SIERRA RUTILE PROJECT AREA 1

Environmental, Social and Health Impact Assessment:

Radiological Assessment & Gap Analysis

Sierra Rutile Limited

Control Status

Document No: SRLRM004

Document Title: SIERRA RUTILE PROJECT AREA 1 - ENVIRONMENTAL, SOCIAL AND HEALTH IMPACT ASSESSMENT: RADIOLOGICAL ASSESSMENT & GAP ANALYSIS

"CONTROLLED" stamped in red ink indicates a controlled and maintained copy. Otherwise this document is rendered as unmaintained.

This revision of the specification was:

Authored by:	Name:	Clasina Roodt	Signature:	
	Position:	Senior Environmental and Radiation Specialist	Date:	15/01/2018
Reviewed By:	Name:	Clovie Erasmus	Signature:	
	Position:	Senior Environmental and Radiation Specialist	Date:	15/01/2018
Approved By:	Name:	Anél Joubert	Signature:	
	Position:	Manager Environment	Date:	

Revision Status

Revision	Date	Purpose
1	15/01/2018	Draft
2	03/02/2018	Final
3		
4		

ACRONYMS

α	Alpha
ß	Beta
γ	Gamma
a	Annum
AG	Acid Generating
ALARA	As Low as Reasonably Achievable
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
ASS/ML	Acid sulfate soil and metal leaching
Bq	Becquerel
C	Conductor or Concentrate
CET	Course Electrostatic Tails
CRP	Contamination Remediation Project
Cs	Cesium
DFC	Dose Conversion Factor
D1	Dredge Mining at Lanti
DM1	Dry Mining 1 (Gbeni / Lanti)
DM2	Dry Mining 2 (Gangama)
EPA	Environmental Protection Agency
ERICA	Environmental Risk from Ionizing Contaminants Assessment
ESHIA	Environmental, Social and Health Impact Assessment
ESIA	Environmental Social Impact Assessment
FEL	Front End Loader
FET	Fine electrostatic tailings
FPP	Feed Preparation Plant
g	Gram
h	Hour
HM	Heavy mineral
HMC	Heavy mineral concentrate
HTRS	High Tension Roll Separator
HTT	High Tension Tails
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IGR	Industrial Grade Rutile
IMDG	International Maritime Dangerous Goods
IP	Ilmenite Product
IT	Ilmenite Tails
K	Potassium
kg	Kilogram
l	Liter
LLAA	Long Lived Alpha Activity
LLD	Lower Limit of Detection
m	Meter or minute or milli as appropriate
MET	Medium Electrostatic Tails
MSP	Mineral Separation Plant
mSv	Millisievert
NAF	Non-acid forming
NAG	Net acid generation
NC	Non-Conductor

NORM	Naturally Occurring Radioactive Material
NSRPA	Energy Nuclear Safety and Radiation Authority
OEP	Occupationally Exposed Person
PAG	Potentially acid generating
pH	Measure expressing acidity or alkalinity of solution on logarithmic scale
ppm	Parts per million
Ra	Radium
RESRAD	Residual Radiation (modelling tool for human health risk assessment)
RMP	Radiation Management Plan
Rn	Radon
SGR	Standard Grade Rutile
SLEP (M&M) Regs 2013	Sierra Leone's Environmental Protection (Mines and Minerals) Regulations
SFT	Sulfur flotation tailings
SRK	SRK Consulting (South Africa) (Pty) Limited
SRL	Sierra Rutile Limited
Th	Thorium
TLD	Thermoluminescent Dosimeter
TSF	Tailings Storage Facility
TT	Total tailings
U	Uranium
WCP	Wet Concentrator Plant
WHO	World Health Organization
XRF	X-Ray fluorescence

