REX MINERALS

Hillside Project
Radiation Impact Assessment
Technical Note

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1. INTRODUCTION

This assessment has been conducted for the proposed Rex Minerals Hillside project In South Australia.

The project is aiming to mine and process a large copper/iron deposit on the Yorke Peninsular that contains elevated concentrations of uranium. The average uranium content of the whole deposit is 57ppm (approximately 0.7Bq/g) with specific mining zones reaching an average of 81ppm uranium (1Bq/g). Exploratory drilling has identified patches of higher grade material.

The average uranium grade of the mineralised material is below the criteria for classification as a radioactive material and consequently, worker and public doses will be low. To demonstrate this, the potential doses and impacts been calculated and are outlined in this technical note.

Rex Minerals has an approved Radiation Management Plan (RMP) for its exploration activities and has processes in place to monitor and manage the low levels of radioactivity from the uranium mineralisation.

Note that the dose assessment is based on the impacts from the project and does not include the doses that would be received from natural background radiation in the environment.

2. RADIOLOGICAL DOSE ASSESSMENT

2.1 Exposure Pathways

Dose estimates have been calculated for the following groups:

- workers in the open cut and underground mine,
- processing plant operators,
- members of the public.

Dose assessments consider the main exposure pathways as follows:

- Gamma irradiation
- Inhalation of the decay products of radon (RnDP)
- Inhalation of radionuclides in dust

Doses from the ingestion of radioactive material have not been assessed as it is assumed that they will be negligible due to the establishment of an operational management plan which will include requirements for personal hygiene, such as washing and changing at end of shift.

2.2 Dose Assessment Assumptions

The following assumptions about the orebody have been used when assessing potential doses.

Parameter	Assumption
Ore mining rate	15 Mtpa
Waste mining rate	60 Mtpa
Copper concentrate production rate	70 ktpa
Iron ore production rate	1.2 Mtpa
Average ore uranium grade	57 ppm
Highest average uranium grade (ore zone)	81 ppm
Average waste uranium grade	16 ppm
Average tailings uranium grade	57 ppm
Weighted average uranium grade of ore and waste	24 ppm

For the dose assessment, it has been assumed that workers will be exposed for 2,000 hours per year and that members of the public would be exposed all year round, which is a total of 8,760 hours per year.

The appendix provides a summary of the dose factors used.

2.3 Occupational Radiation Doses – Open Pit Mine Workers

2.3.1 Gamma Radiation

Gamma radiation exposure estimates are based on the work of Thompson and Wilson (1980) which quotes a gamma exposure constant of 65µSv/h per %U for a 2π exposure situation (which is equivalent to standing on an infinite plane source).

Over the course of a working year, it is expected that the miners will work in both ore and waste material. The weighted average uranium grade of ore and waste rock is 24ppm. Therefore their dose rate is;

- 65µSv/h x 0.0024 = 0.2µSv/h

For a working year of 2,000h, this equates to;

- 0.2µSv/h x 2,000h/y = 0.4mSv/y.

Note that this is a conservative estimate (that is, an upper estimate) as there is no account for any shielding factor from the mining equipment which can usually reduce gamma exposures by a factor of 2. Therefore the estimate has been halved to reflect a more realistic gamma dose estimate.

2.3.2 Radon Decay Product (RnDP) Exposure

For open pit mining, natural ventilation will quickly dilute any build up of radon and its decay products.

To estimate the doses from RnDP, the overall method is as follows;

- Estimate the rate of radon release into the mine void,

- Calculate the rate at which the pit is ventilated to determine an equilibrium radon concentration,
- Convert the radon gas concentration to a RnDP concentration and
- Convert the RnDP concentration to dose.

Occupancy factors and recognised dose conversion factors have also been used (see appendix).

Radon Emission into Pit

The radon emission into the mine is related to the internal surface area of the mine which emits radon. The mine dimensions have been assumed to be 2.4km x 1.0km x 0.45km and the shape has been approximated to a rectangle. For this assessment, it has been assumed that the whole internal surface area of mine walls is available for radon emission giving a surface area of;

$2 \times (0.45 \times 2.4) + 2 \times (0.45 \times 1) + 1 \times (1 \times 2.4)\ km^2 = 5.46 \times 10^6 m^2$

The rate of radon emission is from published work by BHP Billiton (BHP Billiton 2009) and is assumed to be $50Bq/m^2.s$ per %U (see appendix).

Therefore for a mine average of 24ppm uranium (equivalent to 0.0024%), the radon emission rate into the mine is calculated as follows;

0.0024%U x $50Bq/m^2.s$ per %U x $5.46 \times 10^6 m^2$, giving 660kBq/s.

