OZ MINERALS

CARRAPATEENA PROJECT

Environmental and Public

Radiation Impact Assessment

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1. INTRODUCTION

The aim of this technical report is to provide an assessment of the radiation related impacts to the public and to non-human biota for the OZ Minerals proposed development at Carrapateena.

This report consists of the following

- an outline of the relevant radiological characteristics of the project,
- a description of the methods for the assessments,
- an assessment of the radiological impacts to the public,
- an assessment of the radiological impacts to a standard set of representative flora and fauna (referred to as non-human biota (NHB) and
- an assessment of post closure radiological impacts.

Assessment of occupational (worker) doses is provided in the Occupational Radiation Assessment Appendix to this EPBC Referral.

A detailed description of the proposed project is not presented in this report, however, a summary of the key aspects of the project relevant to the assessment are provided here for context.

OZ Minerals intends to mine copper ore from the Carrapateena deposit using the sub-level caving (SLC) mining method. The copper ore contains low levels of uranium.

Ore is to be hauled to the surface to undergo treatment in a conventional concentrator consisting of a crush, grind and flotation circuit. Approximately 5% of the mass of the original ore containing the copper minerals reports as a 'copper concentrate', with the remaining waste material reporting as tailings. The copper concentrate will undergo additional treatment to remove impurities and remnant radionuclides, producing an enhanced copper concentrate for the export market. Wastes from the impurity treatment are combined with the concentrator tailings for disposal in the tailings storage facility (TSF).

From a radiological perspective, the majority of the uranium and radioactive decay products in the original ore will report to the TSF.

2. RADIOLOGICAL CONSIDERATIONS OF THE CARRAPATEENA PROJECT

2.1 Overview

This section of the report provides an overview of the methods and parameters used to assess the impacts to members of the public and to NHB from operations.

It is usual for radiation related impacts to be quantified by determining the potential radiation doses to the public and by calculating a risk quotient based on a dose rate for NHB.

Doses to members of the public are then quantified by identifying a representative person at locations of interest and then determining the potential dose for those people from the project emissions. For impacts to non-human biota, a similar method is used, where project emissions result in impacts outside of the operational area. It is generally usual to use the same location to quantify the impact to NHB.

In this assessment, the locations of interest have been selected conservatively and are:

- Closest project eastern boundary (approximately 5 km to the east of the main processing plant area)
- Closest project western boundary (approximately 10 km to the west of the main processing plant area)
- South Eliza Dam (approximately 10 km south of the main processing plant area and approximately 2 km south of the southern-most edge of the proposed TSF)
- Accommodation camp (approximately 5 km to the south-south-west of the main processing plant area).

Choosing these locations represents a worst case exposure scenario. For the accommodation camp, the assessment assumes that camp workers, such as cleaners and chefs, are members of the public with reduced exposure hours. This means that they are subject to the member of public dose limit of 1 mSv/y.

The results from air quality modelling provide estimates of radiation levels in the wider environment as a result of airborne emissions from the Project Area. The results that have been used for the radiological impact assessment are as follows:

- Radon concentrations (in Bq/m^3) at the locations of interest,
- Total dust deposition (in g/m^2.month) at the locations of interest,
- Total suspended solids (TSP) dust concentrations (in g/m^3) at the locations of interest.

2.2 Methods of Impact Assessment

The potential exposure pathways for members of the public are:

- irradiation by gamma radiation,
- inhalation of the decay products of radon,
- inhalation of radionuclides in dust, and
- ingestion of animals or plants that have come in contact with emissions.

Table 1 provides a summary of the dose assessment methods for the different exposure pathways.

Table 1: Exposure Estimation Methods

Exposure Pathway	Assessment Method
Gamma radiation	Estimated from first principles
Inhalation of radionuclides in dust	Estimation based on air quality modelling results
Inhalation of radon decay products	Estimation based on air quality modelling results
Ingestion of radionuclides	Estimation based on modelled dust deposition and transfer factors

For NHB, the assessment method is via the ERICA assessment software (http://www.erica-tool.com/) which uses changes in the radionuclide concentration of media (such as soil and water) as a result of emissions from the operation, to determine a dose rate and radiological risk quotient. The method for determining the change in media concentration is via modelled dust deposition results.

2.3 Assessment Factors

The following factors have been used in the radiological impact assessment. Note that the numbers presented in the project description may vary slightly from the numbers used in this assessment, however, any changes are small and therefore any changes to the final assessed impacts are expected to be not material.

Production Factors

- Average total mining rate – 5.1 Mtpa (ore and waste rock)
- Average ore (mineralised material) mining rate – 4.8 Mtpa
- Average 'mineralised' waste mining rate – 0.03 Mtpa
- Average waste rock mining rate – 0.3 Mtpa
- Average uranium grade of mined ore –239 ppm
- Average uranium grade of 'mineralised' waste rock – 192 ppm
- Average uranium grade of waste rock – 20 ppm
- Average uranium grade of all material mined – 226 ppm (calculated as a weighted average)
- Average annual tailings production rate – 5 Mtpa
- Mine operating life is 28 years.

Exposure Factors

- member of the public exposure hours – 8,670 h/y
- member of the public breathing rate – 1.0 m^3/h
- camp worker exposure hours (working year) – 4,000 h/y (assumes 2,000 h/y working and 2,000 h/y not working).

Physical Property Factors:

- relationship between uranium grade and radionuclide activity is 1 ppm U = 12.3 mBq(U^{238})/g
- uranium in ore is in approximate secular equilibrium when mined
- radionuclides report to tailings
- deposited dust will mix in the top 10 mm of soil (Kaste et al, 2007)
- bulk density of soil in the environment is 1 m^3 = 2 tonne
- Rn^{222} emission rates are shown in section 2.5.

