RADIATION PROTECTION PLAN & RADIOACTIVE WASTE MANAGEMENT PLAN

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Project Name: Nolans Rare Earths

REVISION HISTORY

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July 2022	Rev 1	Issued to DITT	Michael Robinson ESG Manager	Michael Robinson ESG Manager	Stewart Watkins GM Projects
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1.0 INTRODUCTION

This document is the combined Radiation Protection Plan and the Radioactive Waste Management Plan (collectively referred to as the RMP) for the Arafura Resources (Arafura) Nolans Project (the Project). It has been written by Arafura's radiation advisor [redacted] BSc, GDipOHM, MAppSci, MARPS, MEIANZ, MAusIMM) of JHRC Enterprises Pty Ltd of Stirling, South Australia, in collaboration with Arafura.

This RMP is intended for use during the construction, commissioning and initial operation of the Project, and it will undergo review at relevant times to ensure that it remains pertinent.

The Project aims to mine and produce rare earth concentrates for market. The mineralisation is known to contain elevated concentrations of naturally occurring uranium and thorium which will be concentrated during the processing of ore.

The purpose of the RMP is to outline the plans, systems and methods that will be used by Arafura to ensure that workers, the public, and the environment are protected from any harmful effects of radiation that may arise due to operations. It is important to note that the deposit (mine site) exists in an area with naturally elevated concentrations of uranium and thorium, and therefore has an elevated natural background radiation level. The proposed accommodation village, processing plant area, tailings storage area and bore field sites exist in areas where the natural background is lower than that in the mine area.

It is noted that radiation can elicit emotional responses and is sometimes misunderstood. Attachment 1 of this document provides an Introduction to Radiation, for information purposes.

The potential radiological impacts of the Project were investigated in detail in the Environmental Impact Statement, [ARAFURA 2016] and it was shown that radiological impacts would be low, with predicted miner doses less than 5mSv/y and processing plant workers of the order of 1mSv/y. it was also concluded that doses during operations would be maintained As Low As Reasonably Achievable through effective design controls and administrative processes.

It is relevant to note that measures required for control of radiation in rare earths mining and processing are very similar to those required in mineral sands mining and processing and are well understood by the mining industry.

2.0 REFERENCES

2.1 International Codes and Standards

Reference	Details
ARPANSA 2005	The Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing Radiation Protection Series. Canberra. RPS 9.
ARPANSA 2019	Code of Practice for the Safe Transport of Radioactive Material. Melbourne. Radiation Protection Series.
Arafura 2016	Nolans Environmental Impact Statement Appendix P Radiation Report March 2016
DMP 2010	WA Govt, 2010, 'Managing naturally occurring radioactive material (NORM) in mining and mineral processing guideline', Government of Western Australia DMP, Monitoring NORM - Airborne radioactivity sampling
ERICA 2021	http://erica-tool.com/ (accessed July 2021)
ICRP 1977	Recommendations of the ICRP, Publication 26. Ann. ICRP 1 (3)
ICRP 2007	The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37 (2-4)
ICRP 2017	ICRP, 2017. Occupational Intakes of Radionuclides: Part 3. ICRP Publication 137. Ann. ICRP 46(3/4).
IAEA 2014	Radiation Protection And Safety Of Radiation Sources: International Basic Safety Standards. General Safety Requirements Part 3 No. GSR Part 3— Vienna: International Atomic Energy Agency,
UNSCEAR 2000	Annex B: Exposures from natural radiation sources, United Nations Scientific Committee on the Effects of Atomic Radiation, New York
UNSCEAR 2000b	UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes UNITED NATIONS New York, 2000 VOLUME I: SOURCES

3.0 ABBREVIATIONS AND DEFINITIONS

3.1 Abbreviations

Abbreviation	Meaning
Arafura / ARU	Arafura Resources Limited
ALARA	As Low As Reasonably Achievable
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ERICA	Environmental Risk from Ionising Contaminants
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
NORM	Naturally Occurring Radioactive Material
OSLD	Optically Stimulated Luminescence
PTW	Permit-to-Work
RP Act	Radiation Protection Act
RPP	Radiation Protection Plan
Statutory RSO	Statutory Radiation Safety Officer
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WI	Work Instructions
Bq/cm2	Becquerel per square centimetre
m3/h	Cubic metres per hour
mSv/y	Millisievert per year
µJ	Microjoule
mJ	Millijoule

4.0 BACKGROUND

4.1 Approach to Radiation Protection

Radiation and its effects have been studied for more than 100 years, and there is international consensus on its effects and controls. The main organisations that oversee radiation and radiation protection and provide guidance and standards are:

- The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), which provides a consolidated overview of the effects of radiation by regularly reviewing research and publishing the summaries. UNSCEAR provides the scientific basis for radiation protection.
- The International Commission on Radiological Protection (ICRP) is recognised as the pre-eminent authority on radiation protection and has developed the philosophy for radiation protection and publishes recommendations on radiation protection. ICRP provides the philosophical basis for radiation protection.
- The International Atomic Energy Agency (IAEA) develops and publishes industry standards and guides and provides advice on basic safety precautions when dealing with radiation for both operators and regulators. The IAEA develops operating standards.

The standards and guidelines established at an international level are adopted in Australia as National Standards and Codes of Practice, through the work of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). The national standards are then taken up by Australian States and Territories as necessary and enacted in legislation or are enforced through conditions of licence.

The basis of radiation protection regulation is outlined in ICRP Publication number 26 [ICRP 1977], in which the ICRP first recommended the *system of dose limitation*. This is recognised as the internationally accepted approach to radiation protection and is universally adopted as the basis of legislative systems for the control of radiation. It is made up of three key elements as follows:

- Justification – this means that a practice involving exposure to radiation should only be adopted if the benefits of the practice outweigh the risks associated with the radiation exposure.
- Optimisation – this means that the protection mechanisms for radiation protection have been optimised so that doses are *As Low As Reasonably Achievable*, taking into account economic and social factors. This is also known as the *ALARA* principle.
- Limitation – this means that individuals should not receive radiation doses greater than the prescribed dose limits.

The ALARA principle is generally regarded as the most important and the most effective of these elements for the control and management of radiation.

While the ALARA principle is the foundation for radiation protection, radiation dose limits have been established to provide an absolute level of protection. The limits apply only to the radiation dose received as a result of a *practice* and excludes natural background radiation. The limits are:

- 20 mSv/y for a worker (whilst at work), and
- 1 mSv/y for a member of the public (total year).

Radiation protection is regulated in the Northern Territory under the Radiation Protection Act (RP Act) (2004) and Regulations (2007) and the requirements of the Mining Management Act and Work Health and Safety Act. Arafura has committed through the EIS [Arafura 2016], to abiding by Territory, National and International standards for radiation protection.