Mine Ventilation Rate

The ventilation rate or the number of air changes per hour in an open cut mine can be calculated using a formula of Thompson (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 = $1.1 \times 10^9 m^3$

L and W = mine length and width (m); 2,400m x 1,000m

U_r = the surface wind speed (m/h); assumed to be 3m/s giving 10,800 m/h

x = angle of the wind relative to the longer mine dimension. Note that the modelling assumes the wind is along the long axis, making $(0.7\cos(x) + 0.3)$ equal to 1 in the calculation.

Entering the values into the formula gives a mine ventilation rate of 1.4h, which is equivalent to approximately 0.7 air changes per hour.

Mine Equilibrium Radon 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.

The equilibrium concentration of radon in the mine is then calculated as follows;

$[Rn]Bq/m^3$ = Radon generation rate (Bq/h) /(Mine volume x number of air changes per hour),

$[Rn]Bq/m^3 = 660 \times 10^3 Bq/s \times 3{,}600 s/h / (1.1 \times 10^9 \times 0.7)$, giving an equilibrium concentration of approximately $3Bq/m^3$

Conversion to Decay Product Exposures

The conversion of radon gas concentrations to the radon decay product concentrations requires assumptions about the ratio between the gas and its decay products (known as the equilibrium factor). The Western Australian NORM Guideline (WA Govt 2010) provides equilibrium factors and a method for calculating the decay product concentration.

The guideline notes the following equilibrium factors for radon;

- 0.4 for indoors
- 0.2 for outdoors.

The RnDP concentration is then calculated as follows (using the most conservative equilibrium factors and standard conversion factors).

$$[RnDP]\ mJ/m^3 = 5.56 \times 10^{-6} mJ/Bq \times 3Bq/m^3 \times 0.4 = 7nJ/m^3$$

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

$$[RnDP]\ uJ/y = 7nJ/m^3 \times 2000h/y \times 1.2\ m^3/h = 17\mu J/y$$

Calculation of RnDP Dose

The RnDP dose conversion factor as provided in the appendix is 2.4 Sv/J. This gives a calculated RnDP dose of 41µSv/y.

Impacts of Stable Atmospheric Conditions

In BHP Billiton 2009, the assessment of doses for open pit mine workers includes consideration of doses under “inversion conditions”. This takes into account the effects of very stable atmospheric conditions which can lead to a build up of radon in the pit.

There are two factors that need to be considered here; the ventilation rate of the mine and the equilibrium factor (since RnDP have a longer period to grow into equilibrium with the radon concentration).

For the assessment of the Hillside open pit, it has been assumed that stable atmospheric conditions could exist in the mine pit for 12 hours, (equivalent to approximately 0.08 air changes per hour and simulating a build up in radon in the pit every night). Therefore the equilibrium concentration of radon in the mine under these conditions is calculated as follows;

[Rn]Bq/m^3 = Radon generation rate (Bq/h) /(Mine volume x number of air changes per hour),

[Rn]Bq/m^3 = 660 x10^{3}Bq/s x 3,600s/h / (1.1 x10^9 x 0.08), giving an equilibrium concentration of approximately 27Bq/m^3

However, the average pit radon concentration would occur after 6 hours, therefore the average equilibrium concentration for the 12 hours period would be approximately 14Bq/m^3.

During the stable conditions, it has conservatively been assumed that the equilibrium factor is 1.

Therefore the average RnDP concentration during the stable atmospheric conditions is then calculated as follows.

[RnDP] mJ/m^3 = 5.56x10^{-6}mJ/Bq x 14Bq/m^3 x 1 = 78nJ/m^3

If it is assumed that stable atmospheric conditions occur during the winter months and that a worker works half their number of shifts at night, then the exposure hours can be calculated to be 250 hours per year (assuming 2,000 hours per year, 500 hours per season and half time spent on night shift and half time spent on day shift). Therefore the potential exposure from stable atmospheric conditions can be calculated as follows;

[RnDP] uJ/y = 78nJ/m^3 x 250h/y x 1.2 m^3/h = 23µJ/y

The RnDP dose conversion factor as provided in the appendix is 2.4 Sv/J. This gives a calculated RnDP dose during stable atmospheric conditions of 56µSv/y.

If it is assumed that the mine workers are exposed to “normal” ventilation exposure conditions for 1,750 hours per year and stable atmospheric ventilation conditions for 250 hours per year, then the total estimated does would be;

- (1,750/2,000) x 41µSv/y + 56µSv/y, giving 92µSv/y or 0.09mSv/y.