Radon and Dust Factors:

- The primary source of exposure from radon is from the radon decay products (RnDPs). The relationship between radon and RnDPs is shown in the following equation (IAEA, 2003):
  - $F = PAEC(nJ/m^3) / (5.56 \times C(Rn^{222}) (Bq/m^3))$ where:
    - F is Equilibrium Factor,
    - PAEC is potential alpha energy concentration of the RnDPs, and
    - $C(Rn^{222})$ is the concentration of radon.
- Dose conversion factors are used to calculate the dose from inhalation of radionuclides. The most recent figures are published in ICRP 2012. In this assessment, a conservative particle size of 1 µm is used along the most restrictive lung solubility class. It is also assumed that secular equilibrium exists for the decay chain radionuclides.

2.4 Radionuclide Analysis of Materials

Preliminary testwork of material has been conducted and is summarised in Table 2. It is relevant to note that the majority of radionuclides report to tailings.

Table 2: Indicative Radionuclide Deportment

Radionuclide	Ore	Combined Tailings		Final Copper Concentrate Product
	Bq/g	Solids (Bq/g)	Liquids (Bq/l)	Solids (Bq/g)
U238	3	~3	10	<0.2
U234	3	~3	10	<0.3
Th230	3	~3	10	<0.3
Ra226	3	~3	10	<0.5
Pb210	3	~3	2	<0.5
Po210	3	~3	0	<0.5

2.5 Radon Emission Rates

For radon emissions from the project, the following factors are used:

- For both broken and unbroken ore and waste rock, the radon emission rate is 50 $Bq/m^2/s$ per %U
- For tailings, the radon emission rate is 10 $Bq/m^2/s$ per %U.

The method for assessing total radon release is based on throughput and residence time of process materials (see Appendix A of this report for more details). The radon release is then used as input to the air quality modelling to provide calculated long term average radon concentrations at the locations of interest.

A summary of the radon emission rates is shown in Table 3.

Table 3: Estimated Radon Releases

Source	**Radon (MBq/s)**
Mine exhausts and Processing Plant	6.06
ROM Stockpile	0.02
Surface Waste Rock Stockpiles	0.001
Processing Tailings	1.9
Total	**7.98**

2.6 Dust Emissions

The dust sources for the air quality assessment are based on project characteristics (such as stockpile sizes and areas of exposed materials) and standard emission factors for equipment and processes. The air quality modelling calculates an increase in dust concentration at the selected locations for TSP in units of $\mu g/m^3$ and a project originated dust deposition in units of g/m^2.month based on an emission rate from the operation.

For the radiological impact assessment, it has been assumed that all ore dust, processing dust and tailings dust emissions contains radionuclide concentrations identical to the original mined ore, which has an average uranium grade of 239 ppm. At this concentration, there will be approximately 3 Bq/g of each of the main long lived uranium decay chain radionuclides.

This is a reasonable assumption for the following reasons. The majority of the mined material is ore and therefore any dust emissions are likely to be ore dust. Where there may be higher concentrations of radionuclides in the intermediate process materials, these process flows are usually wet and therefore not prone to dusting. As for tailings, it essentially contains the ore without the copper, so any tailings dust would have radionuclide concentrations very similar to ore dust.

This is a conservative assessment, as there are likely to be sources of dust (such as road dust and waste rock dust) that contain no radionuclides at all.

2.7 Air Quality Modelling Outputs

2.7.1 Background

Air quality modelling was conducted to determine the potential increments in airborne concentrations as a result of airborne emissions from the project. The modelling utilises the radon emission rates outlined in Section 2.5 and dust emission factors as described in Section 2.6.

2.7.2 Radon

When modelling radon, it is usual to assume that there is no decay of the original emitted radon over the modelled spatial domain. This is a reasonable assumption because the half-life of radon is approximately 3.5 days, and in that time, the radon concentration is unlikely to decrease significantly due to radioactive decay across the modelled spatial domain.

The modelled annual average ground level concentrations during operations at each of the areas of interest can be seen in Table 4. It should be noted that the baseline monitoring has shown that the average naturally occurring radon concentration is approximately 15 Bq/m^3.

Table 4: Annual Average Modelled Radon Ground Level Concentrations

Location	Incremental Ground Level Radon Concentrations Annual Average (Bq/m^3)
Closest eastern boundary	< 0.4
Closest western boundary	< 0.1
South Eliza Dam	0.4
Accommodation camp	0.5

2.7.3 Airborne Dust Concentrations

Table 5 shows the modelled TSP dust concentrations during operations. The assessment uses the 'most likely' modelled results which take into account the dust control measures most likely to be implemented for the Project. The air quality modelling also considered the scenario of maximum dust emission conditions where no controls are in place. In this scenario, the modelled ground levels concentrations were effectively double the most likely modelled results.

The dust concentration is multiplied by the weighted specific activity of the dust (see Section 2.3) to give an activity concentration and these are also shown in Table 5.

Table 5: Annual Ground Level Concentrations

Location	Ground Level Concentrations Total Dust (µg/m³)	Equivalent Uranium Chain Radionuclide Concentration (µBq/m³)
Closest eastern boundary	1	3
Closest western boundary	<1	<3
South Eliza Dam	<1	<3
Accommodation camp	1	3

2.7.4 Dust Deposition

The deposition rate of dust into the environment was modelled, and from the results the deposition rate of radionuclides into the environment can be calculated. The modelling was conducted for two scenarios, being the most likely case where dust controls are in place and the most conservative case where no dust controls are in place. The modelling for the most conservative case gave deposition rates that were twice that for the most likely case.

