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Occupational and Environmental Radiation Predictions and Controls, Mulga Rock Uranium Project

RADIATION REPORT

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Vimy Resources (Vimy) is proposing to develop the Mulga Rock Uranium Project (MRUP) which lies approximately 240km east-north-east of Kalgoorlie-Boulder in the Shire of Menzies. The area is remote, located on the western flank of the Great Victoria Desert and comprising 102,000 hectares of dune fields on granted mining tenure (M39/1080 and M39/1081) within Unallocated Crown Land

There are no regional communities within the vicinity of the Project. The nearest residential town to the Project is Laverton which lies approximately 200km to the north-west. The only other regional residential communities are Pinjin Station homestead located approximately 100km to the west, Coonana Aboriginal community situated approximately 130km to the south-south-west, Kanandah Station homestead positioned approximately 150km to the south-east and the Tropicana Gold Mine lying approximately 110km to the north-east of the Project. The nearest critical groups (or representative most-exposed persons) for assessment of radiation doses to members of the public, are people living at Pinjin, 100 km to the west, and at Tropicana, 110 km to the NE.

The MRUP will mine and treat run-of mine (ROM) ore ranging in uranium grade from 200 to 1000 ppm, and thorium content ranging in the order of 10 to 250 ppm. The processing facility will produce on average 1360 tonnes of Uranium Ore Concentrate (UOC) per year and by-product base metal concentrates.

The operation will be regulated as a radiation practice under the Western Australia (WA) Radiation Safety Act (1975) and under the requirements of the WA Mines Safety Inspection Act (1994) and, in particular, Part 16 of the Mines Safety Inspection Regulations (1995) which relates to mining and processing of radioactive ores.

It should be noted that measures required for control of radiation in uranium mining and processing are well-known and will be committed to in the design and operation of the Project.

This report describes:

- The regulatory regime applicable to uranium mining for radiation control,
- The underlying control philosophy and approach which will be followed,
- The present radiological background as derived from baseline monitoring results,
- Estimates of radiation source terms arising from proposed project activities,
- Estimated environmental radiation increments which will result,
- Estimated doses to workers and Members of the Public,
- Description of design and management controls for radiation and
- Assessment of risk to Non-Human Biota.

Radioactive emission source terms (i.e., gamma shine, releases of radon, and releases of dusts containing long-lived alpha emitting radionuclides) and radiation doses to workers and others from these sources, can be readily assessed based on well-known principles and on comparisons with other uranium operations. These assessments are given in subsequent sections of this report.

Key findings from these assessments are:

- The estimated doses to workers on the Project will be low, in the order of 3 to 4 mSv/yr, and thus a small fraction of the maximum allowable limit of 20mSv/yr,
- Predicted Project incremental (additional) radiation will be negligible compared with the natural background and also small compared with the variability in natural background,

- The Project incremental dose to members of the public resident at other centres (Pinjin, 100 km west; Tropicana, 110 km NE; other) will be 'negligible', too small to be measurable, and
- The risk of radiological harm to Non-Human Biota has been assessed to be 'negligible'.

A complete list summarising the radiation dose information from this report is detailed in the Table below.

Table: Radiation dose information

Radiation parameter (Report section)	**Value**	**How estimates were determined (and where referenced in Report)**
Doses to mine workers (Section 6)	4 mSv/yr (max)	Gamma dose based on first principles and consideration of exposure rates at other mines; Dust doses based on estimate of dust concentrations at other open cut mines combined with standard dose conversion factors; and Radon decay product doses based on estimate of modelled radon levels in pit (including a range of atmospheric conditions.
Doses to metallurgical plant workers (Section 6)	1.5 mSv/yr	Data from the existing operations
Member of public dose in Accommodation Village	0.024 mSv/yr	Gamma doses negligible; Dust and Radon decay product doses based on modelled airborne dust and radon concentrations combined with standard dose conversion factors.
Dose to Indigenous people from consumption of local bush tucker	< 0.2 mSv/yr	Calculated based on worst case consumption, transfer factors and uptakes over 1 year at the Project boundary.
Dose to hypothetical member of public living at closest project boundary	0.18 mSv/yr	Estimates of long-lived alpha dust and radon concentrations from air dispersion modelling.
Doses to UOC truck drivers	0.37 mSv/yr	Doses based on estimates and other operations and a worst-case number of trips that one driver might make.

The results of 7 years of environmental radiation monitoring onsite, covering gamma radiation, radionuclides in airborne dust, radon and radon progeny, show overall levels which are in line with the rest of inland Australia. In addition, the monitoring results show (as indeed they do everywhere else) significant variations spatially across the Project area, and significant variations with time, both on short and long time scales. The table below summarises the key radiological assessment information derived from literature reviews, modelling, investigative analysis and baseline studies.

Table: Summary of additional radiological assessment information

Radiation parameter	Summary additional information
Mine gamma dose rates	Potential doses were determined from multiple literature sources, and crosschecked with other open pit Uranium mine reports.
Mine dust levels and potential doses	Dust concentrations were based on estimates from other open pit operations. The uranium grade of the ore dust provided an average radionuclide concentration for the dust. The dose conversion methods as outlined in the Mining Code 2005 (ARPANSA 2005) were used to determine potential doses.
Radon emanation rates	Radon emanation rates were measured from samples for two different ore types. The measured emanation rates were also checked against the literature.
Radon in pit	The estimated equilibrium concentration of radon in the pit is based on a combination of the emanation rate, the emanating surface area of the pit and pit ventilation rate.
Radon levels under normal atmospheric conditions	Estimates of pit concentrations were made based on a box model which calculates an air-in-pit residence time based on surface wind speeds.
Radon levels under inversion atmospheric conditions	Inversion conditions occur on the surface, and are predicted to exist in the pit during cold, still atmospheric conditions. Conservative estimates of the depth and the frequency of probable inversions were made, resulting in estimates of potential doses under inversion conditions.
Radon emanation from the TSF	A radon emanation rate of 0.5 $Bq/m^2/s$ was chosen based on review of results reported from other operations; actual measurements done on wet fine crushed ore as a surrogate to tailings suggest nearly a power of ten lower, so this assessment is highly conservative .

ENVIRONMENTAL REVIEW REQUIREMENTS

The Environmental Scoping Document (ESD), in its Review of Preliminary Key Environmental Factors (PKEFs), specifically raised the following PKEFs under the heading 'Human Health' which need to be addressed within the PER:

1. Characterisation of expected levels of radioactivity associated with each stage of the mining process including transportation of the final product. **This is discussed in Section 6, 'MRUP Radiation Assessment', of this Report,**
2. Assessment of the potential radiological impacts on workers (including transport workers) and members of the public both during operation and post closure, including a radiological dose assessment. **This is discussed in Section 6, 'MRUP Radiation Assessment' for project workers, and Section 7, 'Public and Environmental Radiation Assessment', for members of public.**

3. Collection and analysis of radiological baseline data. This is addressed in **Section 4, 'Historical and Baseline Studies' of this report.**
4. Description of potential implications for health and safety due to the mining or processing of lignitic material, during operations and to infrastructure; **This is discussed in MRUP Dispersion Modelling attached to the PER in Appendix E1 (GHD, 2015A); MRUP Mine Closure Plan in Appendix H1 (Vimy, 2015), and MRUP Radon Test Work, Technical Note in Appendix F3 (Sonter et al, 2015)**
5. Assessment of risks to human health from 'bush tucker' consumption in the region from radiological sources and other contaminants, based on local diet. Where a local community is not present a hypothetical model should be used, taking into account a 'worst case' scenario. **This is shown to be negligible, and is addressed in Appendix B**
6. Discussion of proposed best practice management, monitoring and control/mitigation methods to be implemented for a remote site so that the cumulative impacts from all sources do not pose an unacceptable risk to the health and amenity of site personnel or the environment. **This is addressed in Section 9, Controls and Mitigation,** and
7. Outline the outcomes/objectives, management, monitoring, trigger and contingency actions, within environmental management plans, to ensure impacts (direct and indirect) are not greater than predicted. **This is addressed in Section 10, Monitoring Plan and Responses.**

The ESD has identified, under the PKEFs for Flora and for Fauna, a required work task being assessment of potential radiological impact via the ERICA tool. **This is addressed in Appendix B, ERICA Assessment**

The ESD has identified, under the PKEF 'Rehabilitation & Closure', the following *radiation management related* required work:

1. A preliminary Radioactive Waste Management Plan (RWMP) is to be prepared and included in the PER. This is discussed in a standalone Appendix within the PER. The RWMP considers the following:
    - PKEFs and how the environmental objectives of the ARPANSA Radiation Protection Series (incl. RPS6, RPS 9 and RPS 15) and International Atomic Energy Agency (IAEA) Safety Standard SSR-5 'Disposal of Radioactive Waste' 2011 are to be achieved and
    - Identify, characterise and classify each waste stream (including intermediate processing waste) associated with the operation of the mine, in accordance with ARPANSA RPS20. **This is discussed in the Preliminary Radiation Waste Management Plan (RWMP) attached to the PER in Appendix H3 (JRHC, 2015).**

2. An assessment of radon exhalation performance of the capping material and its significance. **This is addressed in Section 6.2, 'Radon Sources and Dose Predictions'.**

1 INTRODUCTION

The Mulga Rock Uranium Project (MRUP) lies approximately 240km east-north-east of Kalgoorlie-Boulder in the Shire of Menzies (Figure 1.1). The area is remote, located on the western flank of the Great Victoria Desert and comprising series of large, generally parallel sand dunes with inter-dunal swales and broad flat plains. The MRUP covers approximately 75,700 hectares on granted mining tenure (M39/1080 and M39/1081) within Unallocated Crown Land.

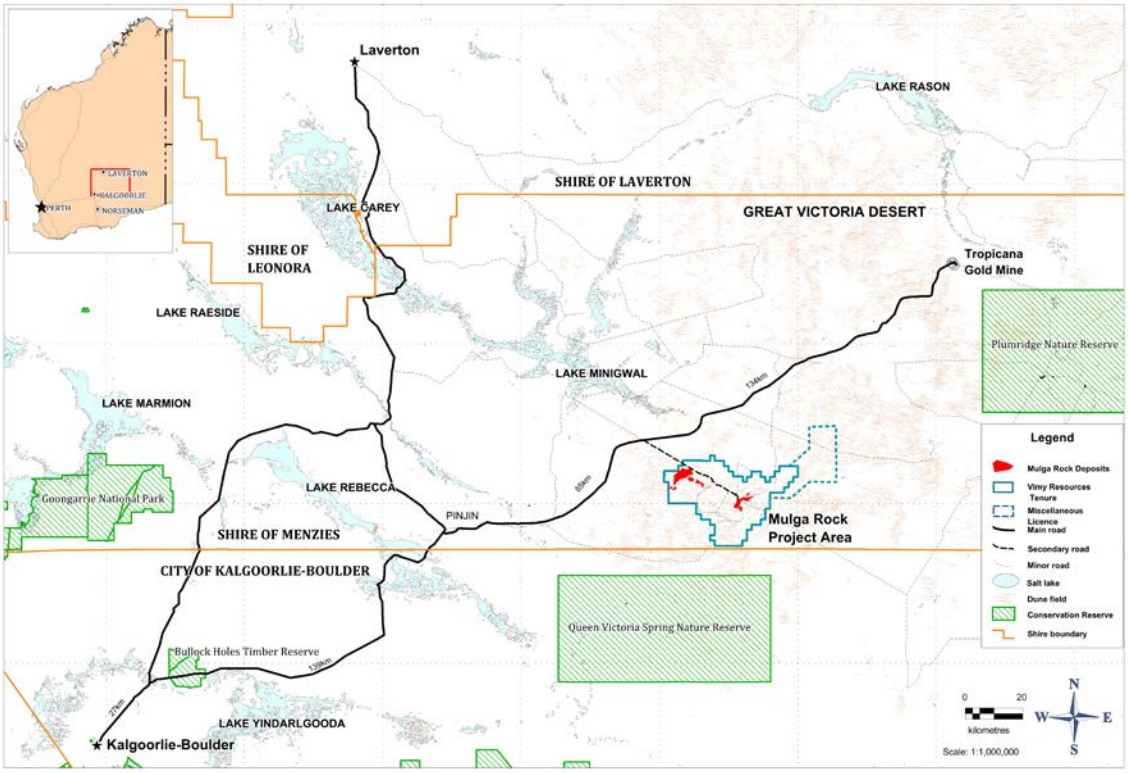


Figure 1.1: Location map of Mulga Rock Uranium Project.

There are no regional communities within a 100km radius of the Project. Access to the Project area is limited and is only possible using four-wheel-drive vehicles. The nearest residential town to the Project is Laverton which lies approximately 200km to the north-west. Other regional residential communities include Pinjin Station homestead located approximately 100km to the west, Coonana Aboriginal community situated approximately 130km to the south-south-west, Kanandah Station homestead positioned approximately 150km to the south-east and the Tropicana Gold Mine lying approximately 110km to the north-east of the Project (**Figure 1.2**). The nearest critical groups (or representative most-exposed persons) for assessment of radiation doses to members of the public, are people living at Pinjin, 100 km to the west, and at Tropicana, 110 km to the NE.

The MRUP comprises two distinct mining centres, Mulga Rock East (MRE) comprising the Princess and Ambassador resources and Mulga Rock West (MRW) comprising the Emperor and Shogun resources, which are approximately 20km apart (Figure 1.3). MRE contains over 65% of the total recoverable uranium and is of a higher grade than MRW. Mining will commence at MRE which will include the location of the plant. Up to 4.5 Million tonnes per annum (Mtpa) of ore will be mined using traditional open cut techniques, crushed, beneficiated and then processed at an acid leach and precipitation treatment plant to produce, on average, 1,360 tonnes of uranium oxide concentrate (UOC) per year over the life of the Project. The anticipated Life-of-Mine (LOM) is up to 16 years, based on the currently identified resource.

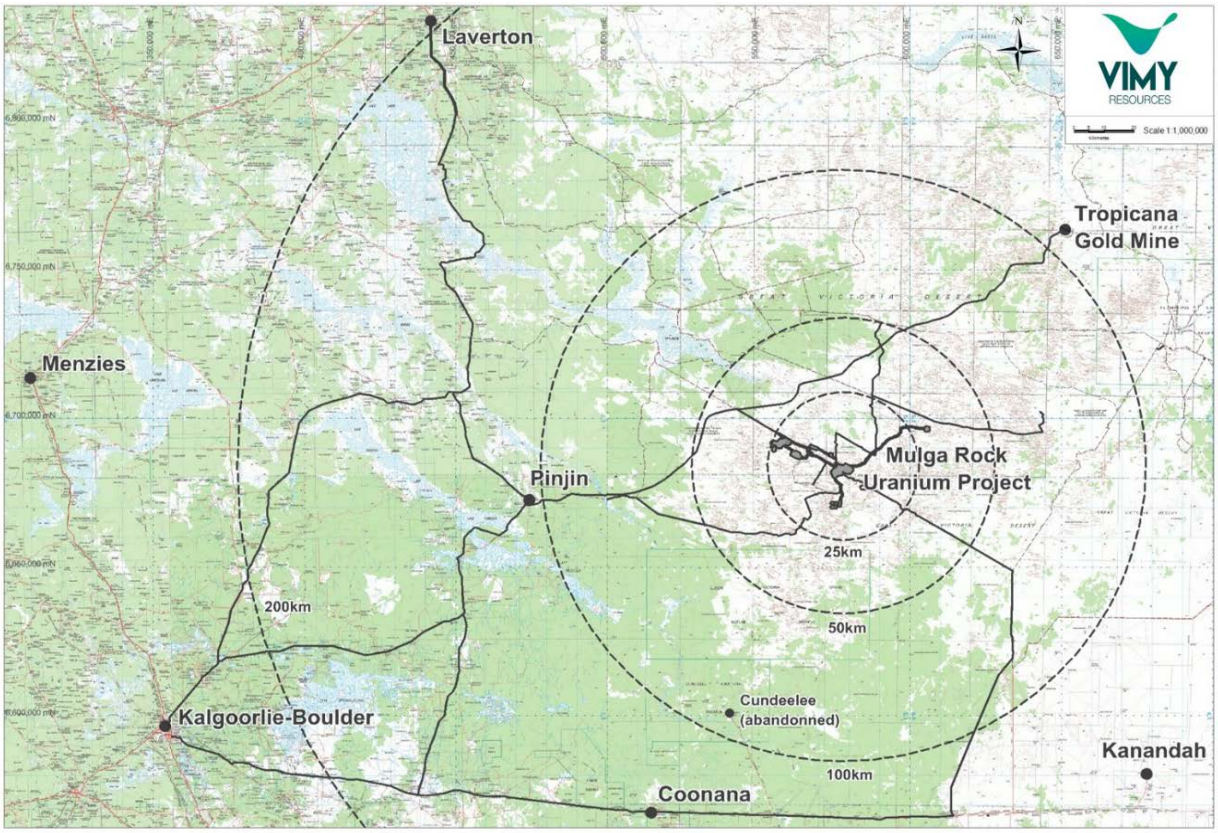


Figure 1.2: Location of regional communities to the Project.

Other metal concentrates will be extracted using sulphide precipitation after the uranium has been removed and sold separately. These metal concentrates will not be classified as radioactive.

Vimy recognises that there may be a potential need for specific processing to be carried out to remove other radionuclides from by-products produced on-site to enable transport as non-radioactive material and to meet purchasers' specifications.

The UOC product will be sealed in drums and transported by road from the mine site in sealed sea-containers to a suitable port (expected to be Port Adelaide) which is approved to receive and ship Class 7 materials for export.

The MRUP will require the clearing of vegetation, borefield abstraction, mine dewatering and reinjection, the creation of overburden (non-mineralised) landforms and the construction of on-site processing facilities and waste management systems. Major built infrastructure will include a centralised processing plant, a Run-of-Mine (ROM) ore stockpile area, the construction of above-ground overburden landforms for non-mineralized mined materials, an above-ground tailings storage facility TSF) and water storage / evaporation facilities. Once there is sufficient void space created, use of the above-ground TSF will cease and tailings material will be re-directed into an adjacent pit, capped using non-mineralised overburden material and then rehabilitated.

Required Project infrastructure will include mine administration and workshop facilities, fuel and chemical storage depots, a diesel-fired power plant of up to 12 megawatt (MW) capacity, an abstraction borefield and a mine water reinjection borefield with associated pipelines and power supply units, an accommodation village servicing a fly-in / fly-out workforce, an airstrip, laydown areas and other supporting ancillary infrastructure including communications systems, roads, a waste water treatment plant and solid waste landfill facilities. Transport to site for consumables, bulk materials and general supply items will be via existing public road systems linked to dedicated Project site roads.

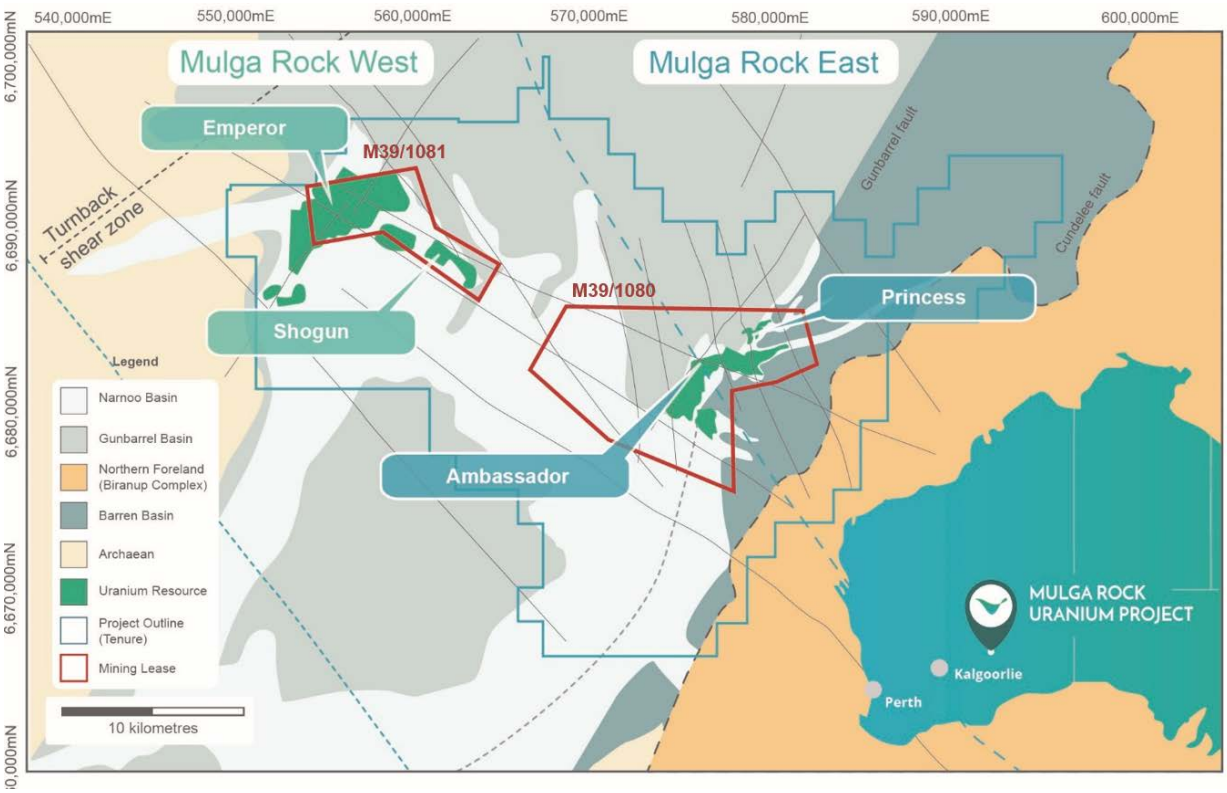


Figure 1.3: Location of the MRUP Mineral Resources.

At the completion of operations, the Project site will be decommissioned and rehabilitated in accordance with an approved Mine Closure Plan.

1.1 INTRODUCTION TO RADIATION

Ionizing radiation was first discovered, and almost immediately began to be used in medicine, over 100 years ago, when Prof Wilhelm Roentgen discovered x-rays (1895) and Marie Curie discovered radium (1898). Very soon thereafter (within 2 to 5 years), the immediately damaging effects (burns) and longer term risk (of cancer) arising from excessive doses began to be reported in the literature.

The health risks from ingesting and inhaling radioactive substances became obvious from the mid-1920s with the bone cancer deaths of radium dial painters, and in response, the first workplace radiation hygiene and airborne radioactivity standards were developed (by RD Evans of the US Public Health Service) in the early 1930's.

The first international recommendations for control of the health risks of x-rays and radium were published in 1928, by a committee of the International Congress on Radiology, later to evolve into the ICRP (see below).

Excess lung cancers in underground radium miners were observed in the mid 1920's and in underground uranium miners in the 1950's. Radon progeny air concentration limits and mine ventilation controls were developed and implemented in the 1960's and by the early 1970's the risk of lung cancers from inhalation of excess radon progeny levels in mine air was essentially understood and controlled.

A suitable general introduction to radiation protection in mining and processing of radioactive ores, is the Radiation Workers' Handbook, developed as a joint publication of the Commonwealth Department of Resources Energy & Tourism, and the Australian Uranium Association, and available on the AUA web page (www.aua.org.au).

1.2 NATIONAL AND INTERNATIONAL REGIMES FOR RADIATION DOSE CONTROL

1.2.1 REGULATION

Radiation doses to workers and to members of the public are (and have been since the 1950's) controlled in all Australian states under the various state Radiation Safety, Control or Protection Acts and associated Regulations. These Acts and Regulations are (as required by COAG rules) all in general conformity with Codes and Guidelines issued by the Commonwealth agency, being the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), under its National Directory for Radiation Protection (RPS #6). ARPANSA, in turn, bases its advice on guidance documents published by the International Atomic Energy Agency (IAEA), being primarily IAEA Basic Safety Standards, Safety Series Publication #115; on the Recommendations the International Commission on Radiological Protection (ICRP), being primarily ICRP Publication 103; and on the Reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

Thus, it can be argued that radiation is very well understood and regulated, with a very structured and mature internationally agreed approach which has been developed over many decades.

In Western Australia, the regulatory requirements for radiation safety in *Mining and Processing of Radioactive Ores* are set down in Part 16 of the Mines Safety and Inspection Regulations 1995. The Western Australian Department of Mines and Petroleum (DMP) has issued a very extensive 'textbook-style' set of guidelines for managing Naturally Occurring Radioactive Materials (known as the NORM guidelines). They are intended to provide general guidance in interpretation of these requirements, together with a wide range of useful technical advice. It must be noted these guidelines are not a substitute for Regulations and compliance with the Guidelines is not mandatory. The Guidelines are presently under review, and slated for rewriting (and simplifying) in 2015.

The State Acts and Regulations also address the requirements for avoidance or minimisation of detrimental impact on the environment.

1.2.2 EPBC ACT

The Proposal represents a green fields operation, and was referred to the Environmental Protection Authority (EPA) under Part IV of the *Environmental Protection Act 1986* (EP Act). The Proposal was determined by the EPA as requiring assessment at the level of Public Environmental Review (PER) with a four week public comment period.

Under the *Environmental Impact Assessment (Part IV Divisions 1 and 2) Administrative Procedures 2012*, the EPA prepared the Environmental Scoping Document (ESD). The ESD identified the environmental factors of the Proposal and the environmental studies required to allow an environmental impact assessment.

The Proposal has been referred and determined to be a controlled action under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) and is being assessed under the Bilateral Agreement between the Commonwealth of Australia and the State of Western Australia made under Section 45 of that Act. The relevant matters of national environmental significance (MNES) for this proposal are:

- three listed fauna species (S18),
- one listed plant species (S18),
- mining of uranium ore (S22) and
- decommissioning and rehabilitation of a uranium mine (S22).

After assessment, the Proposal will require approval from both State and Commonwealth Governments.

1.2.3 RADIATION LIAISON COMMITTEE

The Radiation Liaison Committee (RLC) was established to enable the WA Department of Mines and Petroleum (DMP) and the Radiological Council to implement a Memorandum of Understanding (MoU) to prevent the overlap or duplication of regulatory responsibilities in relation to radiation safety for mining operations. The RLC is comprised of representatives nominated by DMP and the Radiological Council.

The Radiological Council is charged with administering the *Radiation Safety Act 1975* and its subsidiary legislation. The Act regulates the keeping and use of prescribed radioactive substances, irradiating apparatus and electronic products and establishes the Radiological Council as an independent statutory authority responsible directly to the Minister for Health. Radiation protection controls are also placed on the mining industry, through Part 16 of the *Mines Safety and Inspection Regulations 1995*, under the *Mines Safety and Inspection Act 1994*, which falls under the portfolio of the Minister for Mines and Petroleum. Part 16 is administered by the State Mining Engineer and its primary aim is to protect mine workers from the effects of radiation exposure with the regulations also covering the effects of radiation to the public and the environment.

To enhance the coordination of the administration of joint regulatory responsibilities under the *Radiation Safety Act 1975* and the *Mine Safety Inspection Act 1994* and subsidiary regulations, the duties of the RLC will include the approval of radiation management plans and the management of mine decommissioning and rehabilitation.

1.2.4 LEGISLATION AND GUIDANCE DOCUMENTS

The Legislation and guidance documents relevant to radiation management as it applies to MRUP are listed below (including 'Relevant Policy, Guidance, and Legislation', ref ESD p15):

- Mines Safety and Inspection Act 1994, & Mines Safety and Inspection Regulations 1995,
- Department of Mines and Petroleum (DMP, 2010). Managing Naturally-Occurring Radioactive Material (NORM) in Mining and Mineral Processing – Guidelines ('The WA NORM Guidelines', in particular NORM 3.1 which deals with pre-operational monitoring requirements),
- Radiation Safety Act 1975, and Radiation Safety (General) Regulations 1983-2003.

ARPANSA Radiation Protection Series (RPS) Guidelines -– particularly:

- RPS F-1 (Fundamentals for Protection Against Ionising Radiation (2014)),
- RPS 2 (Code of Practice for the Safe Transport of Radioactive Material (2008)),
- RPS 2.1 (Safety Guide for the Safe Transport of Radioactive Material (2008)),
- RPS 2.2 (Safety Guide for the Approval Processes for the Safe Transport of Radioactive Materials (2012)),
- RPS 6 (National Directory for Radiation Protection (NDRP) 2014),
- RPS 7 (Recommendations for Intervention in Emergency Situations Involving Radiation Exposure (2004)),
- RPS 9 (Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005)),
- RPS 9.1 (Safety Guide for Monitoring, Assessing and Recording Occupational Radiation Doses in Mining and Mineral Processing (2011)),
- RPS 15 (Safety Guide for Monitoring, Assessing and Recording Occupational Radiation Doses in Mining and Mineral Processing (2011)),

- RPS 16 (Safety Guide for the Predisposal Management of Radioactive Waste (2008)),
- ARPANSA (2011) Joint convention on the safety of spent fuel management and on the safety of radioactive waste management, Australian National Report.

(Of the above, RPS 9, the 'Mining Code', and its daughter publications, RPS 9.1 and RPS 15, are the key planning and operational guidance documents for industry. RPS F-1 and RPS 6 provide philosophical and legal support. RPS 2 and its supporting documents RPS 2.1 and 2.2 provide detailed instructions on transport of radioactive materials and are thus also directly relevant.)

International Commission on Radiological Protection (ICRP) relevant publications, specifically

- ICRP Publication 103 - The 2007 Recommendations of the ICRP

International Atomic Energy Agency relevant documents, specifically

- IAEA Safety Series No. 115: International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources,
- IAEA Safety Standards Series RS-G-1.6 - Occupational Protection in Mining and Processing of Raw Materials.
- IAEA International Transport Regulations TS-R-1 (incorporated in RPS#2)

Other relevant Australian Federal and Western Australia legislative requirements are:

- Environment Protection and Biodiversity Conservation Act 1999 (definition of 'Nuclear Action'),
- Nuclear Non-Proliferation (Safeguards) Act 1987,
- Dangerous Goods Safety Act (2004) of WA.

These references have been reviewed by Vimy and Statutory Regulations will be covered in the relevant management plans to be developed and listed in the main PER document.

1.2.5 ICRP System of Dose Limitation, ALARA, and Regulatory Limits

ICRP promotes (and the Australian regulatory regime adopts) a 'System of Dose Limitation' whereby all planned doses to workers or to members of the public from industrial activities need to be (a) *justified*; (b) *optimised*; and (c) *limited*.

Justification means generally that the benefits must be recognised by society to outweigh the detriments of any incurred dose. In the context of a uranium mine, 'justification' is demonstrated by regulatory acceptance of the proposal, endorsement by the DMP and licensing by the Radiological Council of WA.

Optimisation means that doses are to be controlled so as to remain 'as low as reasonably achievable, social and economic factors being taken into account'. In the mining industry context this implies at the design stage that 'best practices' are applied; and in operations, that they will be implemented through the occupational component of the Mining and Processing - Radiation Management Plan (RMP) incorporating an appropriate radiation monitoring program. 'ALARA' is thus a primary tool for control, prompting application of design standards in the design stage, and a philosophy of continuous improvement in operations. The administrative processes used for optimisation involve:

1) Classification of working conditions and workplaces;
2) Application of dose constraints to certain work categories;
3) Implementation of investigation and reporting levels;

4) Formulation, distribution and implementation of safe work procedures for identified critical tasks and provision of awareness training to all employees.

Limitation means of course that doses will be controlled so as to remain below statutory limits.

1.2.6 DOSE LIMITS

The world-wide (and WA) annual limits for radiation doses to be accrued from planned and licenced human activities ('practices'), as recommended by ICRP, are 20 millisieverts per year (mSv/yr) to 'radiation workers', and an annual dose limit to members of the public (incremental to natural background, and arising from nearby radionuclide-emitting industrial activity) of 1 mSv/yr.

These limits apply only to doses arising from work or industrial activities, i.e. from controllable and licensable activities, and do not include dose from natural background, nor medical doses incurred during diagnostic tests or therapeutic procedures.

For example, a worker may receive 10 mSv from a medical CAT scan, or 12 mSv from a heart stress test using an injected radiopharmaceutical tracer for imaging, or 0.1 mSv from an abdominal x-ray, but these doses are not counted against his or her 'annual worker dose limit' for workplace control purposes; basically because (a) they are outside the control of the employer, and (b) they are separately justified on medical grounds.

It is the responsibility of a uranium mining company, just as it is of a radiology practice or a radiation research organisation or a radiopharmaceutical production facility, or any other radiation operation, to ensure that the doses of all of its workers are kept below the annual limit of 20 mSv, and indeed, 'As Low As Reasonably Achievable' below that limit; and that the doses from the operation or practice, received by residents living nearby, are kept well below the limit for members of the public, that being 1 mSv/yr.

