which provide guidance on the factors to be considered when planning near-surface burial of radioactive wastes/residues.

Transport accidents

In most cases, because of the relatively low radionuclide concentrations in most NORM materials, cleanup of contaminated areas is straightforward.

In the case of a transport accident involving dry material, removal of loose material on surfaces, or suppression of dust by spraying can significantly reduce the potential exposures. Solid materials can be collected by conventional methods such as scraping, sweeping and vacuuming. Where this has the potential to raise large quantities of dust, personal protective equipment (PPE) should be used, and access to contaminated areas by members of the public should be restricted until the hazard has been reduced to an acceptable level.

For spillage of liquids as a result of a transport accident, the spill should be contained and the liquid removed as soon as possible. Public access to contaminated areas should be restricted, particularly in cases where the liquid is likely to pose a chemical hazard. PPE should be used where necessary.

For release of gas(es) following a transport accident, public access to the affected areas should be restricted. Under normal atmospheric conditions, dispersal of airborne contamination is usually rapid, and remaining indoors is an effective way of minimising exposures.

Optimisation of discharges to the environment

Particulates and volatile polonium and lead isotopes can be discharged from stacks at processing plants, coal-fired power stations and smelters. The use of

scrubbers on discharge stacks will significantly reduce the discharge of particulates to the environment.

Use of physical barriers (e.g. concrete, HDPE liners or clay) can significantly inhibit leaching of radionuclides into groundwater, and surface water discharges to the environment (NCRP, 2006).

Dispersal of dust can be reduced by using any of the dust mitigation methods discussed earlier.

5.3.2 Monitoring programs

A monitoring program has several basic aims:

- to check the validity of the initial assessment;
- to identify gaps in the initial assessment;
- to check the efficiency of control/mitigation measures that have been put in place (evaluate residual risks);
- to provide data for ongoing risk/dose assessments;
- to provide data for environmental impact assessments;
- to show justification for continued exemption; or
- to demonstrate compliance with licence requirements (see Section 4.5.2).

An effective radiation protection program will include means of assessment of the impact of the operation, in terms of doses to workers and the public and impact on the environment. The general principles for the design of monitoring programs have been summarised in several publications (IAEA, 2004b; IAEA, 2005a). The details of a monitoring program should be discussed with the regulator.

Monitoring programs should be set up to determine the concentrations of radionuclides in the materials being handled, and in the workplace in general. Monitoring of discharges to the environment in air or surface water or groundwater should also be carried out.

Monitoring is also needed to assess differentiation of radionuclides (for example, in the phosphate industry), to ensure radionuclide concentrations in the different process streams remain at levels that are not considered to pose any risk and, to verify the efficiency of control measures.

If monitoring results indicate that the radionuclide concentrations in any of the different processing streams increase to a level requiring further action, the operator should investigate the cause, and where necessary, notify the appropriate regulator and agree with the regulator on an appropriate course of remedial action.

Where there is concern about the doses received, the use of monitoring devices such as personal monitors or dose rate meters to check exposure levels is recommended. If doses or dose rates are found to be unacceptably high, time management methods can be used to reduce doses, or extra shielding can be installed, e.g. in transport vehicles.

Monitoring programs can include measurements of environmental variables such as radon concentrations in air, radionuclide concentrations in air, soil, surface water, groundwater, airborne dust, surface dust, locally grown foods, relevant plants and animals, as well as personal and/or area doses.

Periodic monitoring checks should be carried out to verify that the assumptions on which the initial assessment was based are still valid. In the event of significant process change or where external events have impacted on the operation, (flooding, fire, land slippage, subsidence) a new assessment may be required.

It is often difficult to determine the incremental dose to a member of the public resulting from an operation involving materials containing NORM, for several reasons. The first is that the increment is often small. The second is that the natural background can vary considerably across a site, which introduces 'noise' into the measurements. Another possibility is that for many existing operations, no baseline was determined prior to the commencement of operations, and it is difficult to retrospectively determine the baseline once operations have commenced because of the difficulty of deciding what constitutes a representative set of measurements.

This problem can also occur when trying to determine the levels of contamination in food and groundwater.

5.3.3 Dose and safety assessment

Periodic dose assessments should be carried out for licensed operations using the results of the monitoring program. This ongoing assessment and review process should consider doses to both workers and members of the public and should also consider environmental impacts (ICRP, 2008) with the aim of achieving continual improvement in radiation protection.

Several methods of dose assessment can be used, including:

- a comparison of measured radionuclide concentrations against reference levels (e.g. background levels);
- a spreadsheet analysis which makes use of tables of dose coefficients (IAEA, 1995; ICRP, 1990; ICRP, 1994b; ICRP, 1995; ICRP, 1996a; ICRP, 1996b); or
- the use of detailed computer models.

Models are available for internal dosimetry calculations (Jarvis et al, 1996; Birchall et al, 2003; Birchall et al, 2006) and for environmental impact assessments (Yu et al, 1993; Yu et al, 2007). The use of computer models is discussed in more detail below.

The aim of safety assessment is to minimise the risk of accidents in the workplace and discharges to the environment. Safety assessment should include a regular review of the process stages, the equipment and procedures, controls and contingency plans that may impact on assessed and potential doses.

5.3.4 The iterative improvement approach

The basic idea of the iterative improvement approach to NORM management is to start with a relatively simple (preliminary) assessment, since data are likely to be limited at the planning stage or in the early stages of an operation. If this preliminary assessment suggests that the estimated risk is very low, then it may be appropriate for the regulator to exempt the operation from regulatory control.

If the preliminary assessment indicates that the situation warrants more detailed investigation, procedures should be implemented for carrying out this more detailed assessment process. This will usually involve measurement programs to gather data, the use of these data in more detailed impact assessments, and regular reviews of NORM management procedures. These assessments and reviews can also include the effects of technical and socio-economic developments (ICRP, 2008). The aim of the whole process is to ensure that radiological protection is optimised for the specific situation. Since circumstances can change (e.g. more information becomes available, or technical procedures improve) and adjustments to the management plan need to be made to accommodate these changes, the process is one of continuous iterative improvement.

In order to build confidence and trust it is important that the process is transparent to all stakeholders.

The iterative improvement approach to the management of NORM wastes and residues and other operations involving NORM is illustrated in Figure 3 for the case of a proposed operation (for example, a new mine or mill or waste repository, etc.).

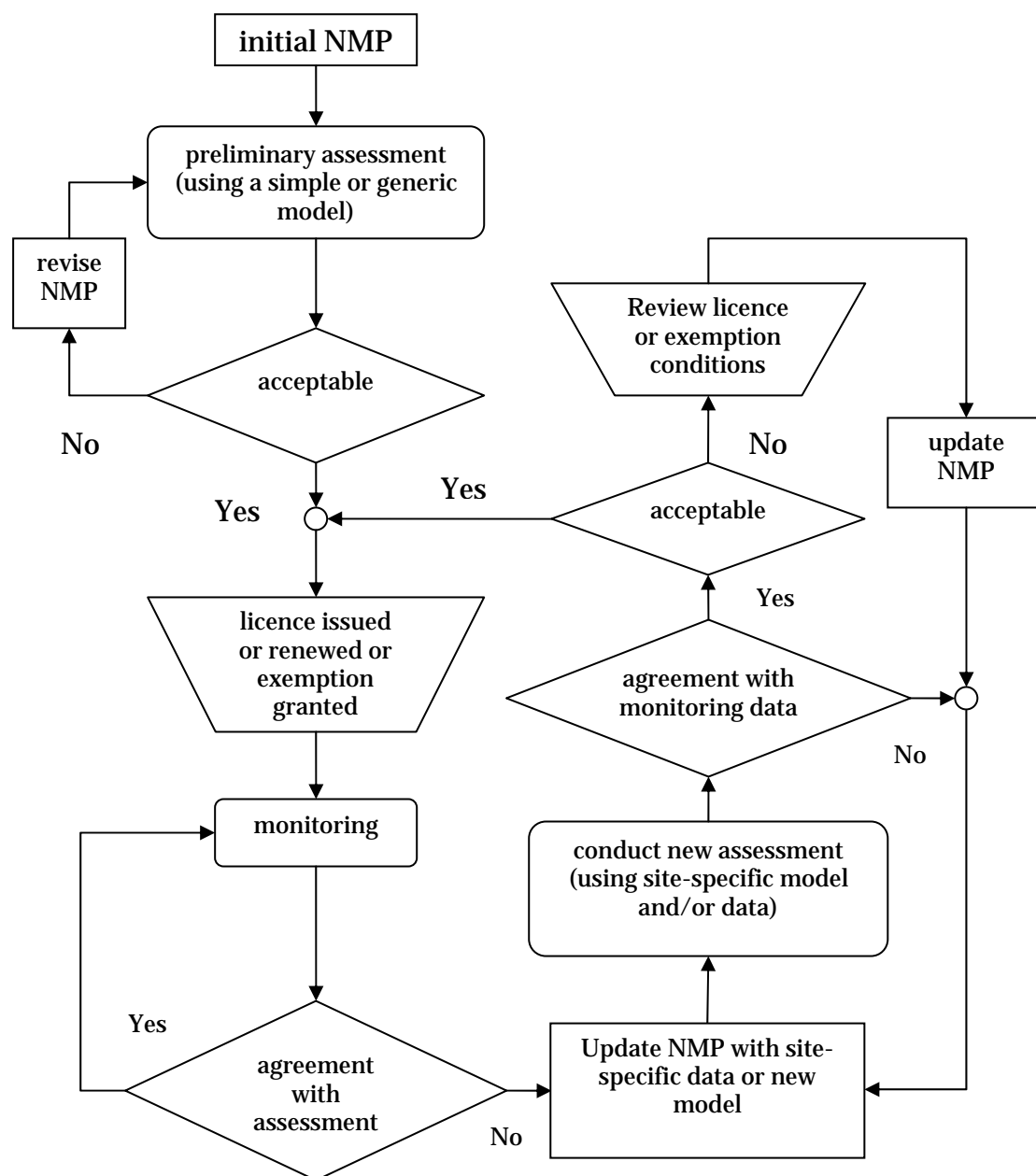


Figure 3: an iterative improvement approach to risk and impact assessment

5.3.5 The use of computer models

Computer models are very useful for workplace or environmental impact assessment. However there are several points that need to be borne in mind, when using these models or contemplating their use:

- the more complex the model, the more data are required;
- in many situations a simple calculation may be enough to provide the required estimate(s);
- many of the computer models currently available are not particularly well documented;
- the model has to be appropriate for the particular situation;

- many of the available computer models assume idealised geometry (for example for waste disposal) and uniform conditions (for example rainfall) – real situations rarely correspond to these ideal cases;
- considerable skill and experience is required to understand the assumptions on which a particular model is based, and the limiting effect of the assumptions on the applicability of the model;
- considerable skill and experience may be needed to interpret the results of model predictions;
- the assumptions used in all modelling work should be clearly stated together with the results of the work to which the assumptions are applicable.

Monitoring programs and risk and impact modelling should be used in conjunction with each other. In some cases default data have to be used in a computer model, because site-specific data are not available. The choice of parameter values can depend on climate, soil type, and other considerations (see, for example, IAEA Technical Reports Series No. 364 (IAEA, 1994)). When default data are used the results of model calculations are limited to prediction, and do not allow any conclusions to be made about the validity of the model or whether the model is appropriate for the specific situation being considered.

Where site-specific data are available (as the result of a monitoring program) these data should always be used in preference to default data. In this situation the site-specific data (for example radionuclide concentrations in airborne dust) can be used to validate the predictions of model being used. If the model is found to be inadequate, a different model can be used or the existing model can be updated to make use of the new information provided by the monitoring program.

5.4 REMEDIATION AND CLOSE-OUT REQUIREMENTS FOR OPERATIONAL SITES

For existing operational sites, the remediation and close-out criteria should be part of the NMP agreed between the operator and the regulatory authority.

5.5 NON-RADIOLOGICAL ISSUES

Non-radiological issues are outside the scope of this document and will not be discussed in detail. However, it should be noted that there are several non-radiological issues that need to be considered in any assessment of risk or health impact associated with operations where materials containing NORM are present. These include the use of blasting (extraction of ore), chemicals (processing), heavy earth-moving and transport equipment, and the presence of heavy metals.

6. Remediation of legacy sites

Remediation may also be required at sites (legacy sites) that have been contaminated as a result of past operations that were conducted prior to the introduction of regulatory requirements or under a different regulatory regime. In many of these situations there is little or no documentation available to describe the operations that were carried out at the site or the levels of contamination that were present when the site was abandoned. In many cases it is difficult to assign responsibility for any remediation work required, because the owner/operator of the site cannot be easily identified. In these situations the responsibility for any remedial work may have to be taken by government.

Remediation consists of several stages (IAEA, 1998), similar to those in an operational NMP. The first stage is a characterisation of the site and the surrounding areas, by monitoring, to determine the nature and level of any contamination present, and to determine whether contamination has migrated into the environment. The second stage is to predict the impact of contaminants on the site itself, on the surrounding environment, on members of the public who use the site, and on members of the public who use the areas surrounding the site.

If these impacts are assessed as being acceptable, no further work may be required. However, if further remediation work is required, the third stage is to determine an appropriate strategy. Computer models (using the results of the monitoring carried out when characterising the site) are very useful for evaluating the impact of different remediation strategies.

Once an appropriate remediation strategy/plan has been determined, the remediation work can be carried out. The procedure is similar to the iterative improvement approach described in sections 4.5.1 and 5.3.3. As the work proceeds, monitoring and assessment should be carried out to determine if the plan needs to be modified.

When the remediation work has been completed, the site may be released for use, subject to the approval of the Authority.

7. Summary

This Safety Guide discusses the issues involved in consideration of risks associated with naturally-occurring radioactive material (NORM). It does not discuss uranium mining and processing or mineral sand extraction as they are dealt with in existing regulatory frameworks.

