



Rum Jungle Radiological Hazard Assessment Report

Department of Primary Industry and
Resources



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EXECUTIVE SUMMARY

EcOz was engaged by the Northern Territory Department of Primary Industry and Resources (DPIR) to determine the radiological hazards at the Rum Jungle mine site and the associated satellite sites of Mt Burton and Mt Fitch. This assessment was necessary to determine the current condition of the land and water resources within the mine site, to inform the excavation plan for remedial works, and to estimate the Stage 3 rehabilitation worker dose rates and potential future land use rates. The information provided in this report will directly feed into the Environmental Impact Statement that is being undertaken by DPIR for the Rehabilitation of the former Rum Jungle mine site.

The definitions of the two types of radiation scenarios – *practice* and *intervention* – are discussed. The distinction between these is important, as each had its own guidelines for radiation dose limits. Using the ICRP System of Radiological Protection, the Rum Jungle mine site can be regarded as an existing exposure situation and thus, it is recommended that further remedial actions are classified as *intervention* and the corresponding guidelines should be applied. These guidelines maintain that calculated annual doses to be constrained to the range of 1 to 20 mSv per year. While 1 to 20 mSv/a may be a published intervention range, reasonable caution should be exercised in adopting the upper end of this range without suitable justification because the principle of *as low as reasonably achievable* (ALARA) must also be considered. ARPANSA (*Guide for Radiation Protection in Existing Exposure Situations - Radiation Protection Series G-2*) recommends a 10 mSv per year reference level as a suitable starting point in an 'Australian context'. This 10 mSv per year guideline would also be a suitable limit for any future work and could inform the post rehabilitation land use plan and is therefore recommended as the clearance criteria level.

A radiological risk identification process for identifying and recording potential project risks has been undertaken for this project. The identified risks in this report have been taken from the project's radiation risk register and presented in a summary form. This step is important for the efficient management of radiological risks throughout the project.

In 2010, CSA Global characterised parts of the Rum Jungle mine site to determine the levels of metals. Only the uranium results from these surveys have been reported here as part of this assessment, and where information is available, an estimation of volumes has also been included. The assessment of uranium contamination across the site is somewhat confounded by the natural mineralisation of the area and Naturally Occurring Radioactive Material (NORM). CSA Global identified areas where uranium concentrations were greater than a trigger value set at 100 ppm of uranium as measured by field X-Ray Fluorescence (XRF). Identified areas were not quantified above this concentration. In total, 116.26 hectares and a known volume of 259,316 m³ of material greater than the trigger value of 100 ppm of uranium is present on site. The measurements of uranium were to a depth of 1.3 metres and a measurement of total uranium content has not been calculated due to the 100ppm screening cut off level.

Tropical Water Solutions (2008) assessed the water in the two pit lakes and found a significant decrease in overall radionuclide activity in the surface layer of the Main Pit between 1998 and 2008, with activity currently well below guideline values. Activity in the deep contaminated waters of the Main Pit remains orders of magnitude above the guideline values and correlates to the presence of the known chemocline. The chemocline is currently estimated at 5 m thickness and lies above the backfilled tailings within the Main Pit lake. Data reported in the Tropical Water Solutions report for the Intermediate Open Cut Pit demonstrate that samples obtained from the surface (~0.1 m), 15 metres and 31 metres depth are well below the gross α and K40-corrected β activities referenced in the water quality guidelines. There is no documented historical evidence of mill tailings being discharged to the Intermediate Pit though it is possible that overland flows from the former plant area could have transported sediments to that Pit.

Bollhöfer *et al.* (2007) undertook a gamma radiation survey of the mine site. If the 1 mSv/yr public dose limit is applied, from Table 5 of this report, all the areas are above the monthly maximum limit of 0.083 mSv per month needed to be above the public dose limit. Alternatively, if the existing clearance criteria value of

10 mSv/yr is used, two areas fall above this level, the Acid Dam Area and the Tailings Area, south of the Tailings Dam.

The Hughes and Bollhöfer (2010) investigation of the four Rum Jungle and four Mt Fitch anomalies indicate that six (RJ1, RJ3, RJ4, MFA, MFC and MFD) locations are comprised of thin layers of (approximately 10–30 cm) of sediment containing radioactive process residues, mainly tailings. One anomaly at Mt Fitch (MFB) is a locally-derived mineralised spoil from the Mt Fitch mine and one at Rum Jungle (RJ2) appears to be caused by residual mineralised stockpile material. Lower levels of gamma anomalism are apparent along the course of the East Finnis drainage system downstream of Rum Jungle that appear to be sourced from the site. It was concluded that three of the four main gamma anomalies in the immediate mine site area were caused by small volumes of tailings residues that were not completely removed in earlier remediation work, and the fourth by residual mineralised bogum adjacent to the old ore stockpile area, the volume of which is more substantial than the tailings residues. Three of the downstream anomalies in the Mt Fitch area have similar geochemical and radiological signatures to the Rum Jungle anomalies leading to the conclusion that they were also sourced from the Rum Jungle operations. The fourth Mt Fitch anomaly is attributed to local, naturally-occurring mineralisation at the Mt Fitch mine and is not sourced from residues of milling operations at Rum Jungle. Profiling by auger drilling indicates that six tailings-related anomalies have sources with depth extents that are typically between 0.1 and 0.5 metres.

In 2012, a geochemical characterisation was conducted by SRK (2012) on Main, Intermediate and Dysons Overburden Heaps and Dyson's Pit which was backfilled with tailings, contaminated soils and copper extraction residues. The study revealed that the readily soluble solutes such as uranium were released at significant concentrations from Dysons Heap and Dysons Pit. The study suggested that for some elements, such as the uranium in the waste rock, and the radium and its progeny in the tailings, the long-term metalliferous drainage potential could be guided by an assessment of future rates of oxidation and consideration of the total mass of element present within the solid materials.

It was found by Hydrobiology (2016) that the analysis of radionuclides in fish, mussel and plant tissues displayed none of the patterns of radionuclide activity concentrations that were consistent with a substantial source from the Rum Jungle mine area. There was no indication of elevated bioaccumulation in specimens in the Finnis River downstream of the East Branch, and also no indication of increased bioaccumulation downstream of the abandoned Mount Burton mine. There was an indication of naturally higher bioavailability of ^{210}Po and ^{228}Ra in the East Branch catchment upstream of the mine. As mussels were not present in the East Branch from the mine area downstream, it was not possible to examine any further influence on bioavailability of radionuclides from the Rum Jungle mine area on mussels. The absence of large specimens of fish at most East Branch sites amenable to radionuclide analysis resulted in only one specimen from the East Branch downstream of the site being analysed.

The lack of research information on ingestion pathway factors contributes to a knowledge gap regarding potential exposure pathways for people using the Rum Jungle site for traditional purposes. Currently the site is NT Crown Land and access to site is restricted. There is no known access to site for traditional purposes and no site occupation either temporary or permanent. This ingestion pathway information is an important component of any dose assessment for people who may use the site in future, whether it be for traditional ceremonies or customary harvesting practices. Access will remain restricted until restoration works are complete and a radiological dose assessment is undertaken.

The information presented in this report indicates that there are other gaps within the data, some of which are of material importance to understanding Stage 3 worker safety or long term exposure scenarios, and some of which are less critical. Recommendations for further work are detailed.

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1 INTRODUCTION

1.1 Mining history

The Rum Jungle deposit is approximately 75 km south-west of Darwin in the Northern Territory and was mined for copper and uranium. During operation the mine had three open pits and several mineral processing facilities on site. Approximately 20,000 tonnes of copper and 3,500 tonnes of uranium were produced between 1954 and 1971. Mt Burton was also mined for uranium and copper in 1958. The ore body at Mt Fitch was exposed during exploratory investigations between 1968 and 1969 but was not mined due to its low grade.

As a consequence, some of the material present at these sites is the by-product of uranium mining. Uranium is the 'parent isotope' of a series of radioactive isotopes that emit alpha, beta, and gamma radiation. As such, its presence represents a radiological hazard during rehabilitation works.

Operations at Rum Jungle severely impacted the environment on-site, and downstream of the mine along the East Branch of the Finniss River, and the Finniss River itself. The environmental impact off-site primarily affected surface and subsurface water and arose from acid mine drainage, which liberated heavy metals from waste rock dumps and released them into the environment.

The site was effectively abandoned after mining ceased, with no significant efforts to rehabilitate the disturbed areas. Community concerns about the downstream environmental impacts of the site grew through the 1970s, and ultimately a rehabilitation program for Rum Jungle was instigated and delivered by the Commonwealth and Northern Territory Governments in the 1980s.

1.2 Rehabilitation

The rehabilitation program was conducted between 1982 and 1986, and the works were initially conceived to have an effective life of at least 100 years. One of the objectives was a reduction in public health hazards, in particular, the reduction of radiation levels (NT Department of Mines and Energy, 1986).

To achieve this, a three-layer cover system was constructed for the overburden heaps (Main, Intermediate and Dysons). The tailings were placed in the bottom of Dyson's open cut and covered with copper heap leach material, contaminated soil and other material, before placement of a final clean cover layer. Water in the Whites (Main) and Intermediate open cuts was treated to establish a layer of clean water overlying a denser layer of contaminated untreated water in order to isolate that water from the environment (Kraatz 2004).

Recent assessments have indicated that the rehabilitation works – in particular the covers over the waste dumps – have deteriorated (increasing infiltration and oxygen penetration) and the flux of metals may have the potential to increase in future.

1.3 Purpose and scope

In this study, the term 'radioactive waste' as determined by the IAEA definition in the International Atomic Energy Agency Waste Management Glossary (2003) is '*waste that contains or is contaminated with radionuclides at concentrations or activities greater than clearance levels as established by the regulatory body*'.

This study aims to assess the radiation hazards arising from radioactive waste at the Rum Jungle Mine site and to assess both current (Stage 3) rehabilitation and future land use radiological hazards. To this end, a review on the available radiological hazard information for the project was conducted. Based

primarily on the studies reviewed in this report, a series of potential radiological hazards have been further identified and characterised.

The information provided in this report will directly feed into the Environmental Impact Statement that is being undertaken by DPIR for Stage 3 of the rehabilitation of the former Rum Jungle mine site, and will form an appendix of that report. The focus of the report will be on addressing in detail the information requirements relating to radiation hazards that are applicable in an occupational setting, to members of the public, and to Traditional Owners and their future land use plans. The EIS Terms of Reference stipulate that the EIS should identify and assess radiation hazards presented by the Project, including:

- Details of radiation dose potential from Project elements to construction workers, the public and the environment including consideration of exposure due to all pathways:
 - radon and its decay products
 - radioactive particles in dust
 - alpha and gamma radiation.
- Assessment of potential radiation dose delivered via the consumption of local commonly-utilised bush foods if customary harvesting becomes part of future land use plans.
- Potential for radioactive elements to concentrate and partition in waste rock disposal facilities and waste rock disposal facility seepage/discharges.

The hazard assessment will be undertaken in accordance with Australian Radiation Protection and Nuclear Safety Agency (ARPANSA 2004, 2005 and 2019) codes, standards and guidelines.

1.4 Practice versus Intervention

There are two types of radiation exposure scenarios – *practices* and *interventions*. These are defined in detail by the International Commission for Radiological Protection (ICRP 60) (1991), paragraphs 106 and 130, and in ICRP 103, paragraphs 176 to 181. Put simply, a *practice* is an intentional activity in which the practitioner is routinely at risk of exposure – e.g. workers who are exposed to radiation during the course of their duties. An *intervention* is an action that one takes to reduce a radiation exposure (often to other individuals or groups) from specific radiation sources. It is an important distinction to make, as each scenario type has its own dose guideline levels.