It is clearly understood by Vimy Resources as the proponent for the Mulga Rock Uranium Project, that doses must be minimised (as low as reasonably achievable), and not merely kept 'below the limit'.

Vimy understands that ALARA means that doses will be effectively monitored, and controlled, using good industrial practices, so as to minimise doses, to levels which are "as low as reasonably achievable, social and economic circumstances being taken into account".

Demonstration of ALARA is shown by implementation of, and active management via, a formal Radiation Management Plan, including implementation and review of the results of a structured Radiation Monitoring Program.

ALARA in practice usually comprises of:

- Using best or leading practices,
- Ensuring staff are suitable trained and qualified,
- Specific radiation design criteria, and
- Initial and periodic radiological risk assessments.

2 NATURAL BACKGROUND RADIATION

Radiation is ubiquitous: it is present everywhere: worldwide, natural radiation doses to populations arise from exposure to cosmic rays, gamma radiation from uranium and thorium in soil and rock, from inhalation of radon in air which has passed over continental landmass, and from radionuclides ingested in food and water.

The average concentration of uranium in rocks and soils, worldwide, is about 3 parts per million (ppm). Some uraniferous granites however may contain 50 ppm or more. Some copper ores contain over 100 ppm uranium. Uranium mineralization containing over 300 ppm may, depending on mining and processing costs, be considered to be 'ore'.

Natural background radiation is highly variable: worldwide annual average dose to the human population is quoted by UNSCEAR to be about 2.4 mSv/year. However, some locations incur doses which are more than tenfold higher, including Guarapari in Brazil (35 mSv/yr), Kerala, India (35 mSv/yr) and Ramsar in Iran (a small area giving 260 mSv/yr), due to the presence of radium, uranium or thorium in the local soils and rocks.

It is noteworthy that populations living in areas having higher levels of background radiation do not show deleterious health effects: UNSCEAR in its ongoing comprehensive review of the literature (as tasked by the UN General Assembly) consistently fails to find epidemiological evidence of health problems in populations living in areas of high natural background.

3 RADIATION DOSE DELIVERY PATHWAYS

Uranium and thorium bearing minerals contain a 'suite' of 'daughter' radioactive elements, produced by the nuclear breakdown or transformation of the parent element, called collectively the uranium and thorium decay chains. (See Appendix A)

All of these elements are present in uranium ores, or thorium-bearing minerals, as the case may be. In cases where there is no active leaching or deposition in the ore, the decay chain elements will come to a state of 'secular equilibrium', in which the activities (in Bq/g) of all radionuclides are the same. These radionuclides give out alpha, beta, and gamma radiation, and the intensity or strength of the emissions depends on the amount (or 'activity') present in the ore or mineral, i.e. the grade.

The main pathways by which employees and members of the public may receive radiation doses at or from the proposed operation of the Mulga Rock Uranium Project (or indeed any uranium mining project) must be identified, so that the measures that are to be taken to control these exposures can be identified and implemented.

They are:

- Direct gamma irradiation from radioactive material. Gamma irradiation is electromagnetic radiation, like x-rays and light. Exposure occurs from sources of radiation outside of the body. This is only significant if long periods are spent by workers close to large volumes of ore grade material, or high activity radioactive sealed sources. This is minimised using time, distance and shielding – minimising time spent near radioactive sources, maximising distance from sources, and when that is not practical, placing shielding between workers and sources.
- Inhalation of radon (Rn222) decay progeny. These radon decay progeny are radioactive metallic atoms formed by the breakdown of Rn, present in the air. They attach (collect) on the bronchial walls and when they decay they deliver a radiation dose to the bronchial cells. The radon decay product concentration in air is generally only a concern in enclosed spaces, such as in underground mines, or inside covered tanks or ore bins. This is minimised through ventilation; and by use of air filtration. This will generally be insignificant but may intermittently require active control measures during early morning periods of low level atmospheric temperature inversions and very low wind speeds.

- Inhalation and transport to internal organs of airborne dusts containing long-lived alpha-emitting uranium, thorium, and radium. This 'internal dose' pathway will be minor and will be minimised by use of normal dust suppression methods, mainly by watering of haul roads.
- Ingestion and absorption of radioactive material. Ingestion typically occurs through poor hygiene practices where accidental transfer of radioactive material from a person's hand to their mouth occurs. The radionuclides dissolve in the stomach and transport to various internal organs and deliver a dose extending over time. Ingestion (and hence internal dose) is minimised by good personal hygiene. Hands and face must be washed before eating, and workers may only eat in designated regularly cleaned crib rooms and offices. Absorption through the skin occurs through undressed open wounds.

All these pathways contribute differently, depending on the ore grade, the work circumstances and the controls in place. All these pathways need to be monitored, and controlled as outlined above.

Estimates for these pathway doses are provided in following Sections.

4 HISTORICAL AND BASELINE STUDIES

The MRUP was discovered and explored by PNC Exploration Pty Ltd, a wholly owned subsidiary of the Japanese government-owned Power Nuclear Corporation during the period 1979-1990. The Leases were acquired by Vimy Resources' precursor company (Energy and Mineral Australia) in 2003.

Environmental and occupational radiation monitoring by Vimy/EAMA has been ongoing since 2007 and summarised in various annual reports.

Baseline studies relevant to the radiation impact assessment of the MRUP include the following:

On behalf of PNC:

- Ethnographic Survey (1982) by Dr Robert McKeich;
- Archaeology Survey (1984) by Dr Sue O'Connor.

On behalf of Vimy Resources:

- Heritage surveys (2015) by Western Heritage Research and Dr Mathieu;
- Heritage surveys (2015) by W Glendenning;
- Radiation, emissions, air quality and climate surveys (2009-2015) by Radiation Advice and Solutions and GHD;
- Ambassador Scoping Study (2010), Coffey Mining and Amec Foster Wheeler (2015).

On behalf of third parties:

- Geochemistry, mineralogy, hydrogeochemistry and organic matter characterisation (1993-1996) – CSIRO
- Closure report for the Shogun trial pit by the DMP (2001), following back-filling and rehabilitation
- Bureau of Meteorology, Climatic data of Australia (BOM 2014), and
- Numerous heritage surveys (2002-2009) by the Tropicana Joint Venture (Matner 2009 & Matner & Bergin 2009).

A timeline of recent baseline and investigational radiation monitoring is provided below:

- Passive Radon Monitors: First set-up in 4th Quarter of 2007 and continuously since October 2012.
- Environmental Thermoluminescent Dosimeters (TLDs issued by ARPANSA) on a quarterly basis since October 2008.
- High Volume Sampler (for airborne dust concentration, and radionuclides concentrations in dust) since May 2012
- Continuous radon daughter monitoring (using an ERDM from Radiation Detection System) since May 2012
- Dust Deposition Gauges (DDG) , for passive dust measurements, recorded at 10 sites across the project since July 2013
- Weather data: Continuous records have been collected since late 2009 across three stations using Mark4 automated weather stations
- Continuous environmental radon monitoring in December 2014-January 2015 (using Durridge RAD7 units on loan from Cameco Australia)
- Charcoal canister (Countess Method) radon emanation measurements on ore and cover material in February 2015
- Measurements of radon emanation from dry and wet ore and potential liner clay material using Durridge RAD 7 units

The above studies were used to identify the potential environmental receptors, establish baseline radiation levels and document the lack of human occupancy in the Regional and Project areas.

The findings from these extensive environmental radiation studies are that the Mulga Rock Project area is similar in radiological characteristics to the rest of inland Australia, with gamma, airborne radon and radon decay products, and soil radionuclide measurements all within the normal range.

4.1 DETAILS OF ENVIRONMENTAL RADIATION STUDIES

4.1.1 BACKGROUND STATIONARY GAMMA SURVEYS

The levels of background gamma radiation (everywhere) depend primarily on the concentrations of natural radionuclides in the soil, namely U238 and Th232 and their daughters, and K40. Typical gamma background levels across Australia range from below 0.1 to above 0.25 µSv/hr.

Table 4.1 shows a comparison of the Australian average gamma radiation and a number of uranium project locations including Mulga Rock. The Mulga Rock regional background gamma doserates are in very close agreement with the Australian average.

Table 4.1: Comparison of background gamma radiation from Environmental TLD surveys.

Locality	Environmental Gamma (µSv/hr)	Reference
Australian average	0.07	Inferred from ARPANSA 2005
Central South Australia	0.10	BHPB 2009
Honeymoon, SA	0.10	Honeymoon EIS 2006
Kintyre, WA	0.09	Kintyre EIS
4-Mile, SA	0.11	Four Mile PER 2009

Mulga Rock, WA	0.06	This report

provides the MRUP Project Area gamma doserate average for the various survey locations. Figure 4.1 and Figure 4.2 show the background gamma radiation survey locations. Multiple sites have been selected to account for spatial and temporal variabilities.

The Project average derived from the data in Table 4.2 is approximately 0.06 μGy/hr (but there is variability, both by location, and year-to-year). This result is consistent with naturally occurring radiation doserates observed elsewhere in inland Australia.

Table 4.2: Environmental background gamma doserates in uGy/hr from ARPANDA TLDs.:

Location	**Environmental Gamma TLD results (uGy/hr)**			
	2010-11	**2011-12**	**2012-13**	**2013-14**
1: E 574715 N 6684600 Airstrip weather station	0.06	0.05	0.07	0.07
2: E 577808 N 6682159 Crossroad nr Ambassador	0.06	0.05	0.07	0.06
3: E 576993 N 6682647 Gravity GPS base	0.05	0.05	0.07	0.08
4: E 563180 N 6687441 Shogun Pit	0.07	0.05	0.08	0.08
5: E 563531 N 6687735 Shogun campsite	0.06	0.06	0.06	0.07
6: E 558217 N 6690936 Emperor saltpan	0.08	0.05	0.08	0.09
7: E 557391 N 6691424 Emperor pit	0.05	0.07	0.07	0.08
8: E 563569 N 6687909 Shogun weather station	0.06	0.06	0.06	0.07
9: E 559526 N 6693062 Traffic Island	0.06	0.06	0.07	0.08
10: E 574763 N 6683979 Airstrip (Project) Camp	0.07	0.06	0.07	0.08
Annual averages:	***0.06***	***0.06***	***0.07***	***0.08***

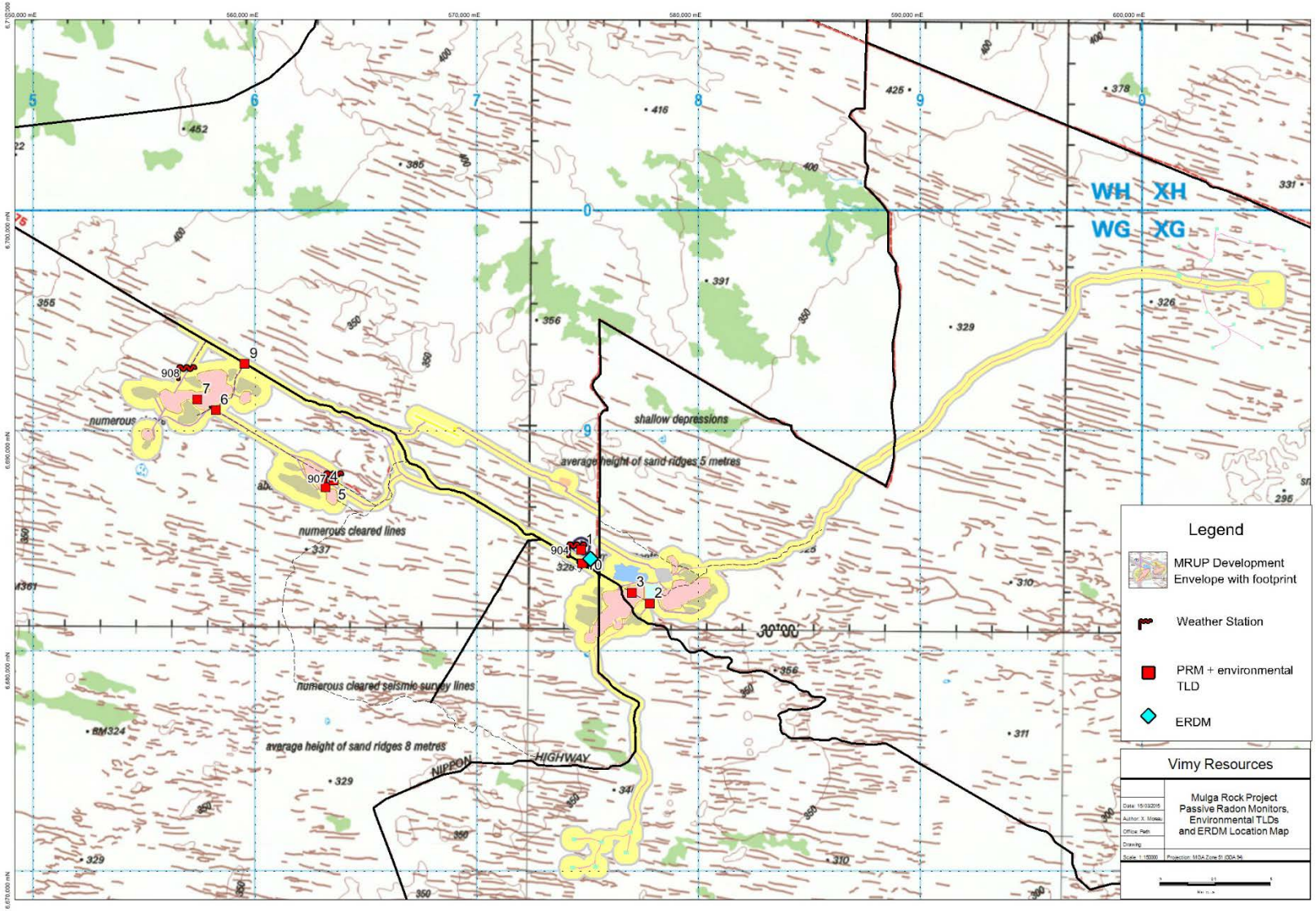


Figure 4.1: Location of TLD and PRM monitoring sites.

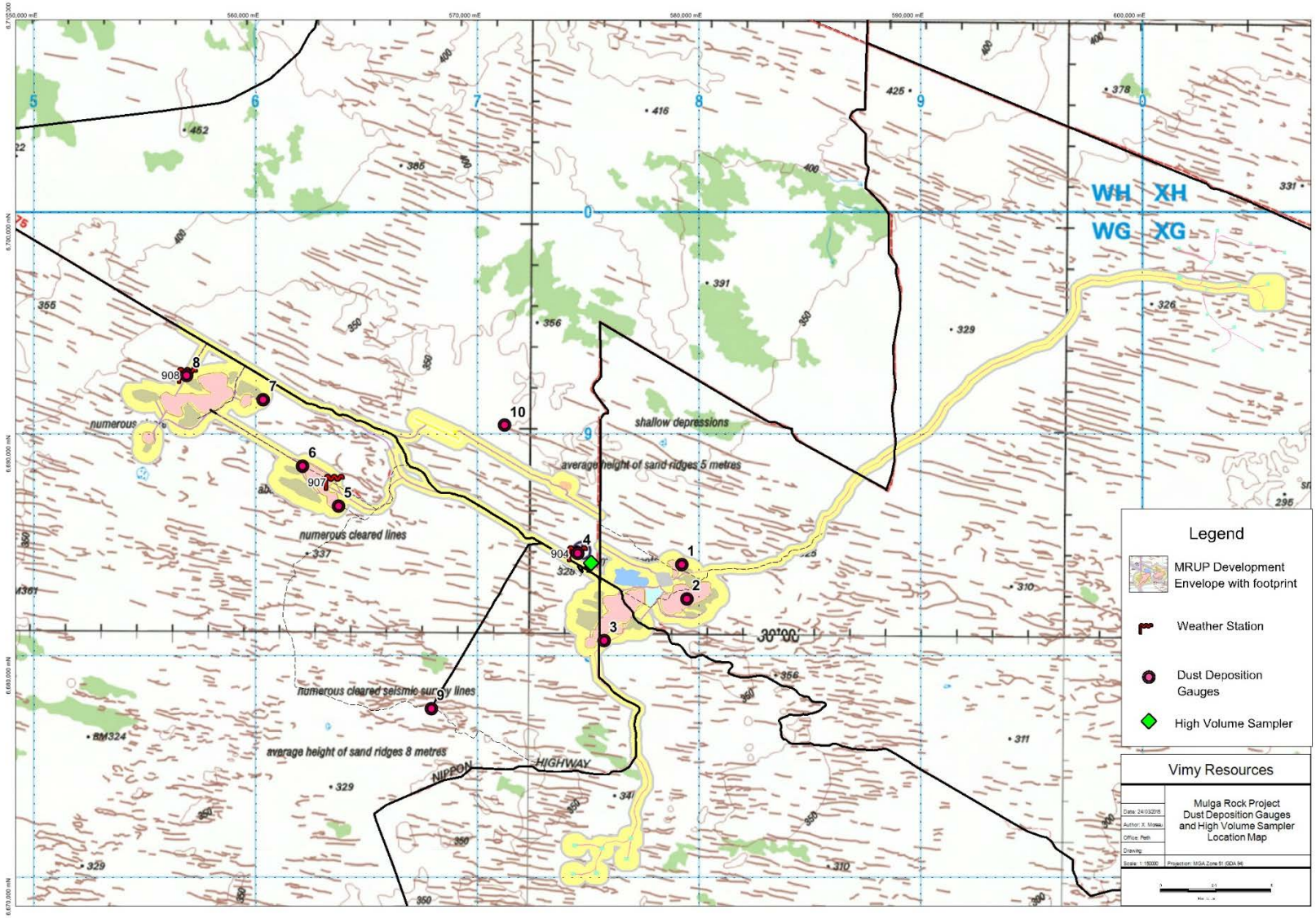


Figure 4.2: Location of high volume sampler and dust deposition gauges.

4.1.2 SURFACE AND AERIAL RADIOMETRICS

Radiometric surveys over the MRUP have been performed as follows:

- Regional radiometric airborne surveys, resulting in typically 200-400m spaced
- Ground survey (for a total of 20 line km) using a hand-held GR 135 in survey mode along proposed drilling traverses above the Ambassador deposit, measuring U, Th, K equivalent concentrations and Total dose rates.
- Detailed high resolution airborne survey, carried in mid-2014 by Thomson Aviation on behalf of Vimy, using self-calibrating high sensitivity detector and spectrometer.

Airborne Surveys

A compilation of regional airborne radiometric survey datasets (see Figure 4.3) shows clear associations of regional landforms with particular signatures:

- The MRUP surface radiometric signature is characterised by very low dose rates, consistent with Aeolian sediment landforms blanketing the deposits which are at depth and thus show no radiation signature.
- Increased dose rates (more typical of inland Australia) are due primarily to:
    - higher potassium concentrations, associated with the surface expression of ephemeral water bodies and drainage associated with the Lake Raeside regional drainage, and
    - higher dose rates associated with elevated thorium concentrations in lateritic duricrusts forming the surface of plateaux and breakaways located north, east and southeast of the MRUP.
- Low level dose rates associated with gypsiferous (kopi) discharge zones to the east of the project, primarily due to slight increases in uranium background levels, and
- High potassium a long distance to the southeast and south of the MRUP (~35km and ~40km respectively) associated with Paleo Proterozoic granitic/gneissic basement outcrops of limited surface expressions.

The red earthy sands present in the swale areas and within corridors usual coincident with underlying paleochannels and tributaries show greater total counts and uranium and thorium dose rates.

Ground spectrometer survey

In 2011, a total of 29 ground traverses were completed over the Ambassador deposit using a portable PGIS1 differential gamma ray spectrometer (measuring the 36 KeV to 3Mev spectrum), for a total of approximately 20,000m, with readings recorded at a 20m spacing. These traverses showed across the project area equivalent uranium and thorium grades ranging from 0.4 to 4ppm and 3 to 25ppm respectively.

Thermoluminescent dosimeters (TLD)

These dose rates compares favourably with 10 time-integrating thermo luminescent dosimeters (TLDs) operated across the project since October 2008. Those monitors showed an average of 0.06µGy/hr across the project (ranging from 0.05µGy/hr to 0.08µGy/hr), illustrating both geographic and time variability of gamma radiation levels, and consistently low levels compared to worldwide averages (UNSCEAR 2008).

Summary

In summary, time-integrated, ground traverse, and airborne surveys have all demonstrated the MRUP surface gamma doserate is typical of inland arid Australia, which is characterised by extremely low dose rates, consistent with Aeolian sediments landforms.

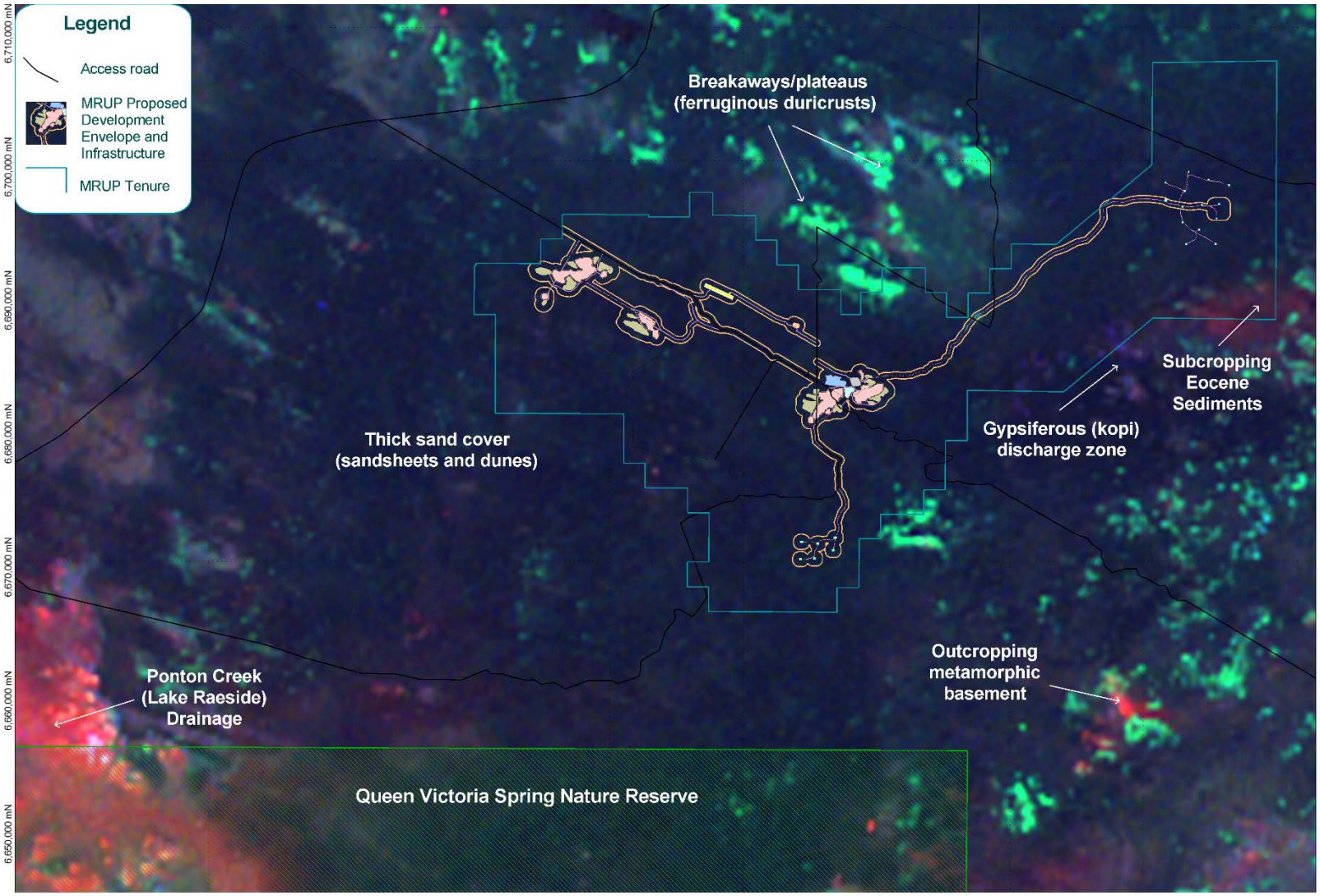
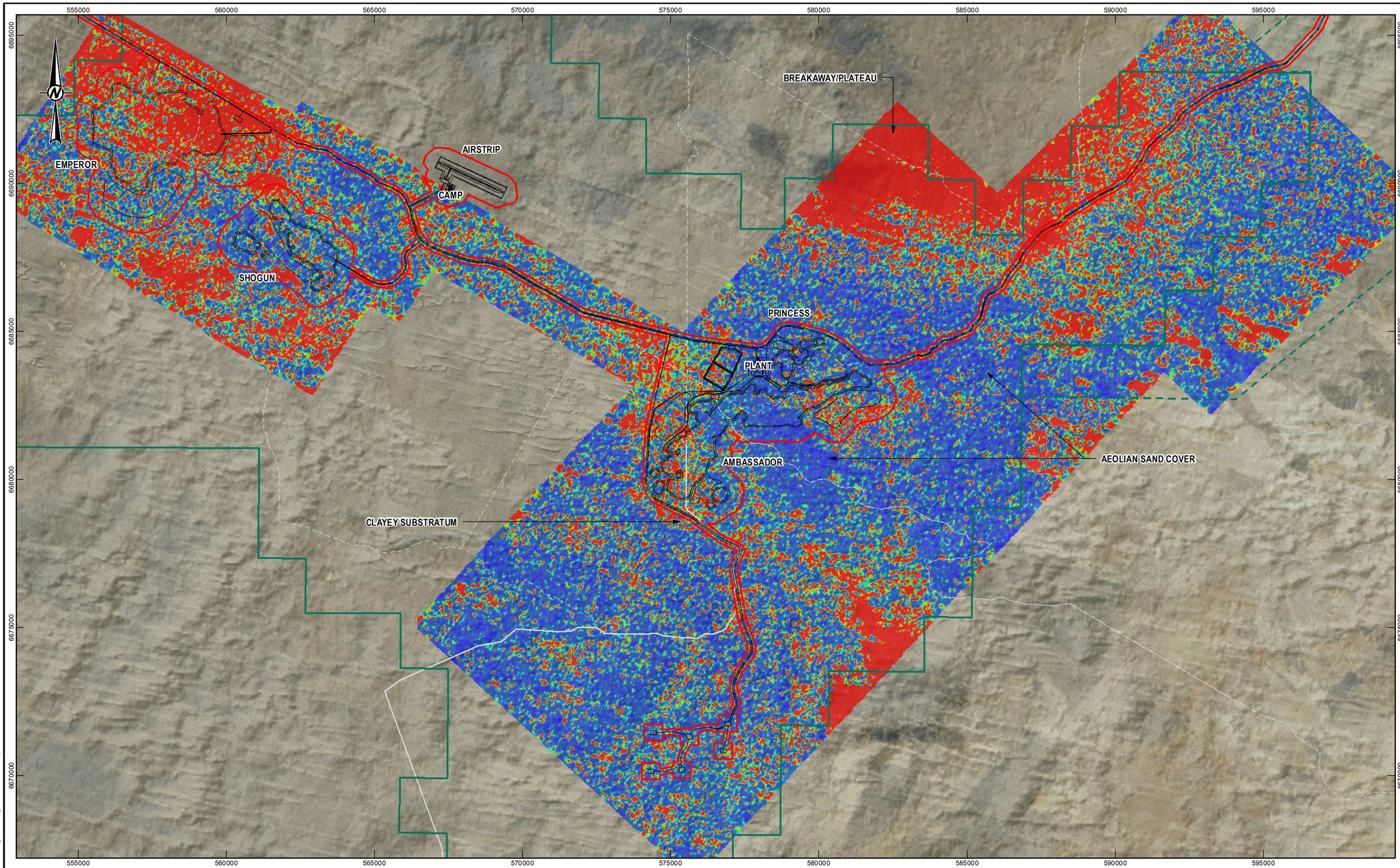


Figure 4.3: Regional airborne ternary radiometric background image.



LEGEND

- MINOR ROAD/TRACK
- ROAD
- MRUP DEVELOPMENT ENVELOPE
- PROJECT BOUNDARY (MINING TENURE)
- PROJECT BOUNDARY (MISCELLANEOUS TENURE)
- INFRASTRUCTURE

URANIUM CONCENTRATION (U ppm)

High : 6.656

Low : -0.160752

NOTES

1. COORDINATE SYSTEM: GDA 1994 MGA ZONE 51

REFERENCE

URANIUM CONCENTRATION AND INFRASTRUCTURE DATA PROVIDED BY CLIENT
AERIAL IMAGERY SOURCED FROM ESRI ONLINE
TOPOGRAPHY BASED ON NATIONAL DEM 1 S SOURCED FROM GEOSCIENCE AUSTRALIA

0 1 2 3 4 5

1:120,000 KILOMETRES

CLIENT
VIMY RESOURCES LIMITED

PROJECT
MULGA ROCK URANIUM PROJECT

CONSULTANT
Golder Associates

YYYY-MM-DD	2015-10-27
DESIGNED	MS
PREPARED	MS
REVIEWED	DCR
APPROVED	DCR

TITLE
MRUP DETAILED AIRBORNE EQUIVALENT URANIUM CONCENTRATION AT SURFACE

PROJECT NO.	CONTROL	REV.	FIGURE
1540340	F1	0	**4.4**

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET SIZE HAS BEEN MODIFIED FROM ISO A3

25mm

0

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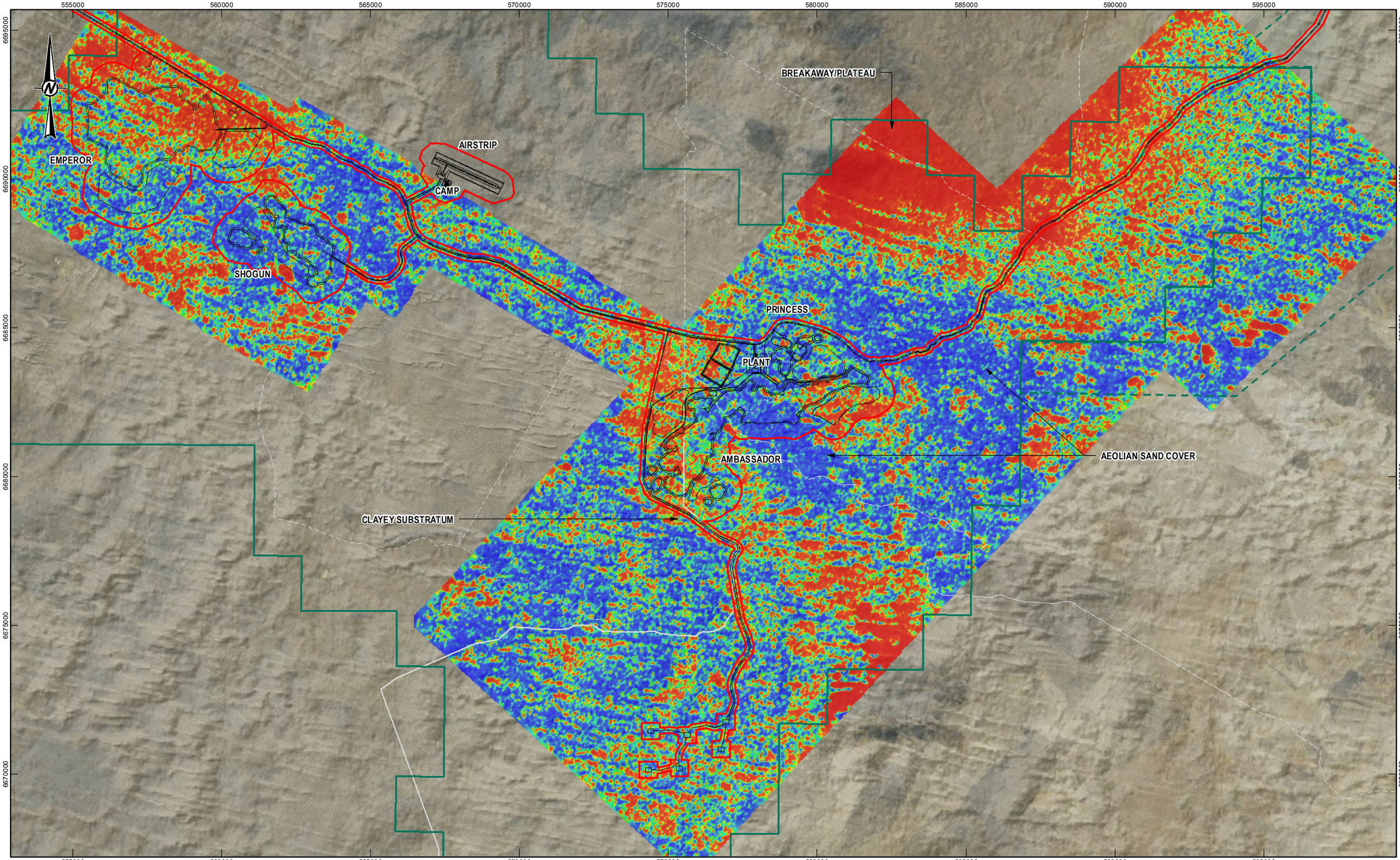

LEGEND

- MINOR ROAD/TRACK
- ROAD
- MRUP DEVELOPMENT ENVELOPE
- PROJECT BOUNDARY (MINING TENURE)
- PROJECT BOUNDARY (MISCELLANEOUS TENURE)
- INFRASTRUCTURE

THORIUM CONCENTRATION (U ppm)

High : 28.1085

Low : 0.00312916

NOTES

1. COORDINATE SYSTEM: GDA 1994 MGA ZONE 51

REFERENCE

THORIUM CONCENTRATION AND INFRASTRUCTURE DATA PROVIDED BY CLIENT
AERIAL IMAGERY SOURCED FROM ESRI ONLINE
TOPOGRAPHY BASED ON NATIONAL DEM 1 S SOURCED FROM GEOSCIENCE AUSTRALIA

0 1 2 3 4 5

1:120,000 KILOMETRES

CLIENT
VIMY RESOURCES LIMITED

CONSULTANT
Golder Associates

YYYY-MM-DD	2015-10-27
DESIGNED	MS
PREPARED	MS
REVIEWED	DCR
APPROVED	DCR

PROJECT
MULGA ROCK URANIUM PROJECT

TITLE
MRUP DETAILED AIRBORNE EQUIVALENT THORIUM CONCENTRATION AT SURFACE

PROJECT NO.	CONTROL	REV.	FIGURE
1540340	F1	0	**4.5**

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET SIZE HAS BEEN MODIFIED FROM ISO A3

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4.2 RADIONUCLIDES IN SOILS

Worldwide background level of radionuclides in soils is about 3 ppm U (or approx. 40 BqU/kg) and about 10 ppm Th (or about 40 BqTh/kg), with associated decay daughters. Eisenbud & Gesell (Environmental Radioactivity, 4th ed, Table 6-6) gives global average for U in 'all rock' as 7-60 Bq/kg, and 7-40 Bq/kg for Th232. UNSCEAR 2008 quotes global average soil U238 and Ra226 levels are 35 Bq/kg. In arid (and leached-out) central Australia the figures for all radionuclides except Po and Pb are expected to be lower

The Kintyre ERMP (Cameco 2013) reported averages of 24 and 21 Bq/kg for U and Ra respectively, and 13 Bq/kg for Th.

