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January 2013
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REVISIONS TRACKING TABLE

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<td>MSP</td>
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<td>ROM</td>
<td>Run of Mine</td>
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</tr>
<tr>
<td>TiO₂</td>
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</tr>
<tr>
<td>TLD</td>
<td>Thermoluminescent Dosimeter</td>
</tr>
<tr>
<td>UN</td>
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EXECUTIVE SUMMARY

World Titanium Resources Pty Ltd is currently involved in the evaluation of the heavy mineral deposit located in the Toliara region of the Malagasy Republic.

The project will involve the mining, processing and beneficiation of a heavy minerals sands ore body containing minerals with elevated concentrations of the radionuclides of the uranium and thorium decay chains. The uranium and thorium radionuclides and their decay products are concentrated in the monazite and zircon minerals in the dune belt.

As the monazite and zircon minerals are progressively concentrated through the mining and minerals process, the uranium and thorium concentrations of some process flows will increase.

The terrestrial gamma dose rates and radon gas concentrations on the mine lease appear to be significantly higher than the UNSCEAR world average values. The enhanced radionuclide concentrations in the ore body and the mining and processing operations will result in the radiation exposure of workers and, possibly, members of the public. The process data indicates that workers who will spend long periods of time performing tasks in close proximity to the zircon and monazite circuits and the associated tails could receive elevated annual gamma doses. Additional exposure to workers may arise as a result of airborne dust associated with these materials.

The current radiological data indicates that workers and, possibly, members of the public will be exposed to ionising radiation at levels that need to be controlled. The waste streams from the MSP may be significantly enhanced in radioactivity and will require to be disposed of in a manner that will ensure the long term protection of the public.

The report provides an overview of the positive and negative radiological impacts associated with the project. The report also makes recommendations regarding the prospective radiological assessment of worker and public doses and the design and engineered controls to be considered in order to keep doses as low as reasonably achievable.
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1. INTRODUCTION

1.1 The Project Area

The Toliara heavy mineral deposit was discovered in 1999 by Madagascar Resources NL (MRNL). World Titanium Resources Pty Ltd (WTR) is currently involved in the evaluation of the heavy mineral deposit located in the Toliara region of the Malagasy Republic (Refer to Appendix 1).

The zone of mineralisation can be divided into two areas:
- The southern Ranobe deposit
- The northern Manombo-Morombe deposit

These two areas are together designated the Toliara Sands Project (TSP). The primary focus of the project is on the exploitation of the Ranobe deposit. The northern zone of mineralisation extends approximately 100km north from the Manombo River to Morombe.

The Ranobe deposit contains a number of heavy minerals of economic interest such as magnetite, ilmenite, rutile and zircon. These minerals are globally required as raw material feedstocks for several industries (e.g. pigments and ceramics).

It is well known that heavy mineral sands contain radionuclides of the uranium and thorium decay chains which emit ionising radiation. As the heavy mineral (HM) is concentrated, the radionuclide concentrations also increase resulting in higher levels of radiation exposure to workers in close proximity to the material.

The project will involve the mining, processing and beneficiation of the heavy minerals sands containing minerals with elevated levels of the radionuclides of the uranium and thorium decay chains. The recoverable mineral deposits extend from the surface down to a depth of 10-30 metres.

Although the radioactive materials are of natural origin, the mining and processing activities may give rise to enhanced concentrations of radioactivity in the plant process and tails streams and may theoretically result in additional exposure pathways to human populations living near the site.

The mine lease is situated approximately 40 km north of the town of Toliara (Tulear) in the coastal region of southwest Madagascar. The study area is bounded to the north by the Manombo River which drains the limestone plateau which lies to the east of the mine lease area. The coastal dune belt lies approximately 15 km to the east of the mine lease area.

There are numerous small villages located in the lowlands to the west of the mine lease area between the coast and the mine lease area. A number of hotels are found along the coastal dune belt. The R9 road from Toliara runs in a northerly direction approximately 10-12 km to the west of the mine area.

There is a hot wet season from October to May and a cool dry season from June to September.

The south west coast is characterised by a semi arid climate with limited fresh water resources. Most of the population is reliant on groundwater from shallow wells exploiting the groundwater aquifers. The Manombo River does not flow continuously throughout the year; the only reliable water sampling point is located at the irrigation barrage which is approximately 25 km upstream from the coast.

Freshwater springs are located at Ranobe and at various points along the coast north and south of the La Plage hotel. On the northern site of the Manombo River a large spring emerges from the base of the limestone massif at Amboboka (referred to as the Ranozaza Spring), this spring feeds an extensive crop irrigation system.
The Ranobe ore body which lies to the south of the Manombo River is located in an area that to a great extent is deforested and uninhabited, but it is located close to forests with a high conservation value.

1.2 Geology and Mineralisation of the Deposit Area

The mineral deposit occurs in an ancient quaternary dune at the base of the limestone fault scarp. The deposit is situated immediately west of a prominent north-south trending escarpment, with tertiary limestone to the east and unconsolidated sand sediments to the west. The deposit sits against the eastern side of a large sand dune which extends from just east of the current coastline up to the limestone escarpment in places. The limestone extends beneath the mineralised ore body.

The Ranobe mine project area has a north south orientation and is approximately 16 km from north to south and varies in width from 1-4 km. The mine lease area is bounded to the east by a limestone escarpment and uplands. The mine lease area is located 80-160 metres above mean sea level. The drilling program has confirmed that the mineralised sand dune system lying to the west of a limestone cliff is around 12 km long, 1-2 km wide and 2-50 metres thick. Drilling has clarified the stratigraphy of the mineralised zone (Refer to Appendix 2), which comprises three units, that can be distinguished on colour and clay content as follows:

- Upper Sand Unit: 10-30 metres thick.
- Intermediate Clay Sand Unit: up to 15 metres thick.
- Lower Sand Unit: up to 30 metres thick.
- Limestone basement

All of the layers contain heavy minerals, but the grades appear to diminish on the western and southern sides of the deposit.

The upper surface of the resource boundary is the natural surface in all locations i.e. it appears that there is little or no un-mineralised overburden.

The lack of an un-mineralised overburden has important implications with regard to the gamma dose rates found above the soil surface. Since the mineralisation extends to the surface the enhanced radionuclide concentrations in the ore body will result in enhanced levels of gamma radiation above the soil.

The mineralisation in the Upper Sand layer is currently favoured for mining due to its high grade, high tonnage, low slimes content and relatively high HM content.

1.3 Project Overview

The current plan is to mine the Ranobe deposit for saleable minerals of commercial significance including ilmenite and a rutile/zircon concentrate.

At this stage of the project a number of options are being considered. This assessment is made using the following assumptions.

The unconsolidated sands will be excavated by a dry mining method using a frontend loader with the ore being pumped over land to a stationary Primary Concentrator Plant (PCP). The Mineral Separation Plant (MSP) will be located west of the mine lease area. Construction labour accommodation will be located close to the mine site; however operational staff will be bussed from Toliara. There will be approximately 400 people living on site during the construction phase. The approximately 340 people employed during the operating phase will be spread across
continuous shifts, plus a day crew of administrative and maintenance staff, with fewer than 250 people on site at any given time.

There is no overburden and blasting will not be required. As the mining void advances, the area behind will be backfilled with tailings material from the PCP and MSP. The MSP products will be transported by road to an export facility located at the coast. The products will then be exported by ocean-freight to their final destination.

The heavy minerals in the ore will be separated from the barren sands in the PCP. The separation process in the PCP is purely a physical process that produces a heavy minerals concentrate (HMC), and does not alter the physical form of the individual minerals.

Trommel screen oversize material from the PCP will be deposited directly into the mine void. A portion of the water used to slurry the ore overflows the plant surge bin and carries a portion of the fine material (commonly referred to as slimes) found in the upper zone of ore, to a thickener. The water recovered from the thickener is recycled into the process water system. Thickened slimes is pumped to the coarse tails pumping system, where it will be mixed with coarse sand tails and pumped to the required deposition site.

HMC will be pumped from the PCP to a stockpile area outside the MSP.

At the MSP the HMC will be processed using a combination of mineral processing techniques commonly found in the heavy minerals industry. Heavy mineral species are separated from one another by exploiting their inherent differences in magnetic susceptibility; surface electrical conductivity; and particle density. While the individual mineral products have strictly controlled chemical specifications, the actual grains of sand are unaltered from their original state. Some heavy minerals from the HMC have no commercial value, and are returned to the mine backfill.

The MSP predominantly consists of dry separation processes, with the incoming HMC being dried in a fluidised bed dryer. Any dust generated in the dryer will be collected and disposed of along with other MSP reject material. The MSP separation equipment is individually enclosed, and connected to a reticulated dust collection system, to control worker exposure to airborne dust inside the plant. The collected dust is removed by means of a bag house, and stored in a closed bin until ready for mixing with water and pumping to the mine backfill with other MSP rejects and the main sand tailings flow from the PCP.

Some minerals in the HMC contain thorium and uranium in higher concentrations than others, and most of these minerals will be returned to the mine backfill. Airborne dust inside the MSP building is also expected to contain radioactive material in various concentrations, and its levels will be controlled to maintain worker exposures below statutory limits and as low as reasonably achievable. Temporary storage of MSP sand rejects can be safely carried out in open stockpiles, with wind breaks and water sprays being used to prevent windblown sand losses, however the dust collector rejects will be stored in enclosed bins until the active disposal site is available to accept the dust as a wetted product.

Aside from the non-magnetic circuit spiral tails, the discard streams from the MSP processing equipment are dry. The dry reject streams will be slurried and blended with the non-magnetic circuit spiral tails streams at the MSP. The current project concept allows for blending of the MSP tailings stream with the PCP final tailings for final pumping back to the mining void.

The underflow from the thickener will be pumped to the mining void and deposited with the sand tailings.

All products will be exported from Madagascar.
1.4 Radiological Implications of the Project

1.4.1 The Presence of Radioactive Materials in the Heavy Mineral Deposit

Heavy minerals deposits are enriched by geological processes in the naturally occurring radionuclides of the uranium and thorium decay chains. The radioactivity is primarily associated with specific minerals within the deposit (e.g., especially monazite and to a lesser extent, zircon). The potential radiation hazard increases with the concentration of these minerals in the beach sands. The project will therefore involve the mining, processing and beneficiation of a heavy minerals sands ore body containing minerals with elevated levels of the radionuclides of the uranium and thorium decay chains.

1.4.2 The Radiological Implications of the Mining and Processing Operations

Although the radioactive materials are of natural origin, the mining and processing activities will concentrate the ore, giving rise to further enhancement of the concentrations of radionuclides in the plant process, stockpiles and certain reject streams. The reject streams will include radioactive sands, dusts and possibly also waters containing radioactive suspended solids. The presence of radionuclides in such ores has the following major radiological implications:

- Occupational exposures of workers.
- Potential exposure of members of the public living nearby.
- Waste management and environmental impact issues.

The main exposure pathways of workers and members of the public living near to the site comprise the following:

- External gamma irradiation from the gamma emitting radionuclides.
- The inhalation of radioactive radon gas.
- The inhalation of radioactive dusts containing long lived alpha emitters of the uranium and thorium decay chains.

In addition, the operational areas may experience accumulation of reject materials and product resulting in elevated radiation levels around the processing facility, along the transport routes and at the export facility.

1.4.3 The Importance of the Pre-operational Baseline Background Radiation Surveys

The naturally occurring undisturbed levels of radioactivity will be assessed prior to any mining and processing operations in order to compare these undisturbed values with the values occurring during the mining and processing phase when the mineral body is exposed, mined, transported and exported. In addition, these undisturbed levels will be quantified in order to provide a natural radiation benchmark for use during rehabilitation and mine closure activities.

1.5 Terms of Reference

The terms of reference for this specialist study are discussed in Chapter 2 of this report.

1.6 Structure of the Report

Chapter 1: Introduction. This section provides a brief overview of the project.

Chapter 2: Purpose and scope. This section summarises the purpose and scope of the assessment.
Chapter 3: An overview of natural background radiation. This section provides a brief overview of natural background radiation sources.

Chapter 4: Naturally occurring radioactive materials associated with heavy minerals. This section provides an overview of naturally occurring radioactive materials in the mining and processing of heavy minerals.

Chapter 5: An overview of the Dose Limitation System. This section provides an overview of the international system of dose limitation recommended by the ICRP and IAEA.

Chapter 6: An overview of IAEA guidelines specific to the exploitation of NORM materials. This section provides a brief review of the IAEA safety standards and guideline documents on the mining of NORM materials.

Chapter 7: An overview of the radiological characteristics of the Toliara Sands ore body. This section provides a summary of the radiological characteristics of the ore body.

Chapter 8: An overview of the projected radiation hazards arising during operations. This section identifies the potential radiological exposure pathways to both workers and the public which may result from the proposed mining and processing activities.

Chapter 9: Provides an overview of the process reject streams management options.

Chapter 10: An overview of the Radiation Protection Programme. This section provides an overview of the components of the radiological protection programs for workers and the public that will be required during the mining and minerals processing operations.

Chapter 11: Engineered controls over the radiation exposures of the workers and the public. This section provides generic recommendations regarding the engineered controls that can be used in the plant design to keep doses as low as reasonably achievable.

Chapter 12: Administrative controls over the radiation exposures of the workers and the public. This section provides generic recommendations regarding the administrative controls that can be used during operations to keep doses as low as reasonably achievable.

Chapter 13: The anticipated radiological impacts of the project. This section describes the anticipated negative and positive radiological impacts during the construction, operation, decommissioning and mine closure phases and how these impacts should be managed and incorporated into the engineering and administrative specifications for the mine.

Chapter 14: Conclusions. This section summarises the main conclusions of the report.

Chapter 15: Recommendations. This section provides recommendations arising out of the specialist report.

Chapter 16: References.

Appendices: The appendices provide detailed information on aspects referred to in the main text as well as maps and plans and other information relevant to the specialist study.
2. PURPOSE AND SCOPE OF THE ASSESSMENT

2.1 Purpose

The purpose of the study is to examine the radiological aspects of the Toliara Sands project. The ore body contains minerals enhanced in uranium and thorium, which will be concentrated and extracted during mining and processing. In addition a variety of process reject/tailings streams containing uranium and thorium will be generated. The presence of uranium and thorium in the products, and rejects from the project will result in the exposure of workers and, possibly, the public to ionising radiation. These issues need to be identified and addressed.

2.2 Scope of Work

The scope of the report covers the following aspects:

- An overview of background radiation sources and exposure.
- An overview of naturally occurring radioactive materials in the mining and processing of heavy minerals.
- An overview of the international system of dose limitation recommended by the ICRP and IAEA.
- A brief review of the safety standards and guideline documents on the mining of NORM materials produced by the IAEA.
- A summary of the radiological characteristics of the Ranobe mine ore body.
- Identify the potential radiological exposure pathways to both workers and the public which may result from the proposed mining and processing activities.
- Examine and discuss the radiological implications of the various process reject stream disposal options.
- Provide an overview of the components of the radiological protection programs that will be required during the mining and minerals processing operations.
- Provide generic recommendations regarding the engineered controls that can be used in the plant design to keep doses as low as reasonably achievable.
- Provide generic recommendations regarding the administrative controls that can be used during operations to keep doses as low as reasonably achievable.
- Identify and describe the anticipated negative and positive radiological impacts during the construction, operation, decommissioning and mine closure phases.
- Describe how the negative issues and impacts should be managed and incorporated into engineering and administrative specifications for the mine.
3. AN OVERVIEW OF NATURAL BACKGROUND RADIATION

3.1 Radiation and Radioactivity

The field of radiation studies and radiation protection has developed its own terminology and language. An overview of the common radiological terms and concepts used in this specialist report is provided in Appendix 3.