In a previous assessment of the former Rum Jungle mine, the Commonwealth Office of the Supervising Scientist (2002) indicated that any further remedial actions would constitute a *practice* because the site has never been officially handed back to the Traditional Owners by a supervising authority and there has always been institutional control of access to the site since mining ceased. However, one of the purposes for rehabilitating Rum Jungle is to reduce public health hazards, including from radiation exposure. Therefore, it is more appropriate to consider the rehabilitation action as an *intervention*. The sources of exposure and exposure pathways are already present due to earlier practices that precede regulatory control; it is an existing exposure situation.

For these existing exposure situations, it is recommended that doses be optimised below a dose constraint. In ICRP 103 (2007), paragraph 240, it is recommended that '*existing exposure situations are exposure situations that already exist when a decision on control has to be taken*' and thus calculated annual doses can be compared to the dose constraint of 1 to 20 mSv per year.

Using the ICRP System of Radiological Protection, the former Rum Jungle mine can be regarded as an existing exposure situation and thus, it is recommended that further remedial actions are classified as *intervention* and the corresponding guidelines should be applied. These guidelines maintain that calculated annual doses to be constrained to the range of 1 to 20 mSv per year. While 1 to 20 mSv per year may be a published intervention range, reasonable caution should be exercised in adopting the upper end of this range without suitable justification, because the principle of *as low as reasonably achievable* (ALARA) must also be considered. The *Guide for Radiation Protection in Existing Exposure*

Situations - Radiation Protection Series G-2 (ARPANSA, 2017) recommends a 10 mSv per year reference level as a suitable starting point in an 'Australian context'.

It is therefore recommended that a 10 mSv per year reference level be used for this project.

1.5 Units

Radiation activity is measured in an international (SI) unit called a Becquerel (Bq). The Becquerel counts how many particles or photons (in the case of wave radiation) are emitted per second by a source.

Radiation exposure is expressed in several ways to account for the different levels of harm caused by different forms of radiation and the different sensitivity of body tissues.

Radiation exposure is measured in an international (SI) unit called the Gray (Gy). The radiation exposure is equivalent to the energy "deposited" in a kilogram of a substance by the radiation. Exposure is also referred to as absorbed dose.

A quantity called the equivalent dose relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is measured in an international (SI) unit called the Sievert (Sv).

The probability of a harmful effect from radiation exposure depends on what part or parts of the body are exposed. Some organs are more sensitive to radiation than others. A tissue weighting factor is used to take this into account. When an equivalent dose to an organ is multiplied by the tissue weighting factor for that organ the result is the effective dose to that organ. The unit of effective dose is also the Sievert (Sv).

2 POTENTIAL RISKS

There are three types of ionising radiation that are of concern with the uranium material in the project area. Alpha and beta radiation consist of particles, whereas gamma rays consist of waves of electromagnetic energy.

Alpha radiation has a low penetrating power; alpha particles can travel only a few centimetres in air before losing all of their energy. Alpha radiation can easily be stopped by a piece of paper, plastic or even an outer dead layer of skin on our body. To be a health hazard alpha emitters need to be inside the body in order to irradiate sensitive living cells.

Beta radiation has moderate penetrating power and typically can penetrate up to one metre in air or a few centimetres in water or tissues. The cells most at risk are the skin cells because of its short range. However other cells can be irradiated if the beta emitters enter the body.

Gamma radiation can penetrate centimetres of steel and can easily pass through the human body and are similar to X-rays used in medicine and other diagnostic processes.

There are four principal worker dose exposure pathways that need to be considered in this hazard assessment (see Figure 1):

- **Exposure to external gamma radiation.** Doses from the direct gamma pathway depend on the activity concentration of the material (grade), geometry, shielding, and time spent in the radiation affected area.
- **Inhalation of radon decay products (RDP).** Situations where the inhalation of short-lived RDP in the air include closed work spaces. These are areas where adequate ventilation must be present or engineered, and workplaces monitored, so as to ensure RDP levels are controlled.
- **Inhalation of long-lived alpha (LLA) emitting radionuclides,** i.e., uranium, thorium, radium, polonium, and radioactive lead, in airborne dust. The effectiveness of these dust particles in delivering a radiation dose, depends on the particle size inhaled, and the chemical form of the dust and hence its solubility.
- **Ingestion of radionuclides (water, foodstuffs).** Radioactive contamination can be transferred from hands to mouth when eating, drinking and smoking or through poor personal hygiene. Smaller particles can reach the lungs and cause serious health problems. Larger particles may irritate the nose, throat and eyes. Personal hygiene, including washing of hands before and after eating and drinking is very important. Radiation exposure can also occur through open wounds and all such wounds must be adequately covered.

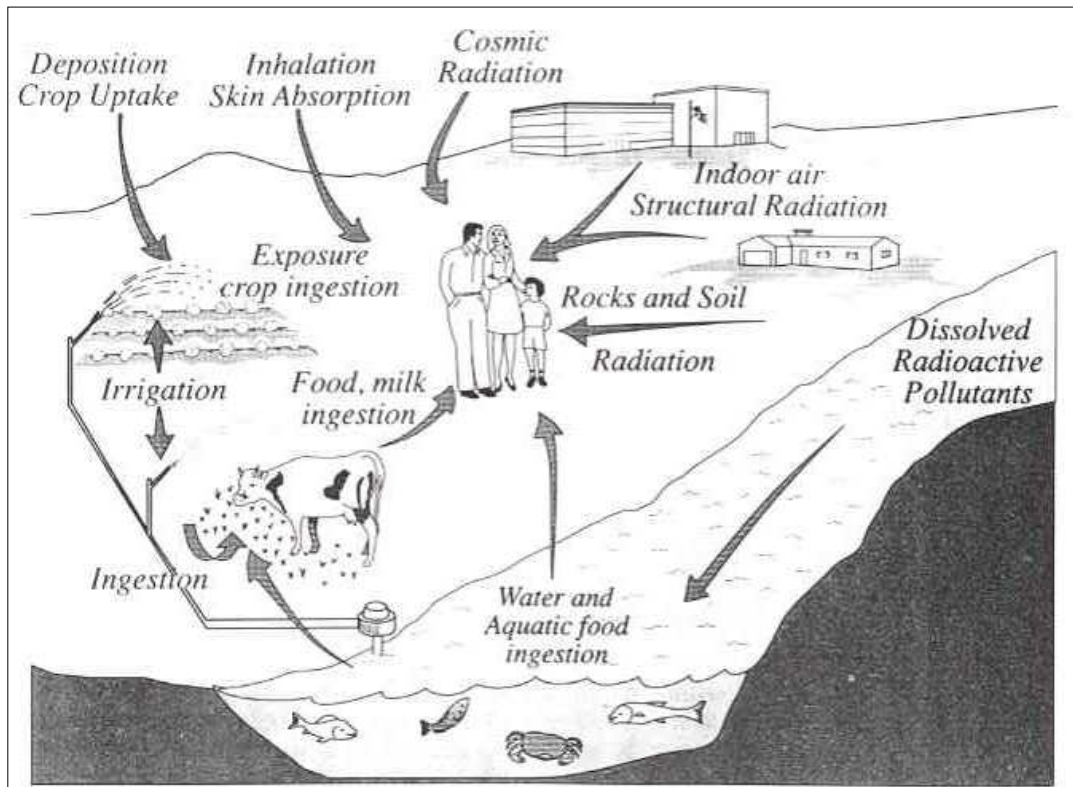


Figure 1. Simplified diagram of the primary pathways leading to dose

Source unknown

The main radionuclides of concern are members of the uranium decay series, as shown in Figure 2.

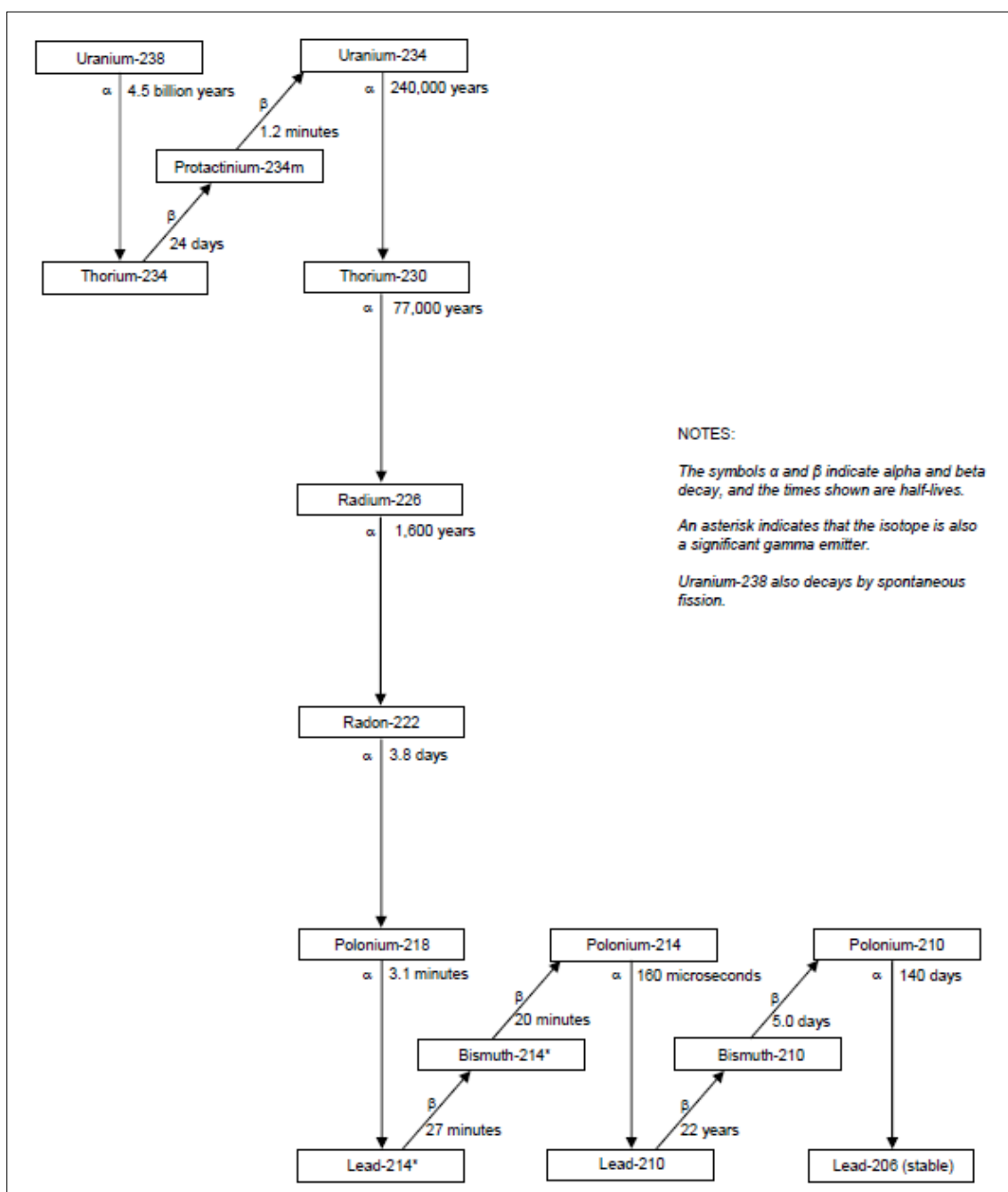


Figure 2. Diagram showing the Uranium 238 decay chain

A radiological risk identification process for identifying and recording potential project risks has been undertaken for the project during the EIS process. The likelihood and consequence categories adopted in the risk register are provided in Table 1 and Table 2, and have been combined to derive an overall risk rating using the matrix in Table 3. The inherent risk register of potential radiation-related impacts is included as Table 4.