Monitoring of radionuclides in soils over the MRUP has been carried out through two conventional soil sampling programs[1]. In 1995 and 2014, 214 and 100 samples respectively were sampled and analysed for uranium and thorium using appropriate analytical techniques for the low levels present. Analyses of the fine fraction (silt and clay) of deeper soils samples (0.8-0.9m from surface) from a regional survey indicate averages of about 1.0 and 11.0ppm for uranium and thorium respectively, as shown in Table 4.3.

The measured total U and Th concentrations are generally much lower than the world median for soils (UNSCEAR, 2000, Annex B), which is consistent with a surface material dominated by aeolian sediments, with a very limited fine fraction. This correlates with the low values obtained from a high resolution detailed airborne radiometric survey completed in 2014 over the MRUP (see Figure 4.4 and Figure 4.5). Variations in natural background seem to reflect changes in the thickness of the most recent aeolian sand cover (locally up to 10m thick).

Generally speaking, the radionuclide levels are low across the Southwest Great Victoria Desert in comparison to world averages (UNSCEAR 2008), as shown by a regional geochemical soil survey carried out by the GSWA in 2010 (Morris 2012), and both regional and project-scale detailed airborne radiometric surveys. In Table 4.3 the finer size fractions in the soils sampled across the MRUP have a typical range in uranium from 0.1 to 1ppm U. The finer size fractions are more likely to become airborne. When accounting for all size fractions local soils across the Mulga Rock Project area have a uranium content in the range 0.25 - 0.5 ppm U, which corresponds to 3-6 BqU/kg.

Table 4.3: Radionuclides in soils analyses.

Sources of soil	Value	Radionuclide concentration				Number of Samples
		Uranium		Thorium		
		ppm	Bq/kg[2]	ppm	Bq/kg	
MRUP, 1996 (<180µm fraction)	Range	0.06 - 0.85		0.02 - 2.4		214
	Average	0.18	4.6	0.43[3]	1.4	
MRUP, 2014 (<180µm fraction)	Range	0.06 - 0.71		0.21 - 8.82		102
	Average	0.31	7.8	2.59	20.7	
Regional, 2010 (<50µm fraction)	Range	0.23 - 2.92		2.64 - 17.5		198
	Average	0.96	24.3	10.8	86.4	

[1] Sampling approximately the first 10-20cm of soil.

[2] Assuming a specific activity of 25,28kBq/g for U and 8kBq/g for Th, assuming secular equilibrium in both cases.

[3] Partial leaches via cold dilute HCl.

4.3 BACKGROUND RADIONUCLIDES IN AIRBORNE DUST

Radionuclide concentrations in airborne dust are usually determined through air particulate sampling and analysis of the collected particulates.

Active sampling, using high volume or medium volume sampling devices, provides a quantitative value for total suspended particulate (TSP) and via assay of collected dust, the concentration of radionuclides in air.

Passive sampling using dust deposition gauges (DDGs) measures the rate at which airborne dust (and its contained radionuclides) deposits out on the ground (measured in µg/m^2/month).

It must be noted that these are quite different parameters and provide different assessments: airborne activity concentration is required for estimation of doses to members of the public at various 'receptor points'; whilst dust fallout is needed for estimation of impact if any on Non-Human Biota, and for assessment of 'bushtucker' radionuclide pathway.

Passive dust monitors are also particularly useful provided their monitoring campaign extends from pre-construction through construction and during operations so that changes over the long term can be tracked and can then map the actual real footprint of project-increment dust deposition.

The locations of the high volume sampler and passive dust deposition gauges (DDGs) are shown previously in Figure 4.2.

Results from stationary dust deposition gauges located over the Project area for the period from August 2013 – October 2014 is shown in Figure 4.6. For comparison, average dust deposition value of 1.5g/m^2/month was reported for the Kintyre Uranium Project ERMP document (2013). Due to the MRUP being located in a similar arid environment, the above recorded figures are consistent with other arid inland Australia projects.

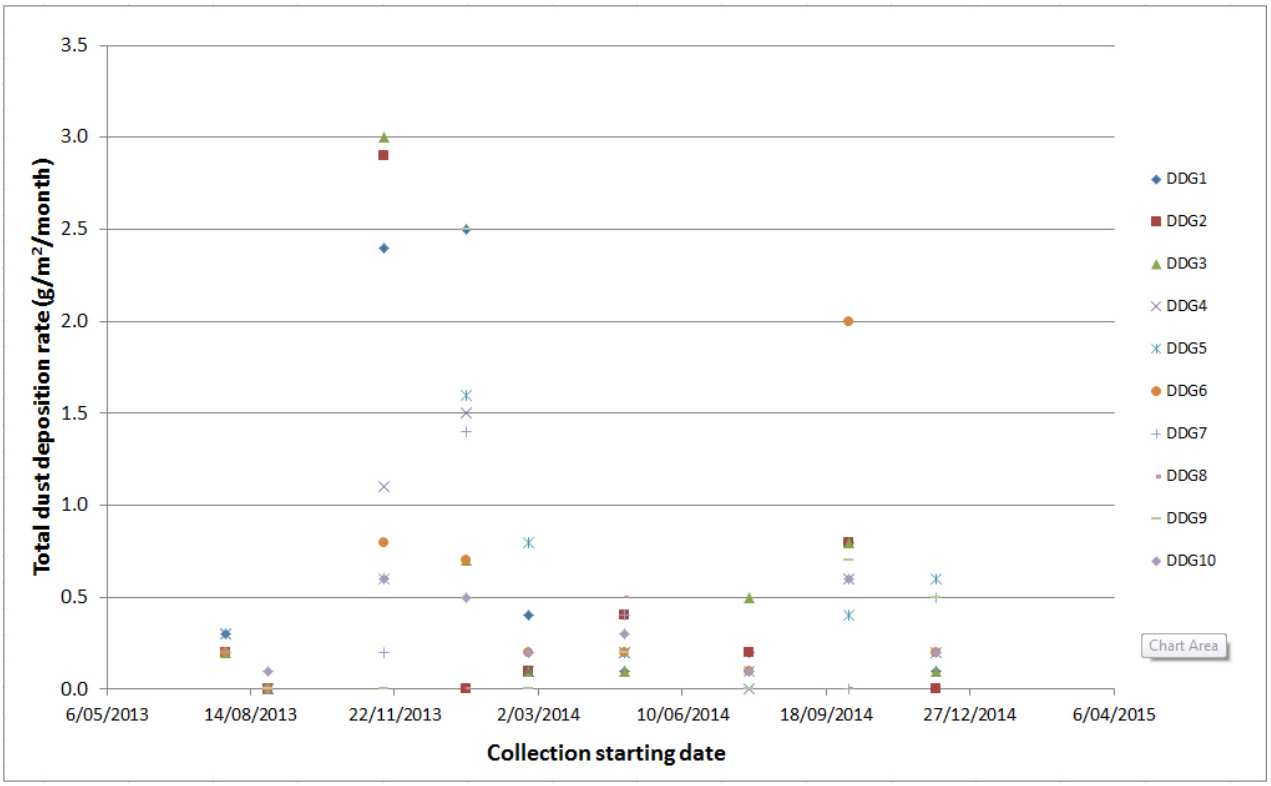

Figure 4.6: Dust deposition rate across the MRUP from dust deposition gauges.

A high volume air sampler has been operating continuously at the Mulga Rock Project site, directly adjacent to the Ambassador proposed pit, since May 2012. Airborne dust concentrations and sampling periods for the high volume sampler is shown in Figure 4.7. Dust concentration measurement show a clear annual cycle with higher dust levels during the summer months. Notably, the variation from 'high' to 'low' monthly dust loadings is about an order of magnitude.

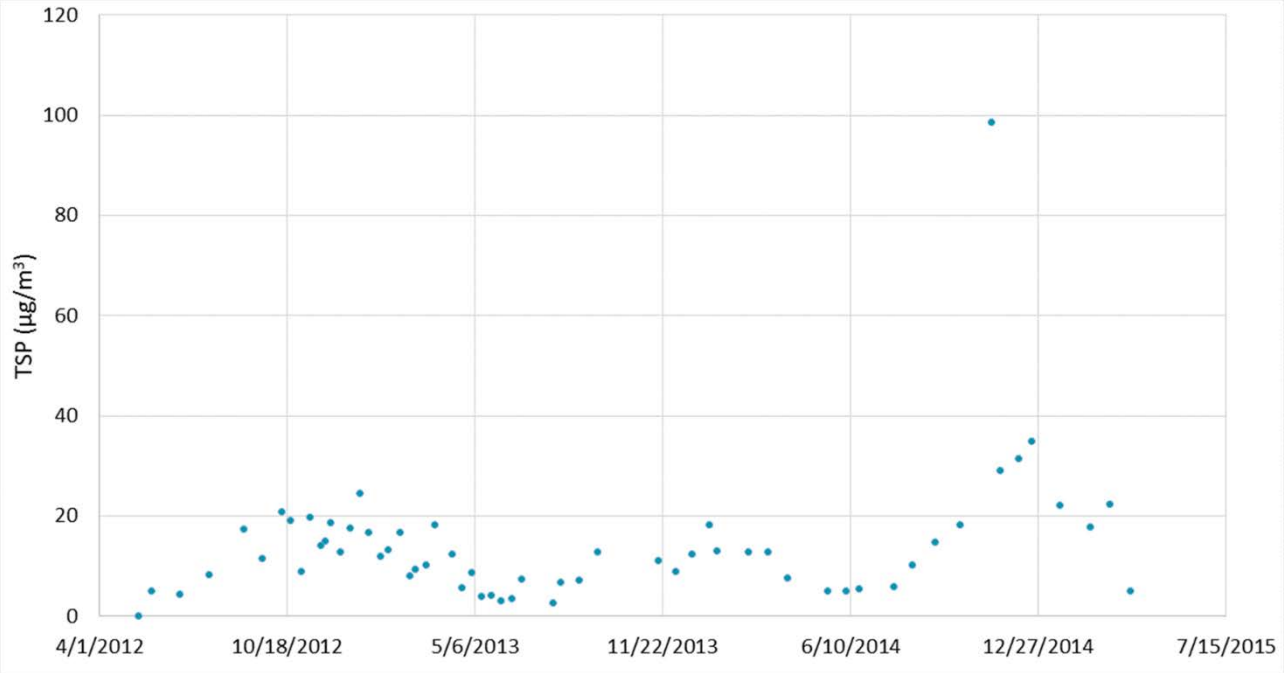

Figure 4.7: Airborne Dust (TSP) Concentrations (high reading was from natural bushfire).

A comparison of dust concentrations measured for other inland Australian uranium projects is shown in Table 4.4.

Worldwide airborne radionuclide dust concentrations (from UNSCEAR 2008) are estimated to be in the order of 1 µBq/m^3 for uranium, based on soil concentrations and assumed airborne dust loading (Lake Way ERMP, Toro 2011). UNSCEAR (2000) provides world averages and ranges for the main radionuclides found in soils (see Table 4.5)

Table 4.4: Comparison of airborne dust concentrations for inland Australian uranium projects.

Operation	Airborne Dust (µg/m^3)	Source
Olympic Dam	20	WMC (Roxby Mgt Services) 1982
Honeymoon	15	Honeymoon EIS
Lake Way	15	Lake Way ERMP, Toro 2011
Mulga Rock	14	GHD MRUP Air Dispersion Modelling, 2015

Table 4.5: UNSCEAR (2008) World averages for radionuclides in airborne dust (ranges in brackets).

Radionuclide	Airborne Radionuclide Concentration ($\mu Bq/m^3$)
U238	1 (0.02 – 18)
Th230	0.5 (0.02 – 1.7)
Ra226	1 (0.8 – 32)
Pb210	500 (<40 – 2250)
Po210	0 (10 – 80)

In an arid environment such as at Mulga Rock, one can expect to see elevated dust loadings and hence higher airborne activities compared with the figures quoted in the international literature. In support of this, it is noted that the airborne dust mass and activity (Figure 4.6 and Figure 4.8) suggest airborne dust activity concentration ratio which equates with soil uranium levels of 0.25 to 0.5 ppm U, which is exactly in line with direct soil assay results.

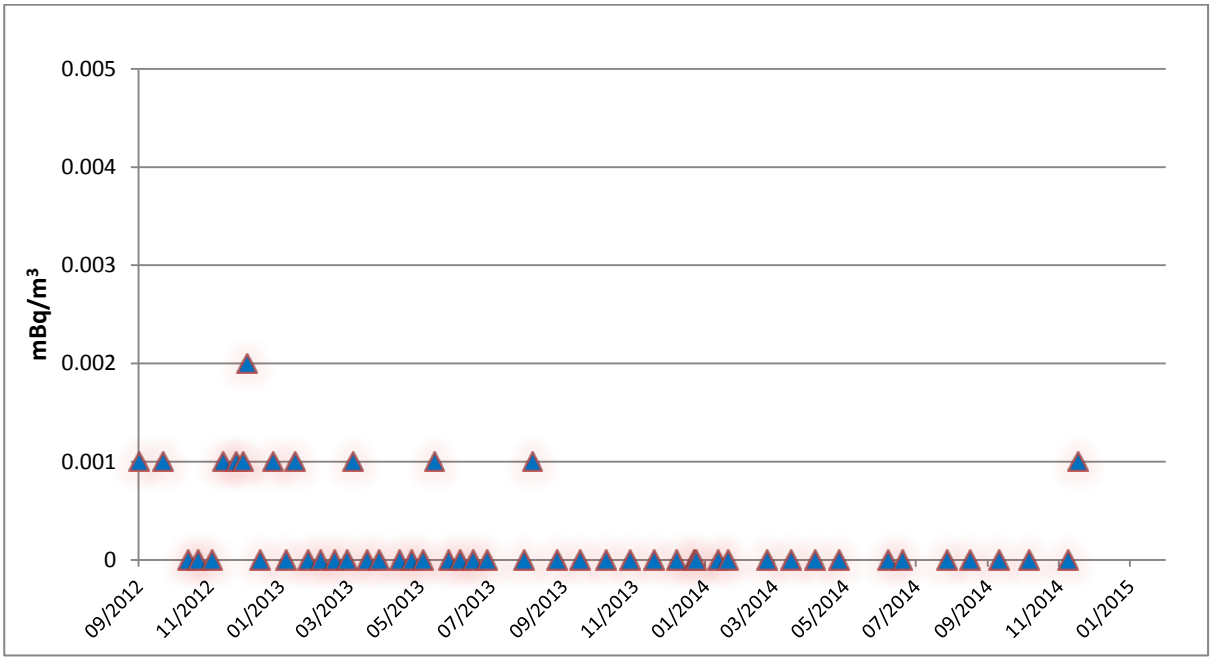

Figure 4.8: Long-Lived Alpha (LLA) radionuclides in airborne dust (minimum detection limit 1$\mu Bq/m^3$)

4.4 BACKGROUND RADON IN AMBIENT ATMOSPHERE

Radon is a naturally occurring inert gas that is present in the atmosphere, generated from the radioactive decay of parent radium in soil and rock. A proportion of the radon, after its formation, will diffuse through the soil and escape into the air.

Because radon has a half-life of 3.8 days, maritime air which has not been in contact with soil or rock for many days is depleted in radon. This effect is evident in the drop in atmospheric radon that one sees in monitoring results when the 'quasi-weekly' weather pattern fronts bring maritime air from the Southern Ocean over continental Australia.

In addition, there is a pronounced *diurnal* cycle, particularly evident during winter, when night time temperature inversions create a very stable atmosphere and mixing of the surface air layer is almost completely inhibited. In these circumstances, near surface radon concentration can build to levels that are an order of magnitude more than average daytime levels, which are kept low by convective mixing which begins shortly after dawn due to solar heating.

Airborne radon concentration is thus extraordinarily variable, ranging well over a factor of 10 fold in a typical 24 hour period, possibly from 1 Bq/m^3 to 1000 Bq/m^3. UNSCEAR (2000) reports worldwide average radon concentration as 10 Bq/m^3.

Time-integrating track-etch passive radon monitors (PRMs), supplied and analysed by Radiation Dosimetry Services (RDS) of Adelaide, have been placed at locations shown in Figure 4.1. Results and long term average are given in Table 4.6. The monitoring results show a noticeable temporal and locational variability.

Table 4.6: Passive Radon long-term averages (Bq Rn/m^3) as reported by RDS

Location	4Q2007	3Q2012	4Q2012	2Q2013	Average
	Bq/m^3	Bq/m^3	Bq/m^3	Bq/m^3	
1	31	22	17	17	**21**
2	29	37	13	22	**25**
3	20	10	20	33	**21**
4	17	60	31	31	**35**
5	20	10	18	30	**20**
6	31	26	20	38	**29**
7	17	22	31	28	**24**
8	10	29	24	23	**21**
9	29	33	17	18	**24**
10	27	41	13	25	**27**
Average	**23**	**29**	**20**	**26**	**25**

Comparison with radon data from other projects is provided in Table 4.7. The table shows that the local atmospheric Radon figures for Mulga Rock are consistent with the rest of outback Australia.

Table 4.7: Reported Average Environmental Radon Concentrations Elsewhere.

Location	Airborne Radon Concentration (Bq/m3)	Year of report/monitoring
Lake Way	27	2011
Beverley	36	2003
Honeymoon	28	2003
Olympic Dam	20	2008
Kintyre	16	2013
Mulga Rock (see above)	25	2007, 2012, 2012, 2013

4.5 BACKGROUND RADON DECAY PRODUCTS (RADON DAUGHTERS)

As mentioned earlier, Radon has a half-life of 3.8 days and decays to form Radon daughters which are collectively termed Radon Decay Products (RnDP). In the same way as for Radon, atmospheric RnDP concentrations are also highly variable, depending on weather (temperature, windspeed and direction, rainfall), atmospheric stability (presence, height, and strength of inversions), presence or absence of local sources, and time of day.

Vimy Resources has been running a real-time ERDM (Environmental Radon Daughter Monitor), supplied by RDS, since mid-2012. Below is a representative time plot of several days' worth of ten-minute real time readings recorded by the site ERDM RnDP monitor, covering a typical winter period. RnDP concentration emulate those of Radon measurements at Mulga Rock.

The charts below show real time radon and radon daughter concentrations coincident in time, at the high volume sampler site. The location of the high volume air sampler has previously been shown in Figure 4.2. The Equilibrium Factor that can be inferred, from comparison of the plots, is about 0.5, which compares well with the UNSCEAR quoted value of 0.4.

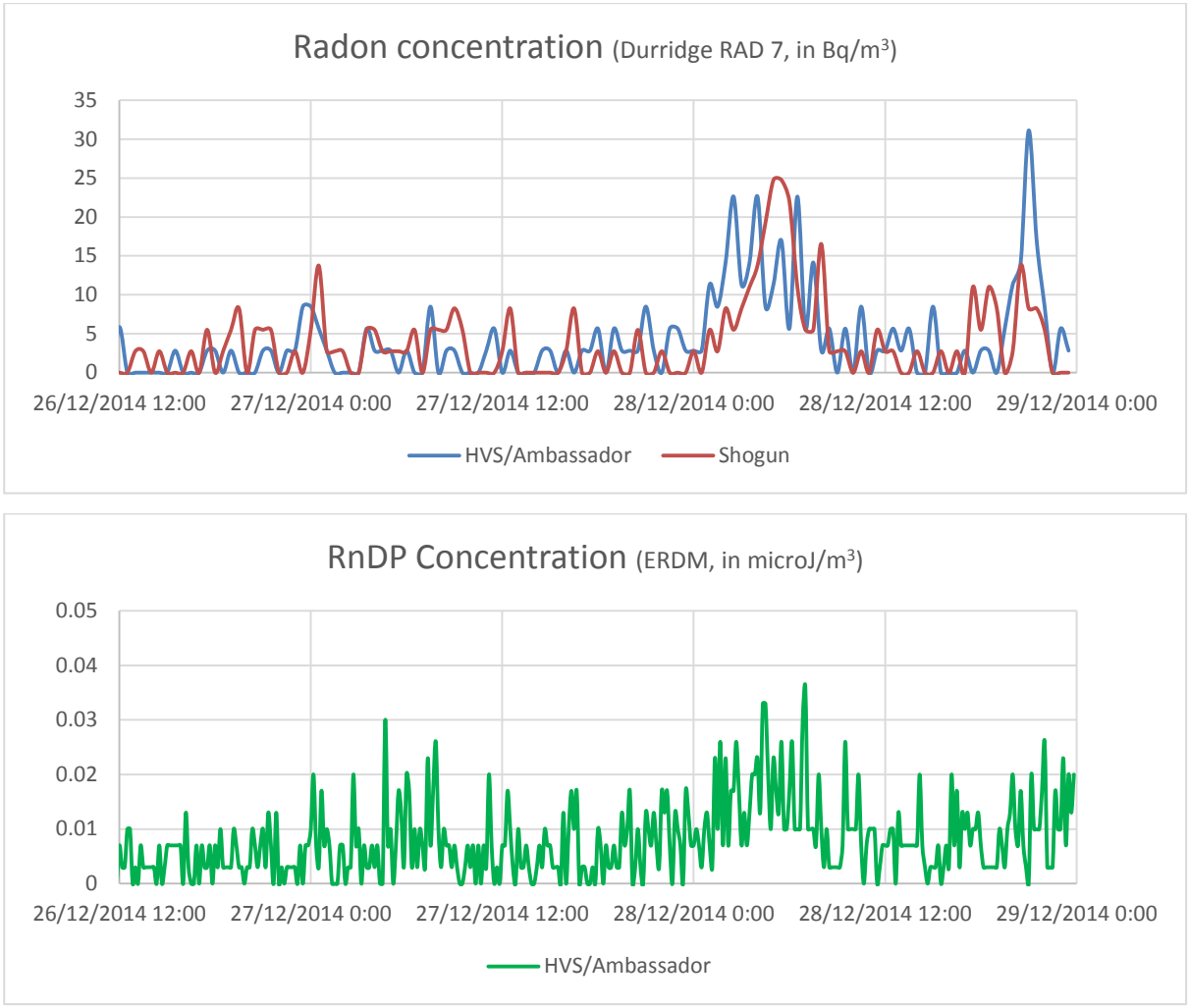

Figure 4.9: Radon concentrations recorded at the Ambassador and Shogun stations, using RAD7 continuous monitors (above), and corresponding RnDP concentrations recorded at the Ambassador station using an ERDM (below).

The daily pattern of RnDP concentrations shows a maximum reading between 4:00am and about 6:00am, and minimum reading in mid-afternoon. This diurnal (day/night) variation of Rn222 concentration has been widely observed before, and results from the formation of a near surface atmospheric inversion at night and high thermally-induced turbulence in the daytime mixing layer.

This diurnal effect is most pronounced in winter during stable air conditions.

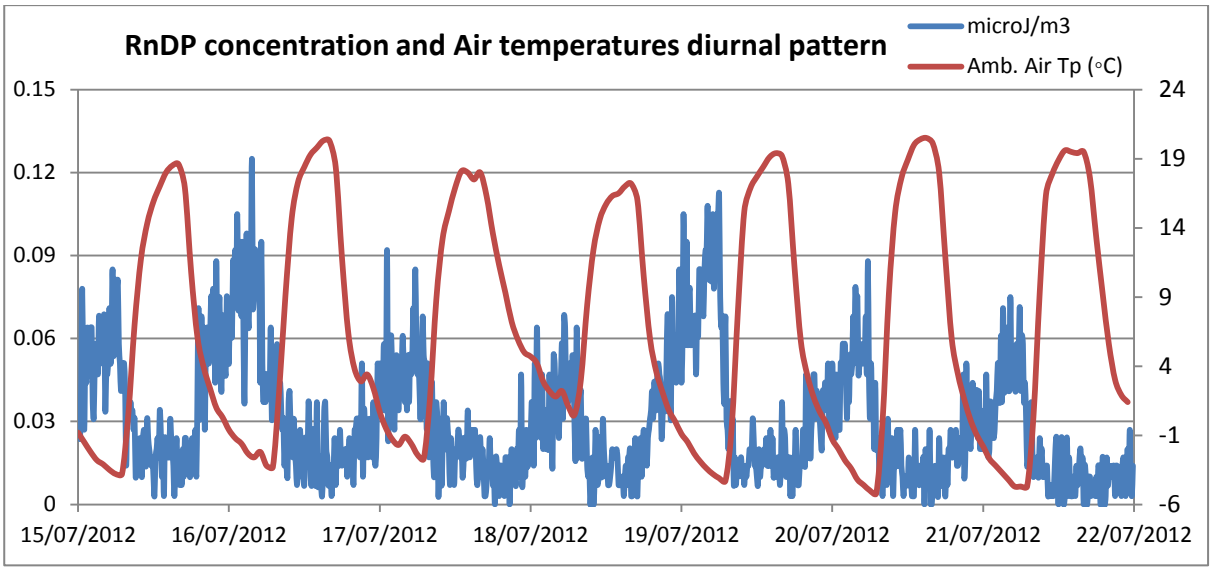

Figure 4.10: Example of a diurnal cycle pattern under mid-winter settled weather conditions.

In addition to the large diurnal variation (discussed above), there are also longer timescale temporal patterns, both 'quasi-weekly', associated with seasonal weather patterns due to displacement of continental air mass by maritime air mass movement which results in a temporary lowering of Radon concentration .

These large natural variations will swamp any Project-increment RnDP, rendering it essentially un-measureable in comparison. RnDP concentrations over extended winter period are in the range of 0.01-0.02µJ/m^3 (see Figure 4.11).

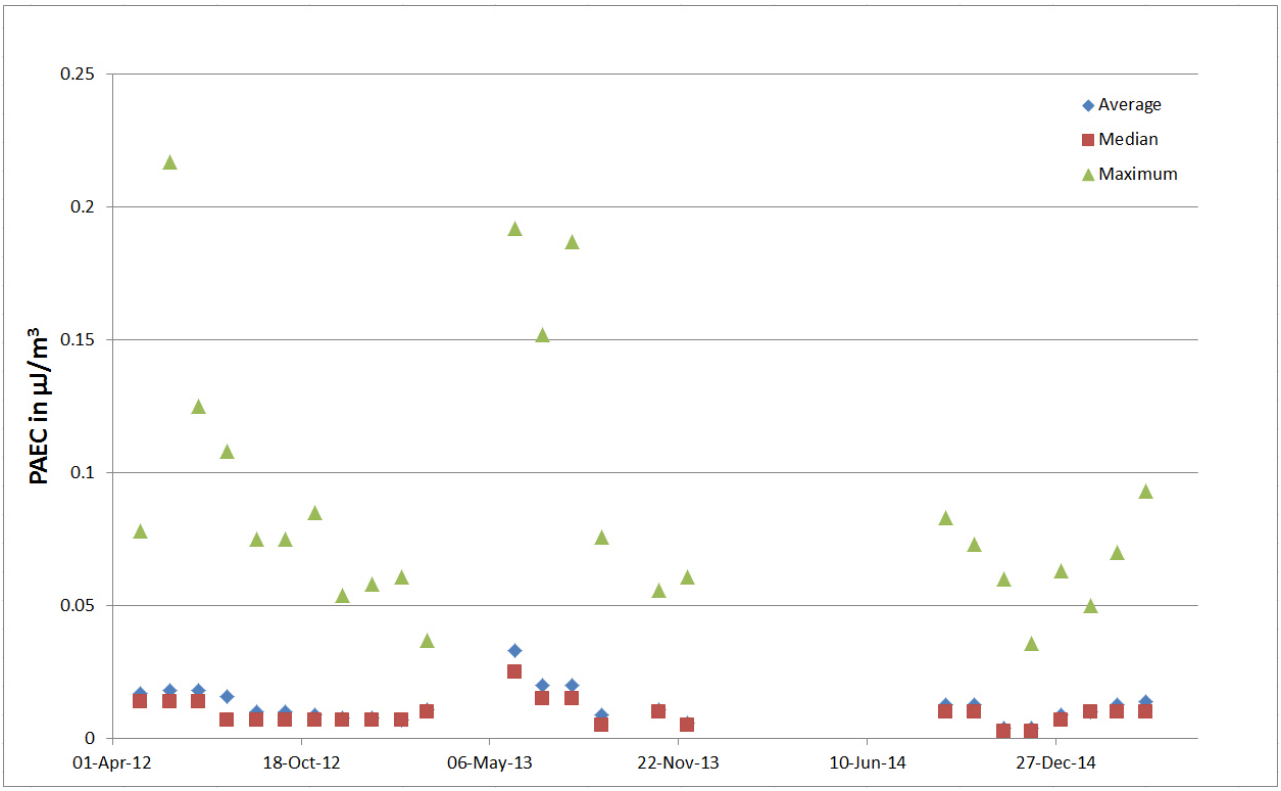

Figure 4.11: Potential Alpha Energy Concentration decay products (monthly figures)

5 RADIATION OVERVIEW OF PROPOSED PROJECT

The MRUP consists of four separate resources or conceptual pits with ore thicknesses varying from 12m in Emperor to 32m in Ambassador. The uranium mineralisation is overlain by a cover sequence that ranges in thickness from 26m to 36m of overburden sands. The deposits extend over a total length of 30km in west-northwest direction with the individual deposits ranging in length from 3 to 8 km.

The deposit geometry lends itself to a strip mine mining method with both conventional truck and shovel mining equipment and mechanised strip mining systems feasible. In its most basic form, a strip mine commences with the excavation of an initial slot to expose the ore, with the overburden placed in a waste rock dump or used for civil construction purposes. After mining the ore exposed by the first slot cut, a pit void is created which is then used to place the overburden from the next mining strip along strike. In general, mining advances one strip at a time with previously mined areas backfilled and rehabilitated. This mining method will result in a small environmental footprint at any given time.

The regular geometry of a strip mine, with a fixed distance to the overburden sands, lends itself to a continuous mechanised waste haulage system. A conveyor system is proposed for Mulga Rock to transport the waste from the advancing face to the overburden dump. Loading of the conveyor can be by conventional excavator, continuous miners such as a bucket wheel excavator, or a semi-mobile dozer trap. The total exposed ore at any time will be in the order of 20 to 40 hectares, within an open pit area of approximately 60 to 100 hectares. Mining rate will be approximately 2.3 to 4.5M tonnes of ore per year (see Figure 5.1). In the active mining area, overburden is removed and then placed in the trailing mining void and continuous rehabilitation will take place in parallel with mining.

