NORTHERN MINERALS LIMITED

Browns Range Rare Earths Project

Radiation Technical Report

Revised FINAL

June 2014

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Northern Minerals Limited (NML) is proposing to develop the Browns Range Rare Earth Project (BRP) for the production of both light and heavy rare earth elements near Halls Creek in Western Australia.

The project consists of a number of discrete ore deposits containing naturally occurring uranium (U) and thorium (Th) as oxides. The concentrations of U and Th in the deposits are approximately 40ppm and 30ppm respectively. These concentrations of U and Th are below the classification for radioactive material, however, during processing, some radionuclides concentrate and exceed the trigger for classification as a "radioactive material".

NML have chosen to consider the occupational and environmental radiological impacts of the proposed project, and the assessment is contained in this document.

Existing radiological work associated with the project includes;

- Baseline radiological survey (Radiation Professionals 2013)
- Air quality assessment report (Air Assessments 2014 – in draft).
- Metallurgical testwork report (ANSTO 2013 and ANSTO 2014)

These documents will be referred to in this document where appropriate.

1. RADIATION & RADIATION PROTECTION

1.1 INTRODUCTION

This document assumes a basic understanding of physics, chemistry and the principles of radiation protection. A brief summary of the key aspects is provided to re-enforce terms and concepts used in this document. For a more detailed introduction to radiation and radiation safety, refer to the published work, *Radiation Workers Handbook* (http://www.aua.org.au/Content/RadiationSafety.aspx).

1.1.1 OVERVIEW OF RADIATION

"Radiation" is a term used to describe the movement or transfer of energy through space or through a medium. It occurs when unstable atoms give off radiation to move to a lower energy state. The unstable atoms are known as "radionuclides" and when they exist in a material (such as rocks), above a prescribed concentration, the material is classified as "radioactive".

When a radionuclide emits radiation, it changes into a new element or a different isotope of the same element, which is known as the decay product. Usually a decay product is itself radioactive and emits radiation, changing into a new decay product. This sequence of decays is known as a decay chain which ends when the newly formed decay product is stable (non-radioactive) isotope.

There are three naturally occurring decay chains and the head of these decay chains are two isotopes of uranium (uranium 238 and uranium 235) and an isotope of thorium (thorium 232) as seen in Figure 1.

Figure 1: U^{238}, U^{235} and Th^{232} Decay Chains

Uranium-238 Decay Chain

Radionuclide	Half-life	Decay
Uranium-238	4.5×10^9 a	a
Thorium-234	24.1 d	b, g
Protactinium-234m	702 s	b, g
Uranium-234	2.5×10^5 a	a
Thorium-230	7.5×10^4 a	a,
Radium-226	1.6×10^3 a	a, g
Radon-222	3.82 d	a
Polonium-218	183 s	a
Lead-214	1608 s	b, g
Bismuth-214	1194 s	b, g
Polonium-214	1.6×10^{-6} s	a
Lead-210	22.3 a	b, g
Bismuth-210	5.0 d	b, g
Polonium-210	138.4 d	a
Lead-206	stable	

Uranium-235 Decay Chain

Radionuclide	Half-life	Decay
Uranium-235	7.0×10^8 a	a, b, g
Thorium-231	1.1 d	b, g
Protactinium-231	3.3×10^4 a	a, g
Actinium-227	21.8 a	b, g
Thorium-227	18.7 d	b, g
Radium-223	11.4 d	a, g
Radon-219	3.96 s	a, g
Polonium-215	1.8×10^{-3} s	a g
Lead-211	2166 s	b, g
Bismuth-211	128 s	b, g
Polonium-211	0.5 s	a, g
Thallium-207	286.2 s	b, g
Lead-207	stable	

Thorium-232 Decay Chain

Radionuclide	Half-life	Decay
Thorium-232	1.41×10^{10} y	a, b, g
Radium-228	5.57 a	b
Actinium-228	6.13 h	b, g
Thorium-228	1.91 a	a
Radium-224	3.66 d	a, g
Radon-220	55.6 s	a
Polonium-216	0.145 s	a
Lead-212	10.6 h	b, g
Bismuth-212	3630 s	a, b, g
Thallium-208	186 s	b, g
Lead-208	stable	

ARPANSA 2008: Management of Naturally Occurring Radioactive Material (NORM) - Radiation Protection Series Publication No. 15, August 2008

Note that naturally occurring uranium contains both the U^{235} and U^{238} decay chains. The mass ratio of U^{235} to U^{238} is approximately 0.7% and the activity ratio is 4%.

1.1.2 DESCRIBING THE IMPACTS OF RADIATION

Radionuclides occur naturally in soils, water and the air, and are responsible for the naturally occurring radiation known as “background radiation”. Background radiation is variable and causes radiation exposure to people everywhere.

When discussing impacts of radiation on people, it is usual to say that people are “exposed” to radiation resulting in a “dose”. The term “dose” is a standardised measure of radiation impact, reported as “Sieverts” (Sv), which takes into account the different types of radiation and the way that exposure occurs.

The effects of radiation depend upon the size of the dose received. At high doses, above 1Sv, a range of radiation effects are *immediately* observable in individuals. At doses below about 1Sv, effects are observable in populations or groups of people, and there is a *probability* that the dose may result in an impact to an individual. Below a dose of 0.1Sv, it is difficult to observe any effects, however, it is assumed that the probability of an effect still exists.

Background radiation produces doses ranging from 1 to 10mSv/y (0.001 to 0.01Sv/y) in different parts of the world. In Australia, the average dose from background radiation is about 2.3mSv/y (http://www.arpansa.gov.au/radiationprotection/basics/understand.cfm).

To describe the amount of radioactivity in a material, it is usual to use the term “activity” or “activity concentration”. The unit of activity is the Becquerels (Bq) which is equivalent to one radioactive decay per second. For example, a rock may contain 100Bq of U^{238}, meaning there are 100 radioactive decays occurring in the rock each second. A more common way to describe the radioactivity in a material is through its activity concentration. For example, the same rock may weigh 100grams (g), therefore the activity concentration of the rock is 1Bq/g.

1.2 FRAMEWORK FOR RADIATION PROTECTION

Radiation is well regulated by state legislation which is based on national and internationally accepted approaches that aim to ensure that radiological impacts to people and the environment from projects are maintained at acceptable levels.

1.2.1 INTERNATIONAL APPROACH

Radiation and its effects have been studied for almost 100 years and there is International consensus on its effect and controls. The main organisations that contribute to knowledge on radiation and radiation protection and provide guidance and standards are as follows:

- The United National Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (http://www.unscear.org) provides an authoritative overview of the effects of radiation by regularly reviewing and collating leading research and publishing the summaries.
- The International Atomic Energy Agency (IAEA) (http://www.iaea.org) develops and publishes “codes of practice” and provides broad advice on basic safety precautions when dealing with radiation.
- The International Commission on Radiological Protection (ICRP) (http://www.icrp.org) is recognised as the pre-eminent authority on radiation protection and regularly publishes specific guidelines and recommendations on radiation protection.

In Publication 26 (ICRP 1977), the ICRP recommended a “system of dose limitation” which has become the internationally accepted foundation for radiation protection and is universally adopted as the basis of legislative systems for the control of radiation and as the basis for standards. It is made up of three key elements as follows:

- “Justification” – a practice involving exposure to radiation should only be adopted if the benefits of the practice outweigh the risks associated with the radiation exposure.

- "Optimisation" – radiation doses received should be As Low As Reasonably Achievable, taking into account economic and social factors (also known as the ALARA principle).
- "Limitation" – individuals should not receive radiation doses greater than the prescribed dose limits.

The ALARA principle is generally regarded as the basis of radiation protection. In the design stage of a project ALARA means identifying radiation hazards and making design, engineering and infrastructure decisions to ensure that potential doses to workers, the public and the environment are as low as reasonably achievable. During operations, ALARA is usually part of wider continuous improvement.

While the ALARA principle is the foundation for radiation protection, radiation dose limits have been established to provide an absolute level of protection. The limits apply to the total radiation dose, as a result of a "practice", from all exposure pathways (excluding natural background radiation), and are;

- an annual limit to a worker of 20mSv (occupational dose), and
- an annual limit to a member of the public of 1mSv.

When assessing compliance with the limits, occupational doses may be averaged over a five-year period and there is an absolute annual limit of 50mSv in any one year for workers. (ICRP 2007)

1.2.2 AUSTRALIAN NATIONAL APPROACH

The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is the Australian National authority on radiation protection. ARPANSA co-ordinates national uniformity on radiation protection and develops national codes of practice based on the IAEA and the ICRP publications.

The primary National Codes of Practice in Australia related to radiation protection in the mining or processing of radioactive materials are:

- Recommendations for Limiting Exposure to Ionising Radiation (ARPANSA 2002)
- The Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing 2005 (ARPANSA 2005)
- The Code of Practice for the Safe Transport of Radioactive Material 2008 (ARPANSA 2008)
- Safety Guide for the Management of Naturally Occurring Radioactive Material (ARPANSA 2008)

1.2.3 WESTERN AUSTRALIAN APPROACH

In Western Australia, the primary controlling legislation is the Radiation Safety Act (RSA) 1975 and associated legislation. Radiation is also subject to regulation under the Mines Safety and Inspection Act 1994 and associated legislation.

The Department of Mines and Petroleum in Western Australia has issued the NORM guidelines which is a series of documents that provide detailed advice on radiation protection in mines. These documents have been used to guide the radiation management measures for the NML Browns Range project.

1.2.4 CLASSIFICATION FOR RADIOACTIVE MATERIAL

The primary guidance for radioactive materials is provided in national standards by the Australian Radiation Protection and Nuclear Safety Agency (ARAPNSA). ARPANSA 2005 and ARPANSA 2014 note that material containing naturally occurring radionuclides in secular equilibrium, with head-of-chain uranium or thorium activity concentrations less than 1 Bq/g would generally be considered inherently safe and therefore exempt from regulation. 1Bq/g is equivalent to 81ppm uranium or 245ppm thorium and also applies to the combined activity if both decay chains are present.

(For example, if a material contains 0.5Bq/g of uranium (as U^{238}) and 0.2Bq/g of thorium (as Th^{232}), then the activity of the material is considered to be 0.7Bq/g.)

Table 1 provides a comparison of the radionuclide concentrations of material currently associated with the project and the classification levels for radioactive material.

Table 1: Uranium and Thorium Content of NML Related Materials

Material	Uranium		Thorium	
	(ppm)	(Bq/g)	(ppm)	(Bq/g)
Soils (above ore body)	1.2	0.02	11	0.05
Ore Bodies (average)	40	0.50	30	0.12
Threshold for Classification as Radioactive	81	1.0	245	1.0

ARPANSA (ARPANSA 2014) provides guidance for materials that contain radionuclides that are not in secular equilibrium. In these cases, the concentrations of individual radionuclides in the material are divided by exemption threshold levels (provided in ARPANSA 2014) and the fractions are added together. If the total exceeds 1, then the material is defined as radioactive.

2. PROJECT OVERVIEW

2.1 SUMMARY

NML is intending to undertake mining and processing of xenotime ore for the production of light and heavy rare earths at its Browns Range deposit near Halls Creek in Western Australia.

Ore is planned to be mined from up to 5 open-cut mines at a rate of approximately 750,000tpa, with the ore being processed through an onsite metallurgical processing facility. Unmineralised mining overburden is to be placed into a waste rock storage facility, with process residues disposed in a purpose built tailings storage facility (TSF).