The extraction and processing of mineral ores containing low levels of naturally-occurring radionuclides can lead to the generation of products, by-products, wastes and residues containing elevated concentrations of these radionuclides. There is also considerable variability in quantities of material and radionuclide concentrations within and between industries. Potential exposures from NORM can occur in a wide range of industries and for a wide range of materials. A short description of known industries where NORM may arise is given in Section 2. The long half-lives of some of the radionuclides means that radionuclide concentrations in NORM tend to decrease only slowly with time. These features mean that management of NORM is a long-term issue, and it is important that operators acknowledge that it is their responsibility to understand and manage the NORM issues relevant for their industry. These issues include radiological protection during extraction, processing, transport, storage and disposal of NORM. Section 3 describes the radiological issues associated with NORM management.

In general, the activity concentrations in NORM are low. This means that in many cases, regulation is unlikely to be necessary. Guidance for both regulators and operators is given on assessing the need for regulation, including consideration of unconditional or conditional exemption, which could be appropriate in many NORM situations. In particular, guidance is given on the need for a graded approach to regulation, which places emphasis on the need for optimisation of protection. The costs and benefits of introducing a regulatory approach need to be considered and compared with those for other options that would achieve the same objective.

Implementation of a NORM Management Plan, including characterisation of materials, monitoring of radionuclide concentrations, and ongoing risk/dose assessment is an important management tool, whether or not regulation is applied. The main features of a NORM Management Plan are described.

Section 5 deals with operational issues, giving guidance on characterisation of materials, identification of potential risks, risk assessment and risk mitigation.

Guidance on remediation of legacy sites (sites contaminated as a result of past operations) is given in Section 6. In particular, guidance is given on the use of computer models as an aid to planning and assessing alternative remediation strategies.

Public perception is important in any issue involving radioactive materials. Involvement of stakeholders is therefore an important consideration when assessing the optimisation of protection when utilising NORM, or disposing of NORM residues and wastes. There is a clear need for communication of the potential risks and benefits associated with proposals of this nature.

Relating the normally low risks from NORM exposure to other risk factors understood by the public (e.g. road accidents, heart attacks) may be useful.

There is growing interest in utilising NORM residues because of the difficulties associated with long-term storage and/or disposal, as a consequence of the large volumes of material involved. Many of the residues are generated in large quantities, e.g. megatons per year. Potential uses include incorporation in landfill, roadfill and building materials. In considering potential disposal options for NORM, there is a need for careful assessment of radiological risks. Guidance on a framework for such assessments is provided.

This Safety Guide currently incorporates three Annexes giving detailed information on the oil and gas, bauxite/aluminium and phosphate industries. It is anticipated that further Annexes will be developed in future on other industries dealing with NORM.

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Glossary

Acceptable risk

For the purposes of this Safety Guide, is the level of risk acceptable to all stakeholders in a particular operation.

Activity

the measure of quantity of radioactive materials, except when used in the term 'human activity'.

Activity, A , is a measure of the amount of a radioactive material given by:

$$A = \frac{dN}{dt}$$

where dN is the expectation value of the number of spontaneous nuclear transitions which take place in the time interval dt .

The SI unit of activity is s^{-1} with the special name becquerel (Bq).

Decay chain

a series of radionuclides, each of which (except for the first, or parent) is formed as a result of the radioactive decay of the previous member of the chain.

Secular equilibrium

the condition in which successive members of a decay chain have the same activity.

NORM

radioactive material containing no significant amounts of radionuclides other than naturally-occurring radionuclides.

Radioactive material

any material that emits ionizing radiation spontaneously.

Responsible person

in relation to any radioactive source, ionizing or non-ionizing radiation apparatus, nuclear installation, prescribed radiation facility or premises on which unsealed radioactive sources are stored or used means the person:

- (a) having overall management responsibility including responsibility for the security and maintenance of the source, apparatus, installation or facility;
- (b) having overall control over who may use the source or apparatus, installation or facility; and
- (c) in whose name the source, apparatus, installation or facility, would be registered if this is required.

Screening assessment

This is a simple assessment of the risks/doses associated with an existing or planned operation. It should be based on conservative assumptions, so that if the estimated risks/doses are found to be well below regulatory limits, no further action needs to be taken, and to ensure that risks are not underestimated

Sealed radioactive source

radioactive material that is permanently sealed in a capsule or closely bonded in a solid form.

Annex 1

Management of NORM in the Oil & Gas Production Industry

A1.1 INTRODUCTION

The whole of the oil and gas industry is by convention separated into two sections:

- ‘Upstream’, also called production, which includes exploration, the development of facilities (platforms, wells, plants, etc.) and sufficient processing to provide crude oil, methane (‘natural gas’), ethane, propane and butane at marketable qualities. Propane and butane are frequently sold as mixtures and collectively are called liquefied petroleum gas (LPG). Crude oil exits the upstream when it is sold to a refinery.
- ‘Downstream’ starts at the refinery which converts crude oil into a range of marketable products, such as gasoline, jet fuel, kerosene, diesel, fuel oil, etc.

This Annex deals with NORM in the Upstream in detail, with more limited discussion of NORM in the Downstream in section 4.

- IAEA Safety Report 34 (IAEA, 2003b) provides additional detail in its chapter on NORM in the oil and gas industry.

A1.2 RAW MATERIALS

The ‘raw materials’ are the hydrocarbons and water existing in the sand formations into which oil and gas wells are drilled. The NORM is present as:

- Radium (^{226}Ra , ^{228}Ra and ^{224}Ra) dissolved in the formation water. Given the geological timescales involved, it is presumed that the water will be saturated with radium under the prevailing solubility conditions of temperature, pressure, pH, and salinity.
- Radon (^{222}Rn) dissolved in the oil and in the water. The short half life (55 seconds) of ^{220}Rn (sometimes called thoron) from the thorium decay chain make it of little practical importance.

The low proportion of ^{235}U decay chain radionuclides compared with the much greater abundance of ^{238}U decay chain members means that they will be ignored for the rest of this Annex.

A1.3 PROCESSING STEPS

The first two steps described below apply to all the fluids produced from the formation; the latter two steps may not apply in all cases. Production operations vary considerably depending on the characteristics of the fields being produced and the availability of local infrastructure to take products.

A1.3.1 Bringing the fluids to the surface

The fluids brought to the surface vary from well to well and field to field, and vary considerably over the life of a field. For example, when an oil field starts production usually only hydrocarbons are produced; but as the field is depleted, an increasing proportion of water is usually produced, with almost all of the daily produced volume being water towards the end of the economic life of the field. Examples of the fluids that might be produced are:

- ‘Wet’ gas. This is usually a mixture of methane, ethane, propane and butane together with heavier (higher carbon number) hydrocarbons in the vapour phase. Water vapour or mist may be present, as may contaminants such as H₂S and CO₂. The heavier hydrocarbons (pentane and up) are liquids at normal atmospheric pressure and temperature; as they condense out as temperatures and pressures reduce during processing they are often called ‘condensate’.
- ‘Dry’ gas is mainly methane with perhaps some ethane, propane and butane, but no heavier hydrocarbons – no condensate. Gaseous contaminants may still be present. There is no hard and fast division between ‘wet’ and ‘dry’ gas.
- Crude oil may contain gases – methane, ethane, propane and butane – dissolved under pressure. As the pressure is reduced, these gases effervesce out of solution. Crude oil may also contain contaminants such as H₂S and CO₂ (also dissolved under pressure) and other materials such as heavy metals (mercury, arsenic, etc). While water and crude oil are generally immiscible, they can be produced as a mixture or as an emulsion of oil in water or water in oil. Solids – sands from the formation – can also flow to the surface with the fluids.

The formation pressure which drives the fluids to the surface decreases over time, and the methods employed to maintain fluid flows can influence the amounts of NORM encountered. Depending on the circumstances, one or more of the following methods may be used to increase the recovery of oil and gas:

- Gas may be reinjected into the formation to maintain pressures, or because there is no current sales route for the gas.
- Gas may be injected towards the bottom of individual wells (‘gas lift’) to enhance the oil recovery from the wells.
- Water may be injected into the formation to maintain pressure and to sweep the oil and gas from the injection wells to the production wells. In offshore fields, the injected water could be sea water.
- Direct pumping from down-hole pumps is also used.

When the water used to flood the reservoir is different chemically from the formation water, then chemical incompatibilities between the water flood and the formation water can lead to the development of significant levels of scaling in the production system. These scales can include barium compounds (e.g. barium carbonate and sulphate), and their precipitation can lead to the co-precipitation of radium compounds, very significantly concentrating the radium in the scales from the formation water. Some of the highest NORM levels found (e.g. ²²⁶Ra in scale of 1,000 to 100,000 Bq g⁻¹) have been associated with this process.

A1.3.2 Initial separation

The fluid mixture brought to the surface is first separated; depending on the circumstances, the separation can be into three phases: water, oil and gas. This separation is typically done by gravity in a large vessel. Setting the operating pressure of the vessel to below the formation pressure allows gases (hydrocarbons, CO₂ and H₂S) to come out of solution. Produced fluids usually leave the formation at elevated temperatures, which reduce over distance from the formation. Fluids from offshore wells, in particular, are cooled as they traverse the ocean water column. The reduced temperature and pressure and the increased pH all lead to a reduction in the solubility of radium and other minerals in the water, leading to precipitation and NORM accumulation in the separator vessel and in the production piping.

It is at this stage that the first separation of the radium and radon that were brought to the surface occurs. The radium either stays in the water phase or precipitates out, while the radon either follows the gas stream or remains dissolved in the oil.

A1.3.3 Crude treatment

The presence of dissolved gases (methane, ethane, propane, butane, radon) in crude oil make it unsafe to transport and store at atmospheric pressure. The removal of such gases and the removal of almost all of the water is required to bring the crude oil to the quality required for trade. These processes are referred to as 'crude stabilisation'. Typically, simple physical separation processes, such as driving off the gases using heat and reduced pressures are employed. Further opportunities for radium precipitation occur during crude stabilisation.

A1.3.4 Gas treatment

The input feed to a gas plant is typically a wet gas stream, with how 'wet' being variable from field to field. As the water content is typically in the form of water vapour – at least under the input feed conditions – radium is not usually an issue in gas plants. The ultimate separation between methane, ethane, propane and butane is usually done based on boiling point; as the boiling point of radon is intermediate between those of ethane and propane, the radon can be expected to be split between the ethane and the propane. Because the separations are never 100% efficient, small amounts of radon might still be able to be found in the methane and butane streams.

Ethane is not conveniently liquefied by either increased pressure or reduced temperature, and so plants consuming ethane as a feedstock (typically in polyethylene production) are usually connected to a gas plant via a pipeline and receive their feedstock as a gas with no intermediate storage of the ethane. Because pipeline transit times may often be less than the 3.8 day half-life of ^{222}Rn , it is common for plants using ethane to experience NORM in the form of radon and its decay products.

Propane is conveniently liquefied by either increased pressure or reduced temperature and so can be stored for extended periods. Depending on the residence time, this can reduce or practically eliminate radon as a contaminant in the propane when the propane leaves the storage facility. However, the longer lived decay products of ^{222}Rn , particularly ^{210}Pb and ^{210}Po will accumulate in propane storage systems which receive fresh propane.

The decay chain starting with ^{222}Rn can be conveniently grouped into two:

- The short-lived radon decay products ^{218}Po , ^{214}Pb , ^{214}Bi and ^{214}Po have a collective half-life of approximately 30 minutes, which means that they will grow in to a stream containing just ^{222}Rn within 30 to 60 minutes; if separated from the ^{222}Rn they will decay with a half-life of approximately 30 minutes.
- The longer-lived radon decay products consisting of ^{210}Pb , ^{210}Bi and ^{210}Po . The 21 year half life of ^{210}Pb means that while these grow in to radioactive equilibrium with the parent ^{222}Rn slowly, they persist in equipment for significant periods.

As all the decay chain members below radon are solids, they will not indefinitely follow the fluid flow lines in the equipment. Instead they will tend to accumulate at points of impaction, such as control valves, orifice plates, pump suction strainers and pump impellers, and will also accumulate where flows are very low, such as in a storage vessel. There is also the possibility of a thermal precipitation effect in heat exchangers. These accumulation points can be thought of as being inefficient filters, which separate the radon from its decay products.

- Figure 4 describes the dynamics of short-lived (^{218}Po , ^{214}Pb , ^{214}Bi , ^{214}Po) and longer-lived radon decay product (^{210}Pb , ^{210}Bi , ^{210}Po) production within an LPG processing system in an idealised way assuming the filters are highly efficient. After each 'filter' only radon is present; however over time (passage further

through the process) radon decay products will grow in until they once again encounter a 'filter'. The radiation from the short-lived radon decay products includes some high energy gammas which penetrate the steel walls of pressure equipment and potentially lead to external gamma radiation fields outside the equipment. In contrast, the longer lived radon decay products do not have gamma emissions which can be detected outside the equipment.

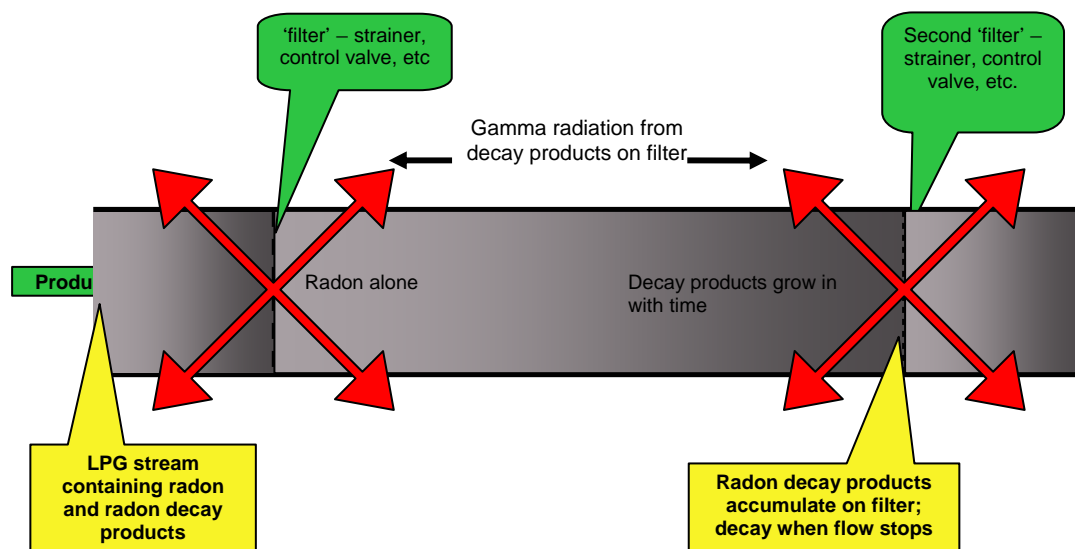


Figure 4: External gamma radiation from radon decay products

In the common situation of two identical LPG pumps arranged in parallel, in which one is a spare for the other and only one is running at any time in a service which includes significant levels of ^{222}Rn in the LPG:

- when a pump is first brought into service, external gamma radiation levels from its suction strainer and impeller will increase over a few hours and will then remain steady (assuming a constant radon concentration in the LPG);
- when a pump is taken out of service, the external gamma radiation levels from it will decay with a half life of approximately 30 minutes;
- assuming the average duty cycle of each pump is 50%, when they are opened, they will be found to contain equal amounts of the longer lived radon decay products, which will not have been detectable from outside the pumps.