EXECUTIVE SUMMARY

Sierra Rutile Limited (SRL), a wholly owned subsidiary of Iluka Resources Limited (Iluka), is an existing mining operation located in the Bonthe and Moyamba Districts of the Southern Province of Sierra Leone, 30 km inland from the Atlantic Ocean and 135 km south east (geodesic distance) of Freetown. The mine has been in operation for over 50 years and produces rutile, ilmenite and zircon rich concentrate. The SRL operation has an existing Environmental Licence (reference number EPA-SL030) and has undertaken two previous Environmental and Social Impact Assessment (ESIA) studies for their operations in 2001 and an update in 2012 respectively. When these studies were undertaken, the primary mining process was dredge mining (referred to as wet mining). During 2013, SRL commenced a distinct open cast mining operation (referred to as dry mining) as an auxiliary method of ore extraction in conjunction with wet mining. In 2016 a second dry mining operation (Gangama) was commissioned. It is anticipated that, over time, dredge mining will cease and dry mining would be the primary mining method employed.

The previous ESIA studies did not include the second dry mine expansion and contained limited information on the radiological aspects of operations at Area 1.The objective of the current study was to assess potential radiation pathways of exposure that relate to SR Area 1 operations, including a dose estimation for the workforce and members of the public in proximity to the operations. This study forms part of the current Environmental, Social and Health Impact Assessment (ESHIA) and Environmental, Social and Health Management Plan (ESHMP) for Area 1.

There are two main sources of radiation exposure in mineral sands mining and processing at SRL: man-made sources, i.e. density gauges, which are used in various processes of the operation to determine slurry densities; and naturally occurring radioactive materials (NORM) in the ore, products and tailings.

The Government of Sierra Leone Ministry of Energy Nuclear Safety and Radiation Authority (NSRPA) have issued two Certificates of Registration (licenses) to SRL for density gauges: APN-USE-0026/16 Authorization for possession and use; and APN-POS-001/16 Authorization for possession. Regular inspections are conducted by the NSRPA in which they assess the physical condition of all the sources and measure gamma radiation levels around the sources. To date, no exceedances of dose rate levels around sources were observed.

All density gauges at SRL are caesium-137 (Cs-137) sources in ceramic form, thereby being insoluble in water, even if the source encapsulation is compromised. Further to this, all SRL sources are classified as Category 4 and Category 5, thereby the most unlikely to be dangerous of all gauges used in industry. It would be virtually impossible for a souce in Caterogy 2 to 5 to contaminate a public water supply to dangerous levels.

SRL also has a radiation management plan (RMP) for sealed radioactive sources (2017) detailing the requirements for the safe storage; transport and use of portable and fixed industrial gauges. The purpose of the RMP is to ensure that all practices involving radiation gauges at SRL are conducted as safely as possible and in compliance with the Sierra Leone *Nuclear Safety and Radiation Protection Act 2012.* Compliance with the RMP ensures that the radiation doses to all employees, contractors and visitors to site are managed appropriately and below the prescribed statutory limits and are as low as reasonable achievable (ALARA). It also ensures that the number of people exposed to radiation, and the likelihood of unexpected exposure to radiation, are minimised.

The SR Area 1 operations involve the mining, processing and beneficiation of a heavy minerals sands ore bodies containing minerals with elevated concentrations of radionuclides of the uranium and thorium decay chains (NORM). The uranium and thorium radionuclides and their decay products are concentrated in the monazite and zircon minerals. As the monazite and zircon minerals are progressively concentrated through mining and upgrading processes, the uranium and thorium concentrations of some process streams will increase.

The enhanced radionuclide concentrations in ore bodies; mining; and processing operations will result in the radiation exposure of workers and, possibly, members of the public. Potential

exposure pathways for workers and members of the public include external gamma; radon inhalation; dust inhalation; and inadvertent soil ingestion. Members of the public could additionally be exposed to potential dose from water ingestion and other secondary pathways.

To investigate the risk of radiation exposure to fauna and flora, the ESHIA Faunal Assessment concluded that: "Ongoing impacts as a result of human occupation in the area are evident, largely in the form of slash and burn clearing activities in order to make way for agricultural crops. As such, the loss and modification of the faunal habitat as well as increased hunting pressures have had evident impacts on the abundance and diversity of faunal species within the study area. Mining activities within the study area have also been underway for the past 50 years, and as such has had a notable impact on the habitat and ecological drivers within the study area. Loss of forest habitat and the degradation of the watercourses and associated riparian habitat are evident, and had a notable impact on the faunal abundance and diversity of the study area".