The assessment in this document is based on the following facilities;

- 5 open-cut mines (approximately 200m deep and base surface area of 1Ha each)
- crushing and grinding circuit,
- physical separation plant (including magnetic separation and flotation)
- acidification and roasting plant,
- precipitation and calcinations,
- waste rock disposal facility, and
- tailings disposal facilities.

Ancillary facilities include; reagent storage area, sulphuric acid plant, water treatment plant, warehouse, workshops, offices, change-rooms and control rooms.

The mined ore is below the criteria for classification as a radioactive material, however, the metallurgical processing indirectly concentrates radionuclides in various processes, therefore radiation impacts have been considered.

The processing methods are not new and the radiological aspects are manageable through effective design controls and management measures.

2.2 MINING

Ore will be mined from up to 5 separate open-cut mines using conventional mining methods.

For this assessment, it has been assumed that each open-cut mine is circular, with identical sizes of diameter of 350m by 200m deep. The basement footprint of each of the mines (where mineralised material would be exposed) is expected to be approximately 1Ha.

The volume of each open-cut mine is therefore calculated to be approximately 10Mm^3 (using the formulae for a truncated cone).

Barren overburden will be placed in waste rock storage stockpiles, with no specific radiological design requirements or constraints and ore will be trucked to surface stockpiles for processing.

For this assessment, it is assumed that the maximum ore stockpile will be 100,000tpa.

The mineralised material contains an average of 40ppm uranium and 30ppm thorium. As noted in section 1.2.4, the mineralised material does not exceed the classification for a radioactive material.

2.3 PROCESSING

The metallurgical testwork has shown that concentrations of radionuclides from the U^{238}, U^{235} and Th^{232} decay chains vary through the processing plant as the ore undergoes a range of chemical and metallurgical processes which affect the various elements differently (ANSTO 2013, 2014).

The processing plant consists of two main sections; a benefication plant and a hydrometallurgical plant.

In the benefication plant, following crushing and grinding, magnetic separation is used to reject inert material, with approximately 80% of the feed material being rejected at this step. The remaining 20% of the feed material undergoes a flotation step to produce a mineral concentrate containing rare earth minerals and elevated concentrations of other metals including radionuclides. The flotation underflow stream is combined with the magnetic separation reject material to produce a beneficiation tailings which is approximately 96% of the mass flow, with the mineral concentrate forming approximately 4% of the mass flow.

As well as concentrating the rare earth minerals, this process also concentrates other heavy metals, including uranium and thorium which are expected to reach 620ppm and 240ppm respectively. At these levels, the concentrate exceeds the classification for “radioactive” and is defined as a radioactive material, requiring an assessment of potential impacts on people and the environment and consideration of appropriate controls.

Residue from the milling and flotation process, known as the benefication tailings, will contain radionuclides in concentrations similar to the ore and is consequently not defined as radioactive.

The mineral concentrate is dried and combined with sulphuric acid in a baking kiln and then leached in water. The output is a leach solution, containing the minerals and a separate solid residue. The leach solution (also known as “pregnant liquor solution” (PLS)), which contains the rare earths and other impurities then undergoes purification during which radionuclides and other metals, such as iron and aluminium, are selectively precipitated and removed as residue streams. An ion exchange purification step will remove remnant impurities from the PLS which will then be treated with oxalic acid and the precipitate calcined to produce a final product for export. Approximately 4,000tpa of mixed rare earth oxide will be produced.

The various residue streams from the hydrometallurgical processes will be combined into a single residue stream that will be combined with the beneficiation tailings to produce an overall process tailings stream that will be disposed of in a purpose built tailings storage facility. The concentration of uranium and thorium in the combined tailings will be practically identical to the ore (approximately 40ppm uranium and 30ppm thorium), meaning that means that the combined tailings is will not be classified as a radioactive material.

3. RADIOLOGICAL ASSESSMENT

3.1 INTRODUCTION

The potential radiological impacts of the proposed project are detailed in this section. Impacts are assessed as potential radiation exposures to workers, the public and the environment and are based on such factors as the radionuclide content of process materials, deportment of radionuclides through the processing and a description of emission sources.

3.2 RADIONUCLIDE CONTENT OF PROCESS MATERIALS

The ANSTO (ANSTO 2014) testwork provided an indication of the radionuclide content of various process materials. The work shows that radionuclides concentrate in a number of the process streams and a summary is provided in Table 2.

Table 2: Radionuclide Concentrations in Main Processing Plant Streams

Radionuclide	Ore	Benefication Concentrate	Impurity Removal PLS	Ion Exchange PLS	Final Product	Final Tailings	
	Bq/g	*Bq/g*	*Bq/mL*	*Bq/mL*	*Bq/g*	*Bq/g*	*Bq/mL*
U^{238}/U^{234}	0.6	7.6	0.396	0.012	< 1	0.3	0.041
Th^{230}	0.5	5.5	0.0033	0.0033	< 1	0.4	0.0005
Ra^{226}	0.6	6.8	0.0004	0.0004	< 1	0.6	0.0002
Pb^{210}	0.6	7.9[a]	0.0022	0.002	< 1	0.6	0.0005
U^{235}	0.03	0.30	0.018	0.0005	< 1	0.02	0.002
Ac^{227}	0.02	0.30	0.029	0.029	< 1		
Th^{232}	0.1	1.1	0.0006	0.0006	< 1	0.1	0.0001
Ra^{228}	0.1	0.9	0.000.	0.0003	< 1	0.1	0.0001
Th^{228}	0.1	0.9	0.0006	0.0006	< 1	0.1	0.0001

Note that the results presented in Table 2 are actual analytical results of individual samples from bench-top test work and the NML final product target. Therefore these results may vary from mine averages that are used elsewhere in this report.

3.3 AIR EMISSIONS

NML has commenced assessing the impact of its operation on ambient air quality through air quality modelling (Air Assessment 2104 – in draft). Air quality modelling uses meteorological data and predicted emission data (known as source terms) to model the concentrations of the emissions at locations around the operation with results usually presented as contour plots. The results provide an indication of the impact of the project above natural background levels.

For radiological impact assessment it is usual to use the annual average results produced from air quality modelling. This is because the basis of radiation exposure limits is full years. (For example, the member of the public radiation dose limit is 1mSv per year).

The radiological impacts from air emissions from the project are calculated from air quality modelling as follows:

- An estimate of the radionuclide content of emitted dusts is combined with the dust concentration and dust deposition contours plots to calculate the radionuclide in air concentration and radionuclide deposition impacts.
- Radon (Rn^{222} and Rn^{220}) gas concentrations are used to calculate the respective decay product concentrations.

Particulate emission rates from the processing plant facility have yet to be considered in the air quality modelling because final source terms have not been finalised. It is not expected that processing plant dust sources will significantly contribute to the impacts.

Therefore, for the radiological assessment, the modelled particulate emission impact contours have been conservatively increased by 50% to account for any processing plant emissions. (Note that this is very conservative. A review of a similar project shows that particulate emission from the processing facility is approximately 10% of the mining emissions (Alkane 2013)).

Air Assessments 2014 – in draft (AA2014) was also based on lower uranium and thorium in ore grades, therefore the assess impacts of radon and thoron have been increased by 50% to account for this.

3.3.1 PARTICULATE EMISSIONS

AA2014 notes that PM10 particulate emissions from mining and tailings management is approximately 30.8g/s. The report also notes the following:

- The emission estimates are for the first year of operations, when maximum earthmoving will be occurring.
- The proportion of waste rock (overburden) to ore during this period is greater than 15:1.
- The proportion of dust emissions from the tailings storage facility from wind erosion is approximately 10% of the total wind erosion emissions.
- Wind erosion accounts for approximately 10% of all dust emissions.

Therefore ore dust is estimated to be 10% of the total dust emissions and dust lift off from tailings would be approximately 1% of all dust emissions. (Note that tailings dust has been considered to have the same radionuclide content as ore.)

For the radiological assessment, it has been assumed that 10% of the dust emissions are ore and 90% of the dust emissions are inert overburden.

The draft air quality assessment indicates that the modelled 24 hour TSP concentration at the closest receptor is 50µg/m^3 at the accommodation village.

As noted, the mineralised component of dust is estimated to be 10% of the total dust emitted from the project. Therefore, the TSP concentration can be converted to a radionuclide concentration at the accommodation village as follows:

- Radionuclide composition of dust = 10% x radionuclide concentration in ore + 90% x radionuclide concentration in overburden
- Radionuclide concentration in ore from Table 2.
- Assume the overburden contains 10ppmU and 10ppmTh, giving 0.12Bq/g U and 0.04Bq/g Th
- Uranium radionuclide composition of dust (Bq/g) =0.1 x 0.6 + 0.9 x 0.12 = 0.17Bq/g
- Thorium radionuclide composition of dust (Bq/g) =0.1 x 0.1 + 0.9 x 0.04 = 0.05Bq/g.

Based on modelled dust concentration and the uranium and thorium activity concentration of the dust, the average radionuclide concentration at the accommodation area is calculated to be is 8.5 and 2.5µBq/m^3 respectively for each radionuclide in the U^{238} and Th^{232} decay chains. Receptors at sites further away would experience lower concentrations.

Due to the limitations from the incomplete air quality assessment, the 24 hour maximum concentration has been used, which will overestimate the longer term annual conditions by at least a factor of two.

3.3.2 RADON AND THORON

The radon isotopes that are of interest in this assessment are radon222 (Rn^{222}) and radon220 (Rn^{220}). Rn^{222} (from the uranium decay chain) is usually known as “radon” and Rn^{220} (from the thorium decay chain) is known as “thoron”.

Rn^{222} is a product of the U^{238} decay chain and has a half-life of 3.8 days. It is produced from the decay of Radium (Ra^{226}) which exists naturally in soils, rocks and water. Rn^{222} makes its way into the atmosphere by diffusing through the host material. Rn^{220} is a decay product of the Th^{232} decay chain and has a half-life of less than one minute. It is produced when its parent, Ra^{224} undergoes alpha decay. With such a short half-life, Rn^{220} is less likely to diffuse to the atmosphere from its host material before decaying to its decay product. In the event that it is able to diffuse, its short half-life means that it does not travel far in air before decaying. (UNSCEAR 2000 Annex b).

Radon and thoron are not significant sources of radiation exposure however the decay products are radioactive solids and can be hazardous if inhaled in high concentrations. The radon and thoron act as transport mechanisms for the more hazardous decay products and it is usual to model the gas concentrations and convert to the decay product concentration.

The major emissions sources that were considered were;

- Mine
- Ore stockpile
- Processing facility
- Residue storage facility

3.3.2.1 RADON (Rn^{222})

Details of the radon emission factors are provided in Appendix B. The radon emissions were calculated as follows:

Mine

The rate of radon emission that has been used in 0.5Bq(Rn^{222})/m^2.s per Bq(Ra^{226})/g. For mineralised material containing uranium with a grade of 40ppm (which is equivalent to approximately 0.5Bq/g of Ra^{226}), the calculated radon emission rate is 0.25Bq/m^2.s. For a mine area of 1Ha, this gives an emission rate of 2.5kBq/s.

Ore Stockpile

Emissions rates are higher for broken ore per unit areas due to the higher surface area. BHP Billiton calculated a factor of 5 for converting unbroken ore emission rates to broken ore emission rates (BHP Billiton 2009). Therefore, for a stockpile of 100,000t of ore (assuming a rectangular stockpile) the surface area is 11,000m^2, giving an emission rate of 0.25Bq/m^2.s x 11,000m^2 x 5 = 13.8kBq/s.

Processing Facility

For the processing facility, the rate of radon emission release is conservatively assumed to be the total contained radon in the ore that is process over the full year. Therefore, if 750,000t of ore is processed each year, then the total contained radon that could be released in one year is; 750,000 x 10^6g/y x 0.5Bq/g. This equates to 12kBq/s.