The results are used to provide an estimate of human doses from ingestion of food that has taken up radionuclides. The results are also used for determining project originated soil radionuclide concentration estimates for the NHB assessment.

Results for the most likely scenario are shown in Table 6 (note that for the most conservative case, the results and subsequent impacts would be double).

Table 6: Dust Deposition

Location	Cumulative Dust Deposition (28 years) (g/m²)	Uranium Chain Radionuclide (Bq/m²)
Closest eastern boundary	14	42
Closest western boundary	1.4	4.2
South Eliza Dam	7	21
Accommodation camp	7	21

3. PUBLIC DOSE ASSESSMENT

3.1 Background

The potential exposure pathways for members of the public are:

- irradiation by gamma radiation,
- inhalation of the decay products of radon,
- inhalation of radionuclides in dust,
- ingestion of animals or plants that have come in contact with emissions.

The assessment assumes that a member of the public resides at the locations of interest for a full year for the three boundary locations and for workers at the accommodation village, it is assumed that the residence time is 4,000 hours per year.

3.2 Gamma Radiation

Gamma radiation exposure to members of the public from sources within the Project Area is considered to be negligible due to the distance between the sources and the public. The sources of gamma radiation (for example ore stockpiles) are well within the Project Area boundary and inaccessible by the public.

Gamma radiation intensity reduces significantly with distance (as one divided by the distance squared, when the source is at such a distance that it can be considered to be a point source). The gamma levels at the closest accessible area are unlikely to be detectable.

Using the on-line WISE radiation gamma dose calculator software (WISE, 2015), the gamma dose rates can be calculated at distances from a 1,000,000 t ore stockpile containing the uranium at the mined grades. At 1 m from this stockpile, the gamma dose rate is approximately 1 µSv/h. At 1 km, the gamma dose rate is calculated to be 4 pSv/h. For a member of the public at this location (1 km from stockpile), for a full year, the gamma dose is calculated to be approximately 40 nSv/y.

3.3 Airborne Dose Estimates

Doses from inhalation of both dust and RnDP are based on the modelled annual average concentrations at each of the locations of interest.

3.3.1 Dust

The dust dose is based on the modelled average radionuclide concentrations in air (see Table 5) and the individual radionuclide inhalation dust factors as outlined in ICRP Publication 119 (ICRP, 2012). The formula is:

Inhalation dose (mSv/y) = Dust activity concentration (Bq/m^3) x Breathing rate (1.0m^3/h) × Hours per year (8,760 h/y and 4,000 h/y as appropriate) × Dose Conversion Factor for each radionuclide (mSv/Bq)

3.3.2 Radon Decay Products

For RnDP the first step is to convert the modelled radon concentration to a RnDP concentration using a variation of the equation in Section 2.3 as follows:

RnDP Concentration (µJ/m^3) = Equilibrium factor x 0.00556 x Rn concentration (Bq/m^3)

For this assessment, a conservative equilibrium factor of 0.4 has been used, as recommended by UNSCEAR (UNSCEAR, 2000).

The RnDP dose is then calculated using the following formula (ARPANSA, 2005):

Dose (mSv/y) = RnDP Concentration (mJ/m^3) x Exposure hours (8,760 h/y and 4,000 h/y as appropriate) x Breathing rate (1.0 m^3/h) × Dose Conversion Factor (1.2 mSv^3/mJ)

3.3.3 Inhalation Dose Summary

A summary of the inhalation dose estimates can be seen in Table 7.

Table 7: Public Inhalation Dose Estimates

Location	TSP Dust Dose (mSv/y)	RnDP Dose (mSv/y)
Closest eastern boundary	0.004	0.009 (0.022) [1]
Closest western boundary	0.004	0.002 (0.006) [1]

Location	TSP Dust Dose (mSv/y)	RnDP Dose (mSv/y)
South Eliza Dam	0.004	0.009 (0.022) [1]
Accommodation camp	0.002	0.005 (0.013) [1]

Note 1: The ICRP has recently recommended an increase in the dose conversion factor for radon decay products (ICRP 2015), although this has yet to be adopted in Australia. The increase is a factor of 2.4 and the doses using the new dose conversion factor can be seen in parentheses.

3.4 Ingestion Dose Estimates

3.4.1 Overview

The ingestion doses have been calculated for people living at each of the locations of interest based on the conservative assumption that all food consumed is sourced from the location. In practice, the Carrapateena region is sparsely populated with plants and animals due to the lack of surface water. Therefore, consuming food solely generated in the Project Area is highly unlikely, although this provides a conservative estimate of the ingestion doses.

The assessment method assumes that dust emissions from the proposed operation deposit in the surrounding environment and are taken up by plants and animals. Exposure to people occurs when the plants and animals are consumed. The assessment only considers the project originated radionuclides.

There are three main factors to consider when making an ingestion dose assessment as follows:

- food consumption rates and characteristics,
- concentration factors into foods,
- incremental concentrations of radionuclides from project.

3.4.2 Consumption Rates

The assessment is based on the following consumption rates from http://www.goodfood.com.au/

- Vegetation
    - 40 kg/y of non-leafy vegetables
    - 10 kg/y of leafy vegetables
    - 70 kg/y of root vegetables
- 110 kg/y of meat (assumed to be beef from cattle that have been grazing in the area).