3.2 Naturally Occurring Radioactive Materials

Naturally occurring radioactive materials are found throughout the environment and expose the human population to ionising radiation. These radioactive materials were created many billions of years ago and were distributed throughout the earth and its living organisms. Both uranium and thorium (and their associated decay products) are radioactive materials, which are widely distributed in nature. Levels of natural background radiation can vary significantly from place to place mainly due to the following factors:

- Variations in the concentrations of natural radionuclides in soils and rocks, air and water
- Variations in the type of dwelling design
- Variations in altitude and the intensity of cosmic radiation

The most important radioactive materials found in the natural environment are uranium and thorium and their associated decay chains (Refer to Appendix 4):

Naturally occurring radioactive materials are found in the following environmental media:

- Soils
- Many types of mineral deposits
- Groundwater
- Surface waters
- Dusts
- Air
- Animals and plants
- Humans

The levels of radioactive materials and ionising radiation vary with time and location across the world (Refer to Appendix 5).

3.3 Exposure Pathways to Natural Environmental Radiation

Human beings can be exposed to ionising radiation through external exposure (e.g. from radioactive sources outside the body) and internal exposure (the ingestion of food and drink and the inhalation of dusts and gases).

External sources (e.g. the gamma emitting radionuclides in surface soils) irradiate the body with gamma photons, whereas the main internal hazard is the incorporation of radioactive materials into the body through ingestion or inhalation. Once incorporated the radionuclides may be distributed in the body and could irradiate living tissues by alpha and beta particle emission. In the case of natural background radiation exposure, the predominant exposure pathways are external radiation from radionuclides in the soil and from cosmic radiation and internal exposure through the inhalation of radon ($^{222}$Rn) and thoron ($^{220}$Rn) gas released from the soil. These two pathways normally account for approximately 85% of the total background dose. Minor contributions are made through the incorporation of radionuclides in foods and waters. The most important pathways to measure are:
- External gamma radiation (indoors and outdoors)
- Radon and thoron gas (indoors and outdoors)
- Radioactive materials in soils, dust and water

The major exposure pathways are summarised in Table 3-1 and Figure 3-1.

**Table 3-1: Exposure Pathways**

<table>
<thead>
<tr>
<th>Source</th>
<th>Pathway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radioactive materials in soils</td>
<td>External-gamma rays</td>
</tr>
<tr>
<td>Radon and thoron gas in the air</td>
<td>Internal-breathing</td>
</tr>
<tr>
<td>Cosmic</td>
<td>External-gamma rays</td>
</tr>
<tr>
<td>Radioactive materials in waters</td>
<td>Internal-drinking, cooking</td>
</tr>
<tr>
<td>Radioactive materials in foods</td>
<td>Internal-eating</td>
</tr>
<tr>
<td>Radioactive materials in dusts</td>
<td>Internal-breathing</td>
</tr>
</tbody>
</table>

**Figure 3-1: Background Radiation Exposure Pathways**

Additional information on background radiation is provided in Appendix 5.
4. NATURALLY OCCURRING RADIOACTIVE MATERIALS ASSOCIATED WITH HEAVY MINERALS

4.1 Introduction

The radioactive elements, uranium and thorium, together with other radionuclides of their decay series, occur widely in nature. With half-lives in excess of one billion years much of the uranium and thorium and their daughter products present at the time of the formation of the earth are still in existence. These radioactive elements can become concentrated in certain types of minerals such as those that occur in mineral sands deposits.

The total amount of uranium and thorium per unit weight (in parts per million – “ppm”) in an ore body can be widely variable. The mining and processing of a heavy mineral sands deposit results in the physical concentration of specific mineral products from the ore body. The uranium and thorium concentrations of these product minerals (e.g. zircon) are significantly higher than the average concentration in the ore body due to the association of uranium and thorium with the crystal structure of the mineral. Enhanced concentrations of uranium and thorium are also found in the various reject streams produced from the process (e.g. magnetic rejects, which contains monazite).

4.2 Heavy Mineral Sands

Heavy mineral sands are placer deposits that are often formed in beach environments by concentration due to wave action. Extensive beach deposits are found in many parts of the world (e.g. South Africa, Mozambique, India, Australia, USA, Sri Lanka, Vietnam and Brazil). The source rocks which provide the heavy mineral sands determine the composition of the economic minerals. The source of zircon, monazite, and rutile, is usually granite, while the source of the ilmenite is usually dolerite.

Heavy mineral sands are an important source of zircon, minerals containing titanium, tungsten, and rare earth elements, industrial diamond, sapphire, garnet, and occasionally precious metals or gemstones. The relative abundance of these minerals within a mineral sands deposit and their constituents is largely dependent on the geological source of these minerals. In heavy mineral sands deposits the natural radioactivity is associated mainly with the uranium and thorium contained in the monazite, zircon and sometimes the titanium minerals. The uranium and thorium atoms are locked firmly into the crystal structure of these minerals. The following is a general description of the various mineral products and their radioactivity as they relate to the project. Additional information on the radiological characteristics of monazite and zircon can be found in Appendix 6.

4.2.1 Zircon

Zircon (ZrSiO₄) is a mineral belonging to the group of nesosilicates. It is a typical accessory mineral of acidic igneous rocks and their metamorphic derivatives. It is normally found concentrated in alluvial deposits. Zircon contains widely varying concentrations of uranium and thorium (from 10 ppm up to 10 000 ppm). Owing to their uranium and thorium content, some zircons may undergo a process referred to as metamictization (Refer to Appendix 6). This process partially disrupts the crystal structure and explains the highly variable properties of zircon. Zircon has numerous industrial applications such as in ceramics, refractories, and foundry sands.

4.2.2 Monazite

The mineral monazite is a yellowish – green phosphate containing rare earth metals and is an important source of neodymium, lanthanum, and cerium. It occurs usually in small isolated crystals. It is often found in placer deposits. The beach deposits in India are particularly rich in monazite. Monazite can contain significant concentrations of the radioactive element thorium. The most
common varieties of monazite contain 4 to 12% ThO$_2$, present in the crystal structure. Uranium concentrations vary between 0-3%.

### 4.2.3 Ilmenite

Ilmenite (FeTiO$_3$) is a weakly magnetic iron-black or steel-grey mineral found as a common accessory mineral in many igneous and metamorphic rocks. It is a ubiquitous element in detrital deposits and becomes concentrated in some beach sands. Ilmenite undergoes alteration in the natural environment resulting in the titanium content varying from the about 47% to 66%. Ilmenite can be smelted to produce pig iron, and titanium slag (TiO$_2$) products. The uranium and thorium content of ilmenite is variable depending on its degree of alteration.

### 4.2.4 Rutile

Rutile (TiO$_2$) is the most common form of natural TiO$_2$ in nature and is widely distributed in minute grains in many igneous rocks and is also a common detrital material. Rutile, when present in large enough quantities in beach sands, forms an important constituent of heavy mineral sands ore deposits. Ilmenite and rutile are the primary source materials used to manufacture titanium dioxide pigments. These pigments are often used in the manufacture of paint, varnish and lacquers, plastics, and paper. Rutile in its concentrated natural form is widely used in the manufacture of welding rods. The rutile contains residual amounts of uranium and thorium.

### 4.3 The Concentration of Uranium and Thorium During Heavy Minerals Processing

The mining and processing of heavy mineral sands containing monazite, zircon, rutile, and ilmenite results in the physical separation of various products and process intermediates which contain varying amounts of uranium and thorium radionuclides.

The run of mine (ROM) material is processed in the primary concentrator plant (PCP); this produces the heavy mineral concentrate (HMC), a coarse sand tails and slimes (thickener underflow) reject stream. These reject streams are low in radioactivity and high in volume.

The HMC contains the majority (90%+) of the radioactive minerals in the ore body (monazite and zircon). The PCP process will therefore concentrate the uranium and thorium in the HMC.

The HMC is then processed in the MSP producing a variety of products with varying radionuclide concentrations. The highest uranium and thorium concentrations are expected to be found in the streams with a high monazite content such as the non-mag circuit reject streams. The radionuclide content of the magnetic rejects stream can be significantly higher than the ROM radionuclide concentration. Significantly lower radionuclide concentrations are usually found in the other waste streams such as the wet gravity tails.

As the radioactive minerals are processed and concentrated, the varying uranium and thorium concentrations in the process may pose a risk of radiation exposure to workers. The highest exposure potential is expected to occur in plant sections producing the zircon/rutile concentrate. The primary exposure pathway will be from external exposure to gamma radiation. The inhalation exposures in the wet plant areas arising from radioactive dusts are likely to be insignificant. The potential for inhalation exposures will only occur in the dry sections of the MSP and where there are stockpiles of dry concentrate materials.
5. AN OVERVIEW OF THE DOSE LIMITATION SYSTEM

5.1 International Agencies and Organisations Involved in Developing Radiation Protection Standards

The acceptance by society of the risks associated with radiation is a compromise against the benefits to be gained from the use of radiation and radioactive materials. These risks need to be minimised by the application of radiation safety standards. The International Basic Safety Standards for Radiation Protection and Safety of Radiation Sources published by the International Atomic Energy Agency (IAEA 2011) provide an international consensus for this purpose.

The (IAEA) is an autonomous intergovernmental body and comprises 158 member countries. It was established in 1957 and has its headquarters in Vienna. The IAEA Basic Safety Standards is be based on the recommendations of the International Commission on Radiological Protection (ICRP).

The IAEA Basic Safety Standards are intended to form the basis for the radiation protection programmes implemented in its member countries. The IAEA standards are applied to all types of radiation sources and practices where workers and the public may be exposed to ionizing radiation. The Standards draw upon information derived from extensive research and development by scientific and engineering organizations, at national and international levels on the health effects of radiation and the systems of protection.

5.2 Annual Dose Limits

The dose limits recommended by the IAEA are set down in the Basic Safety Standards of the International Atomic Energy Association (IAEA, 2011). The exposure of individuals must be restricted so that both the total effective dose and the total equivalent dose to relevant organs or tissues do not exceed any of the relevant dose limit specified below:

5.2.1 Occupational exposure

- An effective dose of 20mSv per year averaged over five consecutive years, and of 50 mSv in any single year,
- An equivalent dose to the lens of the eye of 20 mSv per year averaged over 5 consecutive years and of 50 mSv in any single year, and
- An equivalent dose to the extremities (hands and feet) or the skin of 500mSv in a year.

5.2.2 Public exposure

- An effective dose of less than 1mSv in a year
- An equivalent dose to the lens of the eye of 15mSv in a year,
- An equivalent dose to the extremities (hands and feet) or the skin of 50mSv in a year.

5.3 Government Regulation and the Application of the Basic Safety Standards

The member governments of the IAEA have the responsibility for the enforcement of the IAEA standards through a system that includes an independent Regulatory Authority. The IAEA Basic Safety Standards are therefore based upon the presumption that a national infrastructure is in place enabling the Government to discharge its responsibilities for radiation protection and safety.
5.4 **The Scope of Regulation over NORM**

The IAEA provides guidance on the radioactive materials that should fall within the scope of regulation (IAEA, 2004b). It is usually unnecessary to regulate materials with an activity concentration of less than 1 Bq/g per individual radionuclide. The limits apply irrespective of quantity, or whether the materials are natural or processed materials.
6. AN OVERVIEW OF IAEA GUIDELINES SPECIFIC TO THE
EXPLOITATION OF NORM MATERIALS

6.1 Introduction
The exploitation of naturally occurring radioactive material (NORM) is widespread in the world wide
mining and minerals processing industry. A wide variety of NORM products are further exploited by
industry (e.g. zircon, rutile and monazite). Since NORM contains radionuclides of the uranium and
thorium decay chains these materials produce ionising radiation that may result in the exposure of
workers and the public. In addition the mining and minerals processing industry produces large
quantities of low level long lived alpha emitting wastes which will persist in the environment for the
foreseeable future.

6.2 IAEA Guides and Standards Relating to NORM
The following Safety Requirements documents contain specific reference to NORM:


The following IAEA Safety Guides contain specific recommendations relating to NORM:

- Safety Guide on Occupational Radiation Protection in the Mining and Processing of Raw
Materials RS-G-1.6 (IAEA 2004).
- Safety Guide on The Management of Radioactive Wastes from the Mining and Milling of
Ores WS-G-1.2 (IAEA, 2002).
- Safety Guide on Application of the Concepts of Exclusion, Exemption and Clearance RS-G-
1.7 (IAEA, 2004).
- Advisory material for the IAEA Regulations for the Safe Transport of Radioactive Materials
- Safety Guide on Remediation of Areas Affected by Past Activities and Accidents WS-G-3.1
(IAEA 2007).
- Safety Guide on Environmental and Source monitoring for the purpose of Radiation
Protection RS-G-1.8 (IAEA 2005).
- Safety Guide on Release of Sites from Regulatory Control on Termination of Practices WS-
G-5.1 (IAEA) 2006

In addition a number of Safety Reports have been developed for specific sectors of the mining and
minerals processing industry:

- Report No 51: Radiation protection and NORM residue management in the Zircon and
Zirconia industries
- Report No 68: Radiation protection and NORM residue management in the production of
Rare Earths from thorium containing minerals
- Report No 76: Radiation protection and NORM residue management in the Titanium
Dioxide and related industries.
- Report No 49: Assessing the need for Radiation Protection Measures in Work Involving
Minerals and Raw materials.
In addition the following IAEA Technical Documents provide specific guidance on environmental contamination by NORM and the options for remediation and clean up:

- Regulatory and Management Approaches for the Control of Environmental Residues Containing Naturally Occurring Radioactive Material (NORM) TECDOC-1484 (IAEA, 2006f).
- Exposure of the Public from Large Deposits of Mineral Residues TECDOC-1660 (IAEA, 2011)
- Soil Sampling For Environmental Contaminants TECDOC-1415 (IAEA, 2004c).
- Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Mitigation Technical Report Series No 419 (IAEA, 2003b).

6.3 Application of the IAEA Guides and Standards to the Ranobe Mine Project

The IAEA Basic Safety Standards and associated guide and technical documents represent an international consensus regarding the best practice approach in the case of radiological issues related to the exploitation of NORM in the mining and minerals processing industry.

In the case of the Ranobe mine project, the relevant regulatory authorities - Institut National des Sciences et Techniques Nucléaires (Madagascar-INSTN) will ultimately determine the radiological protection and waste management requirements associated with the project. The INSTN will be notified of the intention to process radioactive minerals, but the regulation of such materials in Madagascar will depend on discussions with the INSTN at the time of or before notification. The mine, will as a minimum, meet the requirements of the local Madagascar legislation and will in addition strive to meet international best practice.
7. AN OVERVIEW OF THE RADIOLOGICAL CHARACTERISTICS OF THE ORE BODY

7.1 Introduction

This section provides a summary and review of the currently available information on the radiological characteristics of the Ranobe ore body. The uranium and thorium data is reviewed and compared to data from the UNSCEAR report (UNSCEAR, 2000) and other sources.