Table 1. Likelihood categories

Categories	Likelihood Description
Rare	<ul style="list-style-type: none"> • The event may occur only in exceptional circumstances • This event is not expected to occur except under exceptional circumstances (up to once every 100 projects of this nature) • Less than 1% chance of occurring during the project
Unlikely	<ul style="list-style-type: none"> • The event could occur but is improbable • This event could occur up to once every 10-100 projects of this nature • 1-10% chance of occurring during the project
Possible	<ul style="list-style-type: none"> • The event could occur but not expected • This event could occur up to once every 10 projects of this nature • 11-50% chance of occurring during the project
Likely	<ul style="list-style-type: none"> • The event will probably occur in most circumstances • This event could occur up to once during a project of this nature • 51-90% chance of occurring during the project
Almost certain	<ul style="list-style-type: none"> • The event is expected to occur in most circumstances • This event could occur at least once during a project of this nature • 91-100% chance of occurring during the project

Table 2. Consequence categories

Categories	Consequence Description
Insignificant	<ul style="list-style-type: none"> • Reversible health effects of little concern. • First aid treatment.
Minor	<ul style="list-style-type: none"> • Reversible health effects of concern. • Medical treatment.
Moderate	<ul style="list-style-type: none"> • Severe reversible health effects of concern. • Lost time illness.
Major	<ul style="list-style-type: none"> • Single fatality or irreversible health effects or disabling illness.
Catastrophic	<ul style="list-style-type: none"> • Multiple fatalities or serious disabling illness to multiple people.

Table 3. Risk matrix

		Consequence				
		Minor	Moderate	Serious	Major	Catastrophic
Likelihood	Rare	Low	Low	Low	Medium	Medium
	Unlikely	Low	Low	Medium	Medium	High
	Possible	Low	Medium	Medium	High	High
	Likely	Medium	Medium	High	High	Extreme
	Almost certain	Medium	High	High	Extreme	Extreme

Table 4. Risk register

Potential event	Description of impact	Consequence	Likelihood	Inherent risk rating
Run-off from incomplete/open waste rock dumps or waste storage facilities contains leachable solutes (incl. Acid and Metalliferous Drainage (AMD) and radioactive materials), due to rainfall events during earthworks.	Radioactive contamination of surface water and/or aquatic foods (e.g. fish) causing increased dose to humans.	Serious	Unlikely	Medium
Dispersion of particulates and dust, due to excavation and material handling	Dispersion of dust causing an increase of inhalation and ingestion of radionuclides causing an increase in radiological dose to workers	Catastrophic	Almost Certain	Extreme
	Transport of pollutants beyond the site boundary or to nearby sensitive receptors with impacts to human health. (i.e. dispersion of radionuclides in dust causing health effects to public from radiation exposure)	Catastrophic	Possible	High
Remediation works at sites containing radioactive material	Increased occupational exposure from gamma radiation which may lead to detrimental health effects	Major	Possible	High
	Ingestion or exposure of radioactive materials causing health effects to workers	Major	Possible	High
	Exposure to radon causing health effects to workers onsite	Major	Possible	High
	Exposure to radon causing health effects to members of the public	Moderate	Possible	Medium
Vehicles or equipment contaminated by radioactive material leaving the project area	Health effects to members of the public from exposure to radiation	Moderate	Possible	Medium
Flora and fauna inhabiting areas with high radiation levels	Consumption by Traditional Owners of contaminated or irradiated animals and plants leading to an increase in dose	Catastrophic	Likely	Extreme
Traditional Owners, members of the public and staff spending extended periods in areas with high radiation levels	Increased radiological dose	Major	Possible	High
Disturbance of unidentified areas containing materials that have elevated levels of radionuclides	Increased exposure to radiation increasing the dose to critical groups.	Serious	Likely	High
Onsite radiological hazards not identified, and therefore not remediated	Potential increase in exposure to radiation increasing the dose to site end user groups	Serious	Unlikely	Medium

Potential event	Description of impact	Consequence	Likelihood	Inherent risk rating
Increase concentration of contaminants when plants uptake metals and/or salts, due to roots extending into waste material on top of the Waste Storage Facility (WSF)	Consumption by Traditional Owners of contaminated animals and plants leading to an increased radiological dose that may lead to detrimental health effects	Major	Possible	High
Post-rehabilitation radiation dose target levels not reached	Unacceptable radiological exposure increasing dose to post land use groups	Major	Possible	High
Uncontrolled release, spill or passive discharge of hazardous materials at project site	Dispersion of dust causing an increase of inhalation and ingestion of radionuclides causing an increase in radiological dose	Major	Possible	High
	Radioactive contamination of water and/or aquatic foods (e.g. fish or mussels) causing an increase in dose to critical groups.	Major	Possible	High
	Increase in dose for Traditional Owners using the area from increased radiological exposure due to the creation of un-remediated hotspots	Major	Possible	High

3 STUDIES

There is minimal historical characterisation of the radiological conditions of the area since mining ceased in 1971. Sporadic studies were conducted in the 1970s to the 1990s, but little data on radiation issues was collected. Post rehabilitation several studies (1990s to present) have been completed and provide characterisation of the mine. These more recent studies form the basis of information for the radiological hazard assessment. This chapter details the studies that have been undertaken and, for some, includes analysis and further investigation of the results.

3.1 Office of the Supervising Scientist (2002)

In 2001, a study was conducted by the Office of the Supervising Scientist (OSS) and a private consultancy, Sulphide Solutions. The OSS was asked for advice by the Commonwealth Department of Industry Tourism and Resources concerning management options for the Rum Jungle mine in the Northern Territory. Members of the Supervising Scientist Division (SSD) staff and Australian Nuclear Science and Technology Organisation (ANSTO) undertook a short program of observational field visits, together with a study of available reports and some unpublished data. The outcomes from these activities were used to comment on the suitability of the site for unrestricted release, the extent to which the site met and continues to meet the original rehabilitation criteria, and the need for active management of the site.

In summary, the conclusions were that there are a number of reasons – physical, radiological and chemical – why the site could not be released for human habitation without land-use restrictions. Most relevant to this report was the finding that there were very little radiological data available on the entire site, and insufficient data available for a complete radiological impact assessment of the site.

3.2 Bollhöfer *et al.* (2007)

The Supervising Scientist Division of the Commonwealth Department of the Environment and Water Resources was commissioned by the Northern Territory Department of Primary Industry, Fisheries and Mines (now Department of Primary Industry and Resources), to determine the radiological conditions at the Rum Jungle mine site towards the end of the 2006 dry season. The study is documented in Bollhöfer *et al.* (2007) and was based on an airborne gamma survey that was flown in 2005 – see Figure 3.

This radiological assessment undertaken was a more thorough radiological study than had been attempted previously and was used to determine the current radiological state, the condition of the land, and the water resources within the mine site. These factors were used to determine whether land-use restrictions may need to be applied for human habitation or worker access.

As detailed in Section 3.8, EcOz (2019) used the results from this study to further delineate areas with elevated radiation levels to help inform the development of an excavation plan for radiological materials.

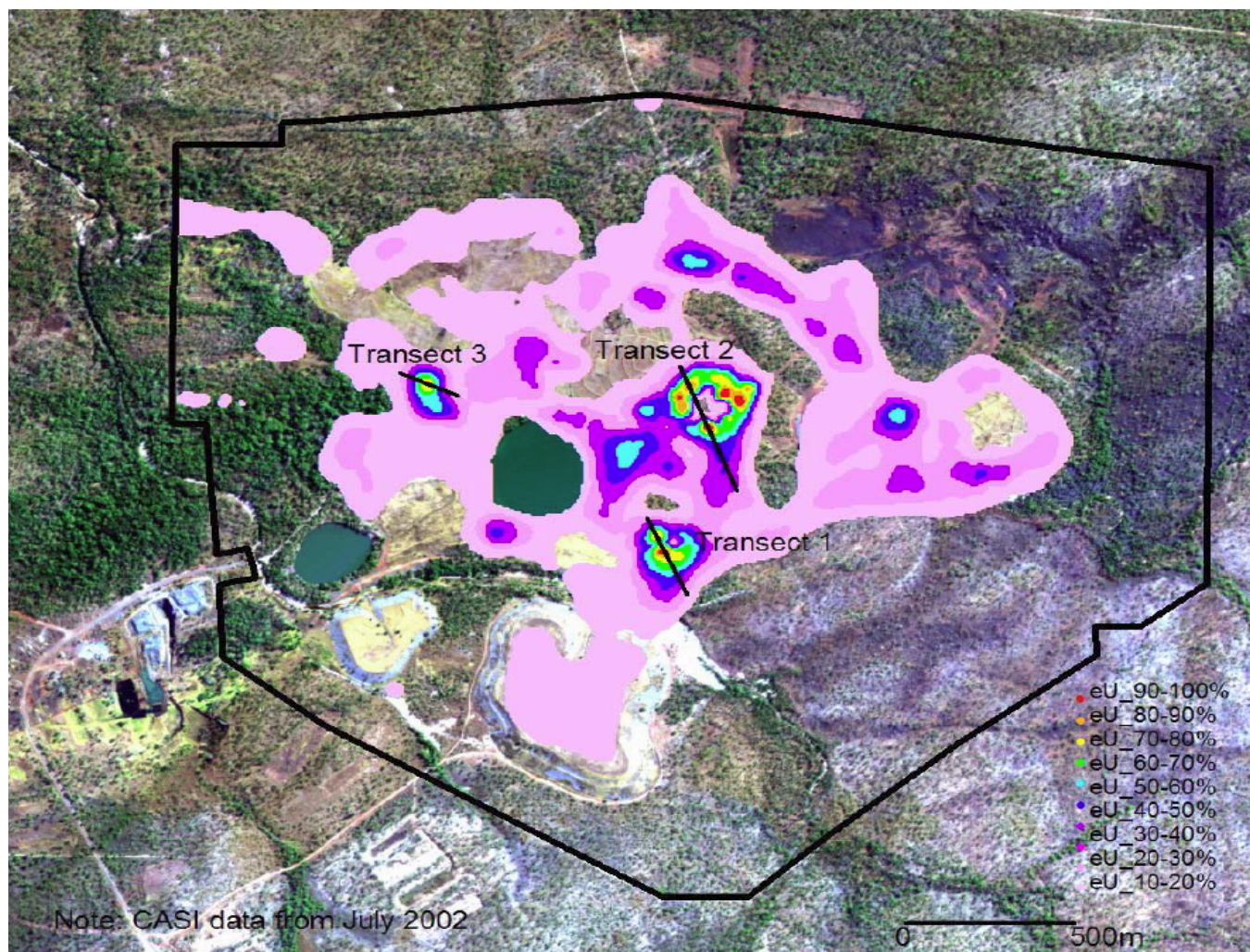


Figure 3. Compact Airborne Spectrographic Imager data showing the airborne radiometrics overlain over the mine site from Bollhöfer *et al.* (2007)

3.3 Tropical Water Solutions (2008)

Tropical Water Solutions conducted a study in 2008 on the two surface water storage areas on the site's Main Pit and Intermediate Pit. Tropical Water Solutions found 'a significant decrease in overall radionuclide activity in the surface layer of the Main pit between 1998 and 2008, with activity currently well below guideline values. They found that the activity concentrations at the depths of the water columns in both the Intermediate and Main Pits were significantly higher than the guideline values.

The ingestion of water is an important conduit for radiological exposure, especially in the tropics with a person drinking up to 4 litres of water daily (Reference Person as per ICRP 2005). The drinking water sources for human consumption is assumed to be within the Rum Jungle site for any customary harvesting activities that may take place.