2.3.3 Airborne Dust

The assessment of radioactive dust dose is based on an estimated total suspended dust concentration in the mine workings of 1mg/m^3 and the conservative assumption that all dust is mineralised dust containing 57 ppm uranium.

To calculate the radioactivity of the dust, the uranium grade is converted to activity concentration using the following relationship;

81 ppm uranium = 1 Bq/g of U^{238} (see appendix)

Therefore, dust containing 57 ppm uranium contains 0.7Bq/g of U^{238} and its decay products in equilibrium.

At $1mg/m^3$, the calculated activity concentration is $0.7mBq/m^3$. Using the dust dose conversion factor of 3.6×10^{-5}Sv/Bq (see appendix) and a working year of 2,000 hours per year, the potential dust dose can be calculated as follows;

$$0.7mBq/m^3 \times 3.6 \times 10^{-5}Sv/Bq \times 2{,}000h/y \times 1.2\ m^3/h = 0.06mSv/y$$

Note that the calculated dose is linearly proportional to the dust concentration. If the average annual dust concentration that a worker is exposed to is $2mg/m^3$, then the calculated dust dose is 0.12mSv/y.

Note that miners usually work in air conditioned cabins therefore it can be assumed that the calculated doses are conservative.

2.3.4 Summary of Open Pit Miner Doses

A summary of the estimated doses can be seen in the table below. Note that the worker dose limit is 20mSv/y and the member of the public dose limit is 1mSv/y.

Doses are low due to the low uranium content of the mined material.

Occupational Dose Estimates for Open Pit Miners

Work Group	Average Annual Dose (mSv/y)			
	Gamma	RnDP	Dust	Total
Open Pit Miner	0.20	0.09	0.06	0.35

2.4 Occupational Radiation Doses – Underground Mine Workers

Assessment of doses for the underground miners is based on published doses from the Olympic Dam underground mine.

In BHP Billiton 2009, average underground miner doses for the period 2002 to 2007 were reported. The miner doses were, on average, 3.5mSv/y with approximately 45% of the dose from inhalation of RnDP, 40% from gamma radiation and 5% from inhalation of radionuclides in dust. This gives approximate average doses from each of the exposure pathways as follows;

- Gamma radiation – 1.4mSv/y
- RnDP exposure – 1.6mSv/y
- Dust exposure – 0.2mSv/y

The reported uranium ore grade at Olympic Dam was 500ppm. For the Rex Minerals deposit, the reported mineralised uranium grade is 57ppm. Therefore, using a ratio, the doses for underground mine workers at the Rex Minerals deposit could be expected to be approximately 8 times less than the Olympic Dam doses as follows;

- Gamma radiation – 0.2mSv/y
- RnDP exposure – 0.2mSv/y
- Dust exposure – 0.03mSv/y

To take account of a potential legislative change to the dose conversion factor for RnDP, the potential dose from inhalation of RnDP should be doubled. (Note that this factor has been included in the open pit worker doses).

A summary of the estimated doses can be seen in the table below. Note that the worker dose limit is 20mSv/y and the member of the public dose limit is 1mSv/y.

Doses are low due to the low uranium content of the mined material.

Occupational Dose Estimates for Underground Miners

Work Group	Average Annual Dose (mSv/y)			
	Gamma	RnDP	Dust	Total
Underground Miner	0.20	0.40	0.03	0.63

2.5 Processing Plant Worker Doses

The proposed processing plant consists of:

- a crushing, grinding and flotation circuit (concentrator)
- a final products loading and shipment facility (port facility) and
- a tailings storage area (TSF)

For the purposes of this assessment, it is assumed that doses will be similar for workers in all work areas.

Two methods of dose assessment have been used. The first method uses the conservative dose factors provided by the IAEA. The second method uses published data from the Olympic Dam processing plant.

In publication 49, the IAEA (IAEA 49), provides the following factors to estimate doses:

- gamma radiation, 0.4µSv/h per Bq/g in the material,
- inhalation of dust, 37µSv/Bq inhaled.

Conservatively, if it is assumed that concentrator workers are exposed to only ore, containing 57ppm uranium (equivalent to 0.7Bq/g), for a full year of 2,000h/y, then the potential gamma doses are calculated to be 0.8mSv/y.

For dust, considering the assumptions in section 2.3.4 of this note, the inhalation dose would be approximately 0.06mSv/y for exposure to a dust cloud of 1mg/m^3 for a full year.

This gives a total dose of approximately 0.9mSv/y for processing plant workers using the IAEA method.