A1.4 WASTE STREAMS

A1.4.1 Waste water

A good summary of this waste stream is provided in the IAEA Safety Report 34 (IAEA, 2003b):

'Produced water volumes vary considerably between installations and over the lifetime of a field, with a typical range of 2400–40 000 m³ d⁻¹ for oil producing facilities and 1.5–30 m³ d⁻¹ for gas production [59]. Produced water may contain ^{226}Ra , ^{228}Ra , ^{224}Ra and ^{210}Pb in concentrations of up to a few hundred becquerels per litre but is virtually free of ^{228}Th . Mean concentrations of 4.1 Bq L⁻¹ of ^{226}Ra and 2.1 Bq L⁻¹ of ^{228}Ra were recorded from a recent survey of Norwegian offshore oil production installations [60] but concentrations at individual facilities may well reach levels 50 times higher. Ratios between the concentrations of the radionuclides mentioned vary considerably. As a consequence, the dominant radionuclide may be ^{226}Ra or ^{228}Ra or ^{210}Pb .'

A1.4.2 Scales and oily sands

These are precipitates from oil/water service. 'Scales' are harder deposits on the inside of production piping and other equipment, while the 'oily sands' are looser precipitates also referred to as 'sludges'. Typically, oily sands are found in the bottom of the larger vessels when they are opened for cleaning and internal inspection, although drier, loose materials can also be found in equipment such as pumps and valves.

As is common in the oil and gas industry, the activity concentrations involved in these materials cover a very wide range: at the low end ^{226}Ra concentrations can be 0.1 to 10 Bq g⁻¹, while at the high end concentrations can exceed 10, 000 Bq g⁻¹.

A1.4.3 ^{210}Pb contaminated equipment

As discussed in section A1.3.4, gas processing plants and ethane transmission and use facilities accumulate ^{210}Pb , ^{210}Bi and ^{210}Po deposits at impaction points, at points of low flow rates and in heat exchangers. The waste arising from these processes consists of contaminated equipment removed from service and dust from cleaning and maintenance activities. The volume of such waste is typically much smaller than the volume of scale and oily sands waste.

The activity concentrations of this waste stream have not been widely reported in the literature. However, experience at one Australian production operation has seen loose dust up to 20 Bq g⁻¹ of ^{210}Pb in very low flow LPG environments and impacted material of over 800 Bq g⁻¹ of ^{210}Pb on pump impellers.

A1.4.4 Miscellaneous contaminated items

Operational precautions for the handling of NORM contaminated equipment invariably produces additional NORM contaminated waste in the form of plastic sheets, air filters, gloves, disposable coveralls, etc.

A1.5 OPERATIONAL ISSUES

A1.5.1 Occupational health issues

External radiation

Oil and gas production and initial downstream processing takes place within closed systems that very often operate at pressures above atmospheric. The production equipment therefore mainly consists of pressure vessels and pressure piping. The steel walls of this equipment mean that apart from maintenance work involving the opening of the production equipment, only energetic gamma emitters capable of penetrating the steel from NORM inside the equipment could become a source of external radiation exposure. The radionuclides involved are:

- the short-lived radon decay products (from ^{222}Rn); and
- ^{208}Tl from the ^{228}Th decay series.

The first of the above can be found in both main situations: water-related NORM (radium scales and sands) and gas-related NORM, while ^{208}Tl is only associated with water-related NORM. In some operations, external gamma radiation from water-related NORM may be higher than those from gas-related NORM, while in other operations, the opposite can be the case.

External gamma radiation levels from NORM scales and sands (water-related NORM) depend on the activity concentrations involved, the amount of scale or sand present and the wall thickness of the equipment. As usual, these factors are highly

variable, with some production operations experiencing insignificant external gamma levels, and others experiencing levels requiring considered responses. As an example of the latter, one operation found external gamma levels of up to 600 $\mu\text{Sv hr}^{-1}$ at the surface of some small containers of scale (< 50 kg in total) which was found upon analysis to contain up to 1,700 Bq g^{-1} of ^{226}Ra , 2,600 Bq g^{-1} of ^{228}Ra and 1,000 Bq g^{-1} of ^{228}Th .

External gamma radiation levels from gas-related NORM follow the dynamics described in Section A1.3.4 above: as the gamma emissions from the longer lived radon decay products (^{210}Pb , ^{210}Bi and ^{210}Po) are too weak to be of significance outside the equipment, only the gammas from the short lived radon decay products are of potential significance.

Depending on the circumstances, the control of external radiation exposures may not be necessary, as levels may be too low. Monitoring will be necessary to determine if further controls are necessary and to detect any changes over time. The general control approaches available are:

- For both water-related and gas-related NORM: erecting barriers around areas of significant external radiation levels, posting warning signs, limiting access times, requiring additional pre-job planning for work within the barriers, etc.
- For gas-related NORM, taking the item of equipment to be worked on out of service for a few hours prior to the commencement of work. While this will greatly reduce the external gamma levels from the equipment, it will have no impact on the potential internal radiation hazard when the equipment is opened.

Internal radiation

All of the NORM radionuclides have the potential to cause committed doses once inside the body. In particular, a number of the alpha emitting radionuclides are of increased significance if inhaled or ingested. IAEA Safety Report 49 contains estimates of effective doses from a range of NORM materials, including scales and sludges. The kinds of activities and the routes of exposure that could give rise to internal exposures are:

- Larger pieces of equipment that contain radium scales (water-related NORM) have the potential to have radon (^{222}Rn) and thoron (^{220}Rn) concentrations if unventilated, potentially leading to inhalation exposures of radon decay products. However, as industry good practice is to ensure good vessel ventilation prior to entry, this is not likely to be a significant source of exposure.
- When equipment is opened it may contain loose material (both water-related and gas-related NORM). This material may be wet (oily sands or sludges), in which case it will not pose an immediate risk of inhalation exposure, but could pose an increasing risk if allowed to dry and contaminate work surfaces, walkways, etc. The material could be dry and friable, in which case its risk of inhalation exposure would be greater, or it could be hard, as in many scales and the thin deposits of gas-related NORM at impaction points, in which case the risk of inhalation exposure will depend on the extent to which it is disturbed.
- The containment of NORM materials from inside equipment is important for both occupational and environmental reasons. Uncontained materials could accumulate on work surfaces and walkways where subsequent activities could disturb the material making it airborne and available for inhalation. In addition, NORM from such surfaces or directly from the equipment being handled could contaminate skin, leading to direct skin exposures, and via the hands could lead to ingestion via hand to mouth transfer.

- When pressure vessels are opened, they usually need to be cleaned for inspection. The cleaning process has the potential to disturb NORM deposits, and this needs to be considered when planning the work. If metal defects are found by the inspection, actions such as welding, grinding and air-arc gouging may be used to remedy the defects; if residual NORM is present, these also have the potential to make the NORM airborne. Some of these activities (air-arc gouging in particular) have sufficient potential to cause non-NORM airborne contaminants to require a high standard of respiratory protection, which should also protect against the NORM.
- Other work on equipment internals may disturb NORM. Even if the equipment is to be discarded (sold for reuse or for scrap), as discussed later it may need to be cleaned (made acceptably NORM-free) before being discarded. Depending on the cleaning method employed, airborne NORM dust could be generated.
- Repair work on equipment may involve the generation of airborne NORM. For example, pump impellers may be ground as part of a re-balancing process; if the impeller has a thin layer of ^{210}Pb , ^{210}Bi and ^{210}Po , some or all of the layer could be made airborne by the grinding process. Similar repair works could apply to valve seats, to re-tubing heat exchangers, etc.

The control strategies for all the above examples of potential inhalation and ingestion exposure risk are no different in principle from the control approaches recommended by occupational hygienists for the control of exposures to other hazardous materials. As in other occupational health control matters, the hierarchy of control should be applied, although given NORM's status as an unwanted contaminant in an industry which does not in this case set out to handle radioactive substances, the application of the first two options: elimination and substitution is not available.

Engineering controls apply to:

- The use of ventilation, both local and general for work inside NORM contaminated vessels and on NORM contaminated equipment.
- The use of enclosed cleaning equipment such as a glass bead blaster for cleaning NORM from equipment removed from service. The bead blasting would take place inside a ventilated cabinet, with the air exhausted from it being cleaned by HEPA filters before release.
- The use of any purpose designed and built cleaning facility for removing NORM from oil and gas industry equipment. Such facilities exist in oil and gas producing areas outside Australia, but no such facility is available in Australia.

Procedural controls apply to virtually all work potentially involving NORM contaminated items. Such a procedure might contain:

- working definitions of 'NORM contaminated' used for determining when the NORM procedure applies;
- a classification of tasks on NORM contaminated equipment on the basis of their potential for generating NORM dust;
- options for carrying out tasks by methods which generate a minimum of airborne dust;
- personal protective equipment by NORM task classification;
- methods for containing NORM, preventing the spread of contamination, and for collecting, storing and labelling waste; and
- steps to be taken if it is proposed to release a NORM contaminated item of equipment from site.

Personal protective equipment controls are likely to be embedded in the NORM procedure as described above. These controls will focus on preventing skin contamination (e.g. impermeable gloves), on preventing the accumulation of NORM on clothing worn outside the immediate work area, and most importantly, on achieving effective respiratory protection against airborne NORM.

Achieving effective respiratory protection against any hazardous dust requires significant effort in the form of a formal respiratory protection program with elements including the selection, cleaning and maintenance of respirators, the training of respirator wearers, and the individual fit testing of respirators for each wearer. Australian Standard AS/NZS 1715 'Selection, Use and Maintenance of Respiratory Protective Devices' (SAI, 1994) provides detailed advice on the content of an effective respiratory protective equipment program.

Contamination control

Contamination control is usually achieved through a combination of:

- ensuring that equipment with NORM inside is sealed at all openings;
- working over plastic sheeting or a similar collection system to ensure that any NORM released by the work underway is caught and retained;
- wearing impermeable gloves to prevent hand contamination;
- wearing disposable coveralls;
- wet wiping tools and other items used for the work.

The extent of the contamination control required will depend on the specific circumstances.

A1.5.2 Public health issues

NORM in products

Ethane is the product most commonly contaminated with NORM. However, NORM can also occur in LPG and methane products, and to a smaller extent, in crude oil. LPG comes to market from two distinct sources:

- From Upstream operations with wet gas fields which separate out the LPG for sale. This source of LPG can contain NORM contamination: the quantity depends on the source of the LPG, the transit time from well to sale, and to some extent on processing arrangements.
- Oil refineries also make LPG, by cracking larger hydrocarbon molecules into smaller ones. This refinery made LPG is not expected to contain any NORM.

Apart from ethane, the presence of NORM in the other products is not likely to reach the levels found in the Upstream oil and gas production industry. However, there is little data available on the build-up of ^{210}Pb , ^{210}Bi and ^{210}Po in LPG transport and storage equipment and the likely exposures of persons specialising in their maintenance. Accordingly, it would seem prudent for Upstream sellers of LPG to measure the radon levels in their products and to disclose the results in the Material Safety Data Sheets for their products.

NORM residues on items released from the industry

The oil and gas industry relies on a significant number of service organisations to help maintain its equipment. Some of these are offsite workshops carrying out work such as pump rebalancing, exchanger retubing, valve refurbishing, etc. These workshops may therefore receive items bearing NORM contamination and may

carry out work on those items which disturbs the deposits and carries a risk of inhalation exposure to NORM as well as leaving some residual contamination in the workshop.

The industry also generates equipment items for which it no longer has any use. Well tubing and drill piping is perhaps the largest single category by number of items. These items can be sold for scrap metal – thus recycled through a smelter – or may be sold for reuse. Well tubing and drill piping is attractive for reuse, for example as irrigation piping, because of its standard lengths and threaded connections making joining easy.

Regardless of the destination of a NORM contaminated item after it leaves an oil and gas production site, those receiving the items should be made aware of its NORM contamination status. An example process is:

- the oil and gas operator's internal procedures forbid the release from site of equipment items unless they have been shown to be NORM-free or a specific NORM item release process has been completed;
- items that are NORM contaminated do not leave the industry site until the recipient has been advised in writing of the NORM-positive status of the item(s) and has indicated their willingness to accept the item(s) in that state.

The absence in Australia of any third party NORM cleaning facility makes it harder for oil and gas operators to guarantee that only NORM free items will be released to service workshops or into the wider community for reuse or recycling.