Residue Storage Facility

For the residue storage facility, the rate of radon emission is based on the US EPA "Final Rule" for uranium tailings which is 1Bq(Rn^{222})/m^2.s per Bq(Ra^{226})/g. Therefore for the NML ore which contains uranium with a grade of 40ppm (0.5Bq(Ra^{226})/g), the calculated radon emanation rate from the mine is 0.5Bq/m^2.s. The residue storage facility is expected to be 73Ha. Therefore the maximum emanation rate would be 365kBq/s.

A summary of the radon emissions is provided in Table 3.

Table 3: Radon Source Estimates used in Atmospheric Modelling

Source	Radon Emissions (kBq/s)
Mining*	13
Stockpiles	14
Processing Plant	12
Residue Storage Facility	365

* Mining assumes 5 open-cut mines in operation at the same time

The air quality modelling provides average annual estimates of Rn^{222} concentrations in Bq/m^3, above natural background concentration. The average incremental radon concentration at the accommodation village is approximately 0.1Bq/m^3.

The radon decay product (RnDP) concentrations can be determined from radon concentrations using standard constants that convert the gas concentrations to decay product concentrations at equilibrium and are described by the following (UNSCEAR 2008);

- 1Bq/m^3 of radon (in equilibrium with its decay products) is equivalent to 5.56nJ/m^3 of RnDP.

Therefore the conservative estimate of the RnDP concentration at the accommodation village is approximately 0.6nJ/m^3.

3.3.2.2 THORON (RN^{220})

Estimates of thoron emission rates are difficult and variable. Details are provided in appendix B. The thoron emissions were calculated as follows:

MINE

The thoron emissions rates from thorium mineralised material used in this report is 10(Rn^{220})Bq/m^2.s per Bq(Ra^{224})/g, which equates to an emission rate of 1.0Bq/m^2s for the NML ore (containing 30ppm Th which is equivalent to approximately 0.1Bq/g of Ra^{224} assuming secular equilibrium). For a mine area of 1Ha, this gives an emanation of 10kBq/s.

STOCKPILE

Using the method outlined for Rn^{222} emission, including a factor of 5 for broken ore, the Rn^{220} emission rate from a 100,000t stockpile of ore is calculated to be 1.0Bq/m^2s x 11,000 m^2 x 5 = 55kBq/s.

PROCESSING PLANT

For the processing facility, the rate of thoron emission release is conservatively assumed to be the total contained radon in the ore that is process over the full year. Therefore, if 750,000t of ore is processed each year, then the total contained radon that could be released in one year is; 750,000 x 10^6g/y x 0.1Bq/g. This equates to 2.2kBq/s.

RESIDUE STORAGE FACILITY

For the residue storage facility, the rate of thoron emission used in this report is 10(Rn^{220})Bq/m^2.s per Bq(Ra^{224})/g, which equates to an emission rate of 1.0Bq/m^2s for the NML. For a residue storage facility of 73Ha, the maximum emanation rate would be 730kBq/s.

A summary of the thoron emissions can be seen in Table 4.

Table 4: Thoron Source Estimates used in Atmospheric Modelling

Source	Thoron Emissions (kBq/s)
Mining*	50
Stockpiles	55
Processing Plant	2.2
Residue Storage Facility	730

* Mining assumes 5 open-cut mines in operation at the same time

Note that the very short half-life (55.6s) of thoron means that even if it is able to emanate from ore, then it will not travel far before decaying [UNSCEAR 2000]. The half-life factor has been taken into account as part of the air quality modelling. The modelling indicates that the thoron concentration at the accommodation village will be approximately 0.0001Bq/m^3.

The thoron decay product (TnDP) concentrations can be determined from thoron concentrations using standard constants that convert the gas concentrations to decay product concentrations at equilibrium and are described by the following (UNSCEAR 2000 Annex B clause 122);

- 1Bq/m^3 of thoron (in equilibrium with its decay products) is equivalent to 76nJ/m^3 of TnDP

Therefore at the accommodation village, the TnDP concentration is approximately 0.008nJ/m^3**.**

Based on the modelled results, it can be seen that environmental and public impacts of project originated thoron are negligible.

3.3.3 RADIONUCLIDE DEPOSITION

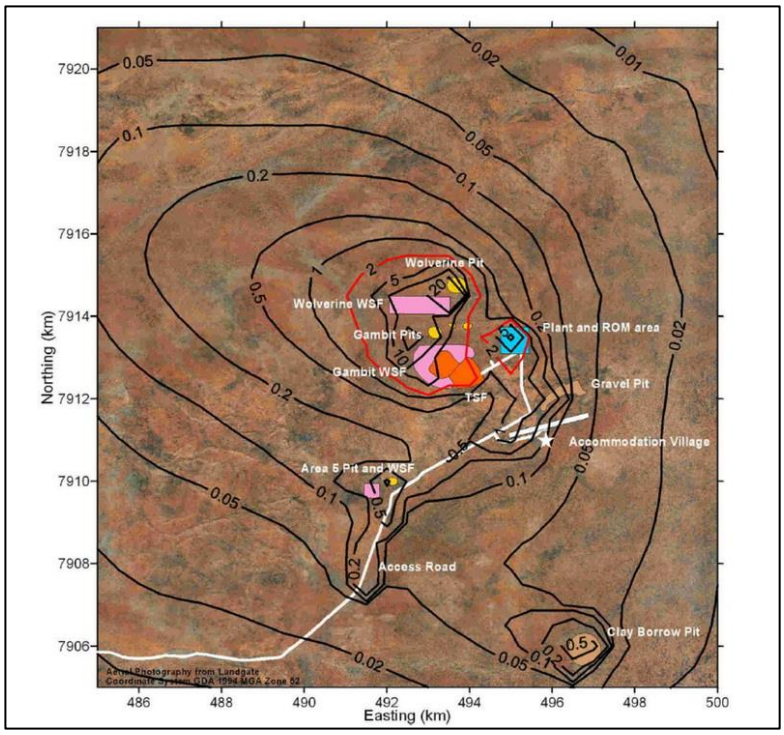
Dusts containing radionuclides from the proposed project may deposit from the air. Deposited radionuclides can potentially lead to changes in soil and surface water radionuclide concentrations and result in impacts on flora and fauna.

The air quality modelling provides predicted contours of dust deposition from the proposed activities which can be converted to radionuclide concentrations using the activity of the dusts (uranium being 0.5Bq/g, thorium being 0.1 Bq/g) and assuming secular equilibrium.

Figure 2 shows the modelled dust deposition in g/m^2.month. The deposition at the accommodation village is approximately 0.2 g/m^2.month. Based on the radionuclide composition of the dust emissions (as outlined in section 3.3.1), the annual deposition of radionuclides from dust equates is calculated by multiplying the dust deposition rate by the number of months by the specific activity of the dust. This gives deposition of;

- 0.4Bq/m^2 per year for U^{238} and its decay products, and
- 0.12Bq/m^2 per year for Th^{232} and its decay products.

Figure 2: Modelled Dust Deposition Contours (g/m^2.month) (Air Assessments 2014 – in draft)



3.4 OCCUPATIONAL DOSE ASSESSMENT

Radiation from the project can impact on workers resulting in doses. The dose assessment aims to estimate the potential doses based on the characteristics of the project and the material being handled and processed.

3.4.1 OPEN-CUT MINERS

The activity concentrations of uranium and thorium in the ore are less than the cut off for classification as radioactive however, an assessment of doses has been conducted for miners.

The main exposure pathways are;

- gamma irradiation,
- inhalation of radon decay products (RnDP) and thoron decay products (TnDP), and
- inhalation of radionuclides in dust.

For the dose assessments, the following assumptions have been made;

- each open-cut mine has nominal surface area of 10Ha and a base area of 1 Ha and a depth of 200m,
- the base of the mine is mineralised material,
- the walls are inert,
- the activity concentrations of uranium and thorium grades of the ore are 0.5Bq/g and 0.1Bq/g respectively and
- a work year consists of 2,000 hours.

3.4.1.1 GAMMA RADIATION

Estimates of gamma radiation doses are based on published factors (WA NORM guidelines and IAEA 2006) for gamma radiation from radionuclides in the thorium decay chain. The guidelines provide factors to convert an average uranium or thorium grade into a gamma dose rate at one metre above that material. Table 5 shows the factors and the calculated dose rates for the estimated grades of the mineralised material.

Table 5: Gamma Dose Rate and Calculation Factors for Miners

Decay chain	Conversion factors (µSv/h *per* %)	Estimated Grade (%)	Dose rate (µSv/h)
U^{238}	35	0.004	0.14
Th^{232}	16	0.003	0.05

The total dose rate is the sum of the dose-rate from the U^{238} and Th^{232} decay chains, being approximately 0.19µSv/h. (Note that the dose rate is slightly higher than natural background gamma radiation levels.)

This corresponds to an annual calculated dose of 0.38mSv/y. This estimate does not take into account any shielding factor from equipment and assumes that all work hours are spent in mineralised areas.

3.4.1.2 RnDP and TnDP Exposure

To estimate the doses from RnDP and TnDP, a number of factors need to be taken into account. These include;

- the rate of emission of radon and thoron gas into the mine voids,
- the rate at which the mine is ventilated (mine air changes),
- the mine equilibrium concentration of radon and thoron gas,
- the calculation of decay product concentration from gas concentration and calculation of exposure, and
- the conversion of exposure to dose.

As part of this assessment, the number of work hours, assumed to be 2,000h/year, and standard dose conversion factors have also been used.

Rate of Radon Emission

It has been assumed that each of the proposed open-cut mines will be approximately the same dimension and that there is an exposed base of mineralised material of 1Ha per mine. It is assumed that all broken rock has been removed from the mine. The emission figures provided in section 3.3, show that the total emission into each mine void is 2.5kBq/s.

Rate of Thoron Emission

The assumptions are the same for radon emissions and based on the emission figures provided in section 3.3. The total thoron emission into each mine void is 10kBq/s.

MINE AIR CHANGES

The number of air changes per hour in an open-cut mine can be calculated using a formula of Thompson 1993 as follows;

$$T = 33.8 \times (V/U_rLW) \times (0.7\cos(x)+0.3),$$

where:

T = rate of change (h),

V = mine volume (m^3) – (calculated to be = 10Mm^3 – see section 2.2)

L and W = mine length and width (m) – (length and width are estimated to be 350m)

Ur = the surface wind speed (m/h) – (assumed to be 3m/s (10,800 m/h)

x = angle of the wind relative to the longer mine dimension. (Note that the modelling assumes a circular mine, making (0.7cos(x) + 0.3) equal to 1 in the calculation).

Entering the values into the formula gives 0.25h, which is 4 air changes per hour.

MINE EQUILIBRIUM RADON AND THORON CONCENTRATIONS

The equilibrium concentration is the steady state concentration of gas that is reached when the generation rate is balanced by the ventilation rate. For a radioactive gas, the half-life is important as decay of the gas will also occur. For radon, the half-life is sufficiently long to discount the effect of decay, however it needs to be considered for thoron.

The equilibrium concentration of radon in any volume is calculated as follows (Cember 2009);

[Rn]Bq/m^3 = {Radon generation rate (Bq/h)} / {(Volume x air changes per hour)}.

The radon generation rate is 2. kBq/s (calculated by multiplying the unit area emission rate by the emission area), therefore, the radon equilibrium concentration is;

[Rn]Bq/m^3 = (2.5kBq/s x 3,600s/h) / (10Mm^3 x 4/h) = 0.2 Bq/m^3.