Run-of-mine (ROM) Ore will be beneficiated by wet gravity within the mining area and a mineral concentrate transport to the main processing plant via either a slurry pipeline or haul trucks. ROM ore grade will typically range in the order of 250 to 1000 ppm U_3O_8, and thorium content is in the range 10-250 ppm. There is known to be decay chain disequilibrium within the upper levels of the lignitic ore, with the ore showing depletion in radium. This actually reduces the radiological significance of the topmost ore levels.

The metallurgical treatment plant will comprise a relatively conventional circuit comprising an acid leach process followed by a resin-in-pulp ion exchange extraction circuit for uranium recovery, and sequential precipitation of the base metals by-products from the barren solution.

The plant will treat the ore to extract uranium as uranyl peroxide product, at an average production rate of 1360 tonnes UOC per year, plus various base metals (Copper, Zinc, Nickel and Cobalt) as by-products.

Tailings from the process plant will be discharged into an above-ground facility for an initial 12-24 month period and then into the Princess pit void once it has been mined out.

MINING FRONT

RECONSTRUCTION FRONT

CONVEYOR SYSTEM
REMOVING MATERIAL
TO BE USED AS BACKFILL

OVERBURDEN FROM
CONVEYOR SYSTEM
DEPOSITED AS BACKFILL

IN-PIT TSF

BACKFILLED
OVERBURDEN

CLAY ENRICHED BASAL LAYER

ORE

WATERTABLE

SATURATED, REDUCED
EOCENE SEDIMENTS

ELEVATION (m AHD)

380
360
340
320
300
280
260
240

1000
2000
3000
4000
5000
6000
7000

DISTANCE (m)

LEGEND

- PROPOSED MINE PIT
- QUATERNARY SEDIMENTS
- MIOCENE SEDIMENTS
- OXIDISED EOCENE SEDIMENTS
- U-ENRICHED LIGNITE, CLAY, SILT
- REDUCED EOCENE SEDIMENTS
- HIGH PERMEABILITY BASAL SAND
- PERMIAN SEDIMENTS (BASEMENT)
- MIXED BASAL OVERBURDEN & BENEFICIATED SAND PREFERENTIALLY PLACED AT BASE OF PIT
- MIXED MIOCENE AND OXIDISED EOCENE SEDIMENTS
- TAILINGS
- ENGINEERED EMBANKMENT WALL

0 10 20 30 40 50
V 1:1,000 METRES

0 200 400 600 800 1,000
H 1:20,000 METRES

CLIENT
VIMY RESOURCES LIMITED

CONSULTANT
Golder Associates

PROJECT
MULGA ROCK URANIUM PROJECT

TITLE
ILLUSTRATION OF PROPOSED MINING OPERATION AT MRUP

YYYY-MM-DD	2015-11-11
DESIGNED	MS
PREPARED	MS
REVIEWED	EWC
APPROVED	EWC

PROJECT NO.	CONTROL	REV.	FIGURE
1540340	F1	0	**5.1**

IF THIS MEASUREMENT DOES NOT MATCH WHAT IS SHOWN, THE SHEET SIZE HAS BEEN MODIFIED FROM ISO A3

25mm

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5.1 RADIATION SOURCES AND RELEASES

The Project will generate radiation source terms as described in the following paragraphs.

5.1.1 GAMMA RADIATION

Gamma radiation arises from large volumes of:

- Exposed ore materials in the open pit,
- Low grade ore stockpiles, being surge inventory in the event of mill downtime,
- Ore in process, process scale build-up on plant and equipment,
- Exposed tailings material and tailings solution,
- Packed UOC product, and
- Sealed source gauges and x-ray process control sources.

5.1.2 RADON (RN222)

Radon is produced from:

- Emanation from ore surfaces and low grade stockpiles,
- Emanation from exposed tailings,
- Releases from ore in process within the metallurgical plant, and
- Releases from pit dewatering.

5.1.3 AIRBORNE DUSTS CONTAINING LONG-LIVED ALPHA (LLA) EMITTERS

Ore, tailings, and product dusts contain long-lived alpha emitting radionuclides U, Th, Ra, and Po. These radionuclide bearing dusts can potentially arise from:

- Fugitive suspended ore dust from mine operations, haul roads and spillages,
- Dried and resuspended tailings dust (eliminated by being kept wet), and
- Fugitive product dust from drying and packing circuit.

5.1.4 WATERBORNE RADIONUCLIDES

Waterborne radionuclides will be present in groundwater which seeps into any pit exposure below the water table. This water is captured and used, for dust-suppression purposes, and in the ore beneficiation concentrator. Any excess will report to the project water handling system, noting that ultimate disposal after recycle of excess will be via disposal wells as approved. There will be no releases to watercourses, and thus no surface water radiation delivery pathways.

6 MRUP RADIATION ASSESSMENT (OPERATIONAL)

The following Sections provide the results of estimations and calculations of various radiation parameters.

6.1 GAMMA DOSERATE AND DOSE PREDICTIONS

As a general statement, the gamma doserates in mine pits will be low, because the ore uranium grade is low. Negligible gamma doserates are expected from the slurry pipeline following ore beneficiation within the mining area. There will be limited gamma shine from process material in the plant.

In-pit gamma doserate assessments were carried out using as guidance from the literature, a figure of 3.5 uSv/hr per 1000 ppm U_3O_8, applicable over an extensive flat slab, such as an extended ore bench or large stockpile (Saito & Jacob, UNSCEAR, RESRAD and others). This number is also supported by professional experience including direct readings on other orebodies, and by recent ore drum readings onsite, recently reported in the literature (Sonter, Moreau & Wu, 2015)

Since the average ore grade at MRUP is approximately 600 ppm U_3O_8, the expected doserate over bare ore, without shielding, using this guidance is 2.1 uSv/hr.

At this doserate, the annual gamma doses to in-pit peripatetic workers such as Pit Surveyors and Geologists is assessed to be: if it is assumed 30% of their time is spent in the Pit and continuous exposure to 'average ore grade', this implies an annual dose in the order of 1.6 mSv/yr.

Grade control technicians (spotters / markers) and drillers: assuming 50% time spent in the Pit implies an annual dose of about 2.6 mSv/yr.

Thus there will be no necessity to implement any specific gamma dose controls, for pedestrian workers such as pit surveyors, geologists, drillers, or grade control technicians.

In-pit heavy equipment operators will have their gamma doses attenuated by approximately 50 to 70%, due to the mass of equipment between them and the surrounding ground, and so they will receive no more than about 2 mSv/yr.

Gamma doses in the metallurgical plant will be low, as ore will be in slurry form and in vessels, and hence (a) diluted, and (b) somewhat shielded. Experience at other uranium operations show that Metallurgical Plant workers consistently receive about 1 mSv/yr total dose, a significant fraction being from gamma radiation. See for example the doses reported in the Olympic Dam 2009 EIS, relevant given similar uranium head grades, and ARPANSA National Dose Register for 'Hydrometallurgical' workers (see Figure 6.1 and Figure 6.2). As a result, and in line with historical data from elsewhere, it is expected that process plant workers' gamma doses will be about 0.7 mSv/yr.

Gamma doses to maintenance workers are assumed to be similar to those of metallurgical plant operators, as this is what is seen generally at Ranger and Olympic Dam (total doses to maintenance personnel as recorded by ANRDR average under 0.5 mSv/yr, see Section 6.5.1).

Gamma radiation from surface of moist tailings is estimated to be approximately 3.5 µSv/hr, based on the grade of concentrate feed to the treatment plant, being about 1000 ppm U_3O_8. Note that tailings line operation and maintenance is considered to be part of the metallurgical plant operations.

Table 6.1: Estimated annual gamma doses for representative MRUP worker categories

Worker Type	Estimated annual gamma dose[4]
Geologists	1.6 mSv

[4] Work-related, see details in Appendix 6.

Pit Technicians	2.6 mSv
Mine heavy equipment operators	2 mSv
Metallurgical Plant operators	0.7 mSv
UOC product transportation truck driver	< 0.5 mSv
Management	<< 1 mSv

6.2 RADON SOURCES AND DOSE PREDICTIONS

6.2.1 RUN-OF-MINE ORE

Recent test work has been performed on-site, to measure experimentally the radon emanation from packed drums of crushed and consolidated uranium ores. These tests were performed using Countess Method via charcoal cans, and Durridge Rad-7 continuous radon monitors. Test work results showed a radon emanation rate of 0.5 $Bq/m^2/s$ for 315 ppm U_3O_8 ore and 2.24 $Bq/m^2/s$ for 830 ppm U_3O_8 ore. (Sonter, Moreau, & Wu 2015)

These measured Rn emanation values compared favourably with reported values in earlier work by Australian Radiation Laboratory (ARL 1982, now ARPANSA), which inferred a 'global' emanation rate of 3 $BqRn/m^2/s$ for a deposit with a uranium grade of 600 ppm U_3O_8. The Olympic Dam Expansion EIS (BHP 2009) also used a radon emanation value of 2.5 $BqRn/m^2/s$ for in-situ ore of similar grade.

For source term estimation and air dispersion modelling, an emanation rate of 2 $Bq/m^2/s$ for 600 ppm U_3O_8 ore was chosen.

6.2.2 RADON SOURCES

The whole of project radon (Rn222) source terms will comprise radon from:

- Open pit ore benches and faces (for a maximum of about 20 ha),
- Initial surface tailings repository (until covered; about 60 ha),
- Active in-pit tailings deposition (60 ha, later 150 ha),
- Low grade surface stockpile (surge inventory 7.5 ha),
- Ore present in-process, and
- Pit dewatering.

As discussed above, a radon emission rate (or emanation rate, or flux) for the MRUP mining operation is conservatively assessed to be 2 $Bq/m^2/s$ assuming the benches have a grade of 600ppm U_3O_8.

6.2.3 TAILINGS

For estimation of radon from tailings, guidance has been taken from data published by Kintyre and Olympic Dam, plus measurements performed by Vimy onsite with MRUP ore. The Kintyre EIS estimated for its (moist) tailings Rn emanation, 1 $BqRn/m^2/s$ for 1000 ppm U_3O_8 ore. BHP Billiton reported a measured radon emission rate from semi dried tailings of 0.5 $Bq/m^2/s$ for ore that originally contained approximately 600 to 700ppm U.

Radon daughter products from uranium are expected to follow the ore feed through to final tailings, and therefore, the radon emanation rates from ore is a conservative basis for assessment of tailings. Measurements of radon emanation from wet MRUP ore as a surrogate for wet tailings, gave (scaled to 1000 ppm U_3O_8 equivalent, to most closely represent the radium content reporting to plant tails) values of 0.07 to 0.08 $Bq/m^2/s$ (Sonter Moreau & Wu 2015).

Taking into account the Kintyre and Olympic Dam guidance, along with direct MRUP ore measurements, the assessed value for moist MRUP tailings for use in modelling, has been chosen as 0.5 Bq/m^2/s, to be conservative. Radon release from tailings is substantially mitigated due to the material being saturated.

6.2.4 METALLURGICAL PLANT

Radon release from the Metallurgical Plant as result of leaching is calculated from activity throughput of ore, which at 1,360 t/a UOC, equates to 0.45 MBq/s. Complete release of radon from the ore has been assumed to occur during leaching.

6.2.5 PIT DE-WATERING

In addition, there will be radon released as a result of pit dewatering at 4000 m^3/day. The radon content of the groundwater is modelled to be approximately 5 MBq/m^3. This is derived on the basis of a porosity of 50%; grade of 8 BqRa/g; and 50% partitioning of Rn between solids and water. On this basis, the radon released from pit dewatering will be 200 kBq/s.

6.2.6 RADON SOURCE TERMS TOTAL

The radon source terms for various project elements, based on the above, are given below:

Table 6.2: Radon emanation rates.

Project Element	**Radon Release**
Open pit areas (20 ha at any one time, using an emanation rate = 2 BqRn/m^2/sec):	0.4 MBq/s
Tailings (60 ha exposed at any one time, using emanatopm rate = 0.5 BqRn/m^2/sec):	0.3 MBq/s
Low Grade Stockpile (7.5 ha exposed, at 400 ppm U_3O_8 grade):	0.1 MBq/s
Radon from Plant: assume complete release during grinding and leaching:	0.45 MBq/s
Pit dewatering:	0.2 MBq/s

These source terms are the values used as input to meteorological modelling or assessment for calculation of doses to offsite receptors.

6.3 PREDICTIONS OF CONCENTRATIONS OF RADON & DECAY PRODUCTS

It is recognised that winter-time early morning still air conditions are conducive to stable air and near-surface inversions. These inversions can trap radon and give periods of relatively high RnDP concentrations (see Figure 4.10). These occurrences are identified as the most-likely radiation exposure situations requiring active controls. The timeline generally shows a build-up of RnDP during the pre-dawn period with rapid decrease in concentration coinciding with breakup of the temperature inversion soon after solar heating commences, and thus thermal convection.

The radon concentration in pits can be estimated using a volume-flushing model, similar to that used in recent environmental reviews (Toro 2011, BHP Billiton 2009 and 2011 and Cameco 2013).

Modelling of radon concentrations in-pit was carried out assumed the following:

- Dimensions of exposed ore of 20 ha,
- 2 Bq/m^2/s radon emanation,
- Overall pit dimensions of 500 m by up to 1,200 m, depth 50 m,
- Corresponding volume of air capped by atmospheric inversion at surface, and

- Low airspeeds, of 1 m/s (3.6 km/hr); giving air transit times of 500 seconds in contact with ore, and total in-pit air age up to 1200 seconds.

Calculating for instantaneous radon injection rate into 'pit box' then (2 $Bq/m^2/s$ x 20 ha) = 4 x 10^5 Bq/s;

Volume into which Rn is injected = (20 ha x 50m) = 1 x 10^7 m^3.

So concentration increase rate $\Delta C/\Delta t$ = 0.04 $Bq/m^3/s$.

Maximum concentration occurs at maximum air transit time across ore, which is 500 seconds, which equates to 20 Bq/m^3.

The Equilibrium Factor for air of age 1,200 seconds is approximately 0.3, so the PAEC (Potential Alpha Energy Concentration) of the ingrown radon decay products will be in this worst case approximately 0.03 $\mu J/m^3$. This resultant RnDP concentration is less than 0.5% of the allowed derived air concentration (DAC), which is 7 $\mu J/m^3$.

The key variable is the depth of the stable layer within the pit, and the assumption here is that there is uninhibited mixing through the depth of the pit, capped by a ground level inversion. If there is an inversion within the pit, of depth (say) 10 m, then the estimate will be increased accordingly. If the windspeed drops to zero, then again the concentration will build accordingly.

In these most extreme conditions where the air is totally still for up to two hours or more, the in-pit RnDP concentration may increase to a few $\mu J/m^3$. In this case modelling shows Rn concentration after 3 hours could reach 150 to 750 Bq/m^3, which equates to Rn PAECs of 0.8 to 4.2 $\mu J/m^3$. Whilst these levels are still under the DAC for RnDP, such circumstances, depending on their frequency, may prompt the need to manage exposure for personnel who are not in filtered air cabins.

Thoron release at the Metallurgical plant occurs due to in-growth from thorium in process. Noting that about 50% of thorium in ore is rejected at the ore beneficiation stage, the thoron generation rate is conservatively calculated to be 10 MBq/s.

In zero wind speed conditions, and assuming total release of this generated thoron into a Metallurgical plant 'pizza box' air volume of 500m x 500m x 10m, and in the absence of any design feature specifically intended to aid dispersion, this would give maximal airborne thoron concentration increase rate of 4 $Bq/m^3/s$ and an equilibrium thoron concentration in plant air of 320 Bq/m^3. However, application of basic micrometeorology theory using eddy diffusivity and friction velocity concepts shows that for even as low a velocity as 1 or 2 m/s, the half-life for dilution via vertical diffusion is several tens of seconds, and thus the plant air thoron concentration will generally equilibrate at about half of this level. The dose implications are that thoron daughters might at worst add something under 1 mSv/yr to Metallurgical plant workers' annual doses.

6.4 PREDICTIONS OF AIRBORNE LONG LIVED ALPHA-EMITTERS IN DUST

Dusts containing long-lived alpha (LLA) emitting radionuclides comprise ore, tailings, or product dusts. The contained alpha-radiation-emitting radionuclides will be U, Th, Ra, and Po. Airborne radionuclide bearing dusts arise from:

- Fugitive suspended dust from ore handling and movement (primarily in-pit) and from Ore Beneficiation circuit (minimal because wet process),
- Dried and resuspended plant spillage (controlled by prompt washing to sumps),
- Dried and resuspended tailings dust (minimal because wet) and
- Product dust from drying and packing circuit (controlled by total enclosure).

The Safe Work Australia (SWA, 2013b) *Guidance on the Interpretation of Workplace Exposure Standards for Airborne Contaminants* recommend the exposure to dust should be maintain below 10mg/m^3, measured as inhalable dust (8 hour TWA). In its 2014 position paper the Australian Institute of Occupational Hygienist

recommended that dust airborne concentrations be kept at less than 5mg/m^3 (inhalable fraction expressed as 8 hour TWA). An industry review of respirable dust concentrations from surface coal mining operations between the period of 1950 to 1990 showed a downward trend in dust concentrations with most recent dust concentrations ranging between 1 to 2.5mg/m^3 (Cherrie and Cowie, 2013). For onsite occupational impact from inhalation of airborne dust, it was decided to take a suitably conservative approach to estimate dust doses as follows:

- Assumed inhalable dust concentration in the pit of 2.5mg/m^3,
- At 6.4Bq/g U238 activity in this dust, the 'global average' for MRUP ore, this equates to 0.125 αdps/m^3, which is low compared with the DAC of 2.4 αdps/m^3 and
- Continuous exposure for a full year (nominal 2,500 hours/a) will amount to 1.25mSv/a, without controls (either PPE or active management).

This implies for our 'peripatetic, in-pit workers', as discussed in Section 6.1, for annual hours in pit of 1200 hrs, a committed dose from LLA of about 0.6 mSv/a.

Dust-derived (LLA) doses to metplant workers will be small, due to the entirely wet processes opersting. We have not tried to calculate or estimate the dust dose for metplant workers but instead base our prediction considering the LLA doses reported for other uranium hydrometallurgical operations (see Fig 6.1 below).

6.5 RESULTANT PREDICTED TOTAL DOSES FOR PROJECT PERSONNEL

6.5.1 MRUP MINING OPERATION

For the MRUP mine workers, the low ore grade and generally wet or moist condition of the ore will result in relatively low exposures. Concentrations of radon progeny from in-pit and process plant sources have been estimated as above, and will be monitored and managed using controls and mitigations outlined in a RMP.

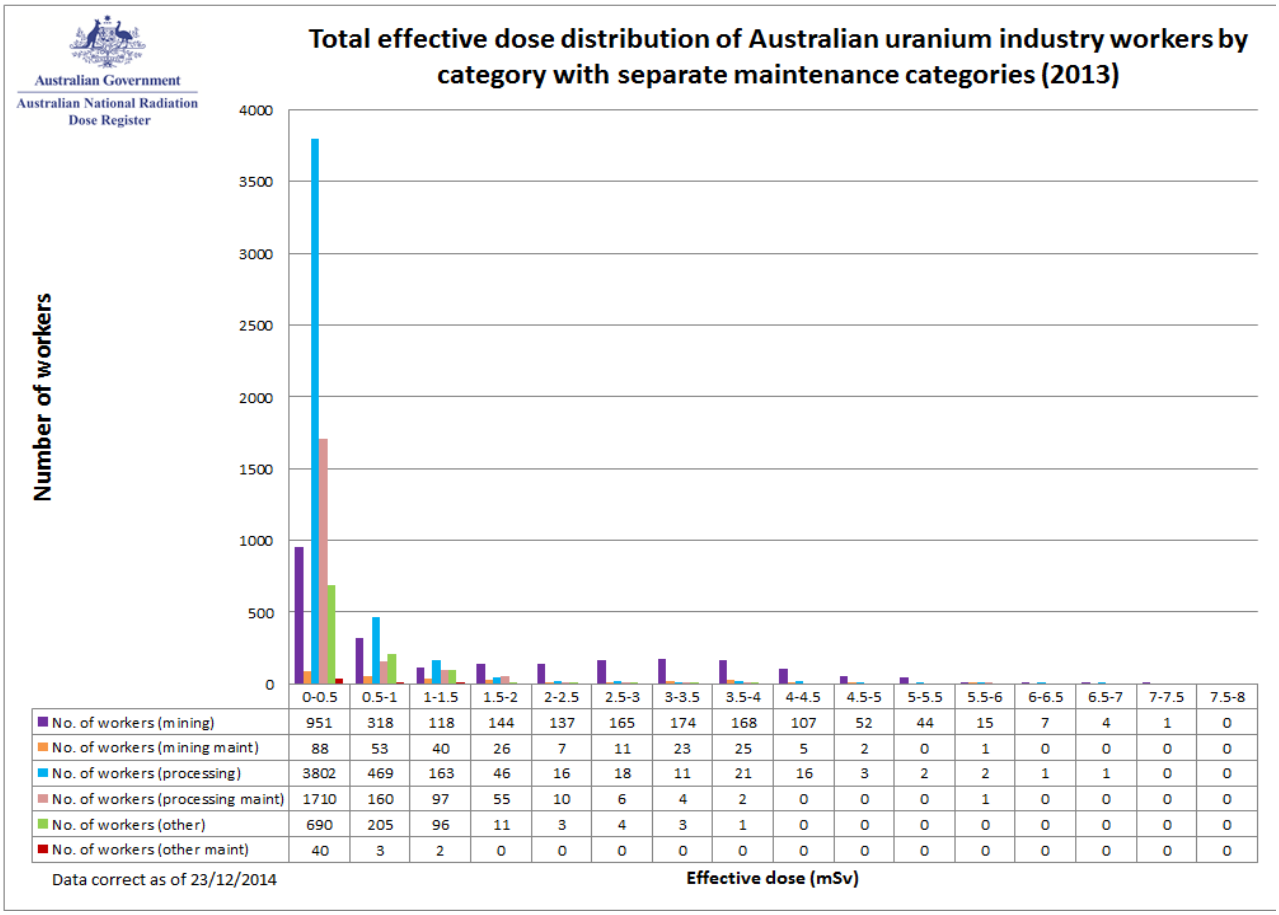
Table 6.3 shows the total dose predictions within the MRUP mining area.

Table 6.3: Total dose predictions for MRUP Mining operation.

Worker category	Radiation pathway			
	Gamma	Dust (LLa)	RnDP	Total (mSv/yr)
Mine peripatetic	1.6-2.6	0.6	<0.1	2-3
Mine heavy equipment	2.0	<0.1[1]	<0.1[1]	2
Metallurgical Plant operator	0.7	0.15	0.15	1.0

Note 1: assuming mine heavy equipment operators are inside filtered-air cabins

Total predicted doses for Mulga Rock workers are thus expected to be in line with actual dose data recorded throughout the uranium industry (see Figure 6.1 and Table 6.4).



	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5	5-5.5	5.5-6	6-6.5	6.5-7	7-7.5	7.5-8
No. of workers (mining)	951	318	118	144	137	165	174	168	107	52	44	15	7	4	1	0
No. of workers (mining maint)	88	53	40	26	7	11	23	25	5	2	0	1	0	0	0	0
No. of workers (processing)	3802	469	163	46	16	18	11	21	16	3	2	2	1	1	0	0
No. of workers (processing maint)	1710	160	97	55	10	6	4	2	0	0	0	1	0	0	0	0
No. of workers (other)	690	205	96	11	3	4	3	1	0	0	0	0	0	0	0	0
No. of workers (other maint)	40	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6.1: Australian uranium industry worker dose data (from ANRDR, B. Paritsky, ARPANSA)

Table 6.4: Comparison of radiation dose to workers at various uranium operations (reproduced from BHP 2009)

Mine and type of worker	Ore grade ($\%U_3O_8$)	Total dose		Gamma		Radon		Dust	
		Avg	Max	Avg	Max	Avg	Max	Avg	Max
Ranger Mine Worker	0.29	1.0	4.8	0.5	4.3	0.1	0.4	0.3	0.9
Rössing pit equipment operator	0.035	2.1	n.a.	0.6	n.a.	1.2	n.a.	0.4	n.a.
Rössing pit field staff	0.035	2.5	n.a.	1.0	n.a.	1.1	n.a.	0.4	n.a.
McLean Lake open pit workers	1.6	<1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Canadian surface miners 2004	Various	1.1	< 5	n.a.	n.a.	0.3	n.a.	n.a.	n.a.
Nabarlek open pit worker	2	6.6	n.a.	2.3	10	0.3	n.a.	4	n.a.
Olympic Dam underground mine worker	0.07	3.8	10	1.8	4.8	1.8	4.7	0.2	0.5
Estimated (maximum probable) Olympic Dam Expansion open pit worker	0.05	3.5	8	1.4	4	-	2.3	0.1	1.7

n.a. – not available

6.5.2 MRUP METALLURGICAL PLANT

The MRUP Metallurgical plant workers are likely to get doses similar to those reported for Olympic Dam hydrometallurgical plant workers.. The Olympic Dam EIS (2009) reported average total dose to workers in the hydrometallurgical plant of 1.5 mSv/yr (Figure 6.2), broken down as follows (converted from percentages):

- Dust: 0.75 mSv/a
- Gamma radiation: 0.60 mSv/a
- Radon Decay Products: 0.15 mSv/a

In light of the fact that modelling cannot give more accurate information, it is considered that MRUP Metallurgical Plant workers will accrue no more than 1.5 mSv/yr.

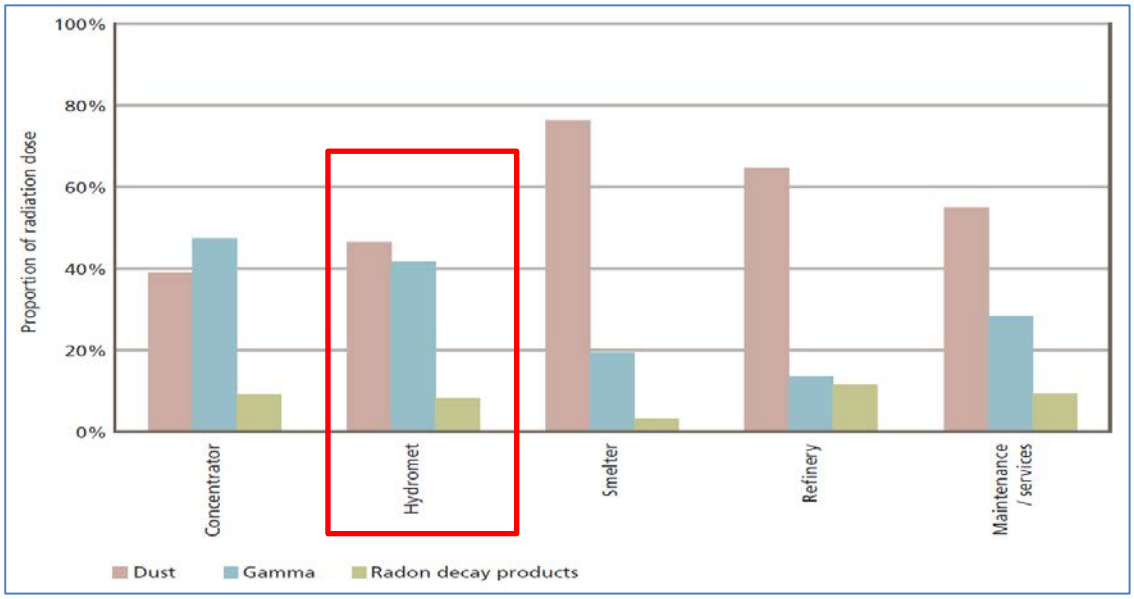


Figure 6.2: Proportion of radiation dose for processing plant workers (BHP 2009)

6.5.3 UOC PRODUCT TRUCK DRIVERS

Truck drivers transporting the final UOC product to port will be full time employees, permanently employed on this duty. Drivers will be monitored using TLD badges to determine exposures are well within acceptable limits. Truck drivers transporting the UOC product will be exposed to low levels of gamma radiation for the duration of the trip, at approximately 0.20 to 0.25 µSv/h (see Table 6.6 below).

Table 6.5: Conceptual Gamma dose rates in truck cabin from UOC Container (Cameco Australia Data)

Age of UOC (Days)	Gamma Dose Rate in Cabin (uSv/h)
30	0.15
60	0.21
90	0.25
120	0.26
180	0.26

These estimates are consistent with the information available on dose rates within cabins of trucks operating at other Australian uranium mines.

The preferred route from the MRUP to Port Adelaide is approximately 2,450 km. This equates to approximately 27 to 30 hours of driving. Transportation Regulations restrict a driver from driving for more than 12 hours out of every 24 hours. However, Vimy intends to use two drivers per truck to allow rest periods while promoting continuous movement of product, equating to continuous 12 hour shifts. From the doserates given in Table 6.5, the distance from the container to the driver's compartment, additional shielding from the driver's compartment and comparison with other similar operations within Australia, a doserate of 0.2 to 0.25 µSv/h is estimated inside the driver's compartment. The highest exposure scenario, assuming that the drivers also slept inside the cabin during all breaks, would result in each driver receiving a dose of 7.5 µSv for each journey. Assuming the drivers completed a round trip per week, then the annual dose will be 0.37 mSv/yr, still well below the Public Limit.

6.5.4 MRUP Administrative and Support Personnel

Workers in the Accommodation Village will not be radiation workers. Average annual radon concentrations based on air modelling by GHD ranges from 0.2-0.3 Bq/m^3 (from long lived alpha radionuclides). Resulting doses from airborne dust were modelled using the following assumptions:

- Grass alpha activity concentration: 0.3Bq/m^3
- Hours of exposure: 5,200 per year (inclusive of work and rest time)
- Assumed breathing rate: 1.2m^3/h
- Dose Conversion Factor of 2.91 x 10^{-5} Sv/Bq, assuming an Activity Mean Aerodynamic Diameter (AMAD) of 5µm (as recommended for occupational exposure assessment by ICRP 66 (1995), using the conversion factor listed in NORM 5.0 (Dose assessment), in Table C.9.

The resulting dose from radionuclides in dust is anticipated to be 0.05mSv/yr.

The dose to village workers from radon was calculated from the air dispersion model as follows:

- Time average Rn concentration: approximately 0.4 Bq/m^3 worst case
- 5,200 hours per year as above
- Breathing rate as above
- Dose Conversion Factor for Rn assuming Equilibrium Factor of 0.5: 3.9 x 10^{-6} mSv/Bq.hr/m^3

The resulting dose from RnDP at the Village is thus anticipated to be 8 µSv/yr.

7 PUBLIC AND ENVIRONMENTAL RADIATION ASSESSMENT

This section discusses the potential for radiation impacts on the public and environment from Project Emissions. Airborne and surface concentrations associated with emissions from the project are estimated via dispersion modelling. Results are discussed below.

7.1 CRITICAL GROUPS

The nearest critical groups (or representative most-exposed persons) for assessment of radiation doses to members of the public, are people living at Pinjin, 100 km to the west, and at Tropicana, 110 km to the NE. At these distances, radiation doses from any dust or radon emissions from the project will be negligible, and not able to be distinguished from natural background.

In order to predict total doses a hypothetical scenario of a person encamping at the Project Boundary has been considered.

7.2 DUST

Source terms have been developed by GHD, based on mining rates, pit sizes and scheduling, haul road distances, tailing disposal areas, etc., as supplied by Vimy Resources, and using standard dust re-suspension factors as quoted in National Pollution Inventory Emissions Estimation Techniques Manual for Mining. (http://www.npi.gov.au/resource/emission-estimation-technique-manual-mining).

These source terms were then modelled for dispersion using site specific weather and atmospheric data, from 3 site weather stations which have been operational since 2009.

The outputs of significance for environmental impact are:

(i) airborne dust (PM10) concentration contours; these are relevant to assessment of dust doses to members of the public hypothetically residing at MRUP boundary; and

(ii) dust deposition contours; these allow estimation of end-of-mine surface soil project increment radionuclide concentration, and thus potential for impact on non-human biota (NHB); and they also provide necessary input to calculations of radionuclide uptake and hence incurred dose from ingestion of local 'bushtucker' food .

7.3 RADON

Radon source terms for the mining pits, stockpiles, and tailings disposal areas, were calculated based on literature review of other uranium projects, general guidance from UNSCEAR and first-principles calculations, and on-site measurements.

These source terms were applied as point source inputs to the atmospheric dispersion model developed by GHD from the site weather data, to give airborne concentration contours, from which were calculated annual member of the public (MoP) doses from inhalation of the resulting radon decay products.

Thoron was reviewed separately, and assessed as negligible as an environmental factor due to its very short half-life.