A1.5.3 Monitoring programs

Monitoring program objectives

NORM monitoring programs can be performed for a number of reasons, and the objectives of the program will drive how the monitoring is approached. Possible objectives are:

- surveillance - this monitoring is done to answer questions such as:
 - is NORM occurring in this operation?
 - how much NORM is present, and what type is it?
 - is the NORM changing over time?
- confirmation of controls - this monitoring is done in order to check that assumed parameters on which controls are based are accurate, or that controls are working. Examples of such monitoring are:
 - carrying out personal dosimetry for external radiation exposures to confirm that exposures fall into the range expected from external radiation surveillance monitoring;
 - measuring airborne radioactive dust during maintenance activities to check that the assumptions upon which respirator selections were made are accurate – or if respirators are needed at all;
 - a surface contamination survey in a workshop to confirm that NORM contamination controls are working;
 - sampling and analysis of waste streams to confirm that they remain within regulatory limits.
- Operational - this is monitoring done during day-to-day operations to determine if NORM precautions are required for a particular piece of equipment, or to determine the NORM status of an item prior to release off site.

Operators may decide to treat all equipment as NORM contaminated unless tested; however, the additional costs this approach will entail means that some NORM status monitoring to determine the applicability of precautions is likely to be necessary. Depending on the operator's NORM procedures, this monitoring may be pass/fail, or it may give rise to some kind of graduated set of precautions.

External radiation

The monitoring of external radiation levels outside oil and gas equipment is relatively easily performed using readily available equipment such as energy-compensated GM detectors. The industry requirement for intrinsically safe electrical equipment (or the need for additional precautions when using non intrinsically safe monitors) does complicate monitoring slightly, but suitable monitors conforming to intrinsic safety standards are available.

The major issue with external radiation monitoring is the need for those involved to understand its important limitations when it comes to gas-related NORM for equipment that has been offline for several hours. For such equipment, the low energy alpha, beta and gamma emissions associated with ^{210}Pb , ^{210}Bi and ^{210}Po mean that when the equipment is closed, the radiation is unable to penetrate the steel walls; when the equipment is open, the usual external radiation detectors may still be very inefficient at detecting this radiation. The potential therefore exists, if external radiation monitors are relied upon, for the hazard due to surface contamination with those radionuclides to be missed. It is for this reason that criteria for 'NORM contaminated' based solely on external $\mu\text{Sv hr}^{-1}$ readings are to be avoided.

Surface contamination

Several different types of surface contamination monitors exist from the uranium mining industry that have the capability of detecting emissions from NORM radionuclides. Some detectors are capable of separately measuring α and β/γ radiation. Some detectors have the capability of identifying which radionuclides are present. In the uranium mining industry, such instruments are typically used to measure against surface contamination criteria for work surfaces, lunch rooms, etc. expressed in Bq cm^{-2} . There are some significant difficulties in applying these in the oil and gas industry:

- The detectors are usually flat and designed and calibrated to measured surface contamination on flat surfaces. The oil and gas industry has few flat surfaces when it comes to inside equipment.
- The measurement of radiation from scales and other deposits is likely to be subject to self-absorption in the deposit, particularly for α radiation.

Because of the above measurement difficulties, the use of criteria for 'NORM contaminated' expressed in Bq cm^{-2} is very problematic. As a result, industry operators may instead adopt working definitions of 'NORM contaminated' that are conservative and based on a pass/fail approach, such as whether readings from the equipment being tested are significantly above background.

Airborne dusts

The measurement of airborne NORM dusts involves occupational hygiene issues of size-selective air sampling devices and radionuclide laboratory on-filter counting and analysis. As in other workplace monitoring, personal monitoring, in which the air sampling device is worn by the worker whose exposure is being monitored is the preferred strategy.

Radon in products

This is a specialist monitoring process that is available in Australia. The usual method for gaseous products involves passing a known volume of product through a trap containing activated charcoal. The timing of the sample collection and subsequent analysis is important, as the radon concentration in the product is inferred from measured decay product concentrations as the decay products grow-in over time.

A1.5.4 Issues needing additional consideration

The absence of a risk-based, field measurable definition of 'NORM contaminated' is a significant issue for the oil and gas industry that needs additional consideration. The use of pass/fail criteria based on deviations from background, while conservative, suffers from anomalies due to the varying backgrounds encountered in the industry: the background level on an offshore platform with little NORM and no radioactive sources on board can be as low as one-tenth of the background at an onshore plant. This leads to items being 'NORM-positive' in one environment and 'NORM-negative' in another.

A1.6 ENVIRONMENT PROTECTION

A1.6.1 Waste streams

Produced formation water

In the absence of considerations of its NORM content, produced formation water is typically disposed of:

- into the ocean in the case of offshore facilities;
- by re-injection into the formation in the case of either onshore or offshore facilities; or
- by evaporation in evaporation ponds.

Ocean disposal is conditional on meeting regulatory criteria for hydrocarbon content.

Operators should be expected to have a surveillance system in place through which long term trends in the activity concentration of NORM in their produced formation water are tracked. Produced formation water is produced continuously while a facility is in operation.

Scales, sands and sludges

As discussed this group of wastes can be very variable in both annual volume production and radionuclide content. It is possible, through careful management and with good record keeping, for operators to dilute higher activity material with lower activity material to bring the mixed waste down to below a regulatory activity concentration limit for disposal. This approach requires the analysis of samples from each batch of waste generated. These wastes are produced when equipment is shut down and cleaned, and are thus produced in batches as a result of planned activities.

The presence of oil in sands and sludges can complicate the regulation of its disposal, as the waste may fall into the jurisdiction of the relevant environmental protection regulator due to its oil content and into the jurisdiction of the relevant radiation protection regulator due to its NORM content.

Management of contaminated items

These fall into two groups:

- production equipment, virtually always metal items such as pipes, pumps, and valves; and
- materials used in NORM control procedures, such as gloves, plastic sheeting, disposable coveralls, etc.

NORM contaminated production equipment is frequently stockpiled awaiting further consideration, testing, or regulatory clarity. The main environmental issues associated with this practice are the potential for ground and water contamination if loose NORM materials in the equipment are allowed to spill or be washed out by rain.

In the past, these items may not have always been well managed – perhaps because the presence of NORM was not recognised. The Australian Government has received a communication from another country in the region complaining of the presence of NORM in scrap oil industry components sent to the other country for smelting.

NORM contaminated materials are typically stored in drums or bins. As contamination levels may typically be low on these items, the main environmental issue may be the collision between waste minimisation objectives and the NORM occupational health and contamination control objectives which generate this waste.

Waste disposal options

The selection of which waste disposal option is to be employed in any particular case should be the result of discussions between the industry operator and the relevant regulatory bodies. In some cases, formal studies have been required which consider all relevant environmental pathways from the disposed waste to people and which estimate committed equivalent doses to members of critical groups. As discussed, the presence of oil in addition to NORM can complicate this process.

Waste disposal routes that have or are being used or are being considered in Australia include:

- on-going ocean disposal of produced formation water following a formal study of the kind referred to above;
- ocean (overboard) disposal of sands and scales from platforms, provided oil content criteria have been met and again following formal studies;
- down-hole disposal of smaller volumes of higher activity scales and sands into disused oil wells followed by cementing of the wells;
- onshore near surface disposal of stabilised oily sands and sludges into engineered clay pits which are covered by a defined thickness of clean fill after disposal. Some contaminated plastic sheet, gloves, etc., has also been disposed of via this route;
- disposal of contaminated items via smelter recycling has occurred in Australia after careful definition of contamination limits and associated measurement protocols.

A1.7 NORM ISSUES IN DOWNSTREAM PROCESSING

A1.7.1 Use of ethane as a feedstock

Ethane is a valuable feedstock for the petrochemical industry. In the absence of an ethane customer, an oil and gas production operator may blend the produced ethane

into natural gas, or may use the ethane as a process fuel. Ethane customers need to be connected to the production operation by pipeline; as economics limit the length of such pipelines, some radon commonly enters the ethane customer's plant, with the activity concentration depending on the radon activity concentration at source and the transit time from well to customer.

Once the radon has arrived at the customer plant, its behaviour and potential exposure risks are as described for gas processing. NORM precautions are commonly required and implemented at such plants. In addition, it is possible for the plant using the ethane to separate some of the radon into a side-stream which is on-sold to another petrochemical facility, providing the second facility with the need to also consider NORM precautions.

A1.7.2 Potential radon decay product contamination in LPG distribution systems

There is very little information in the literature or in international guidance documents about this potential. This may need some further investigation and field surveys.

A1.7.3 NORM in oil refining

Low levels of NORM are occasionally encountered in oil refineries. The limited experience to date has been that while the NORM is concentrated in the highest boiling point streams in the refinery, the activity concentrations found are low and that specific NORM precautions and waste disposal considerations are not required. Additional data on this would be valuable.

Annex 2

Management of NORM in the Bauxite/ Aluminium Industry

A2.1 BRIEF DESCRIPTION OF INDUSTRY

The industry description draws on material from Cooper (2005), from Woodcock and Hamilton (1993), from the Australian Bureau of Agricultural and Resource Economics (ABARE, 2007) and from the Australian Aluminium Council (2007).

The main source of aluminium is bauxite ore which contains 30 to 50% hydrated aluminium oxide, in the mineral forms gibbsite and boehmite, for the Australian deposits currently being mined. Australia has vast deposits of bauxite, with identified supplies expected to last 70 to 75 years at the current level of extraction. It is the world's largest producer and exporter of both bauxite (63.6 Mt in 2006) and alumina (18.4 Mt in 2006), and the fifth largest producer of aluminium metal (1.9 Mt in 2006). The difference between the bauxite and alumina values gives an indicative figure for the production of solid residue (45 Mt in 2006). The Australian aluminium production industry receives its entire alumina demand from the domestic alumina industry, amounting to 20% of alumina production in 2006. The residual 80% of alumina production is exported. In 2007 Australia had 5 bauxite mines, 7 alumina refineries and 6 aluminium smelters.

The schematic in Figure 5 shows the principal steps in the production of smelter grade alumina which is the feedstock for the production of aluminium metal (bauxite mining; and then the production of smelter grade alumina through the Bayer process). The natural radioactivity present in the ore transfers almost entirely to the solid residue stream from the Bayer processing stage. The solid residue comprises a mud residue stream to which most of the bauxite radioactivity transfers and a lower-activity sand residue stream. The radioactivity in the bauxite ore, Bayer process materials and mud residue (and perhaps sand residue) may be potentially of radiological interest, but not aluminium production as the carry through of radionuclides into smelter grade alumina (and therefore alumina metal from smelting) is minimal.

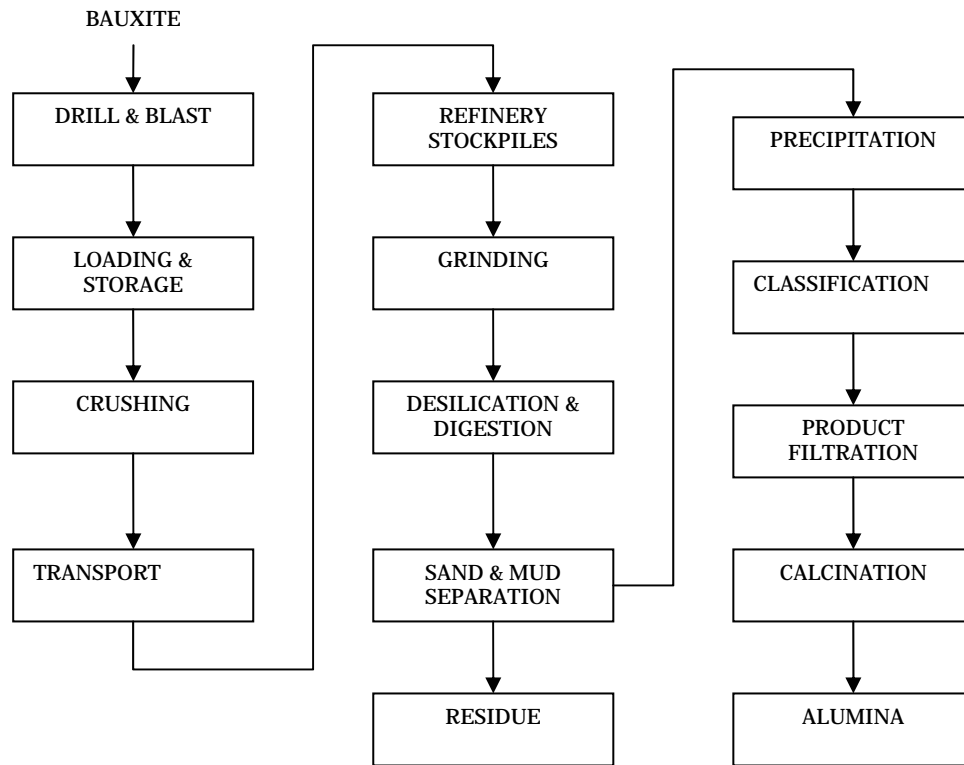


Figure 5: Simplified schematic showing the steps involved in the processing of bauxite ore to produce smelter grade alumina, with reference to potential radiological impacts. The ore may be washed prior to being transported to the bauxite refinery

Raw materials

The five bauxite mines operating in Australia produce feedstock for the Bayer process covering broad ranges in available alumina content and in radionuclide concentrations which accounts for the wide range of solid residue volumes produced per tonne of bauxite feed as well as the wide range in residue radionuclide concentrations. Bauxite mined at Gove in the Northern Territory and Weipa in Queensland have close to 50% extractable alumina, placing them amongst the world’s highest grade deposits, compared with the lower-grade Western Australian deposits (ca. 30 % available alumina) mined in the Darling Range at Willowdale and Huntly. The extensive undeveloped Mitchell Plateau deposits in Western Australia also have around 30 % available alumina.

Typical volumes

Table 9 summarises the materials volumes for the Australian industry, in terms of bauxite ore, alumina production and solid residues. The data are consistent with statistics reported by the ABARE (2007).