7.2 The Radionuclide Content of the Orebody

The heavy mineral content of the upper sand layer averages ~6-7% (range 3-10%) by weight. The zircon fraction comprises approximately 6% and the monazite fraction 1-4% of the heavy mineral.

The mean grades of the radioactive minerals (zircon and monazite) form a small fraction of the total heavy mineral content; however they account for a large fraction of the total radioactivity in the heavy mineral fraction.

The first baseline survey in 2006, indicated a clearly elevated (factor of 3-4) uranium and thorium concentrations on the mine lease compared to the areas outside the mine lease. The highest mineralization was encountered at the pilot plant test pits and this mineralization extended to a depth of 4.5 metres.

During 2006 the drill cores from the exploration activities around and on the deposit were sampled and analysed to determine the radionuclide concentrations. The results showed a wide degree of variability. The uranium concentrations ranged from 2.4-8.1 ppm and the thorium concentrations from 11.6-66.4 ppm. The uranium values were not greatly different from the surface soil samples taken on the mine lease during the baseline survey; however the thorium values were significantly lower. The results indicate the variability of the radionuclide concentrations across the deposit.

The preponderance of thorium in the heavy mineral prospects indicates the significant presence of monazite. The values derived from the Toliara soil sampling programme can be compared to the average uranium and thorium values in world surface soils and common rock types. The median uranium concentrations in the world soils (UNSCEAR, 2000) average 2.8 ppm (range 1.3-8.9 ppm) and the thorium concentrations average 7.4 ppm (range 2.7-15.7 ppm). The thorium concentrations are usually higher than the uranium concentrations in most rock types (range 2.6-5.4 times higher).

It should also be pointed out that absolute values measured across the world, given in the UNSCEAR 2000 Report, are sometimes much higher. For example, concentrations of uranium in soil can be up to 27-30 ppm in Germany and Thailand, and up to 56 ppm in China; concentrations of thorium in soil have been measured at 44-54 ppm in Kazakhstan, Greece, United Kingdom and Spain, and up to 88 ppm in China.

The higher uranium and thorium contents in the Ranobe mine mineral prospect result in elevated potential pre-mining gamma dose rates compared to the world average background levels.

It is important to note that these potential dose rates, are not unique to the project area and it appears that level of natural radiation background is not significantly different from the level of exposure of members of the general public in other areas where heavy mineral sands were concentrated – such as, for example, in the State of Kerala in India, or in the State of Minas Gerais in Brazil.

It also appears that current levels of exposure of the members of the general public residing in the project area and in its immediate vicinity are lower than in the city of Ramsar in Northern Iran, where exposure is caused by high radium concentrations in rocks, soils and drinking water and
around Mrima Hill in Southern Kenya, where exposure is caused by surface deposits of niobium and rare earths ore.

International radiation protection programs do not hold the operator responsible for background induced radiation doses. However such programs do hold the operator responsible for any radiation dose above the natural background. So the main purpose of this radiation management programmes that will be implemented in the future is to ensure that the exposures to both workers and members of the general public are kept as low as reasonably achievable above the existing natural background.

The background dose rates recorded on the mine lease were of the order of 7 mSv per annum during a preliminary pre-mining survey. Further detailed background studies will be done to establish the statistical variation of the background, as the operator will be responsible for doses incurred above this level.
8. EXPOSURE OF WORKERS AND THE PUBLIC TO RADIATION AT THE RANOBE MINE PROJECT

8.1 Introduction

This section identifies the potential radiation exposure pathways to both workers and the public, which may result from the proposed mining and processing activities at the Ranobe mine project. As discussed previously the two primary exposure pathways to ionizing radiation are:

- The inhalation and ingestion of long lived alpha emitting radionuclides (e.g. dusts, waters and food containing radionuclides).
- Exposure to external beta and gamma radiation fields associated with NORM (e.g. arising from stockpiles of materials, accumulations of materials in the plant, soils contaminated with tails and products)

8.2 The Potential Radiation Hazards Associated with Alpha, Beta and Gamma Radiation

8.2.1 Long-lived Alpha Emitters

Alpha emitters present no external hazard as the primary hazard arising from alpha emitters occurs when they are inhaled or ingested. Many alpha emitters of the uranium and thorium decay chains are long-lived alpha emitters and continue to irradiate the body over the individual's lifetime. The most important long-lived alpha emitters in terms of the exposure of workers and the public are $^{238}\text{U}$, $^{234}\text{U}$, $^{230}\text{Th}$, $^{226}\text{Ra}$, $^{210}\text{Po}$, $^{232}\text{Th}$, $^{228}\text{Th}$. Dry and dusty operations will result in the re-suspension of alpha emitting dusts into the air.

The envisaged operations at the PCP and at the MSP have a low potential for dust generation as a large proportion of the material treated is processed under wet conditions. The only dry operations with a potential for dust generation will occur in the mining area and the dry sections of the MSP, however by keeping the ROM and the HMC damp before processing the dust exposures will be manageable.

Engineering and administrative controls will be required to control occupational inhalation exposures in the dry process areas of the MSP in order to maintain the workers exposures as low as reasonably achievable. Additional engineered controls are normally required to control the particulate discharges from the dry section of the MSP. This issue will be addressed at the design stage of the MSP project.

8.2.2 Beta Emitters

The primary radiological hazards arising from beta particles are associated with external exposure to the skin surface and the inhalation of dusts containing beta emitters e.g. $^{210}\text{Pb}$, $^{228}\text{Ra}$. In heavy minerals mining and minerals processing operations a limited amount of beta exposure to the skin will occur. No specific administrative or engineered measures to control beta exposure are required provided that adequate controls are implemented over the individual’s exposure to alpha inhalation and gamma dose rates.

8.2.3 Gamma Radiation

Some of the radionuclides of the $^{238}\text{U}$ and $^{232}\text{Th}$ decay chains are strong gamma emitters. The strength of the gamma radiation fields is dependent on the radionuclide activity concentration in the materials as well as the quantity of the material in the vicinity. Areas in which enhanced gamma radiation fields may be encountered at the operations include the following:

- HMC stockpiles
- MSP rejects stockpiles
Areas of the MSP containing concentrated streams of monazite, as well as accumulations of the process materials

The generic methods of protection against gamma radiation fields include limiting the time of exposure, maintaining a distance from the source of gamma radiation and engineered controls such as the use of shielding e.g. concrete bunkers and bins for the collection of the high activity concentrates and tails.

8.3 An Overview of the Operations

The mining and minerals processing operation comprises the following operations and facilities:

- Mining operations: comprising a dry mining operation with a stationary PCP.
- A PCP plant producing HMC which will be pumped to a stockpile prior to being fed into the MSP.

In the MSP the HMC is processed in wet circuits and dry circuits to produce ilmenite, and a mixed zircon, rutile concentrate. A variety of feed and rejects stockpiles will be associated with the above operations.

The process circuits, feed materials, products and rejects streams are summarised in Table 8-1.

Table 8-1: A Summary of the Process Circuits, Feed Materials, Products and Waste Streams

<table>
<thead>
<tr>
<th>Location</th>
<th>Feed Materials</th>
<th>Waste Streams</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining unit</td>
<td>Run of mine.</td>
<td>Oversize materials.</td>
<td>Undersize material to the PCP.</td>
</tr>
<tr>
<td>PCP</td>
<td>Run of mine from the Trommel screen.</td>
<td>Thickener underflow fines, Coarse sand tailings.</td>
<td>HMC directly to the MSP.</td>
</tr>
<tr>
<td>MSP</td>
<td>HMC feed.</td>
<td>Various magnetic and non magnetic tails. Baghouse dust</td>
<td>Ilmenite, zircon and rutile concentrate</td>
</tr>
</tbody>
</table>

The mining and processing operation will involve the handling, stockpiling and transport of significant quantities of materials per annum.

8.4 The Concentrations of Radionuclides During Mining and Mineral Processing

The radioactivity associated with the mining and processing of heavy mineral sands arises from the presence of radionuclides of the $^{238}$U and $^{232}$Th decay chains in the mineral ore. The majority of the radioactivity is associated with the monazite and zircon fractions in the heavy mineral ore.

Physical processes in the PCP and MSP act to concentrate the heavy mineral fractions and, therefore, the associated radioactivity by many orders of magnitude above that found in the ROM materials. As a result elevated gamma dose rates are expected to occur in the vicinity of the plant process and stockpiles. Significant levels of radioactive materials may be encountered in the air inside dry dusty plants. Elevated levels of gaseous $^{222}$Rn (radon) and $^{220}$Rn (thoron) can occur in poorly ventilated areas.

The mining of the ore body and the concentration of the HMC by the PCP will act to significantly increase the radioactivity content per gram of the material. The further processing of the HMC in the MSP will produce a wide variety of product and waste streams with different radionuclide concentrations.
The uranium (8.9ppm) and thorium (140.7ppm) levels in the topsoil overlying the ore body represent the undisturbed background levels prior to the development of the mine. These values can be compared to the uranium (10.4ppm) and thorium (23.8ppm) concentrations in the ROM.

The concentration of the heavy minerals into the HMC at the PCP results in an increase in the uranium (120ppm) and thorium (2,345ppm) concentrations. The uranium (~0ppm) and thorium (1ppm) concentrations in the PCP coarse tails are significantly lower than in the ROM material and in addition the concentrations are significantly lower than in the overlying soils.

As the mineral streams are treated through the various MSP processes, the uranium and thorium concentrations are increased when compared to the concentrations in the ROM. The highest uranium and thorium concentrations are found in the magneticsrejects.

In the initial stages of the operation the various waste streams will be stockpiled at a start-up tailings stockpile area until sufficient space has been created at the mine to accept the waste to be disposed. This will be detailed during the final design stage of the project.

The data indicates that the majority of the radioactivity from the HMC will report to the various reject streams. Since these materials are expected to contain elevated concentrations of uranium and thorium the localized gamma dose rates close to accumulations of these materials are expected to be enhanced when compared to the natural background radiation levels. In order to control the exposure of workers exposed to these materials, administrative and engineered controls will be established prior to the start up of the operation.

### 8.5 Occupational Exposure to Ionising Radiation

The occupational exposures associated with the project will be widely variable due to:

- The range of radionuclide concentrations in the process materials.
- The varying gamma dose rates and concentrations of long lived alpha emitters in air associated with the various operations.
- The varying nature of the working conditions e.g. dry versus wet operations
- The occupation factors of workers (e.g. the time spent in dusty and high gamma dose rate areas).

An occupationally exposed person (OEP) is defined as an individual who receives a dose of more than 1mSv per annum at the workplace (ICRP, 2007; IAEA, 2004a). The occupational exposure excludes the annual dose received from natural background radiation sources at the worksite. The principal pathways of exposure by which employees may receive a radiation dose are:

- Direct external irradiation by gamma rays
- Internal exposure from inhaled long-lived alpha emitters in dusts

Additional minor exposure pathways are beta exposures of the skin and the ingestion of radioactive material and internal exposure from inhaled radon and thoron decay products.

Occupational exposure to radiation may occur at the following stages of the project:

- Exploration, prospecting and pilot plant operations.
- Construction of the mine and process plants and the associated infrastructure.
- Commissioning and operation of the plant.
- Decommissioning, closure and rehabilitation activities.

The IFC EHS General Guidelines (section 2.6) specify that exposure to non-ionizing radiation should also be controlled to internationally accepted limits. This form of radiation will be considered
in the Radiation Management Plan however, non-ionising radiation is not likely to be an issue in a mineral sands plant.

8.6 The Potential Occupational Exposures Arising from Toliara Process Materials

The potential exposures arise from gamma radiation and the inhalation of long lived alpha emitters in the dust. An additional exposure may arise from the inhalation of radon gas released from the concentrated minerals in the process. Experience in the South African mineral sands industry indicates that this is a minor pathway.

All of the PCP and some of the MSP process areas will be wet process areas with dry processes at the MSP being enclosed with dust extraction and filtration systems. With these engineering controls in place the inhalation doses will be controlled within the limits set for workers. However materials from these areas may be stockpiled near the plant and could dry out resulting in an inhalation dose.

The expected gamma radiation levels from the ore, coarse tails, fines, primary and secondary ilmenite and NM wet circuit tails are well within levels of natural background and, therefore, no additional exposure to gamma radiation will occur when workers will be dealing with these materials.

Estimates of possible radiation exposures of workers in the PCP indicated expected levels of gamma radiation above the typical background. Doses on the HMC stockpile are predicted to be around 5 µSv/hour, and inside the PCP around 1 µSv/hour. It is, therefore, concluded that the radiation exposure expected for the worker involved in mining and operation of the PCP will be in order of 5-6 mSv/year. A similar evaluation of possible radiation exposures of workers in the MSP concluded that the radiation exposure expected for the workers involved in operation and maintenance of the MSP will be in order of 12-13 mSv/year.

Workers are considered to be occupationally exposed to radiation when their annual exposures exceed 1 mSv. This preliminary dose assessment indicates that this could occur at all stages of the process from the HMC production onwards. The highest potential doses are associated with the magnetics rejects and this will be the area of the process that will require the greatest degree of control over exposures.

Typically three different types of areas are established to control radiation exposures:

- Areas where exposure of workers above the public exposure limit of 1 mSv per year is possible are classified as supervised and areas are monitored.
- Areas where exposure of employees may exceed 5-6 mSv per year are classified as controlled and workers are monitored individually,
- Areas where exposure may reach 20 mSv/year are typically classified as restricted and specific access rules will be developed to ensure that access to these areas is strictly controlled.

The HMC stockpiles at both PCP and MSP and wet gravity section of the MSP will likely require to be classified as supervised areas and a formal radiation protection program will be required to limit doses.

The remaining areas of the MSP are expected to be classified as controlled areas with engineered controls to keep doses as low as possible.

The plant processes will give rise to a number of product and waste streams which will require to be stockpiled close to the plants. These stockpiles are expected to accumulate and may dry out unless mitigation measures are taken to control dust generation. A mitigation requirement will be to
control the spread of materials from the stockpiles. As the stockpiles dry out the wind will spread materials away from the stockpiles. Mitigation can be achieved through a variety of methods:

- Wetting down
- Windbreaks around the stockpiles
- Covering active materials with radiologically inert materials.

The preliminary dose assessment of the Ranobe mine project indicates that the gamma and inhalation exposures will require that workers in most areas are classified as occupationally exposed. In order to ensure that workers exposures are kept as low as reasonably achievable, a variety of engineered and administrative controls will be implemented. The degree of control will be assessed during to the design of the facility. As part of the detailed design phase of the project a prospective safety assessment will be used to estimate the total radiation exposure to the workers at all stages of the mining and minerals processing operation. This assessment will be used to design the engineered controls needed to limit occupational exposures.

8.7 Public Exposure to Ionising Radiation

Members of the public may be exposed to ionising radiation arising from the mining and processing of heavy minerals through the following mechanisms:

- The release of solid materials from the operations outside the mining and processing sites (e.g. windblown materials from stockpiles, materials dropped during transport, the diversion (theft) of materials).
- The seepage of process waters containing radioactive particles into groundwater
- The release of dust from the MSP and the PCP and MSP stockpiles
- The release of gaseous effluents (e.g. radon and thoron released from the mine area and stockpiles).