The dust and radon doses to members of the public hypothetically residing at project boundary are shown to be negligible. A fortiori, potential doses to actual members of the public (typically residing 100km from the MRUP or greater, i.e. at Pinjin and at Tropicana) are assessed as **insignificant**.

7.4 PRODUCT TRANSPORTATION

7.4.1 EXPOSURES TO MEMBERS OF THE PUBLIC FROM PRODUCT TRANSPORTATION

The only realistic exposure scenario for members of the public during product transportation is from public loitering (and perhaps conversing with the driver) next to a freight container while the UOC transport truck is pulled up at a roadhouse for the drivers to have a meal, shower, and refuel. It is estimated that the truck might stop for a rest break for approximately 1 hour. Cameco Australia, in their Kintyre EIS, quoted a doserate at 1 metre from a container of UOC as 2.8 µSv/hr, so a member of the public in such a scenario might in one hour receive 2.8 µSv, a low dose. All more distant exposure circumstances result in doses which are even more trivial.

Security requirements (to be determined in consultation with ASNO) may require one driver to stay with the load while the other has his/ her shower etc, or other requirements.

7.4.2 MEMBERS OF THE PUBLIC DURING A TRUCK BREAKDOWN

In the non-routine but potential event of a breakdown, the truck carrying UOC may remain stationary in a public area. Access by the general public would be restricted by the driver of the vehicle in such an event.

Exposure by mechanic working on truck: say 2 hours @ 1 µSv/hr = 2 µSv, a lowdose.

Other potential exposure scenarios exist during routine operations, (e.g. car tailgating the truck for several hours, person standing on roadside and exposed for a couple of seconds as the truck passes by) but all were considered to be either unrealistic or result in negligible potential exposures.

7.5 NON-HUMAN BIOTA

Following further discussions with the EPA, Vimy Resources committed to carrying out an assessment of potential impact on representative flora and terrestrial fauna using the ERICA tool, at Tier 2 assessment level, which is detailed in Appendix B and a summary is provided here.

The assessment method is based on calculating the change in soil radionuclide concentrations from airborne emissions from the project. The soil radionuclide concentrations are then used as the "media concentration" values in the ERICA software.

The company reports that no endangered species in the general region, therefore the assessment has been conducted for all reference species in the ERICA database

The output of the assessment can be seen in Table 7.1 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 7.1: Output of ERICA Assessment

ERICA Outputs	After 16 years of Deposition
Species Considered	ERICA Standard Terrestrial Species List
Screening Value (µGy/h)	10
Total Dose Rate (µGy/h)	<0.1
Risk Quotient (expected value)	<0.01

It can be concluded that the ERICA assessment indicated that there is no radiological risk to reference plants and animals from emissions from the proposed project.

7.6 BUSH TUCKER

A potential exposure pathway to people of the region is through the ingestion of local bush tucker that has been impacted by dust emissions from the project. An assessment was conducted to determine the potential dose from this pathway.

Ingestion doses from bush tucker were determined for residents of Pinjin, Cundeelee and Tropicana Gold Mine. Doses were also calculated for hypothetical communities on the southern and north western boundaries of the project area to provide a worst case assessment.

Details of the assessment are outlined in Appendix B and a summary is provided here.

It should be noted that the Mulga Rock area is desert, with minimal plants and animals in the region, mainly because of the lack of surface water. Therefore, a diet consisting completely of locally grown food from a single area is unlikely.

The assessment has been based on an annual diet of 155kg/y of vegetation material and 125kg/y of animal material (AAEC 1985) and used concentration ratios for Australian animals (kangaroos and reptiles) (ARPANSA 2014a) and vegetation concentrations ratios for two Australian species of plants calculated from published data from the Lake Way region (Toro Energy 2011).

The assessment method involves calculating the change in soil radionuclide concentration determined from the dust deposition from the air quality modelling and applying the concentrations ratios. This provides a measure of the radionuclides in the specific plants and animals as a result of the operations. The consumption rate of the plants and animals provides a measure of the intake of radionuclides and the dose from the intake can be determined using the recognized ICRP (ICRP 1995) dose factors.

The calculated human doses are shown in can be calculated for residents at the sensitive receptor locations, with results shown in Table 7.2.

Table 7.2: Data for Ingestion Dose Assessment

Location	Dose (µSv/y)		
	Vegetation Ingestion	**Meat Ingestion**	**Total Ingestion**
Cundeelee	0.02	0.02	~0.1
Pinjin	0.05	0.03	~0.1
Tropicana Gold Mine	0.02	0.01	~0.1
Southern Tenement Boundary	24	44	68
North West Corner Boundary	46	83	129
Mining Accommodation Village	16	29	45

As noted the ingestion dose is worst case assumption. It is highly unlikely that ingestion doses would reach the calculated levels. In practice, it is expected that actual ingestion doses would be negligible.

8 TRANSPORT

The transport of any radioactive material into and out of the MRUP will be carried out in compliance with all relevant WA and SA State transport Regulations and ARPANSA Code of Practice for Radiation Safety in the Transport of Radioactive Materials (RPS 2, 2008), and IAEA Regulations for Safe Transport of Radioactive Materials TS-R-2 (version current at time of transport). A Transport Management Plan will be developed to support operations, which will include an Emergency Response Procedure for use in the event of a transport accident (road or rail).

The basic regulatory requirements are as follows:

- Packaging (container) must meet design requirements,
- Packages must be labelled,
- Vehicles must be placarded and
- Driver must be given instruction, including:
    - Formal relevant training in radiation protection,
    - Consignor's Declaration for Dangerous Goods, Class 7 Radioactive Material (if necessary),
    - Radioactive Monitoring Record relating to dose rates per container

- Copies of Export and Import Licenses issued by DRET and ANSO respectively,
- Supplement International Maritime Dangerous Goods (IMDG) documents,
- Safety Data Sheet for drummed UOC
- In-case of an emergency a copy of the ERMP.

- Packages and equipment departing site must be clear of radioactive contamination;
- Appropriate training and licencing of workers, as required.

Uranium product (Uranium Ore Concentrate, UOC) is classified as a Dangerous Goods Class 7 Radioactive, with its Proper Shipping Name being Uranium Ore Concentrate, Low Specific Activity LSA-1, UN2912. It will be transported packaged in 205 litre heavy gauge steel drums, classified as IP-1 industrial packaging, in locked and security-sealed sea freight containers, labelled and placarded.

All UOC transport arrangements will in addition require approval by ASNO, including real-time tracking of containers to destination and security of storage at port.

8.1 PACKAGING OF MATERIAL AT MINE SITE

The intent of packaging requirements is to ensure that there is no loss of containment during the transport of consignments of UOC.

The UOC will be placed into Industrial Packaging Type 1 (IP-1) 205 litre steel drums at the processing plant onsite and then loaded into General Purpose (GP) containers conforming to ISO 1496 (Figure 8.1). The drums will be secured with required strapping as specified by the Australian Maritime Safety Authority (AMSA).

Figure 8.1: Drums fastened and secured safely within a GP container.

The doors of the GP vessels containing the UOC will be sealed using bolt-type seals which will be consecutively numbered. The bolt security seals will comply with Customs-Trade Partnership against Terrorism (C-TPAT) and ISO 17712 standards, which meet ASNO standards as part of the Security Plan for the movement of UOC from the Project.

Prior to leaving site, and in accordance with the Code, a Radiation Safety Officer or their delegate will conduct thorough monitoring of the GP containers for non-fixed surface contamination and will monitor the exterior gamma radiation to confirm the Transport Index (TI).

The TI is an indicative measure of the potential gamma radiation level at 1 m for each 20 ft container and is recorded on the Yellow III label. All radiation measurements will be appropriately recorded and retained for future reference.

8.2 MARKING, LABELLING AND PLACARDING

In accordance with the Code, all 205L drums and GP containers will be legibly and durably marked with the gross mass and weight of the vessel.

All 205L drums will be appropriately labelled and all GP containers will be clearly and correctly placarded. Labels will be Class 7, UN2912, III – Yellow labels conforming to the requirements in the Code (Figure 8.2)

Figure 8.2: Category III – Yellow Label displayed on a GP container.

There will also be a requirement for a UN 3077, Environmentally Hazardous Substance, Solid, Not Otherwise Specified (NOS) placard to be placed on the GP container along with a placard meeting the requirements for a Class 7 UN 2912 label (Figure 8.3 and Figure 8.4)

Placards and labels will be removed from drums and containers when they have been emptied of their contents.

Figure 8.3: Radioactive 7 and Environmentally Hazardous Substance (NOS) placards

Figure 8.4: Alternative UN 2912 placard

8.3 ROAD TRANSPORTATION

Road transport, and indeed all transport segments including by ship to final destination, and any in-transit temporary storage, requires prior approval by ASNO (Australian Security and Non-Proliferation Office). Among other things, real-time communications are a necessary prerequisite to the secure transport of UOC. Vimy will implement the following requirements for all road vehicles used to transport UOC from the Project site to Port Adelaide:

- At all times, travel in convoys of at least two trucks which would remain in close proximity throughout the journey,
- Use appropriately trained drivers accredited with all necessary licences,
- As a minimum, trucks will be outfitted with equipment to communicate quickly, efficiently and reliably with an operational base. This may include two-way radios and satellite phones and
- A global positioning system (GPS) will be fitted to each prime mover.

A GPS fitted to each truck will provide three main security functions:

- A duress pendant or similar device would be provided to each driver so that if he/she was involved in an incident en-route, the pendant could be activated within 50 m of the vehicle and a duress message would be triggered,
- Out-of-zone (geo-fence) requirements around the approved road transport routes would be defined and, if a vehicle moved outside of these zones or travelled in an alternative direction, a back-to-base alarm would be activated and
- En route checking (with automatic updates through to an authorised user website) would display the location of vehicles during their journey at both the Project main security gate and Transport Service Provider operational centre.

8.4 TRANSPORT ROUTE

Vimy Resources proposes to transport UOC from MRUP to the Port of Adelaide via road. The transport route would be from the Mulga Rock Uranium Project site to the Western Australia – South Australia border via Kalgoorlie, Kambalda, Norseman and the Eyre Highway to the WA/SA border and then on to the Port of Adelaide (see Figure 8.5).

The total distance of the preferred road route from the project site to the border is approximately 2,450 km. This involves travel along an unsealed road ((260km) from the MRUP to Kalgoorlie and henceforth along sealed roads to the WA/SA border. All roads proposed to be used for the transport of UOC, with the exception of the MRUP to Kalgoorlie road, are existing heavy haulage routes. It is proposed that an average of two road trains per week will operate along the route, with an average of 6-8 containers shipped per month. The trucks will be operated on continuous 12 hour shifts, with two drivers per truck. The sealed roads currently carry road trains and other vehicles from a number of different industries. The inclusion of road trains from the MRUP at the frequency described above is considered to pose only minimal additional burden on the road infrastructure and minimal additional risk to the degradation of the roads.

Following the announcement by a number of companies to develop uranium mines in Western Australia, the State Government announced that it would not permit the export of UOC from Western Australian ports that are located adjacent to residential areas. This effectively means that UOC cannot be exported from Western Australia. Subsequent to this announcement, the State Government announced plans to consider the development of a road-to-rail transfer hub at Parkeston, just north of Kalgoorlie, to allow offloading and transfer of bulk freight between road and rail transport networks. This facility would allow uranium producers to road freight to Parkeston and transfer to rail for the next leg of the journey to Port Adelaide. Currently, there is no certainty that the Parkeston facility will be developed and, therefore, Vimy Resources has proposed road freight as its preferred mode of transport as it remains the only option

available at the time. However, should alternative transport opportunities become available during the life of the MRUP then Vimy Resources would consider the viability of each of these options on a case by case basis and seek the appropriate approvals, as required.

Figure 8.5: Proposed Preferred UOC Transport Route.

Transportation of UOC will occur through the following City Councils or Shires:

Western Australia:

- Shire of Menzies
- City of Kalgoorlie-Boulder
- Shire of Coolgardie
- Shire of Dundas

South Australia:

- Outback Communities Authority
- District Council of Ceduna
- District Council of Streaky Bay
- District Council of Wudinna
- District Council of Kimba
- Port Augusta City Council
- District Council of Mount Remarkable
- Port Pirie Regional Council
- Wakefield Regional Council
- District Council of Mallala
- City of Playford
- City of Salisbury
- City of Port Adelaide Enfield

8.5 ENVIRONMENTAL IMPACT OF TRANSPORT

The transport of uranium oxide from the Mulga Rock project site to its destination at Port Adelaide in sealed steel drums housed within general purpose containers minimises any opportunities for contact with the environment along the transport route. The UOC is effectively double encapsulated or 'wrap' protected, consisting of an inner sealed container (the drum) within an outer shipping container. This greatly reduces the likelihood of there being an incident involving a spillage of the material. However, in the unlikely event of an incident resulting in loss of containment of UOC then it should be treated no differently than any other Class 7 dangerous goods for emergency response purposes. Other than being an inhalation hazard, spilled UOC does not pose any immediate danger. An Emergency Response Management Plan (ERMP) will be developed to ensure the safe recovery of any spilt UOC occurs, so there is no ongoing environmental impact.

9 CONTROLS AND MITIGATION

Essential to radiation management is ensuring review of radiation control features at early stages of project and operational design studies. Design for radiation dose control and radioactive waste management will follow a risk management approach. This means that design and proposed operation will be reviewed to determine likely radiation sources and levels, and options for control will be identified for these sources. Options will be chosen on the basis of effectiveness, robustness and simplicity, and following the hierarchy of controls as far as possible, with substitution and engineering prioritised before administration and PPE.

The approach will be iterative, with input from the regulator agencies from an early stage.

ALARA (the principle that doses be kept As Low As Reasonably Achievable, social and economic circumstances being taken into account), will be followed, both in design and in operations.

This will be achieved by implementing and resourcing a robust Radiation Management Plan, and by regular senior management review of, and response to, the data generated by on-going monitoring.

9.1 RADIATION CONTROL IN DESIGN AND OPERATION

The radiation control aspects of the Mulga Rock Uranium Project are not expected to be highly onerous in terms of design and operational constraints, as the ore is relatively low grade; thus gamma doses will be low and easy to control; and the dust control is also expected to be minor, as the ore will be damp when mined, and kept wet throughout its handling from the mining operation to the processing plant. Periods of radon decay product build-up in-pit and in-plant, in atmospheric inversion conditions, may require active response for dose mitigation.

Atmospheric conditions which give rise to higher levels of radon progeny cannot be controlled. Therefore, there will need to be measures in place to monitor these conditions and limit workers' doses in these circumstances:

- All heavy equipment in-pit will have filtered air and air-conditioned cabins, minimising dust and radon progeny inhalation to mine workers,
- Radon progeny (RnDP) monitoring will be performed on a routine basis and in a manner to be determined in the Radiation Management Plan, yet to be developed, and as agreed with the DMP and Radiological Council inspectorates.
- All peripatetic workers in pit will not enter the pit for work if levels are above the DAC, or will require appropriate respiratory PPE.
- Any essential work outside of filtered air cabins during excessive RnDP concentrations will require respiratory protection.

Radon daughter controls will be provided, primarily, by well-maintained air filtration units on all mobile equipment in pit; and by delay of work in-pit by pedestrian workers (surveyors, grade control techs, geologists) until after the inversion breakup, which generally if present, will have dispersed from about 7 am onwards.

Dust controls in-pit ripping and haulage activities will involve primarily application of water during ore handling (if necessary). Haul and access roads will require watering, to minimise dust generation.

In the Metallurgical process plant, there will be suitable engineering design to minimise dust.

Dust controls in-plant will (as in other mining projects) focus on spillage control and easy clean-up. It is essential for all plant areas to be bunded and sealed so that spills of slurry flow automatically to sumps, and there are readily pumped back into process. The bunding must contain the total contents which can be released in any tank rupture, or foreseeing the necessity to drain a tank for major maintenance. Real-time monitoring of slurry pipelines will ensure prompt response to any potential spills. The MRUP is unlikely to

require a crusher due to the nature of the ore body. This will greatly minimise dust levels within the process plant.

Dust production in the yellowcake precipitation, drying and packing facility will be addressed by choice of new-generation product precipitation process. That technology features recirculating bed precipitation, resulting in a coarser particle size of product and hence reduced dusting propensity, and reduced inhalability.

Environmental releases of radon and dust from tailings will be mitigated by (a) wet placement of the tailings and the natural retention of moisture by the interparticle capillary or matric potential; and (b) by placement subsequent to drying to enable earthmoving equipment access, of cover material. The effectiveness of local sand-clay material from overburden has been tested on site and found to be effective for radon attenuation (see Sonter, Moreau & Wu 2015).

9.2 ACCESS CONTROLS

Supervised and Controlled restricted areas for radiation control will be described in full in the RMP, after deliberations with the DMP and Radiological Council inspectorates.

Product precipitation, drying, and packing area will be accessible only by swipe card, as specified by ASNO for compliance with non-proliferation commitments; workers in this area will have dedicated clothing, change-room, and laundry.

9.3 RADIATION CLEARANCES

There will be close control of equipment packages and material leaving the site. This will involve specific 'Gatehouse Control' at the Supervised Area boundary; with vehicle and equipment wash facilities, and checking before release. All equipment leaving dirty areas, e.g. for maintenance, or at end of lease period, must be washed and checked before exiting the dirty area. Radiation clearances may only be performed by trained and authorised personnel.

10 MONITORING PLAN AND RESPONSES

10.1 OCCUPATIONAL RADIATION MONITORING

There are several reasons for carrying out workplace monitoring programs, depending on the details of what is to be measured and how the data are to be handled.

- Provide day-to-day engineering feedback and operational control - this requires rapid reporting of high readings to foremen and senior management,
- In fulfilment of operating licence conditions; regulators will generally require periodic workplace monitoring data that gives them an ongoing auditing capability,
- Provide input for personal dose assessments - these are required under the Code of Practice; these results also tend to set the agenda for long-term dose control actions including strategic changes in engineering, procedures, and personal protective measures,
- For input to future epidemiological studies; note that it is essential to retain raw data, so that dose calculations can be reworked if conversion factors, internal dosimetry models, etc, are changed. This is facilitated by the required hand-on of dose data to the ANRDR and
- To manage legal liability, prove duty of care etc. This requires good record keeping.

Thus, the monitoring program is shaped by the pathways to be monitored, the purpose to be accomplished, and the associated data handling and reporting requirements, and the methods and technologies available.

Monitoring is quite demanding not only in terms of technician man hours expended gathering data, but also in terms of clerical time manipulating data, and required management review.

The table below give indicative instrumentation but other or newer technologies may be adopted.

A broad summary of the occupational radiation monitoring plan is shown in (*Table 10.1*).

Table 10.1: Occupational Radiation Monitoring Plan

Radiation type	Measurement Method	Application
Gamma direct shine	Thermoluminescent dosimeter (TLD) badges	All plant & pit personnel
	Electronic Personal Dosimeters (EPDs)	Specific maintenance tasks / purpose
	Gamma survey meters	Routine surveys, pit & plant
Inhalation LLα dust	Personal Air Samplers (PAS) plus drawer assembly	Issue to personnel in each SEG; plus investigative
	Locational	for investigative purposes
Inhalation RnDPs & TnDPs	Grab samples (Borak, Rolle)	for investigative purposes
	Continuous Rn, Tn, & RnDP monitors	Continuous in-pit, in-plant, for control; investigation
Surface alpha contamination	Large-area alpha probe, survey	Workplace & crib-room checks
		Equipment and outgoing checks

10.2 ACTION LEVELS

In conformity with good ALARA practice, and as a management tool, there will be pre-determined responses at particular trigger levels. ***These will be defined in consultation with DMP and RH regulators at the time of development of the operational RMP***.

The Action Levels set in consultation with regulators, and bound to in the RMP, will depend on the parameter being tracked, its short and long term variability, and the observed average as a fraction of the 'limit' figure. In other words, a parameter which is tracking at a higher fraction of the allowable figure, and which is more variable, must be controlled more closely than one which is at a lower fraction of allowable, and less 'volatile'.

As a general guide however, and without prejudicing the conversations with the regulators, it is usual to set Investigation and Action Levels for dust and for RnDP at (respectively) some substantial fraction of, and at, their DAC.

This approach avoids the otherwise fraught situation of having to consider appropriate responses at the time of occurrence, by putting effort into prior deliberation.

10.3 ENVIRONMENTAL RADIATION MONITORING

Environmental radiation monitoring aims to characterise natural background radiation; and hence provide baseline and ongoing data for identification of any project-origin increments. This is a difficult task, because it involves seeking to identify small signals which are additive to a spatially and temporally variable natural background.

The keys to success are to focus on time-integrated data, as such data signals accumulate over time, and also inherently smooth out short term variability. It is also important to ensure the areal extent of the baseline and ongoing surveys extend well beyond the immediate footprint of the project, to capture clearly 'non-impact' area data.

Thus Vimy Resources has been collecting, for some years now, the following data sets:

1. An array of environmental TLD badges for long-term gamma dose data,
2. Wide area instrumental gamma survey information and aerial radiometrics,
3. An array of passive radon track etch monitors, for time-averaged airborne radon,
4. Passive dust deposition collectors,
5. A Hi-Volume air sampler,
6. A suite of surface soil samples for radionuclide assay and
7. A suite of groundwater samples.

Not so relevant to long term trends or measurements, but more to demonstrate the huge natural diurnal and weekly variability, Vimy Resources also runs an ERDM continuous radon daughter monitor.

These data accurately characterise the regional radiation environment and its variability.

All these monitoring tasks will continue into operation.

11 CONCLUSIONS

The Mulga Rock Uranium Project is being designed with full recognition of the radiation management process and tasks, to ensure both negligible environmental impact and well-controlled worker doses.

Nearest critical group is located 100km from the Project and the impacts of radiation from the Project are expected to be negligible.

Assessment of credible scenarios show low worker doses, negligible Member of Public doses and negligible non-human biota impact.

Progressive rehabilitation will provide great benefits for environmental impact mitigation and management.

A Radiation Assessment has been completed on the Mulga Rock Uranium Project. Significant prior environmental baseline radiation and weather data provide a sound basis for this assessment. There exists much detailed information on doses to workers and members of the public from other uranium projects, which also provide sound basis for estimates and conclusions.

Doserates to radiation workers within project have been calculated and are a small fraction of the regulatory limit. Doserate are summarised in Table 11.1.

Exposure action levels will be defined within the yet to be approved Mining Radiation Management Plan (RMP) to ensure environmental and occupational impacts are not greater than predicted.

Table 11.1: Radiation dose information.

Radiation parameter (Report section)	Expected Value	Limit/ Standard	How estimates were determined
Doses to mine workers (Section 6.5)	3 mSv/yr (max)	20mSv/yr	Gamma dose based on first principles and consideration of exposure rates at other mines Dust doses based on estimate of dust concentrations at other open cut mines combined with standard dose conversion factors Radon decay product doses based on estimate of modelled radon levels in pit (including a range of atmospheric conditions

Doses to metallurgical plant & maintenance workers (Section 6.5)	1.5 mSv/yr	20mSv/yr	Data from the existing operations
Member of public doses in Accommodation Village (Section 6.5)	0.024 mSv/yr	1mSv/yr	Gamma doses negligible Dust and Radon decay product doses based on modelled airborne dust and radon concentrations combined with standard dose conversion factors
Dose to Indigenous people from consumption of local bush tucker (Section 7.6)	< 0.2 mSv/yr	1mSv/yr	Calculated based on worst case consumption, transfer factors and uptakes over 1 year at the Project boundary.
Dose to hypothetical member of public living at closest project boundary (Appendix B)	0.18 mSv/yr	1mSv/yr	Estimates of long-lived alpha (LLA) dust and radon concentrations from air dispersion modelling
Doses to UOC truck drivers (Section 6.5)	0.37 mSv/yr	20mSv/yr	Doses based on estimates and other operations and a worst-case number of trips that one driver might make

12 REFERENCES

AAEC 1985. *Options for Clean-up of the Maralinga Test Site.* Australian Atomic Energy Commission Research Establishment Lucas Heights Research Laboratories, Environmental Science Division, June 1985.

Amec Foster Wheeler 2015. *Mulga Rock Uranium Project Scoping Study,* Amec Foster Wheeler and Coffey Mining, April 2015.

ARPANSA 2004. *Recommendations for Intervention in Emergency Situations Involving Radiation Exposure.* Radiation Protection Series Guideline RPS 7

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

ARPANSA 2008. *Code of Practice for the Safe Transport of Radioactive Material.* Radiation Protection Series Guideline RPS 2

ARPANSA 2008a. *Safety Guide for the Safe Transport of Radioactive Material.* Radiation Protection Series Guideline RPS 2.1

ARPANSA 2008b. *Safety Guide for the Approval Processes for the Safe Transport of Radioactive Materials.* Radiation Protection Series Guideline RPS 2.2

ARPANSA 2008c. *Safety Guide for the Predisposal Management of Radioactive Waste.* Radiation Protection Series Guideline RPS 16

ARPANSA 2011a. *Safety Guide for Monitoring, Assessing and Recording Occupational Radiation Doses in Mining and Mineral Processing.* Radiation Protection Series Guideline RPS 9.1

ARPANSA 2011b. *Safety Guide for Monitoring, Assessing and Recording Occupational Radiation Doses in Mining and Mineral Processing.* Radiation Protection Series Guideline RPS 15

ARPANSA 2011c. *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, National Report of the Commonwealth of Australia.* October 2011

ARPANSA 2014a. *Fundamentals for Protection Against Ionising Radiation.* Radiation Protection Series Guideline RPS – F-1.

ARPANSA 2014b. *National Directory for Radiation Protection.* Radiation Protection Series Guideline RPS 6.

BHP Billiton 2009. *Olympic Dam Expansion: Draft Environmental Impact Statement 2009*. Main Report – Volume One. Unpublished Report. December 2008.

BHP Billiton 2011. *Olympic Dam Expansion: Supplementary Environmental Impact Statement 2011*. Unpublished Report. April 2011

BHP 2013. *Emergency Response Management Plan*. Unpublished report for Kintyre Uranium Project

Bureau of Meteorology 2014. Climatic data of Australia http://www.bom.gov.au/

Cameco 2013. *Kintyre Uranium Project: Chemical and Fuel Storage Management Plan*. Unpublished internal report. June 2013.

Cherrie J. & H. Cowie 2013. Occupational Exposure Limits for Dust. Presentation at the OAM ISRP Spring Meeting

Coffey Mining 2010. *Ambassador Scoping Study, Energy and Minerals Australia, Mulga Rock Uranium Deposit.* October 2010

CSIRO 1996. *Geochemistry, Mineralogy and Hydrogeochemistry of the Ambassador Multi-Element Lignite Deposit, Western Australia* (GB Douglas, DJ Gray & CRM Butt 1993) with Additional Investigations on the Characterization of Organic Matter (DJ Gray 1996) Final Report Volume 1. April, 1996. Unpublished report prepared for Energy and Minerals Australia Limited, April 1996. [PER APPENDIX D6]

Department of Minerals and Petroleum 2001. *Rehabilitation Works at Mulga Rocks: EL 39/3, MLs 39/39-41, 43-44 & 47-50.* Report to PNC Australia Pty Ltd. April – December 2001.

ICRP 1995. *Age-dependent Doses to Members of the Public from Intake of Radionuclides – Part 3 Ingestion Dose Coefficients*. International Commission on Radiological Protection, Publication 69 Ann. 25 (1), 1995.

JRHC 2015, *Radiation Waste Management Plan.* Unpublished report prepared for Vimy Resources Limited, May 2015. [PER APPENDIX H3]

McKeich R. 1982. *A Survey for Aboriginal Sites in the Cundeelee Minigwal Area*. Unpublished report prepared for PNC Exploration (Australia) Pty Ltd, August 1982. [PER Appendix G3]

Mathieu, C., 2015. Report of an ethnographic survey of the Mulga Rock Uranium Project Area, Great Victoria Desert, Western Australia, Warranup Pty Ltd, June 2015, Unpublished report to Vimy Resources

Morris PA 2012. *Fine-fraction geochemistry of regolith from the east Wongatha area, Western Australia: tracing bedrock and mineralization through cover.* Geological Survey of Western Australia, Record 2012/13, 58p.

O'Connor S. 1984. *An Archaeological Survey for Aboriginal Sites in the PNC Exploration Lease Area Officer Basin, Great Victoria Desert*. Unpublished report prepared by Centre for Prehistory, University of Western Australia for Energy and Minerals Australia Limited, February 1984 [PER Appendix G5]

Sonter M., X. Moreau & M. Wu 2015. *"Mulga Rock Uranium Project Radon Test-work: Technical Note" in:* Radiation Protection in Australasia Vol 32 (1): 15-21 [PER APPENDIX F3]

Safe Work Australia 2013. *Guidance on the Interpretation of Workplace Exposure Standards for Airborne Contaminants.* April 2013

Toro Energy Limited 2011. *Environmental Review and Management Programme (ERMP) for the Wiluna Uranium Project.* EPA Assessment No 1819, July 2011.

Matner J. 2009. Archaeological Studies of the Tropicana Gold Project Area (including the infrastructure Corridors and Water Supply Area) Great Victoria Desert. Unpublished Report prepared by Waru Consulting Pty Ltd for AngloGold Ashanti Australia Ltd. March 2006-December 2008. July 2009.

Matner J & T Bergin 2009. Ethnographic Studies of the Tropicana Gold Project Area (including the infrastructure Corridors and Water Supply Area) Great Victoria Desert. Unpublished Report prepared by Waru Consulting Pty Ltd for AngloGold Ashanti Australia Ltd. June 2002 - December 2008. February 2009.

UNSCEAR 2008. Sources and Effects of Ionizing Radiation, United Nations Scientific Committee on the Effects of Atomic Radiation, Report to the General Assembly with Scientific Annexes, Volume 1. United Nations, New York, 2010.