Table 9: Summary of bauxite volumes mined in 2006 and estimates resulting volumes of extractable alumina and solid residues (AAC, 2007)

Mine	Refineries	Bauxite Mined and Corresponding Estimates of Bauxite and Residue (Mt a ⁻¹)			
		Bauxite	Alumina	Mud Residue	Sand Residue
Gove, NT (Rio Tinto Alcan)	Gove, NT	6	3	1.3	1.7
Weipa, Qld (Rio Tinto Alcan)	Gladstone, Qld (QAL); Yarwun, Qld (Rio Tinto Alcan); plus exports	16.5	8.3	3.1	5.1
Huntly, WA (Alcoa)	Kwinana and Pinjarra, WA (Alcoa)	20	6	8	6
Willowdale, WA (Alcoa)	Wagerup, WA (Alcoa)	8.5	2.5	3.9	2.1
Boddington, WA (BHP Billiton)	Worsley, WA	12	3.5	5.4	3.1

Note: Estimates based on AAC Sustainability Data – indicative estimates only

The Gove bauxite is a lateritic deposit mainly composed of gibbsite, with boehmite as a minor component. Hematite and goethite are the iron oxide constituents, while silica is in the form of kaolinite and quartz. The Weipa bauxite resource occurs naturally in pisolitic (pea-like) form, with about 70 to 80% of the extractable alumina in the bauxite present as gibbsite and containing 1 to 2% quartz. Around 150,000 tonnes per year of Weipa bauxite is roasted in the range 900°C and 1200°C for 50-60 minutes to produce calcined bauxite, which is exported for use as an industrial abrasive. Darling Range bauxite is predominantly gibbsite and typically is covered by topsoil and overburden which is removed and conserved for later remediation. The cap rock bauxite is drilled and blasted before extraction with the more friable bauxite below.

The open cut mining procedures used by all five mines indicate that dust inhalation and radon exposure may possibly result in some above-background radiological impacts, in addition to that from gamma emission – see following sub-section.

Typical radionuclide concentrations and potential radiological significance

Chemical concentrations for Th and U in bauxite, and the corresponding ²³²Th and ²³⁸U activity concentrations have been reported by Cooper (2005), von Philipsborn and Kühnast (1992) and Sato et al (1986). The indicative ranges for the reported Th and U trace levels taken across the Australian operations are 10 – 200 ppm for Th and 5 – 23 ppm for U. The corresponding spreads in activity concentrations for bauxite are 0.04 to 0.8 Bq g⁻¹ for ²³²Th and 0.06 to 0.3 Bq g⁻¹ for ²³⁸U.

In addition to radiation associated with ²³²Th and ²³⁸U and their decay products, there is a relatively small contribution to radiation dose estimates from ⁴⁰K in the bauxite. Measurement of potassium levels in bauxite by companies has indicated that the ⁴⁰K component makes a negligible contribution to above-background radiological estimates.

Direct measurement of gamma levels from ores has indicated that above-background doses from this source are unlikely to have any radiological consequences, but may still require assessment. Dust inhalation and radon may provide above-background doses of radiological interest, but these sources may be discounted if ventilation is adequate.

A2.2 MINERAL PROCESSING STEPS

The main raw materials for the Bayer process, as well as bauxite, are caustic soda and lime, with these latter not being of possible consequence radiologically.

There are six basic steps in the Bayer process. The following description is based on information provided by the industry and also from MCA (2007).

Step 1. Bauxite mining and washing

Following open-cut mining of the ore, the material is transported to the refinery. The extracted ore may be washed prior to transportation.

Step 2. Bauxite grinding and slurry production

The crushed ore is ground, with a solution of hot, recycled concentrated sodium hydroxide being added during grinding to produce a bauxite slurry. The slurry is pumped to holding tanks prior to the digestion stage. There is some removal of silica from the bauxite at this stage which may result in some transfer of radioactivity from the bauxite.

Step 3. Bauxite digestion in caustic soda at high temperature and pressure

The bauxite slurry is fed into a digester where it is mixed under pressure with additional recycled caustic soda. The slurry leaves the digestion stage with the hydrated alumina in solution as sodium aluminate solution (designated *green liquor*), plus undissolved ore solids.

Step 4. Separation and washing of solid residues

The green liquor is then passed to *clarification vessels* (also termed *mud thickeners*) which allow the undissolved bauxite solids to settle out. Separation of the undissolved residue from the liquor involves three stages: first, the coarse sand-sized residue (or *sand residue*) is removed and washed to recover caustic soda; second, the mud residue is separated out; and, third the remaining green liquor is pumped through filters to remove any remaining impurities. The sand and mud residues are together pumped to residue lakes and the green liquor then passes to the hydrated alumina precipitation stage.

Step 5. Precipitation of aluminium hydroxide

The hydrated alumina is precipitated from the liquor as crystals of aluminium hydroxide. To do this, the green liquor solution is seeded in precipitator vessels with fine crystalline aluminium hydroxide, which seeds the precipitation of solid aluminium hydroxide as the solution cools. When completed the solid aluminium hydroxide is passed on to the next stage and the remaining liquor, which contains caustic soda and some sodium aluminate, goes back to the digesters.

Step 6. Calcination to remove water and produce anhydrous alumina

Aluminium hydroxide is washed to remove any remaining liquor and dried. Finally it is heated to approximately 1000°C to drive off the water of crystallisation, leaving the alumina, which is a dry, pure white, sandy material. A portion of the alumina may be left in the hydrate form or further processed for the chemical industry.

Steps 1 – 5 may require radiological evaluation depending on the radionuclide levels in the bauxite feed as well as plant design. Step 4, *and the subsequent storage of the solid residue material, is the step of principal radiological interest as the bauxite radioactivity passes almost entirely to residue.* In addition to radiological evaluations of the residue production in Step 4, and subsequent residue storage, further evaluations for Steps 1 - 3 and 5 may be required with reference to –

- (a) The mining and crushing of ore in Step 1 will result in some emission of radionuclide-containing dust and also radon gas, which may require radiological impact assessment. Plant survey measurements by Alcoa of gamma levels, atmospheric gross alpha concentrations and radon concentrations have indicated that above-background doses above 1 mSv a⁻¹ are highly unlikely for any staff involved with Step 1, provided that adequate ventilation is maintained during this stage.
- (b) As for Step 1, there may be release of radionuclide-containing dust and radon during Step 2. There may also be some leaching of radionuclides into the caustic wash solution. Additionally, there is the possibility during Step 2 of discernible gamma exposure from the radionuclides in the solids.
- (c) The slurry produced in Step 2 carries the NORM activity to Step 3 as the undissolved solids fraction. Also, as for Step 2, there may be some release of radionuclide activity into solution, as well as radon release. In practice, the pH regime is unfavourable for the release of radium into solution.
- (d) Step 5 involves re-circulation of caustic liquor and therefore the possible progressive accumulation of activity in liquor and perhaps the subsequent deposition of radionuclides within Bayer process equipment. This issue requires some further evaluation although results reported to date have not shown indications of activity accumulation within the process.

In addition to Steps 1 – 5, plant maintenance should also be considered with respect to gamma radiation during de-scaling maintenance operations, plus the additional possibility that radionuclide-containing dust and radon might be released during de-scaling.

Roasting of bauxite to produce calcined bauxite also requires radiological evaluation with particular reference to the emission of radon and thoron and their decay products.

A2.3 TYPES OF NORM RESIDUES RESULTING FROM MINERAL PROCESSING

Virtually the entire amount of radioactivity in the bauxite ore is transferred to the mud and sand residue streams and there is practically no department of ²³²Th and ²³⁸U series radionuclides to the Bayer process alumina.

The main solid residues from the alumina production are predominantly undissolved bauxite residues containing iron, silica and titanium removed from the digestion step of the process, plus aluminium hydrate that is not extracted in the process. Some of the radioactivity may be associated with trace quantities of non-

bauxitic minerals, such as ilmenite or monazite. Most alumina producers add lime during the process which forms a number of compounds that end up with the bauxite residue. The following elemental composition data indicate the wide range in chemical composition found in residue from different bauxites:

Fe ₂ O ₃	30 - 60 %
Al ₂ O ₃	10 - 20%
SiO ₂	3 - 50 %
Na ₂ O	2 - 10 %
CaO	2 - 8%
TiO ₂	Trace -10%

The trace element content includes elements such as zinc, phosphorus, nickel and vanadium as well as Th and U.

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

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

Typical volumes

Table 9 shows alumina and residue production estimates derived from the 5 Australian mines. The amount of bauxite residues generated, per tonne of alumina produced, varies greatly depending on the type of bauxite used, from 0.3 tonnes for high grade bauxite to 2.5 tonnes for very low grade (AAC, 2003). There is also substantial variability between the refineries in the relative split of mud residue and sand residue produced per tonne of alumina. The higher concentrations of radionuclides in the mud residue compared with the sand residue are attributed to the strong tendency of radionuclides to be associated with the fine-grained mineralogy in mud residue.

Estimates of residue production associated with each mining operation are given in Table 9.

Typical radionuclide concentrations for each type of material

The chemical concentrations for Th and U in bauxite mud residue, and the corresponding ²³²Th and ²³⁸U activity concentrations, can be expected to increase by as much as a factor of 2-3 relative to the bauxite concentrations, depending on the mineralogy of the ore as well as the level of the bauxite. The indicative activity concentrations for ²³²Th taken across the Australian operations varies from levels substantially less than 0.5 Bq g⁻¹ to values in the vicinity of 1.5 Bq g⁻¹. The corresponding indicative range for ²³⁸U has an upper limit of approximately 0.6 Bq g⁻¹.

The indicative range of ²³²Th activity concentrations signifies that, while the mud residue for some operations slightly exceed the exemption limit of 1 Bq g⁻¹ (1 Bq g⁻¹) specified in *Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing* (ARPANSA, 2005), operators may seek an exemption from the appropriate regulator(s) on a graded basis. For this reason, consideration of an exemption application for such operations would require an assessment of above-background doses for workers

against the 1 mSv a⁻¹ criterion, as well as the demonstration of protection optimisation.

Activity concentrations for sand residue from the operations are substantially less than the corresponding bauxite levels, and therefore the sand residue materials can be expected to gain a regulatory exemption according to activity.

A2.4 MANAGEMENT STRATEGIES FOR EACH TYPE OF RESIDUE

The principal ARPANSA document pertaining to the radiological assessment of bauxite processing is the *Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing* (ARPANSA, 2005). Supplementary information is given in the IAEA document: *Assessing the Need for Radiation Protection Measures in Work Involving Minerals and Raw Materials* (IAEA, 2006a).

Exemption and exclusion principles for bulk materials such as bauxite ore and mud residue are considered in the IAEA guidance *Safety Guide for the Application of the Concepts of Exclusion, Exemption and Clearance Safety Guide* (IAEA, 2004a) which is designated RS-G-1.7. This Guide should be considered together with the IAEA 'BSS115' document *International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources* (IAEA, 1996).

The extent to which radiological management strategies may be required is represented as follows:

1. Evaluation of representative, time-averaged radionuclide activity concentrations (²³²Th and ²³⁸U) for the ore and for the two residue streams (*mud* and *sand*). The head-of-chain activity concentrations are conveniently determined from elemental analysis data, assuming secular equilibrium for each decay chain.
2. Assessment of the likelihood of compliance with the 1 Bq g⁻¹ exemption limit, and, in consultation with the regulator, whether the materials and processes qualify for exemption status. Where the materials exceed the 1 Bq g⁻¹ limit by a small amount (perhaps by *ca.* 1 Bq g⁻¹), the regulator may consider an application for an exemption according to a graded approach.
3. Use of positional and personal monitoring to examine compliance with the 1 mSv a⁻¹ above-background level, where deemed relevant by the appropriate regulator(s). This assessment will also involve assessments of natural background dose to determine above-background doses for designated individuals.
4. Where the 1 mSv a⁻¹ level is exceeded for any worker category, the Company would develop protection optimisation strategies in consultation with the regulator.
5. The regulator may require the operator to develop and operate an on-going NORM management plan as a condition of exemption.

Assessment of Materials

Composite samples of the bauxite and residue streams (mud and sand residue components) should be acquired over an appropriate period to provide representative time-averaged concentrations of the ore body currently being mined. Elemental analysis of the Th and U trace concentrations (typical ranges, up to 500 and 50 parts-per-million dry weight, respectively) should be conducted by an accredited laboratory, with appropriate validation being used. The concentrations are readily converted to ²³²Th and ²³⁸U activities assuming that the two series are in secular equilibrium. Assessments should be conducted for bauxite and residues from new mining and processing operations, as well as for existing operations which have not yet been assessed.

Compliance Testing Against the 1 Bq g⁻¹ Exemption Level

Clear compliance with the 1 Bq g⁻¹ exemption level may form the basis of an application for exemption. However, it must be appreciated that the regulator may

still require an assessment of above-background doses for staff in appropriate work categories to ensure that no staff member is likely to exceed the 1 mSv a⁻¹ dose level.

Positional and Personal Monitoring

Where the 1 Bq g⁻¹ exemption level is exceeded for some or all of the materials, the regulator may still consider an exemption application on a graded basis if the operator can establish that no worker is likely to exceed the 1 mSv a⁻¹ level and also that protection optimisation has been demonstrated according to the ALARA principle. An assessment of incremental doses for appropriate worker categories will normally involve separate assessments of the gamma, radon and airborne gross alpha components. Each of these three assessments will necessarily involve determination of the natural background level. Background assessments will be demanding technically as the increment will be comparable with the natural background level.

Protection Optimisation

Protection optimisation measures may include (i) introducing administrative controls to limit area occupancy times for work categories where the 1 mSv a⁻¹ limit may be exceeded for 100% occupancy, notably for residue area workers; and (ii) applying ventilation measures, where appropriate, as in the mining, washing and crushing of bauxite ore.

On-Going NORM Management

The regulator may require the operator to develop and conduct an on-going NORM management plan as part of exemption compliance. This may involve one or more of the following: materials activity assessments, positional monitoring and personal monitoring.

Transport and Trade

Transport of materials containing radionuclides within Australia is regulated by all jurisdictions using the provisions of the ARPANSA *Code of Practice for the Safe Transport of Radioactive Material* (ARPANSA, 2008). Transport of bauxite, Bayer process materials, residue materials and end-use products within Australia can be expected to gain an exemption from the Code, as the Code adopts a factor-of-ten relaxation of the 1 Bq g⁻¹ exemption value for materials containing only natural radionuclides. IAEA guidance on the transport of radioactive materials applies to the international movement of materials (IAEA, 2005). For materials containing only natural radionuclides, the IAEA has also adopted a factor of ten relaxation of the activity concentration level for exempt material of 1 Bq g⁻¹. There may be some more restrictive, country-specific regulations on the movement of bauxite processing materials and end-use products, depending on the activity concentrations.