Local villagers within SR Area 1 however own some goats; sheep; chickens and ducks, but cattle is not widely found or kept for domestic purposes. A single group of about five cattle were observed to roam mainly the mine tailings area at Mogbwemo historical dredge pond. The remainder of domestic animals mainly resides within the vicinity of the villages and do not regularly roam the mine site or tailings areas, with the exception of some goats. In light of this, cattle, sheep and goats were added to the list of reference animals and plants modelled in a preliminary ERICA assessment (biota modelling).

To quantify the risk, this modelling tool calculates the effective radiation dose rate to the various organisms and these values are then compared to a screening dose rate of 10 μGy/h. Where the ERICA tool shows a dose to an organism to be less than the screening level value, it can be concluded that there is no increased risk to the environment. Where this is not the case, a review of effects data specific to that organism should be undertaken to quantify if there is a potential risk, which would then require further assessment (Tier 2 or Tier 3).

The results from the current ERICA evaluation demonstrate that modelled dose rates for all fauna species exposed to process materials at SR Area 1 are below the threshold dose rate of 10 μGy/h. For mine Slimes tailings (cyclone overflow); HMC; MSP tailings and MSP products, flora species (with the exception of trees) are above the screening dose level. Lichen and Bryophytes are the most sensitive organisms, followed by Grasses and Shrubs respectively.

Based on Derived Concentration Reference Levels (DCRLs), flora species potentially only show effects of reduced reproductive success at levels of 10 – 100 mGy/day (equivalent to 417 to 4170 μGy/h). Preliminary DCRL's are set at 1 – 10 mGy/day (equivalent to 42 to 417 μGy/h), but at these levels, no effects to populations have yet been proven. For mine slimes tailings; HMC; MSP Tailings and MSP Products, Lichen and Bryophyte dose rates are in excess of 42 μGy/h, but still well below 417 μGy/h.

Further to this, it has to be noted that mineral sand tailings, as present around dredge ponds and active mining areas, are well sorted, with minimal fine particles present (with the exception of the slimes tailings which is the – 63 micron material fraction from the wet concentrator plant and mainly consistent of clay phases). Sand tailings have very low nutrient and water holding capacity and are unable to sustain plant growth.

It can therefore be concluded that the activity concentration levels contained within mine sand tailings, or areas contaminated with HMC; MSP tailings or products should not have a significant effect on fauna and flora populations present.

The current radiation assessment study determined that limited data is available on the uranium and thorium content of the ore and tailings streams at SR Area 1. Routine in-house XRF analysis is done on products and some of the tailings materials but currently, a quality control bench-marking exercise is underway to validate the accuracy of in-house analysis. Previous studies aimed at characterizing tailings materials have only evaluated gross alpha (α) and gross beta (β) content and to date, no full decay chain radionuclide analysis are available on any of the process streams.

Available analysis was used to estimate potential doses to workers and members of the public from relevant pathways of exposure. In the absence of suitable environmental data, assumptions about occupancy factors; inhalation rates; dust concentrations in air; dust particle size etc., were used to estimate radiation dose. It has to be noted however that the dose assessment is conservative in estimation, as the initial indications from the quality control benchmarking evaluation confirmed that the SRL in-house XRF thorium and uranium analysis are biased towards the higher end. Dust inhalation doses is further conservative in that a dust loading of 1 mg/m^3 (corresponding to a high dust loading) was assumed for calculation purposes and the initial air quality modeling data for the ESHIA (SRK, 2017a) indicated the maximum $PM_{2.5}$ dust loading to be 0.013 mg/ m^3 which is tenfold lower than the assumed value. This dust monitoring was however conducted during the wet season, and monitoring for the dry season is still required.

From the dose assessment conducted across all the operational sites at Area 1, it was determined that the largest contributing exposure pathway for workers is from external gamma, followed by dust inhalation. Inadvertent soil ingestion dose as well as radon inhalation dose was shown to be negligible contributors to total dose. The estimated dose to workers at mining and wet concentrator plants (WCP) operations was shown to be 0.1 mSv/y.