The *Australian Drinking Water Guidelines* (NHRMC 2004) and the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC 2000b) for irrigation and livestock waters provide guideline values of 0.5 Bq/L for both gross alpha and beta activities (K40-corrected).

Tropical Water Solutions (2008) found a significant decrease in overall radionuclide activity in the surface layer of the Main Pit between 1998 and 2008, with activity currently well below guideline values. Activity in the deep contaminated waters of the Main Pit – from 41 m to 43 m – remains two orders of magnitude above the guideline values (Table 5) which corresponds to the known stratified chemocline at the bottom of the water column.

In the deep dense high-conductivity waters of Main Pit, Lawton (2002) reports alpha activity of 188 Bq/L and beta activity of 162 Bq/L for a sample obtained at 35 metres depth in December 1996. These compare to the May 2008 data from two samples from the same deep layer with alpha activity of 100 Bq/L and 59 Bq/L and beta activity of 120 Bq/L and 72 Bq/L. While the 2008 activities are lower than those found in 1996, they remain elevated compared to those in the surface mixed layer of the Main Pit – alpha activity in the range of 0.1 Bq/L to 0.14 Bq/L and beta activity of 0.19 Bq/L to 0.26 Bq/L.

Radionuclide activity in the upper levels of the Intermediate Pit are well below recommended guideline values, while levels in the deeper portion are above guideline values, but substantially less than the deep water in the Main Pit. Table 5. for the Intermediate Pit demonstrates that samples obtained from the surface, 15 metres and 31 metres depth are well below the gross alpha and K40-corrected beta activities. In September 2008 two samples from the deeper layer at 47 m and 51 m had with alpha activity of 5.4 Bq/L and 6 Bq/L and beta activity of 0.18 Bq/L and 0.24 Bq/L.

The volume of tailings material above the bed of the original Main Pit is estimated to be 800,000 m³ and is currently isolated from environmental receptors. This material will remain a potential radiological hazard until remediation by encapsulation of the tailings at the bottom of the pit and the treatment of the water column directly above these tailings is complete.

Table 5. Radionuclide activity in samples taken from the Main and Intermediate Pits (from Tropical Water Solutions 2008)

Sampling depth (m)	Alpha activity (Bq/L)	K40-corrected beta activity (Bq/L)
Main pit (30 May 2008)		
Surface (~0.1)	0.11 ± 0.01	0.19 ± 0.02
5	0.10 ± 0.01	0.26 ± 0.02
30	0.11 ± 0.01	0.15 ± 0.01
36	0.14 ± 0.02	0.23 ± 0.02
41	100 ± 10	120 ± 9
43	59 ± 6	72 ± 6
Intermediate pit (29 May 2008)		
Surface (~0.1)	0.08 ± 0.01	0.23 ± 0.02
15	0.08 ± 0.01	0.19 ± 0.02
31	0.11 ± 0.01	0.24 ± 0.02
Intermediate pit (7 Sept 2008)		
0.5	0.07 ± 0.01	<0.1
20	0.07 ± 0.01	<0.1
40	0.09 ± 0.01	<0.1
47	5.4 ± 0.9	0.18 ± 0.02
51	6 ± 1	0.24 ± 0.02

Source: Boland, 2008

3.4 CSA Global (2010)

In 2010, CSA Global (Lindsay-Park and Margereson) wrote a report titled *Provision of a detailed Soil and Fluvial Contamination Assessment at the Rum Jungle Mine Site (2010)*. The primary objective of the work was to characterise parts of the Rum Jungle Mine Site to determine metal levels in surface and near-surface soils, fluvial sediments, deep soil and waste material profiles across previously rehabilitated areas and un-rehabilitated areas. Although many metals were analysed only the uranium results have been reported here as part of this assessment and, where information is available, an estimation of volumes is provided.

The study divided the Rum Jungle Mine site into zones based on previous use, rehabilitation attempts and geomorphic parameters. Field analysis was undertaken using a Field Portable X-ray Fluorescence which is a well-documented tool for regulatory-driven analysis of heavy and priority pollutant metals in soils. However, results derived from this instrument must be used with caution, as it is not as accurate as laboratory based analytical equipment.

For Rum Jungle, CSA Global defined the interim threshold (trigger) value for identifying site contamination by uranium is 100 ppm. This threshold of 100 ppm of uranium was not based on *NEPM Health-based Intervention Levels* and appears to be selected as a value that lies between nearby background uranium content of 20 to 30 ppm and a very low-grade uranium ore having a grade of 250 ppm. CSA Global, when defining the areas with uranium higher than the cut-off value of 100 ppm, undertook sampling up to 130 cm depth unless:

- The hand-held XRF reported uranium concentration at more than 100ppm,
- The machine reached its safe working limit,
- Large rock or concrete slabs were encountered, or
- Cultural sensitivities dictated that a less intrusive sampling method was required.

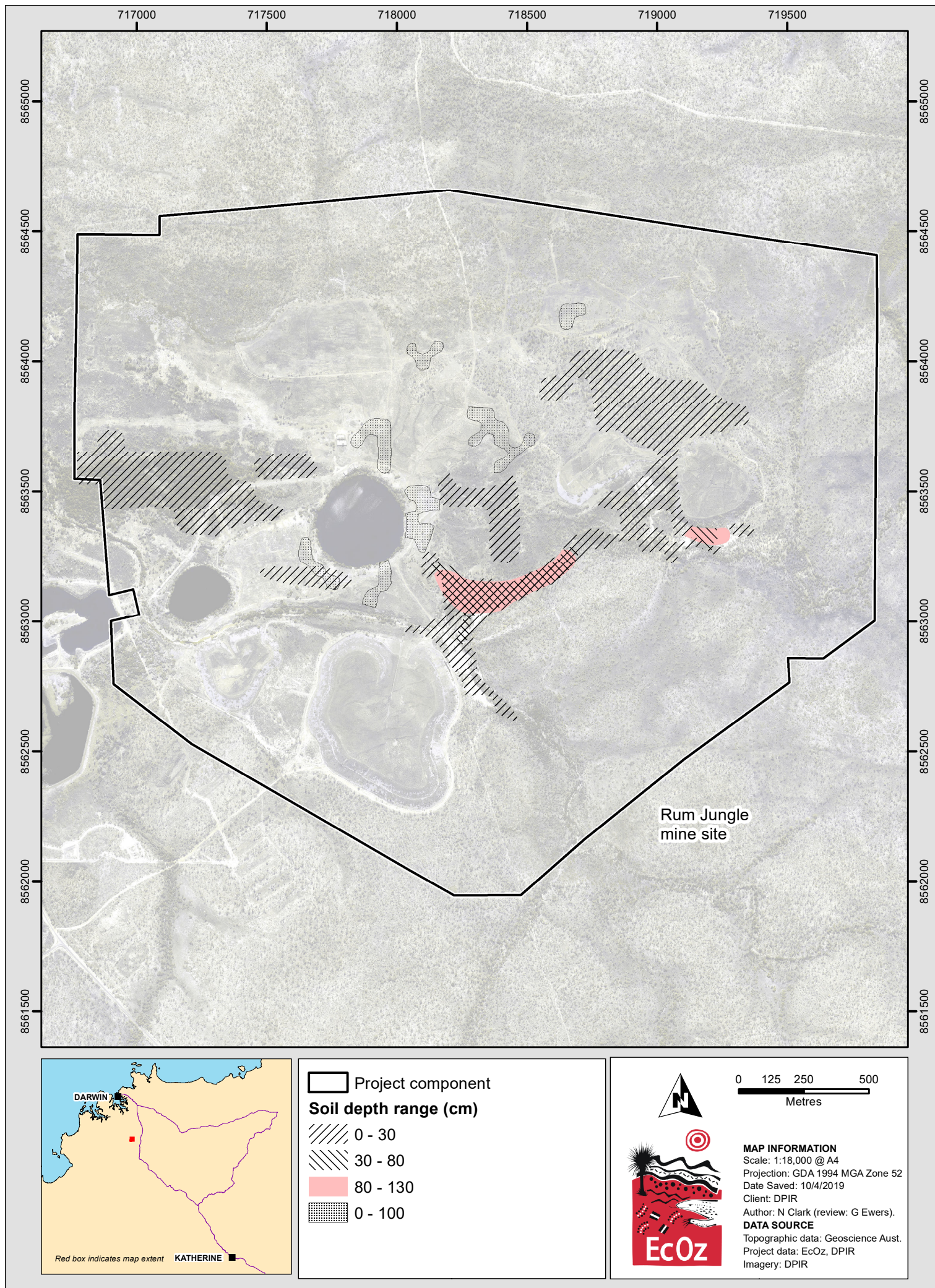
In all sampling zones a single occurrence of uranium that is over the 100 ppm trigger value constituted a contaminated sample. Each zone was further divided into discrete sections that are either separated geographically or associated with a known rehabilitated area. Due to variations in the projected area between depths, the maximum area of all depths is used, and the volume is summed for all sampling depths.

As shown in Table 6 and depicted in Figure 4, an area of 116.26 hectares and a volume of 259,316 m³ of material greater than the trigger value of 100 ppm of uranium is present on the site. These measurements of uranium are only to a depth of 1.3 metres, and exact measurements of uranium content have not been measured. These levels need to be measured and confirmed with other radioisotopes measured to calculate dose measurements for the area and to measure against ARPANSA (2005) guideline limits for soil wastes.

This study identified several sites with greater than 100 ppm of uranium present. Although these areas have been identified as having greater than 100 pm of uranium, there is no upper limit with these measurements.

Table 6. Areas and volumes identified by CSA Global with greater than 100 ppm uranium

Depth (cm)	Area (ha)	Vol (m ³)	Total area (ha)	Total volume (m ³)
0 - 10	15.47	15,470	40.97	40,966
	2.09	2,090		
	4.59	4,593		
	4.49	4,489		
	13.93	13,930		
	0.39	394		
0 - 20	2.21	4,412	2.21	4,412
10 - 20	16.03	16,030	41.68	41,681
	4.16	4,161		
	21.49	21,490		
10 - 30	9.30	18,600	9.88	19,766
	0.44	890		
	0.14	277		
30 - 80	5.74	28,710	6.36	31,819
	0.62	3,109		
80 - 130	5.29	26,465	6.19	30,935
	0.89	4,470		
0 - 100	0.98	9,822	8.97	89,737
	1.57	15,730		
	0.84	8,442		
	0.73	7,309		
	1.92	19,150		
	2.24	22,430		
	0.69	6,854		



Path: Z:\01 EcOz_Documents\04 EcOz Vantage GIS\IEZ18228 - Rum Jungle Radiation\01 Project Files\Figure x. CSA Global soil sampling results.mxd

Figure 4. Map of areas identified in CSA Global (2010) that have greater than 100 ppm uranium

3.5 Hughes and Bollhöfer (2010)

The airborne gamma radiation survey conducted in 2005 (Bollhöfer *et al.* 2007) confirmed that there are still some areas of elevated gamma activity on and downstream of the mine site. That earlier report did not examine the anomalies that occur downstream of the mine site, nor did the work seek to characterise the source or vertical extent of the source of the anomalies. In September 2009, SSD undertook further investigations of the radiological anomalies at Rum Jungle and downstream of the Finnis River and East Finnis confluence in the vicinity of Mt Fitch. This work, which included geochemical sampling of some of the anomalies to determine the nature of the source and its likely thickness, is described in Hughes and Bollhöfer (2010).

Investigation of the four Rum Jungle and four Mt Fitch anomalies indicate that six (RJ1, RJ3, RJ4, MFA, MFC and MFD) comprise thin layers (approximately 10–30 cm) of soil containing radioactive process residues, mainly tailings. One anomaly at Mt Fitch (MFB) is locally-derived mineralised spoil from the Mt Fitch mine and one at Rum Jungle (RJ2) appears to be caused by residual mineralised stockpile material. Lower levels of gamma anomalism are apparent along the course of the East Finnis drainage system downstream of Rum Jungle; these appear to be sourced from the site.