Storage options (surface deposition, landfill, utilisation)

Bauxite residue is most often stored on land using a variety of methods, and there has also been some ocean disposal of residue.

The residue contains some residual alkalinity; and hence the storage areas are constructed to reduce the risks of seepage to groundwater. Storage is mainly accomplished by the 'dry stacking' method. This process produces a thickened residue which is spread in layers over storage areas. Additional water is removed through a combination of drainage and evaporative drying. The advantages include

reduced environmental risk, more stable landforms for remediation and a wider range of potential land uses for storage areas in the future.

Assessments of residue areas have indicated barely discernible transfer of radionuclides to groundwater which is consistent with the highly alkaline condition of the residue. Groundwater monitoring for radionuclide concentrations will test this assumption.

Remediation of bauxite residue areas for specific uses may require formal approval by the appropriate regulator. The regulator may require submission of a radiological assessment of the remediation plan, including details of protection optimisation strategies based on the estimation of potential incremental radiation doses for members of the public.

Suitability for utilisation

The use of residue material has been evaluated for many scenarios. These include use as a:

- soil conditioning additive in agriculture, with particular reference to phosphate binding;
- phosphate removal medium in sewage and industrial wastewater treatment;
- substitute for clay, or as a clay additive, in the manufacture of construction materials such as bricks and tiles;
- road base construction material;
- filler in the production of rubbers and PVC.

The development of end-use strategies may include exploiting the lower activity concentrations of sand residues.

Evaluation of specific end-use applications may require approval by the regulator on a case-by-case basis. This may entail submission of an exemption application which would include a radiological assessment.

Examples of health impact assessments for different management strategies

Company assessments of the possible radiological impact of bauxite processing operations have been conducted for more than 20 years. A succession of studies has included (i) the department of bauxite radionuclide activity through the Bayer process with particular respect to the ores, alumina product and solid residues; (ii) the potential health impacts of the process, residue management and prospective end-uses of residue on the workforce and members of the public; and (iii) health impacts of rehabilitated residue areas.

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Annex 3

Management of NORM in the Phosphate Industry

A3.1 BRIEF DESCRIPTION OF THE PHOSPHATE INDUSTRY

World extraction of phosphate containing rock is in excess of 145 million tonnes per annum (Mew 1994, Mineral Handbook 1994-1995). The majority of the phosphate rock production (>90%) is used for the manufacture of fertilisers.

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

The Australian market for phosphate fertiliser is 3-4 million tonnes of superphosphate (ABARE 2007). Some 75 per cent of the Australian market for phosphates is supplied by locally manufactured superphosphate with the balance by imports of ammonium phosphates, currently around 1 million tonnes. Local production of superphosphate uses imported ore, mainly from Christmas Island, Nauru, North Africa, and China. The major deposit of phosphate rock in Australia is the Duchess ore body in Queensland. Phosphate rock from this mine site is used in an integrated fertiliser plant for the production of ammonium phosphate products, partly to supply the local and export markets.

High purity phosphoric acid is an important industrial chemical as a raw material for phosphate chemicals used extensively in detergents, deflocculants, animal feeds and for corrosion treatment of metal. Phosphoric acid used industrially in Australia is now derived from imported material. For economic reasons, local production of high purity phosphoric acid ceased in the early 1990's (Chemlink).

A3.2 SOURCES OF PHOSPHATE ROCK

The majority of phosphate rock deposits are found in large beds of marine sedimentary rocks, but can be found in other areas. There are three types of phosphate rock:

1. Phosphate rock of sedimentary origin: this type accounts for 85% of the current phosphorus production,
2. Phosphorus rock of volcanic origin, the principle deposit of this rock type is in the Kola Peninsula in Russia;
3. Phosphate rock of biological origin: the accumulation of droppings from marine birds has given rise to deposits of guano from which phosphoric acid has been leached and reacted with calcium in the underlying rock to give tri-calcium phosphate.

All three rock types are mined and processed for the manufacture of fertilisers and other phosphorus containing compounds. Phosphate rock formed primarily from guano, such as that found on Nauru, plays a smaller role in terms of worldwide supply and demand.

The known commercially viable phosphate rock reserves and annual production for 1991 and 1992 are estimated to be 12,586 million tonnes based on a US\$40 per

tonne production cost limit (Mineral Handbook 1994-1995). Estimates based on the current and projected rates of usage indicate that the current reserves will last about 500 years.

The majority of the world's phosphate rock comes from the United States (Florida, North Carolina, and Tennessee) and the Kola Peninsula. Smaller deposits are found throughout North Africa and Asia.

Australia has two active phosphate rock operations. Christmas Island Phosphates Pty. Ltd. (a subsidiary of Western Australia's Phosphate Resources Ltd.) operate an open pit mine on Christmas Island (an overseas dependent area of Australia that is located about 360 km south of Java, Indonesia, in the Indian Ocean) and WMC Fertilisers Ltd. (the wholly owned subsidiary of WMC Ltd.) operate the Phosphate Hill-Duchess open pit mine southeast of Mount Isa, Queensland. Phosphate has been mined on Christmas Island since 1897.

In 1997, the Federal Government awarded a 21-year mining lease to Christmas Island Phosphates, which had been mining phosphate on the island under contract since 1990. Production was marketed to fertiliser manufacturers in Australia and Southeast Asia (Resource Information Unit, 2002, p. 378).

Mining began in 1999 at the Phosphate Hill-Duchess Mine with a planned maximum rate of 2.2 Mt a⁻¹ of phosphate rock for the production of fertiliser. About one-half of production was sold domestically, and the remainder was exported to Southeast Asia and New Zealand (Australian Journal of Mining, 2002).

A3.3 PHOSPHATE PROCESSING

In Australia, phosphoric acid production is confined to the manufacture of phosphate fertilisers and to a lesser extent the production of higher purity polyphosphates by the thermal process using imported elemental phosphorus. Plans to produce phosphoric acid by the wet process are well advanced in Queensland and Western Australia.

Phosphoric acid for production of fertilisers is normally produced via the wet acid process. A simplified view of the wet acid process is shown in Figure 6.

In the wet process facility, phosphoric acid is produced by reacting sulphuric acid with naturally occurring phosphate rock. The phosphate rock is dried, crushed, and then continuously fed into the reactor along with sulphuric acid. The reaction combines calcium from the phosphate rock with sulphate, forming calcium sulphate (CaSO₄), commonly referred to as phosphogypsum in order to differentiate it from naturally occurring gypsum. The phosphogypsum is separated from the reaction solution by filtration. For each tonne of phosphoric acid, approximately 5 tonnes of gypsum is generated (Guimond 1979).

If phosphoric acid derived from the phosphate rock is used, either in place of, or partly as a replacement for sulphuric acid, a higher analysis phosphate fertiliser is produced called double and triple phosphate. This form of phosphate fertiliser contains more phosphorus (typically to 20 percent as phosphorus). High analysis fertiliser is therefore more economic at locations distant from place of manufacture or supply. To address this shift in demand favouring higher analysis fertiliser, certain Australian manufacturers are producing phosphoric acid to replace sulphuric acid.

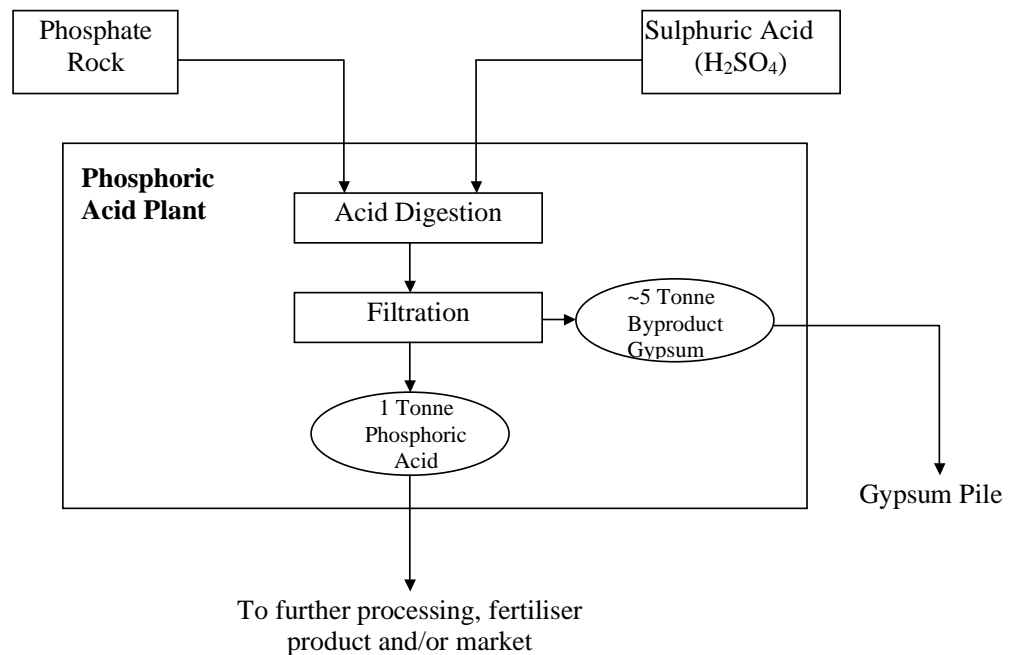


Figure 6: A simplified view of the wet phosphate process

High analysis phosphates are also currently imported (especially ammonium phosphates with a high concentration of nitrogen and phosphorus) and often blended with locally produced single strength superphosphate to provide a double strength fertiliser.

The major solid waste arising from phosphoric acid production is large quantities of calcium sulphate, gypsum. This is often referred to as phosphogypsum to differentiate it from the natural occurring material. As previously mentioned, this is typically about 5 tonnes of gypsum for each tonne of phosphoric acid produced. The gypsum is acidic in nature due to the incomplete removal of the phosphoric acid and is typically stockpiled on site in clay-lined dams or disposed of as landfill along with the scale and filter materials.

The production of wet process phosphoric acid also generates a considerable quantity of acidic cooling water with high concentrations of phosphorus and fluoride. This excess water is collected in cooling ponds that are used to temporarily store excess precipitation for subsequent evaporation and to allow recirculation of the process water to the plant for reuse. Leachate seeping from both the cooling water and gypsum stockpiles is therefore a potential source of groundwater contamination and emission of inventory substances. Excess rainfall also results in water overflows from settling ponds.

Phosphoric acid used for the manufacture of higher value chemicals for use in detergents etc. are produced via the thermal treatment of elemental phosphorus and not directly from phosphate rock. Raw materials for the production of phosphoric acid by the thermal process are elemental (yellow) phosphorus, air, and water. Thermal process phosphoric acid manufacture, involves three major steps: (1) combustion; (2) hydration; and (3) demisting. Concentration of H_3PO_4 produced from thermal process normally ranges from 75 to 85 percent. This high concentration is required for high-grade chemical production and other non-fertiliser product manufacturing. Efficient plants recover about 99.9 percent of the elemental phosphorus burned as phosphoric acid.

A3.4 THE ORIGIN OF PHOSPHATE NORM

Phosphate rock of sedimentary origin contains low levels of naturally occurring uranium and other radionuclides of the ^{238}U decay series as an indigenous inclusion. The concentrations of radionuclides vary according to the origin and intrinsic composition of each deposit. Typical variations in the levels of radionuclides from the major phosphate producing areas are shown in Table 10. As a consequence of this natural variation, the exposure to the phosphate NORM varies considerably depending on the original source of the rock.

Table 10: Specific activities (Bq g^{-1}) and radium equivalent activities (Ra-eq) of natural radionuclides in phosphate rock from some major phosphate producing areas (Beretka & Mathew, 1996)

Country	Specific Activity (Bq g^{-1})			Radium equiv. act.
	Ra-226	Th232	K-40	Ra-eq (Bq g^{-1})
China	0.15	0.025		0.151
Christmas Islands	0.3	0.007		0.329
Israel	1.5-1.7*			1.5-1.7
Jordan	1.3-1.85*			1.3-1.85
Morocco	1.7	0.03		2.087
Nauru	0.85	0.007		0.855
Senegal	1.4	0.067		1.491
Togo	1.2	0.11		1.332
Tunisia	0.52	0.092	<0.1	0.648
Former USSR				
Kola (1)	0.04	0.091	0.17	0.181
Kola (2)	0.07	0.092		0.2
USA		0.016		
Florida (1)	1.6			1.622
Florida (2)	2.1			2.1
Florida (3)	1.0			1.0
Utah	1.85	0.03		1.891
Wyoming	2.3	0.01		2.314

*U-Values

A proportion of the radioactive species within the original rock is retained within the fertiliser and other products from the processing. Uranium and thorium are preferentially extracted with the phosphoric acid. Phosphogypsum on the other hand contains proportionately higher concentrations of radium. The increased concentration of radium within the phosphogypsum results from differences in the chemical and crystal growth behaviour of radium sulphate. These differences also result in the radium content being concentrated within the fine particle sized fractions of the gypsum.

The level of NORM found in the products from phosphate processing are dependent on the level within the original rock. The radiation level typically found within the products from the phosphoric acid process utilising Florida rock is summarised in Table 11 (Guimond 1979). [Note: The level of radioactive material is expressed as Becquerels per gram (Bq g^{-1}) for solids or Becquerel per cubic meter (Bq m^{-3}) for airborne species]. The concentrations of radioactive species within the products of

phosphate processing given in the table are high as a consequence of the levels in the parent rock source (refer to Table 10). Selection of a rock with lower inherent radioactive materials results in a proportionately lower level within the products.