Since the potential for water contamination by radionuclides is very low for heavy minerals plants, the main exposure pathway to the public is likely to be by inhalation of particulate matter.

There are three main categories of particulate emissions that could occur:

- Particulate emissions arising during mining activities e.g. excavation, windblown materials from stockpiles and transport of HMC.
- Particulate emissions from the MSP e.g. from stacks, dust collection systems, dryers.
- Windblown sand emissions from stockpiles e.g. HMC and MSP waste stockpiles.

During mining activities, waste disposal activities and during rehabilitation activities at the mine site, radon and thoron gas may be released from the ROM materials, and the various surface stockpiles.

Provided that the public are kept out of the mining area, the MSP and export facilities; and that there is adequate control over windblown dusts from the stockpiled materials, there should be no incremental gamma dose above normal background levels arising from the mine and plant operations.

The highest theoretically possible exposure of a member of the public has been calculated to be 0.02 mSv/year, which is considered to be negligible – as it represents about 2% of the public annual exposure limit of 1 mSv/year.

During the operational phase of the project the following programmes are expected to be required in order to protect the public from any potential releases of material

Engineered and administrative controls limiting effluents releases
- An effluent monitoring programme
- An environmental radiation monitoring programme
- A waste management programme
- A public radiation monitoring programme.
- Positive exclusion measures (i.e. fencing) to keep the public off the site.

During the detailed design phase of the project a prospective safety assessment of the doses to the public will be done and the results used in determining the required engineered controls to limit public exposures.

### 8.8 Additional Issues

After the decision to proceed, the radiation management and control aspects described above will be considered in specific detail, once the various plant design and waste management options have been finally decided upon. Prior to operation all the radiation protection programmes for workers and the public will be implemented along with the routine monitoring programs at the plants and in the environment.
9. REJECTS MANAGEMENT DISPOSAL OPTIONS AT THE RANOBE MINE

The processing activities associated with the project will give rise to a variety of tails which will require to be disposed of in a safe manner. The uranium and thorium contents and the quantities of the tails are widely variable. These factors will influence the requirements of the tails management program.

In the absence of proper waste disposal and mitigation measures the rejects stockpiles may be dispersed by wind and contaminate the environment. Members of the public who may decide to live in these areas could be exposed to radiation doses in excess of the annual dose limit, particularly if reject materials are used for construction purposes. The radiation doses arising from the various MSP streams will in most cases exceed 1 mSv per annum in the absence of mitigation. Therefore it is essential that the final disposal option ensures that these materials cannot be accessed by the public in the long term.

The activity of the MSP tails will be reduced to the original background levels by blending these tails with PCP tails prior to final disposal. The radioactive mineral in the MSP tails was originally dispersed in the material now called PCP tails before mining, so blending will return the radioactivity of the mix to levels occurring in the deposit prior to mining.

A separate waste management issue, which needs to be considered at a later stage of the project, is the identification and management of contaminated items (e.g. metals, plastic, fibreglass etc) generated in the plant. The monitoring program will include surface contamination monitoring of all items removed from the supervised and controlled areas. No contaminated items will be removed from the site.
10. **AN OVERVIEW OF THE RADIATION PROTECTION PROGRAMME**

10.1 **Introduction**

Workers at the project may be exposed to an annual radiation dose above which they are regarded as occupationally exposed persons (ICRP 2007: IAEA 2011). Members of the public living near to the operations may be exposed to gaseous or particulate effluents released from the operations. This section provides an overview of the components of the radiological protection programs for workers and the public that will be required during the mining and minerals processing operations.

10.2 **Radiation Exposure During the Ranobe mine project**

The following groups of individuals may be exposed to radiation during the project:

- Exploration and prospecting teams
- Construction crews
- Workers at the mine operations
- Drivers and operators of the mining equipment
- Workers at the PCP and MSP and export facilities
- Workers at the mine site involved in the rehabilitation and MSP tailings disposal operations
- Visitors to the operations
- Contractors working at the project
- Members of the public who live close to the mining and processing operations or export facilities and product haulage road

All of these groups need to be addressed by the radiation protection programme. The annual radiation doses received by these different groups will be widely variable and only a proportion of these individuals will need to be classified as occupationally exposed persons.

10.3 **IAEA Standards and Safety Guides**

IAEA Safety Guides recommend actions, conditions or procedures for meeting the IAEA’s Safety Requirements, and reflect current internationally accepted principles and recommended practices. Three interrelated Safety Guides provide guidance on meeting the requirements of the Basic Safety Standards for occupational radiation protection,


A further Safety Guide on *Occupational Radiation Protection in the Mining and Processing of Raw Materials*, (IAEA Safety Standards Series No. RS-G-1.6, 2004), provides more specific recommendations and guidance on meeting the requirements for the establishment of occupational radiation protection programmes in the mining and processing of raw materials.

10.4 Design requirements for future Radiation Protection Programme

At the current stage of the project there is a limited amount of quantitative radiological data and dose projections for the project. Therefore detailed predictions on the requirements of the radiation protection programme cannot be made until more data is available. This section of the specialist report focuses on the elements of the radiation protection programme that need to be considered in the future radiological assessments of the project. The extent and complexity of any radiation protection programme is always tailored to the level of radiation risk to workers and the public arising from a specific project. The risk level can be directly related to the projected annual dose to the workers and the public. Therefore the higher the annual exposure the greater the risk and the extent of the radiation protection programme.

The radiation protection programme is primarily concerned with control over the areas containing sources of radiation and the way humans interact with these sources. These controls will eventually be documented in a Company Code of Practice on Radiation Protection and will include the following components:

- Safety assessments to determine the level of risk to workers and the public
- Engineered controls over radioactive materials and radiation sources
- An overview of the radiation protection personnel requirements at the operations
- Area classification of the workplaces
- Classification of employees
- Routine workplace monitoring programs
- Instrumentation and calibration
- Individual monitoring and a dosimetry program for Occupationally Exposed Persons
- A radiation training programs for workers
- Medical examinations for OEP’s
- Health and dose registers for OEP’s
- Personal protective equipment
- Physical security and access controls to the operations
- Effluent and environmental monitoring programs
- A waste management program
- Control over the release of contaminated items and materials from the operations
- Control over the transport of radioactive materials on public roads
- Record keeping
- Quality management program
- Inspections and audits
- Site decommissioning and closure, and subsequent remediation of the area

10.5 The Assessment of the Radiation Protection Program for the Ranobe mine Operations

The specific requirements of the radiation protection programme for the operation will need to be determined as the project progresses. The requirements will be based upon the following information:

- A detailed description of the proposed process from mining through to the disposal of tails.
- The U and Th content of the ore, HMC, feed, product and waste materials at all stages of the process.
- The quantities of materials processed each year at each stage of the process.
- A radioactive material balance for the whole operation.
- The estimated annual doses to workers and the public arising from the operations.

The above quantitative information can be used to assess the following components of the radiation protection programme:
• The required design and engineered controls
• The required administrative controls
• The assessment of the waste management options
• The assessment of closure, decommissioning and remediation options

The possible administrative and engineered controls required at the project operations are discussed in the next two sections.
11. ENGINEERED CONTROLS OVER THE RADIATION EXPOSURES OF THE WORKERS AND THE PUBLIC

11.1 Introduction

This section provides generic recommendations regarding the engineered controls that can be used in the plant design to keep doses as low as reasonably achievable (ALARA). Engineered controls over radiation sources and radioactive materials are the preferred form of control to keep occupational and public exposures as low as reasonably achievable. These types of controls require a low level of maintenance and active administration and can provide a high level of protection. Every aspect of the mine and plant operations will be systematically examined in terms of keeping doses ALARA. This process requires close cooperation between the radiation specialists and the design engineers. It is important that this definitive study and assessment commence at an early stage prior to the finalisation of the plant design.

11.2 Design and Engineered Controls at the Ranobe Mine Project

The limited data available on the project indicates that the following areas will be carefully investigated with regard to designed engineered controls to limit occupational and public exposures:

- The gamma radiation fields in the MSP and stockpiles. These gamma exposures can be minimised by:
  - Limiting the exposure time
  - Increasing the distance from the source (e.g. locating frequently occupied workplaces such as control rooms at reasonable distances from the source).
  - Installing shielding around the source (e.g. concrete).
  - Installation of bund walls to prevent spread of spillage

- Particulate releases from the MSP and the associated stockpiles\(^1\). These alpha exposures can be minimised by:
  - dust and ventilation controls

It should be noted that the use of personal protective devices such as respirators to limit exposures are neither practical (due to climate) nor good practice, except in the case of short term maintenance activities (e.g. entry into process vessels). A more detailed overview of the various design and engineered controls that need to be considered for the project is provided in Appendix 7.
12. ADMINISTRATIVE CONTROLS OVER THE RADIATION EXPOSURES OF THE WORKERS AND THE PUBLIC

12.1 Introduction

This section provides an overview of the administrative controls that can be used during operations to keep doses as low as reasonably achievable. Whilst engineered controls can result in a significant reduction in occupational exposure, a variety of administrative controls are required to ensure that doses remain ALARA.

12.2 An Overview of Administrative Controls

It is the usual practice, prior to construction, to assess all the potential radiological hazards associated with a planned mining and minerals processing facility. The prospective hazard assessment is normally compiled by analysing the key feed, process and waste streams for critical radionuclides. Simple mathematical models are then used to estimate the projected doses over 2000 hours for workers, the doses for the members of the general public will need to be assessed using realistic assumptions (such as the actual time expected to be spent by the members of the general public in the vicinity of the site). The results of the prospective hazard assessment are then used to optimise the plant design in order to ensure that doses are kept ALARA. The results of the prospective hazard assessment can also be used to classify areas according to their potential radiological hazard. Four levels of area classification are defined and described in Section 8.6.

The following administrative controls will be used in the radiation protection programme:

**Dose Assessment:** In supervised areas individuals’ annual dose will be based upon area survey measurements and estimated occupancy factors. Within controlled areas, personal gamma monitoring utilising TLDs and personal dust monitoring equipment will be used. In supervised areas doses will be determined using a combination of area monitoring and occupancy factors.

**Protective Clothing:** The normal type of protective clothing (boots, gloves, overalls) will be adequate for most areas of the plant.

**Good Housekeeping:** Measures will be implemented to ensure that operational and other areas on site will be kept as free from dust and mineral spillages as practicable. A regular cleanup program will be implemented, with spillages in wet areas being washed into sumps and recycled.

**Operational readiness standards:** Dust control measures such as separator containment shrouds will remain closed to allow the dust containment and vacuum de-dusting system to operate efficiently. Bag houses will be operating effectively as a prerequisite to starting or operating the plant; sand leaks will be fixed immediately to prevent build-ups on the MSP floor.

**Control over Surface Contamination:** Items, materials and persons exiting the classified areas will need to be monitored for alpha and beta surface contamination. At the end of a shift, workers will exit via a change house with showers and a laundry facility. Contamination monitoring will be carried out on random employees with suitable hand held instruments or fixed monitors.

**Rest Room:** A rest area will be provided in the supervised area where workers may eat, drink and smoke. Washing facilities are required prior to entry as well as routine contamination monitoring of the area.

**Training:** Training on the radiation hazards will be provided for workers and contractors associated with the operation.
**Access Controls:** An access/egress control system is required to prevent the unauthorised access and exit of persons, items, materials and vehicles from supervised, controlled areas and the site.

**Release of Materials and Items from the Site:** Contaminated items and materials should not be released to the public domain for unrestricted use. Therefore a control system is required over the release of such materials from the site operations.

**Control Over Contractors:** Contractors may require access to classified areas from time to time e.g. for maintenance and repair activities. It is important that their activities, doses and occupancy factors are recorded.

**Waste Management:** A waste management programme and the associated administrative controls are required in order to ensure that all radioactive rejects and contaminated items are disposed of in an acceptable manner.

**Scrap Wash Bay:** A scrap wash bay is required near the exit point of the classified areas. A small area is required for the storage of scrap prior to washing, and after washing. All items and materials from the process must be monitored for alpha and beta surface contamination prior to leaving the classified areas, together with vehicles which have been driven on the operational site.

**Filter Bag Changing:** Specific provisions are required for the changing, handling and disposal of filter bags.

**Transport of Radioactive Materials:** In the prospective safety assessment of the operation all waste materials or products need to be assessed with regard to their classification as radioactive materials in terms of the IAEA International Transport Regulations (IAEA 2009).
13. THE ANTICIPATED RADIOLOGICAL IMPACTS OF THE RANOBE MINE

13.1 Introduction

This section describes the anticipated positive and negative radiological impacts during the construction, operation, rehabilitation, decommissioning and mine closure phases and how these impacts should be managed and incorporated into the engineering and administrative specifications for the mine.

The mining and processing of the ore body will result in the transfer of a fraction of the radioactive material into the products. The major fraction of the remaining radioactive material will reside in the various solid rejects streams (e.g. sand tails, slimes and MSP solid process waste streams). A very minor fraction of radioactive material will be released in dusts from the MSP and PCP plants and related stockpiles.

The radionuclide concentrations in the various solid waste streams will be significantly different from the original concentrations in the ore body. For example the radionuclide concentrations in the PCP coarse sand tails will be significantly lower than in the ore body as the majority of the uranium and thorium will report to the HMC sent to the MSP. At the MSP, physical separation of the various minerals in the HMC results in a variety of products. The radionuclide concentrations in the various solid waste streams will be highly variable and in some cases will be significantly enhanced compared to the ore body.

The handling and transport of the various products and waste streams that contain enhanced concentrations of the radionuclides of the uranium and thorium decay chains will result in workers and members of the public in close proximity to these materials being exposed to radiation.

The impacts are described and discussed in terms of the radiation exposures to workers and the public that may occur due to the various radioactive materials associated with the project.

13.2 Positive Radiological Impacts

The mining and processing operation will remove the majority of the radioactive mineral fraction (zircon and monazite) from the ore body by processing at the MSP. The coarse tails from the PCP will therefore contain a small fraction of the original radioactivity. Since the product materials produced by the MSP (ilmenite, rutile and zircon concentrates) also contain radioactivity, the export of these materials will permanently remove a fraction of the total radioactive inventory from the project area.

The remaining radioactive inventory comprises a variety of MSP tails containing varying levels of radioactivity. The majority of the radioactive inventory will be contained in the zircon and monazite tails. Provided that these tails are properly disposed of by blending with low radioactivity materials the radiation levels above the surface of the ore body will be reduced to baseline levels or slightly below. This is a minor positive impact of the project.

The positive impact cannot be accurately quantified (in terms of an annual dose to the public) until the following data is collected:

- A detailed description of the proposed process from mining through to the disposal of tails.
- The U and Th content of the ore, HMC, feed, product and waste materials at all stages of the process.
- The quantities of materials processed each year at each stage of the process.
- A radioactive material balance for the whole operation.
13.3 Negative Radiological Impacts

13.3.1 Construction Phase

The construction phase will involve the building of infrastructure and roads on and close to mineralised areas of the dune. The construction workers may be exposed to ionising radiation during their work activities. The degree of exposure needs to be estimated prior to the construction activities by a prospective safety assessment.