On the basis of the work reported in this report, it was concluded that three of four gamma anomalies in the immediate mine site area were caused by tailings residues remaining after earlier remediation work. The fourth was caused by residual mineralised waste rocks. Three of the downstream anomalies in the Mt Fitch area have similar geochemical and radiological signatures to the Rum Jungle anomalies, leading to the conclusion that they were also sourced from the Rum Jungle operations. The fourth Mt Fitch anomaly is attributed to local, naturally-occurring mineralisation at the Mt Fitch mine, and is not sourced from residues of milling operations at Rum Jungle. Profiling by auger drilling indicates that six tailings-related anomalies have sources with depth extents that are typically between 0.1 and 0.5 metres.

Assessment of possible radiological exposure in these anomalous areas is incomplete, as only the external gamma component has been considered to date. The potential contribution of long-lived alpha activity from dust, inhalation of radon and its daughter radionuclides, and possible ingestion through the consumption of locally-sourced food, also need to be considered when making dose assessments.

The airborne gamma survey results also show above background levels of gamma radiation along the northern edge of what was the Old Tailings Dam adjacent to the drainage line that is referred to as Tailings Creek. The material is typically patchy and thin, and sometimes obscured by thin cover materials. Where it surfaces, it is readily recognisable by its relatively uniform mid-grey colour and sandy texture.

It was recommended in the report that if further clean-up and disposal of tailings is intended, then this material should be collected as well, to minimise potential dust hazards along tracks which are currently accessible by vehicle. Volumetrically, these remnant patches are likely to be small and dilution with uncontaminated material would be difficult to avoid while attempting to collect the tailings.

3.6 SRK (2012)

In 2012, a geochemical characterisation (SRK 2012) was conducted on Main, Intermediate and Dysons Overburden Heaps and Dyson's Pit which was backfilled with tailings, contaminated soils and copper extraction residues.

Samples were collected from the four facilities and a subset of these samples were subject to laboratory tests to determine the dissolution of contained metals. The majority of materials gave acidic paste pH, and often gave high paste electro-conductivity (EC) consistent with the presence of abundant stored oxidation products. At some sampling locations, depth profiles showed trends towards increased paste EC. These were interpreted as possible evidence that soluble salts (and therefore metals) are being

leached from upper to lower parts of the profile. The study revealed that the readily soluble solutes such as uranium were released at significant concentrations from Dysons Heap and Dysons Pit.

The study revealed that the uranium associated with the waste rock material, which is the vast majority of the bogum material, was low grade waste and so can be treated as such. With the tailings in Dysons pit, it would still retain about 85 percent of the radioactivity-originally associated with the ore through over a dozen radioactive nuclides. The most important of these are ^{230}Th , ^{226}Ra , ^{222}Rn and the daughter isotopes of radon decay, including ^{210}Po . If this material is re-handled at a later date, it should be done so after being characterised and appropriate handling procedures put in place.

The study suggested that for some elements, such as the uranium in the waste rock, and by association, the radium and its progeny in the tailings, the long-term metalliferous drainage potential could be guided by an assessment of future rates of oxidation and consideration of the total mass of element present within the solid materials.

A commonly used method is kinetic leach columns. Using estimates of solute release rates, models could be developed of the long-term evolution of the facilities as contaminant source terms. Such modelling would assist in determining the longevity of each facility as a contaminant source, and facilitate comparison of the theoretical performance of different remediation options.

3.7 Hydrobiology (2016)

Prior to 2016, there had been studies that described the receiving environment in terms of its key ecological and geomorphological attributes, identified environmental values (EVs) and set appropriate water quality objectives (WQOs). However, in order to refine these default WQOs to locally-derived water quality objectives (LDWQOs) it was necessary to conduct an impact assessment by Hydrobiology in 2016 by river zone, that included wet season sampling.

It was found by Hydrobiology (2016) that the analysis of radionuclides in fish, mussel and plant tissues displayed none of the patterns of radionuclide activity concentrations that were consistent with a substantial source from the Rum Jungle mine area. There was no indication of elevated bioaccumulation in specimens in the Finnis River downstream of the East Branch, and also no indication of increased bioaccumulation downstream of the abandoned Mount Burton mine. There was an indication of naturally higher bioavailability of ^{210}Po and ^{228}Ra in the East Branch catchment upstream of the mine.

As mussels were not present in the East Branch from the mine area downstream, it was not possible to examine any further influence on bioavailability of radionuclides from the Rum Jungle mine area on mussels. The absence of large specimens of fish at most East Branch sites amenable to radionuclide analysis resulted in only one specimen from the East Branch downstream of the site being analysed.

3.8 EcOz (2019)

The purpose of this work was to establish an excavation plan for the Stage 3 rehabilitation program to ensure that the higher risk radiological materials (outside of the waste rock dumps) was clearly identified for removal and storage in the new waste storage facilities. Using the results from Bollhöfer *et al.* (2007), in 2019 the author identified 25 areas as having elevated radiation levels (see Table 7 and Figure 5). These areas were then classified by the author in order of radiation levels based on the measured parameters of radon (^{222}Rn) emanation¹ and ^{226}Ra present in soils. Nine sites had relatively

¹ *Emanation* is the movement of the radon atom inside the soil grain and toward the inter-granular space. After radon is generated from radium in the solid grains, they emanate the radon atom toward pore gases or fluids in the inter-granular space, and then radon can migrate significant distances from the site of generation.

high radiation levels and have been ranked as per order the order of ^{226}Ra in soils and the amount of radon emanation coming from those soils.

These sites were further investigated with a field survey conducted by the author in late July 2019 to determine the extent of the elevated radiation levels of the nine areas (Figure 6). This survey of the areas involved the measuring of the gamma radiation via field survey meters and Geiger Mueller tubes across the areas which also allowed for the delineating of the outer edges of the identified areas. The spatial extent of the nine contaminated areas is shown in Figure 6.

The results of the Bollhöfer survey are summarised in Table 7. The dump area to the west of Dysons is ranked the highest radiologically contaminated area because of the $>30 \mu\text{Sv/hr}$ readings that were measured across the large rocks that were strewn across the area. It seems the area may have been used as a stockpile area for mineralised material for these large boulders, and other rocky piles with a view of processing them at a later date. There is evidence of high uranium content, and mineralisation can be seen on some of the exposed rocks.

As can be seen from the concentration of the highest contaminated sites in Figure 6 – Sites 1, 2, 4, 5 and 7 – and from the airborne gamma survey (Figure 3), as previously mentioned there is high activity around the area west of Dysons (Site 1). It appears as if there has been some erosion from this area over time and that there are active drainage lines with relatively high activity moving down the hill and towards Site 2 and eventually Site 5, with deposition taking place in areas of depression along the way (Site 4 and Site 1). Activity concentrations are elevated at Site 2 (where the material has deposited) and Site 5. All these sites are downstream of Site 1.

Site 6 is a small area approximately $< 70 \text{ m}^2$ and looks to be an area where elevated radiological material was used to build up a road by the fenced area. This material is fine and grey and looks like tailings, but it is difficult to tell without undertaking further radiological analysis. There are a series of drainage lines draining from the material that have concentrated contaminants in them. Gamma survey readings were up to $3 \mu\text{Sv/hr}$ along these lines.

Site 3 is an area with relatively high gamma reading, with some areas measuring up to 3 to $4 \mu\text{Sv/hr}$. The area appears to have been used to hold water, or have been some kind of an overflow pond from the tailings pond. Upon excavation of the area, a fine brown material was removed (see Figure 7), and activity was evident up to a metre below the surface but diminished at deeper levels.

Site 8 was a case of radiologically elevated material being used to build up the road. Site 9 was an area used as a copper leaching pad and has accumulated some radiological material over time.

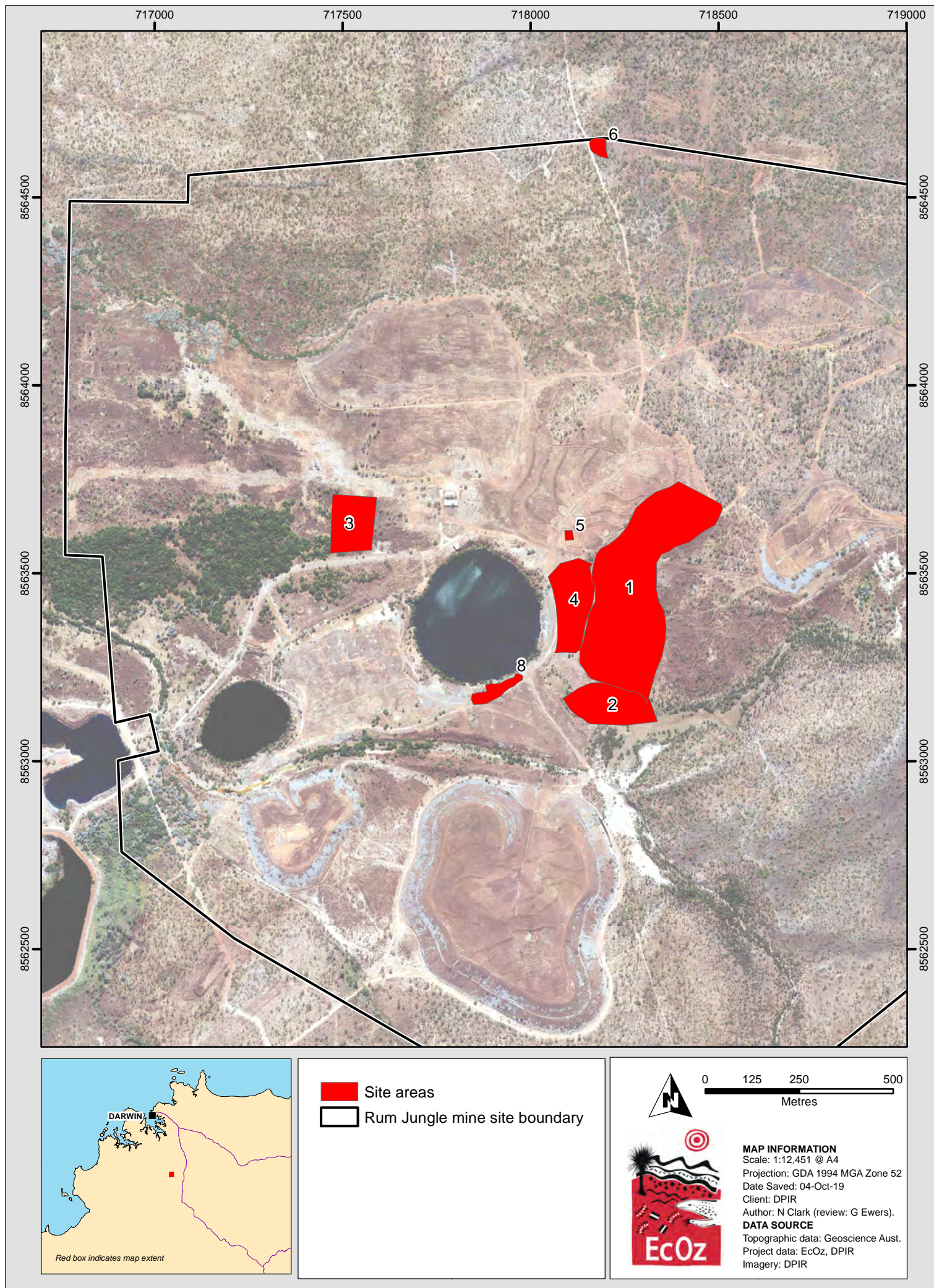
Table 7. Results for radon (^{222}Rn) in air and emanations, and ^{226}Ra activity concentrations in soil ranked