Table 11: The distribution of radionuclides within the products generated from Florida rock

Material	Ra-226 (Bq g ⁻¹)	U-238 (Bq g ⁻¹)	Th-230 (Bq g ⁻¹)	Th-232 (Bq g ⁻¹)
Normal Superphosphate	0.7881	0.7437	0.666	0.0222
Diammonium Phosphates	0.2072	2.331	2.405	0.0148
Concentrated Superphosphate	0.777	2.146	1.776	0.0444
Monoammonium Phosphates	0.185	2.035	1.850	0.0629
Phosphoric acid (29% acid)	<0.037	0.9361	1.0471	0.1147
Gypsum	1.221	0.222	0.481	0.0111

A3.5 OCCUPATIONAL NORM EXPOSURE

Exposure to phosphate NORM in the working environment can occur via several routes during the extraction, processing and storage of finished products and by-products:

- dust exposure from the mining and transportation of the phosphate rock;
- processing of the rock;
- workplace exposure – dust and scale etc;
- products and by-products (gypsum);
- storage of the waste products (gypsum) and water run off from stockpiles.

The control strategies for the exposure to NORM via inhalation and ingestion are no different in principle from the control approaches recommended by occupational hygienists for the control of exposures to many other hazardous materials. As in other occupational health control matters, the hierarchy of control should be applied to mitigate the impact on those working in and around the area. As NORM is present as an unwanted contaminant in the parent phosphate rock, the options of elimination or substitution are not available.

Procedural controls apply to virtually all work potentially involving NORM contaminated items. Such a procedure might contain:

- working definitions of 'NORM contaminated' used for determining when the NORM procedure applies;
- a classification of tasks on NORM contaminated equipment on the basis of their potential for generating NORM dust;
- options for carrying out tasks by methods which generate a minimum of airborne dust;
- personal protective equipment by NORM task classification;
- methods for containing NORM, preventing the spread of contamination, and for collecting, storing and labelling waste; and
- steps to be taken if it is proposed to release a NORM contaminated item of equipment from site.

Personal protective equipment controls are likely to be embedded in the NORM procedure as described above. These controls will focus on preventing inhalation of dust through the use of appropriate effective respiratory protection against airborne NORM and on preventing the accumulation of NORM on clothing worn outside the immediate work area.

Achieving effective respiratory protection against any hazardous dust requires significant effort in the form of a formal respiratory protection program with elements including the selection, cleaning and maintenance of respirators, the training of respirator wearers, and the individual fit testing of respirators for each wearer. Australian Standard AS/NZS 1715 'Selection, Maintenance and Use of Respiratory Protective Devices' provides detailed advice on the content of an effective respiratory protective equipment program.

A3.6 MANAGEMENT OF WASTE AND RESIDUE

The use of waste material from the processing of phosphate ore is primarily concerned with the large quantities of gypsum produces as a by-product from the process. The normal practice is to stockpile the gypsum, although some small amounts are used for soil remediation. As a result of this stockpiling practice the worldwide reserves of by-product gypsum are therefore substantial.

Many scenarios have been evaluated both in Australia and overseas. These include use as a:

- soil conditioning additive in agriculture;
- substitute for natural gypsum in the manufacture of plaster wall board;
- substitute for natural gypsum as a setting control agent in cement;
- road base construction material.

While these alternatives have been considered, the availability of cheap, high quality natural gypsum has resulted in little use of the phosphogypsum produced. This is not the case in some European and Asian countries where gypsum is not as readily available. The use of phosphogypsum in these countries is not highly regulated and is often given a favourable outlook because of the other environmental effects of the stockpiled material and its leachates. As a result of its limited (practically nil) use in Australia, exposure to the radionuclides present in phosphogypsum is not considered a high risk.

While it is unlikely that these uses will become wide spread because of the abundant levels of natural gypsum, each will need to be considered on a case by case basis with particular attention paid to the source of the parent phosphate rock, which has a major influence on the level of radionuclides in the material.

A3.7 PUBLIC HEALTH

The major potential source of public exposure to NORM from the phosphate industry is via through the use of phosphate based fertilisers, which have become essential in agriculture. Phosphate fertilisers are produced and used worldwide to replenish natural nutrients depleted from soils because of farming and erosion. As a consequence of the radionuclides present in the phosphate rock from which it was derived, phosphate fertiliser and waste products contain part of the original radionuclide load. This results in the redistribution of radionuclides throughout the environment and potentially to the food chain.

It must be recognised that there is an indigenous NORM load and so the addition of any additional radionuclide containing material must be seen in this context. The

potential radiological importance of fertilisers in the environment in a specific country is dependent on the concentration of radionuclides in the source rock used to manufacture the fertiliser. The choice of rock source can therefore have a significant effect on any potential exposure to NORM.

Australia takes the majority of its phosphate rock from nearby Nauru and Christmas Island, both of which have significant guano deposits. Guano deposits have the lowest level of NORM (relative to other sources of natural phosphate); as a consequence the concentration of radionuclides is significantly lower than, for example, in phosphates used in the United States where NORM levels are several times higher.

The levels of radionuclides within the phosphate fertilisers are quite small and the impact on a local area is limited by the application to crops and pastures. The application of phosphate based fertilisers provides a typical phosphorus loading in the order of a few kilograms per hectare per year. At normal rates of application there is no significant increase in the overall uranium and thorium levels in soil and consequently individual doses from their use are not enhanced above normal background (Cooper, 2005).

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ARPANSA Radiation Protection Series Publications

Radiation
Protection
Series
No. 15

ARPANSA has taken over responsibility for the administration of the former NHMRC Radiation Health Series of publications and for the codes developed under the *Environment Protection (Nuclear Codes) Act 1978*. The publications are being progressively reviewed and republished as part of the *Radiation Protection Series*. All of the Nuclear Codes have now been republished in the *Radiation Protection Series*.

All publications listed below are available in electronic format, and can be downloaded free of charge by visiting ARPANSA's website at www.arpansa.gov.au/Publications/codes/index.cfm.

Radiation Protection Series publications are available for purchase directly from ARPANSA. Further information can be obtained by telephoning ARPANSA on 1800 022 333 (freecall within Australia) or (03) 9433 2211.

- RPS 1 Recommendations for Limiting Exposure to Ionizing Radiation (1995) and National Standard for Limiting Occupational Exposure to Ionizing Radiation (republished 2002)
- RPS 2 Code of Practice for the Safe Transport of Radioactive Material (2008)
- RPS 2.1 Safety Guide for the Safe Transport of Radioactive Material (2008)
- RPS 3 Radiation Protection Standard for Maximum Exposure Levels to Radiofrequency Fields – 3 kHz to 300 GHz (2002)
- RPS 4 Recommendations for the Discharge of Patients Undergoing Treatment with Radioactive Substances (2002)
- RPS 5 Code of Practice and Safety Guide for Portable Density/Moisture Gauges Containing Radioactive Sources (2004)
- RPS 6 National Directory for Radiation Protection – Edition 1.0 (2004)
- RPS 7 Recommendations for Intervention in Emergency Situations Involving Radiation Exposure (2004)
- RPS 8 Code of Practice for the Exposure of Humans to Ionizing Radiation for Medical Research Purposes (2005)
- RPS 9 Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005)
- RPS 10 Code of Practice and Safety Guide for Radiation Protection in Dentistry (2005)
- RPS 11 Code of Practice for the Security of Radioactive Sources (2007)
- RPS 12 Radiation Protection Standard for Occupational Exposure to Ultraviolet Radiation (2006)
- RPS 13 Code of Practice and Safety Guide for Safe Use of Fixed Radiation Gauges (2007)
- RPS 14 Code of Practice for Radiation Protection in the Medical Applications of Ionizing Radiation (2008)
- RPS 14.1 Safety Guide for Radiation Protection in Diagnostic and Interventional Radiology (2008)
- RPS 14.2 Safety Guide for Radiation Protection in Nuclear Medicine (2008)
- RPS 15 Safety Guide for Management of Naturally Occurring Radioactive Material (NORM)

Safety Guide
Management of Naturally Occurring Radioactive Material (NORM)

- RPS 16 Safety Guide for the Predisposal Management of Radioactive Waste (2008)
- Those publications from the NHMRC *Radiation Health Series* that are still current are:
- RHS 3 Code of practice for the safe use of ionizing radiation in veterinary radiology: Parts 1 and 2 (1982)
- RHS 8 Code of nursing practice for staff exposed to ionizing radiation (1984)
- RHS 9 Code of practice for protection against ionizing radiation emitted from X-ray analysis equipment (1984)
- RHS 10 Code of practice for safe use of ionizing radiation in veterinary radiology: part 3-radiotherapy (1984)
- RHS 13 Code of practice for the disposal of radioactive wastes by the user (1985)
- RHS 14 Recommendations for minimising radiological hazards to patients (1985)
- RHS 15 Code of practice for the safe use of microwave diathermy units (1985)
- RHS 16 Code of practice for the safe use of short wave (radiofrequency) diathermy units (1985)
- RHS 18 Code of practice for the safe handling of corpses containing radioactive materials (1986)
- RHS 19 Code of practice for the safe use of ionizing radiation in secondary schools (1986)
- RHS 21 Revised statement on cabinet X-ray equipment for examination of letters, packages, baggage, freight and other articles for security, quality control and other purposes (1987)
- RHS 22 Statement on enclosed X-ray equipment for special applications (1987)
- RHS 23 Code of practice for the control and safe handling of radioactive sources used for therapeutic purposes (1988)
- RHS 24 Code of practice for the design and safe operation of non-medical irradiation facilities (1988)
- RHS 25 Recommendations for ionization chamber smoke detectors for commercial and industrial fire protection systems (1988)
- RHS 28 Code of practice for the safe use of sealed radioactive sources in bore-hole logging (1989)
- RHS 30 Interim guidelines on limits of exposure to 50/60Hz electric and magnetic fields (1989)
- RHS 31 Code of practice for the safe use of industrial radiography equipment (1989)
- RHS 34 Safety guidelines for magnetic resonance diagnostic facilities (1991)
- RHS 35 Code of practice for the near-surface disposal of radioactive waste in Australia (1992)
- RHS 36 Code of practice for the safe use of lasers in schools (1995)
- RHS 38 Recommended limits on radioactive contamination on surfaces in laboratories (1995)

Regulatory Authorities

Where advice or assistance is required from the relevant regulatory authority for radiation protection, it may be obtained from the following officers:

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For after hours emergencies only, the police will provide the appropriate emergency contact number.

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Index

A

abrasives 16, 50, 93
acceptable risk 76
access times 83
acidic cooling water 104
acidulation 102
action level 40
activity concentration 3, 5, 7, 10, 12, 17,
35-40, 46, 58, 82, 88, 90, 93, 96-99
adequate ventilation 49, 50, 95
air filters 82
air-arc gouging 84
airborne NORM dust 18, 26, 53, 56, 84,
87, 106
ALARA principle 30, 31, 98
alkaline 99
alpha radiation 21
alumina... 4, 10-11, 15, 18, 38, 91-93, 95-96,
99
aluminium
 hydroxide 94-95
 metal 10, 91
 production 91
ammonium phosphates 11, 102, 104
animal feeds 11, 102
approval 34, 43, 45, 57, 99
assessment... 6-7, 21, 29-30, 33-37, 40-48,
52-54, 56-59, 77, 94, 96-99
Australian Standard 85, 107
authorisations 43
awareness 5

B

backfill 12, 32
barium compounds 79
barriers 51-52, 83
baseline assessment 45
bauxite 4, 6-7, 10-11, 30, 38, 59, 91-99
bauxite/aluminium 6, 10, 59
Bayer process 10, 91-92, 94-95, 98-99
Best Practice Regulation Handbook 47
beta radiation 2, 4, 87
binding agent 50
biodiversity 34
blister copper 13
boehmite 91, 93
bottom ash 14-15, 20, 30
building industry 4-5, 9, 12, 20, 22, 24,
29-30, 36, 39, 45, 59, 108
bulk material 23, 27, 46, 97
bunded areas 50
bunds 50-51

burial 29, 31-32, 45, 51
butane 9, 78-79, 80
by-product 4, 7, 11, 21, 24, 58, 106-108

C

calcined bauxite 93, 95
cap rock 93
caustic soda 10, 94
cement 12, 14-15, 32, 89, 107
ceramic glaze 4, 18, 28
ceramic pigments 28
characterisation of materials 58
chemical hazard 51
chemical separation 26
chemicals 24, 47, 56, 104
clarification vessels 94
classification 84, 106
clean 14-15, 22, 26, 29, 50, 82, 84-86,
88-89, 107
clearance 97
close-out requirements 46, 56
coal 4, 14-15, 23, 38, 51
coal-fired power station 23, 51
combustion 14, 38, 104
commodities 4-5, 27, 35
compensating factors 51
compliance 33, 35, 43, 48, 52, 97, 98
Compliance Testing 97
computer model 33, 44, 46, 53, 55-58
concentrate.. 4, 12-14, 16, 19, 34, 36, 38-39,
90, 94, 105-106
concrete extender 20, 30, 45
condensate 79
conditional exemption 42, 58
contaminant ... 9, 14, 19, 21, 57, 79, 80, 84,
106
contaminated
 clothing 50
 equipment 26, 50, 82, 84
 site 5, 7
contamination control 85-86, 89
contingency plans 53
control measures 27, 52, 84, 106
copper 4, 12-13, 38
copper iron sulphides 12
cross-border issues 35
crude oil 10, 78-80, 85
crushed ore 94

D

deflocculants 11, 102
demisting 104
deposition 23, 26, 95, 98

de-scaling..... 95
detergents..... 11, 102, 104
di-calcium phosphate..... 102
digester 94
digestion 10, 94, 95
dilution5, 45
discharge..... 14, 16-17, 26, 49, 51-53
dispersal 6, 45, 51-52
disposable coveralls82, 85, 89
disposal.....5, 8, 11, 14, 16-19, 29-32, 41,
44-45, 50-51, 58-59, 88-89, 96
dose assessment43, 49, 52-53, 58
dose limit31, 36, 39, 42
dose rate meters 52
double strength fertiliser 104
downstream processing 6, 10, 16-17, 26,
82, 89
dredging.....16, 24, 26
dry
material..... 51
separation.....26, 50
weight97
dust15-16, 18, 22, 24-28, 37-39, 45, 47,
50-53, 82, 85-86, 93-95, 106-107
dust mitigation methods..... 52
duty cycle.....81