For comparison, the processing plant worker doses at Olympic Dam Doses for the period 2001 to 2007 give an average total dose of 1.8mSv/y for processing of material containing 500ppm of uranium (BHP Billiton 2009). For the Rex Minerals material, the average uranium concentration is 57ppm, approximately 8 times lower than the Olympic Dam material. If it is assumed that the dose is proportional to the radioactivity of the material, then the potential doses will also be a factor of 8 lower at 0.2mSv/y.

To remain conservative in the dose assessment, the average of the IAEA and the Olympic Dam figures has been used to estimate the plant workers doses at 0.5mSv/y.

2.6 Other Occupational Dose Estimates

Administration workers will mainly work in offices located adjacent to the processing plant. Doses are expected to be less than those for processing plant workers.

2.7 Public Dose Assessment

2.7.1 Introduction

This section describes radiological impacts from emissions from the project impact which effect sensitive receptors outside the project area.

Of the main exposure pathways, gamma radiation is considered to be negligible because the concentration of radionuclides in the ore and waste rock is low, (less than the classification for a radioactive material) and any sources of gamma radiation are well within the mine lease area, thereby not constituting a hazard to the general public.

For the public, the only potential exposure pathways are via the airborne pathways being;

- inhalation of radioactive dust, and
- inhalation of the decay products of Rn^{222}.

An assessment of doses from these two pathways has been conducted.

For this assessment, doses have been calculated for two locations as follows;

- residents living on the southern edge of the project boundary property
- residents at the port.

To estimate doses at these locations, the results of the air quality modelling are used (PEL 2013). The method is as follows;

- establish the dust concentrations at the locations using the contour plots,
- calculate an exposure based on the concentration and occupancy factors, and
- use standard dose conversion factors (DCFs) to determine the doses.

For this assessment, it is assumed that the project boundary and the port are permanently occupied; therefore the residents would be exposed for 8,760 hours per year. It is also assumed that the reference person at each location would have breathing rate of 1.2m^3/h.

2.7.2 Dust Exposure

The air quality report (PEL 2013) shows that the annual average total suspended solids (TSP) dust concentration is a maximum of approximately 40µg/m^3 at project boundary and 27µg/m^3 at the port. It is assumed that the majority of the dust emitted from the project operation is ore dust (containing 57ppm of uranium), therefore the dust will contain approximately 0.7Bq/g. The appendix provides dose conversion factors for dust.

The dose from the dust inhalation is then calculated as follows:

- Average annual dust concentration is 40µg/m^3 at the project boundary and 27µg/m^3 at the port
- The specific activity of U^{238} decay chain radionuclides in the dust is 0.7Bq/g
- Therefore the average annual activity concentration is 28µBq/m^3 at the project boundary and 19µBq/m^3 at the port
- A person breathes at a rate of 1.2 m^3/h, therefore the inhalation intake rate is:
    - 1.2m^3/h x 28µBq/m^3 = 34µBq/h (project boundary)
    - 1.2m^3/h x 19µBq/m^3 = 23µBq/h (port)
- For a full year exposure of 8,760 hour, the total intake is:
    - 34µBq/h x 8,760h/y = 0.3Bq/y (project boundary)
    - 23µBq/h x 8,760h/y = 0.2Bq/y (port)
- With a dose conversion factor of 39µSv/Bq, the estimated inhalation dose is approximately 11µSv/y at the project boundary and 8µSv/y at the port.

2.7.3 Radon

No radon air quality modelling was undertaken for the project however UNSCEAR 2000 provides a reference for general dispersion and is reprinted in the following table as dilution factors for the source and long-term average conditions (note that the dilution factor is the ratio of the radon concentration to the radon emission at each distance).

Downwind distance (km)	Dilution factor (Bq/m^3 per Bq/s)
0.5	9.7 10^{-7}
1	5.3 10^{-7}
2	2.5 10^{-7}
5	7.1 10^{-8}
10	2.5 10^{-8}
20	8.7 10^{-8}
50	2.2 10^{-9}

To utilise these dispersion factors, an assessment of the total radon emission rate from the project needs to be made.

This has been done by assuming that all radon that is present in the ore and waste rock is liberated over the course of the operations. The amount of contained radon is calculated by multiplying the total mining rate of ore and waste by the activity concentration of radon in the material. The activity concentration is determined by assuming that the material is in secular equilibrium and that the activity concentration of radon is equal to the activity concentration of uranium.

The calculation provides a radon emission rate for the whole of the project of 0.7MBq/s.

If it is assumed that the project boundary is 0.5km from the source, then the dilution factor is 9.7 x 10^{-7} Bq/m^3 per Bq/s, giving a project boundary radon concentration of 0.7Bq/m^3.