4.2 Radiation Management Requirements

This RMP follows the structure outlined in the ARPANSA Mining Code [ARPANSA 2005]. The key components of the radiation protection and waste management requirements are as follows:

- A description of the operations and the measures that are intended to be taken to control the exposure of employees and members of the public to radiation.
- An outline of the processes generating radioactive waste, and a description of the radioactive waste generated.
- A description of the system for radioactive waste management.
- Demonstrated access to appropriate professional expertise in radiation protection, and details of appropriate equipment, staffing, facilities and operational procedures.
- A plan for monitoring radiation exposure and for assessing the doses received by workers and the public.
- A program for monitoring the concentration of radionuclides in the environment.
- Details of induction and training courses.
- A plan for dealing with incidents, accidents and emergencies involving exposure to radiation.
- Circumstances which might lead to an uncontrolled release of radioactive material to the environment and contingencies for mitigating / managing the release.
- Details of record keeping and reporting, including personal dose monitoring and a schedule for reporting on the operation and results of monitoring and assessments required by this plan. Record will be kept in accordance with regulatory requirements.
- A system of periodic assessment and review of the adequacy and effectiveness of procedures.

4.3 Requirements of the Northern Territory Radiation Protection and Control Act and Regulations

The requirements for radiation protection in the Northern Territory are outlined in the Radiation Protection Act 2004 and Regulations 2007 (in force as of 2012). The requirements for the transport of radioactive materials are outlined in the Radioactive Ores and Concentrates (Packaging and Transport) Act 1980, and Regulations.

The Arafura mine and processing facility is subject to the requirements of the Act and Regulations, requiring a licence and an approved Radiation Protection Plan (RPP). Arafura will seek a licence in accordance with Part 3 of the Act and provide this RPP as part of the approval process. It is noted that other licences will be required, including:

- Licence for a radiation source

- Registration of a radiation source
- Registration of place where a radiation source will be used or stored
- Disposal of radioactive waste, including general contaminated waste and tailings
- Licences for any radiation apparatus, including XRF equipment and radiation density gauges.

This Arafura Resources Nolan Bore Project Radiation Protection Plan incorporates the requirements of the following:

- The Northern Territory Radiation Protection Act and Regulations
- The ARPANSA Mining Code

5.0 DESCRIPTION OF PROJECT

5.1 Overview

Arafura is proposing to develop and operate the Project approximately 135 kilometres (km) north-northwest of Alice Springs in the Northern Territory. The Project is situated approximately 10 km west of Aileron Roadhouse. The access to the Project site will be from the Stuart Highway, south of Alyuen community. The majority of the Project site is situated on the Aileron Perpetual Pastoral Lease (PPL 703), with the exception of the western part of the borefield area, which is situated on the Napperby Perpetual Pastoral Lease (PPL 747/748).

The Project comprises an open pit mine at Nolans Bore, an associated concentrator and processing plant, with ancillary facilities including a waste rock disposal facility (WRD), tailings storage facility (TSF) for the beneficiation tailings, and residue storage facilities (RSFs) for waste from the processing plant. There will also be a water-supply borefield, gas-fired power plant and accommodation village. The Project plans to produce an average of approximately 1.0 Mtpa of ore, increasing to 1.5 Mtpa later in mine life and approximately 5 Mtpa of other materials (including low grade mineralisation and waste rock), with staged increases to 8 and 10.5 Mtpa. The ore will be beneficiated to produce a concentrate that will be treated in the processing plant which will reject radionuclides to the processing plant residues to produce approximately 5,000 tpa of rare earth oxides and 144,000 tpa of merchant grade phosphoric acid for export.

Life of mine (LoM) is expected to be 38 years, with opportunities to extend beyond this.

The Project site comprises four areas linked by access roads and pipelines;

- The mine site,
- Processing site,
- Accommodation village, and
- Borefield.

5.2 Radiological Characteristics of the Project

Mined material will be trucked from the mining operations to one of four locations, based on material type:

- Material defined as *ore* will be delivered to the plant run-of-mine stockpile for processing.
- Material defined as *low grade mineralisation* will be stored pending potential future processing decisions.
- Material defined as *NORM waste* will be placed in the centre of the WRD, where it will be progressively covered by inert waste material.
- Material defined as *benign or inert clean* material will be used to form the outer cover of the WRD, with some separately stored for final closure cover material.

The definition of NORM waste is material with naturally occurring uranium and thorium concentrations that exceed 80ppm and 240ppm respectively.

A key aspect of operations is the management of mined material with appropriate sorting to optimise feed to the processing plant, and to differentiate benign material from NORM waste and low grade mineralised materials.

The main process streams and their radionuclide concentrations are detailed in Table 5-1 [Arafura 2016]. As can be seen, a number of process streams are expected to contain elevated concentrations of radionuclides.

Table 5-1 Radionuclide Concentration in Various Process Streams

Radionuclide	Radionuclide Concentration Solid (Bq/g) Liquid (Bq/mL)					
	Ore	Beneficiation Concentrate [2016]	Beneficiation Tailings [2016]		Residue Facility Tailings [2019])	
	Solid	Solid	Solid	Liquid	Solid	Liquid
Th-232	9.6	19.0	5.0	0	8.3	96.1
Ra-228	9.6	18.0	5.5	0	10.5	28.4
Th-228	9.6	19.0	5.0	0	9.5	77.2
Ra-224*	9.6	19.0	5.0	0	9.5	77.2
U-238	2.1	4.5	1.0	0	2.8	17.8
U-234	2.1	4.6	0.9	0	3.0	17.0
Th-230	2.1	5.5	0.5	0	4.7	36.7
Ra-226	2.1	4.8	0.8	0	2.3	2.6
Pb-210	2.1	5.1	0.7	0	2.6	0.9
Po-210	2.1	4.5	1.0	0	2.0	0.5
Ac-227	0.0	0.0	0.0	0	0.0	5.8

* Inferred from Th-228 [Year of material analysis]

The final products have not been included in Table 5-1 because they are not defined as *radioactive*, as their radionuclide concentrations are less than 1 Bq/g.

5.3 Predicted Potential Doses

Exposure to radiation occurs when there are radiation exposure pathways. For the Project, the primary radiation exposure pathways have been identified and are described as follows:

5.3.1 Gamma Irradiation

Gamma radiation is emitted from radioactive materials and depends upon the radionuclides in the materials and their concentration. Gamma radiation is usually controlled through:

- limiting time of exposure,

- separating the source of material from people, and
- shielding where necessary.

Gamma radiation results in exposure inside the body from a source that is outside the body. Gamma radiation levels can be predicted, based on empirical relationships between the different radionuclide concentrations and gamma radiation levels. Gamma radiation is also readily measurable.