E

effective dose 37, 39, 83
elemental phosphorus..... 103-104
elimination 84, 106
encapsulation 32
enclosed cleaning equipment 84
end-use 98, 99
engineered barriers 31, 51
environmental impact. 5, 23, 29, 31-32, 37,
40, 44-45, 47, 49, 52-53, 55
environmental impact assessment .. 23, 29,
40, 44-45, 47, 52-53, 55
environmental variables 53
erosion29, 107
estimated doses 45
ethane9-10, 78-80, 82, 85, 89-90
exclusion.....6-8, 35, 97
exemption..... 5-8, 34-43, 46, 52, 96-99
existing operational sites 56
export markets 102
exposure3-7, 10, 18-40, 42-47, 49-52,
58-59, 82-87, 90, 93, 95, 105-108
exposure pathway..... 3, 7, 21, 23, 27-29, 31,
45, 47, 50
exposure time 28
external exposure20, 23-26, 28-29, 45,
47, 50-51
extraction...4, 6, 9, 12-14, 16-17, 20, 24, 26,
36, 38, 44, 46, 50, 56, 58, 91, 93, 102,
106

F

feedstock..... 10, 15, 38, 80, 89-91, 92
fertiliser ... 4, 11-12, 17, 23, 28, 38, 102-105,
107-108
field.....9, 78-81, 85, 88, 90
filter 10, 12, 18-19, 80, 87, 94, 104
fire43, 53
fit testing 85, 107
flood.....43, 53, 79
flotation 13-14
flow rates 82
flue gas..... 14
fluid flow lines..... 80
fluid mixture 79
fly ash 4, 14-15, 20, 30
food chain..... 23, 45, 47, 107
formation water 9, 26, 78-79, 88-89
fume..... 13, 15, 18, 22-24, 37, 39
future land use 45, 47

G

gamma 4, 10, 23, 25, 28, 37, 39, 81-83,
93-95, 98
gas stream 10, 15, 79
gas-related NORM82-83, 87
geometric effect.....24
geometry..... 20, 24, 56
gibbsite 91, 93
glass bead blaster 84
gloves..... 82, 85, 89
goethite.....93
good practice 30, 83
graded approach to regulation 7, 33, 35,
38-40, 58
green liquor 94
grinding..... 10, 29, 50, 84, 94
gross alpha concentrations.....95
groundwater... 19, 23, 29, 31, 51-53, 98-99,
104
guano102, 108
gypsum 11, 20, 30, 103-107

H

habitat degradation.....30-32
half-life 1-3, 22, 27, 49, 80
heat exchangers.....80, 82, 84
heavy metals.....15, 19, 56, 79
hematite93
HEPA filters 84
hierarchy of control..... 84, 106
high rainfall events 51
higher analysis phosphate fertilisers.....102
holding tanks..... 94
homeostatic process.....3
hydrated alumina.....10, 94
hydration.....104

hydrocarbon 9, 78-79, 85, 88
hygiene..... 23, 50, 87

I

ideal site criteria..... 51
ilmenite.....6, 11, 14-17, 96
impact assessment ... 44, 46, 48, 54-55, 95, 99
impaction points 82-83
impeller..... 10, 50, 80-82, 84
industry 6-7, 9-13, 15-17, 20, 35-37, 39-40, 46, 49-50, 58, 78, 83-89, 91-92, 94-95, 102
ingestion .. 21, 23, 25-26, 28-29, 50, 83-84, 106
ingress of groundwater 50
inhalation 4, 20-22, 25-29, 45, 47, 50, 83-84, 86, 93-94, 106-107
initial assessment..... 52-53
injection..... 9, 32, 79, 88
inspection 82, 84
internal exposure 21-22, 25, 83
International Atomic Energy Agency (IAEA).....9-10, 18, 20, 24, 27-28, 32-33, 35-37, 39-40, 44-46, 51-53, 56-57, 78, 81, 83, 97, 98
international experience 9, 40
involvement of stakeholders..... 32, 58
ionizing radiation 32, 76
irrigation..... 23, 86
iterative improvement 44, 54-55, 57

L

land slippage..... 43, 53
land use..... 29, 99
landfill... 5, 12, 14, 17, 19, 23, 29-30, 32, 59, 98, 104
land-spreading 19
lateritic deposit..... 93
leachate.....96, 104, 107
leaching..... 12, 14, 23, 29, 31, 51-52, 95
lead 1, 3-4, 12, 23, 26, 28, 31, 34-35, 39-40, 42, 50-51, 58, 79, 81, 83
leakage 29, 51
legacy site 7, 57, 58
levels of contamination 53, 57
licence requirements..... 41, 52
lime 19, 94, 96
liners 51-52
local infrastructure..... 78
loose material 51, 82, 83

M

maintenance activities 50, 82, 86
management of NORM waste..... 44, 54

measured radionuclide concentrations..33, 53
measurement 37-39, 41, 53-54, 87, 89, 93-94, 95
member of the public.....53
metal defects 84
methane.....9, 78-80, 85
Mg-Th alloy 28
milling 13, 18
mineral 3-4, 6-9, 11, 13-22, 24-26, 29, 34-35, 39, 41, 50, 58, 79, 91, 94-97, 102-103, 108
mineral extraction..... 6-7, 21, 24-26
mineral sands..... 4, 6, 16, 21, 34, 58
mineralisation 13, 96
minimisation of waste.....44
Mining Code..... 4, 6, 34, 43
Mining Safety Guide 6, 34, 43
mitigation
 measures..... 49, 52
 procedures..... 49
mobile.....26
model..... 44, 46, 53, 55-56
model predictions56
monazite 11, 15-16, 36, 38, 96
monitoring requirements 41, 44, 52-53, 56, 86
mono/di-ammonium phosphate.....102
mud residue 11, 30, 91, 93-94, 96, 97
mud thickeners 94

N

natural background radiation . 4, 11-12, 47, 98
natural material35, 46
near surface disposal23, 30, 51, 89
Near Surface Disposal Code31, 45, 51
nickel 96
non-radiological issues56
NORM
 contaminated..... 82, 84, 86-89, 106
 contaminated waste 82
 dust..... 84, 106
 Management Plan 29, 43, 44, 46, 49, 58
 procedure..... 84-85, 87, 106-107
notification 36, 40

O

occupancy..... 28, 98
occupational health and safety 33, 44
occupational hygienists 84, 106
ocean disposal 88-89, 98
off-gases13, 15
offshore.....9, 79, 81, 88
oil and gas industry.....6, 10, 78, 82, 84-85, 87-88, 90
oily sand 26, 82-83, 89

onshore 9, 88-89
 open pit 14, 24-25, 103
 operational issues 7, 49, 58, 82
 operational precautions 82
 operator 33-35, 40-41, 43-46, 52, 56-58,
 86-89, 96-98
 optimisation .. 30, 32-33, 35, 37, 41, 45, 47,
 51, 58
 ore ... 11-17, 21-23, 25-26, 34, 36-37, 56, 91,
 92, 94-98, 102
 overburden16, 25, 93
 overflow 29, 104

P

parent phosphate rock 106-107
 particle 21-22, 29, 105
 particulate14, 16, 51
 past operations 7, 57-58
 personal monitoring 52, 87, 97, 98
 personal protective equipment ...51, 84, 85,
 106, 107
 phosphate
binding99
chemicals 11, 102
fertilisers102-103, 108
industry 6, 52, 107
ore 4, 11-12, 102, 107
processing 105
rock 4, 11-12, 102-108
 phosphogypsum 4, 11-12, 20, 30, 38,
 103-105, 107
 phosphoric acid11-12, 38, 102-106
 phosphorus 11, 37-38, 96, 102-104, 108
 physical separation 80
 planning49, 51, 54, 58, 83-84
 plasterboard5, 12, 20, 30, 45, 107
 plastic sheets 82
 points of impaction 80
 polonium 1, 3-4, 22, 51
 polyphosphates103
 potassium-40 1
 precipitation .10, 19, 39, 79-80, 82, 94, 104
 preliminary assessment 54
 pressure equipment81
 procedural controls 84, 106
 process
plants50
stream52
water11, 96, 104
 processing 4, 6-10, 12-13, 16-18, 20-21,
 24-26, 29, 31, 34, 36, 40-41, 44, 47,
 51-52, 56, 58, 78-80, 82, 85, 90-92,
 94-99, 103, 105-107
 produced fluids 9, 79
 product 1-2, 4-7, 9-18, 21-22, 24-25,
 27-29, 4, 36, 38, 46, 58, 78, 80, 83, 85,
 88, 90, 93, 95, 98-99, 102, 104-107
 production operations9, 79, 82-83

propane9, 78-80
 protection optimisation 97-99
 public health 5, 32, 85, 107
 public perception 32, 58
 pump10, 19-20, 26, 50, 79-82, 84-85,
 89, 94

R

radiation level 47, 81-83, 87, 105
 radiation protection 5-8, 18, 27, 30, 35,
 38-39, 41, 43, 45, 52-53, 88
 radioactive decay...1-2, 4, 10, 17, 22-23, 28,
 76
 radioactive equilibrium17-18, 80
 radiological
issues7, 20-21, 27, 49, 56, 58
risk 19, 20, 22, 30-31, 40, 50, 59
 radionuclide ..1-4, 6, 9, 11-15, 17-26, 28-29,
 31, 34-36, 39, 43, 46, 50-53, 56, 58, 76,
 78, 81-83, 87-88, 91-93, 95-99, 105-108
 radium 1, 4, 9-11, 19-20, 22, 78-80,
 82-83, 95, 105
 radon ..1, 4, 9-10, 20, 22, 25-27, 29, 37, 40,
 45, 47, 49-50, 53, 79-83, 85, 88, 90,
 93-95, 98
 recycling of scrap metal45
 reference level33, 53
 register of operations42
 registration 42, 43
 regulation 5-7, 27, 33-39, 41, 43, 46-48,
 54, 58, 88, 98
 Regulatory Authority 33-34, 38, 40, 46,
 56, 111
 regulatory impact statement 48
 remediation... 5, 7, 11, 14, 46-47, 52, 56-58,
 93, 99, 107
 repair work 84
 reporting requirements 35, 42, 43
 residence time 22, 27, 80
 residue.. 4-7, 9-12, 14, 17-24, 26-27, 29-33,
 35-36, 38, 41, 43, 45, 51, 54, 58-59, 85,
 91-99, 107
 respiratory protection 84-86, 107
 responsible person 37, 76
 restricted access 31, 50, 51
 resuspension22, 25, 28-29, 50
 reuse 32, 84, 86, 104
 risk1-3, 5, 24-27, 29, 31-35, 37, 39-42,
 49, 52-56, 58, 76-77, 83-84, 86, 88, 90,
 98, 107
 roadbase29-30, 59
 roasting95
 run off106

S

safety assessment 32, 40, 44, 47, 53
 sampling 39, 86, 87

sand residue stream 91, 95
scale 12, 20, 22, 26, 39, 79, 82-83, 87,
89, 104, 106
scrap metal 18-19, 30, 86
screening assessment 35, 37, 40-43, 77
scrubbers 52
sealed radioactive source 77
secondary containment 50-51
secular equilibrium 1, 76, 97
seepage 50, 98
self-absorption 28, 87
setting control agent 107
settling pond 11, 14, 96, 104
shielding 23, 28, 52
site-specific data 56
siting 51
skin 21, 23-24, 26, 28, 50, 83, 85
 contamination 85
 exposures 83
slag 4, 13-15, 30, 32, 36, 38
sludge .. 19-20, 26, 29, 38-39, 82-83, 88-89
slurry 14, 16-17, 24, 26, 29, 94, 95
smelting 3-4, 11-13, 23, 38, 51, 89, 91
sodium aluminate 94
sodium hydroxide 94
soil conditioning 11-12, 23, 30, 99, 107
solid residue stream 11, 91
solvent extraction 11-13
specific activities 105
spillage 50-51
splashing 25-26, 28
spraying 50-51
stack 14-16, 51
stockpile 12, 29, 39, 50, 89, 104, 106-107
storage 29, 31, 44, 58-59, 80, 85, 95,
98, 106
substitution 84, 106
sulphuric acid 11-12, 17, 103
sumps 50
superphosphate 11, 102, 104, 106
suppression of dust 51
surface contamination 86, 87
surface water 23, 45, 47, 52-53

T

tailings 4-5, 12-14, 16, 29, 32, 45, 51
tantalum 4, 13-14, 36
thermal process 103-104
thorium 1, 4, 10-18, 28-29, 34, 36, 39,
78, 105, 108
thoron 22, 78, 83, 95

time management methods 52
time-averaged 97
tin 4, 13-14, 38
titanium 15-17, 95
transfer points 50
transport 7, 17, 22, 26-28, 32, 46, 51-52,
56, 58, 80, 85, 94, 98, 106
Transport Code 27, 46
tri-calcium phosphate 102
triple superphosphate 102

U

unconditional exemption 40-42
underground mining 20, 24-25, 37
underground work areas 22, 50
undissolved solids fraction 95
UNSCEAR 3, 47
upstream 78, 85
uranium 1, 4, 6, 9-19, 21, 28, 34, 39, 58,
87, 105, 108

V

valves 10, 80, 82, 84-85, 89
vanadium 96
ventilation rate 22, 49
volatilisation 3-4, 13-15, 18, 23, 39, 51

W

warning signs 83
washing 10-11, 23, 50, 94, 96, 98
waste 4-5, 8, 11-20, 23-25, 30-32, 34, 41,
43-45, 51, 54, 56, 81-82, 84, 86, 88-90,
104, 106-107
 disposal 5, 45, 56, 89-90
 rock 24-25, 30, 32
 rock pile 24
water sprays 50
welding 4, 29, 38, 84
wet separation 14
work areas 29, 50
work categories 98
worker ... 4, 7, 10, 20, 26-28, 36-37, 40, 49,
50, 52-53, 87, 96-98

Z

zinc 12, 96
zircon 6, 14-16, 18, 38
zirconia 16, 18, 37-38