3.4.3 Concentration Ratios

The concentration ratio is a factor that relates the concentration of an element in the media (such as soil and foods) and the concentration of the element in the plant or animal. For plants, it is the ratio between the soils and the plant. For animals, it is the ratio between the food and the animals.

Published factors are available in IAEA 2010 and the Compendium of Transfer Factors (DoE, 2003). For this assessment, the uptake factors used can be seen in Table 8.

Table 8: Uptake Factors

	Vegetation[1] **Bq/kg (dry weight)/Bq/kg (dry soil weight)**			**Beef** **Bq/kg (whole body) per Bq/d (ingested)**
	Non Leafy	**Leafy**	**Root**	**Whole Body**
Uranium	0.053	0.020	0.028	0.0003
Thorium	0.0022	0.0012	0.0087	0.00004
Radium	0.061	0.091	0.071	0.0009
Polonium	0.00019	0.0074	0.077	0.005
Lead	0.015	0.080	0.063	0.0004

Note 1: The concentration ratio figures are quoted as ‘dry weight’. To apply the ratios to live plant matter, a factor needs to be applied which converts the dry weight to a wet weight. For this assessment it has been conservatively assumed that the wet weight is twice the dry weigh. In reality the wet weight may be 4 or 5 times higher and depends upon the plant species, so the number used is conservative.

3.4.4 Incremental Radionuclide Concentrations

The calculated change in soil radionuclide concentrations at each of the locations of interest is based on the air quality deposition modelling. Table 9 shows the calculated change in soil concentration based on soil density of 2 t/m^3 and a mixing depth of 10 mm. It is assumed that the uranium decay chain is in secular equilibrium, therefore the radionuclide concentration applies to each of the radionuclides in the uranium decay chain.

Table 9: Change in Soil Radionuclide Concentration (after 28 years of operations)

Location	Radionuclide Deposition (Bq/m^2)	Change in Soil Radionuclide Concentration (Bq/kg)
Closest eastern boundary	42	2.1
Closest western boundary	4.2	0.21
South Eliza Dam	21	1.1
Accommodation camp	21	1.1

3.4.5 Assessment of Intakes

The intake of radionuclides is a function of the quantity of radionuclides in the soil, the quantity of radionuclides that transfer to food and the food intake rate.

For example, to calculate the dose from project originated uranium (238) from ingestion of leafy vegetables at the closest eastern boundary, the calculations are as follows:

- Data:
  - Assumed ingestion of leafy vegetables is 10 kg/y
  - The soil uranium 238 concentration is 2.1 Bq/kg
  - The concentration ratio for uranium for leafy vegetables is 0.02 Bq/kg (dry weight) per Bq/kg (soil) (converting to wet weight gives 0.01 Bq/kg (wet weight) per Bq/kg (soil)
- Calculation of plant uptake:
  - Plant uranium concentration is 0.01 x 2.1, giving 0.021 Bq/kg
- Calculation of intake:
  - Assume consumption of 10 kg per year, giving an intake of uranium 238 of 0.21 Bq

This calculation method is then applied to each radionuclide for the different food types and consumption rates and added together to give the total intake of each radionuclide.

3.4.6 Convert Intake to Dose

Standard ICRP ingestion dose conversion factors convert an intake (in Bq) into a dose (mSv) for different radionuclides (ICRP, 2012). The total dose can be calculated at the sensitive receptor locations and the results shown in Table 10.

Table 10: Data for Ingestion Dose Assessment

	Dose (mSv/y)		
Location	**Vegetation Ingestion**	**Meat Ingestion**	**Total Ingestion**
Closest eastern boundary	0.014	0.001	0.015
Closest western boundary	0.001	0.000	0.001
South Eliza Dam	0.008	0.001	0.009
Accommodation camp	0.008	0.001	0.009

3.5 Total Dose Estimates

The total dose estimates at the sensitive receptors can be seen in Table 11. Note that the doses are based on 100% occupancy (that is 8,760 hours per year) at these locations (apart from the accommodation camp, which is based on 4,000 hours per year occupancy). The numbers in parenthesis represent the calculated dose based on the new ICRP dose factor of RnDP.

Table 11: Public Total Dose Estimates

Location	Exposure Pathway Dose (mSv/y)				
	Gamma	**Dust**	**RnDP**	**Ingestion**	**Total Dose**
Closest eastern boundary	0.000	0.004	0.009 (0.022)	0.015	0.024 (0.041)
Closest western boundary	0.000	0.004	0.002 (0.006)	0.001	0.007 (0.011)
South Eliza Dam	0.000	0.004	0.009 (0.022)	0.009	0.022 (0.033)
Accommodation camp	0.000	0.002	0.005 (0.013)	0.009	0.016 (0.024)

3.6 Bush Tucker Assessment

3.6.1 Introduction

An estimate of the potential dose from the ingestion of bush tucker has been made for people living at the sensitive receptor locations and consuming bush tucker from that immediate location. It is relevant to note that that there are few plants and animals in the Carrapateena region due to the lack of surface water. Therefore, it is unlikely that inhabitants of the region would take their entire food intake as bush tucker from the region.

3.6.2 Approach

The assessment method is identical to the method used for assessing ingestion doses (see Section 3.4), however, in this case, more relevant data are used if available.

The AAEC (1985) assumed a diet that consisted of an intake of 155 kg/y of plant material and 125 kg/y of animal material for traditional owners of the Maralinga lands. These consumption estimates have been used and a factor has been applied for likely bush tucker consumption rates that will occur (based on predicted occupancy in the region).