5.3.2 Inhalation of long-lived radionuclides in dust

Dusts can contain different radionuclides which can be inhaled. Depending upon the dust particle size and solubility of the radionuclides, the dose received from the inhalation can vary. The dose from dust inhalation is generally due to the longer lived radionuclides in the dusts which can continue to emit radiation until cleared from the body. The chemical characteristics of the radionuclides mean that they can be transported to different parts of the body through normal biokinetic processes. For predictive modelling, conservative default values are used when making dose assessments. During operations, dust inhalation can be measured, through monitoring. The radionuclide characteristics of the dust can also be measured, or a knowledge of the process that generated the dust can be used to determine the characteristics.

5.3.3 Inhalation of radon and thoron decay products

Due to the presence of both uranium and thorium in the Project materials, there will be two isotopes of radon present. Radon-222 (known as radon) and radon-220 (known as thoron). Each of these radon isotopes decays to produce short lived decay products which can be inhaled and deliver an immediate dose in the lungs. The doses that arise from the inhalation of the isotopes of radon are treated differently from the doses received through inhalation of radionuclides in dusts. This is because the radon isotope decay products are short lived, while the radionuclides in dust are long lived. (In this RMP, the term *radon* refers to the Rn-222 isotope and the term *thoron* refers to the Rn-220 isotope).

5.3.4 Surface contamination (as a source of potential ingestion of radionuclides).

Ingestion of radionuclides can occur when radioactive contamination is, for example, transferred from dirty hands to food. The ingestion pathway is generally a low exposure pathway and not usually considered in worker dose assessment, unless an incident occurs where there is exposure. For the public, the ingestion pathway is considered and occurs when radioactive emissions from the Project deposit in the environment and are taken up into the food chain. The ingestion dose pathways can be predicted from air quality modelling before an operation commences and can be monitored during operations through deposition monitoring.

As part of the EIS [Arafura 2016], dose estimates were made for workers and the public. Worker doses were estimated to range between 1 and 3 mSv/y for mine workers and 1.3 mSv/y for processing plant workers. For workers in the mine village, doses were estimated to be approximately 0.1 mSv/y. For members of the public, the maximum dose was estimated to be 0.06 mSv/y for residents of Aileron Roadhouse, with residents of Alyuen Community and Alice Springs < 0.06 mSv/y.

Since the publication of the EIS in 2016, new dose conversion factors for the inhalation of radon decay products, and for the inhalation and ingestion of radionuclides have been published [ICRP 2017].

Due to the relatively low predicted doses, estimates have been made of the changes in the predicted doses due to the changes, rather than completely re calculating the predicted doses. The changes can be seen as follows:

- Radon decay products – factor increases by 2.5
  Note that this change was already taken into account in dose estimates for the EIS because the change was imminent at the time of publication of the EIS.
- Thoron decay products – factor increases by 2.5.
- Inhalation of uranium decay chain radionuclides;
  - Workers – Approximate 5 fold increase, and
  - Public – 2 fold increase.
- Inhalation of thorium decay chain radionuclides;
  - Workers – 3 fold increase,
  - Public – slight increase (considered negligible).
- Ingestion of radionuclides – overall, all factors decrease.

Based on the change in dose factors, the estimated doses continue to remain low and are as follows.

- Mine workers – up to 5 mSv/y
- Processing plant workers – up to 2.5 mSv/y
- Mine village workers – up to 0.2 mSv/y
- Residents of Aileron Roadhouse – up to 0.09 mSv/y
- Residents of Alyuen Community and Alice Springs less than 0.05 mSv/y

6.0 CONTROLS FOR RADIATION

6.1 Design Controls for Operations

The specific design controls to be implemented for the project are as follows.

6.1.1 Sorting Of Mined Material

To ensure that mined material is properly sorted, and that material with low uranium and thorium levels is segregated and stored for final closure, controls are planned as follows:

- The primary control will be mine planning which will identify areas where radioactive mineralised material exists. Confirmatory grade control will complement the planning.
- A radiometric sorter will be installed in a suitable location, to assist with sorting of materials.
- Detailed procedures for the use of the radiometric sorter will be developed to ensure that the effects of natural background are minimised.

Note that material for closure is intended to have naturally occurring uranium and thorium concentrations that are below the criteria for being defined as radioactive.

6.1.2 Mining Operations

Arafura will implement standard management controls to ensure that doses remain low. These are as follows:

- Restricting access to the main mining areas to ensure that only appropriately trained and qualified personnel are able to access the work areas.
- Ensuring that all heavy mining equipment is air conditioned to minimise impacts of dust.
- Minimising dust using standard dust suppression techniques (wetting of materials before handling, wetting of roadways, provision of dust collection systems on drills) and protective measures to reduce subsequent exposure (use of respiratory protection).
- Monitoring the levels of dust generated during tipping of material onto stockpiles, and implementing standard dust control techniques as necessary.
- Establishment of a clean and dirty boundary for personnel, vehicles and machinery.
- Separate wash-down pad within the site area for vehicles that have exited the mine area.

6.1.3 Concentrator and Processing Plant

The material will be both wet and dry, requiring specific design considerations for dust control and spillage containment. Controls include the following:

- Crushers and conveyor systems fitted with appropriate dust control measures such as dust extraction.
- Consideration of enclosed facilities, during design, to ensure that dust emissions are minimised.
- Use of scrubbers or bag houses where appropriate.
- Bunding to collect and contain spillages from tanks containing radioactive process slurries, with bunding to capture at least the volume of the tank in the event of a catastrophic failure.
- Tailings is a slurry containing up to 50% water and the tailings pipeline corridor will be bunded to control spillage from pipeline failures.
- Sufficient access and egress for mobile equipment to allow clean-up where there is the possibility for large spillages.
- Wash-down water points and hoses supplied for spillage clean-up.
- Procedures to control exposures during the maintenance of the ventilation systems and plant work.

6.2 Induction, Training, and Information

All employees and contractors will receive an induction upon commencement (with an annual refresher), informing them of the hazards associated with the workplace. The induction will include an introduction to radiation, controls to ensure radiation safety and responsibilities of personnel. Specific training will be provided to personnel involved in the handling of process materials containing elevated levels of radionuclides, including in-pit workers.

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

Information on radiation will be made available, to new workers, as required, and a key role of the Radiation Safety Officer and staff will be communicating all aspects of radiation. At the completion of the reporting years, workers will receive a formal communication about their radiation exposures for the previous year.

The inductions and training would be undertaken by qualified trainers under the instruction of the Project Radiation Safety Officer.

6.3 Record Keeping

A computer-based data management system will be used to store and manage all information relating to radiation management, monitoring and worker doses.