Location	^{222}Rn (mBq/m/s)	^{222}Rn (Bq/m ³)	Ra 226 (Bq/kg)	Ranking	Comments
Dump area west of Dysons	227 ± 100	-	1255 ± 206	1	The dump area west of Dysons Pit area is approximately 6.4 ha, it has a number of rocks exposed at the surface throughout the area that have uranium mineralization evident and exhibit over 25 uSv/hr. The dose from dust was high for this Dump area.
Hot spot at Acid Dam area	3908±784	276±110	2219±18	2	The acid dam area is approximately 2.9 ha and has high readings for gamma radiation (external dose), radon emanations and ^{226}Ra in soils. The area's dust readings were amongst the highest for the Rum Jungle area and will be more hazardous when the area is disturbed and rehabilitated.
Hot spot south of tailings dam	378±38	236±58	675±6	3	This area is approximately 1.3 ha and displays a high gamma dose, high ^{226}Ra in soils, high radon emanations and high dust dose readings.
Next to drill rig	356±74	113±14	1658±14	4	This area is situated next to an old abandoned drill rig that was left at the Rum Jungle site. It has high ^{226}Ra in soils and average to medium radon emanation rates. The site was not characterised for dust levels.
Soft soil, Para grass, Sweetwater Dam	1174±362	152±7	789±7	5	Sweetwater dam area has high numbers for gamma radiation, radon emanations and ^{226}Ra in soils.
Along fence near gate	168±34	25±7	5563±45	6	This area has the highest reading of ^{226}Ra in soil, more than double the reading of the Acid Dam area. It has a medium radon emanation rate. There is no dose in dust recorded for this site.
Compound (dust & Rn monitor)	189±67	57±23	2208±18	7	This area is a small fenced area along the road to Dysons Pit. It is characterised by high ^{226}Ra in soils and low to medium radon emanations. There are no levels of dust recorded for this site.
Shale, next to Whites OC	319±137	119±86	699±6	8	This area is typified by relatively medium to high ^{226}Ra in soils and low to medium radon emanations. No dose in dust was calculated for this site.
Cu heap leach pile	73±1	116±21	208±18	9	This area has low to medium levels of ^{226}Ra in soils. The area has low radon emanation levels. No dose from dust has been calculated for this area.
In between core sheds	203±86	98±28	623±6	10	The area between the core sheds has medium to high radium in soils and low to medium radon emanations. No dose from dust has been calculated for the area.
Next to slope of Dysons OB bare ironstone	80±20	75±23	476±4	11	This area has low radon emanation and low to medium ^{226}Ra in soils. This area will probably be encapsulated within the main rehabilitation works.
Top of Dysons open cut (OC)	70±12	27±14	511±4	12	The top of Dysons open cut is an area of approx. 6.3 ha and has medium levels of ^{226}Ra in soils. The radon emanations are average. This site will be encapsulated in the main rehabilitation of the area.

Location	²²² Rn	²²² Rn	Ra ²²⁶	Ranking	Comments
Natural site upstream	86±4	106±21	364±3	13	This area has low radon emanation and low to medium ²²⁶ Ra in soils.
Base of Dysons OB, sulfates	493±52	60±21	326±3	14	This area has low to medium radon emanation and low to medium ²²⁶ Ra in soils. This area will probably be encapsulated within the main rehabilitation works.
Burnt area forest	353±25	78±44	173±2	15	This area has low to medium radon emanation and low to medium ²²⁶ Ra in soils. This area will not be encapsulated within the main rehabilitation works.
next to Intermediate OC	245±26	52±14	167±2	16	This area has low to medium radon emanation and low to medium ²²⁶ Ra in soils. This area will probably be encapsulated within the main rehabilitation works.
Sulfates at Sweetwater Dam	56±81	65±7	237±2	17	This area has low to medium ²²⁶ Ra in soils and average radon emanations from soils.
Dysons sulfates, middle	26±28	75±37	118±2	18	²²⁶ Ra in soils and the radon emanations are average. This will be encapsulated in the rehabilitation of the site.
Dysons OC - bare ironstone	57±9	20±7	321±3	19	²²⁶ Ra in soils is low in the soils with radon emanations average. This area is to be encapsulated in the rehabilitation.
East branch of Finniss	43±38	57±23	199±2	20	The radium in soil/sediments in the east branch of the Finniss are low and the radon emanations are average.
Top of Whites Overburden (OB)	1034±657	24±8	175±2	21	This site has a high radon emanation rate and a medium radium in soil rate. The very low radon in air is due to the exposure to wind and dilution effects of the atmosphere at the top of the overburden heap.
Bare area ironstone	143±9	35±7	91±1	22	The radon emanations from the bare area ironstone are low and radium in soils average.
next to East Branch creek bed	117±112	42±14	59±1	23	Radon emanation from soils are slightly elevated. ²²⁶ Ra in soils are average
Borrow area (bare)	55±8	25±7	140±1	24	This area had low ²²⁶ Ra in soil and average radon emanation rate
Bottom of rocky slope at Whites OB	44±10	47±14	69±1	25	All results were equal to or below averages



Figure 5. Locations of 25 highest radiation areas ranked in order of approximate radiation levels



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Figure 6. Extent of elevated gamma radiation after an on-ground survey (EcOz 2019)



Figure 7. Site 3 test pit excavation for the investigation of radiation levels

3.9 Other reports

3.9.1 Rehabilitation Proposals for Abandoned Uranium Mines in the Northern Territory (1988)

This report was put together by the Commonwealth Department of Administrative Services on behalf of the Northern Territory Department of Primary Industries and Energy in 1988. The mines it dealt with were Mt Burton, Mt Fitch, Rum Jungle and Rum Jungle Creek South, Adelaide River, George Creek and Fleur de Lys. The mines that are of interest are Mt Burton and Mt Fitch.

This report found that the water in the open pit at Mt Burton was deemed by the Australian Radiation Laboratory to be below the annual dose limits for consuming 1 litre of water per day. While gamma radiation levels around the open cut and waste heap were generally below 3 uGy/hr, a 500m² area to the north of the open cut was found with gamma radiation readings up to 35 uGy/hr. DME (2016) concluded from their survey that, using the International Commission for Radiological Protection criteria, there is no significant human health hazard at the site.

At Mt Fitch, water assays in 1988 showed uranium levels at 124 ug/L, which is above the current drinking water quality guideline of 17 ug/L. Assessment of the water by the Australian Radiation Laboratory was deemed below the then annual dose limits for consuming 1 litre of water per day. Gamma radiation levels around the waste heap and the access to the mine were less than 0.5 uGy/hr, with the exception of a few locations along the access to the open-cut pit where levels of 2 uGy/hr were recorded.

3.9.2 Radiation Advice and Solutions (2015)

In 2014, the Rum Jungle project team carried out a significant sampling program on the waste rock dumps onsite. As part of this program, Radiation Advice and Solutions were contracted by the Department of Primary Industry and Resources to review the radiological assessment performed by Bollhöfer *et al.* (2007) and to run a monitoring program for the excavation works on the waste rock dumps. This small study was to measure actual exposure to workers and to provide radiological information on the drilling and digging activities performed by the workers.

The conclusions were that the maximum dose received by workers engaged in these excavation works at Rum Jungle was 0.15 mSv per year for a 3000 hour working year. This would be 0.10 mSv per year adjusted to a 2000 hour working year and in the hypothetical case of full-year exposure would have remained well below 'member of public' limit of 1 mSv per year. This information source is critical in understanding the potential dose to Stage 3 workers as it provides directly measured data from activities similar to that which will be undertaken in Stage 3 works.

The report recommended that similar excavation works in the future, with the same controls, would not require this same level of radiation monitoring. In lieu of the full monitoring program undertaken during the 2015 excavation project, it was recommended all earth-moving equipment undergo radiation clearance before being released from site and, for reassurance, monitoring of radioactive dust levels be undertaken using a Microvol low volume air sampler.

3.9.3 DME (2016)

On 24 February 2016, staff from the Department of Mines and Energy (DME) carried out a gamma radiation survey (Figure 8) to assess radiation levels emanating from the mined area and stockpiled materials at Mt Burton. A grid-based survey was conducted that included the main site features, the nearby residential property and main access routes and tracks. Outlying areas were also investigated and background radiation levels measured during the survey.

The results of the survey using the ICRP criteria indicated that there is no significant human health hazard at the site. However, as there would be a suitable disposal option for the radioactive material available nearby during a major remediation project at Rum Jungle, the recommendation was made that all identified materials be relocated to Rum Jungle at the appropriate time. Until the material is relocated, it was recommended that the landowners be advised to limit time spent in the vicinity of the stockpile and warning signs be erected.

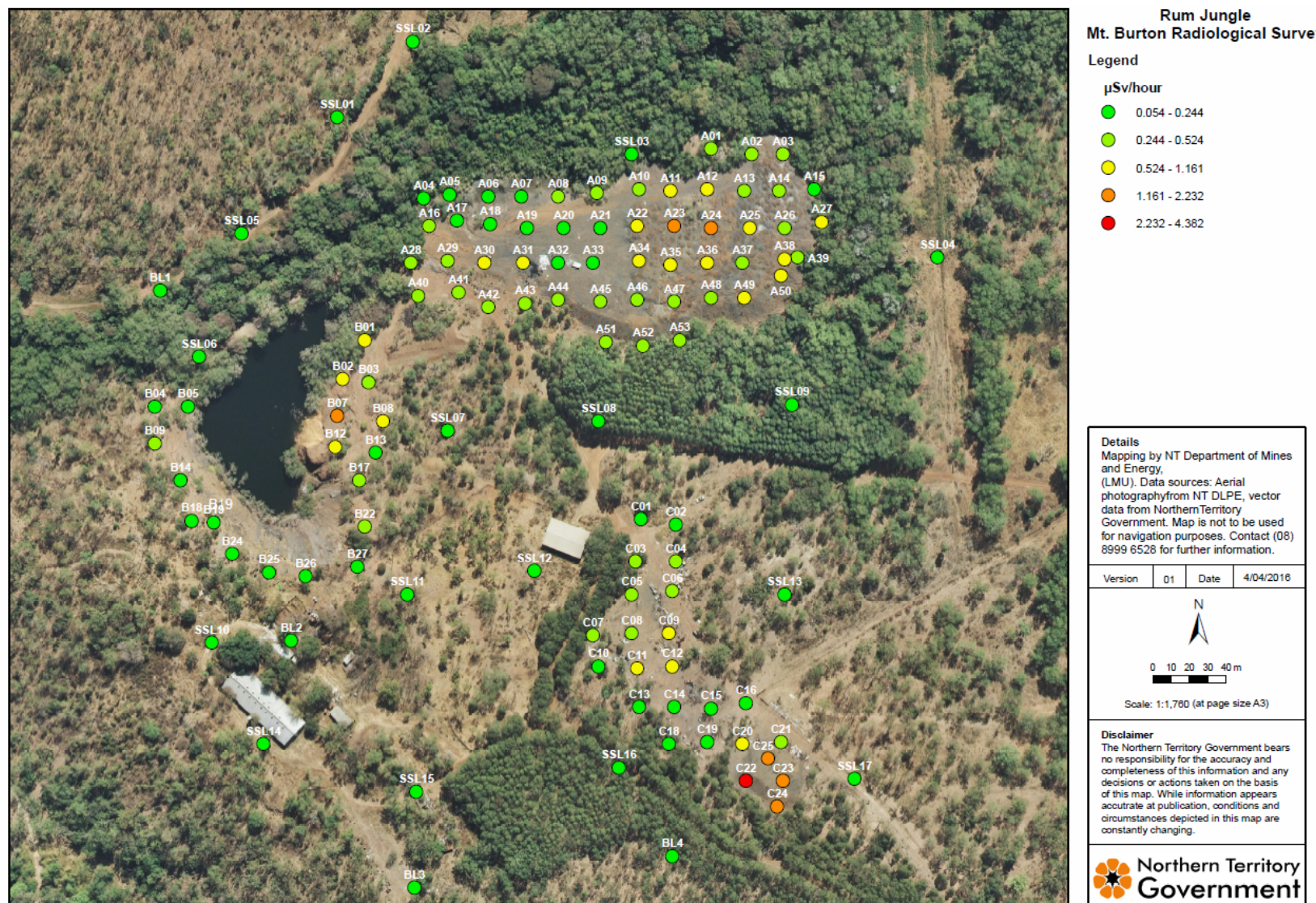


Figure 8 Rum Jungle Mt. Burton grid survey from Mount Burton Radiation Survey, DME, 2016

4 RADIOLOGICAL ASSESSMENT OF THE MINE SITE

The radiologically hazardous elements presented in this chapter are derived from the studies discussed in the previous chapter. The elements have been listed below, namely:

- Gamma radiation measurements
- ^{226}Ra in soils
- Radon emanations
- Radon in air.