Concentration ratios for specific species are difficult to obtain and published data for kangaroo and goanna are available in ARPANSA (2014). Since there are no readily available published data for vegetation, the IAEA (2010) values have been used.

3.6.3 Estimate of Annual Food Consumption

The following assumptions have been made:

- It is assumed that locally sourced bush tucker makes up half of the diet, therefore local vegetation ingestion is estimated to be 80 kg/y and local meat ingestion is 60 kg/y based on the AAEC figures.
- The composition of the meat portion of the bush tucker consists of:
    - 90% kangaroo
    - 10% goanna.
- The vegetation portion of the bush tucker consists of:
    - 50% leafy and non leafy vegetation
    - 50% root vegetation.

Therefore, the annual bush tucker consumption estimates for this assessment are as follows:

- 54 kg of kangaroo
- 6 kg of goanna
- 40 kg of leafy and non leafy vegetation
- 40 kg of root vegetables.

3.6.4 Uptake Factors

The published factors for kangaroo and goanna are shown in Table 12. The uptake factors for vegetation were shown in Table 8.

Table 12: Summary of Concentration Ratios

Species	Elemental Uptake Factors Ratio (Bq/kg (species))/(Bq/kg (soil))					Source
	Uranium	Thorium	Radium	Lead	Polonium	
Kangaroo	0.007	0.00016*	0.41	0.022	0.55	ARPANSA 2014
Goanna	2.5	0.027	0.0044#	1.2	11	ARPANSA 2014

Note *: No APRANSA data, therefore the ERICA values large mammal has been used

Note #: No APRANSA data, therefore the ERICA values reptile has been used

3.6.5 Dose Estimate

The assessment method is identical to that outlined in Section 3.4 and the results can be seen in Table 13.

Table 13: Doses from Ingestion of Bush Tucker

	Dose (mSv/y)		
Location	Bush Tucker Vegetation Ingestion	Bush Tucker Meat Ingestion	Bush Tucker Total Ingestion
Closest eastern boundary	0.009	0.174	0.183
Closest western boundary	0.001	0.017	0.018
South Eliza Dam	0.005	0.091	0.096
Accommodation camp	0.005	0.091	0.096

3.6.6 Summary

Estimates of the potential dose as a result of consuming bush tucker have been made using conservative assumptions. The majority of the final dose estimate is due to the relatively high uptake factor for polonium 210. Consumption of local bush tucker in the Carrapateena region is unlikely to occur in any significant quantities due to the lack of animals and plants in the region because of the lack of surface water sources.

4. NHB IMPACT ASSESSMENT

4.1 Background

This section discusses the potential radiological effects of the proposed operation on NHB. The assessment has been conducted based on the potential airborne emissions from the project which leads to the deposition of radioactive dusts on surrounding soils.

The protection of the natural environment from emissions from nearby operations has historically been based solely on the protection of humans. This approach was outlined by the ICRP which stated that "*if man is protected then it can be assumed that the environment is protected*" (ICRP, 1991).

It is now generally accepted, however, that there is a need to demonstrate that NHB is protected from emissions from operations.

This has been addressed by the ICRP in more recent publications (ICRP, 2014), in which it is recommended that assessments be made of the impact of radiation on NHB. An important aspect is that protection of NHB is at the species levels rather than the individual levels, as is the case for humans.

4.2 The ERICA Tool

ARPANSA notes that the ERICA Software Tool (where ERICA is short for Environmental Risk from Ionising Contaminants: Assessment and Management) is applicable for use in Australia (ARPANSA, 2010) for assessing radiological impacts to NHB. The software uses changes in media radionuclide concentrations and concentration ratios in species, derived from studies, to provide a measure of radiological impact to a number of reference species.

An ERICA assessment is a tiered assessment. This means that the level of assessment depends upon the level of impact (i.e. the higher the potential impacts, the higher the level of scrutiny) (ARPANSA, 2010). Tier one is the simplest assessment level, requiring the minimum input data. Where more data is available, or the potential impacts are higher, then a Tier 2 assessment can be conducted.

The final level is Tier 3 which occurs when the likely impacts need to be better defined. The aim of the tiered approach is to ensure that the level of assessment is commensurate with the actual risk.

The assessment method produces a dose rate which is compared to a 'screening level' which is the level below which no effects would be observed. The default ERICA level is set at 10 µGy/h (ARPANSA, 2010).

The two important inputs for an ERICA assessment are:

- Operationally derived changes in media concentration, which is the additional radionuclide concentration in either soils or waters attributable to the operation and is in units of Bq/kg or Bq/l,
- The radionuclide concentration ratios, which is the ratio of radionuclide concentrations in the media and the concentrations in the flora and fauna.

The latest version of the ERICA software was released in February 2016 (version 1.2.1).

4.3 Assessment Approach

A Tier 2 ERICA assessment was conducted because some additional concentration ratio data is available.

The assessment was conducted for the full set of default terrestrial flora and fauna defined within the software tool. A user defined species was added to the assessment as follows:

- The 'Kangaroo' with dimensions of mass 50 kg, height 1.5 m, width 0.75 m and depth 0.75 m (based on best estimate).

4.4 ERICA Concentration Ratios

The key factors in an ERICA assessment are concentrations ratios (CR). These are the ratios of the whole body average radionuclide concentrations in the specific species to the concentrations of the radionuclides in the media (e.g. soil and water). ERICA provides a series of default CR values, however there is some recent published information that can complement the default set of CR values.