Periodic reports will be prepared from information stored in the electronic database. Regular dose reports will be provided to workers and upon request.

All new workers will be asked about previous experience in radiation workplaces, and a record of any previous exposures will be obtained where appropriate.

All records will be maintained for the life of the Operation and worker dose information will be made available to the ARPANSA National Dose Registry on an annual basis as required.

6.4 Accident, Incident and Emergency Response

The Project will establish and maintain a site-wide Emergency Response Plan which will be further developed as the project progresses. Within this plan would be the provision for accidents and incidents involving radioactive materials, including density probes and density gauges.

It should be noted that it is highly unlikely that there would be an incident resulting in harm due to radioactivity, due to the low concentration of radioactivity in the ore and products.

Potential incidents have been identified as follows:

- Radiation monitoring, either routine or investigative, identifying elevated radiation levels, which would be considered an incident within the Arafura incident management system, and therefore be investigated, with remedial actions implemented.
- Loss of containment of radioactive tailings or residues resulting in environmental contamination. The potential radiological risk from such an event is very low and was assessed by Arafura during the EIS process.

Where an incident occurs that results in an exposure to a worker, an incident dose assessment will be made by the Radiation Safety Officer. This will involve the Radiation Safety Officer investigating the incident and determining a conservative dose estimate. If the incident involved a worker, then the incident dose estimate will be filed with the workers dose records.

6.5 System of Review

An annual review of the RMP will include the following:

- Assessment of the monitoring results and review of monitoring program.
- Consideration of any changes that have occurred over the previous 12 months and potential radiological impacts.
- Review of the effectiveness of the radiation protection controls.
- Confirmation of work area classifications.
- Identification of improvement opportunities.

The annual review will be an internal review with a summary provided to the relevant regulatory authority. Any changes to the RMP identified through the review would be subject to regulatory authorisation.

Arafura will undertake an external audit of the RPP at least every five years and at a frequency agreed to by the regulatory Authority. The external audit would be conducted by a recognised radiation protection practitioner.

6.6 Reporting

An Annual Radiation Report will be prepared which will cover the following;

- Summary of monitoring results,
- Discussion on trends in the data,
- Investigation reports into anomalous monitoring,
- Details of any incidents or accidents,
- Details of any changes in monitoring or monitoring methods, and
- Outcomes of any reviews.

The Annual Radiation Report would be made available to the Regulatory Authority.

6.7 Transport Requirements

Any radioactive materials that require transport from site (for example samples for analysis), will be transported in accordance with the ARPANSA Transport Code [ARPANSA 2019]. Transport of radioactive materials will be authorised by the appropriately qualified officer of the company.

6.8 Clearance Check for Tools and Equipment Leaving Project Area

All vehicles or equipment leaving site, that have been used in the mining operation or in the processing plant, will be required to be washed by the relevant item owner, and then checked for radioactive contamination by suitably trained personnel. If free from contamination, a certificate will be issued, and the item will be allowed to be removed from site. Washing, cleaning and obtaining a radioactive contamination clearance is the responsibility of the user of the equipment, whether they are company staff or contractors.

No item from the mining operation of processing plant will be allowed to leave site without a certificate of clearance or documentation as required by the Transport Code [ARPANSA 2019].

Radiation Clearance Certificates will be issued for items that are permanently leaving site, such as hire equipment items being returned to owners, earthmoving equipment and departing drill rigs. Copies of the certificates will be kept on file for future reference. An item will be defined as not contaminated when there is less than 0.4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters and less than 0.04 Bq/cm^2 for all other alpha emitters as defined in the ARPANSA Transport Code [ARPANSA 2019]. Equipment that cannot be cleaned below this level will be subject to controls as defined by the Radiation Safety Officer.

6.9 Safety Systems

Arafura will establish and maintain a safety management system for operations. Radiation is one of the hazards considered in the system. Specific safety system controls that will include radiation hazards are as follows.

- Work Instructions (WI) will be developed for routine tasks, based on job hazard analysis, and radiation hazards will be considered in their development.
- Permit-to-Work (PTW) process will ensure that appropriate steps are taken to identify hazards and risks to people, environment and equipment.
- Job Hazard Analysis (JHA) process will be used for situations when a WI is not available. The JHA serves the same function as a WI, which is to document how to complete a task in a step-by-step process, with hazards and controls identified and documented at each step. Authorisation of JHA shall be gained before commencing the task.

6.10 Classification of Work Areas and Workers

The Mining Code provides guidance on classification of workplaces for radiological purposes, as follows:

- A *controlled area* is an area to which access is subject to control, and in which employees are required to follow specific procedures aimed at controlling exposure to radiation. Where workers may receive exposures above 5mSv/y, personal monitoring will be used.
- A *supervised area* is an area in which working conditions are kept under review but in which special procedures to control exposure to radiation are not normally necessary. Workers in the *controlled* areas are usually designated as *radiation workers*, and are subject to additional controls to ensure that their doses remain low. Workers in the *supervised* areas are unlikely to receive elevated doses, however their exposures and doses are monitored to ensure that the classifications remain valid. Monitoring of workgroups will occur.

For the project, the following areas will initially be defined as *controlled areas*;

- Mining area,
- Laboratory and sample preparation
- Core yard
- ROM pads and
- Processing area.

The remainder of the operations (including maintenance, stores and office areas) will be considered to be *supervised areas*. The classifications of the working areas will be reviewed as part of the annual reviews.

Depending upon work type and work areas, workers will be grouped into similar work groups for the purpose of dose assessment.

During construction of the Project, the workers will not be classified as *radiation workers* because it is unlikely that their doses will exceed 1 mSv/y. However, the workers will be subject to administrative controls and monitoring to ensure that their doses are less than 1 mS/y. Workers details and estimated doses will be recorded.

6.11 Site Access Control

Access to the main operational site would be through a secure site entrance (which may be a manned gatehouse or a remote-controlled recorded access/egress arrangement). The system will link to a record keeping system to ensure that all personnel accessing the site have been appropriately inducted and trained.

6.12 Change-rooms

The Project will have a changeroom arrangement to enable workers to change into *work clothes* at the commencement of their shift and then shower and change into *street clothes* at the end of their shift, as per the routine site requirements. This would be a general health and hygiene requirement and not just a radiation requirement.

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

6.13 Other General Controls

The Project would implement broader site-wide operational and administrative controls for radiation protection. These controls will include the following:

- Pre-employment medical checks.
- Development of safe work procedures, which include radiation safety aspects.
- Requirements for personal protective equipment (PPE), such as fit testing.
- Procedures to segregate, isolate and clean contamination or contaminated equipment.
- Mandatory use of personal hygiene facilities (such as boot wash and hand wash facilities) at entrances to lunchrooms and offices.
- Specific controls for pregnant workers.
- Specific controls for any laboratory based equipment that uses radiation (such as x-ray fluoroscopy).
- The final design of the plant is yet to be completed, and it has not been determined if radiation density gauges will be used. In the event that radiation density gauges are present on site, then they would be dealt with in accordance with legislative requirements for sealed sources.