As the half-life of thoron is short (less than 1 minute), it needs to be taken into account when calculating the equilibrium concentrations. The formula used is as follows (from Cember 2009).

[Tn]Bq/m^3 = Thoron generation rate/((Ventilation rate) + (volume x λ),

Where;

λ is the decay constant for thoron ($1.33x10^{-2}s^{-1}$),

the ventilation rate is calculated by dividing the mine volume by the number of air changes per second.

This gives a thoron equilibrium concentration of 0.01Bq/m^3.

Calculation of Decay Product Concentration from Gas Concentration and Calculation of exposure

The conversion of radon or thoron gas concentrations to the respective decay product concentrations requires assumptions about the ratio between the gas and its decay products (known as the equilibrium factor). Published guidance in Western Australian (WA Govt 2010b) provides equilibrium factors and a method for calculating the decay product concentration. The guideline notes the following factors;

- Equilibrium factor for radon
  - 0.4 for indoors
  - 0.2 for outdoors
- Equilibrium factor for thoron
  - 0.1 for indoors
  - 0.02 for outdoors

The decay product concentrations are then calculated as follows (using the most conservative equilibrium factors and standard conversion factors).

$[RnDP\ nJ/m^3] = 5.56nJ/Bq \times 0.2Bq/m^3 \times 0.4 = 0.4nJ/m^3$

$[TnDP\ nJ/m^3] = 75.7nJ/Bq \times 0.01Bq/m^3 \times 0.1 = 0.1nJ/m^3$

An exposure for the full year can then calculated by multiplying the concentrations by the exposure hours and breathing rates as follows;

$[RnDP\ \mu J/y] = 0.4x10^{-3}\mu J/m^3 \times 2000h/y \times 1.2\ m^3/h = 1.0\mu J/y$

$[TnDP\ \mu J/y] = 0.1x10^{-3}\mu J\ J/m^3 \times 2000h/y \times 1.2\ m^3/h = 0.25\mu J/y$

Calculation of Doses

ARPANSA 2005 provides dose conversion factors for radon and thoron decay products as follows;

- Radon decay products = 1.2Sv/J
- Thoron decay products = 0.39Sv/J.

Using these factors gives doses as follows;

- 1.2µSv/y from RnDP and
- 0.1µSv/y from TnDP.

This is the calculated potential dose above natural background.

The combination of low grade and relatively high wind speed means that RnDP and ThDP do not constitute a risk for miners.

3.4.1.3 AIRBORNE DUST

The assessment of radioactive dust dose is based on an estimated total suspended dust concentration in the mine of 1mg/m^3.

The ore dust is estimated to contain 0.5Bq/g of radionuclides from the U^{238} and 0.1Bq/g of radionuclides from the Th^{232} decay chains, giving an activity concentration of the dust as 0.5mBq/m^3 (U^{238}) and 0.1mBq/m^3 (Th^{232}). The NORM guidelines (WA Govt 2010b) provide factors to convert an activity intake (through inhalation) to a dose (called dose conversion factors (DCF)) and are;

- U^{238} chain = 3.6 x 10^{-5} Sv/Bq, and
- Th^{232} chain = 6.8 x 10^{-5} Sv/Bq.

Note that the DCFs assume that the dust contains radionuclides in the respective decay chains that are in secular equilibrium (that is; the activity concentration of each of the decay products is same as the head of the decay chain).

Dose is calculated by multiplying the airborne activity concentration by the amount of air inhaled during a working year. This is calculated by multiplying the average breathing rate (1.2m^3/h) by the average hours worked in one year (2,000h/y) (Ref: ICRP), giving an inhaled volume of 2,400m^3/y. The inhaled activity is then calculated by multiplying the radionuclide concentration of the dust by the inhaled volume and this gives; 1.2Bq for the U^{238} chain and 0.24Bq for the Th^{232} chain.

Multiplying by the DCF gives 43uSv/y from the U^{238} decay chain and 16uSv/y from the Th^{232} chain.

3.4.1.4 SUMMARY OF OCCUPATION RADIATION DOSES FOR MINERS

A summary of the estimated doses is provided in Table 6.

Table 6: Occupational Dose Estimates for Miners

Work Group	Average Annual Dose (mSv/y)					
	Gamma	Decay Products		Dust		Total
		Radon	Thoron	Uranium	Thorium	
Miners	0.380	0.000	0.000	0.043	0.016	0.439

3.4.2 PROCESSING PLANT WORKER DOSES

In 2013, ANSTO (ANSTO 2014) conducted testwork on process material which provides an indication of potential radionuclide concentrations in the process streams. As noted in Section 3.2, radionuclides concentrate in various process materials throughout the processing plant requiring an assessment of potential doses to workers.

The main areas where materials may result in employee exposure are;

- Ore handling and milling (gamma exposure and dust from ore),
- Mineral concentrate handling (gamma exposure and dust from mineral concentrates),
- Baking (emissions during baking), and
- Hydrometallurgy (spillages that have dried and dusted).

Doses have been assessed for workers in these areas.

It should be noted that there may be specific tasks which will result in higher exposure to workers, including some maintenance tasks (such as cleaning of baghouses). Exposures in these situations have not been included in this dose assessment because these tasks would be conducted under work permit situations, requiring specific protection measures and, in addition, the individual tasks would not generally be full time jobs. Section 4 provides an outline the general radiation management measures (including radiation work permits) that would be implemented to ensure that doses remain controlled and low.

The primary exposure pathways are;

- gamma irradiation,
- inhalation of radionuclides in dust.

For surface operations, doses from inhalation of the decay products of radon and thoron are usually considered to be negligible because the emitted radon and thoron quickly dilutes in the atmosphere, resulting in little to no exposure. Therefore doses for this pathway have not been calculated.

For gamma radiation, increased exposure occurs when workers are working near large quantities of materials than contain higher concentrations of radionuclides. Exposure decreases with distance from the source material. An assessment has been conducted to quantify the maximum expected gamma dose.

In the processing plant, the major exposure pathway is through the inhalation of radionuclides in dust. The radionuclide content of materials from these areas can be seen in Table 7.

Table 7: Radionuclide Concentrations in Main Processing Plant Streams

Radionuclide	Ore	Mineral Concentrate	Baking	Hyrdromet PLS
	Bq/g	*Bq/g*	*Bq/g*	*Bq/mL*
U^{238}/U^{234}	0.6	7.6	7.6	0.396
Th^{230}	0.5	5.5	5.5	0.0033
Ra^{226}	0.6	6.8	6.8	0.0004
Pb^{210}	0.6	7.9[a]	7.9	0.0022
U^{235}	0.03	0.30	0.30	0.018
Ac^{227}	0.02	0.30	0.30	0.029
Th^{232}	0.1	1.1	1.1	0.0006
Ra^{228}	0.1	0.9	0.9	0.0003
Th^{228}	0.1	0.9	0.9	0.0006

Maximum inhalation dose assessments have been made based on these materials.

3.4.2.1 GAMMA RADIATION

The uranium and thorium levels in the mineral concentrate are could reach approximately 620ppm and 240ppm respectively, with material located in stockpiles of up to 4,000t. This is likely to be the area in the processing plant where gamma levels would be highest. Accordingly, the assessment has considered the potential gamma doses to a worker working full time in the area that directly handles the mineral concentrate.

Using the standardised gamma factors for uranium and thorium (WA Govt. 2010 and IAEA 2006), the gamma dose-rate from the mineral concentrate can be calculated, and can be seen in Table 8.

Table 8: Gamma Dose Rate and Calculation factors for Mineral Concentrate Workers

Decay chain	Conversion Factors (µSv/h *per* %)	Inferred Grade (%)	Dose rate (µSv/h)
U^{238}	35	0.062	2.2
Th^{232}	16	0.024	0.4

The total dose rate is the sum of the dose-rate from the U^{238} and Th^{232} decay chains, being approximately 2.6µSv/h.

For this assessment, the maximum potential exposure scenario is based on a worker who spends all of their working time adjacent to a stockpile of the mineral concentrate material (at a distance of 1m). This scenario is unlikely, but has been included to identify the maximum possible gamma dose.

This scenario calculates to an annual calculated dose of 5.2mSv/y and does not take into account practicalities such as shielding from equipment and actual working location. Experience shows that measured gamma doses are usually less than the calculated figures and it is unlikely that a worker would spend all of their work time at a distance of one metre form the material. Therefore it is expected that gamma doses would not exceed 3mSv/y.

Although the mineral concentrate is being processed in the acid bake area, it is unlikely that gamma doses will be elevated due to the smaller volumes of material and the fact that the material will be inside a steel hearth which would significantly attenuate gamma radiation from the material.

Gamma levels may be elevated in the leach plant area, but are expected to be lower than for the acid bake area and the mineral concentrate area due to the material being in slurry form (and therefore more disperse). All other areas are expected to have low gamma rate. Experience in other leach processing plant (Arup 2009) indicates that gamma doses are approximately 1mSv/y.

3.4.2.2 DUST EXPOSURES

The method to calculate processing plant radionuclide in dust doses is identical to that used for miners. This broadly involves calculating an exposure (based on exposure hours and an estimate of radionuclides in dust in air concentrations) and then applying a dose conversion factor specific to the type of dust inhaled (which is based on the radionuclide content of the dust).

For the dust dose assessment, the following assumptions have been made:

- Dust is generated from the process material, therefore the process material radionuclide concentrations can be used to estimate the dose conversion factors for the dusts.
- Dust concentrations in the ore milling/handling, mineral concentrate handling and baking area have been conservatively estimated to be 2mg/m^3, (note that in practice, higher concentrations would be untenable requiring remediation or mandatory personal protective equipment).

- The process material in the hydrometallurgy area is in liquid form and therefore not readily inhalable. However, a very conservative exposure estimate has been made where it has been assumed that spillage occurs which dries and then dusts. It is assumed that all of the radionuclides in 1 litre of liquid reports to one gram of dust. The annual average dust concentrations have been estimated to be 0.2mg/m^3, (a factor of 10 times lower was applied since material will mainly be in liquid form and spillages would not be a regular event.)

The dust dose conversion factors (DCFs) for the materials have been calculated using the IAEA 1996 Basic Safety Standards dose conversion factors (IAEA 1996).

The calculated dust doses for the processing plant workers can be seen in the Table 9 based on;

- the specific radionuclide content of process material streams,
- DCFs provided in IAEA 1996,
- the most conservative solubility class,
- an activity median aerodynamic diameter of 1µm,
- a breathing rate of 1.2m^3/h,
- a working year of 2,000h/y and
- the estimated dust concentrations.

Table 9: Estimated Dust Doses for Processing Plant Workers

Processing Plant Material	Dust Doses (mSv/y)
Ore Milling/Handling	0.14
Mineral Concentrate Handling	1.5
Baking	1.5
Hydrometallugical PLS	3.1

3.4.2.3 SUMMARY OF OCCUPATIONAL RADIATION DOSES FOR PROCESSING PLANT WORKERS

A summary of the estimated doses is provided in Table 10.

Table 10: Processing Plant Work Area Doses

Processing Plant Work Area	Doses (mSv/y)		
	Gamma	Dust Inhalation	Total
Ore Milling/Handling	0.4*	0.14	**0.54**
Mineral Concentrate Handling	3.0	1.5	**4.5**
Baking	1.0	1.5	**2.5**
Hydrometallugical PLS	1.0	3.1	**4.1**

* Based on open-cut miners doses.

As noted, the assessments presented here are considered to be conservative and represent maximum doses.