The following areas must be considered:

- Mine site
- The PCP and MSP sites
- The transport routes.
- Jetty and product storage area
- The sites of construction worker facilities (e.g. housing)

The above areas can be assessed during the prospective safety assessments to estimate the construction worker doses. In addition, the safety assessment should identify and quantify any potential radiological impacts on the public arising from construction activities. The site of the construction worker facilities should preferably be located in a low background radiation area identified during the baseline survey.

The safety assessment must be completed a few months prior to construction in order to put in place any mitigation measures.

13.3.2 Operation of the Mining and Minerals Processing Facility

There are a variety of potential negative impacts during this phase of the mining and minerals processing operations that need to be assessed and quantified prior to the detailed design phase of the project.

These impacts include:

- The radiation exposure of workers
- The possible radiation exposure of members of the public to releases of radioactive materials from the operations

These potential exposures to radiation can arise at the following locations:

- The mine and PCP operations and site offices
- Transport routes
- The MSP
- Stockpile areas
- The export facilities on the coast

The potential radiation exposures need to be determined by a prospective safety assessment in order to quantify the radiological impacts and doses. The results of the assessment can then be used to optimise the design and operation of the project to keep radiation doses as low as reasonably achievable.

The following information is required for the prospective safety assessment of the operations:

- The results of the baseline radiation survey
- A detailed description of the proposed process from mining through to the disposal of tails.
The U and Th content of the ore, HMC, feed, product and waste materials at all stages of the process.
The quantities of materials processed each year at each stage of the process.
A radioactive material balance for the whole operation.
A realistic assessment of occupancy patterns, particularly for the employees involved in operation and maintenance of the MSP and for the members of the general public will be required.

The prospective safety assessment must be completed well in advance of the final design stage of the project.

13.3.3 Waste Management Issues

A variety of tails with varying radioactivity levels will be produced from the operations. It is important that these materials are disposed of in a safe manner and that any long term negative impacts resulting in public exposures to radiation are minimized.

The proper disposal of these materials needs to be assessed by a detailed safety assessment which must be completed prior to the final design stage of the project. If there are a variety of long term disposal options to consider, each option must be evaluated and quantified.

13.3.4 Decommissioning and Mine Closure Phases

The decommissioning and mine closure phases of the proposed project lie far in the future. However it is good practice to identify and consider any negative impacts from the beginning of the project. For example the use of designed and administrative controls during the operational phase of the project can be used to minimise long term negative impacts such as the contamination of areas around the operations and along the transport routes.

13.4 Evaluation of the Positive and Negative Impacts Arising from the Project

The radiological impacts arising from the mining and processing of heavy mineral ores need to be expressed as annual doses to workers and to potentially exposed members of the public. At present there is insufficient data to precisely quantify all the various radiological impacts which have been identified. Additional data will be collected and incorporated into a variety of radiological safety assessments of the project in order to provide this data. These studies and assessments will be completed prior to the final design stage of the project.

The key radiological impacts have been rated using the CES rating system. The CES rating system is described in Appendix 8.

The impacts are assessed with and without mitigation. Without mitigation means that no attempt has been made to control the effects of the negative impact.

The following areas of impact have been identified:

- Occupational exposure of workers to ionizing radiation at the operations
- Disposal of homogenous solid wastes from the PCP and MSP process and the impact on public radiation exposure
- Spillage of product along the transport route and export facility
- Disposal of slightly contaminated equipment from the PCP and MSP and the impact on public radiation exposure
- Release of radioactive materials into the air and water from the MSP and PCP operations and during transport to the mine void and the impact on public radiation exposure
- The contamination of the operational areas with NORM residues over the life of the mine
- Requirement to reuse the topsoil for rehabilitation.
13.5 Issue Assessment

13.5.1 Issue 1: Disposal of Homogenous Solid Wastes from the PCP and MSP Process: Impact on Public Radiation Exposure

Cause and Comment

The operations at the PCP and MSP will give rise to a variety of tailings streams with widely variable levels of radioactivity. Some of these waste streams will be significantly higher in radioactivity compared to the ore body. These tailings streams are commonly referred to as NORM wastes (IAEA, 2006b). NORM wastes contain long lived alpha emitting radionuclides with very long half lives.

In accordance with the IAEA waste classification system (IAEA, 2010) most of the wastes that will be produced at the Ranobe mine operations can be classified as “very low level long lived alpha emitting wastes” and some as “low level waste”. Although the radiation risks arising from such materials are low, the materials will require to be disposed of in a safe manner that ensures that the public is protected in the long term.

If members of the public are exposed directly to these waste materials or if the materials are diverted for construction purposes, their exposures could exceed the annual public dose limit of 1mSv per annum. Therefore these wastes need to be disposed of in an acceptably safe manner to ensure that future exposures of the public are below the annual dose limit and are as low as reasonably achievable in the long term.

Mitigation and Management

The MSP tails will be returned to the mine site. In order to ensure that the public is not exposed to the highly concentrated MSP tails in the long term, the tails will be blended with the PCP tails. The mixing system will be designed to ensure that poor mixing does not occur and this will be monitored throughout the life of the mine, to ensure potential exposure targets are achieved.

Significance Statement

The public radiation exposures associated with the disposal of homogenous solid wastes will definitely occur and as the potential impacts are likely to persist beyond the life of the mine should be considered as permanent but confined to the district. Without mitigation the severity of the impacts should probably be regarded as severe (i.e. public exposures could exceed the annual dose limit) but with mitigation the severity could be reduced to slight. The overall significance of the impact without mitigation would be high, however with mitigation this would be reduced to a low significance.

13.5.2 Issue 2: The Disposal of Slightly Contaminated Equipment from the PCP and MSP. Impact on Public Radiation Exposure

Cause and Comment

Although the processing of heavy minerals is a physical process, items of plant equipment can become contaminated on their surfaces in the plants (e.g. fibreglass spirals, trays, troughs rubber lined items, filter bags, painted metals and stainless steel pipes). The quantities of equipment involved are small and the contamination levels are relatively low. The surface contamination is predominantly alpha contamination.
Mitigation and Management

In many cases the contamination is easily removable (for example by washing). In some cases the surface contamination will be fixed to the surface and high pressure washing may be required to remove it.

A variety of clearance and exemption levels can be derived (IAEA, 2009) for such contaminated items.

Significance Statement

The public radiation exposures associated with the release of slightly contaminated equipment will definitely occur and, as the potential impacts are likely to persist for the life of the mine, should be considered as long term but confined to the district. Without mitigation the severity of the impacts should probably be regarded as moderately severe (contaminated items could be sold to the public) but with mitigation the severity could be reduced to no effect/slight. The overall significance of the impact without mitigation would be moderate, however with mitigation this would be reduced to no significance/low significance.


Cause and Comment

Radon gas will be released from the surface of various stockpiles of materials at the MSP and the PCP, and in addition dust will be released from the MSP and any dry stockpiles. Process waters and storm waters leaving the site may contain suspended materials from the process and stockpiles.

The gaseous, particulate and liquid effluents released from the operation may result in some exposure of the public living or working close to the mining and processing operations. Historical information from heavy mineral plants in Australia (IAEA, 2011) and South Africa (Alara, 2003) indicates that the maximally exposed critical groups close to the plant cannot receive more than a fraction of a millisievert per annum from these radioactive discharges (the annual exposures range from 0.01-0.30mSv per annum).

Mitigation and Management

The public doses can be kept ALARA through a number of simple mitigatory measures such as windbreaks, dust suppression systems and settling ponds.

Significance Statement

The public radiation exposures associated with the release of radioactive materials from the operations will definitely occur and, as the potential impacts are likely to persist for the life of the mine, should be considered as long term but confined to the district. Without mitigation the severity of the impacts should probably be regarded as moderately severe (i.e. public exposures will occur) but with mitigation the severity could be reduced to slight. The overall significance of the impact without mitigation would be moderate, however with mitigation this would be reduced to low significance.
13.5.4 Issue 4: Occupational Exposure of Workers to Radioactive Materials and Ionising Radiation at the Toliara Operations

Cause and Comment

Workers will be exposed to radiation during the construction, operation, decommissioning and rehabilitation of the operations and at the export facility. The levels of exposure will be widely variable and will be dependent on a wide variety of factors such as:

- The annual occupation factor (number of hours exposed to the radioactive materials).
- The concentration of uranium and thorium in the radioactive materials.
- The quantities of materials in the workplace.
- The operations carried out in the workplace.
- The concentration of respirable dust in the workplace.

Thus the annual doses to individual workers will be highly variable. Past experience in the South African (Alara, 2003) and Australian mineral sands industry (IAEA 2011) indicates that the highest doses are usually associated with the dry sections of the MSP plant and stockpiles and arise from the inhalation of dusts containing zircon and monazite particles. Significant exposures exceeding the annual dose limit are possible if no mitigatory actions are taken (e.g. no dust control and suppression systems) to control exposures.

Mitigation and Management

When dust control systems and radiation protection programs are put in place, the maximum occupational exposures will normally not exceed 5mSv per annum (i.e. a quarter of the annual dose limit).

Significance Statement

The occupational exposures associated with the project will definitely occur and, as the potential impacts are likely to persist for the life of the mine, they should be considered as long term but confined to individuals. Without mitigation the severity of the impacts should probably be regarded as severe (i.e. occupational exposures could be close to or exceed the annual dose limit) but with mitigation the severity could be reduced to slight. The overall significance of the impact without mitigation would be high, however with mitigation this would be reduced to a moderate significance.

13.5.5 Issue 5: The Contamination of the Operational Areas with NORM Residues over the Life of the Mine

Cause and Comment

Some of the product and waste streams will contain enhanced concentrations of uranium and thorium. Quantities of these materials over the course of the project lifetime will tend to be dispersed and could contaminate areas on and surrounding the MSP. Soil contamination may also occur along the transport routes to the export facility where the bulk product is stored and loaded.

The presence of enhanced concentrations of these materials in and on the surface soils can result in the exposure of the public that utilizes the sites after decommissioning of the operations.

Impacts at the export facilities are not considered significant, as this will be final product and any losses will have financial implications. Design of these systems and procedures will therefore focus on the minimization of losses, which in turn are expected to result in the minimization of any possible mineral spillages.
Mitigation and Management

In order to ensure that public exposures after decommissioning and rehabilitation are comparable to the levels found prior to the operations commencing, the site and environs may need to be cleaned up and the contaminated soil removed to a suitable disposal site such as the base of the mine void. Guidance on the cleanup of land contaminated with NORM residues is provided by the IAEA (IAEA, 2003b). The site will be equipped with an emergency response team to clean up any product spillages on the public roads.

Significance Statement

The public radiation exposures associated with land contaminated with NORM residues of homogenous solid wastes will definitely occur and, as the potential impacts are likely to persist for the life of the mine, should be considered as long term but confined to localised areas. Without mitigation the severity of the impacts should probably be regarded as moderately severe (i.e. public exposures could exceed the annual dose limit) but with mitigation the severity could be reduced to slight. The overall significance of the impact without mitigation would be moderate, however with mitigation this would be reduced to a low significance.
### Table 14-1: A Summary of Issues and Impacts Arising from the Radioactive Materials Associated with the Proposed Ranobe Mine Project

<table>
<thead>
<tr>
<th>ISSUE / IMPACTS</th>
<th>WITHOUT MITIGATION</th>
<th>WITH MITIGATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LIKELIHOOD</td>
<td>TEMPORAL</td>
</tr>
<tr>
<td><strong>Positive Impacts of the Project</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of radioactivity in the rehabilitated dune</td>
<td>Will definitely occur</td>
<td>Permanent</td>
</tr>
<tr>
<td><strong>Negative Impacts of the Project</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issue 1 – Disposal of homogenous solid wastes from the PCP and MSP process. Impact on public radiation exposure</td>
<td>Will definitely occur</td>
<td>Permanent</td>
</tr>
<tr>
<td>Issue 2 – Disposal of slightly contaminated equipment from the PCP and MSP. Impact on public radiation exposure</td>
<td>Will definitely occur</td>
<td>Long term</td>
</tr>
<tr>
<td>Issue 3 – Release of radioactive materials into the air and water from the MSP and PCP operations and during transport to the mine void. Impact on public radiation exposure.</td>
<td>Will definitely occur</td>
<td>Long term</td>
</tr>
<tr>
<td>Issue 4 – Occupational exposure of workers to ionising radiation</td>
<td>Will definitely occur</td>
<td>Long term</td>
</tr>
<tr>
<td>Issue 5 – The Contamination of the Operational Areas with NORM residues</td>
<td>Will definitely occur</td>
<td>Long term</td>
</tr>
</tbody>
</table>
14. CONCLUSIONS

The proposed project will establish an extensive heavy minerals sands mining and processing operation, which will include a minerals recovery plant. The project will involve the mining, processing and beneficiation of a heavy minerals sands ore body containing minerals with elevated levels of the radionuclides of the uranium and thorium decay chains.

The presence of radioactive materials in such ores has the following major radiological implications:

- Occupational exposures of workers.
- Possible exposure of members of the public living nearby.
- Waste management and long-term radiological environmental impact issues.

The main exposure pathways of workers and members of the public living near to the site comprise the following:

- External gamma irradiation from the gamma emitting radionuclides.
- The inhalation of radioactive radon and thoron gas.
- The inhalation of radioactive dusts containing long lived alpha emitters of the uranium and thorium decay chains.

The main conclusions arising out of this specialist report are as follows:

- The baseline background annual doses in the project area were significantly higher than the UNSCEAR world average values.
- The baseline results indicated that the radon exposure pathway is the dominant pre operational exposure pathway
- As the HMC is processed through the MSP process, the uranium and thorium concentrations of several mineral streams are increased.
- The data indicates that the majority of the radioactivity in the HMC will eventually reside in the MSP reject streams, since these materials contain significant concentrations of uranium and thorium the localized gamma dose rates close to accumulations of these materials will be significantly enhanced when compared to the natural background radiation levels. In order to control the exposure of workers exposed to these materials administrative and engineered controls will be required.
- The majority of the occupational radiation exposure in the PCP and the MSP arises from gamma radiation, provided the dry sections of the plant are equipped with an efficient dust removal system.
- Workers are considered to be occupationally exposed to radiation when their annual exposures exceed 1 mSv. This preliminary dose assessment indicates that this will occur from the production of HMC and all process steps onwards.
- A major mitigation requirement will be to control the spread of materials from the stockpiles.

The final disposal option will be decided after radiological modelling during the detailed design phase and will either be blending of MSP with PCP tails or the MSP tails will be buried in the mine void under an inert layer of coarse sand tails.
15. RECOMMENDATIONS

It is the responsibility of the project operator to identify and address the key radiological issues and determine the engineered and administrative controls required to keep the radiation exposures of workers and the public in accordance with the dose limitation system throughout all stages of the project. A variety of radiological issues have been identified in this specialist study, which need to be considered and assessed at an early stage in the project.

The following recommendations are made:

Prior to the mining and processing operations a detailed prospective safety assessment of the doses to the workers and the public arising from normal mining and plant operations needs to be carried out. In order to carry out the prospective safety assessment the following information needs to be obtained:

- A detailed description of the process from mining through to the disposal of tails.
- The U, and Th content of the ore, HMC, feed, product and waste materials at all stages of the process.
- The quantities of materials processed each year at each stage of the process.
- A radioactive material balance for the whole operation.
- Occupancy models for workers in controlled areas.