6.14 Procedures and Work Instructions

The project would establish a set of radiation related work procedures that would be developed prior to operations commencing. These would include (and not be limited to), the following;

- Radiation Clearance Procedure for Equipment Leaving Site,
- Monitoring Procedures for:
  - Gamma Radiation,
  - Radionuclides in Dust,
  - Radon and Thoron Decay Product concentrations,

  - Surface Contamination, and
  - Environmental Radiation ,
- Radiation Density Gauge Clearance Certificate (if required),
- Radiation Monitoring Data Entry,
- Radiation Equipment Maintenance, and
- Confined Space Radiation Clearance.

Radiation control aspects will also be included in all procedures and work instructions.

7.0 RADIATION SAFETY EXPERTISE AND RESOURCES

Arafura will employ a suitably qualified and experienced radiation safety professional for operations as the Statutory Radiation Safety Officer (Statutory RSO).

The Statutory RSO will directly advise the site General manager (as licence holder) and will be with responsible for:

- Fulfilling the responsibilities of the Statutory RSO, as required by the regulatory authority.
- Overseeing the implementation of the RMP and its procedures.
- Ensuring that all regulatory requirements for radiation protection are met, and that related reports are submitted on time.
- Advising senior management on radiation protection requirements.

8.0 OCCUPATIONAL RADIATION MONITORING PROGRAM

8.1 Exposure Pathway Monitoring

The radiation monitoring is aligned to identifying and quantifying radiation impacts from the following radiation exposure pathways:

- Gamma irradiation,
- Inhalation of long-lived radionuclides in dust,
- Inhalation of radon and thoron decay products, and
- Surface contamination (as a source of potential ingestion of radionuclides).

8.2 Monitoring Program

Arafura will implement a two-stage monitoring program. The first stage will focus on start-up and commissioning, with the twin aims of confirming the preliminary dose estimates and also to ensure that the installed radiation controls are effective. The second stage will be focussed on the routine operations.

The Commissioning Radiation Monitoring Program is outlined in Table 8-1 and is expected to run for approximately three to six months or when the process is deemed to be stable. Once this point has been reached, a review of all monitoring would be undertaken, and a decision made on implementing the Routine Radiation Monitoring Program, as outlined in Table 8-2

Table 8-1 Commissioning Radiation Monitoring Program

Radiation Exposure Pathway and Monitoring Method	Mine	Processing Plant	Administration and Workshop Areas
Gamma radiation Survey with handheld monitor	Weekly areas surveys in mining operations areas, including mining face, truck unloading areas, go-line, maintenance areas, Monitoring to occur when ore reached,	Weekly walkthrough survey of all plant areas.	Monthly area surveys
Gamma radiation Personal OSLD badges	Monthly OSLD badges on all production miners (those involved with ore), Monthly OSLD badges on selected development miners (those not involved with ore), Monthly OSLD badges on selected support staff (such as maintenance personnel),	Monthly OSLD badges on all processing plant workers. Monthly OSLD badges on selected support staff (such as maintenance personnel),	
Airborne dust Sampling pumps with of determination filter paper dust mass and gross alpha	Five (5) x weekly personal dust sampling for: ▪ equipment operators ▪ maintenance personnel	Ten (10) personal samples each week. Ten (10) locational samples each week in selected work areas.	Monthly area samples
Radon and Thoron Decay Products Grab sample using the appropriate method	Selective real time continuous monitoring in mining area. Daily grab sample in each mining area.	Weekly grab samples in processing plant area.	
Surface Contamination Surface alpha and beta monitoring	Weekly survey of: ▪ workshop ▪ lunchroom	Monthly survey of: ▪ plant ▪ workshop ▪ lunchroom	Monthly area survey

Table 8-2 Routine Radiation Monitoring Program

Radiation Exposure Pathway and Monitoring Method	Mine	Processing Plant	Administration and Workshop Areas
Gamma radiation Survey with handheld monitor	Monthly areas surveys in mining operations areas, including mining face, truck unloading areas, go-line, maintenance areas.	Monthly walkthrough survey of all plant areas including conveyors.	Quarterly area surveys
Gamma radiation Personal OSLD badges	Quarterly OSLD badges on production miners (those involved with ore). Quarterly OSLD badges on selected development miners (those not involved with ore). Quarterly OSLD badges on selected support staff (such as maintenance personnel).	Quarterly OSLD badges on selected processing plant workers. Quarterly OSLD badges on selected support staff (such as maintenance personnel).	
Airborne dust Sampling pumps with radiometric and gravimetric analysis of filters	Five (5) monthly personal dust sampling for: ▪ equipment operators ▪ maintenance personnel	Ten (10) monthly personal samples Ten (10) monthly locational samples in selected work areas.	Monthly area samples
Radon and Thoron Decay Products Grab sample using the appropriate method	Selective real time continuous monitoring in mining area. Weekly grab sample in each mining area.	Monthly grab samples in concentrator area and hydrometallurgical area.	
Surface Contamination	Monthly survey of: ▪ workshop ▪ lunchroom	Monthly survey of: ▪ plant ▪ workshop ▪ lunchroom	Quarterly area survey

An overview of the monitoring methods is provided below, and monitoring methods and training will be developed to ensure that staff undertake monitoring in the correct manner.

Gamma Radiation

- Survey with handheld gamma monitor
- Personal gamma radiation badges
- For identified tasks, real time electronic gamma dosimeters will be used to provide immediate and detailed information for task management.

Radionuclides in Airborne Dust

- Low volume air sampling pumps with inhalable sampling heads will be used to collect an air sample onto a filter paper which would then we be gross alpha counted to determine the alpha activity concentration in air. The collected mass would also be measured to determine the mass concentration in air.

Radon Decay Product Concentrations

- Grab sample using the Borak method (note that that there are a range of methods available [DMP 2010]).
- Ingestion of Radionuclides
- Walkthrough surveys of workplaces, changerooms and offices will be conducted using a surface contamination probe.

8.3 Action Levels

If radiation measurements are at or above Arafura's Action Levels, then the Response, as detailed in Table 8-3 shall occur immediately. Note that the intention of the action level is to initiate an investigation, with the aim of identifying root causes. The method of investigation would be defined by the general site wide accident and incident investigation process.