3.4.3 UNDERGROUND MINERS

NML is planning to undertake underground mining as well as open-cut mining. Design work is preliminary, however an initial assessment of the potential doses for underground miners has been made. For this assessment, mine averages have been assumed based on conservative but realistic exposure parameters.

3.4.3.1 GAMMA RADIATION

Estimates of gamma radiation doses are based on published gamma factors (WA NORM guidelines and IAEA 2006) for gamma radiation from radionuclides in the thorium decay chain. The factors are valid for 2π exposure situation (exposure from one side). To take account of a 4π exposure situation in an underground mine (where exposure is from all sides), the gamma factors have been doubled and the dose rates can be seen in Table 11.

Table 11: Calculated Gamma Doses for Underground Miners

Decay chain	4π Conversion factors (µSv/h *per* %)	Estimated Ore Grade (%)	Dose rate (µSv/h)
U^{238}	70	0.004	0.28
Th^{232}	32	0.003	0.10
Total			0.38

The calculated doses, based on 2,000 hours per year working underground, the average dose is calculated to be 760µSv/y.

3.4.3.2 RnDP and TnDP

To determine the potential doses from inhalation of RnDP and TnDP, it has been assumed that all underground workplaces will be ventilated with fresh air from intake raises or via fans and ducting that pump fresh air to workplaces.

However, a conservative exposure scenario has been developed which involves workers at a workplace at the beginning of a 200m underground tunnel, with dimensions of 5m by 5m. Fresh air is being pumped to the face of the tunnel, however, the air flows back along the tunnel and reaches the workplace. Therefore, emissions of radon and thoron from the walls of the drive result in a concentration building up along the length of the drive.

The method for calculating the concentration at the end of the drive takes into account the emission rate and the ventilation rate.

It is assumed that the uranium grade of the underground workings is 40ppm and the thorium grade is 30ppm. The emission rates (as shown in appendix B) are 0.25Bq/m^2.s for radon and 1Bq/m^2.s for thoron.

Therefore for a tunnel that is 200m by 5m by 5m, the total surface area is 4,000m^2, giving a total emission rate of 1kBq/s for radon and 4kBq/s for thoron.

If it is assumed that the air is moving at 1m/s, (equivalent to 25m^3/s) then the residence time of the radon and thoron in the drive is 200s. The exit concentration of radon and thoron is therefore 40Bq/m^3 and 160Bq/m^3 respectively.

The radon and thoron decay product (RnDP and TnDP) concentrations can be calculated from radon and thoron concentrations using standard constants as follows; (UNSCEAR 2000 Annex B clause 122);

- 1Bq/m^3 of radon (in equilibrium with its decay products) is equivalent to 5.56nJ/m^3 of RnDP
- 1Bq/m^3 of thoron (in equilibrium with its decay products) is equivalent to 76nJ/m^3 of TnDP

If it is assumed that the equilibrium factors (the ratio between the gas concentration and the decay product concentration) are 0.2 and 0.02 (based on the high ventilation rate), then the RnDP and TnDP concentrations are 44nJ/m^3 and 243nJ/m^3.

For a worker exposed for 2,000 h/y at a breathing rate of 1.2m^3/h, then the exposure is calculated as follows:

- 44nJ/m^3 x 1.2 m^3/h x 2,000 h/y, which gives 0.1mJ/y
- 243nJ/m^3 x 1.2 m^3/h x 2,000 h/y, which gives 0.6mJ/y

ARPANSA 2005 provides dose conversion factors for radon and thoron decay products as follows;

- Radon decay products = 1.2Sv/J
- Thoron decay products = 0.39Sv/J.

Using these factors gives doses as follows;

- 1.2mSv/y from RnDP and
- 0.2mSv/y from TnDP.

3.4.3.3 AIRBORNE DUST

The assessment of radioactive dust dose is based on an estimated total suspended dust concentration in the mine of 2mg/m^3.
Using the method outlined in Section 3.4.1.3, the estimated dust dose to underground miners is 86µSv/y from the U^{238} decay chain and 32µSv/y from the Th^{232} chain, giving a total inhalation dust dose of 118µSv/y.

3.4.3.4 SUMMARY OF UNDERGROUND DOSES

A summary of the estimated doses is provided in Table 12. Table 13 provides a comparison of reported doses from a similar operation in South Africa.

Table 12: Occupational Dose Estimates for NML

Work Group	Average Annual Dose (mSv/y)				
	Gamma	RnDP	TnDP	Dust	Total
Underground Miners	0.8	1.2	0.2	0.1	2.3

Table 13: Radiation Doses at Other Operation

Mine	Total Average Annual Dose (mSv/y)
Palabora Mine South Africa (NORM, 2013)	1.0[1]

Note 1: Doses reported for mine and plant workers mining and treating a copper ore containing naturally occurring uranium at concentrations greater than 1 Bq/g.

3.5 PUBLIC DOSE ASSESSMENT

This section describes the potential radiological impacts to the public. This occurs when emissions from inside the project impact on people outside the project.

The closest areas occupied by the public are;

- Residents of Ringer Soak (approximately 25km WNW of the project area)
- Occasional visitors to the special water hole (approximately 10km W of the project area)

However, the air quality modelling does not extend this far due to impacts being negligible at these distances from the project. Therefore, the public dose assessment has been conducted at the project accommodation village location.

This location is relatively close to the project area and would give a "worst case" dose estimate. People living at locations further away would experience lower impacts.

The exposure scenario is for a person living and working in the accommodation village full time, with a full year exposure (8,760 hours per year).

There are three main exposure pathways that are considered when assessing dose to members of the public. These are;

- Gamma irradiation,
- Inhalation of the decay products of radon and thoron,
- Inhalation of radionuclides in dust.

Of these exposure pathways, gamma radiation is not considered to be significant because sources of gamma radiation are well within the mine lease area and inaccessible. Gamma radiation levels decrease significantly with distance, therefore levels beyond the boundary of the processing plant and mine will be negligible.

3.5.1 INHALATION OF THE DECAY PRODUCTS OF RADON AND THORON

In Sections 3.3.2.1 and 3.3.2.2, the RnDP and TnDP concentrations at the accommodation village were presented from the air quality modelling. This showed that average annual concentrations were;

- 0.6nJ/m^3 for RnDP, and
- 0.008nJ/m^3 for TnDP.

An exposure for the full year can then calculated by multiplying the concentrations by the exposure hours and breathing rates as follows;

- [RnDP μJ/y] = 0.6x10^{-3}μJ/m^3 x 8760h/y x 1.2 m^3/h = 1.1μJ/y
- [TnDP μJ/y] = 0.008x10^{-3}μJ/m^3 x 8760h/y x 1.2 m^3/h = 0.01μJ/y

ARPANSA 2005 provides dose conversion factors for radon and thoron decay products as follows;

- Radon decay products = 1.2Sv/J
- Thoron decay products = 0.39Sv/J.

Using these factors gives doses as follows;

- 1.3µSv/y from RnDP and
- 0.004µSv/y from TnDP.

As explained in the last paragraph of Section 3.3, the revised doses are;

- 1.9µSv/y from RnDP and
- 0.008µSv/y from TnDP.

3.5.2 INHALATION OF RADIONUCLIDES IN DUST

In section 3.3.1, the air quality modelling results showed that the average airborne TSP particulate concentration at the accommodation village was approximately 50µg/m^3. Based on the weighted average of the radionuclides in the dust sources, the equivalent radionuclides in airborne dust concentrations were calculated to be;

- 8.5µBq/m^3 for U^{238} (and its decay products)
- 2.5µBq/m^3 for Th^{232} (and its decay products).

An exposure for the full year can then calculated by multiplying the concentrations by the exposure hours and breathing rates as follows;

- U^{238} in dust exposure mBq/y = 8.5x10^{-3}mBq/m^3 x 8760h/y x 1.2 m^3/h = 89mBq/y
- Th^{232} in dust exposure mBq/y = 2.5 x10^{-3}mBq/m^3 x 8760h/y x 1.2 m^3/h = 26mBq/y

The exposure can be converted to dose using the dose conversion factors provided in IAEA 1996 and assuming the most conservative solubility classes and using a 1µm particle size (AMAD) giving annual inhalation doses of;

- 3.2µSv/y (for U^{238} decay chain)
- 1.8µSv/y (for Th^{232} decay chain).

The calculated doses to a resident of the accommodation can be seen in Table 14.

Table 14: Predicted Dose to closest public group

Public Group	Dose From Pathway (mSv/y)					
	Gamma Radiation	Inhalation of RnDP	Inhalation of TnDP	Inhalation of U^{238}	Inhalation of Th^{232}	Total Dose
Accommodation Village	0	0.002	0.000	0.0032	0.0018	0.007

As previously noted, the potential doses for people at distances beyond the accommodation village would be lower than those received at the village.

3.6 EXPOSURE TO NON-HUMAN BIOTA

The impact of radionuclide emissions from the project on non-human biota was assessed using the ERICA software tool (http://www.erica-tool.com/ - last accessed Feb 2014). The assessment involves identifying impacts to species rather than individual organisms.

To undertake this assessment, the predicted dust deposition contours from the air quality modelling were used to provide a measure of the predicted worst case increase in soil radionuclide concentrations (above the naturally occurring concentrations). The changes in soil concentrations were then used as input data for the ERICA software.

The calculations used for determining changes in soil concentrations are shown in Appendix C and the output of the ERICA assessment is shown in Appendix D.

The ERICA approach is based on determining a relative radiological risk factor to various reference species of animals and plants. Data for specific Australian animals and plants are not yet available, and therefore the reference species are used in the assessment.

The ERICA assessment is based on a series of tiered assessments which require successively more detail. A higher tier of assessment is triggered when the assessed radiological risk exceed a reference dose rate level. When a species triggers a higher tier of assessment, it is usual to determine the abundance of the particular species or to obtain more specific characteristics of the particular species.

Figure 2 shows the modelled annual average dust deposition rate. The location selected for the assessment is the accommodation village, which is relatively close to the project and provides a conservative (worst case) estimate of the potential impacts. At this location, the dust deposition is 0.2g/m^2.month. Based on the weighted average radionuclide concentrations in the dust sources, the average annual radionuclide deposition is calculated to be;

- 0.4Bq/m^2 per year for U^{238} (and its decay products)
- 0.12Bq/m^2 per year for Th^{232} (and its decay products).

Appendix C: Part B outlines the method for determining the soil concentration, using a soil mixing depth of 10 mm. After 20 years of operation there would be 8BqU^{238} and 2.4BqTh^{232} deposited in 10,000g of soil (the amount of soil in one square meter to a depth of 10mm), giving a project originated increase in soil concentration of 0.8mBq/g and 0.3mBq/g of U^{238} and Th^{232} radionuclides respectively. This concentration is used as the input to the ERICA assessment.

Appendix D: shows the output of the ERICA assessment and indicates that all species of reference animals and plants do not exceed the reference level and therefore do not warrant further assessment.

Potential exposures to plant and animals at distances further than the accommodation village would be lower.

3.7 PUBLIC DOSE FOLLOWING CLOSURE

NML have developed closure and rehabilitation plans for the proposed activities. From a radiological perspective, the overall approach is to ensure that the radiation levels at the site are returned to levels similar to that which existed prior to the proposed project. With the implementation of the closure and rehabilitation plans, there are no reasonable long term exposure pathways for public exposure, and doses are expected to be negligible and much less that the member of public dose limit of 1mSv/y (above natural background).

3.8 SUMMARY OF RADIOLOGICAL IMPACTS

The assessment has shown that the radiological impacts of the proposed project will be low. Conservative estimates of worker doses show that doses to miners will be <1mSv/y, however, doses to some plant workers may reach up to 5mSv/y, compared to the annual limit of 20mSv/y. Public doses are expected to be well below the public dose limit of 1mSv/y, and there are expected to be no impacts to non-human biota outside of the proposed project area.