Additional CR data can be found in ARPANSA 2014 and in the Toro Energy Impact Assessment (Toro Energy, 2011). The additional CR vales used in this assessment are shown in Table 14.

Table 14: Published and ERICA Default Concentration Ratios

Species	Elemental Concentration Ratio (Bq/kg (species))/(Bq/kg (soil))					Source
	Uranium	**Thorium**	**Radium**	**Lead**	**Polonium**	
Red Kangaroo[1]	0.007	No data[3]	0.41	0.022	0.55	ARPANSA, 2014
Large Mammal	*0.0044*	*0.000136*	*0.044*	*0.037*	*0.089*	*ERICA Default*
Vegetation Average[2]	0.22	0.10	0.07	0.70	0.46	Toro Energy, 2011
Shrub	*0.061*	*0.061*	*0.33*	*0.32*	*0.33*	*ERICA Default*

Note 1: ARPANSA 2014 figures are reported as concentration ratios – average of two sample sets used

Note 2: Values have been derived from reported vegetation and soil concentrations. The activity concentrations reported did not provide information on whether vegetation samples were wet or dry. For this assessment, it has been assumed that the reported are 'wet' which is the conservative assumption.

Note 3: Default 'large mammal' value for thorium has been used in assessment.

4.5 ERICA Assessment Outputs

The media concentrations are seen in Table 9. For this ERICA assessment, the maximum media concentration has been used (2.1 Bq/kg).

The output of the assessment can be seen in Table 15 which shows that 10 µGy/h screening level is not exceeded at a Tier 2 level, using the default values.

The species with the highest level of exposure is lichen and bryophytes, however the exposure level remains well below the trigger level for further assessment.

Table 15: Output of ERICA Assessment

Species (all ERICA Default Species Unless Noted)	Total Dose Rate (µGy/h)
Amphibian	0.02
Annelid	0.02
Arthropod - detritivorous	0.02
Bird	0.01
Flying insects	0.02
Grasses and herbs	0.10
Lichen and bryophytes	0.50

Species (all ERICA Default Species Unless Noted)	Total Dose Rate (µGy/h)
Mammal – large	0.02
Mammal – small-burrowing	0.02
Mollusc – gastropod	0.02
Reptile	0.02
Shrub[1]	0.10
Tree	0.01
Kangaroo (user defined)[2]	0.02

1: Non default CR values

2: Non default species

4.6 Summary

A survey of the existing lichen and bryophyte environment at Carrapateena and surrounding pastoral leases was undertaken in order to provide context to the ERICA assessment outputs. The results of this survey concluded that lichen is common across both the Carrapateena proposed Mining Lease as well as the surrounding regional landscape. The density at which they occur however varies. Any radiological impacts local to the Project are not expected to affect regional populations.

The ERICA assessment indicates that there is no radiological risk to reference plants and animals or kangaroos from emissions from the proposed project.

5. POST CLOSURE EXPOSURE SCENARIOS

OZ Minerals has indicated that the closure goals for the project are to ensure that radiation levels are such that they are consistent with pre-operational levels. Therefore, it is expected that there will be no long term radiological impacts of the project following closure.

Following closure, the surface infrastructure would be removed and recycled or disposed of in accordance with the appropriate requirements. The mine openings would be sealed to prevent unauthorised access and any mine surface depression would be made safe and secure. The main remaining structure would be the proposed TSF.

Radon and dust concentration modelling has shown that despite emissions from the tailings surface, the longer term post closure concentrations are minor.

At the edge of the TSF surface footprint, the radon emissions will add an additional 10% to the average naturally occurring radon concentrations. Away from the TSF, the radon concentrations reduce substantially and would be difficult to measure and discern from natural background concentrations. The low impact of the radon is due to relatively low radon emission rate from the tailings and the natural atmospheric dispersion and dilution that occurs.

Dust emissions post closure are expected to be negligible and not measurable beyond the edge of the TSF, whether or not the tailings surface was capped or remained uncapped.

In addition to considering the post closure radiation concentrations, an assessment was conducted as part of the preliminary design work on the TSF. This assessment was a Features, Events, Processes (FEP)-style assessment which is used to identify potential future radiological exposure situations and make an assessment on the potential doses from those scenarios.

Table 16 shows the potential exposure scenarios from the assessment.

Table 16: Post Closure Exposure Scenarios

Exposure Scenario	Dose Pathway and Potential Dose
Long-term degradation of the TSF cover leading to exposure of tailings	Tailings contaminate traditional or future food sources leading to increase in human doses. Considered to be unlikely in the near-term, due to rehabilitation performance targets. Potential doses likely to be less than 1 mSv/y due to: • low radionuclide content of tailings • low uptake as radionuclides would need to transfer from tailings to soils, to plants and animals and then to humans
Inadvertent intrusion into TSF	Information on the final location of the TSF is lost and cover is breached, for example in future drilling exploration programs or

Exposure Scenario	Dose Pathway and Potential Dose
	earth moving programs. Additional scenario is that tailings are mined as resources – in this case, it is appropriate to assume that protection mechanisms would be in place. Potential doses likely to be low due to identification of material once cover is breached. This assumes that if there is sufficient technology for drilling or earthmoving, then there would be technology to identify hazards.
Seepage from tailings to groundwater	Seepage from the TSF enters existing groundwater and is expressed in potable water supplies. Groundwater Modelling shows the following: • Seepage from the TSF is captured by the SLC subsidence-zone lake within 5000 years of completion of mining (year 7045) with the earliest arrival taking place around 400 years post-mining. A Tailings Storage Facility liquor migration assessment shows the following: • Uranium concentrations are higher in the TSF liquor seepage relative to background groundwater composition. • Uranyl in fluid at a maximum concentration of 0.063 mg/L, at approximate distance of 500 m from the TSF at 60 years from commencement. The concentration in solution diminishes over time and is predicted to be to be approximately 0.02 mg/L at a distance commensurate with the SLC subsidence-zone lake at around 3,700 years. • A guideline criterion for uranium in water is available within the ANZECC (2000) water quality guidelines with respect to use of water for livestock purposes (0.2 mg/L). This modelled seepage concentrations do not exceed this criterion, with the the maximum natural background uranium concentration of 0.016 mg/L and the predicted concentration of uranyl in solution at 500 m from the TSF being 0.063 mg/L. • The salinity of the groundwater is significantly high and is not suitable for stock watering.