Table 8-3 Site Wide Radiation Action Levels

Radiation Measurement Type	Action Level	Response
Gamma radiation (handheld)	5 µSv/h	Investigate and identify source. Consider additional shielding. Provide real time electronic monitoring.
Gamma radiation (OSLD) (monthly result)	1.5 mSv	Investigate and identify source.
Radon/thoron decay product concentrations	2µJ/m^3	Increase monitoring – if levels do not reduce, consider PPE

Radiation Measurement Type	Action Level	Response
Surface Contamination	Visual contamination and/or 0.4 Bq/m^2 ($\alpha+\beta$)	Immediate clean up.
Airborne Dust	0.2 Bq/m^3	Identify source and review controls. Investigate additional controls.
Total Dose	2.5mSv per quarter	Investigate exposure pathways and review controls

8.4 Monitoring Equipment and Support

Arafura will source appropriate monitoring equipment that is approved for use by the Regulator Table 5 provides a typical list of monitoring equipment. In addition, the monitoring programs would ensure the following:

- Recognised sampling methodologies that are documented and regularly reviewed are used, which include pre-operational checks.
- Procedures for routine instrument calibration, including regular traceable calibration checks and more frequent on-site calibration checks.
- An instrument maintenance and repair program is developed.

Table 8-4 List of Typical Equipment Required for Occupational Radiation Monitoring

Radiation Measurement Type	Sampling Methods and Equipment
Gamma radiation	• Hand-held gamma radiation monitor • Electronic dosimeters
Personal gamma monitor	• OSLD badges (provided and analysed by service provider)
Airborne Dust	• 2 L/min personal dust pumps fitted with approved *inhalable* filter holders • Microbalance for weighing of filters • Alpha slide drawer assembly and rate-meter
Radon and Thoron Decay Products	• Real time radon and thoron detectors • 2 L/min personal dust pumps fitted with approved *inhalable* filter holders

Radiation Measurement Type	Sampling Methods and Equipment
	• Portable alpha slide drawer assembly and rate-meter
Surface contamination	• Surface contamination probe and rate-meter

8.5 Dose Assessment Method

The method for calculating worker and public doses will be in accordance with the recognised international methods outlined by the ICRP [ICRP 2007], the IAEA [IAEA 2014] and in Australia by ARPANSA [ARPANSA, 2005] and a summary is provided here.

Total dose is calculated as the sum of the effective doses from each of the exposure pathways, which are;

- Irradiation by gamma radiation,
- Inhalation of the decay products of radon and thoron, and
- Inhalation of radionuclides in dust.

8.5.1 Gamma Radiation

OSLD badges are provided to workgroups and the average would be applied across the entire workgroup. When the results for an entire workgroup are not available (for example through a massive loss of badges), then estimates will be made based on the previous set of results. The estimates will be made by the Statutory Radiation Safety Officer who will take into account the work conditions during the period when monitors were not available. All assumptions will be recorded.

Individual results that are anomalous may be excluded from the overall workgroup average if there is good reason and this reason is formally justified and noted. For example, an outlier may be due to identified variances in work, tasks, hours or incidents which does not reflect the overall workgroup. Therefore, after investigation, the Statutory Radiation Safety may exclude this result and record the justification for its exclusion.

8.5.2 Radionuclides in Dust

The assessment of dose from the inhalation of radionuclides in dust can be complex. The recognised process considers such factors as the radionuclide composition of the dust, and characteristics of the dust (including particle size, solubility and biokinetics of the dust). Summary dose conversion factors (which are factors that convert an intake into a dose) are provided in Table 8-5 and are based on the most conservative solubility values provided by ICRP [ICRP 2017].

Note that dose conversion factors are provided for two particle sizes. It is anticipated that the dose assessment will use the more conservative 1μm factors. However, there may be circumstances where the factors for 5μm may be used and these will be determined and justified by the Statutory Radiation Safety Officer.

Table 8-5 Dust Dose Conversion Factors

Dust Type	Dust Dose Conversion Factor (μSv/αdps*)	
	AMAD = 1 μm	AMAD = 5 μm
Ore dust	6.0	3.5
Beneficiation Tailings	6.2	3.6
Beneficiation Concentrate	5.9	3.4
Processing Residue	5.4	3.1

* The unit αdps refers to *alpha disintegrations per second*' and is measured during gross alpha counting of dust filters.

When calculating a dust dose, the steps will be as follows:

- Determine an average long lived radionuclide concentration in air (in units of αdps/m^3), by averaging the activity concentrations for a number of dust samples for a particular workgroup.
- Multiply the average concentration by the exposure period in hours to determine an exposure (in αdps h/m^3) for the exposure period.
- Multiply by the standard breathing rate of 1.2 m^3/h to give an intake (αdps) for the exposure period.
- Multiply by the dust dose conversion factor to give a dose (μSv) for the exposure period.

8.5.3 Radon and Thoron Decay Products

The general method for calculating doses from exposure to radon and thoron decay products is based on determining an exposure and then applying a dose conversion factor. The ICRP have recently adopted a new dose conversion factor for radon and thoron decay products, and these are listed in Table 8-6. Note that a calculated average is included in this table as the ICRP dose conversion factors do not cover all workplace types.

Table 8-6: Radon and Thoron Decay Product Dose Conversion Factors

Project Area	Dose Conversion Factor (mSv per mJ.h.m^{-3})	
	Radon Decay Products	Thoron Decay Products
Mine	3.3	1.4
Indoor Workplaces	5.7	1.6
Average	4.5	1.5

When calculating radon and thoron decay product dose, the steps will be as follows:

- Determine an average radon and thoron decay product concentrations in air (in units of μJ/m^3), by averaging the activity concentrations for a number of filter samples for a particular workgroup. The sampling methods are referred to in section 6.2 of this document.

- Multiply the average concentration by the exposure period in hours to determine an exposure (in μJ.h/m^3) for the exposure period.
- Multiply by the standard breathing rate of 1.2 m^3/h to give an intake (μJ) for the exposure period.
- Convert μJ to mJ and apply dose conversion factor to give dose (mSv) for the exposure period.

9.0 ENVIRONMENTAL RADIATION

9.1 Monitoring Program

Arafura had undertaken environmental baseline monitoring since commencing exploration, and has an extensive database of measurements.

Arafura will aim to install a fixed network of Environmental Radiation Monitoring Locations (ERMLs). At each ERML, passive dust deposition samples will be collected and radon, thoron and gamma will be passively measured. The purpose of the ERML network is to provide a standard and regular method to monitor potential increases in environmental radioactivity due to the operation of the project. The monitoring results will be compared to the pre-operational results and reported annually. A high volume sampler may be used, where power is available on a rotation basis.

Monitoring procedures will be developed prior to installation of the monitoring network.