The above quantitative information can be used to assess the following components of the radiation protection programme:

- The estimated annual doses to workers and the public arising from the operations
- The required design and engineered controls to limit the radiation doses
- The required administrative controls
- The finalisation of the plant design
- The assessment of the waste management options

The specific requirements of the radiation protection programme for the Ranobe Mine Project operations will need to be iteratively determined as the project progresses. The IAEA Basic Safety Standards and associated guide and technical documents on NORM operations will be used to assist in this process.

Prior to operation all the radiation protection programmes for workers and the public should be implemented along with the routine monitoring programs at the plants and in the environment.

It is expected that all aspects of the radiation protection programme will be detailed in a “radiation management plan” that will be developed prior to the commencement of operations and progressively updated during the operational stage.
16. REFERENCES


- IAEA (2011) Radiation Protection and NORM Residue Management in Production of Rare Earths from Thorium Containing Minerals, Safety Reports Series No.68. IAEA. Vienna.


• Department of Mines and Petroleum, 2010, Managing naturally occurring radioactive material (NORM) in mining and mineral processing — guideline (2nd edition): Resources Safety, Department of Mines and Petroleum, Western Australia
LANDSAT VIEW

Landsat View of the Toliara Area (Source: Hydromad 2004)
Villages Situated Close to the Toliara Sands Project Area
Overview Map of the Toliara Sands Survey Area
Regional Overview of the Project Location
18. APPENDIX 2 : VERTICAL SECTION THROUGH THE RANOBE DEPOSIT

Section through the Mineral Deposit
APPENDIX 3: RADIOACTIVITY AND IONISING RADIATION

RADIOACTIVE MATERIALS

Various radioactive isotopes (e.g. $^{40}$K, $^{238}$U, $^{232}$Th) are widely dispersed at low levels in the solids, liquids and gases of the geosphere, biosphere, hydrosphere and atmosphere.

The great majority of elements in nature are comprised of stable atoms, which cannot spontaneously convert into a different element. Radioactivity consists of a spontaneous nuclear transformation in unstable radioactive isotopes, which changes the number of protons and neutrons in the nucleus of an atom. This process continues until a stable isotope is formed.

IONISING RADIATION

Nuclear transformation is accompanied by the release of energy (radiation) in the form of the emission of alpha particles ($\alpha$), beta particles ($\beta$) and gamma rays ($\gamma$). Ionising radiation is therefore energy in the form of waves or particles. A nuclide that spontaneously emits radiation from its nucleus is referred to as a radioactive nuclide. Ionising radiation is capable of producing ion pairs in living tissue.

ALPHA PARTICLES

An alpha particle is the largest particle of radiation emitted from a nucleus. It is composed of 2 protons, 2 neutrons and no electrons. The alpha, therefore, has a plus 2 charge. The size of the alpha and its plus 2 charge determines its penetrating power and how it interacts with matter.

Alpha particles are typically emitted from the nucleus of heavier atoms, such as $^{238}$U and $^{232}$Th. Because of its large size and positive charge, an alpha particle is not very penetrating, e.g. the range in air depends upon the emission energy and ranges from about 3-10 centimetres. An alpha particle will not penetrate a thin sheet of paper or the dead layer of the skin surface.

The main radiation hazard arising from alpha particles is due to inhalation and ingestion into the body. Once inside the body the alpha particle can directly irradiate sensitive tissues.

BETA PARTICLES

A beta particle is a high-energy electron emitted from the nucleus. Beta particles are the smallest particles of radiation emitted from the nucleus; in addition, a beta particle has a charge of minus 1. Due to its smaller size and smaller charge a beta particle is more penetrating than an alpha particle. The energy of the beta particles emitted from a specific nuclide is not discrete, but varies over a continuous spectrum.

Beta particles are more penetrating than alpha particles. Their range in air depends upon their maximum energy ($e_{\text{max}}$) and can vary from a few centimetres up to 20 metres. Even the most energetic beta emitters associated with the $^{238}$U and $^{232}$Th decay chains are completely blocked by about 1cm of soil or process materials. The main hazard arising from beta particles is due to the irradiation of the skin and the ingestion and inhalation of beta radionuclides into the body.

GAMMA RAYS

The third type of radiation emitted by radioactive nuclides is the gamma ray, which is a form of electro-magnetic radiation (photon), which travels at the speed of light. When a gamma ray is emitted by a nucleus, there is no change in the mass number or atomic number of that nucleus. Gamma ray emission usually accompanies alpha and beta particle emission.
Gamma radiation is difficult to stop because of its high energy, no mass and zero electrical charge. It is the principal type of external radiation hazard to humans. It can easily pass through human tissue and can only be stopped by high-density materials e.g. concrete and lead.

HALF-LIFE

A characteristic of all radionuclide atoms is that they emit ionizing radiation and spontaneously decay forming an atom of another element. Each radionuclide has a characteristic rate of transformation referred to as the decay constant. The half-life refers to the period of time in which it takes half the atoms of a radionuclide to decay into another type radionuclide.

For example the half life of $^{226}$Ra is 1,600 years. A tailings facility at mine closure that contains $^{226}$Ra will have half the original amount of $^{226}$Ra remaining in the tailings after a period of 1,600 years has elapsed.

After four half-lives (6400 years), approximately 6% of the original $^{226}$Ra inventory will remain in the tailings. After 10 half-lives (16,000 years) have elapsed approximately 1% of the original $^{226}$Ra inventory will remain in the tailings.

DOSE AND DOSE RATE

A radiation dose (more correctly referred to as the effective dose) is a measure of the radiation energy absorbed by the body during a defined time period. The unit of effective dose is referred to as the Sievert. Results are reported in millisieverts (mSv) and microsieverts (µSv) per hour or per year.

In the control of radiation hazards it is necessary to know the rate at which radiation is received.

The relationship between dose, dose rate and time is:

$$Dose = dose\ rate \times time$$

For example if a worker is exposed to a dose of 2 microsieverts in one hour, the dose rate is 2 $\mu$Sv.h$^{-1}$.

THE HARMFUL EFFECTS OF IONISING RADIATION

The harmful effects of radiation can be broadly divided into somatic (those affecting the body) and genetic effects (those affecting future generations). Somatic effects include the production of cancers and various forms of tissue damage. Genetic effects arise due to damage to the parent germ cells (sperm and ovum), which are then transmitted to future generations.

Owing to differences in cell structure and in the degree of maturity of cells, some cells are more susceptible to radiation damage than others. Blood cells and reproductive cells are more susceptible to radiation damage, whereas brain cells and the cells of the lymphatic system are less susceptible.

Radiation damage may include the following outcomes:

- The cell is irradiated, but the energy goes through the cell without causing appreciable damage.
- The cell absorbs the radiation and is damaged, but recovers and functions properly.
- The cell is damaged so severely that it cannot recover its normal function and retains the damage, i.e. a mutated or cancerous cell is created.
- The cell is damaged to such an extent that it dies.
Exposure to radiation can take the form of acute or chronic exposures. If the whole body is exposed to radiation of sufficient intensity to outstrip the cellular repair mechanisms of the body, a condition known as the acute radiation syndrome will result. Acute effects can range from nausea, vomiting and diarrhoea followed by a quick recovery to severe vital system damage and death.

It should be noted that acute radiation exposure cannot occur under any circumstances during the processing of mineral ores.

A chronic dose is a dose that is received over an extended period of time e.g. exposure to background radiation or during work with mineral ores. The harmful effects of chronic radiation exposure are long-term effects. Of these effects, the three most serious are the possibility of increased risk of cancer, the possibility of a shortened life span, and the possibility of a genetic mutation.

Studies have shown that a lifetime dose of 500 mSv may shorten your life by about three months (ICRP 1990). In comparison, smoking one pack of cigarettes a day during your adult life may shorten your life by about three years. Being overweight will statistically shorten your life by more than three years.

In addition to life shortening, the increased risk of cancer is another harmful effect. Relationships between radiation exposure and cancer incidence have been statistically demonstrated in many different occupational groups exposed to ionising radiation. Among these are the occurrence of bone tumours among the early radium watch dial painters, the increased incidence of leukaemia among physicians using X-rays and among the Japanese survivors at Hiroshima, the increased incidence of thyroid cancers and leukaemia in certain patients treated with therapeutic X-rays, and many groups of miners exposed to radon gas and its short lived decay products underground. This last group forms the largest body of evidence related to chronic exposures.

The third harmful effect is the increased possibility of genetic mutations. Any increase in the rate of genetic mutations due to radiation would result in an increase in the total amount of mutations, and by implication an overall reduction in the biological fitness of the species.

The evidence is well established that there is no threshold for the genetic effects of radiation. Any dose of radiation is accompanied by the production of mutations, and the number of mutations produced is proportional to the dose.
20. APPENDIX 4: THE URANIUM AND THORIUM DECAY CHAINS

RADIOLOGICAL CHARACTERISTICS OF MINERALS CONTAINING URANIUM AND THORIUM

The radiological characteristics and properties of uranium and its decay chain radionuclides are complex, as it comprises a mixture of elements and isotopes with significantly different chemical properties. This can have a strong influence on its potential health hazards (Mekisich, M 1988), (UNSCEAR 2000), (Carter, 1983), (Carter et al 1993).

Uranium ore as it is found in nature contains three uranium isotopes and eleven major decay products. These decay products comprise a wide variety of elements with different radiological and chemical properties. In the undisturbed ore the activity concentration of the parent $^{238}\text{U}$ and $^{235}\text{U}$ radionuclides are in secular equilibrium with their main decay products. Secular equilibrium refers to the state where each radionuclide in a piece of ore has the same activity concentration per gram. For example if the $^{238}\text{U}$ activity concentration in the ore is 1 Bq/g$^{-1}$ the activity concentration of each decay product (e.g. $^{234}\text{U}$, $^{230}\text{Th}$, and $^{226}\text{Ra}$) will also be 1 Bq/g$^{-1}$.

Under secular equilibrium conditions the activity concentrations of the decay chain radionuclides in the ore will be equal; however the physical mass of each radionuclide per gram of ore is not the same. The half-life of the decay products are all significantly shorter than the parent $^{238}\text{U}$ radionuclide and as a result the masses of the daughter nuclides in secular equilibrium with 1 gram of $^{238}\text{U}$ are therefore very small. In the uranium decay chains the parent radionuclides will contribute the majority of the mass per gram of 100% uranium ore.

The half-lives of the radionuclides of the uranium decay chain range from 1.3 minutes ($^{210}\text{Tl}$) to 4.5 billion years ($^{238}\text{U}$). The longer lived radionuclides found in the tailings (e.g. $^{238}\text{U}$, $^{234}\text{U}$, $^{230}\text{Th}$, and $^{226}\text{Ra}$) will therefore persist in the tailings for many millions of years into the future.

THE URANIUM DECAY CHAIN

The $^{238}\text{U}$ decay chain comprises fourteen discrete decay steps to stable lead ($^{206}\text{Pb}$) (Refer to Figure below). Each decay step will result in the emission of ionising radiation (alpha or beta particles or gamma photons, or some combination) with characteristic energies and probabilities of emission.

The majority of the radionuclides in the chain have relatively short half-lives; only five radionuclides have half-lives exceeding one year; these are referred to as “long lived radionuclides”

The half-lives of the long lived radionuclides of the $^{238}\text{U}$ Decay Chain are provided in the table below.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>$4.51\times10^9$</td>
</tr>
<tr>
<td>$^{234}\text{U}$</td>
<td>$2.45\times10^5$</td>
</tr>
<tr>
<td>$^{230}\text{Th}$</td>
<td>$7.80\times10^4$</td>
</tr>
<tr>
<td>$^{226}\text{Ra}$</td>
<td>$1.60\times10^3$</td>
</tr>
<tr>
<td>$^{210}\text{Pb}$</td>
<td>21</td>
</tr>
</tbody>
</table>

As a result of the very long half-lives these radionuclides will persist, if released into the environment, for a very long time, and if incorporated into the body they will remain until death.
238U Decay Chain

THORIUM DECAY CHAIN

The parent $^{232}$Th decays to stable $^{208}$Pb through ten decay steps (Refer to Figure below). With the exception of the parent radionuclide $^{232}$Th (half-life $1.41 \times 10^{10}$ years) the daughter half-lives are all less than 7 years. $^{228}$Th and $^{228}$Ra have half-lives measured in years (1.9 to 6.7 years). The remaining radionuclide half-lives range from nanoseconds to 10.64 hours.

There are seven radionuclides, which decay primarily through alpha emission. The most important long-lived alpha emitters of radiological significance are $^{232}$Th and $^{228}$Th. The 224Ra radionuclide with a half life of 3.64 days is not usually included as a long lived alpha emitter when unsupported by $^{232}$Th, however if incorporated into the body is has some radiological significance. Thoron gas ($^{220}$Rn) decays producing a number of short lived alpha emitters which are of radiological significance ($^{216}$Po, $^{212}$Bi and $^{212}$Po) when inhaled.
The symbols α and β indicate alpha and beta decay, and the lines shown are half-lives.

An asterisk indicates that the isotope is also a significant gamma emitter.

232Th Decay Chain
21. APPENDIX 5: AN OVERVIEW OF NATURAL BACKGROUND RADIOACTIVITY AND RADIATION

SOURCES OF EXPOSURE

The UNSCEAR reports provide a wealth of information on background radiation levels across the world. The UNSCEAR reports (1977, 1982, 1988, and 2000) provide extensive data on the exposure of the human population to a variety of natural background radiation sources. Natural radiation and radioactivity in the environment is the major source of collective human exposure to ionising radiation. Human exposure to natural background radiation arises from several main sources, which can vary significantly with space and time (Refer to Figure below). A wide variety of natural alpha, beta and gamma emitting radionuclides are widely distributed throughout the geosphere, hydrosphere, biosphere and atmosphere. Background radiation levels can vary widely with location, altitude, geology and dwelling design. Since human exposure occurs through a variety of pathways (e.g. external, ingestion, and inhalation) all the above factors need to be carefully considered and assessed in order to determine individual and per capita population exposures to background radiation.

Individual Exposure to Natural Radiation

A wide variety of radionuclides contribute to human exposure through a variety of terrestrial and extraterrestrial external and internal exposure pathways. The most important radionuclides contributing to human exposure are those of the $^{238}\text{U}$, $^{232}\text{Th}$ decay series and $^{40}\text{K}$ which are mainly found in the soil. These primordial radionuclides contribute on average ~85% of the total natural background radiation dose to the human population.

Natural uranium comprises two separate decay chains headed by $^{238}\text{U}$ and $^{235}\text{U}$ parent radionuclides and natural thorium a decay chain headed by $^{232}\text{Th}$. The parent radionuclides decay through a complex series of radionuclides (e.g. radium, thorium, polonium, lead, bismuth, thallium,
radon, thoron, thorium, protactinium), which emit a variety of radiations (alpha, beta and gamma radiation).

The main sources of natural radiation exposure and their relative importance are indicated in the Table below.