Vimy 2015. *Mine Closure Plan: Mulga Rock Uranium Project*. Unpublished report, May 2015. [PER Appendix H1]

Glendenning, W. 2015. A report of an archaeological survey of the proposed Mulga Rock Project northeast of Kalgoorlie, Warranup Pty Ltd, June 2015, Unpublished report to Vimy Resources

13 GLOSSARY

Definitions sourced from the Radiation Worker Handbook (ANA web page, copyright RAS)

Absorbed dose:	the amount of energy (in joules) deposited by radiation in a kg of matter; one Gray of absorbed dose = 1 J/kg
Activity	amount of radioactive material in a sample, measured in Becquerels, where 1 Bq = 1 atomic decay per second
ALARA	As Low As Reasonably Achievable, social and economic circumstances being taken into account
Alpha	high energy, high speed particle radiation, actually a double-ionized helium nucleus, emitted from a decaying atom
AMAD	Activity Median Aerodynamic Diameter
AMSA	Australian Maritime Safety Authority
ANA	Australian Nuclear Association
ANRDR	Australian National Radiation Dose Register
ASNO	Australian Safeguards and Non-Proliferation Office
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AUA	Australian Uranium Association
Becquerel	Unit of Activity see above; named after the discoverer of natural radioactivity
Beta	energetic particle radiation, actually a high speed electron emitted from a decaying atom
BHP	BHP Billiton Pty Ltd
COAG	Council of Australian Governments
Committed dose	dose which you are 'committed to' following inhalation or ingestion of radionuclides; once incorporated into the body, these may continue giving a dose for many years
Contamination	unwanted radioactive material, on surfaces or in air or water
Controlled Area	area within which there must be specific procedures for ensuring control of worker doses below the limit; also, area within which the worker may get more than 3/10 of the limit.
DAC	Derived air concentration
DDG	Dust Deposition Gauges
Decay chain	sequence of transformations that a radioactive 'parent' atom passes through as it decays, giving out alpha, beta, and gamma radiation; see uranium and thorium decay chains.
DMP	Department of Mines and Petroleum
Dose	may be absorbed dose, committed dose, equivalent dose, or effective dose
DRET	Department of Energy, Resources and Tourism
Effective dose	dose to human body, taking into account the radiation weighting factor for effectiveness of different radiation types, and the organ/ tissue weighting

	factor for differing radiosensitivities for cancer induction of the target organs
EIS	Environmental Impact Statement
EPA	Environmental Protection Authority
Epidemiology	study of disease incidence in large groups of people
ERDM	Environmental Radon Daughter Monitor
ERICA	Environmental Risk from Ionising Contaminants
ERMP	Emergency Response Management Plan
ESD	Environmental Scoping Document
Exposure	used in various contexts: may refer to the existence of an exposure pathway for delivery of internal or external dose; or sometimes may be inaccurately used meaning 'dose'; may mean period of time in a radiation field.
Gamma radiation	electromagnetic radiation like x-rays but emitted from nucleus of atom
GHD	Gutteridge Haskins & Davey
GP	General Purpose
GPS	Global positioning system
GSWA	Geological Survey of Western Australia
Half-life	time for a radionuclide to decay to half its original amount
Half Value Layer	the thickness of shielding which will reduce the strength of a penetrating gamma beam by half
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IMDG	International Maritime Dangerous Goods
Joules	unit of energy (1 watt of power for 1 second)
Kerma	kinetic energy delivered from radiation into air: essentially same as absorbed dose in air
LNT	Linear No Threshold hypothesis
LLα	Long lived alpha emitters (see decay chains)
LOM	Life-of-Mine
Member of Public	not occupationally exposed to radiation
MNES	Matters of national environmental significance
Monazite	mineral, a rare earth-thorium phosphate, very resistant to leaching
MoP	Member of the public
MoU	Memorandum of Understanding
MRE	Mulga Rock East
MRUP	Mulga Rock Uranium Project
MRW	Mulga Rock West
MW	Megawatt

NORM	Naturally Occurring Radioactive Materials
NHB	Non-human biota
NORM	Naturally Occurring Radioactive Material
NOS	Not Otherwise Specified
PAEC	Potential Alpha Energy Concentration (radon decay product in air)
PAS	Personal Air Sampler, for sampling airborne dust onto a filter paper
PER	Public Environmental Review
PKEF	Preliminary Key Environmental Factors
PNC	PNC Exploration Australia Pty Ltd
PPE	personal protective equipment e.g. dust masks
PRM	Passive radon monitors
Quality Factor	old terminology for Radiation Weighting Factor
Radiation	transfer of energy through space
Radionuclide	also radioisotope, a radioactive element
Radium	radium226 was discovered by Marie Curie, 88^{th} element in the Periodic Table, the only source of intense radiation other than x-rays, until the development of nuclear reactors and artificial radioisotopes in the 1940s and 1950s
Radon	Rn222, decay product of radium-226, inert gas, similar to argon, neon, xenon etc.
Radon progeny / radon daughters / radon decay products	being: Po218, Pb214, Bi214, Po214, the short lived radionuclide breakdown products of the decay of Rn222
RDS	Radiation Dosimetry Services
RH	Radiological Health
RLC	Radiation Liaison Committee
RMP	Radiation Management Plan
RnDP	Radon Decay Products
ROM	Run-of mine
RPS	Radiation Protection Series
RWMP	Radioactive Waste Management Plan
Secular Equilibrium	the state in a decay chain when all nuclides are decaying at the same rate, i.e., all have the same activity, i.e., in each 'species', new atoms are being generated by breakdown of the parent just as fast as they are being removed by decaying to form the daughter
SEG	Similar Employment Group
Sievert	Unit of effective dose
Supervised Area	workers outside supervised area will not need to be regarded as occupationally exposed and will not get more than Member of Public limit; within supervised area, worker dose may exceed the Member of Public annual limit, but is most

	unlikely to exceed 3/10 of the Radiation Worker limit, and specific procedures to avoid going over the limit are not necessary
TI	Transport Index
TLD Badge	Thermo-luminescent Dosimeter, personal radiation badge, records time-integrated gamma dose
Thorium	Th232, 90^{th} element in the Periodic Table
TSF	Tailings Storage Facility
TSP	Total suspended particulate
TWA	Time Weighted Average
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UOC	Uranium Ore Concentrate
Uranium	92^{nd} element in the Periodic Table: three natural isotopes: U238, U234, and U235
WA	Western Australia
Working Level	old unit for radon daughter concentration, equal to 1.35 x 10^7 MeV of ultimately delivered alpha energy per litre of air, also equals (new units) 20.7 $\mu J/m^3$; originally defined as the alpha energy equivalent to 100 pCi/l of radon in equilibrium with its four short-lived daughters.
X-rays	discovered by Prof Wilhelm Roentgen in 1895
Yellowcake	bright yellow uranium precipitate, but also colloquially used for uranium oxide in forms of $UO_4.nH_2O$ (yellow), UO_2 (black) or U_3O_8 (dark green)

APPENDIX A: URANIUM AND THORIUM DECAY CHAINS

Uranium bearing minerals contain a suite of 'daughter' radioactive elements, the uranium decay chain, shown below: *The nuclides in **bold** are the radon decay products (RnDP or 'radon daughters')*

U-238 Decay Chain

Nuclide	Radiation	Half-life
Uranium 238	α	4.5 billion yrs
Thorium 234	β, γ	24 days
Protactinium 234	β	1.2 minutes
Uranium 234	α	250 000 yrs
Thorium 230	α	80 000 yrs
Radium 226	α, γ	1600 yrs
Radon 222 (gas)	α	3.8 days
Polonium 218	α	3 minutes
Lead 214	β, γ	27 minutes
Bismuth 214	β, γ	20 minutes
Polonium 214	α	160 microsecs
Lead 210	β, γ	22 yrs
Bismuth 210	β	5 days
Polonium 210	α	140 days
Lead 206	---	stable

α = alpha particle, doubly charged helium nucleus, 2 protons + 2 neutrons, emitted from nucleus.

β = beta particle, high speed electron emitted from nucleus.

γ = gamma ray, electromagnetic radiation, similar to x-ray.

U-235 Decay Chain

Nuclide	Radiation	Half-life
Uranium 235	α, γ	710 million yrs
Thorium 231	β	25.5 hrs
Protactinium 231	α	33 000 yrs
Actinium 227	β	22 yrs
Thorium 227	α	18 days
Radium 223	α	11 days
Radon 219 (Actinon)	α	4 seconds
Polonium 215	α	1.8 milliseconds
Lead 211	β	36 minutes
Bismuth 211	α, γ	2.1 minutes
Thallium 207	β	4.8 minutes
Lead 207	nil, stable	infinite, lasts forever

Note: In nature, e.g. ore or mineral samples, U-235 is about 5% of the activity of U-238 (and about 0.7% of the mass of U-238). Similarly, each U235 decay chain daughter is approx. 5% of the activity of each U-238 decay chain daughter.

Th-232 Decay Chain

Nuclide	Radiation	Half-life
Thorium 232	α	14 billion yrs
Radium 228	β	5.7 yrs
Actinium 228	β, γ	6.1 hrs
Thorium 228	α, γ	1.9 yrs
Radium 224	α, γ	3.6 days
Radon 220 (Thoron)	α	55 seconds
Polonium 216	α	0.15 seconds
Lead 212	β, γ	10.6 hrs
Bismuth 212	β (64%), α (36%), γ	61 minutes
Polonium 212 **(64%)**	α	300 nanoseconds
Thallium 208 **(36%)**	β, γ	3.1 minutes
Lead 208	nil, stable	infinite, lasts forever

Main gamma emitters are Tl-208, photon energy 2.6 MeV, and Ac-228, about 1 MeV

APPENDIX B: NON-HUMAN BIOTA AND BUSH TUCKER ASSESSMENT

VIMY RESOURCES

MULGA ROCK PROJECT

HUMAN HEALTH, BUSHTUCKER AND NON-HUMAN BIOTA RADIOLOGICAL ASSESSMENT TECHNICAL REPORT

October 2015

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INDEX

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 from the proposed Vimy Resources Mulga Rock project.

This report consists of the following:

- an outline of the relevant radiological characteristics of the project,
- details for the public dose assessment,
- assessment of potential doses from bush tucker, and
- radiological impact assessment for non-human biota.

The work is based on the results of the air quality modelling undertaken by GHD (GHDa, GHDb).

2. RADIOLOGICAL CONSIDERATIONS OF THE MULGA ROCK PROJECT

2.1 INTRODUCTION

This section describes the criteria and assumptions used in the radiological assessments.

2.2 SENSITIVE RECEPTORS

Impacts are assessed as potential radiation doses to members of the public and as a calculated dose rate for non-human biota. The assessments are based on the results of air quality modelling which provide a measure of project originated radioactivity in the environment outside the mine tenement area and then uses recognised standard methods to calculate the radiological impact.

The sensitive receptors locations, as defined by the air quality modelling, are locations where people may be located and where the non-human biota impact assessments are necessary. These are as follows;

- Tropicana Gold Mine, an active mining operation, located approximately 110km north east of the operation,
- Pinjin, an existing pastoral station located approximately 105km west of the operation,

- Cundeelee, an abandoned Aboriginal community, located approximately 90km NW of the operation, (note that this location has been included in the assessment because it is the location of the closest Aboriginal community) and,
- The proposed location of the mining accommodation village, located within the mining lease area and approximately 10km from the proposed processing plant.

An additional two locations were selected for public and environmental radiological assessment. One of these locations is on the south east project boundary (approximately 9km from the proposed processing plant location) and one is located on the north western access road into the operations (approximately 40km from the proposed processing plant location). These are not permanently occupied locations, but will provide estimates of "worst case" exposure situations.

2.3 METHODS OF IMPACT ASSESSMENT

For members of the public, doses are estimated for each of the main exposure pathways as follows;

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

A summary of the methods used to determine the radiation impact to the public is shown in Table 1 for the different exposure pathways.

Table 1: Dose Estimation Methods

Dose Pathway	Member of Public
Gamma Radiation	Modelled
Inhalation of radionuclides in dust	Estimation based on air quality modelling results
Inhalation of RnDP	Estimation based on air quality modelling results
Ingestion of radionuclides	Estimation based on modelled dust deposition and transfer factors

The impact to non-human biota (flora and fauna) is assessed by determining the change in radiation dose rates to standard species of flora and fauna as a result of emissions from the operation. The change in concentration is then used as input date for an ERICA assessment which calculates a dose to set of reference species.

The method for determining the change in media concentration is via modelled dust deposition results.

2.4 DOSE ASSESSMENT CRITERIA

The following criteria have been used in the radiological impact assessment:

Production Factors

- Average total mining rate – 44mtpa (ore and waste rock)
- Average ore mining rate – 2.6mtpa (maximum ore mining rate is approximately 4.7mtpa in year 10)
- Average uranium grade of ore –600ppm
- Average uranium grade "low grade" ore - 300ppm
- Average uranium grade of waste rock – 20ppm
- Average annual production of uranium – 1,360tpa
- Average annual tailings production rate – 2.4mtpa

Exposure Factors

- member of the public exposure hours – 8,670h/y
- member of the public breathing rate – 1.0m^3/h

Physical Property Factors:

- relationship between uranium grade and radionuclide activity is
  - 1ppm U = 12.3mBq(U^{238})/g
- ore is not in secular equilibrium when mined (see section 2.5)
- the majority of radionuclides, apart from uranium, report to tailings
- the concentration of radionuclides in tailings is approximately equal to the concentration in the ore (apart from uranium)
- deposited dust will mix in the top 10mm of soil (over approximately a 16 year period) (Kaste 2007)
- specific gravity (density) of soil in the environment is 1m^3 = 1.5 tonne
- radon emanation rate from ore is 50Bq/m^2.s per percent of uranium
- radon emission rate from tailings is the same as that for ore.

Dose factors:

- the dose conversion factor for members of public for radon in equilibrium with progeny is 1.1µSv/(µJh/m^3) (ICRP 1993))
- the dust inhalation dose conversion factor is 7.2µSv/αdps (ARPANSA 2005).

2.5 RADIONUCLIDE ANALYSIS

Previous work (ANSTO 1989) has indicated that radionuclides in the ore and the waste material are not in secular equilibrium. The calculated radionuclide concentrations are shown in Table 2.

Table 2: Radionuclide analysis of ore

Material	Uranium Grade (ppm)	Radionuclide Concentration(Bq/g)[1]					
		U^{238}	U^{234}	Th^{230}	Ra^{226}	Pb^{210}	Po^{210}
Ore	600	7.5	7.5	7.5	5.8	5.8	5.8
Low grade ore	300	3.75	3.75	3.75	2.75	2.75	2.75
Waste	20	0.25	0.25	0.25	0.36	0.36	0.36

***Note 1**: Measurements were available only for U^{238} and Ra^{226}. It has been assumed that the U^{234} and Th^{230} concentrations will be the same as the U^{238} concentrations. It has been assumed that the concentrations of Pb^{210} and Po^{210} will be the same as the Ra^{226} concentration.*

The processing of the ore will use a standard milling, leaching and precipitation process and the deportment of radionuclides through this flowsheet are well known with the majority of uranium reporting to final product and remnant radionuclides reporting to tailings.

2.6 DUST EMISSION FACTORS

The dust sources for the air quality assessment are based on standard emission factors for equipment and processes (GHD 2015a). The air quality modelling uses estimates of dust emissions from various processes and calculates increases in dust concentration at the sensitive receptors in units of $\mu g/m^3$. The modelling also calculates project originated dust deposition in units of g/m^2.month.

Air quality modelling was conducted for a number of scenarios to reflect the changing operational status and location of the project source terms. For all modelled scenarios, the average sources of dust emissions are shown in Table 3 as proportions of total emitted dust.

Table 3: Average proportion of dust emission for all years of operation

Emission Source	Proportion of TSP Emissions (%)
Ore	7.4%
Low grade ore	20.9%
Waste	71.5%

To calculate the radionuclide emissions, a weighted average technique is used, which takes into account the different radionuclide compositions of the dust sources (as shown in section 2.5).

Using the dust radionuclide composition as shown in Table 2, the average specific activity of the dust can be calculated as is as follows;

- 1.5Bq/g for U^{238}, U^{234} and Th^{230}
- 1.3Bq/g for Ra^{226}, Pb^{210} and Po^{210}

Potential emissions of dust containing higher concentrations of uranium or other radionuclides from the processing plant are unlikely to occur and therefore not considered for long term modelling. This is because once the ore is crushed and ground, it becomes a slurry and therefore unable to dust. The final product packaging area would be self-contained with exhaust scrubbing systems to eliminate emissions.

2.7 PROJECT RADON EMISSIONS

For radon emissions from the project, the following criteria are used;

- The U grade is used to estimate the radon emission rates. This is based on the ratio between U^{238} and Ra^{226} as seen previously.
- Published emission data has been used to determine the unit emission rate of 50Bq/m^2.s per %U (BHP Billiton 2009, ERA 2014). As discussed in a separate report (Radiation Advice & Solutions 2015), this is a very conservative assumption given preliminary experimental data obtained on MRUP ore.
- No difference in emission rates between broken and unbroken ore has been used. This is based on other recent impact assessment assertions (ERA 2014).
- For tailings, generally, all Ra^{226} in ore will report there, and therefore the activity concentration of Ra^{226} in tailings is approximately the same as that for the ore.

The air quality assessment (GHD 2015b) describes four scenarios for radon emission based on various stages of the project. The emissions rates for the modelled years can be seen in Table 4.

Table 4: Estimated Radon Releases

Source of Radon	Emission Rate (MBq/s)			
	Year 3	Year 10	Year 11	Year 14
Mining	0.26	0.36	0.58	0.66
Low Grade and Overbuden Stockpiles	0.60	0.90	1.20	1.50
Tailings	0.30	0.30	0.30	0.30
Processing Plant	0.45	0.45	0.45	0.45
Total	1.61	2.01	2.53	2.91

2.8 AIR QUALITY MODELLING

2.8.1 BACKGROUND

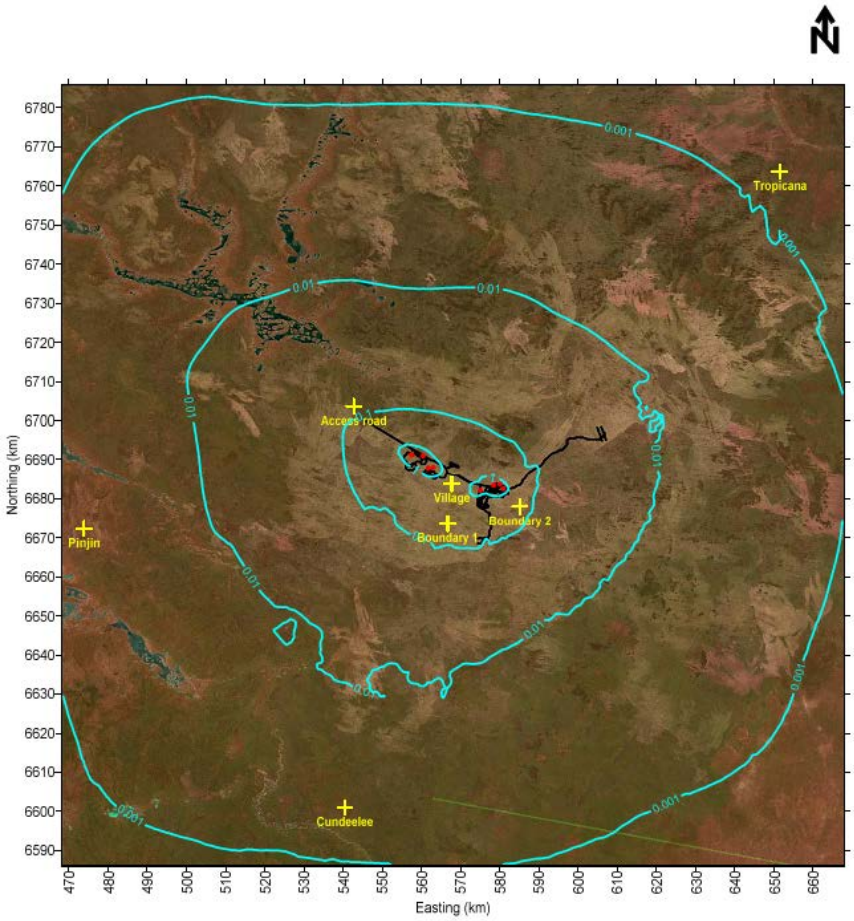
During 2015, Vimy Resources commissioned air quality modelling to determine the potential impacts of airborne emissions from the Mulga Rock project. The modelling utilises the radon emission rates outlined in Sections 2.7 to calculate concentrations of radon concentration at sensitive receptor locations. For dust, emission factors outlined in Sections 2.6 are used to provide dust concentrations at sensitive receptor locations.

The modelling method and more detail are available in the air quality reports (GHD 2015a and GHD 2015b).

2.8.2 RADON

Figure 1 shows the incremental annual average radon concentration from the air quality modelling at year 14 of operations, when radon emissions are at their highest rates. The plots of incremental radon concentrations for other modelled years can be seen in the air quality reports (GHD 2015a and GHD 2015b).

Figure 1: Annual Average Modelled Radon Concentrations Bq/m^3 from the MRUP



The predicted annual average ground level concentrations at each of the main receptor locations can be seen in Table 5. It should be noted that these figures do not include naturally occurring background radon concentrations which are approximately 10 to 20 Bq/m^3.

Table 5: Annual Average Radon Ground Level Concentrations

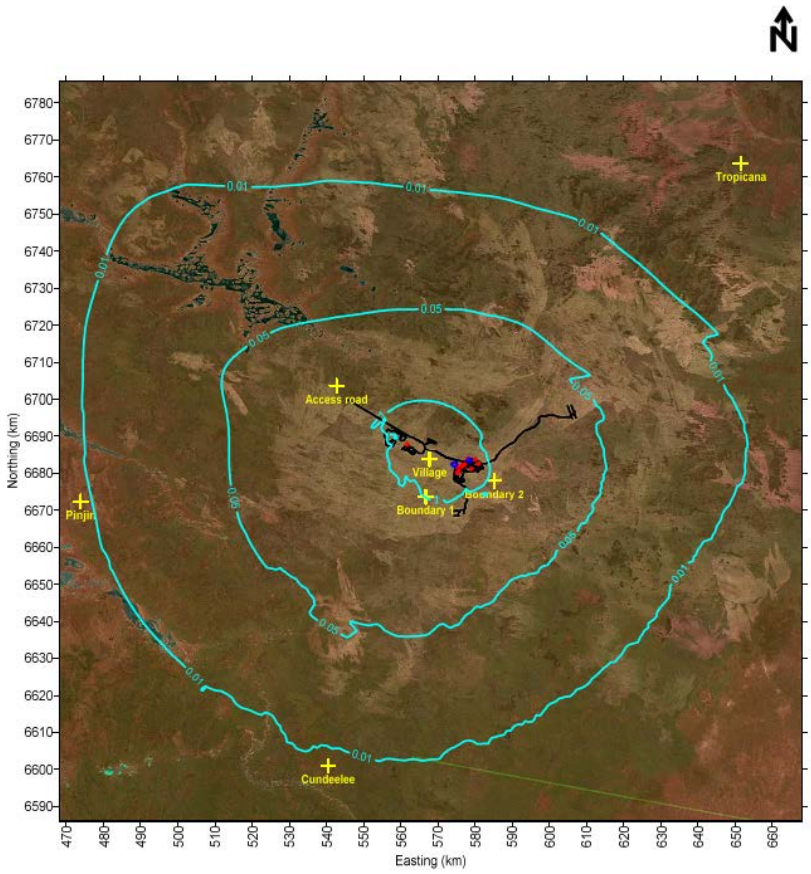
Location	Ground Level Concentrations Annual Average (Bq/m^3)			
	Year 3	Year 10	Year 11	Year 14
Mining Village	0.26	0.37	0.52	0.52
Cundeelee	0.001	0.001	0.002	0.002
Pinjin	0.001	0.001	0.002	0.002
Tropicana Gold Mine	<0.001	<0.001	<0.001	<0.001
South Eastern boundary	0.19	0.20	0.21	0.19
North West boundary[1]	0.02	0.03	0.04	0.07

***Note 1**: Modelled location is on access road.*

2.8.3 AIRBORNE DUST

Figure 2 shows the incremental annual average PM10 dust concentrations for a typical modelled year (year 10 of operations). Note that the TSP levels were not modelled and for this radiological assessment and therefore, the TSP figures have been assumed to be double the modelled PM10 results.

Figure 2: Modelling PM10 Dust Concentrations (µg/m^3)



The air quality modelling was conducted for a number of scenarios and for the radiological assessment, the maximum modelled annual average dust concentrations at each receptor locations have been used and can be seen in Table 6.

The radionuclide concentrations have been calculated from the modelled dust concentrations and the calculated weighted average specific activity result from section 2.6 of this report.

The dust concentration is multiplied by the weighted specific activity to give an activity concentration.

Table 6: Annual Ground Level Concentrations (maximum result for all modelled years)

Location	**Ground Level Concentrations PM10 Dust (µg/m^3)**	**Assumed Ground Level Concentrations TSP Dust (µg/m^3)**	**Equivalent Radionuclide Concentration (µBq/m^3)**
Mining Village	3.16	6.32	9.48
Cundeelee	0.01	0.02	0.03
Pinjin	0.01	0.02	0.03
Tropicana Gold Mine	<0.01	<0.02	<0.03
South Eastern boundary	0.73	1.46	2.19
North West boundary	0.96	1.92	2.88

2.8.4 DUST DEPOSITION

The air quality modelling has calculated the cumulative dust deposition for the life of the project and can be seen in Table 7.

The radionuclide deposition rates have been calculated from the modelled dust deposition rates and the calculated weighted average specific activity result from section 2.6 of this report (note that 1.5Bq/g has been used conservatively for all radionuclides). The dust deposition rate is multiplied by the weighted specific activity to give an activity deposition rate.

Table 7: Cumulative Dust Deposition (16 years)

Location	**Ground Level Concentrations Dust Deposition (g/m^2)**	**Radionuclide Deposition (Bq/m^2)**
Mining Village	8.62	12.9
Cundeelee	4.6×10^{-3}	6.9×10^{-3}
Pinjin	1.1×10^{-2}	1.7×10^{-2}
Tropicana Gold Mine	4.3×10^{-3}	6.5×10^{-3}
South Eastern boundary	3.8×10^{-1}	5.7×10^{-1}
North West boundary	1.7×10^{-1}	2.6×10^{-1}

3. PUBLIC DOSES

3.1 BACKGROUND

Doses to members of the public occur when emissions from inside the operation impact upon people outside the operation. It is usual to identify a representative person at a sensitive receptor location and determine the potential dose for that person from project emissions.

The sensitive receivers for public dose have been identified for the project and are detailed in Section 2.1. These are:

- Residents of Pinjin and Cundeelee
- Workers at Tropicana gold mine
- Workers at the mining accommodation camp (note that for this assessment, the accommodation camp workers are considered to be members of the public because they are unlikely to come into contact with radioactive materials)

Two sensitive receptor locations have also been defined at the north west tenement boundary and the south east tenement boundary and assessment is based on a person being located at these locations for a full year and living on bush tucker. This is considered to be the most conservative assessment of public dose.

The potential exposure pathways for members of the public are:

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

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 boundary and at least 5km from the closest publicly accessible area (the north west corner of the project by the site access road).

Gamma radiation intensity reduces significantly with distance (as one divided by the distance squared when the source is at a distance to be considered to be a point source). The gamma levels at the closest accessible area would not be detectable.

By way of example, using the WISE radiation gamma dose calculator software (WISE 2015), the gamma dose rates can be calculated at distances from a 100,000t ore stockpile, (similar to the stockpile sizes that will be used). At 1m from this stockpile, the gamma dose rate is approximately 10µSv/h. At 5km, the gamma dose rate is calculated to be less than 1pSv/h. For a member of the public at this location, for a full year, the gamma dose is calculated to be 0.01µSv/y.

3.3 AIRBORNE DOSE ESTIMATES

Doses from inhalation of both dust and decay products of radon (RnDP) are based on the modelled annual average concentrations at each of the sensitive receptor locations.

The dust inhalation doses have been based on the maximum modelled dust concentrations at each of the receptor locations (see table 6). Similarly, the radon decay product doses are based on the maximum modelled radon concentrations at each receptor location (see table 5).

Dust

The dust dose is calculated for 8,760h/y (full time occupancy), a breathing rate of $1m^3/h$ and a dust dose conversion factor of 7.2µSv/αdps and the formula is:

Dose (µSv/y) = Dust activity concentration (Bq/m^3) x

Number of long lived alpha per Bq (5αdps/Bq) ×

Breathing rate ($1.0m^3/h$) ×

Hours per year (8,760h/y) ×

Dose Conversion Factor (7.2µSv/αdps)

Radon and radon decay products

The RnDP dose is calculated from the modelled radon concentration at the sensitive receptor locations. The first step is to convert the modelled radon concentration to a RnDP concentration as follows;

RnDP Concentration ($\mu J/m^3$) = Equilibrium factor (unit less) x

0.00556 µJ/Bq x

Rn concentration Bq/m^3

For this assessment, a conservative equilibrium factor of 1 has been used. The RnDP dose is then calculated using the following formula:

Dose (mSv/y) = RnDP Conc (mJ/m^3) x

Exposure hours (8,760h/y) x

Dose Conversion Factor ($1.1mSv.m^3/mJ.h$)

A summary of the inhalation dose estimates can be seen in Table 8.

Table 8: Public Inhalation Dose Estimates

Location	TSP Dust		Radon/RnDP	
	Concentration (µBq/m^3)	Dose (mSv/y)	Radon Concentration (Bq/m^3)	RnDP Dose (mSv/y)
Mining Village	9.48	0.004	0.52	0.073
Cundeelee	0.03	<0.001	0.002	<0.001
Pinjin	0.03	<0.001	0.002	<0.001
Tropicana Gold Mine	<0.03	<0.001	0.001	<0.001
South Eastern boundary	2.19	0.001	0.21	0.030
North West boundary	2.88	0.001	0.07	0.010

3.4 INGESTION DOSE ESTIMATES

An estimate of the potential annual dose from the ingestion exposure pathway as a result of emissions from the project has been made for people living at the sensitive receptor locations and consuming food from that location. Note that the Mulga Rock area is sparse with minimal plants and animals in the region, mainly because of the lack of surface water. Therefore, permanently consuming locally grown food is unlikely to occur in practice, however the assessment is provided to show the most conservative assessment of ingestion doses.

The assessment method assumes that dust emissions from the 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. It should be noted that all plants and animals already contain low levels of naturally occurring radionuclides and this assessment is for the contribution by the operations, above those naturally occurring levels.

To determine the potential doses from the consumption of bush foods, an estimate of the amount of food consumed needs to be made. AAEC (AAEC 1985) assumed an intake of 155kg/y of plant material and 125kg/y of animal material for traditional owners of the Maralinga lands and these estimates have been used in this assessment.

Measured concentration ratios for local species of plants and animals are not available however some published soil and organism data from elsewhere is available from which concentrations ratios can be estimated. The main source of data used in this assessment is from the Lake Way region in Western Australia (Toro Energy 2011) and from ARPANSA (ARPANSA 2014).

The data from the Lake Way region consists of radionuclide in soil samples and radionuclides in species of vegetation (longer lived Acacia Aneura and shorter lived Tecticornia). The reported average vegetation radionuclide activity concentrations have been divided by the reported average soil radionuclide concentrations to drive a concentrations ratio (CR). Results for the Lake Way region and the published ARPANSA figures are shown in Table 9.

Table 9: Concentration Ratios for Ingestion Dose Assessment

Species	Concentration Ratio(Bq/kg (species))/(Bq/kg (soil))[1]					Source
	Uranium as U^{238}	**Thorium as Th^{230}**	**Radium as Ra^{226}**	**Lead as Pb^{210}**	**Polonium as Po^{210}**	
Red Kangaroo[2]	0.007	No data[5]	0.41	0.022	0.55	ARPANSA 2014
Large Mammal	*0.0044*	*0.00016*	*0.044*	*0.037*	*0.089*	*ERICA Default*
Reptile (Goanna)	2.5	0.027	No data[4]	1.2	11	ARPANSA 2014
Reptile	*0.0052*	*0.0022*	*0.0044*	*0.039*	*0.13*	*ERICA Default*
Long lived Vegetation[3]	0.21	0.02	0.05	1.06	0.58	Toro Energy 2011
Short Lived Vegetation[3]	0.23	0.17	0.09	0.33	0.34	Toro Energy 2011
Shrub	*0.061*	*0.061*	*0.33*	*0.32*	*0.33*	*ERICA Default*
Tree	*0.0066*	*0.00126*	*0.0116*	*0.0697*	*0.0733*	*ERICA Default*
Grasses	*0.128*	*0.16*	*0.18*	*0.12*	*0.28*	*ERICA Default*

Note 1: The ERICA CR values are provided for comparison – see section 4 of this report for further information on ERICA

Note 2: *ARPANSA 2014 figures are reported as concentration ratios – average of two sample sets used*

Note 3*: Figures 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 4*: Assumed to be 0.0443 (from ERICA CR database for reptiles)*

Note 5*: Assumed to be 0.000136 (from ERICA CR database for large mammals)*

The ingestion dose assessment is based on consumption rates as follows;

- 125kg/y meat (assumed to be 110kg kangaroo flesh and 15kg reptile)
- 155kg/y vegetable (80kg/y of short lived vegetation and 75kg/y of long lived vegetation)

Using the estimates of annual consumption, the intake of radionuclides can be calculated and used to calculate the dose to individuals based on the human ingestion dose conversion factors from the ICRP (ICRP 1995).

An overall summary of the method is as follows;

- determine the change in soil radionuclide concentration due to deposition of radionuclides in dust from the operation for a nominal period (assumed to be for the full life of operation - 16 years) – this gives a project contributed radionuclide in soil concentration at the receptor locations (Bq/kg)
- use the concentration ratios to determine the concentration of radionuclides in plants and animals from the soil using the concentration ratios (Table 9)
- determine the human intake from the consumption of plants and animals (multiply the consummation rate (kg/y) by the radionuclide concentration (Bq/kg) to give the Bq/y intake)
- use the ingestion dose factors from ICRP 1995 to determine the dose that is received by the consumption the plants and animals.

The calculated change in soil radionuclide concentrations at each of the sensitive receptor locations can be seen in Table 10 and is based on soil density of 1.5t/m^3 and a mixing depth of 10mm.

Table 10: Change in Soil Radionuclide Concentration (after 16 years of operations)

Location	Radionuclide Deposition (Bq/m^2)	Change in Soil Radionuclide Concentration (Bq/kg) (for each radionuclide)
Mining Village	12.9	0.862
Cundeelee	6.9×10^{-3}	0.0005
Pinjin	1.7×10^{-2}	0.001
Tropicana Gold Mine	6.5×10^{-3}	0.0004
South Eastern boundary	5.7×10^{-1}	0.038
North West boundary	2.6×10^{-1}	0.017

Using the standard ICRP ingestion dose conversion factors (ICRP 1995), the human doses can be calculated for residents at the sensitive receptor locations, with results shown in Table 11.

Table 11: Data for Ingestion Dose Assessment

	Dose (mSv/y)		
Location	**Vegetation Ingestion**	**Meat Ingestion**	**Total Ingestion**
Mining Village	0.144	0.085	0.229
Cundeelee	<0.001	<0.001	0.001
Pinjin	<0.001	<0.001	0.001
Tropicana Gold Mine	<0.001	<0.001	0.001
South Eastern boundary	0.006	0.004	0.010
North West boundary	0.003	0.002	0.005

3.5 TOTAL DOSE ESTIMATES

The total dose estimates at the sensitive receptors can be seen in Table 12. Note that the doses are based on 100% occupancy (that is 8,760 hours per year) at these locations.