The ERML network will be established in a timely manner to ensure that two to three years of continuous baseline data is collected prior to the commencement of operations. The ERMLs will continue to function through the operation phase, and then continue post-closure. This will provide a continuous record of any impact that the operation is having on the environment.

The pre-operational baseline data will also provide the naturally occurring radiation levels that will be subtracted from the member of public doses estimates to ensure that only the Project increment is being reported.

Figure 9-1 shows the locations of existing environmental dust monitoring sites which are intended to be the locations of the ERMLs and outlines the monitoring that will be undertaken at each ERML.

Table 9-1outlines the monitoring that will be undertaken at each ERML

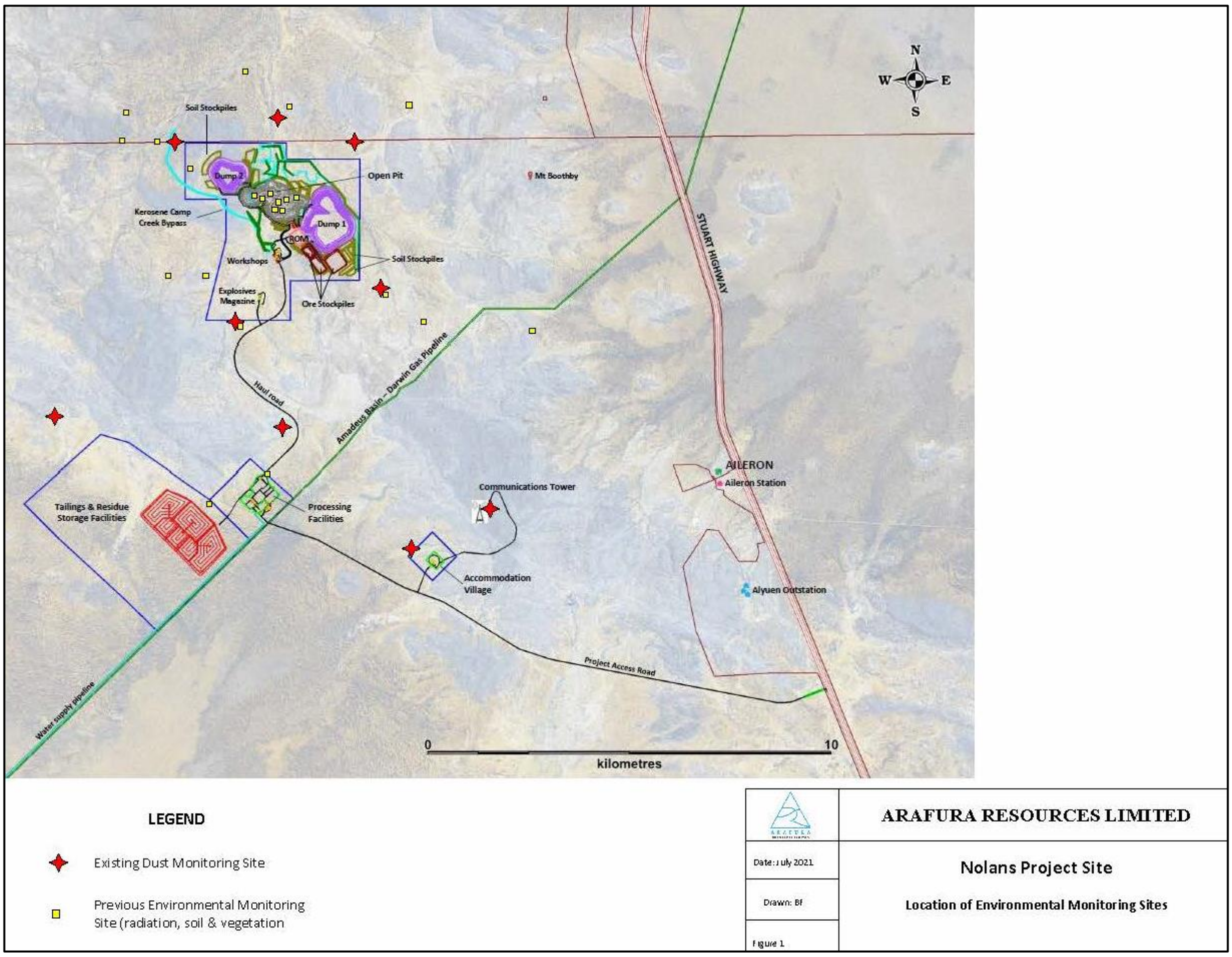

Figure 9-1 Location of ERMLS

Table 9-1 Environmental Radiation Monitoring Program at each ERML

Medium	Analysis Parameter	Monitoring at each ERML	Used for
Air	Gamma	Quarterly passive - Environmental OSL dosimeter	Identification of Changes
		At installation & every 3 years - Hand-held gamma meter	Identification of Changes
	Radon and Thoron	Quarterly	Identification of Changes Public Dose Assessment
	Dust suspended in Air Radionuclides - long-lived of U and Th decay chains	Rotational between off-site powered locations High Vol Sampler (power required)	Public Dose Assessment
Dust - naturally depositing from air	Radionuclides - long-lived of U and Th decay chains	Quarterly passive - mass Annual composite for radionuclides	Identification of Changes Non-human biota assessment
Soil	Radionuclides - long-lived of U and Th decay chains	At installation & Prior to closure	Identification of Changes Confirmation of Non-human biota assessment
Ground Water (GW)	Gross α + Gross β	As per GW program	Identification of Changes
	Elemental U and Th		
	Radionuclides - long-lived of U and Th decay chains	One-off selected bores	

Note that for dust deposition, elemental analysis of the dust can also assist in providing an indication of the source of the deposited dusts.

9.2 Impacts to Non-Human Biota

The recognised method for determining the impacts to non-human biota (NHB) is the ERICA assessment method (where ERICA is short for Environmental Risk from Ionising Contaminants: Assessment and Management). ARPANSA notes that the ERICA Software Tool is applicable for use in Australia for assessing radiological impacts to NHB [ARPANSA 2010]. The software uses changes in media radionuclide concentrations and species-specific whole-body concentration ratios, to provide a standardised measure of radiological impact to reference species.

The latest version of the ERICA software was released in June 2019 (version 1.3) [ERICA 2021].

Arafura undertook predictive ERICA modelling for the EIS which indicated that radiological impacts to non-human species would be low. To confirm the modelling and provide ongoing monitoring, Arafura will undertake annual ERICA assessments for standard species, including Australian specific species which have published concentrations ratios.

Assessments will be undertaken at locations defined by the location of the ERMLs. This is because the *media concentration* data, which is the foundation of an ERICA assessment, would be derived from annual composites of dust deposition monitoring results at the established ERMLs.