Assuming that the port is 5km from the project area, using the same method, the radon concentration is calculated to be 0.05Bq/m^3.

Assuming that the radon is in equivalent equilibrium concentration, UNSCEAR (in UNSCEAR 2000 Annex B, paragraph 153) provides a dose conversion factor (DCF) of 9nSv$(Bq.h/m^3)^{-1}$. The DCF is then multiplied by the radon concentration to give the dose rate per hour, which is then multiplied by the exposure hours.

For both the project boundary and the port, the exposure hours are 8,760h/y, giving RnDP doses of 56µSv/y and 4µSv/y respectively.

2.7.4 Summary

A summary of public dose estimates is shown the following table. Note that the public dose limit is 1mSv/y.

Predicted Public Dose

Sensitive Receptor	Dose From Pathway (mSv/y)			
	Inhalation of RnDP	Inhalation of Dust	Gamma Radiation	Total Dose
Southern Project Boundary	0.056	0.011	0	0.067
Port	0.004	0.008	0	0.012

2.8 Environmental Impacts

An assessment of the environmental radiological impact of the project has been made by considering the dust deposition from the project.

The air quality modelling (PEL 2013) shows that the highest annual average dust deposition is 1.3g/m^2.month at the southern project boundary. If it is assumed that the mine weighted average uranium grade is 24ppm, then is can be assumed that the deposited dust will contain 24ppm uranium.

This gives an activity concentration of U^{238} (and all decay products) of 0.3Bq/g. Therefore, this equates to a deposition rate at the project boundary of 0.39Bq/m^2.month. Over the course of a year, the deposition rate is therefore 4.7Bq/m^2.year.

For the assessment it has been assumed that the project runs for 20 years. Therefore the total deposition is 20 x 4.7Bq/m^2 = 94Bq/m^2.

It is assumed that the deposited dust mixes in the top 10cm of soil, and therefore the volume of soil in this “mixing zone” is 0.1m^3, which is approximately 100kg (100,000g) (assuming a density of 1).

Therefore change in radionuclide concentration can be calculated as follows by dividing the additional radionuclides (94Bq/m^2) by the mass of soil in the deposited area. This gives 0.9Bq/kg for each of the radionuclides.

Rex Minerals has reported on naturally occurring radionuclides in soil in the region from a number of scrapes. The average U^{238} and Ra^{226} soil concentrations are 7.8Bq/kg and 18.1 Bq/kg respectively. Therefore, over a 20 year period, the modelling shows that the operation will increase U^{238} and Ra^{226} soil concentrations, above the naturally occurring concentrations, by 12% and 5% respectively at the southern project boundary. This change is within the variation that occurs naturally.

2.9 Summary of Radiological Impacts

The assessment has shown that the radiological impacts of the proposed project will be low. Conservative estimates show that doses to all workers will be less than 1mSv/y, compared to the annual limit of 20mSv/y. A summary of the worker doses can be seen in the following table.

Work Group	Average Annual Dose (mSv/y)			
	Gamma	RnDP	Dust	Total
Underground Miner	0.20	0.40	0.03	0.63
Open Pit Miner	0.20	0.09	0.06	0.35
Processing Plant Workers	N/A	N/A	N/A	0.50

Public doses are expected to be well below the public dose limit of 1mSv/y and a summary of the doses can be seen in the following table.

Sensitive Receptor	Dose From Pathway (mSv/y)			
	Inhalation of RnDP	Inhalation of Dust	Gamma Radiation	Total Dose
Southern Project Boundary	0.056	0.011	0	0.067
Port	0.004	0.008	0	0.012

Appendix: Dose Factors and Assumptions

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

Conversion of dust mass to radionuclide in dust concentration

The following method was used:

- Assume that the uranium is in secular equilibrium with its decay products (the most conservative assumption).
- Pure U^{238} contains 12,400Bq/g (meaning 1,000,000ppm U^{238} equals 12,400 Bq/g).
- In naturally occurring uranium, the overwhelming isotope is U^{238}.
- Therefore 1Bq/g of U^{238} is approximately 81 ppm uranium.

Dose assessment

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

Radon Decay Product (RnDP) Factors

1.2 mSv/mJ (ARPANSA 2005)

Assume 2.4 mSv/mJ (pending advice from ICRP regarding the revised RnDP dose conversion factor).

Unit radon emission rates are (BHP Billiton 2009);

- 50Bq/m^2/s per %U for unbroken rock
- 250Bq/m^2/s per %U for broken rock

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