6. ENVIRONMENTAL MONITORING PROGRAM

An environmental radiation monitoring program for operations will be prepared as a part of the project's regulatory approvals and secondary permitting process prior to the commencement of construction. The aims of the program are to provide data for the assessment of radiation doses to the public, to provide data for the assessment of radiological risks to NHB and to ensure that the radiation controls for off-site impacts are effective. The elements of such a plan are shown in Table 17.

Table 17: Proposed Environmental Radiation Monitoring Programme

Environmental Pathway	Measurement Method	Location and Frequency
Direct (external) gamma	Handheld environmental gamma monitor, TLDs	Annual survey and passive detectors (TLDs) at the background environmental monitoring locations.
Radon Decay Product Concentrations	Real time monitor	Monitor will move between the off-site environmental monitoring locations.
Radon Concentrations	Long term passive monitors	Places at the environmental monitoring locations and changed out quarterly.
Dispersion of dust containing long-lived, alpha-emitting radionuclides	High volume samplers	Sampler will rotate between suitable off-site locations (requires mains power).
Dispersion of dust containing long-lived, alpha-emitting radionuclides	Dust deposition gauges	Sampling at off-site environmental monitoring locations. Samples composited for one year then analysed for radionuclides.
Seepage of contaminated water	Groundwater sampling from monitoring wells	Quarterly sampling from monitoring wells and analyses for radionuclides and other constituents.
Run off of contaminated water	Surface water sampling	Opportunistic surface water sampling will occur following significant rainfall events.
Radionuclides in potable water supplies	Sampling and radiometric analysis	Annually

7. SUMMARY

The assessment has shown that the proposed operation at Carrapateena will result in negligible or minor radiological impacts to the public and NHB. Post closure doses are expected to be lower than those during operations. Any failure events are highly unlikely to result in significant exposure due to the low radionuclide content of the materials.

8. APPENDIX A: RADIOLOGICAL PARAMETERS FOR AIR QUALITY ASSESSMENT

Radiological Parameters for Air Quality Assessment

INTRODUCTION

This appendix provides the basis for the estimates of the rate of release of radionuclides from the proposed operations at OZ Minerals Carrapateena project.

A summary of the estimate radon emissions and the factors for dust emissions can be seen in Table A1 and Table A2.

Table A1: Estimated Radon Emissions

Source Of Radon	Value (rounded)	Units
Mine exhaust and processing plant – ore	6	MBq/s
Mine exhaust and processing plant – mineralized waste	0.03	MBq/s
Mine exhaust and processing plant – waste	0.03	MBq/s
ROM stockpile	1.0 0.02	$Bq/m^2/s$ MBq/s
Waste rock stockpiles	0.14 0.001	$Bq/m^2/s$ MBq/s
TSF	0.24 1.9	$Bq/m^2/s$ MBq/s

Table A2: Factors for Dust Emission Assessment

Source of Dust	Dust Factor	Units
Ore dust including, dust from mining and processing	3	Bq/g
Mineralised waste rock	2.4	Bq/g
Non mineralized waste rock	0.25	Bq/g
Tailings	3.0	Bq/g
Non mining activities (eg earthworks or roads)	0	Bq/g

ASSESSMENT ASSUMPTIONS

Production Factors

All figures are based on average annual production rates as follows:

- Average total mining rate – 5.1 Mtpa (ore and waste rock)
- Average ore (mineralised material) mining rate – 4.8 Mtpa
- Average 'mineralised' waste mining rate – 0.03 Mtpa
- Average waste rock mining rate – 0.3 Mtpa
- Average uranium grade of mined ore –239 ppm
- Average uranium grade of 'mineralised' waste rock – 192 ppm
- Average uranium grade of waste rock – 20 ppm
- Average uranium grade of all material mined – 226 ppm (calculated as a weighted average)
- Average annual tailings production rate – 5 Mtpa (approximately)
- Mine operating life is 28 years
- ROM stockpile 3mt (pad dimensions 130 m x 90 m x 20 m)
- Full size TSF (790 Ha) (tailings surface only)
- Surface subsidence zone considered to be background levels and therefore not included as a source.

Physical property Factors

- Relationship between uranium grade and radionuclide activity is 1 ppm U = 12.3 mBq(U238)/g
- Uranium concentration in rock is in approximate secular equilibrium when mined and processed
- All radionuclides report to tailings in approximate secular equilibrium
- The calculated radionuclide concentrations are:
    - Ore (239 ppmU) – 3.0 Bq/g
    - Mineralised waste (192 ppmU) – 2.4 Bq/g
    - Waste rock (20 ppmU) – 0.25 Bq/g
    - All mined material (229 ppmU) – 2.8 Bq/g
    - Tailings (239 ppmU) – 3.0 Bq/g
- Specific gravity of mined rock is 2.8 t/m^3 (based on the average of in situ and mined rock)
- Specific gravity of tailings is 2 t/m^3 (based on the average of the initial and settled densities).