Table 12: Public Total Dose Estimates

Location	Exposure Pathway Dose (mSv/y)[1]			
	Dust	RnDP	Ingestion[2]	Total Dose
Mining Village	0.004	0.073	0.229	0.306
Cundeelee	<0.001	<0.001	0.001	0.003
Pinjin	<0.001	<0.001	0.001	0.003
Tropicana Gold Mine	<0.001	<0.001	0.001	0.003
South Eastern boundary	0.001	0.030	0.010	0.041
North West boundary	0.001	0.010	0.005	0.016

***Note 1**: As noted in Section 3.2, the gamma dose is negligible (<0.001mSv/y).*

***Note 2**: As noted the ingestion dose is worst case assumption. It is highly unlikely that ingestion doses would reach this level. In practice, it is expected that actual ingestion doses would be negligible.*

3.6 PUBLIC DOSES DURING TRANSPORT

During the routine trucking of final uranium product to Port Adelaide or Darwin, there is the potential for members of the public to be exposed to gamma radiation. The exposure is limited due to relatively low gamma dose rates and also the limited exposure situations.

Based on gamma dose rates of 5µSv/h at 1m from a container of uranium oxide, and 1µSv/h and 0.2µSv/h at a distance of five and 10 metres respectively (BHP Billiton 2009) from a container, doses for the following exposure scenarios were estimated:

- the dose to a person in a car travelling behind a product container on a truck for six hours at a distance of 5m is calculated to be 0.006mSv.
- The dose to a person standing on side of road as every truck passes in a year (assume 50 occasions and one minute per occasion for the truck to pass, and a distance of 1 m from truck) is calculated to be 0.004mSv/y.

In the event of an accident and a release of radioactive material, an emergency response plan (ERP) would be initiated. The priorities of the ERP are first aid and containment of any product spillage. The area would be segregated and any spilled product covered.

4. FLORA AND FAUNA IMPACT

4.1 BACKGROUND

This section provides an assessment of the potential radiological impacts on non-human biota (NHB) from the operation. The assessment considers airborne emissions from the project which results in 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 explicitly demonstrate that the natural environment is protected from authorised discharges of radioactive substances.

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 non-human biota (plants and animals). An important aspect of the assessment is that protection of plants and animals is at the species levels rather than the individual levels. For humans, the impact assessment and protection systems are established to protect individuals.

It is noted that non-human biota are listed in the MRUP Draft Environmental Scoping Document as environmental factors which do not require further assessment in the PER, as they have been judged by EPA as "not significant or can be regulated and managed to meet the EPA's objectives". However, Vimy Resources has undertaken this assessment using the ERICA software tool.

4.2 THE ERICA TOOL

The ERICA Software Tool (where ERICA is short for Environmental Risk from Ionising Contaminants: Assessment and Management) is a widely used method for assessing radiological impacts to plants and animals. The software uses a collection of impact databases and is based on a three tiered approach to assessing the radiological risk to plants and animals (Beresford et al. 2007). Tier one is the simplest assessment level, requiring the minimum input data, and if the results of an assessment meet a predefined screening level, then further assessment is not required. If the screening level is exceeded, then further more detailed tiered assessments occur. Tier two assessment are also undertaken if further data is available. The idea behind the tiered approach is that assessments are undertaken with an appropriate level of information and effort.

The screening level is the radiation dose rate below which no effects would be observed and the ERICA default level is set at 10 μGy/h.

The input data for an ERICA assessment is media concentration. This 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 other important information in an ERICA assessment is the concentration ratio, which is the ratio of radionuclide concentration in the media (such as soil) to that in the different non-human species. The ERICA software accesses a standard set of databases to determine radionuclide uptake by various species which are based on northern hemisphere species. It is important to note that the ERICA assessment is not based on specific species, rather, it is based on types of species. Recently ARPANSA has released a publication which provides information on concentration ratios for a limited number of Australian species (ARPANSA 2014).

The latest version of the ERICA software was released in November 2014 and the ERICA software package has been endorsed for use in Australian by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA 2010).

4.3 ASSESSMENT

For the proposed MRUP, a tier 2 ERICA assessment was undertaken. This is to take into account the recently published Australia data (ARPANSA 2014), which includes concentration ratios for kangaroos.

An ERICA assessment is usually conducted on a set of reference plants and animals and it is possible to create representative species within the system if necessary. The company reports that no endangered species in the general region, therefore the assessment has been conducted for all reference species in the ERICA database being;

- Amphibians,
- Annelids,
- Arthropod – detritivorous,
- Birds,
- Flying insects,
- Grasses and herbs,
- Lichen and bryophytes,
- Large mammals,
- Mammal - small-burrowing,
- Mollusc – gastropod,
- Reptiles,
- Shrubs,
- Trees,

The ERICA software allows for user defined species based on a geometrical model of the species. A species called kangaroo was added, with the following parameters;

- Kangaroo; mass 50kg, height 1.5m, width 0.75m and depth 0.75m.

Table 10 shows the results of the air quality modelling and provides a measure of the change in radionuclide composition in the soils at the sensitive receptors due to the operations.

4.4 ERICA ASSESSMENT OUTPUTS

The ERICA assessment was conducted using a soil radionuclide concentration of 0.862Bq/kg (for each long lived uranium-238 series radionuclide). This is the location of the highest radionuclide deposition, being at the proposed mining camp area. The output of the assessment can be seen in Table 13 which shows that 10 µGy/h screening level is not exceeded at a Tier 2 level.

Table 13: Output of ERICA Assessment

Organism	**Concentration Ratio source**	**Dose Rate (µGy/h)**
Lichen & bryophytes	ERICA default	0.182
Arthropod - Detritivorous	ERICA default	0.007
Flying insect	ERICA default	0.006
Grasses & herbs	ERICA default	0.035
Mollusc – Gastropod	ERICA default	0.007
Shrub	ERICA default	0.051
Bird	ERICA default	0.005
Amphibian	ERICA default	0.009
Reptile	ERICA default	0.009
Kangaroo	ARPANSA 2014	0.020
Tree	ERICA default	0.004
Mammal (small burrowing)	ERICA default	0.008
Mammal (large)	ERICA default	0.008

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

It can be concluded that the ERICA assessment indicated that there is no radiological risk to reference plants and animals from emissions from the proposed project.

5. ENVIRONMENTAL MONITORING PROGRAM

In addition to the occupational monitoring program, an environmental radiation monitoring program will be developed for operations. The aims of this program are to provide data for the assessment of doses to the public, to measure any radiological impacts on the off-site environment and to ensure that the radiation controls for off-site impacts are effective.

A detailed environmental monitoring plan will be prepared for approval prior to construction commencing and an outline of the elements of such a plan is shown in Table 14.

Table 14: Outline environmental radiation management programme

Environmental Pathway	Measurement Method	Location and Frequency
Direct (external) gamma	Handheld environmental gamma monitor	Annual survey at perimeter of operational area.
Radon Decay Product Concentrations	Real time monitors	Monitors will rotate between off-site locations.
Dispersion of dust containing long-lived, alpha-emitting radionuclides	High volume samplers	Monitors will rotate between approved off-site locations.
Dispersion of dust containing long-lived, alpha-emitting radionuclides	Dust deposition gauges	Sampling at identified locations. Samples composited for one year then radiometrically analysed.
Seepage of contaminated water	Groundwater sampling from monitoring bores	A network of monitoring bores will be sampled quarterly and analysed 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

6. REFERENCES

AAEC 1985	Australian Atomic Energy Commission Research Establishment Lucas Heights Research Laboratories, Options for clean-up of the Maralinga test site, Environmental Science Division, June 1985
ANSTO 1989	Secular Equilibrium in Ores from the PNC Exploration Site – Report to PNC Exploration Pty Ltd, 1989, K. P. Hart, ANSTO, Lucas Heights Research Laboratories.
ARPANSA 2005	Code of Practice and Safety Guide, Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005), RPS 9
ARPANSA 2010	Environmental Protection: Development of an Australian approach for assessing effects of ionising radiation on non-human species. Technical Report Series No. 154.
ARPANSA 2014	A review of existing Australian radionuclide activity concentration data in non-human biota inhabiting uranium mining environments, Technical Report 167, May 2014.
Beresford, et al 2007	Beresford, N, Brown, J, Copplestone, D, Garnier-Laplace, J, Howard, B, Larson, C-M, Oughton, D, Prohl, G & Zinger, I (2007) D-ERICA: An INTEGRATED APPROACH to the assessment and management of environmental risks from ionising radiation, Description of purpose, methodology and application, European Commission.
BHP Billiton 2009	Olympic Dam Expansion Draft Environmental Impact Statement (DEIS) 2009, Supplementary Environmental Impact Statement (SEIS) 2011.
ERA 2014	Ranger 3 Deeps Draft Environmental Impact Statement (accessed from http://www.energyres.com.au/whatwedo/3108_draft_eis.asp November 2014)
GHD 2015a	Vimy Resources Limited, Mulga Rock Uranium Project, Dispersion Modelling, October 2015 Perth.
GHD 2015b	Vimy Resources Limited, Mulga Rock Uranium Project, Tracer Dispersion Modelling, October 2015 Perth.
ICRP 1991	Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Ann. ICRP 21 (1-3), 1991
ICRP 1993	Protection Against Radon-222 at Home and at Work, ICRP Publication 65, Ann. ICRP 23 (2), 1993
ICRP 1995	Age-dependent Doses to the Members of the Public from Intake of radionuclides - Part 5 Compilation of Ingestion and Inhalation Coefficients ICRP Publication 72, Ann. ICRP 26 (1), 1995
ICRP 2014	'Protection of the environment under different exposure situations. ICRP Publication 124', Annals of the ICRP 43 (1): 58.

Kaste et al., 2007	Kaste JM, Heimsath AM & Bostick BC, 'Short-term soil mixing quantified with fallout radionuclides', Geology, 2007, 35, pp. 243–246.
Toro Energy 2011	Environmental Review and Management Programme (ERMP) EPA Assessment No 1819 July 2011, Toro Energy Limits, Wiluna Uranium Project
WISE 2015	www.wise-uranium.org/calc.html

APPENDIX C: ANSTO RADIONUCLIDE DEPORTMENT REPORT

AUSTRALIAN NUCLEAR SCIENCE
AND TECHNOLOGY ORGANISATION
LUCAS HEIGHTS SCIENCE AND TECHNOLOGY CENTRE

A REPORT TO VIMY RESOURCES

on

RADIONUCLIDE DEPORTMENT IN MULGA ROCK PROCESS

by

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March 2015

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EXECUTIVE SUMMARY

ANSTO Minerals (AM) was requested by Tony Chamberlain from Vimy Resources (Vimy) to determine the radionuclide deportment in selected stages of the process proposed for treating Mulga Rock uranium ore. This information is required as part of a PER submission planned for March 2015.

AM has conducted a program for Vimy related to tailings characterisation test work. The radionuclide contents of some of these samples were determined for this deportment study. Leach tests were also undertaken as part of the deportment study to produce samples generated under a range of conditions, not covered by the tailings characterisation test work.

The objective of the work program was to determine the radionuclide and elemental concentrations of a range of solids and liquors produced from several ore samples treated by the Mulga Rock process, over a range of conditions.

Three ROM ores (Princess, Ambassador East and Ambassador West) were supplied by the client and assayed for radionuclide and elemental concentrations. The three ores contained a similar uranium concentration (600-650 ppm U), but variable concentrations of other potentially recoverable elements, eg Co, Cu, Ni, and Zn. The Ambassador East sample contained significantly more carbon (total) than the other two ores, at 21%, which was matched by a ~ 10% lower Si content.

Data for MP2 ore, which was used for the tailings characterisation program (ANSTO/C1422), was also included and assessed as part of the radionuclide work program. The MP2 ore had a much higher uranium grade (2070 ppm), and greater carbon content (25%), with a corresponding lower Si content. The concentration of Fe in MP2 was 3-4 times greater than in the other ores.

For all ores, there appeared to be disequilbrium in the ^{238}U decay chain as radium-226 was consistently less than the uranium activity. This was possibly due to leaching of the radium by high-chloride groundwater.

Ambassador East was the ore used to generate samples to determine radionuclide behaviour. A leach PLS was generated using standard leach conditions and a high chloride liquor (9 g Cl/L). A leach using standard leach conditions (as above) and a high chloride liquor (9 g Cl/L) in the presence of Purolite PFA133S resin was also carried out to generate a barren PLS. The barren PLS was batch neutralised with lime/limestone to pH 4.5.

The major conclusions from the testwork program are given below:

- For Ambassador East (AE) ore, the addition of resin increased the uranium extraction from 52.6 to 82.7%. Uranium extraction increased by 1.8% between the 4 and 8 h final sample, suggesting that an extended leach time (eg 12 h) could be beneficial;
- For the higher grade MP2 sample, final uranium extraction was 87.7%. The increase in extraction was a function of the higher head grade as the MP2 leach residue grade was more than twice that for AE;

- In all leaches, the ORP was less than 400 mV, particularly for the AE RIL test, and the ferric ion concentrations were corresponding low. The low ORP/ferric concentration may have impacted uranium leach rate;
- Radionuclide mass balances for the leaching of the AE and MP2 ores showed that uranium was the only radionuclide that leached to any significant extent – AE: 52% in the standard leach and 83% in the RIL leach; MP2: 87.7% in the RIL leach;
- Based on the liquor assays, radium isotopes, polonium-210 and protactinium-231 were not leached (< 0.6%) in the standard AE leach or RIL leaches for both AE and MP2 ores. Conversely, 18% of actinium-227 was leached in the standard AE leach, 15% was leached in the AE RIL leach, while only 8% was leached in the RIL leach for MP2;
- The average leaching of thorium isotopes was 10% in the standard AE leach and slightly lower (~7%) in the RIL leaches for both ores. For a typical uranium ore, extraction of Th-230 would usually be > 30%;
- The behaviour of Pb-210 showed the greatest variation. In the standard AE leach, 14% of lead-210 was leached while in the AE RIL leach, ~9% was leached. In contrast, ~1% was leached in the MP2 RIL leach. The greater extraction of Pb-210 for the AE ore was most likely due to the high chloride concentration, 9 g/L versus 2 g/L for MP2;
- The behaviour of polonium-210 during leaching (dissolution was virtually zero) was not anticipated. Generally, polonium-210 would be expected to leach, at least to some extent, with lead-210. The presence of 21% of carbon in the Ambassador East ore used for the leach testwork may be the reason for this. Despite this, polonium-210 will increase exponentially and reach secular equilibrium with its parent, lead-210 after ~ 2 years;
- Neutralisation of the barren PLS with lime/limestone removed all of the thorium isotopes and ~ 93% of the lead-210, ~55% of uranium, ~ 24% of radium-226 and ~17% of actinium-227 from solution;
- As very little actinium-227 was precipitated in the neutralisation step, the concentration of Ac-227 (36 Bq/L) remaining in the neutralised liquor was the same as Pb-210, and significantly greater than Ra-226 (3.5 Bq/L);
- The concentrations of radionuclides in the neutralised PLS were as would be expected in a uranium ore processing circuit for a final neutralisation pH of 4.5;
- Because of the relatively low "neutralisation" pH, the treated PLS still contained a range of elements. Treatment to pH 4.5 did however remove the bulk of the Cr, Fe^{3+}, P, Pb and V;
- The neutralisation residue residue composition was dominated by gypsum, and compared to leach tailings, the residue contained higher concentrations of the more soluble radionuclides, which are dissolved in leaching and precipitated into the small mass of the residue;

- Overall, the deportment and concentrations of radionuclides in the leaching of the Mulga rock ores, and in the neutralisation of PLS, were very similar to those observed by ANSTO Minerals for other uranium ores.

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TABLE OF CONTENTS

APPENDICES

1. INTRODUCTION

ANSTO Minerals (AM) was requested by Tony Chamberlain from Vimy Resources (Vimy) to determine the radionuclide deportment in selected stages of the process proposed for treating Mulga Rock uranium ore. This information is required as part of a PER submission planned for March 2015.

AM has conducted a program for Vimy related to tailings characterisation test work. The radionuclide contents of some of these samples were determined for this deportment study. Leach tests were also undertaken as part of the deportment study to produce samples generated under a range of conditions, not covered by the tailings characterisation test work.

2. OBJECTIVES

The objective of the work program was:

- To determine the radionuclide and elemental concentrations of a range of solids and liquors produced from several ore samples treated by the Mulga Rock process, over a range of conditions.

3. SCOPE OF WORK

The following tasks were undertaken for the deportment study:

1. Three (3) typical ROM samples (Princess and Ambassador East and West) were analysed for radionuclide and multi-element concentrations;
2. A leach test on Ambassador East ore using standard leach conditions with high chloride water (9 g Cl/L) was carried out to generate fresh PLS. The PLS and leach residue were analysed for radionuclide and multi-element concentrations (the ore was analysed as part of Item 1);
3. A RIL leach test on Ambassador East ore using standard leach conditions with high chloride water (9 g Cl/L) was carried out to generate a barren PLS. The residue and barren PLS were analysed for radionuclide and multi-element concentrations;
4. The barren PLS generated in Item 3 was neutralised with limestone/lime to pH 4.5. The gypsum solid and neutralised effluent were analysed for radionuclide and multi-element concentrations;
5. A sample of site water was analysed for radionuclide and multi-element concentrations;
6. A report presenting all results from the deportment study, and relevant data from the tailings characterisation program was prepared.

4. WORK PLAN

4.1 Radionuclide Analyses

The following techniques were used for analysis of radionuclides in the U-238, U-235 and Th-232 decay chains in solid and liquor samples:

- Delayed neutron activation (DNA) analysis for parent U-238 in solids.
- Solid fusion/acid digest followed by inductively coupled plasma mass spectrometry (ICPMS) for parent Th-232 in solids.
- ICPMS for parent U-238 and parent Th-232 in liquors.
- Alpha spectrometry for Po-210 in solids and liquors.
- Gamma spectrometry for U-238 and Th-232 decay progeny, and U-235 and its decay progeny[1] in solids and liquors. Note that Ac-227 is not a gamma emitter and its concentration is determined from its daughter, Th-227. Secular equilibrium between Ac-227 and Th-227 is established after 3 months. A second gamma count is then carried out to accurately determine Ac-227.
- X-ray fluorescence spectrometry (XRF) analysis for major elemental concentrations in solids. This data is used for self-absorption corrections in gamma spectrometry.

4.2 Multi-element Analyses

Final solids and liquors included in the deportment study, as detailed in **Sections 4.3** and **4.4**, together with those generated in other work programs, were analysed as follows:

Solids were analysed by XRF, DNA, Digest-ICP and LECO for the following elements: Al, Sb, As, Ba, Be, Bi, B, C(tot), Ca, Cd, Cl, Cr, Co, Cu, Fe, P, Pb, Li, Mg, Mn, Na, Hg, Mo, Ni, K, Se, Ag, Si, Sr, S^{2-}, S(tot), Tl, Th, Sn, U, V and Zn;

Liquors were analysed by ICP/OES/MS, ion selective electrode and LECO for the following elements: Al, Sb, As, Ba, Be, Bi, B, C(tot), Ca, Cd, Cl, Cr, Co, Cu, Fe, P, Pb, Li, Mg, Mn, Na, Hg, Mo, Ni, K, Se, Ag, Si, Sr, S(tot), Tl, Th, Sn, U, V and Zn.

4.3 Analysis of ROM Samples

Three (3) typical ROM samples (from Princess and Ambassador deposits) were analysed for radionuclides and multi-element concentrations. The radionuclide results and elemental assays are given in **Tables 1** and **2**, respectively. A sample of site water, used for ASLP leaching testwork, was also analysed for radionuclide and multi-element concentrations (see **Tables 5** and **7**). Also included are data for a Mulga carbonaceous ore, designated as MP2, which was used in sveral previous studies by ANSTO Minerals[2].

The three ores contained a similar uranium concentration (600-650 ppm U), but variable concentrations of other potentially recoverable elements, eg Co, Cu, Ni, and Zn. The Ambassador East sample contained significantly more carbon (total) than the other two ores, at 21%, which was matched by a ~ 10% lower Si content. The MP2 ore had a much higher uranium grade (2070 ppm), and greater carbon content (25%), with a corresponding lower Si content. The concentration of Fe in MP2 was 3-4 times greater than in the other ores.

[1] This includes Pa-231.
[2] See ANSTO Minerals' Reports C1120 and C1442.

For all ores, there appeared to be disequilbrium in the ^{238}U decay chain as radium-226 was consistently less than the uranium activity. This was possibly due to leaching of the radium by high-chloride groundwater. The concentrations of polonium-210 in the ores were consistently lower than the secular equilibrium activity. As the parent, lead-210 has a half life of only 22 years, secular equilibrium would be expected. This result is most likely due to incomplete dissolution of samples, given that the ores contain between 6 and 25% of carbon. Polonium-210 is determined by alpha spectrometry, which is a very sensitive technique, however, because of its volatile nature, high temperature dissolution processes (e.g. fusion) cannot be used. Fusion/acid digestion procedures are required for complete dissolution of the ores in this study.

The ^{235}U and ^{232}Th chains were in secular equilibrium.

Only radium and thorium isotopes were detected in the site water, at 1-2 and 0.13 Bq/L, respectively. The water contained 2.7 g/L chloride, with Na, S, Mg, Ca, Si, K, Sr and B being the only other elements detected. Apart from the introduction of chloride ions, the water would appear very suitable for use in plant process circuits.

TABLE 1
Radionuclide Results – Princess, Ambassador and MP2 Ores (Bq/g)

Sample	Princess	Ambassador East	Ambassador West	MP2 Ore
U-238 Decay Chain				
U-238	7.5 ± 0.2	8.3 ± 0.2	7.8 ± 0.2	25 ± 3
Th-230	7.4 ± 0.7	8.2 ± 0.8	7.8 ± 0.7	27 ± 3
Ra-226	6.4 ± 0.6	6.5 ± 0.7	6.1 ± 0.6	21 ± 2
Pb-210	7.5 ± 0.8	8.0 ± 0.8	7.3 ± 0.7	24 ± 2
Po-210	5.3 ± 0.5	5.8 ± 0.6	5.8 ± 0.6	16 ± 2
U-235 Decay Chain				
U-235	0.35 ± 0.04	0.38 ± 0.04	0.36 ± 0.04	1.2 ± 0.1
Pa-231	0.32 ± 0.03	0.33 ± 0.03	0.33 ± 0.03	1.0 ± 0.1
Ac-227	0.37 ± 0.04	0.40 ± 0.04	0.37 ± 0.04	1.2 ± 0.1
Th-227	0.37 ± 0.04	0.40 ± 0.04	0.37 ± 0.04	1.2 ± 0.1
Th-232 Decay Chain				
Th-232	0.090 ± 0.009	0.11 ± 0.01	0.62 ± 0.06	0.10 ± 0.01
Ra-228	0.092 ± 0.009	0.11 ± 0.01	0.59 ± 0.06	0.14 ± 0.01
Th-228	0.090 ± 0.009	0.11 ± 0.01	0.62 ± 0.06	0.10 ± 0.01
K-40	< 0.042	< 0.056	< 0.070	< 0.10

4.4 Generation of Samples

The following samples were generated by tests undertaken at ANSTO.

4.4.1 Standard Leach, High Cl

A standard leach PLS was generated from Ambassador East ore using standard leach conditions and a high chloride liquor (9 g Cl/L).

TABLE 2
Elemental Results – Princess, Ambassador and MP2 Ores

Element	Technique	Concentration				Units
		Princess	Ambassador East	Ambassador West	MP2 Ore	
Ag	digest/MS	2	< 1	3	2	ppm
Al	XRF	2.60	3.40	4.99	2.98	%
As	XRF	30	10	20	20	ppm
B	digest/OES	10	48	< 10	60	ppm
Ba	XRF	0.017	0.028	0.032	0.040	%
Be	digest/MS	< 1	4	< 1	18	ppm
Bi	digest/MS	< 1	< 1	< 1	< 1	ppm
C(tot)	LECO	6.5	21.0	6.0	25.3	%
Ca	XRF	0.079	0.356	0.048	0.268	%
Cd	digest/MS	22	12	14	47	ppm
Cl	CL1/COL	0.26	0.62	0.21	0.26	%
Co	XRF	0.019	0.027	0.009	0.055	%
Cr	XRF	0.071	0.034	0.192	0.076	%
Cu	XRF	0.113	0.054	0.183	0.124	%
Fe	XRF	0.688	0.478	0.399	1.86	%
Hg	digest/MS	20	8	43	36	ppm
K	XRF	0.051	0.110	0.086	0.053	%
Li	digest/OES	< 10	< 10	< 10	24	ppm
Mg	XRF	0.05	0.22	0.05	0.10	%
Mn	XRF	20	20	20	50	ppm
Mo	XRF	< 10	10	< 10	10	ppm
Na	XRF	0.17	0.49	0.15	0.15	%
Ni	XRF	0.057	0.070	0.018	0.183	%
P	XRF	0.008	0.010	0.010	0.009	%
Pb	XRF	0.037	0.025	0.055	0.089	%
S (tot)	LECO	0.88	1.34	0.23	3.74	%
S^{2-}	LECO	0.77	1.10	0.15	3.55	%
Sb	digest/MS	< 2	< 2	< 2	< 2	ppm
Se	digest/MS	103	48	108	66	ppm
Si	XRF	37.8	27.9	35.4	21.7	%
Sn	XRF	0.006	0.012	0.016	-	%
Sr	XRF	60	50	10	30	ppm
Th	digest/MS	15	16	136	< 10	ppm
Tl	digest/MS	12	28	4	40	ppm
U	DNA	600	656	623	2065	ppm
V	XRF	0.008	0.013	0.005	0.021	%
Zn	XRF	0.194	0.219	0.006	0.188	%

The leach was carried out at 60°C in a temperature controlled baffled tank using 500 g (dry equivalent) of ore at a solids density of 40 wt% and site water (doped with NaCl to give a total chloride concentration of 9 g/L). The leaching time was 8 hours. No resin was added.

Sufficient AR Grade ferric sulphate was added to achieve 2 g/L Fe^{3+} in solution. A sulphuric acid dose of 30 kg/t was added at the start of the leach and the pH was monitored throughout, with acid added to adjust the slurry pH to 1.5 if the pH increased above 1.7. The ORP was monitored and no further oxidant was added.

The rate of leaching was determined by taking 20 mL slurry samples at 1, 2, 4 and 8 hours. The sample slurry was centrifuged and the residues repulped, washed with dilute sulphuric acid solution (adjusted to pH slightly higher than the leach pH at the time of sampling), water washed and finally dried at 80°C. All thief solid samples were analysed for uranium using DNA, and for Al, Ca, Co, Cu, Fe, Mg, Na, Ni, U and Zn using XRF.

Leach slurry filtrates were refiltered through a 0.45 μm filter, immediately diluted 1/10 in 3% nitric acid and analysed for Al, Ca, Co, Cu, Fe, Mg, Na, Ni, U and Zn by ICP-OES. Ferrous ion and free acidity were determined in all leach liquor samples by titration methods.

The final leach slurry was pressure filtered and the filter cake washed three times with one bed volume of synthetic site water adjusted to just above the final leach pH, followed by two stages of washing with site water.

The washed filter cake was dried at 80°C (to avoid oxidation of any sulphides remaining in the ore) and pulverised for assay. The filter cake, together with the primary filtrate, were analysed for radionuclide and elemental concentrations, as specified in **Sections 4.1** and **4.2**.

A leach spreadsheet, which summarises the leach data, elemental results for thief samples and the uranium mass balance, is given in **Appendix A**. The leaching results are summarised in **Table 3**. The radionuclide results and elemental concentrations for the leach residue and primary filtrate are given in **Tables 5**, **6** and **7**. Included in the tables are results for a similar leach (at low Cl concentration), without resin, on the MP2 ore, for which the detailed results are reported in ANSTO/C1422.

4.4.2 RIL Leach, High Cl

A barren PLS was generated from Ambassador East ore using standard leach conditions and high chloride liquor (9 g Cl/L). The leach was carried out at 60°C in a temperature controlled baffled tank using 5 kg (dry equivalent) of ore at a solids density of 40 wt% using site water (composition as per **Tables 5** and **7**). The leaching time was 8 hours. The leach was carried out using 1,000 mL (wsr) sulphated Purolite PFA133S resin added at the start of the test. Sufficient AR Grade ferric sulphate was added to achieve 2 g/L Fe^{3+} in solution. A sulphuric acid dose of 30 kg/t was added at the start of the leach and the pH was monitored throughout, with acid added to adjust the slurry pH to 1.5 if the pH increased above 1.7. The ORP was monitored, however no further oxidant was added.

The rate of leaching was determined by taking 20 mL slurry thief samples at 1, 2, 4 and 8 hours. The resin was separated from the slurry (where applicable), washed and stored wet. The sample slurry was then treated and analysed as described in **Section 4.4.1**.

The final leach slurry was screened to remove the resin and pressure filtered. The filter cake was washed three times with one bed volume of site water (spiked to 9 g/L Cl) adjusted to just above the final leach pH, followed by two stages of washing with the spiked site water.

An approximate 500 g (dry equivalent) representative portion of the filter cake was obtained and dried at 70-80^{o}C. The sample was pulverised for assay.

A sample of the primary filtrate was taken for assay. The remaining primary filtrate was retained for the neutralisation test described in **Section 4.4.3**. The filter cake, together with the primary filtrate, were analysed for radionuclide and elemental concentrations, as specified in **Sections 4.1** and **4.2**.

A leach spreadsheet, which summarises the leach data, elemental results for thief samples and the uranium mass balance, is given in **Appendix B**. The leach results are summarised in **Table 3**. The radionuclide results and elemental concentrations for the leach residue and primary filtrate are given in **Tables 5**, **6** and **7**, radionuclides. Included in the tables are results for a similar leach (at low chloride concentration), with resin, on the MP2 ore, for which the detailed results are reported in ANSTO/C1422.

TABLE 3
Summary of Leach Test Results for Ambassador East and MP2 Ores

Leach	Resin	pH	ORP (mV)	Final Fe^{3+} (mg/L)	Acid Addition (kg/t H_2SO_4)	Final Liquor U (mg/L)	U_3O_8 (ppm)		Uranium Ext'n (%)
							Head*	Tail*	
AE	Nil	1.50-1.67	358-375	~ 0	33.8	264	774	373	52.6
AE RIL	PFA133S	1.50-1.69	319-369	~ 0	37.1	11	774	137	82.7
MP2	Nil	1.53-1.62	380-392	286	44	1070	2440	853	68.3
MP2 RIL	PFA133S	1.60-1.68	366-390	~ 0	29.2	17	2450	296	87.7

The results in **Table 3** show the following:

- For Ambassador East (AE) ore, the addition of resin increased the uranium extraction from 52.6 to 82.7%[3]. As shown in **Appendix B**, uranium extraction increased by 1.8% between the 4 and 8 h final sample, suggesting that an extended leach time (eg 12 h) could be beneficial;
- For the higher grade MP2 sample, final uranium extraction was 87.7%. The increase in extraction was a function of the higher head grade as the MP2 leach residue grade was more than twice that for AE;
- In all leaches, the ORP was less than 400 mV[4], particularly for the AE RIL test, and the ferric ion concentrations were corresponding low. The low ORP/ferric concentration may have impacted the uranium leach rate.

[3] A counter-current RIP circuit may result in a greater extraction as the final leach tails will contact barren resin, ensuring maximum desorption of uranium.
[4] All ORP were measured at the leach temperature versus a Ag/AgCl reference electrode containing 3 M KCl.

The concentrations of the major elements in the final leach liquors are compared in **Table 4**.

TABLE 4
Leach Liquor Compositions (mg/L)

	Al	Ca	Co	Cu	Fe	K	Mg	Ni	Si	Zn
AE	409	800	135	160	1990	171	1310	338	206	1480
AE RIL	412	695	134	101	2270	142	1250	340	201	1300
MP2	713	862	346	600	3840	175	1230	958	147	1640
MP2 RIL	665	836	464	371	2828	167	961	875	149	1310

There are no major differences in the liquor compositions**,** with the following worth noting**:**

- Both ores yielded low concentrations of silica in solution;
- The concentrations of iron in solution were considerably less for the AE ore (2 g/L was added at the start);
- The higher grade MP2 ore also yielded higher concentrations of Co, Ni and Cu in solution. Zn concentrations were similar for both ores.