Any dose assessment should take into account the four critical groups listed here:

- a. Critical Group 1 – Occupational: construction workers on-site for the duration of the Stage 3 construction period
- b. Critical Group 2 – Traditional owners: taking into account all potential future land uses
- c. Critical Group 3 – People living downstream of the Rum Jungle Site on the East Branch Finnis River
- d. Critical Group 4 – General members of the public.

These potential future scenarios are described here in relation to the above listed elements. At present the access to site is restricted and the tenure over the property is NT Crown Land. Any unauthorised access to site is difficult to control and fencing and signage has been installed to discourage trespassing. It is recommended to improve the fencing and signage on site to reduce likelihood of trespassing until a higher intensity of land access is safe.

The future Land Use Plan has been established by a Panel of Traditional Owners, NTG and the Commonwealth representatives. This Land Use Plan incorporated traditional views of this land into a modern interpretation of how Traditional Owners may wish to utilise this land in future should the outstanding land claim be resolved over this property. The Land Use Plan identifies that there is no planned permanent occupancy of site though some temporary occupancy for purpose of tourism or cultural practices is envisaged. This Land Use Plan has informed the radiological assessment of the mine site.

4.1 External radiation

4.1.1 Gamma radiation

Bollhöfer *et al.* (2007) determined that the average external gamma dose rate over the mine site amounts to 0.2 $\mu\text{Gy/hr}$. Average dose rates of approximately 0.6 $\mu\text{Gy/hr}$ were measured at three 'hot' areas identified by the airborne survey, an area west of Dysons Open Cut (Dump area) (1), an area close to the Acid Dam (2) and an area close to the Old Tailings Dam (3) – all shown on Figure 6. The averaged whole-body effective dose rate across the entire site from terrestrial gamma radiation is 0.14 $\mu\text{Sv/hr}$, which is approximately twice as high as background effective dose rates.

A background terrestrial gamma dose rate was calculated in the report and amounted to 0.08 $\mu\text{Gy/hr}$. This is similar to background terrestrial gamma dose rates reported for other areas in the Top End (see for instance Martin *et al.*, 2006 or Marten, 1992b).

The areas of radiation levels significantly above background were identified in the vicinity of the footprint of the Dump area west of Dysons, Acid Dam and Old Tailings Dam, and are all regions indicated by elevated counts

(greater than 40% of maximum) from the 2005 airborne gamma survey data. The average whole-body effective dose rate from the Acid Dam area from terrestrial gamma radiation is 0.45 $\mu\text{Sv/hr}$.

During a ground-truthing exercise in July 2019 (see Section 3.8), the Dump Area and the area south of the Old Tailings Dam gamma radiation extents were investigated by a walkover survey, with the latter being trenched to explore the depth of elevated radionuclide activity (see, e.g., Figure 7). These measurements were measured directly in the trench. This area (south of the Old Tailings Dam) had readings between 3 to 4 $\mu\text{Sv/hr}$ at the surface (top 20 to 30 cm of soil), going down to <1 $\mu\text{Sv/hr}$ at 2 metres below the surface.

The extent of elevated radiation level materials at the Dump Area west of Dysons (Site 1) was quite broad, with large rocks showing >30 $\mu\text{Sv/hr}$ at one location and commonly 6 to 8 $\mu\text{Sv/hr}$ across the area. This site covers approximately 6.4 ha.

As a consequence of Stage 3 rehabilitation works, it is expected that the gamma dose rates will be substantially lowered and below the 10 mSv/yr guideline value.

4.2 Internal radiation

4.2.1 ^{226}Ra and uranium

Concentrations of ^{226}Ra in soil can affect the different radiological pathways – including dust, foods and radon. As ^{226}Ra is the parent nuclide for ^{222}Rn and its abundance in soils can play a crucial role in the amount of radon that is present. There are several areas with elevated readings of ^{226}Ra in the soil and several areas of potentially-elevated uranium in soils as identified in Section 3.4.

4.2.2 Dust

Doses received via the dust inhalation pathway are low – less than 0.005 $\mu\text{Sv/hr}$ across the site (Bollhöfer 2007). However, this pathway may play a more prominent role in the unlikely event that the site was inhabited permanently, or in the likely event that workers are engaged in activities such as digging, drilling or heavy traffic movements during the rehabilitation of the site. There is currently no site occupation by Traditional Owners as the land claim has not been resolved and access is restricted. However, in future, some degree of access is indicated by the Land Use Plan. In order to assess this hazard, occupation factors need to be taken into account in future, especially if circumstances change and customary harvesting excursions do take place.

4.2.3 Ingestion of food and water

Traditional Owners may access the Rum Jungle area for customary harvesting purposes post-rehabilitation, although the process for handing over of the site is not yet established and the timeframe for this is unknown.

The author has found on the Magela floodplain in Kakadu National Park – near Ranger uranium mine – that ^{226}Ra and ^{210}Po activity concentrations can be significant in the flesh of feral pigs and aquatic organisms. Data from the Finnis River area on radionuclides in pig flesh or organs are not available

In Bollhöfer *et al.* (2007), the data needed for a full dose assessment was sourced from other studies in the Top End (Martin and Ryan 2004, Ryan and Martin 2005). The ingestion pathway was modelled using an approximated diet and two hypothetical Critical Groups. One group (CG1) was assumed to be living ~5 km downstream of the Rum Jungle site along the Finnis River, using the Finnis River as their source of water and aquatic food items such as mussels, fish and turtle (assuming that such food items could be obtained from this reach of the river). The second hypothetical group (CG2) was assumed to be living on-site using the site and its waterbodies for hunting and gathering activities, and as a source of drinking water. This is a highly unlikely exposure scenario, as site access is currently restricted and will remain so until such time in future where the land use changes can be safely achieved.

In the case of permanent occupation (CG2) of the area by Traditional Owners living a semi-traditional lifestyle, and sourcing aquatic and terrestrial food items from hunting and gathering activities, it can be concluded that ingestion doses will be 2 to 3 times higher than doses received at background areas. This is mainly due to the current radionuclide activity concentrations in the Main Pit and Intermediate Pit waterbodies on-site and the Finnis River immediately downstream of Rum Jungle which may give rise to elevated ingestion doses assuming; (a) year-round harvesting and, (b) the presence of mussels or fish in those waterbodies. Bollhöfer *et al* (2007) estimated that the total annual doses, using default values for various similar food items from studies in Kakadu National Park for the ingestion pathway, to be above natural background would be over 5 mSv per year. This would also include the terrestrial gamma and inhalation pathways.

This elevated exposure under current site condition justifies the current restricted access to site for traditional food sourcing. This elevated exposure also justifies the need to rehabilitate the site conditions prior to permitting any form of more relaxed site land use restrictions.

It is unlikely that the ingestion pathway of food and water will play a role in Stage 3 rehabilitation worker dose.

4.2.4 Radon

The radon inhalation pathway has been identified in many studies as the primary contributor to public radiation dose received from a practice such as uranium mining and milling (ICRP 1993). Airborne radon concentration shows significant seasonal and diurnal variations (Bollhöfer *et al.* 2004; Martin *et al.* 2004; Lawrence, 2005). These are caused by meteorological parameters, such as wind speed and direction, rainfall and humidity and barometric pressure. Day to day variations can be quite large, and average daily airborne radon concentrations can vary by a factor of 25 in extreme cases (Bollhöfer *et al.* 2004).

Long term radon concentration measurements taken at Nabarlek, a rehabilitated uranium mine in the Top End, have shown, however, that wet season radon levels are approximately one order of magnitude lower than dry season levels (Martin *et al.* 2004). The average radon concentration between 9:00 - 18:00 hrs (daytime) will only be approximately 25% of the average total radon concentration measured for the 24 hr period. The average concentration during the night time (20:00 - 9:00 hrs) is approximately 50% higher than the average total for the 24 hr period (Bollhöfer *et al.* 2007).

The average radon activity concentration in the air at Rum Jungle during the Dry season has been determined at 80 Bq/m³ (Bollhöfer *et al.* 2007). Radon concentrations of >200 Bq/m³ were measured at areas associated with higher soil radionuclide activity concentrations such as the Acid and Old Tailings Dam areas. On average the dose rates for 24 hr exposure amount to ~1 µSv/hr for the Acid Dam area and an area immediately to the south of the Old Tailings Dam and 0.4 µSv/hr averaged over the whole of the mine site. Typical dose rates received at environmental (i.e. background) areas from the inhalation of radon are approximately 0.1 µSv/hr.

The average Australian radon exposure is ~25 Bq/m³ (ARPANSA 2019). There is a recommendation of a maximum 200 Bq/m³ for indoor radon levels by ARPANSA (2019). Although it is for indoors, it is the only Australian reference level for radon available. Perhaps a better comparison is the USEPA action levels of 148 Bq/m³ (see below). During the Dry season approximately 5% of the area investigated is above the Australian reference level of 200 Bq/m³.

From ICRP Publication 115 (2010), the relative risk for lung cancer increases by about 10% per 100 Bq/m³ of radon increase with a significant risk for cumulative exposures below 200 Bq/m³. To this end, the United States Environmental Protection Agency (US EPA) has set an action level of 148 Bq/m³ (USEPA, 2019). At or above this level of radon the US EPA recommends taking corrective measures to reduce exposure to radon gas. This does not imply that a level below 148 Bq/m³ is considered acceptable. It is estimated that a reduction of radon levels to below 74 Bq/m³ nationwide (USA) would likely reduce the yearly lung cancer deaths attributed to radon by 50%. However, even with an action level of 74 Bq/m³, the cancer risk presented by radon gas is still hundreds of times higher than the risks allowed for carcinogens in our food and water.

The US EPA recommends that radon exhalation fluxes from uranium mine tailings should not exceed 740 mBq/m²/s (US EPA: 40 CFR, Part 192). The US EPA criterion provides a useful reference value for

comparison with the results obtained in the Bollhöfer survey. Radiation protection is always based on the worst case scenario; it can be seen from Table 7 that Site 2 and Site 5 would not comply with the US EPA criterion on radon exhalation fluxes during the late dry season when soil moistures are at their lowest.

The radon dose for potential future land use would be better assessed in future in post-rehabilitation works.