Radon Exhalation Rate Factors

- 50 Bq/m^2/s per %U for broken and unbroken rock (BHP Billiton, 2009)
- Note that for this assessment, there is no difference between broken and unbroken rock exhalation rates.
- 10 Bq/m^2/s per %U for tailings (Based on actual measurements presented in BHP Billiton, 2009).

- The calculated exhalation rates are therefore:
    - Ore (239 ppmU) – 1.2 Bq/m^2/s
    - Mineralised waste (192 ppmU) – 0.96 Bq/m^2/s
    - Waste rock (20 ppmU) – 0.10 Bq/m^2/s
    - All mined material (229 ppmU) – 1.1 Bq/m^2/s
    - Tailings (239 ppmU) – 0.24 Bq/m^2/s.

Radon Production Rate

Radon production rate P(Bq·m^{-3}s^{-1}) for a material is defined in IAEA 2013 as follows:

$$P = \lambda E R \rho_b$$

Where;

λ	is the decay constant for radon (s^{-1}) (2.1 x 10^{-6})
E	is the emanation coefficient (dimensionless)
R	is the radium activity concentration in the material (Bq/kg)
ρ_b	is the bulk density (kg/m^3).

RADON EMISSION RATES

Mining and Processing

For this assessment, it has been assumed that the mine and processing plant is a ‘black box’ and that all radon emissions occur as one output from this box. The reason for taking this approach is that there is large uncertainty in the emission rate of radon from the sub level caving method. A conventional approach would be to calculate (or estimate) the surface area of ore containing uranium and to apply an exhalation rate (in Bq/m^2/s) to the ore, thereby being able to calculate an overall radon emission rate. This approach is usually appropriate when there is certainty with the surface area (for example when calculating the emissions from a tailings facility or from a stockpile), however it has difficulties when considering a dynamic and changing system. The sub level caving mining method is one such example of a situation where it is difficult to accurately assess surface areas due to the broken rock and large number of openings.

A similar situation applies to the processing plant, with many exposed and changing surface areas (for example through crushing and turbulent materials flow). However, it is expected that radon emission would be relatively low once the ore is in contact with water and becomes a slurry due to the radon attenuating characteristics of moisture.

The black box method considers all of the radon that would be produced in the ore and process material over a unit time and applies an emanation factor which is a measure of how readily radon is able to escape from the particle or rock once it has been produced. In a practical sense, the method calculates how much radon is in the material (as it is being produced by its parent Ra^{226}) and how much of it gets released based on broad assumptions.

The black box method applies the IAEA radon production rate equation (provided above), across the course of the mining and the processing.

The literature quotes an emanation coefficient of between 0.1 and 0.3 for broken rock (see Table 8.1 in http://web.ead.anl.gov/resrad/datacoll/radon.htm and IAEA 2013). Therefore, an emanation coefficient of 0.2 has been used for this assessment and a radium activity of 3 kBq/kg. Ignoring the bulk density factor, there will be 1.26 x 10^{-3} Bq(Rn^{222})/kg.s of ore produced, giving a calculated radon production rates of 6 MBq/s from the black box due to ore.

In a similar manner, the radon production rate from the mining of mineralised waste and waste rock are calculated to be:

- Mineralised waste – 0.03 MBq/s
- Waste rock – 0.03 Bq/s.

Stockpile

The surface area of ore material stored on the ROM stockpile have the assumed dimensions of 130 m x 90 m x 20 m. If it is assumed that the stockpile is a perfect rectangle, the surface area is calculated to be 20,500 m^2 (from 130 m x 90 m + 2x(90x20) + 2x(20x130)).

The radon emission rate is therefore calculated as follows:

- 50 Bq/m^2/s per %U x 0.0239%U x 20,500 m^2 = 24,500 Bq/s

It has been assumed that on average 0.3 Mtpa of underground waste rock will be produced and used variously. For the purposes of emissions estimates, it is assumed that the material is stored in a stockpile. With a specific gravity of 3, this equates to 100,000 m^3 of material. For a stockpile with dimensions of 100 m x 50 m x 20 m, the surface area is 11,000 m^2.

The radon emission rate is therefore calculated as follows:

- 50 Bq/m^2/s per %U x 0.002%U x 11,000 m^2 = 1,100 Bq/s

Tailings Storage Facility (TSF)

The assumed surface area of tailings is 790 Ha, which equates to $7.9 \times 10^6 m^2$.

Using the tailings emission factor, the radon emission rate is calculated to be 1.9 MBq/s.

DUST FACTORS

For the assessing the impacts of radionuclides in dust emissions, an estimate of the radionuclide content of the main dust sources is required. The dust mass concentrations are then multiplied by the radionuclide content of the dusts (also known as the specific activity of the dust). This method converts a modelled mass result (for example dust concentration in g/m^3) figure into a radiation related quantity (for example radionuclide concentration in air in Bq/m^3).

The calculated factors are:

- Ore (239 ppmU) – 3.0 Bq/g
- Mineralised waste (192 ppmU) – 2.4 Bq/g
- Waste rock (20 ppmU) – 0.25 Bq/g
- All mined material (229 ppmU) – 2.8 Bq/g
- Tailings (239 ppmU) – 3.0 Bq/g

Note that dust generated during surface excavation work or from road use is considered to be inert and free of radionuclides that originate as a result of the project.

9. APPENDIX B: REFERENCES

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