### Sources of Natural Radiation Exposure and their Relative Importance

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Source</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>External Exposure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External irradiation by gamma rays</td>
<td>Extraterrestrial primary and secondary cosmic rays</td>
<td>Major source. (70% is highly penetrating)</td>
</tr>
<tr>
<td></td>
<td>Terrestrial sources of primordial radionuclides in the soil and air</td>
<td>Major source (soil). (^{238}\text{U},^{235}\text{U},^{232}\text{Th} ) Series and (^{40}\text{K})</td>
</tr>
<tr>
<td><strong>Internal Exposure</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inhalation</td>
<td>Primordial: (^{222}\text{Rn}) Primordial: (^{220}\text{Rn}) Primordial: long lived alphas (dusts) Primordial: (^{40}\text{K}) Cosmogenic: (^{14}\text{C},^{7}\text{Be})</td>
<td>Major source Minor source Minor source Minor source Minor source</td>
</tr>
<tr>
<td>Ingestion (food and water)</td>
<td>Primordial: (^{40}\text{K}) Primordial: long lived alphas Cosmogenic</td>
<td>Minor source Minor source Minor source</td>
</tr>
</tbody>
</table>

### RADIOACTIVITY IN SOILS

Uranium and thorium and their decay products are widely distributed in soils and rocks. An overview of the uranium and thorium concentrations in ppm and the thorium to uranium ratios in common soils and rocks is provided in the Table below.

### The Average Concentrations of Uranium and Thorium in Common Rock Types and Soils

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Th/U ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Ca granite</td>
<td>3.0</td>
<td>17.0</td>
<td>5.7</td>
</tr>
<tr>
<td>High-Ca granite</td>
<td>3.0</td>
<td>8.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Syenite</td>
<td>3.0</td>
<td>13.0</td>
<td>4.3</td>
</tr>
<tr>
<td>Basaltic rocks</td>
<td>1.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Ultramafics</td>
<td>0.001</td>
<td>0.004</td>
<td>4.0</td>
</tr>
<tr>
<td>Shale</td>
<td>3.7</td>
<td>12.0</td>
<td>3.3</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.45</td>
<td>1.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Carbonates</td>
<td>2.2</td>
<td>1.7</td>
<td>0.8</td>
</tr>
<tr>
<td>Deep sea clay</td>
<td>1.3</td>
<td>7.0</td>
<td>5.4</td>
</tr>
<tr>
<td>World soils</td>
<td>2.8</td>
<td>7.4</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Uranium and thorium concentrations in common rock types range widely from 0.001 to 3.7 ppm for uranium, and from 0.004 to 17 ppm for thorium (Faure 1977). Uranium concentrations in the world soils average 2.8 ppm (range 1.3-8.9 ppm) and thorium concentrations average 7.4 ppm (range 2.7-15.7 ppm) (UNSCEAR 2000). Thorium concentrations are usually higher than uranium concentrations in most rock types (range 0.8-5.4 times higher).

It should also be pointed out that absolute values measured across the world, given in the UNSCEAR 2000 Report, are sometimes much higher. For example, concentrations of uranium in soil can be up to 27-30 ppm in Germany and Thailand, and up to 56 ppm in China; concentrations
of thorium in soil have been measured at 44-54 ppm in Kazakhstan, Greece, United Kingdom and Spain, and up to 88 ppm in China.

**URANIUM AND THORIUM DECAY CHAIN RADIONUCLIDES IN AIR**

There are three inhalation components to consider in the air:

- Radon ($^{222}\text{Rn}$) and thoron ($^{220}\text{Rn}$) gas and their short-lived decay progeny.
- Dust particles containing long-lived alpha and beta emitters.
- Free $^{210}\text{Pb}$ and $^{210}\text{Po}$ metallic ions produced by the decay of the short-lived products of the uranium decay chain.

The primary source of radon gas in the air arises from the diffusion of radon produced in the soil across the soil surface layer. The radon gas in the air then rapidly decays into short lived radon decay progeny which are inhaled and irradiate the lung with alpha particles.

The short-lived radon decay progeny in the air eventually decay into $^{210}\text{Pb}$ and then $^{210}\text{Po}$ radionuclides. These two long-lived radionuclides are found at significantly higher concentrations in the air than the long-lived radionuclides in the dust particles suspended from the soil surface.

The overwhelming majority of the radiation dose arising from the inhalation of air is contributed by the short lived decay products of $^{222}\text{Rn}$.

$^{222}\text{Rn}$ gas is the largest single component (~48%) of the total per capita (per individual) dose. Approximately 80% of this exposure usually occurs indoors. It is therefore the most important component to assess accurately when determining the population-weighted exposure to background radiation. In addition the radon concentrations at a specific location will usually vary widely with time. Since it is such an important component of background radiation, it therefore needs to be assessed over at least at full year in order to obtain an accurate mean exposure value.

Important characteristics of radon impacting on any survey strategy are indicated below:

- Gaseous radon is highly mobile and is released from rocks and soils into the atmosphere. In general as the soil uranium concentrations increase, the quantity of radon released per square metre of soil will also increase.
- $^{222}\text{Rn}$ concentrations in outdoor air are largely dependent on the $^{226}\text{Ra}$ concentration in the soil, the $^{222}\text{Rn}$-exhalation rate from the soil and atmospheric dispersion factors.
- Atmospheric radon concentrations vary substantially with location, altitude and the season.
- Values near to and over large areas of water will be lower than over land areas.
- Radon concentrations outdoors usually reach a maximum around sunrise and a minimum in the afternoon; this diurnal variation is largely due to meteorological factors related to ground warming and atmospheric temperature.
- The ratio of the maximum to minimum diurnal variation is usually in the range two to five times.
- Seasonal variations are also observed with minimum values generally occurring in the spring and maxima occurring in the summer and autumn.
- Due its relatively short half-life radon exhibits a sharp vertical concentration profile ranging from a maximum value at the soil-air interface to immeasurable low values in the stratosphere.
- Outdoor concentrations are widely variable; limited studies in Southern Africa (Alara 2002) indicate long term average values ranging from $<10\text{-}150 \text{Bq.m}^{-3}$.
- Indoor concentrations are higher ($<10\text{-}1000\text{s Bq.m}^{-3}$ in South Africa and Europe) and more variable, in particular in northern climates.
- The majority of human exposure arises indoors, and may be many times the outdoor contribution.
- From the radiation protection point of view, the most important property of radon in the
environment is the “equilibrium factor”, which is, simplistically, the indicator of the ratio of concentrations of radon short-lived decay products to the actual radon concentrations. The dose received by people inhaling radon is significantly dependent on this factor and in most situations it is essential to determine the value of this factor specific to a particular mine site and/or processing plant, to ensure that the doses are assessed accurately.

RADIONUCLIDES IN DUSTS

In the airborne particulates, the main natural source of uranium and thorium decay chain radionuclides are the dust particles resuspended from the soil. The dust particles also contain minute quantities of radon and thoron gas which contributes an insignificant dose compared to the longer lived radionuclides found in the dust particles.

The inhalation of dust particles makes only a minor contribution to the total inhalation exposure.

A dust loading of 50 µg/m³ is generally assumed for urban areas (UNSCEAR 1977. 1982, 1988, 2000). With $^{238}$U and $^{232}$Th concentrations in the soil ranging from 25-50 Bq/kg, the concentrations of the parent radionuclides in the air would be expected to be ~1.25-2.5 µBq/m³ and this is generally what is measured. Assuming secular equilibrium the long-lived decay products will also be present in similar concentrations. The measurement of these very low activity levels in air presents significant practical problems.

The resuspension of soil particles is therefore not a significant contributor to $^{210}$Pb and $^{210}$Po concentrations in the air.

THE ANNUAL BACKGROUND RADIATION DOSES

The UNSCEAR 2000 report provides an estimate of the average background radiation exposure of the world population. The annual effective dose arising from the various background radiation sources and exposure pathways is provided in the Table below.

### Average worldwide exposures to sources of natural radiation

<table>
<thead>
<tr>
<th>Source</th>
<th>External Exposure (mSv)</th>
<th>Internal Exposure (mSv)</th>
<th>Total Exposure (mSv)</th>
<th>%</th>
<th>Typical Range (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic radiation</td>
<td>0.38</td>
<td>-</td>
<td>0.38</td>
<td>15.7</td>
<td>0.3-1.0</td>
</tr>
<tr>
<td>Cosmogenic</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Soil (terrestrial radiation)</td>
<td>0.48</td>
<td>-</td>
<td>0.48</td>
<td>19.9</td>
<td>0.3-0.6</td>
</tr>
<tr>
<td>$^{222}$Rn gas</td>
<td>-</td>
<td>1.15</td>
<td>1.15</td>
<td>47.6</td>
<td>0.2-10</td>
</tr>
<tr>
<td>$^{220}$Rn gas</td>
<td>-</td>
<td>0.10</td>
<td>0.10</td>
<td>4.1</td>
<td>-</td>
</tr>
<tr>
<td>Dusts (U-Th) (inhalation)</td>
<td>-</td>
<td>0.006</td>
<td>0.006</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Food and water (ingestion)</td>
<td>-</td>
<td>0.29</td>
<td>0.29</td>
<td>12.0</td>
<td>0.2-0.8</td>
</tr>
<tr>
<td>Total</td>
<td>0.86</td>
<td>1.556</td>
<td>2.416</td>
<td>100</td>
<td>1-10</td>
</tr>
</tbody>
</table>

The mean annual effective dose was estimated to be ~2.4 mSv per annum and refers to the adult part of the population. Variations around this mean value are mainly due to variations in internal exposures due to the inhalation of $^{222}$Rn daughters at indoor locations and external exposures to terrestrial gamma radiation from the uranium and thorium in the soil.

The above data can be summarised as follows:

- Terrestrial sources of radiation account for 84% of the total dose and extraterrestrial sources (cosmic radiation) account for 16% of the total dose.
- Of the terrestrial sources of radiation, internal exposure pathways account for 64% of the total dose and external exposures account for 36% of the total dose.
- Of the internal sources of radiation, inhalation dominates over ingestion and accounts for 81% of the internal dose.
• The short-lived decay products of $^{222}$Rn form the dominant inhalation pathway accounting for 92% of the total inhalation dose.

The short-lived decay products of $^{222}$Rn and $^{220}$Rn account for over half (52%) of the total dose from all natural sources of radiation.

Of the total exposure of ~2.4 mSv per annum, the dust inhalation pathway contributes only 0.25% of the total. The radon and thoron inhalation pathway accounts for 99.20% of the total inhalation dose.

There are wide variations around the average exposure estimate. For example populations living on beach sand deposits (with elevated uranium and thorium levels) located in Brazil, India and India can receive annual doses of up to 50 mSv per annum. Significantly lower than average exposures would be received by mariners who spend a large part of their life at sea. In the open ocean the only radiation exposure of significance would be from cosmic radiation (0.38 mSv) and the ingestion of radionuclides in foods (0.29 mSv).

**FACTORS RESPONSIBLE FOR VARIATIONS IN NATURAL BACKGROUND RADIATION LEVELS**

A wide variety of factors can influence the radiation exposures received by discrete groups of individuals in localised areas. The most important factors and their relative significance are indicated in the Table below.

**Factors Influencing Exposures to Background Radiation**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Example</th>
<th>Impact on Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td>Igneous rocks: high natural radioactivity. Sedimentary rocks: lower radioactivity.</td>
<td>Significant impact. Resulting in local variations in gamma dose rate and $^{222}$Rn gas levels indoors and outdoors.</td>
</tr>
<tr>
<td>Dwelling design</td>
<td>Impacts on internal exposure due to $^{222}$Rn and $^{220}$Rn exposures.</td>
<td>Highly significant, particularly in cold and temperate climates due to reduced air exchange with outdoor air of lower radon concentration.</td>
</tr>
<tr>
<td>Dwelling design</td>
<td>Impacts on gamma exposures due to shielding.</td>
<td>Moderate effect on indoor gamma exposures.</td>
</tr>
<tr>
<td>Altitude</td>
<td>Cosmic component of external exposure. Double in Johannesburg compared to Cape Town.</td>
<td>Significant effect with increasing altitude as air shielding decreases.</td>
</tr>
<tr>
<td>Life styles</td>
<td>Cultural factors.</td>
<td>Can be significant as longer periods may be spent outdoors in equatorial areas.</td>
</tr>
<tr>
<td>Population distribution</td>
<td>Interacts in a complex way with other factors such as geology, altitude, dwelling design and living patterns.</td>
<td>Can be highly significant, e.g. high population density at altitude (e.g. Johannesburg) and in areas of elevated terrestrial dose rates (e.g. The heavy mineral deposits on the north east coast of KwaZulu-Natal).</td>
</tr>
<tr>
<td>Other factors</td>
<td>Rainfall, flooding, water logging, atmospheric inversion layers.</td>
<td>Minor effect on internal ($^{222}$Rn) and external exposure. Highly localised and of short term duration.</td>
</tr>
<tr>
<td>Island and coastal populations</td>
<td>May result in reduced $^{222}$Rn exposures by dilution with ocean air.</td>
<td>Minor effect due to possible localised effects due to sea air of low radon concentration swamping land based radon sources.</td>
</tr>
</tbody>
</table>
22. APPENDIX 6: THE CHARACTERISTICS OF MONAZITE AND ZIRCON

MONAZITE (Ce, La, Nd, Th) PO₄

Monazite is a weather resistant, hard, stable chemical compound containing rare earth elements (REE) and is a common constituent in the heavy mineral fraction of sediments. Apart from the REE content, the naturally occurring radioactive elements uranium and thorium are both present in monazite. It is a common accessory in granites, gneisses and syenites and is often concentrated in fluvial and marine placers. It is hard and very heavy (4.6 to 5.7 g/cm³) and is moderately resistant to weathering.

Monazite typically contains 28% cerium, 14% lanthanum, 10% neodymium, 7% thorium and 30% phosphate. Uranium concentrations vary between 0-3%, thus contributing in a significant manner towards the radioactivity potential of monazite.

There are at least four different kinds of monazite, depending on the relative elemental composition of the mineral:

- Monazite-Ce (Ce, La, Pr, Nd, Th, Y) PO₄
- Monazite-La (La, Ce, Nd, Pr) PO₄
- Monazite-Nd (Nd, La, Ce, Pr) PO₄
- Monazite-Pr (Pr, Nd, Ce, La) PO₄

A typical chemical composition of monazite is presented in the Table below.

Example of a Typical Monazite Chemical Composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ThO₂</td>
<td>6.94</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>30.67</td>
</tr>
<tr>
<td>Y₂O₃</td>
<td>2.68</td>
</tr>
<tr>
<td>CaO</td>
<td>1.66</td>
</tr>
<tr>
<td>UO₂</td>
<td>1.54</td>
</tr>
<tr>
<td>Gd₂O₃</td>
<td>1.28</td>
</tr>
<tr>
<td>Sm₂O₃</td>
<td>1.66</td>
</tr>
<tr>
<td>Nd₂O₃</td>
<td>9.64</td>
</tr>
<tr>
<td>Pr₂O₃</td>
<td>2.77</td>
</tr>
<tr>
<td>Ce₂O₃</td>
<td>27.54</td>
</tr>
<tr>
<td>La₂O₃</td>
<td>14.13</td>
</tr>
<tr>
<td>SiO₂</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Although the structure of monazite is fairly resistant to normal chemical attack, it is often in a metamict state. This is caused by the structural damage from the Th and U alpha emitters, which are present in small amounts in monazite. As is the case with zircon, U and Th atoms are housed within selected positions in the crystal lattice and do not occur as distinctly separate mineral inclusions within the monazite matrix.