4.3 Dose estimates

An estimate of the doses received in mSv per month from several different areas across the Rum Jungle mine site has been derived from Bollhöfer et al. (2007) are shown in Table 8. If the existing exposure clearance reference level of 10 mSv/yr is used – as recommended in Section 1.4 – two areas, the Tailings area and the Acid Dam area, are outside of the guideline value. These dose levels are expected to be reduced to all critical groups after the excavation of the elevated material and its storage in the Waste Storage Facility.

It is important to note that these values do not include the dose for the ingestion pathway, which is important, especially for a critical group living a semi-traditional lifestyle on this land. The reason for this is that there is a knowledge gap present, as discussed in Section 6, whereby not enough data existed for the proper evaluation of the ingestion pathway. Default values were used in this study from studies completed by the author in Kakadu National Park.

It is also essential to recognise that if rehabilitation work begins at the site, potential doses from the different factors will increase. Therefore a Radiation Management Plan will need to be enacted to protect worker and public safety. In particular, the inhalation pathway from dust exposure during the rehabilitation work can result in these values increasing by up to two orders of magnitude during the disturbance this work involves.

Table 8 provides the total dose to any persons who may currently access the site in its current condition.

Table 8. Showing the total dose (mSv per month) received from gamma, radon and dust from the Rum Jungle site from various areas from Table 7 in Bollhöfer et al. (2007)

Site	Area ha	Average Rn Bq m-3	Rn dose rate nSv hr-1	Effective Gamma dose rate nSv hr-1	Dose from dust inhalation nSv hr-1	Total mSv per month
Tailings Dam	30.9	78	419	141	0.9	0.4
Whites OH	29.6	36	192	113	0.7	0.22
Intermediate OH	6.8			102	0.6	
Dysons OH	8.9	90	487	165	1.2	0.47
Dysons OC	6.3	35	191	145	1.1	0.24
Borrow area 3	13.5			78	0.4	
Borrow area 5	15	25	132	69	0.4	0.15
Acid Dam area	2.9	193	1042	452	3.9	1.08
Dump Area	6.4	113	610	407	3.7	0.73
Tailings area	1.3	236	1272	417	3.8	1.22
Area 4	616	78	422	142	0.8	0.41
Environment areas		16	86	59	0.3	0.1

According to Bollhöfer et al. (2007), for construction workers accessing the site during the day for 2000 hours per year, the total committed effective dose would amount to only 0.3 mSv. This is provided the construction job is a year-round operation.

During a 2014 radiological monitoring program of excavation work performed on the waste rock dumps at Rum Jungle, Radiation Advice and Solutions (2015) reported that the maximum annual project dose that could have been received by a worker during this operation was 0.15 mSv for a full 3000 hour working year. Although this was only a two-month project it gives a good estimate of the dose that can be expected from any future construction work. It is estimated the dose to Critical Group 1 would be between 0.15 to 0.3 mSv per year based on the current construction scenario.

5 OTHER RELEVANT SITES

5.1 Mt Burton

On 24 February 2016, staff from the Department of Mines and Energy (DME) surveyed to assess radiation levels emanating from the mined area and stockpiled materials of Mt Burton. A grid-based survey was conducted that included the main site features, including the waste rock dump, stockpile, pit area, residential property and main access routes and tracks. Outlying areas were also investigated, and background radiation levels measured during the survey.

The average background gamma radiation at the four sampling locations was 0.07 (+/- 0.01) $\mu\text{Sv/hr}$. The survey found that the area with the highest gamma radiation was the stockpile in Area C (see report) at the south-west corner of the laydown area. The highest recorded result was 4.3 (+/- 0.2) $\mu\text{Sv/hr}$ above background. Generally, the remainder of the site had low levels of radiation.

The maximum gamma radiation level measured during the survey indicates that the stockpile on the property potentially poses a risk to human health under long term exposure scenario, e.g. in excess of 30 days working on the stockpile. It is recommended that the landowner be advised to avoid this area and signage should be installed to warn of elevated radiation levels until the material may be relocated.

As part of the preferred Rum Jungle Rehabilitation Strategy, it is proposed that the stockpile be removed for encapsulation within a newly-constructed waste disposal facility at the Rum Jungle Mine Site. Appropriate radiation management measures will need to be in place when relocating materials from the Mount Burton site to Rum Jungle.

5.2 Mt Fitch

The area was historically disturbed from previous mining activities and is currently Power and Water Corporation tenure. The waste rock dump is relatively low volume and almost entirely devoid of vegetation. This area has a basic radiological assessment performed during the 1988 study by the Commonwealth Department of Administrative Services on behalf of the Northern Territory Department of Primary Industry and Energy and the airborne gamma survey work covered this area.

Although ore from this Pit was never mined, it did have overburden stripped and this material remains on surface. These stripped piles showed gamma activity of $\sim 2 \mu\text{Gy/hr}$ in some spots but were on average $< 0.5 \mu\text{Gy/h}$. As part of the preferred Rum Jungle Rehabilitation Strategy, it is proposed that these clearly visible stockpiles be pushed back into the pit.

6 RECOMMENDATIONS

Despite all the radiological studies that have been undertaken for the Rum Jungle mine, there remain some areas for which further work is recommended.

6.1 Ingestion

There is a knowledge gap for the Rum Jungle site related to potential future ingestion of bush foods in the event that the Traditional Owners receive full access rights in a potential land claim resolution. There is very little radiological information regarding bushfoods on the site. The future Land Use Plan suggests there will be limited customary harvesting of any bushfoods, with no harvesting taking place within a minimum of 10 years as part of the Stage 4 project time line.

There were small collections of bush foods conducted by the Bollhöfer field team for the 2006 study, but this mainly consisted of a few yams and a small number of fruits. There were no terrestrial animals collected and, as this would be an important pathway for exposure to the local people if customary harvesting returns, it should be reviewed at some point in the future. From a study conducted by Ryan and Martin (2005) on pigs on the Magela floodplain in Kakadu National Park, pigs have been identified as possibly having significant amounts of ^{226}Ra and ^{210}Po in their organs and flesh.

The primary sources of data that was used for the ingestion pathway dose calculations for the Bollhöfer *et al.* (2007) report were from the Top End NT mainly around Ranger Uranium Mine and the South Alligator Valley in Kakadu National Park. All water ingested at Rum Jungle will be assumed to have come from the onsite waterbodies.

The Hydrobiology report (2016) contributes some knowledge to the aquatic pathway but more work needs to be done. Downstream of the mine is still not well understood for the East Finnis River due to the lack of fauna present in the aquatic ecosystem of the East Branch. Aquatic food and sediments downstream of the mine on the East Finnis River have not been well studied and it is therefore not currently possible to determine the potential radiological impact of these organisms and sediments on local people's dose.

These factors contribute to a significant knowledge gap with the ingestion pathway for people potentially using the Rum Jungle site in future post-rehabilitation. This gap involves almost all facets of dietary intakes of foods from concentration activities to dietary details on food consumption across the different Aboriginal and non-Aboriginal groups that may utilise the site post-rehabilitation. This information is important in making any assumptions on the dose intake via the ingestion pathway for people using the site whether it be for traditional ceremonies or customary harvesting practices.

6.2 Pits and waste rock dumps

There are some knowledge gaps related to the waste rock and tailings materials on site; however, this gap is not material to the operational safety of Stage 3 works or future land users. The three pits and three waste rock dumps (Main, Intermediate and Dysons) have been characterised chemically, with acid mine drainage being well understood. Uranium analysis has been performed by SRK (2016) on Main, Intermediate, Dysons Overburden and Dysons Tailings. The uranium levels in the material can be classified as low level waste. Even though the tailings material has had the uranium analysed, the radium and its progeny have had no characterisation performed on them, although this material will not be handled throughout the rehabilitation process.

The tailings materials are currently stored within the backfilled Dysons Pit below the natural surface and the bottom elevations of the Main Pit. This material is uranium tailings and, as such, presents the highest radiological hazard to Stage 3 workers on the site if rehandled. Due to the current safe storage location and the potential risks associated with these tailings, they will not be rehandled during Stage 3 restoration works

and there are no plans to relocate the tailings in future. In the event that any plan changed and tailings were to be handled, it is recommended to carry out a more complete radiological characterisation of this material in order to understand expected dose.

The existing waste rock materials onsite all contain uranium mineralogy alongside mineralogy known to produce Acid Metalliferous Drainage. The long term storage of these materials needs to consider the management of both radiological and AMD risks.

6.3 Uranium contamination of soils

The CSA Global (2010) report identified areas with uranium concentration greater than 100 ppm. These values were a minimum of 100 ppm and were not quantified above this concentration. These areas were not sampled for any other radionuclides, and so it is not known what the levels of ^{226}Ra , ^{210}Pb or ^{210}Po are present. A sampling program should be instigated to sample for naturally-occurring radioactive material (NORM) at the areas that have been identified by the CSA Global report that are not being impacted on by the excavation plan. This program would be used to check that uranium levels are below all guideline values for radioactive wastes. Interestingly, much of the area identified as above 100 ppm uranium lies over undisturbed bushland. This may indicate the presence of the zone of mineralisation.

6.4 Mt Burton and Mt Fitch

Mt Burton has had a basic radiation survey performed on-site. This survey revealed where the elevated areas of radiation were situated. All Mt Burton materials are scheduled for relocation from the current stockpiles to the main new storage facilities at Rum Jungle site. A radiological close-out survey should be performed after the relocation of material to the new storage facilities.

Mt Fitch has a very small amount of waste and will be pushed back into the pit from where it came. It is recommended to conduct a basic radiological survey and assessment on the area post-rehabilitation work. This would involve collecting a small gamma radiation survey and the identification of any other areas that had any radiation contamination issues.

6.5 Dose assessments for Rum Jungle

- **Critical Group 1 (construction workers):** Estimates of maximum annual doses for project construction workers are provided in Section 4.3. When construction activities on site begin, worker monitoring of the various exposure pathways will need to be incorporated into the OH&S management plan for the site. The dust inhalation pathway and the gamma exposure pathway will become more important. A Radiation Monitoring Plan should be a substantial part of the health, safety and environmental management system and include the radiation exposure monitoring of workers and environmental monitoring at areas off site.
- **Critical Group 2 (Traditional Owners):** Taking into account the ceremonial, tourism or any future potential customary harvesting activities, potential radiation doses received by accessing the site do very much depend on site use, site use expectations and dietary habits of the people. Without taking into account the ingestion of radionuclides via food items or water, hypothetical occupation of the area in the vicinity of the Acid Dam in the dry season for 5 months, Bollhöfer et al (2007) reported that this would result in a total above background annual dose of ~5 mSv.
- **Critical Group 3 (people living downstream):** With a hypothetical group of people (Aboriginal and non-Aboriginal) living 5 km downstream receiving the bulk of the dose from ingestion of aquatic food items. The aquatic pathway should be studied and then fed into a dose assessment mode of this group and the dose calculated from this data.
- **Critical Group 4 (general members of the public):** Established as totaling less than 1 mSv per year.

7 CONCLUSION

The location, extent and depths of radioactive material that need to be included within the excavation plan for the remediation strategy are depicted in Figure 6.

Before the commencement of any stage of the rehabilitation operation, a Radiation Management Plan (RMP) for the operation must be devised and presented to the relevant regulatory authority for approval. The Plan must be directed towards meeting the objectives of *ARPANSA Code of Practice for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing* (2005) and must be in accordance with best practicable technology and consider all the potential dose delivery pathways.

As part of the RMP a Radioactive Waste Management Plan (RWMP) will be developed to provide for the proper management of the low level radioactive waste arising from the project. Before the commencement of the operation, the RWMP for the operation will be presented to the relevant regulatory authority for approval as part of the RMP.

It can be seen from the data gathered in this report that there is still work that needs to be done to inform the dose assessment for potential future post-rehabilitation land use.

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