Established natural background radionuclide concentrations would be subtracted from the sample results to ensure that only Project originated materials are considered in the impact assessment.

ERICA assessments would commence once operations commence and be conducted annually initially, with the intention to reduce frequency of assessment to every 5 years if this is appropriate.

10.0 RADIOACTIVE WASTE MANAGEMENT

10.1 Process Waste Management

Arafura recognise that additional waste disposal licences are required under the Norther Territory Radiation Protection and Control Act and Regulations and intends to progress this.

The processing site plant will produce three individual residue streams:

- Beneficiation Residue (Tailings)
- Gypsum Residue (Gypsum)
- Water Leach Residue (WLR)

The combined tailings and residue storage facility (referred to as the RSF) will comprise two concurrently operating cells. Gypsum and beneficiation tailings will be combined and will report to a combined larger cell in the RSF. Decant water will be recycled to the beneficiation plant. The smaller poly-lined cell will store WLR, which is the neutralised residue from the extraction process including most of the thorium and uranium present in the processed ore, and also a mixture of other gangue elements, waste brine and separation plant residue.

Each cell will operate for approximately seven to nine years and then will be decommissioned, capped, and progressively rehabilitated. Deposition will continue in additional cells built immediately adjacent to the initial structures. After 23 years, the RSF will consist of three beneficiation tailings and gypsum residue cells, and three WLR cells covering an area of 240 ha. Over the current 38-year LOM, there will be six of each cell type, over 480 ha. Should the LOM be extended beyond this period, following further exploration and evaluation, this area may increase.

Beneficiation residue will be deposited into the purpose-built RFS as a slurry. Solids will settle out and excess water will be recovered during settling and returned to the process plant for reuse via decant towers located in each cell.

10.2 Contaminated Water

Water that has come in contact with mineralised material, such as stormwater runoff from the ore stockpile or processing plant, may contain entrained radioactive materials. The site is designed so that all surface water is collected and contained and does not flow from the site to surface water landforms. The method of control involves the construction of sedimentation dams, from which water can be reclaimed, and appropriate collection bunds and channels.

Wastewater from wash-down areas and clean-up water would also be captured for treatment and re-use or evaporation.

10.3 Contaminated Waste

This material includes equipment and wastes from operational areas, including equipment, steel, discarded conveyor belts, rubber lining material, pipes, filter media and used protective equipment, that is contaminated with radioactive ores or process materials. It is important to note that this section does not refer to routine waste that is not contaminated and which would be managed under the site landfill arrangements.

For contaminated waste, Arafura would implement a contaminated waste program which aims to minimise waste to be disposed of. Where practical, contaminated waste would be decontaminated and disposed of via normal waste disposal methods or sent for recycling. Where this is not possible and depending on the nature of the waste, several disposal options would be available as follows:

- Incorporation into the waste rock stockpile
- Disposal in a dedicated contaminated waste on-site landfill facility (note that this may be a separate area of the site landfill).
- Disposal into the mine at the end of operations

A system that retains records of the disposal, including type of material, quantities and locations of contaminated waste would be maintained.

In some specific circumstances, waste material may be contaminated to such an extent that it is classified as radioactive (i.e. the waste item activity concentration exceeds 1 Bq/g). In these circumstances, the waste would be prepared and disposed into an onsite dedicated radioactive waste facility.

11.0 CLOSURE CONSIDERATIONS

Note that inclusion of closure comments are provided for completeness. At closure, the site would be rehabilitated in accordance with the Mine Closure Plan, which provides extensive detail. From a radiological perspective, the aim is to ensure that post closure, the radiation levels in the region are consistent with the levels that existed prior to operations. This implies that following closure, the Project originated radiological risk would be negligible. The major rehabilitation feature from a radiological perspective is the RSF and the closure plan would detail the control aspects.

It is intended that contaminated plant and equipment would be cleaned and decontaminated (where possible) and moved off site for recycling. Where this is not possible, it is proposed that the remnant waste would be safely and securely disposed as noted in Section 8 in accordance with permit and approval requirements.

ANNEXURE A INTRODUCTION TO RADIATION

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

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

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

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

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

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

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

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

Radiation and radioactivity can be described in a number of ways. The most common way refers to refers to the amount of radioactivity is in a material (or how radioactive it is). This is described by its *activity* and is measured in the unit of *becquerel* (Bq), which is the amount of radioactive material that produces one radioactive decay per second. The *activity concentration* is the amount of radioactivity in a unit mass (or volume) of material and is measured in becquerels per gram (Bq/g) or per litre (Bq/L).

Another way of describing radioactivity is by the radiation *exposure*. Exposure refers to the amount of radiation received at a point or by a person. Radiation *dose* is then a standardised measure of the effect (or detriment) of exposure to the radiation and is measured in the units of *sieverts* (Sv). The unit of dose takes into account different types of radiation and different exposure situations. The sievert is quite a large unit of measure, and doses are usually expressed in millisieverts (mSv) (thousandths of a sievert).

Due to radiation being very common in nature, everyone is exposed to natural radiation throughout their life. This radiation comes from the rocks and soil of the earth, the air we breathe, water and food we consume, and from cosmic radiation from space. Natural background can vary considerably in different places in the world. While the world average dose is 2.4 mSv/y, the typical range is quoted as 1–10 mSv/y [UNSCEAR 2000].

In addition to natural background exposure, some people around the world are regularly exposed to radiation in their work and from leisure activities (such as flying) and in medical procedures. Table A1 shows the average annual dose for a range of different jobs.

Table A1: Occupational Radiation Exposures (in addition to natural background levels)

Source Practice	Average Effective Dose above Natural Background (mSv/y)
Industrial uses of radiation	0.5
Medical uses of radiation (doctors/nurses)	0.3
Air crew (from cosmic radiation)	3.0
Nuclear fuel cycle	1.8
Mining (other than coal)	2.7
Coal mining	0.7

Source: UNSCEAR 2000 Report Vol. I Sources and Effects of Ionizing Radiation

A major source of radiation exposure to the general public is medical exposure. Radiation is used extensively for diagnosis (such as x-rays) and treatment of disease. The average annual radiation dose from diagnostic medical procedures in developed countries is approximately 1.2 mSv/y [UNSCEAR 2000].

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

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

Several studies have found an increased risk of cancer among people exposed to moderate doses of radiation [UNSCEAR 2000]. The studies show that the risk increases as the radiation dose increases.

In general, none of the studies has been able to measure increases in cancer risk from exposures to low doses of radiation (below about 50 to 100 mSv), however, it is conservatively assumed that an increased risk does exist. This is called the linear non-threshold hypothesis.

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

The effective annual dose limits are 20 mSv/y for a radiation worker and 1 mSv/y for a member of the public.