4. MANAGEMENT OF RADIATION

NML intends to manage radiation as one of a number of workplace and environmental hazards that will exist as part of the overall project.

Detailed design of the proposed mine, processing facilities and tailings management facility has yet to occur. However, NML has considered radiation controls at this early stage of the project through;

- the establishment of radiation design criteria for the project, and
- the establishment of specific radiation related management systems and measures.

This section provides an overview of radiation controls.

4.1 GENERAL SITE CONTROLS

The site-wide radiological control aspects are outlined in this section.

4.1.1 CLASSIFICATION OF WORK AREAS & WORKERS

The WA NORM guidelines provide guidance on classification of workplaces for radiological purposes, as follows:

- A "controlled area" is an area to which access is subject to control and in which employees are required to follow specific procedures aimed at controlling exposure to radiation.
- A "supervised area" is an area in which working conditions are kept under review but in which special procedures to control exposure to radiation are not normally necessary.

NML has defined the whole of the project as a "supervised area". Within this area, the following areas will be defined as a "controlled areas";

- Mineral concentrate handling area,
- Acid Baking area, and
- Hydrometallugical Plant

Employees working in the controlled areas will be defined as designated radiation workers. Other workers will be defined as "non-designated" radiation workers.

4.1.2 SITE ACCESS CONTROL

Access to the site will be through a manned gatehouse. Access will be linked to a record keeping system to ensure that all personnel accessing the site have been appropriately inducted.

Vehicle access will be through the main boom-gate, and exit from site would require all vehicles to pass through the wheel-wash. Water from the wheel-wash and wash-down areas will be collected and settled to remove solids, then treated for reuse at the on-site water treatment plant.

4.1.3 CHANGE-ROOMS

Workers in the "controlled area" ("designated workers") will be required to change into work clothes at the commencement of their shift and then shower and change into "street clothes" at the end of their shift. This will be a general health and hygiene requirement (not just a radiation requirement) that will be implemented once the proposed project commences and would continue for the life of the project.

Dirty clothes will be laundered on site, with waste water sent to the on-site water treatment plant.

4.1.4 OTHER GENERAL CONTROLS

NML will develop and implement a series of operational and administrative controls for radiation protection including;

- pre-employment and routine medical checks,
- development of safe work procedures, which include radiation safety aspects,
- procedures to segregate, isolate and clean up contamination or contaminated equipment,
- procedures for equipment or materials leaving the controlled area,
- personal hygiene facilities (wash facilities) at entrances to lunch rooms and offices, and
- lunch-rooms and offices located away from sources of radiation.

4.2 RADIATION CONTROL IN THE MINE

The doses to mine workers are expected to be low (< 1mSv/y), and standard mine management measures will be sufficient to control exposures. These include;

- restricting access to the main mining areas, to ensure that only appropriately trained and qualified personnel are able to access the work areas,
- ensuring that all heavy mining equipment is air conditioned (positive pressure in cabins) ,
- use of standard dust suppression techniques (wetting of materials before handling, wetting of roadways, provision of dust collection systems on drills, use of respiratory protection when dusty),
- standard dust control techniques during tipping of material onto stockpiles, and
- wash-down pad within the site area for vehicles that have come from the mine.

4.3 RADIATION CONTROL IN THE PROCESSING PLANT

Specific radiation design control measures are required in certain parts of the processing plant to ensure that potential doses remain low and well controlled. This includes;

- use of dedicated extraction systems for the dryers and the acid bake kiln
- installation of scrubbers or bag houses where fumes or off gases are generated,
- bunding to collect and contain spillages for tanks containing radioactive process slurries,
- tailings pipeline corridor bunded to control spillage from tailings pipeline failures
- sufficient access and egress for mobile equipment to allow clean-up where there is the possibility for large spillages,
- wash-down water points and hoses supplied for spillage clean-up, and
- specially designed storage area for mineral concentrate to prevent loss of material.

If the monitoring shows that there are elevated levels of dust in the workplace, respiratory protection will be used until a more permanent means to reduce dust is established.

4.4 OPERATIONAL AND ADMINISTRATIVE CONTROLS

The controls are programs outlined in the project Radiation Management plan (RMP) and are summarised here.

4.4.1 RADIATION SAFETY EXPERTISE

NML retains the services of Radiation Professionals from Perth for radiation protection expertise which will be available to assist during the final design, construction and the operational phases of the project. The principal consultant and RSO to NML is Mr Anthony O'Brien, Licence LS 503/11 21085. During operations, NML would employ a suitably qualified and resourced Radiation Safety Officer (RSO) who would influence the day to day workings of the project, ensure that appropriate radiation safety advice is available to implement the Radiation Management Plant (RMP) and provide ongoing advice to the General Manager. NML would ensure that the company RSO is approved and appointed by the State Mining Engineer, fulfils all statutory requirements and meets the minimum statutory experience and qualification requirements.

4.4.2 INDUCTION AND TRAINING

All employees and contractors will receive an induction upon commencement and then again annually, informing them of the hazards associated with the workplace. The induction would include an introduction to radiation, radiation safety and responsibilities. Specific training will be provided to personnel involved in the handling of process materials containing elevated levels of radionuclides.

Managers and supervisors will receive additional training in the recognition and management of situations that have the potential to increase a person's exposure to radiation.

A specific radiation safety work permit system will be developed and implemented for identified tasks that may result in elevated radiation exposure (such as maintenance on the acid bake ventilation system).

4.4.3 RECORD KEEPING

A computer based data management system will be used to store and manage all information relating to radiation management and monitoring, including both occupational and environmental monitoring results and worker doses.

Periodic reports will be prepared from information stored in the electronic database. Dose reports will be provided to individuals upon request.

4.4.4 REPORTING

NML will provide annual reports on occupational radiation exposure and environmental radiological impact to the State Mining Engineer and the Radiological Council..

4.5 RADIATION MONITORING PROGRAMS

As part of the ongoing management of radiation, an occupational and environmental monitoring program will be developed and implemented.

The Radiation Monitoring Programs will include;

- recognised sampling methodologies that are documented and regularly reviewed,
- routine instrument calibration programs, including auditing of calibration sources,
- instrument maintenance and repair programs,
- the use of appropriate monitoring equipment,
- appropriately trained and qualified monitoring personnel,
- review of new equipment, and
- regular external audits of the monitoring program and system.

4.5.1 OCCUPATIONAL RADIATION MONITORING PROGRAM

An outline of the proposed occupational radiation monitoring is shown in Table 15.

Table 15: Dose Assessment Monitoring Program (Indicative only)

Radiation Exposure Pathway & Monitoring Method	**Mine Area**	**Processing Plant Area**	**Administration Area**
Gamma radiation Personal TLD badges		Quarterly TLD badges on selected workers	
Gamma radiation Survey with hand held monitor	Monthly areas survey	Monthly area survey	
Airborne dust Sampling pumps with radiometric and gravimetric analysis of filters	Monthly personal dust sampling for; • truck driver, • loader operator.	Weekly personal samples in; • Mineral concentrate handling area • Acid bake area • Hydromet	Monthly area samples
Surface Contamination	Monthly survey	Monthly survey	Monthly survey

Results of monitoring will be provided to operational personnel for action as necessary.

For routine management control of radiation, NML would establish a series of action levels to ensure that exposures and doses remain well controlled. Exceeding the action levels would require mandatory action by operational personnel. Table 16 provides an overview of the proposed action levels and actions.

Table 16: Exposure Action Levels and Actions

Radiation Measurement Type	Action Level	Actions
Gamma radiation	1µSv/h	• Investigate and identify source. • Consider redesign of workplace or tasks to reduce exposure.
TLD - (¼ly result)	1mSv	• Investigate and identify source. • Redesign workplace or tasks to reduce exposure. • Shield if necessary.
Surface contamination in workshops, control rooms and lunchrooms	4000Bq/m^2	• Immediate clean-up
Airborne Dust	5mg/m^3	• Identify source and suppress (eg; water suppression, housekeeping and ventilation)

Table 17 provides a list of the radiation monitoring equipment that will be used to implement the radiation monitoring program.

Table 17: List of Equipment required for Occupational Monitoring

Radiation Measurement Type	Equipment
Gamma radiation	• Hand held gamma radiation monitor
TLD - (¼ly result)	• TLD badges (provided and analysed by service provider)
Surface contamination in workshops, control rooms and lunchrooms	• Surface contamination probe and rate-meter
Airborne Dust	• 2L/min personal dust pumps fitted with suitable “inhalable” filter holder • Microbalance for weighing of filters • Alpha slide drawer assembly and rate-meter

4.5.2 ENVIRONMENTAL MONITORING PROGRAM

NML maintains a network Environmental Monitoring Locations (EMLs). Table 18 details the ongoing monitoring that will continue to be undertaken at these sites.

Table 18: Environmental Radiation Monitoring Program

Parameter	Monitoring	Location
Gamma radiation	Quarterly environmental TLD badges	EML
Airborne dust	Passive dust sampling, with samples composited for one year then radiometrically analysed	EML
Radon Concentrations	Quarterly passive monitoring	EML
Thoron Concentrations	Quarterly passive monitoring	EML
Radionuclides in Soils	Sampled every 5 years	EML
Radionuclides in Ground Water	Water sampled annually at monitoring bore locations	

4.6 RADIOACTIVE WASTE DISPOSAL

The main categories of radioactive waste generated by the project are"

- Tailings from flotation which is combined with smaller volume waste streams from subsequent processing.
- Solid wastes from ventilation scrubbing systems.
- Rain and stormwater from run off from the processing plant that may have come into contact with the mineral concentrate.
- Miscellaneous wastes that may have become contaminated through contact with concentrate and process residues (referred to as contaminated waste).

Waste rock from clearance and removal of mine overburden is not considered to be radioactive and will be disposal of on waste rock stockpiles with no specific radiation control measures necessary.

4.6.1 PROCESS WASTES

Waste streams and residues from the processing of the ore are combined for disposal and the combined stream is known as tailings. Radionuclides that are in the original ore report through the tailings as the material is progressively processed through the plant.

The tailings stream consists of the following waste streams;

- Magnetic separated reject material,
- Flotation underflow,
- Metal precipitates from hydrometallurgical processing,
- Extraction ventilation scrubbing slurries,
- Neutralisation slurries, and
- Raw water effluent.

The radionuclide deportment into the waste streams has been experimentally verified by ANSTO (ANSTO 2014) and shows that 90% to 95% of the processing plant input radionuclides report to the solids in the solids residue stream, with the majority of the remaining radionuclides reporting to the liquid fraction of the solids residue stream.

The tailings storage facility will be designed as a permanent facility with a clay liner to minimise seepage. The design would ensure that tailings are effectively contained in the long-term and that radiation doses from the tailings to the proposed workforce, members of the public and non-human biota are as low as reasonably achievable both during operations and following closure.

4.6.2 CONTAMINATED SOLID WASTES

NML will implement a system to ensure that contaminated plant and equipment is suitably decontaminated prior to disposal or release from site. Where this is not feasible or not cost effective, some items may need to be disposed on site. For example; items such as broken bags from extraction ventilation systems, contaminated pumps or conveyor belts may not be able to be sufficiently decontaminated and require disposal on site.

In these cases, disposal would be in lined shallow trenches that are backfilled with more than one meter of compacted cover, in accordance with the regulatory requirements.

It is expected that up to $10m^3$ of material of this type would need to be disposed on site each year. In all cases records of the disposal, including type of material, quantities and locations will be kept.