ZIRCON (ZrSiO₄)

The radioactive elements associated with heavy mineral deposits are mainly hosted within zircon grains. Because zircon is a stable chemical compound, it is a common constituent in the heavy mineral fraction of sediments. Zircon sand (containing zirconium as the silicate) currently the only commercial sources of zirconium. Heavy mineral deposits are the main economic source of these minerals.
The naturally occurring radioactive elements uranium and thorium are present in both zircon and baddeleyite. The structure of zircon is shown in the Figure below. Although the structure of zircon is resistant to normal chemical attack, it is often in a metamict state.

The nature of the zircon crystal inhibits the removal of uranium and thorium and is one of the properties that allow this mineral to be used for the dating of rocks (Selby: 2001). The U and Th atoms are firmly locked in the lattice and the decay products e.g. polonium remains in the crystal even up to temperatures of 1200°C (Selby: 2001).

The structure of zircon. The eight bonds from each zircon atom to neighbouring oxygen’s are shown only at the centre of the figure

METAMICTIZATION

Metamictization is a natural process resulting in the gradual and ultimately complete destruction of a mineral’s crystal lattice, leaving the mineral amorphous. Affected material is therefore described as metamict.

Certain minerals occasionally contain interstitial impurities of radioactive compounds and it is the alpha radiation emitted from these compounds that is responsible for degrading a mineral’s crystal structure through internal bombardment. An example of a metamict mineral is zircon. The presence of the uranium mineral coffinite and the thorium mineral thorite are responsible for the radiation damage. Unaffected specimens are termed high zircon while metamict specimens are termed low zircon. Specimens falling between the two extremes are termed intermediate. Metamict minerals can have their crystallinity and properties restored through prolonged annealing.

In order to assess the extent of liberation of radioactive elements from the crystal structure of zircon, it is necessary to determine the metamict state of the zircon grains. In general, the fresh zircon grains are resistant to chemical attack and do not pose a risk in terms of the liberation of radioactive elements.
RADIATION SOURCES AND HAZARDS

The following radiation hazards and sources usually require some form of consideration with regard to designed engineering controls.

a) External exposure i.e. gamma radiation
   - Stockpiles
   - Plant process
   - Silos/storage areas

b) Internal exposure: inhalation (primary route), ingestion (minor route)
   - Radioactive dusts (primary route in most areas)
   - Spills and leakages from the process
   - Radon/thoron gas (this is usually a minor exposure route except in enclosed spaces e.g. tunnels, silos,

GENERIC METHODS USED TO REDUCE RADIATION EXPOSURES

The main methods of reducing radiation hazards and doses comprise the following engineered and administrative controls:

External Exposure
   - Limit occupation time (automation, machinery)
   - Increase distance (location of sources in relation to workers)
   - Provide shielding (bunkers, silos, stockpiles)
   - Location of fixed working positions/plant controls/control room in relation to sources (optimise)
   - Good housekeeping i.e. limiting the spread of materials (spillage controls)

Internal Exposure
   - Provide engineered controls i.e. use an enclosed process (negative pressure), particulate filters, area ventilation and water sprays
   - Limit occupation time
   - Good housekeeping i.e. limiting the spread of materials (dust controls)
   - Respiratory protection (only during maintenance not normal operations)

MINING ACTIVITIES

Controls to be considered during mining activities include the following:

Access controls e.g. fences
   - HMC feed and MSP tails stockpiles (to limit the spread of these materials)
   - Transport aspects (e.g. to limit the spread of HMC or tails along the transport route to the MSP)
   - Methods of working at the HMC stockpiles
   - The primary focus should be on limiting the spread of HMC and MSP tails materials e.g. during loading, transport and disposal
ACTIVITIES AT THE MSP

Siting of the security fence – A security fence will be installed around the MSP and its associated stockpiles.

Siting of the control room – The precise siting of control rooms in the plant should be assessed with regard to access requirements and the prevailing gamma dose rates and inhalation hazards. The design may require to incorporate dust and ventilation controls (e.g. double doors and positive pressure) and should be situated in a low gamma dose rate area.

Stockpiles, bulk handling and storage – High activity materials (e.g. zircon and monazite tails) may require to be stored in bins and bunkers and remotely handled e.g. conveyor to tails bin.

Limiting the spread of stockpiled materials – This can be achieved by building bunds, bunkers and containers, installing water sprays, using surface polymers or covering materials and using shade cloth barriers. Methods by which open stockpiles can be limited in size and remotely moved require to be investigated.

Engineered dust controls – The installation of engineered dust controls in the dry circuits is critical. Dust is normally created at separation units, bucket elevators, conveyor transfer points and drier stacks. The main control mechanism would be to place enclosures around these points, then connect the enclosures and drier stacks to a dust extraction system, filters and an exhaust stack. Plant air from outside the enclosures would also be vented through enclosures, dust filtration systems and exhaust stacks.

Engineered dust controls are required to contain abnormal dust creation, e.g. arising from blockages of the process flow resulting in spillages and sand rain. The design should provide for catchment containers, which then direct the material to appropriate recycling points.

Effluent controls – Provision for engineered controls over the movement of water and liquid effluents.

CONTROLS OVER WATER AND LIQUID EFFLUENTS

Aspects and controls to consider with regard to process waters, storm waters and effluents include:

- Closed loop circulation
- Separation of sewers from all plant waters
- Material collectors/sumps
- Control/collection of storm waters
- Linings, under drains, trenches
- Stockpile locations and their protection from storm waters to limit spread of materials

PROTECTION OF THE PUBLIC

Aspects and controls that require to be considered include:

- Access controls over entry into the mine and processing sites
- The need for engineered controls over particulate releases from stacks e.g. bag filters and electrostatic precipitators.
- Engineered controls over particulate releases from stockpiles, mining activities and tailings dams, e.g. wetting down, surface binders, bunker storage, good housekeeping.
- Engineered controls over the release of process water that may contain suspended mineral particles to surface waters, e.g. controls over the movement of process waters, storm water controls, separation of water circuits, provision of bunds and overflow ponds.
• Engineered controls over the release of process water that may contain suspended mineral particles into the groundwater, e.g. control water movements on site, use under drains for stockpiles.
• Engineered controls over waste management and disposal.
• Engineered controls over the movement of radioactive materials offsite, e.g. through storm water controls and by limiting the spread of stockpiles.
24. APPENDIX 8: AN OVERVIEW OF THE CES IMPACT RATING SYSTEM

INTRODUCTION

The key radiation impacts are rated using the CES impact rating system. To ensure a direct comparison between specialist studies, six standard rating scales are defined and used to assess and quantify the identified impacts. This is necessary since impacts have a number of parameters that need to be assessed. The rating system used is based on three criteria, namely:

- The relationship of the issue to temporal scales
- The relationship of the issue to spatial scales
- The severity of the issue

These three criteria are combined to describe the overall importance rating, namely the significance. In addition, the following parameters are used to describe the impacts:

- The risk or likelihood of the issue occurring
- The degree of confidence placed in the assessment of the issue

TEMPORAL SCALE

The temporal scale defines the significance of the impact at various time scales, as an indication of the duration of the impact.

- **Short term** - less than 5 years. Many construction phase impacts are of a short duration.
- **Medium term** - between 5 and 20 years.
- **Long term** - between 20 and 40 years (a generation) and from a human perspective almost permanent.
- **Permanent** - over 40 years and resulting in a permanent and lasting change that will always be there (e.g. long term disposal of radioactive tails).

SPATIAL SCALE

The spatial scale defines the physical extent of the impact.

- **Individual** - this scale applies to a person or persons in and around the study area.
- **Localised** - at localised scale and a few hectares in extent. The specific area to which it refers is defined in the chapter in which it appears.
- **Study area** - the proposed area and its immediate environs.
- **District** – name the district
- **Regional** – Name province
- **National** – Name country
- **International**

RISK OR LIKELIHOOD

The risk or likelihood scale defines the likelihood that the impact will occur.

The risk categories are as follows:

- Very unlikely to occur – the chance of these impacts occurring is extremely slim.
- Unlikely to occur – the risk of these impacts occurring is slight.
- May occur – the risk of these impacts is more likely, although it is not definite.
- Will definitely occur – there is no chance that this impact will not occur.
DEGREE OF CONFIDENCE OR CERTAINTY

A ‘degree of certainty’ scale has been provided to enable the reader to ascertain how certain the specialists are of their assessment of significance:

**Definite:** More than 90% sure of a particular fact. To use this, one will need to have substantial supportive data.

**Probable:** Over 70% sure of a particular fact, or of the likelihood of that impact occurring.

**Possible:** Only over 40% sure of a particular fact or of the likelihood of an impact occurring.

**Unsure:** Less than 40% sure of a particular fact or of the likelihood of an impact occurring.

SEVERITY/BENEFICIAL RATING SCALE

The *severity/beneficial scale* is used to evaluate how severe negative impacts would be, or how beneficial positive impacts would be on a particular affected system or a particular affected party (Refer to the Table below). It is a methodology that attempts to remove any value judgements from the assessment, although it relies on the professional judgement of the specialist.

The severity of impacts is evaluated with and without mitigation in order to demonstrate how serious the impact is when nothing is done about it. The word ‘mitigation’ means not just ‘compensation’, but also the ideas of containment and control. For beneficial impacts, optimisation means anything that can enhance the benefits. However, mitigation or optimisation must be practical, technically feasible and economically viable.
Impact Severity/Benefit Scale

<table>
<thead>
<tr>
<th>Very severe</th>
<th>Very beneficial</th>
</tr>
</thead>
<tbody>
<tr>
<td>An irreversible and permanent change to the</td>
<td>A permanent and very substantial benefit to the</td>
</tr>
<tr>
<td>affected system(s) or party (ies) which cannot</td>
<td>affected system(s) or party(ies), with no real</td>
</tr>
<tr>
<td>be mitigated. For example the permanent loss</td>
<td>alternative to achieving this benefit. For example</td>
</tr>
<tr>
<td>of land or in this case marine resources.</td>
<td>the creation of improved access.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Severe</th>
<th>Beneficial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long term impacts on the affected system(s) or</td>
<td>A long term impact and substantial benefit to the</td>
</tr>
<tr>
<td>party(ies) that could be mitigated. However, this</td>
<td>affected system(s) or party(ies). Alternative ways</td>
</tr>
<tr>
<td>mitigation would be difficult, expensive or time</td>
<td>of achieving this benefit would be difficult,</td>
</tr>
<tr>
<td>consuming, or some combination of these. For</td>
<td>expensive or time consuming, or some combination of</td>
</tr>
<tr>
<td>example, the clearing of forest vegetation.</td>
<td>these. For example an increase in the local economy.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moderately severe</th>
<th>Moderately beneficial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium to long term impacts on the affected system(s) or party(ies), that could be mitigated. For example constructing a narrow road through vegetation with low conservation value.</td>
<td>A medium to long term impact of real benefit to the affected system(s) or party(ies). Other ways of optimising the beneficial effects are equally difficult, expensive and time consuming (or some combination of these), as achieving them in this way. For example a slight improvement in the existing roads.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Slight</th>
<th>Slightly beneficial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium or short term impacts on the affected system(s) or party(ies). Mitigation is very easy, cheap, less time consuming or not necessary. For example a temporary fluctuation in the water table due to water abstraction.</td>
<td>A short to medium term impact and negligible benefit to the affected system(s) or party(ies). Other ways of optimising the beneficial effects are easier, cheaper and quicker, or some combination of these. For example, a slight increase in the amount of goods available for purchasing.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No effect</th>
<th>Don’t know/Can’t know</th>
</tr>
</thead>
<tbody>
<tr>
<td>The system(s) or party(ies) is not affected by the proposed development.</td>
<td>In certain cases it may not be possible to determine the severity of an impact.</td>
</tr>
</tbody>
</table>

SIGNIFICANCE SCALE

The significance scale is an attempt to evaluate the importance of a particular impact. A six-point significance scale is used.

In many environmental assessment cases scientists have to evaluate impacts in the absence of the necessary data. Under these circumstances the consultant must make clear that such information is lacking if the incomplete information is essential to a reasoned choice among alternatives. If the overall costs of obtaining it are not exorbitant, then the information should be included in the EIA.

There are two acceptable procedures to follow to compensate for a shortage of data:

1. It is more important to identify likely environmental impacts than to precisely evaluate the more obvious impacts
2. All assessors (the different specialists) try to evaluate all the significant impacts, recognising that precise evaluation is not possible. It is better to have a possible or unsure level of certainty on important issues than to be definite about unimportant issues.

Due to the fact that assessing impacts with a lack of data is more dependable on your own scientific judgement, the rating on the certainty scale cannot be too high. If the evidence for a potential type of impact is not definitive in either direction, the conservative conclusion is that the impact cannot be ruled out with confidence, not that the impact is not proven. It is for these
reasons that a degree of certainty scale has been provided, as well as the categories DON’T KNOW and CAN’T KNOW.

THE SIGNIFICANCE RATING SCALE

VERY HIGH

These impacts would be considered by society as constituting a major and usually permanent change to the (natural and/or social) environment, and usually result in severe or very severe effects, or beneficial or very beneficial effects.

Example: The loss of a species would be viewed by informed society as being of VERY HIGH significance.

Example: The establishment of a large amount of infrastructure in a rural area, which previously had very few services, would be regarded by the affected parties as resulting in benefits with VERY HIGH significance.

HIGH

These impacts will usually result in long term effects on the social and/or natural environment. Impacts rated as HIGH will need to be considered by society as constituting an important and usually long term change to the (natural and/or social) environment. Society would probably view these impacts in a serious light.

Example: The loss of a diverse vegetation type, which is fairly common elsewhere, would have a significance rating of HIGH over the long term, as the area could be rehabilitated.

Example: The change to soil conditions will impact the natural system, and the impact on affected parties (such as people growing crops in the soil) would be HIGH.

MODERATE

These impacts will usually result in medium to long term effects on the social and/or natural environment. Impacts rated as MODERATE will need to be considered by society as constituting a fairly important and usually medium term change to the (natural and/or social) environment. These impacts are real but not substantial.

Example: The loss of a sparse, open vegetation type of low diversity may be regarded as MODERATELY significant.

Example: The provision of a clinic in a rural area would result in a benefit of MODERATE significance.

LOW

These impacts will usually result in medium to short term effects on the social and/or natural environment. Impacts rated as LOW will need to be considered by the public and/or the specialist as constituting a fairly unimportant and usually short term change to the (natural and/or social) environment. These impacts are not substantial and are likely to have little real effect.

Example: The temporary change in the water table of a wetland habitat, as these systems are adapted to fluctuating water levels.

Example: The increased earning potential of people employed as a result of a development would only result in benefits of LOW significance to people who live some distance away.
**NO SIGNIFICANCE**

There are no primary or secondary effects at all that are important to scientists or the public.

**Example:** A change to the geology of a particular formation may be regarded as severe from a geological perspective, but is of NO significance in the overall context.

**DON’T KNOW**

In certain cases it may not be possible to determine the significance of an impact. For example, the primary or secondary impacts on the social or natural environment given the available information.

**Example:** The effect of a particular development on people’s psychological perspective of the environment.