TABLE 5
Radionuclide Results – Leaching of Ambassador East (AE) and MP2 Ores
(solids - Bq/g, liquors - Bq/L)

		Standard Leach; High Chloride		Resin** in Leach; High Chloride		MP2 Ore; Resin** in Leach		
Sample	AE Ore	Leach Residue	Primary Filtrate	Leach Residue	Primary Filtrate	Leach Residue	Primary Filtrate	Site Water
U-238 Decay Chain								
U-238	8.3 ± 0.2	4.03 ± 0.02	3400 ± 340	1.48 ± 0.01	136 ± 14	3.10 ± 0.03	282 ± 56	< 12
Th-230	8.2 ± 0.8	7 ± 0.7	580 ± 58	8.2 ± 0.8	470 ± 47	22 ± 2	1500 ± 150	< 2.1
Ra-226	6.5 ± 0.7	8 ± 0.8	8.2 ± 0.8	7.7 ± 0.8	3.1 ± 0.3	23 ± 2	3.0 ± 0.3	1.3 ± 0.1
Pb-210	8.0 ± 0.8	7.5 ± 0.7	790 ± 79	7.6 ± 0.8	470 ± 47	24 ± 2	140 ± 14	< 0.91
Po-210	5.8 ± 0.6	6.4 ± 0.06*	0.0*	6.3 ± 0.06*	0.0*	13 ± 1*	0.0*	< 0.010
U-235 Decay Chain								
U-235	0.38 ± 0.04	0.22 ± 0.02	140 ± 14	0.09 ± 0.02	7.7 ± 0.8	0.143 ± 0.001	13 ± 3	< 0.11
Pa-231	0.33 ± 0.03	0.27 ± 0.03	< 1.6	0.41 ± 0.04	< 1.2	1.1 ± 0.1	< 3.9	< 0.66
Ac-227	0.40 ± 0.04	0.32 ± 0.03	50 ± 5	0.33 ± 0.03	42 ± 4	1.1 ± 0.1	67 ± 7	< 0.12
Th-227	0.40 ± 0.04	0.32 ± 0.03	50 ± 5	0.33 ± 0.03	42 ± 4	1.1 ± 0.1	67 ± 7	< 0.12
Th-232 Decay Chain								
Th-232	0.11 ± 0.01	0.10 ± 0.01	6.4 ± 0.6	0.11 ± 0.01	4.7 ± 0.5	0.093 ± 0.009	5.2 ± 0.5	0.13 ± 0.03
Ra-228	0.11 ± 0.01	0.13 ± 0.01	< 0.17	0.14 ± 0.01	< 0.13	< 0.040	< 0.37	2.2 ± 0.2
Th-228	0.11 ± 0.01	0.10 ± 0.01	6.4 ± 0.6	0.11 ± 0.01	4.7 ± 0.5	0.093 ± 0.009	5.2 ± 0.5	0.13 ± 0.03
K-40	< 0.056	< 0.081	6 ± 1	< 0.021	5 ± 1	< 0.11	< 2.9	< 0.93
Total Contained Activity^	108	97	16596	87	2409	244	3530	13

** PFA 133 resin used in leaches.

* Po-210 concentration on the leach date.

^ Less than values assume zero concentration for those particular radionuclides in the solids and liquors.

TABLE 6
Elemental Results – Leaching of Ambassador East and MP2 Ores – Solids Assays

Element	Technique	Concentration				Units
		Ambassador East Ore	Standard Leach Residue	Resin* in Leach Residue	MP2 Bulk RIL* 2 Leach Residue	
Ag	digest/MS	< 1	< 1	< 1	-	ppm
Al	XRF	3.40	3.89	3.60	3.08	%
As	XRF	10	< 10	< 10	50	ppm
B	digest/OES	48	11	11	-	ppm
Ba	XRF	0.028	0.036	0.032	0.042	%
Be	digest/MS	4	1	< 1	-	ppm
Bi	digest/MS	< 1	3	< 1	-	ppm
C(tot)	LECO	21.0	16.1	14.7	42	%
Ca	XRF	0.356	0.212	0.093	0.040	%
Cd	digest/MS	12	1	2	-	ppm
Cl	CL1/COL	0.61	0.16	0.15	-	%
Co	XRF	0.027	0.010	0.009	0.020	%
Cr	XRF	0.034	0.026	0.033	0.061	%
Cu	XRF	0.054	0.070	0.063	0.222	%
Fe	XRF	0.478	0.429	0.444	2.01	%
Hg	digest/MS	8	8	8	-	ppm
K	XRF	0.110	0.106	0.100	0.044	%
Li	digest/OES	< 10	< 10	< 10	< 10	ppm
Mg	XRF	0.22	0.02	0.03	< 0.01	%
Mn	XRF	20	20	20	20	ppm
Mo	XRF	10	< 10	< 10	30	ppm
Na	XRF	0.49	0.10	0.10	-	%
Ni	XRF	0.070	0.032	0.029	0.001	%
P	XRF	0.010	0.011	0.010	-	%
Pb	XRF	0.025	0.020	0.019	0.002	%
S (tot)	LECO	1.34	2.27	2.04	2.7	%
S^{2-}	LECO	1.10	1.97	1.84	2.5	%
Sb	digest/MS	< 2	< 2	< 2	-	ppm
Se	digest/MS	48	42	39	< 10	ppm
Si	XRF	27.9	26.8	28.5	21.4	%
Sn	XRF	0.012	0.002	0.001	< 0.001	%
Sr	XRF	50	80	80	40	ppm
Th	digest/MS	16	18	17	< 10	ppm
Tl	digest/MS	28	16	12	< 10	ppm
U	DNA	656	327	119	251	ppm
V	XRF	0.013	0.009	0.010	0.013	%
Zn	XRF	0.219	0.056	0.063	0.071	%

* PFA 133 resin used in leaches

TABLE 7
Elemental Results – Leaching of Ambassador East and MP2 Ores – Liquor Assays (mg/L)

Element	Technique	Concentration			
		Standard Leach	Resin* in Leach	MP2 Bulk RIL* 2	Site Water
Ag	ICPMS	< 1	< 1	-	< 1
Al	ICPOES	409	412	538	< 1
As	ICPMS	< 10	< 10	5	< 10
B	ICPOES	13	12	-	2
Ba	ICPMS	< 2	< 2	-	< 2
Be	ICPMS	2	2	-	< 1
Bi	ICPMS	< 1	< 1	-	< 1
Ca	ICPOES	800	695	738	118
Cd	ICPMS	7	2	-	< 1
Cl	ISE	11600	5780	-	2730
Co	ICPMS	135	134	330	< 1
Cr	ICPMS	3	5	7	< 1
Cu	ICPMS	160	101	412	< 1
Fe	ICPOES	1992	2273	2865	< 1
Hg	ICPMS	< 1	< 1	-	< 1
K	ICPOES	171	142	107	79
Li	ICPOES	< 1	< 1	-	< 1
Mg	ICPOES	1313	1246	827	207
Mn	ICPMS	10	11	12	< 1
Mo	ICPMS	< 1	< 1	-	< 1
Na	ICPOES	5569	5478	1796	1513
Ni	ICPMS	338	340	919	< 2
P	ICPOES	1	2	-	< 1
Pb	ICPMS	23	15	-	< 1
S	ICPOES	8537	9365	9602	299
Sb	ICPMS	< 2	< 2	-	< 2
Se	ICPMS	< 10	< 10	-	< 10
Si	ICPOES	206	201	121	27
Sn	ICPMS	< 1	< 1	-	< 1
Sr	ICPMS	7	7	-	2
Th	ICPMS	1	< 1	< 1	< 1
Tl	ICPMS	9	8	-	< 1
U	ICPMS	274	11	18	< 1
V	ICPMS	23	21	33	< 1
Zn	ICPMS	1476	1296	1490	< 2

* PFA 133 resin used in leaches

4.4.3 Neutralisation of Barren PLS

The bulk barren PLS (4.35 L) produced in **Section 4.4.2** was batch neutralised with lime/limestone[5] to pH 4.5. The neutralisation was carried out at 40 ºC over a period of 2 h with air sparging. The reagent addition was measured and 10 mL thief slurry samples were taken[6] at pH 3.8 and pH 4.5 for liquor assay only (Al, Ca, Co, Cu, Fe, Mg, Ni, Th, U, Zn). The pH and ORP were measured as a function of reagent addition. Limestone was added over the first 45 minutes to achieve pH ~ 4.0, followed by lime to achieve the target pH, both as solid reagents. Neutralisation data is shown in **Appendix C**.

Figure 1 shows a plot of reagent addition versus pH. Reagent additions[7] were 8.6 g limestone/L of PLS to achieve pH 4 and 2.05 g lime/L of PLS in the second stage to achieve pH 4.5. Solids generation was 23.2 g/L of PLS. The plot in **Figure 1** shows that the efficiency of limestone addition decreased above about pH 4, and it is suggested that first stage final pH should be reviewed, considering limestone and lime costs.

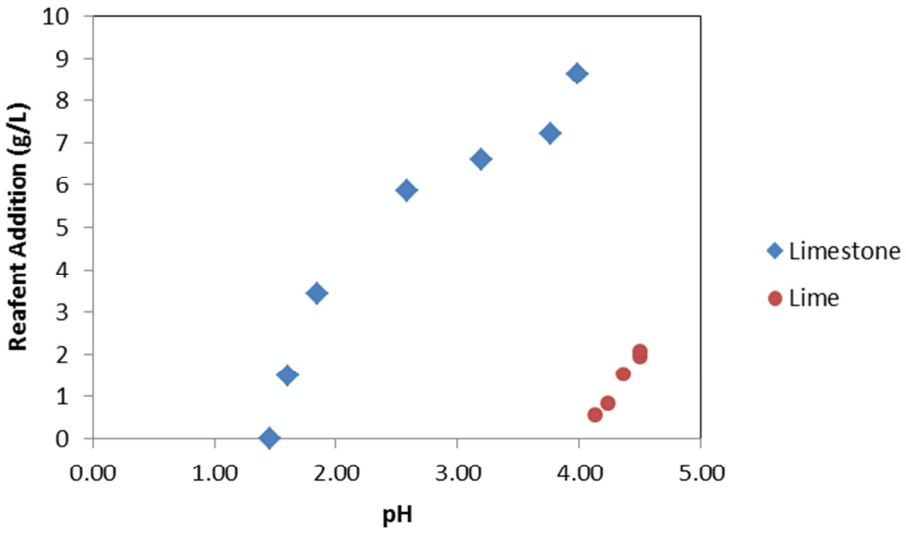

FIGURE 1 pH versus Reagent Addition

On completion of the test, the final slurry was centrifuged in batches to minimise solid losses. The solids were subsequently washed with gypsum saturated water at pH 4.5 and dried at 55 ºC. The dried solids and a stabilised sample of primary filtrate were analysed for radionuclide and elemental concentrations, as specified in **Sections 4.1** and **4.2**. The results are given in **Tables 8** and **9**, respectively.

Under the ARPANSA National Directory[8], a material is deemed to be radioactive if the concentration of any radionuclide in the Th-232, U-238 and U-235 decay chains exceeds 1 Bq/g. The neutralised solid is therefore considered to be radioactive with respect to this

[5] Commercial grade reagents were used.
[6] Sample treatment was as described in **Section 4.4.1**, except that any solids were returned to the test.
[7] Expressed as dry solids
[8] RPS No. 6 – National Directory for Radiation Protection (NDRP) July 2011 (www.arpansa.gov.au).

definition because of the concentrations of thorium-230 (23 Bq/g), lead-210 (20 Bq/g) and uranium-238 (3 Bq/g).

The final neutralised liquor contained the radionuclides uranium-238, uranium-235, radium-226, lead-210 and actinium-227 at concentrations which would be expected in a uranium ore processing circuit at the final neutralisation pH of 4.5. Thorium isotopes have been completely precipitated in the neutralisation (note that the measured activity of thorium-227 is due to ingrowth in the acidified sample from its parent, actinium-227). The Primary Filtrate and Barren PLS results show that very little actinium-227 was precipitated in the neutralisation step, with the result that the concentration of Ac-227 remaining in the neutralised liquor is the same as Pb-210, and significantly greater than Ra-226.

Because of the relatively low "neutralisation" pH, the treated PLS still contained a range of elements. Treatment to pH 4.5 did however remove the bulk of the Cr, Fe^{3+}, P, Pb and V, and about 50% of the uranium. The sparging conditions were not effective in oxidising all the ferrous to ferric ion.

The major components of the final precipitate were Ca (21.3%), S (14.5%), Fe (4.5%) and Al (1.9%). The residue contained 274 ppm U.

TABLE 8
Radionuclide Results – Neutralisation of Ambassador East PLS
(solid - Bq/g, liquors - Bq/L)

Sample	Primary Filtrate	Barren PLS	Neutralisation Solid
U-238 Decay Chain			
U-238	136 ± 14	61 ± 6	3.05 ± 0.02
Th-230	470 ± 47	< 2.0	23 ± 2
Ra-226	3.1 ± 0.3	3.5 ± 0.4	0.032 ± 0.004
Pb-210	470 ± 47	36 ± 4	20 ± 2
Po-210	0.0*	0.0*	0.0*
U-235 Decay Chain			
U-235	7.7 ± 0.8	3.7 ± 0.4	0.21 ± 0.02
Pa-231	< 1.2	< 0.079	< 0.070
Ac-227	42 ± 4	36 ± 4	0.13 ± 0.01
Th-227	42 ± 4	36 ± 4	0.13 ± 0.01
Th-232 Decay Chain			
Th-232	4.7 ± 0.5	< 0.10	0.21 ± 0.02
Ra-228	< 0.13	< 0.10	< 0.012
Th-228	4.7 ± 0.5	< 0.10	0.21 ± 0.02
K-40	5 ± 1	< 1.3	0.10 ± 0.02
Total Contained Activity^	2409	668	79

* Po-210 concentration on the leach date.

^ Less than values assume zero concentration for those particular radionuclides in the solids and liquors.

TABLE 9
Elemental Results – Neutralisation of Ambassador East PLS
(solid – as indicated in table, liquors - mg/L)

Element	Technique (liquors)	Concentration			Units (solid)	Technique (solid)
		Resin in Leach PLS	Barren PLS after Neutralisation	Neutralised Solid		
Ag	ICPMS	< 1	< 1	< 1	ppm	digest/MS
Al	ICPOES	412	16	1.88	%	XRF
As	ICPMS	< 10	< 10	0.005	%	XRF
B	ICPOES	12	12	34	ppm	digest/OES
Ba	ICPMS	< 2	< 2	0.015	%	XRF
Be	ICPMS	2	< 1	44	ppm	digest/MS
Bi	ICPMS	< 1	< 1	2	ppm	digest/MS
C (tot)	-	-	-	0.22	%	LECO
Ca	ICPOES	695	784	21.3	%	XRF
Cd	ICPMS	2	2	1	ppm	digest/MS
Cl	ISE	5780	6680	0.18	%	CL1/COL
Co	ICPMS	134	150	0.014	%	XRF
Cr	ICPMS	5	< 1	0.025	%	XRF
Cu	ICPMS	101	72	0.147	%	XRF
Fe	ICPOES	2273	1141	4.515	%	XRF
Hg	ICPMS	< 1	< 1	< 1	ppm	digest/MS
K	ICPOES	142	148	0.022	%	XRF
Li	ICPOES	< 1	< 1	< 10	ppm	digest/OES
Mg	ICPOES	1246	1358	0.12	%	XRF
Mn	ICPMS	11	15	< 0.001	%	XRF
Mo	ICPMS	< 1	< 1	0.095	%	XRF
Na	ICPOES	5478	5781	0.08	%	XRF
Ni	ICPMS	340	357	0.083	%	XRF
P	ICPOES	2	< 1	0.008	%	XRF
Pb	ICPMS	15	1	0.054	%	XRF
S (tot)	-	-	-	15.50	%	LECO
S^{2-}	-	-	-	0.50	%	LECO
Sb	ICPMS	< 2	< 2	< 2	ppm	digest/MS
Se	ICPMS	< 10	< 10	14	ppm	digest/MS
Si	ICPOES	201	67	0.83	%	XRF
Sn	ICPMS	< 1	< 1	< 0.001	%	XRF
Sr	ICPMS	7	4	0.026	%	XRF
Th	ICPMS	< 1	< 1	48	ppm	digest/MS
Tl	ICPMS	8	7	10	ppm	digest/MS
U	ICPMS	11	5	247	ppm	DNA
V	ICPMS	21	< 1	0.104	%	XRF
Zn	ICPMS	1296	1139	0.265	%	XRF

The compositions (major elemental and radionuclides) of the neutralisation residue and the RIL leach tailings are compared in **Table 10**. The residue composition is dominated by gypsum, and compared to the tailings, the residue contains higher concentrations of the more soluble radionuclides (eg Th-230, Pb-210), which are dissolved in leaching and precipitated into the small mass of the residue.

TABLE 10
Composition of Neutralisation Residue and RIL Leach Tailings (wt% or Bq/g)

Element	Neutralised Solid	RIL Tailings	Radionuclide	Neutralised Solid	RIL Tailings
Al	1.9	3.6	U-238	3.1	1.5
C (tot)	0.22	14.7	Th-230	23	8.2
Ca	21.3	0.093	Ra-226	0.032	7.7
Fe	4.5	0.44	Pb-210	20	7.6
S	15.5	2.0	Po-210	*	6.3
Si	0.83	28.5	U-235	0.21	0.09
Th (ppm)	48	17	Ac-227	0.13	0.33
U (ppm)	247	119	Th-232/228	0.21	0.11

* Po-210 is not leachd but the concentration will increase exponentially over time to be the same as that of Pb-210 after ~ 2 years.

4.4.4 Radionuclide Mass Balance

The radionuclide mass balances for the standard leach, RIL and neutralisation of barren RIL PLS for Ambassador East (AE) ore are given in **Table 11**. The radionuclide mass balance for the RIL leach of MP2 ore is given in **Table 12**. Uranium was the only radionuclide that leached to any significant extent. The solids assays indicated that 52% was leached in the standard leach and that this increased significantly to 83% in the RIL leach. Uranium leaching for the MP2 ore was 87%, which was slightly higher than that for AE ore.

Based on the liquor assays, radium isotopes, polonium-210 and protactinium-231 were not leached (< 0.6%) in the standard AE leach or RIL leaches for both AE and MP2 ores. The average leaching of thorium isotopes was 10% in the standard AE leach and slightly lower (~7%) in the RIL leaches for both ores. Conversely, 18% of actinium-227 was leached in the standard AE leach, 15% was leached in the AE RIL leach while only 8% was leached in the RIL leach for MP2.

The behaviour of Pb-210 showed the greatest variation, based on liquor assays. In the standard AE leach, 14% of lead-210 was leached while in the AE RIL leach, ~9% was leached. In contrast, ~1% was leached in the MP2 RIL leach. The difference in Pb-210 extraction id most likely related to the higher Cl concentration in the AE leach liquors, 9 g/L compared to 2 g/L for MP2. Greater dissolution of Pb-210 has been observed by AM in other studies for leaching of uranium ores containing increased concentrations of chloride.

The behaviour of polonium-210 during leaching was not anticipated. Generally, polonium-210 would be expected to leach, at least to some extent, with lead-210. The presence of 21% of carbon in the Ambassador East ore used for the leach testwork may be the reason for this. There are some industrial processes which use carbon to remove

polonium-210 from solution, for example, in silver electrolyte. Despite this, polonium-210 will increase exponentially and reach secular equilibrium with its parent, lead-210 after ~ 2 years.

Neutralisation of the barren PLS with lime/limestone removed all of the thorium isotopes and ~ 93% of the lead-210, ~55% of uranium, ~ 24% of radium-226 and ~17% of actinium-227 from solution. The polonium-210 concentration in the neutralised solid will increase as described above.

The deportment and concentrations of radionuclides in the leaching of the Mulga rock ores, and in the neutralisation of PLS, were very similar to those observed by ANSTO Minerals for other uranium ores.

TABLE 11
Radionuclide Mass Balance – Leaching and Neutralisation – Ambassador East Ore

	Weight	Volume	Total Bq										
	(g)	(L)	U-238	Th-230	Ra-226	Pb-210	Po-210	U-235	Pa-231	Ac-227	Th-227	Th-232	Ra-228	Th-228
Standard Leach														
Ore (in)	500		4150	4100	3250	4000	2900	190	165	200	200	55	55	55
Leach Residue (out)	492		1983	3444	3936	3690	3149	108	133	157	157	49	64	49
Primary filtrate (out)		0.72	2448	418	6	569	0.0	101	*1*	36	36	5	*0.1*	5
% Leached (solid)			52.2	16.0	-21.1	7.8	-8.6	43.0	19.5	21.3	21.3	10.5	-16.3	10.5
% Leached (liquor)			59.0	10.2	0.18	14.2	0.0	53.1	0.7	18.0	18.0	8.4	0.2	8.4
Accountability (%)			107	94	121	106	109	110	81	97	97	98	117	98
Resin in Leach														
Ore (in)	5000		41500	41000	32500	40000	29000	1900	1650	2000	2000	550	550	550
Leach Residue (out)	4889		7236	40090	37645	37156	30801	440	2004	1613	1613	538	684	538
Primary filtrate (out)		7.3	993	3431	23	3431	0	56	*9*	307	307	34	1	34
% Leached (solid)			82.6	2.2	-15.8	7.1	-6.2		-21.5	19.3	19.3	2.2	-24.4	2.2
% Leached (liquor)				8.4	0.07	8.6	0.0		0.5	15.3	15.3	6.2	0.2	6.2
Accountability (%)				106	116	101	106		122	96	96	104	125	104
Neutralisation														
Leach PLS (in)		4.35	591	2043	13	2043	0.0	33	*5*	182.532	183	20	*1*	20
Neutralised solid (out)	101.3		309	2330	3	2026	0.0	21	*7*	13	13	21	*1*	21
Barren PLS (out)		4.2	256	*8*	15	151	0.0	16	*0.3*	151	151	*0.4*	*0.4*	*0.4*
% Precipitated (solid)			52.3	114.1	24.1	99.2		63.6		7.2	7.2	104.1		104.1
% Precipitated (liquor)			56.7	99.6	-9.1	92.6		53.6		17.2	17.2	97.9		97.9
Accountability (%)			96	114	133	107		110		90	90	106		106

Numbers in italics indicate total Bq calculated from measured concentrations that were less than values.

TABLE 12
Radionuclide Mass Balance – RIL Leaching – MP2 Ore

	Weight	Volume	Total Bq											
	(g)	(L)	U-238	Th-230	Ra-226	Pb-210	Po-210	U-235	Pa-231	Ac-227	Th-227	Th-232	Ra-228	Th-228
Ore (in)	9928		248200	268056	208488	238272	158848	11913.6	9928	11913.6	11913.6	992.8	1389.92	992.8
Leach Residue (out)	10067		31208	221474	231541	241608	130871	1440	11074	11074	11074	936	*403*	936
Primary filtrate (out)		14.8	4174	22200	44	2072	0.0	192	*58*	992	992	77	*5.5*	77
% Leached (solid)			87.4	17.4	-11.1	-1.4	17.6		-11.5	7.0	7.0	5.7	71.0	5.7
% Leached (liquor)				8.3	0.02	0.9	0.0		0.6	8.3	8.3	7.8	0.4	7.8
Accountability (%)				91	111	102	82		112	101	101	102	29	102

Numbers in italics indicate total Bq calculated from measured concentrations that were less than values.

APPENDIX A

Standard Leach – Ambassador East

Leach Data, Elemental Concentrations for Thief Samples and Uranium Mass Balance

MULRN-SL	**Mulga Rock Radionuclides Deportment**		**Oxidant:** Initial 2 g/L Ferric	**ICP/OES Request No:**	1500219
Small Leach without Resin	**Solids:** 500 g	Ambassador E Head	**Leach Duration:** 8 h	**ICP/MS Request No:**	1500219, 1500259
P80 150 microns	**Leach Liquor Matrix:** 750 g	Site Water	**Temperature:** 60 °C	**XRF Request No:**	1500259
pH <1.7		No resin added	**ORP:** Monitor	**DNA Request No:**	1500259, 1500268
	Slurry: 40%		**pH:** <1.7	**Date:**	28/01/15
Fe in feed: 2 g/L					

Sample ID	Leach Conditions							Uranium	
								U_3O_8 (ppm)	Ext'n (%)
	Time (h)	Temp. (°C)	pH	ORP (mV)	Acid Addition (kg/t)	Free Acidity (g/L H_2SO_4)	Acid Cons. (kg/t)	DNA	DNA
Head								774	0
MULRN-SL1	1	60	1.67	375	29.6	4.8			
MULRN-SL2	2	60	1.50	371	33.8	6.3		395	
MULRN-SL3	4	60	1.51	356	33.8	7.2		387	
MULRN-SL4	8	60	1.53	358	33.8	5.7	25.1	373	52.6

Final wt. of Bulk Residue (g)	492
Mass Loss	1.5%

Uranium Mass Balance

Uranium In	
U in head liquor (g)	0.000
U in head solid (DNA) (g)	0.328
Total (g)	**0.328**
Uranium out	
U in product liquor (ICPMS) (g)	0.200
U in solid residue (DNA) (g)	0.156
U in loaded resin (g)	
Total (g)	**0.356**
Accountability	108.5%

Sample ID	Al	As	Ba	Ca	Ce	Co	Cr	Cu	Fe	Fe^{3+}	K	La	Li	Mg	Mn	Mo	Na	Nd	Ni	Pb	Pr	S	Sc	Se	Si	Sn	Sr	Ti	Tl	Th	U (MS)	V	Y	Zn	Zr
Site Water	<1	<1		119	<1	<1	<1	<1	<1	0	80	<1		207	<1	<1	1517	<1	<1		<1	300	<1	<1	27					<1	<1	<1	<1	<2	<1
MULRN-SL1	231	3		930	181	131	2	121	1608	238	150	53		1289	10	<1	5488	95	331		24	7330	4	<1	89					<1	219	21	41	1116	<1
MULRN-SL2	280	3		913	194	128	2	136	1868		157	54		1377	10	<1	5852	101	327		26	8417	4	<1	111					1	240	23	43	1182	<1
MULRN-SL3	307	3		835	194	135	2	142	1888	0	158	54		1298	10	<1	5592	103	336		26	8224	5	<1	142					1	265	23	44	1333	<1
MULRN-SL4	391	3		806	127	129	3	153	1962	0	172	40		1337	10	<1	5681	72	329		17	8517	5	<1	196					1	264	23	42	1440	<1

Sample ID	Al	As	Ba	Ca	Ce	Co	Cr	Cu	Fe	Fe^{3+}	K	La	Li	Mg	Mn	Mo	Na	Nd	Ni	Pb	Pr	S	Sc	Se	Si	Sn	Sr	Ti	Tl	Th	U_3O_8	V	Y	Zn	Zr
Ambassador E Head	3.47	0.00	0.029	0.364		0.028	0.035	0.055	0.49		0.112		0.000	0.226	0.002	0.001			0.072	0.026		0.225		0.005	26.5	0.012	0.005	0.697	0.003	0.000	774	0.013		0.074	
MULRN-SL4	3.88	0.00	0.033	0.050		0.009	0.039	0.043	0.46		0.112		0.000	0.043	0.002	0.001			0.023	0.016		0.229		0.004	26.9	0.0	0.000	0.782	0.001	0.002	373	0.008		0.050	

APPENDIX B

Resin in Leach – Ambassador East

Leach Data and Elemental Concentrations for Thief Samples

MULRN-BL	**Mulga Rock Radionuclides Deportment**		**Oxidant:** Initial 2 g/L Ferric	**ICP/OES Request No:**	1500219
Purolite PFA133 Added	**Solids:** 5000 g	Ambassador E head	**Leach Duration:** 8 h	**ICP/MS Request No:**	1500219, 1500259
P80 150 microns	**Leach Liquor Matrix:** 7500 g	Site Water	**Temperature:** 60 ºC	**XRF Request No:**	1500259
pH <1.7		1 L PFA133 resin added	**ORP:** Monitor	**DNA Request No:**	1500259, 1500268
	Slurry: 40%		**pH:** <1.7	**Date:**	28/01/15
Fe in feed: 2 g/L					

Sample ID	Leach Conditions							Uranium	
								U_3O_8 (ppm)	Ext'n (%)
	Time (h)	Temp. (°C)	pH	ORP (mV)	Acid Addition (kg/t)	Free Acidity (g/L H_2SO_4)	Acid Cons. (kg/t)	DNA	DNA
Head								774	0
MULRN-BL1	1	60	1.69	369	30.5	5.4		193	
MULRN-BL2	2	60	1.47	368	37.1	7.1		175	
MULRN-BL3	4	60	1.51	342	37.1	7.5		151	
MULRN-BL4	8	60	1.55	318	37.1	6.8	26.7	137	82.7

Final wt. of Bulk Residue (g)	4889
Mass Loss	2.2%

Uranium Mass Balance

Uranium In	
U in head liquor (g)	0.000
U in head solid (DNA) (g)	3.3
Total (g)	**3.3**
Uranium out	
U in product liquor (ICPMS) (g)	0.08
U in solid residue (DNA) (g)	0.6
U in loaded resin (g)	?
Total (g)	
Accountability	

Sample ID	**Al**	**As**	**Ba**	**Ca**	**Ce**	**Co**	**Cr**	**Cu**	**Fe**	**Fe^{3+}**	**K**	**La**	**Li**	**Mg**	**Mn**	**Mo**	**Na**	**Nd**	**Ni**	**Pb**	**Pr**	**S**	**Sc**	**Se**	**Si**	**Sn**	**Sr**	**Ti**	**Tl**	**Th**	**U (MS)**	**V**	**Y**	**Zn**	**Zr**
Site Water	<1	<1		119	<1	<1	<1	<1	<1	0	80	<1		207	<1	<1	1517	<1	<1		<1	300	<1	<1	27					<1	<1	<1	<1	<2	<1
MULRN-BL1	214	3		835	177	129	2	106	1541	351	140	51		1275	10	<1	5683	94	326		24	7979	3	<1	77					<1	15	19	39	974	<1
MULRN-BL2	245	3		789	180	122	2	120	1745		137	49		1237	9	<1	5468	94	315		24	8889	4	<1	93					1	15	22	38	992	<1
MULRN-BL3	292	3		791	191	130	2	110	2001	0	143	53		1248	10	<1	5523	101	331		25	9039	4	<1	129					1	13	20	41	1118	<1
MULRN-BL4	351	3		733	148	128	3	88	2176	0	142	45		1272	10	<1	5655	81	329		20	9002	4	<1	180					<1	11	19	40	1184	<1

Sample ID	**Al**	**As**	**Ba**	**Ca**	**Ce**	**Co**	**Cr**	**Cu**	**Fe**	**Fe^{3+}**	**K**	**La**	**Li**	**Mg**	**Mn**	**Mo**	**Na**	**Nd**	**Ni**	**Pb**	**Pr**	**S**	**Sc**	**Se**	**Si**	**Sn**	**Sr**	**Ti**	**Tl**	**Th**	**U_3O_8**	**V**	**Y**	**Zn**	**Zr**
Ambassador E Head	3.47	0.001	0.029	0.364		0.028	0.035	0.055	0.488		0.112			0.226	0.002	0.001			0.072	0.026		0.225		0.005	28.5	0.012	0.005	0.697	0.003	0.000	774	0.013		0.074	
MULRN-BL4	3.51	-0.002	0.032	0.040		0.009	0.057	0.047	0.543		0.099			0.037	0.003	-0.001			0.023	0.019		0.249		0.003	29.1	0.002	0.000	0.728	0.001	0.001	137	0.010		0.061	

APPENDIX C

Neutralisation Data – Ambassador East PLS

Neutralisation of MULRN Bulk RIP Leach

Barren Liquor (MULRN-BL-PF)= 4476 g

40°C, Air sparging throughout duration of test

Dry, powdered Limestone and Lime used for test

Time (min)	°C	pH	ORP	Reagent (g)	cumulative	
0	40.0	1.46	398	Limestone	236.3	start wt.
3	40.1	1.60	396	6.4	229.9	
7	40.2	1.85	392	15.0	221.4	
30	39.7	2.58	383	25.5	210.9	
40	40.4	3.20	341	28.7	207.6	
50	40.2	3.76	251	31.3	205.0	Sample taken. 10mL, 10.42g (MULRN-N1)
70	40.2	3.99	224	37.5	198.9	
				Lime addition	167.7	start wt.
80	40.1	4.13	211	2.3	165.4	
95	40.2	4.24	206	3.6	164.2	
110	40.2	4.37	182	6.5	161.2	
120	40.2	4.50	163	8.4	159.3	
125	40.2	4.50	161	8.9	158.8	Sample taken. 10mL, 10.56g (MULRN-N2)

Filtered at end of test through Filtech 165 (fast) paper

Fines were visible in PF so filtered through a 0.45µm membrane and added solids to bulk residue

PF = 4110 g

Washed solids on filter 4 x 1L gypsum saturated pH 4.5 liquor.

Residue	T	Wet	Dry
	1605.04	1769.7	1706.3

Solids = 101.3 g

% Moisture = 38.5