4.6.3 CONTAMINATED WATER

Water that has come in contact with mineralised material, such as stormwater run-off from the mineral concentrate to hydrometallurgical may contain entrained radioactive dusts and sediments. The site will be designed so that all this surface water is collected and contained, and does not flow from the site or into ground-water. The method of control will involve the construction of sedimentation and evaporations ponds, and appropriate collection bunds and channels.

Waste water from wash-down areas and clean-up water would also be captured, settled to remove solids and then treated for re-use at the on-site water treatment plant.

5. CLOSURE CONSIDERATIONS

In the event that mining ceases during, or at the conclusion of the proposed project, the site will be rehabilitated in accordance with the closure plan. From a radiological perspective, this means a return to the natural background radiation levels that existed prior to the commencement of works.

Contaminated plant and equipment will be cleaned and decontaminated (where possible) and moved off site. Where this is not possible, it will be safely and securely disposed in the open-cut mines.

It is expected that the proposed project will be free from contamination once rehabilitated. Monitoring would occur for a period agreed to by the regulator to confirm this.

6. SUMMARY

The radiation assessment of the proposed project shows that the impacts will be manageable and well below the recognised limits. A summary of the radiological impacts of the proposed project can be seen in Table 19.

Table 19: Summary of Radiation Impacts During the Proposed Project

Dose Groups	Expected Dose/Impact (mSv/y)	Dose Limit/Standard (mSv/y)
Workers	<5	20
Member of Public	<<1	1
Non-Human Biota	No impact	

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APPENDICES

Appendix A: Technical Note: Introduction to Radiation

Appendix B: Technical Note: Estimate of Radon and Thoron Sources

Appendix C: Dose Conversion Factors

Appendix D: References

Appendix E: Glossary

Appendix A:

Technical Note: Introduction to Radiation

INTRODUCTION TO RADIATION

What is Radioactivity?

All matter is made of atoms. Atoms are made up of protons and neutrons in a nucleus, and electrons orbiting around the nucleus. Some atoms are unstable and breakdown, giving off energy in the form of radiation. These are known as radioactive atoms or radionuclides.

Different radionuclides emit radiation at different rates. The breakdown (or decay) of radionuclides reduces the number remaining, so that the amount of radiation emitted continually reduces. The time taken for one half of the radionuclides to decay away is known as the 'half-life'. Each radionuclide has its own half-life which can range from fractions of a second to billions of years.

When a radionuclide decays, the new atom formed may itself be radioactive, which might in turn decay to another radionuclide, and this can continue until a stable element is reached. When this occurs, the chain of radioactive decays is called the 'decay series' or 'decay chain'.

Radionuclides are natural and occur everywhere in the environment, in food, air, water, soils and rocks. For example, uranium is a naturally occurring heavy metal and is widespread in Earth's crust, with an average concentration of about three parts per million (ppm). Since, radionuclides exist naturally in all materials, it is usual to only define a material as "radioactive" when the concentration of a radionuclide in the material exceeds a certain level.

Radiation emitted from radionuclides is known as ionising radiation because it ionises material through which it passes. This means that radiation produces charged particles called ions as it passes through matter.

Types of Radiation

There are three types of radiation emitted by naturally occurring radioisotopes:

- Alpha radiation consists of alpha particles (two neutrons and two protons) and has a very short range in air (a few centimetres), depositing their energy quickly. They are unable to penetrate the outer skin later, but can be hazardous when inhaled or ingested.
- Beta radiation consists of high-energy electrons. They have moderate penetration, typically about one metre in air and a few millimetres in water or tissue.
- Gamma radiation is not a particle but an electromagnetic wave similar to light and X-rays but of much higher energy. Gamma rays are generally able to penetrate up to several centimetres of metal or 10 cm of concrete, and usually pass right through the human body.

Exposure to radiation only can occur when there is an exposure pathway between the radioactive material and the person exposed. This can occur in two ways: external (where the source of radioactivity is outside the body) and internal (where the source of radioactivity is inside the body – for example in inhaled air).

Measuring Radiation

Describing radioactivity and exposure to radiation can be difficult. In general, there are two ways used – one refers to how much radioactivity is in a material (or how radioactive it is), and the other refers to the resultant exposure from the radioactivity (this is also referred to as a "dose").

The amount of radioactivity is described by its 'activity' and is measured in the unit of becquerel (Bq), which is the amount of radioactive material that produces one radioactive decay per second. The activity concentration is the amount of radioactivity in a unit mass of material and is measured in becquerels per gram (Bq/g). For liquids, the activity concentration is measure in becquerels per litre (Bq/L) or Bq/mL (which gives comparison with Bq/g because the volumes are similar.

Dose refers to the amount of radiation received at a point or to a person. Dose is also a relative measure of the effect (or 'detriment') of radiation on the human body and is measured in the units of Sieverts (Sv) and takes into account of different types of radiation and different exposure situations. The sievert is quite a large unit of measure, and doses are usually expressed in millisieverts (mSv), thousandths of a sievert.

Due to radiation being very common in nature, everyone is exposed to natural radiation throughout their life. This radiation comes from the rocks and soil of the earth, the air we breathe, water and food we consume, and from cosmic radiation from space. Natural background can vary considerably in different places in the world. While the world average is 2.4mSv/y, the typical range is quoted as 1–10mSv/y.

In addition to natural background exposure, some people around the world are regularly exposed to radiation in their work (other than in the nuclear industry), and from leisure activities (such as flying) and in medical procedures. Table 1 shows the average annual dose for a range of different jobs.

Table 1: Occupational radiation exposures (in addition to natural background levels)

Source/practice	Average annual effective dose (mSv)
Nuclear fuel cycle	1.8
Industrial uses of radiation	0.5
Medical uses of radiation (doctors/nurses)	0.3
Air crew (from cosmic radiation)	3.0
Mining (other than coal)	2.7
Coal mining	0.7

A major source of radiation exposure to the general public is medical exposure. Radiation is used extensively for diagnosis (such as x-rays) and treatment of disease. The average annual radiation dose per person from diagnostic medical procedures in developed countries is approximately 1.2mSv/y.

Health Effects

The acute health effects of radiation exposure (both internal and external) are well known. At high doses (several sieverts) significant numbers of cells may be killed, leading to the breakdown of the organ or tissue, and possibly resulting in death. The doses required for these effects are similar to those received by Chernobyl fire-fighters.

At lower doses, chronic health effects may arise from cells that are damaged by the radiation but not killed. This may be the initiating event for development of a cancer.

Several studies have found an increased risk of cancer among people exposed to moderate doses of radiation. The studies show that the risk increases as the radiation dose increases.

In general, none of the studies has been able to measure increases in cancer risk from exposures to low doses of radiation (below about 50 mSv), however, it is conservatively assumed that there is an increased risk.

The studies and their results form the basis of the setting of radiation standards for exposure of workers and the general public.

Control of Radiation

The premier international body for radiation protection is the International Commission on Radiological Protection (ICRP). The limits recommended by the ICRP have generally been adopted around the world.

Dose limits form only one part of the ICRP radiation protection system. The three key elements of this system are:

- **Justification**, a practice involving exposure to radiation should be adopted only if the benefits of the practice outweigh the risks associated with the radiation exposure.
- **Optimisation**, radiation doses received should be as low as reasonably achievable, economic and social factors being taken into account (the ALARA principle).
- **Limitation**, individuals should not receive radiation doses greater than the recommended limits.

The effective annual dose limits recommended by the ICRP are 20mSv for a designated radiation worker and 1mSv for a member of the public.

The radiological protection of the non-human living environment (being plants and animals) has, up until recently, been thought to be assured by ensuring that humans have been protected. In recent times this approach has been changed and it is now appropriate for a radiological assessment of non-human biota (NHB) to be conducted. International standards exist to conduct this assessment.

Appendix B:

Technical Note: Estimate of Radon and Thoron Sources

NORTHERN MINERALS

ESTIMATE OF RADON AND THORON EMISSIONS FROM BROWNS RANGE RARE EARTHS PROJECT

FEBRUARY 2014 (REVISED APRIL 2014)

(NOTE: THIS IS A REVISED RADON AND THORON ESTIMATE BASED ON UPDATED URANIUM AND THORIUM ORE GRADES AND ON UPDATED TAILINGS STORAGE FACILITY FOOTPRINT)

INTRODUCTION

The aim of this technical note is to provide estimates of the potential radon (Rn^{222}) and thoron (Rn^{220}) releases for the purposes of air quality modelling.

A summary of the estimated emissions can be seen in the following table and are detailed after the table.

SUMMARY

Source	Radon(Rn^{222}) Emissions (kBq/s)	Thoron (Rn^{220}) Emissions (kBq/s)
Mining*	13	50
Stockpiles	14	55
Processing Plant	12	2.2
Residue Storage Facility	365	730

* Mining assumes 5 open-cut mines in operation at the same time

ASSUMPTIONS AND WORKINGS

All assumptions are based on an operation at full production and maximum size of facilities as follows;

- Mining from 5 open-cut mines with 1Ha of mineralised zone exposed in each
- Mining at a rate of 750,000tpa
- Mineralised material stockpile of 100,000t
- Residue storage area of 73Ha

Mine Emissions Radon (Rn^{222}) Assumptions

Estimates of radon emission rates that have been standardised to Bq Rn^{222}/m^2s per $BqRa^{226}/g$ were obtained from a number of sources as follows;

- Todd et al reports on Rn^{222} emission rates from testwork in the non-mineralised region of the Ranger Uranium mine which results in an average of 0.7 $BqRn^{222}/m^2s$ per $BqRa^{226}/g$
- Sonter et al 2002 reports on a range of radon emission rates and the standardised average is 0.4$BqRn^{222}/m^2s$ per $BqRa^{226}/g$
- BHP Billiton (2009) reports a standardised factor 0.4 $BqRn^{222}/m^2s$ per $BqRa^{226}/g$
- Mudd 2007 reports an Australian average standardised figure of approximately 0.8$BqRn^{222}/m^2s$ per $BqRa^{226}/g$ for soils.

Based on the range of results, a figure of 0.5BqRn^{222}/m^{2}s per BqRa^{226}/g was selected to conduct the assessments for this report.

Mine Emissions Thoron (Rn^{220}) Assumptions

Estimates of thoron emission rates that have been standardised to BqRn^{220}/m^{2}s per BqRa^{224}/g were obtained from a number of sources as follows;

- Todd et al reports on Rn^{220} emission rates from testwork in the non-mineralised region of the Ranger Uranium mine which results in an average of 34BqRn^{220}/m^{2}s per BqRa^{224}/g
- Todd et al also reports on measured Rn^{220} emission rates from monazite containing 6.735% Th232 giving 2BqRn^{220}/m^{2}s per BqRa^{224}/g
- Mudd 2007 reports an Australian average standardised figure of approximately 60BqRn^{220}/m^{2}s per BqRa^{224}/g for soils.
- Ramachandran 2010 reports emission rates of up to approximately 70 for high permeability materials such as soils and 1.6 and 10 for lower permeability materials such as rocks.

Based on the range of results, a figure of 10BqRn^{220}/m^{2}s per BqRa^{224}/g was selected to conduct the assessments for this report. This is based on the higher emission rates being associated with the higher permeability materials such as soils and the lower rates being associated with lower permeability materials such as rocks.

Mine Emissions (in Open-cut Mines Emissions)

The rate of radon emission that has been used in 0.5BqRn^{222}/m^2.s per BqRa^{226}/g. For mineralised material containing uranium with a grade of 40ppm (which is equivalent to approximately 0.5Bq/g of Ra^{226}, the calculated radon emission rate is 0.25Bq/m^2.s. For a mine area of 1Ha, this gives an emission rate of 2.5kBq/s.

The thoron emissions rates from thorium mineralised material used in this report is 10BqRn^{220}/m^2.s per BqRa^{224}/g, which equates to an emission rate of 1.0Bq/m^{2}s for the NML ore (containing 30ppm Th which is equivalent to approximately 0.1Bq/g of Ra^{224} assuming secular equilibrium). For a mine area of 1Ha, this gives an emanation of 10kBq/s.

Mine Emissions (from Broken Ore Stockpiles)

BHP 2009 estimated that the radon emission from broken ore stockpiles was conservatively 5 times higher than emissions from unbroken in situ material. This is due to the higher surface area from which radon can be emitted.

This factor has been used to estimate the emission rates for both Rn^{220} and Rn^{222} from broken rock. Therefore, for broken rock, the emission rates are conservatively assumed to be;

- 50BqRn^{220}/m^{2}s per BqRa^{224}/g
- 2.5BqRn^{222}/m^{2}s per BqRa^{226}/g

Therefore, for a stockpile of 100,000t of ore (assuming a rectangular stockpile) the surface area is 11,000m^2, giving a Rn^{222} emission rate of 0.25Bq/m^2.second x 11,000 m^2 x 5 = 13.8kBq/s.

Including a factor of 5 for broken ore, the Rn^{220} emission rate from a 100,000t stockpile of ore is calculated to be 1.0Bq/m^{2}s x 11,000 m^2 x 5 = 55kBq/s.

Solid Residue

The estimate of Rn^{222} emission from solid residue is from the USEPA (US EPA 1986). The relationship is seen as follows;

$$1BqRn^{222}/m^2s \text{ per } BqRa^{226}/g \text{ in residue}$$

If it is assumed that the solid residue contains all Ra^{226} then the concentration will be $0.5BqRa^{226}/g$, giving a radon emission rate of;

$$0.5BqRn^{222}/m^2s$$

For Rn^{220}, in the absence of any other published data, it is assumed that the emission rate will be the same as that for ore;

$$10BqRn^{220}/m^2s \text{ per } BqRa^{224}/g$$

If it is assumed that the solid residue contains all Ra^{224} then the concentration will be $0.1BqRa^{224}/g$, giving a radon emission rate of;

$$1.0BqRn^{220}/m^2s$$

For the residue storage facility, the rate of radon emission is based on the US EPA "Final Rule" for uranium tailings which is $1BqRn^{222}/m^2.s$ per $BqRa^{226}/g$. Therefore for the NML ore which contains uranium with a grade of 40ppm ($0.5BqRa^{226}/g$), the calculated radon emanation rate from the mine is $0.5Bq/m^2.s$. The residue storage facility is expected to be 73Ha. Therefore the maximum emanation rate would be <u>365kBq/s</u>.

For the residue storage facility, the rate of thoron emission used in this report is $10BqRn^{220}/m^2.s$ per $BqRa^{224}/g$, which equates to an emission rate of $1.0Bq/m^2s$ for the NML. For a residue storage facility of 73Ha, the maximum emanation rate would be <u>730kBq/s</u>.

Processing Plant

To calculate the emission of radon during processing, it is assumed that all contained radon in the ore is released to the atmosphere as the ore is processed. This is a conservative assumption as some radon will remain contained.

It is also assumed that the ore is in secular equilibrium (a fair assumption for newly mined ore) which means that the activity concentration of radon will be the same as the activity concentration for uranium and thorium, being 0.5Bq/g and 0.1Bq/g respectively.

Based on a production rate of 750,000tpa, the Rn^{222} emission rates are as follows;

$$750{,}000 \times 10^6 g/y \times 0.5Bq/g = 375 \times 10^9 \text{ Bq/y}$$

If this radon is released uniformly across the whole year, then the emission rate is;

$$375 \times 10^9 Bq/y \times 1/(\text{seconds in a year}) = 7.1kBq/s$$

Based on a production rate of 750,000tpa, the Rn^{220} emission rates are as follows;

$$750{,}000 \times 10^9 g/y \times 0.1Bq/g = 75 \times 10^9 \text{ Bq/y}$$

If this thoron is released uniformly across the whole year, then the emission rate is;

$$75 \times 10^9 Bq/y \times 1/(\text{seconds in a year}) = 2.2kBq/s$$

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Appendix C:

Dose Factors and Assumptions

Dose Factors and Assumptions

A: Relationship Between uranium and Thorium Grade in a Material and Activity Concentration.

The specific activities of U^{238} and Th^{232} are 12,400 and 4,080Bq/g respectively. This means that 1 gram of pure U^{238} contains 12,400Bq and 1 gram of pure Th^{232} contains 4,080Bq.

So, 1 gram of pure U^{238} (which is the same as 1,000,000ppm) contains 12,400Bq/g, therefore 1Bq/g is equal to 80ppm uranium.

For thorium, 1 Bq/g is equal to 245ppm thorium.

If it is assumed that uranium and thorium are in secular equilibrium with their decay products, then each of the decay products will have the same activity as the respective head of chain.

B: Calculation for determining radionuclide concentration in soil

- It is assumed that as dust deposits in the environment, it will mix in the top layer of soil.
- If it is assumed that the dust mixes in the top 10mm of soil, then for every square meter, there will be a soil mixing volume of $0.01m^3$.
- It has also been assumed that the soil has a density of 1t per cubic metre

C: Dose assessment

There is a general lack of data on dust concentrations in open-cut mines. A long term study presented in HSE2006 notes that 1% of measured respirable dust concentrations, in UK quarries, exceed $3mg/m^3$, although the average is not provided. For this report $1mg/m^3$ has been adopted as the average dust concentration.

When calculating the radiological dose form inhalation of radionuclides in dust, the total suspended solids (TSP) figure is used.

D: Dust Inhalation

Workers:

- Assuming most conservative lung clearance rate (that is, slowest clearance rates)
- AMAD = 1µm, DCF = 3.6 x 10^{-5} Sv/Bq
- AMAD = 5µm, DCF = 2.5 x 10^{-5} Sv/Bq

Members of the Public:

- Assuming most conservative lung clearance rate
- AMAD = 1µm, DCF =3.9 x 10^{-5} Sv/Bq

Inhalation dose conversion factors from ICRP, 2012.

- increase in U^{238} concentration in the soil.

E: Radon Decay Product (RnDP) Factors

1.2mSv/mJ (ARPANSA, 2005)

ARPANSA, 2005 *The Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing* Radiation Protection Series. Canberra. RPS 9.

Appendix D:

Non-human Biota Assessment

ERICA Assessment Report 08/04/2014

Project: NHB Assessment Browns Brange 20140407
Assessment name: NHB Assessment 2014 - 20 year @ accommodation village
Author: JRHC Enterprises
Performed tiers : Tier 1

1. TIER 1

Tier 1 - Stakeholder Involvement

N/A

Tier 1 - Problem Formulation

Description
Deposition for 20 years
Pathways and endpoints
Airborne dust emissions from project resulting in an increase of radionuclides in soil

Tier 1 - Assessment Context

Ecosystem	Terrestrial
Transport model	None
Isotopes	

Pb-210	Po-210	Ra-226	Th-230	U-234	U-238
Ra-228	Th-228	Th-232			

Tier 1 - Inputs

Activity Concentration in soil or air [Bq kg-1 d.w. or Bq m-3]	
Isotope	**Value**
U-238	8.00E-1
U-234	8.00E-1
Th-230	8.00E-1
Ra-226	8.00E-1
Po-210	8.00E-1
Pb-210	8.00E-1
Th-232	3.00E-1
Th-228	3.00E-1
Ra-228	3.00E-1

Tier 1 - Parameters

Terrestrial Environmental Media Concentration Limit (ERICA) [Bq kg-1 or Bq m-3]	
Isotope	**Value**
U-238	1.51E3
U-234	1.67E3
Th-230	1.63E3
Ra-226	2.27E2
Po-210	2.52E1
Pb-210	3.88E3
Th-232	1.90E3
Th-228	2.23E2
Ra-228	1.73E4

Tier 1 - Outputs

Risk Quotient [unitless]		
Isotope	**Value**	**Limiting Reference Organism**
Pb-210	2.06E-4	Lichen & bryophytes
Po-210	3.18E-2	Lichen & bryophytes
Ra-226	3.53E-3	Lichen & bryophytes
Ra-228	1.73E-5	Soil Invertebrate (worm)
Th-228	1.34E-3	Lichen & bryophytes
Th-230	4.91E-4	Lichen & bryophytes
Th-232	1.58E-4	Lichen & bryophytes
U-234	4.80E-4	Lichen & bryophytes
U-238	5.29E-4	Lichen & bryophytes

Sum of Risk Quotients [unitless]
Value
3.85E-2

Tier 1 - Decision

Justification for the decision
No values are above the 10µGyh^{-1} screen dose rate. - Further assessment is NOT required

END OF REPORT

Appendix F:

Glossary

Glossary

Activity
A measure of the level of radioactivity of a radionuclide in units called Becquerels.

Alpha radiation

Bequeral (Bq)
The Standard International (SI)unit of measurement of radioactive activity defined as one radioactive disintegration per second

Beta radiation

Decay Product
The product of the spontaneous radioactive decay of a nuclide (a type of atom). A nuclide such as U^{238} decays through a sequence of steps and has a number of successive decay products associated with it in a decay series.

Dose equivalent
A measure of the radiation dose to tissue where an attempt has been made to allow for the different relative biological effects of different types of ionising radiation. Units are Sieverts (Sv)

Dose
The radiation energy absorbed in a unit mass of material

Electron
A negatively charged particle that rotates around the nucleus of the atom, and is a component of all atoms.

Equilibrium Equivalent Concentration (EEC)
The concentration of Rn^{222} in equilibrium with its decay product.

Gamma radiation
A form of electromagnetic radiation similar to light or x-rays, distinguished by its high energy and penetrating power.

Impact
An effect, either positive or negative, that occurs due to the presence of an external entity.

Ionising radiation
Radiation which interacts with matter to add or remove electrons from the atoms of the material absorbing it, producing electrically charged particles called ions.

Isotope
Forms of a chemical element having the same number of protons but different numbers of neutrons.

Mineralised zone
An area of enriched mineralisation.

Occupational Dose
Radiation dose received by a person which occurs in the course of that person's work

Particulate emission
Dust or particulates that are emitted as a result of an activity.

Member of Public

Any person other than a radiation worker who may be affected or impacted by radiation or radioactive emissions from an activity.

Radiation

Electromagnetic waves or quanta, and atomic or sub-atomic particles, propagated through space or through a material medium.

Radiation Dose

A relative measure of the energy deposited in human tissue by radiation

Radiation Worker

Any person who works, whether full time, part time or temporarily, for an employer and who has recognized rights and duties in relation to occupational radiation protection.

Radioactive Decay Chain

The name given to the progression of naturally occurring radionuclides that occur as a result of radioactive decays.

Radioactive material

Material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity

Radionuclide

Any nuclide (isotope of an atom) which is unstable and undergoes natural radioactive decay.

Radon Decay Products (RnDP)

The short lived radioactive decay products of Rn^{222}

Sievert (Sv)

The SI derived unit of dose equivalent. It attempts to reflect the biological effects of radiation as opposed to the physical aspects.

Thoron Decay Products (ThDP)

The short lived radioactive decay products of Rn^{220}

TLD

Thermoluminescent dosimeter badge which measures gamma radiation exposure

Total Suspended Particulates (TSP)

Airborne dusts, particles or aerosols that are generally less than 100µm in diameter.