At the mineral separation plant (MSP) it was determined that the largest dose from an individual material would be incurred from exposure to zircon product. The zircon product however only constitutes 0.5% of the total material treated through the MSP; is bagged directly from the product chute (to mitigate dust exposure); and stored in an area of the plant with controlled access to workers, thereby limiting gamma exposure. The estimated annual dose for workers at the MSP is 1.49 mSv/y (excluding background), which is consistent with radiation doses of Iluka Resources Limited (Iluka) Australian operations, which record total annual doses below 5 mSv/y. The current personal gamma monitoring program conducted at SRL (TLD badges) to date has shown that doses are in line with those predicted from the dose assessment.

At the tailings storage area, it was determined that the largest dose from an individual material would be incurred from exposure to coarse electrostatic tails (CET). This dose would however be an over-estimate, as CET constitutes only 2.8% of the total tailings material stored in the area. Further to this, the only individuals exposed to radiation dose at the tailings storage area are the security guards which control access to the area (some distance away from the actual tailings stockpiles); front-end-loader (FEL) operators; dozer operators and truck drivers (some shielding provided by the machinery). The estimated annual dose for workers at the tailings storage is 1.19 mSv/y (excluding background) and the current personal gamma monitoring program conducted at SRL (TLD badges) to date have shown that doses are in line with those predicted from the dose assessment.

At Nitti Port, it was determined that the largest worker dose from an individual material would be incurred from exposure to zircon, followed by ilmenite. The estimated annual dose for workers at the Port is however 0.69 mSv/y (excluding background), as calculated from exposure to “reconstructed MSP products”.

All doses calculated for the workforce is an order of magnitude below the annual dose limit of 20 mSv/y, and in line with doses measured at Iluka Australian operations.

The estimated total dose for members of the public on roads or in villages close to dry mining; wet mining; WCP; MSP; Tailings; and Nitti Port is below the public exposure limit of 1 mSv/y.

The emanation of radon from heavy minerals has been found to be very low (KER 1988). In the open, any radon released from an ore body or a stockpile will be rapidly diluted in the atmosphere and dispersed. It is therefore likely that in open pit mining and associated processing, the radon levels will be comparable to ambient levels and this exposure pathway is not considered to be significant for workers or members of the public. It is however recommended to measure radon levels in air as part of the baseline surveys.

Drinking water for workers and some communities surrounding the MSP is provided by SRL. Members of the public also extract water for drinking purposes from wells in their villages and usually not from surface water sources. The location of drinking water wells for the public is far removed from the MSP or tailings storage facility. Even though the public make use of surface water bodies for swimming and bathing, such activities do not occur in close proximity to the MSP or tailings storage area. The amount of water accidentally ingested during swimming would also be minimal. Potential exposure of the public from ingestion of surface or groundwater, is not expected to be significant, but would nonetheless need on-going monitoring.

Surface and groundwater monitoring will be included as part of the overall environmental monitoring program. There may be some seasonal and regional variations, and these variations must be taken into account in assessing the possible long-term impacts of mining or mineral processing on surface and ground water conditions in the area.

The baseline monitoring program will include:

- radionuclide concentrations in soil across the current (and future) project areas through soil profile;
- radionuclide concentrations in tailings across the current project areas. Full radionuclide analysis of selected tailings streams for future human health and biota modeling purposes is also required;
- absorbed (radiation) gamma dose rates in air across the current (and future) project areas;
- radon (Rn-222) and thoron (Rn-220) concentrations in the air;
- groundwater radionuclide concentrations (incl. U, Th, Ra-226, Ra-228, gross alpha and beta);
- surface water radionuclide concentrations (incl. U, Th, Ra-226, Ra-228, gross alpha and beta); and
- long-lived alpha activity (LLAA) in airborne dust.

It is also proposed to conduct a complete ERICA assessment (biota modelling) once processing materials have been characterized in terms of full radionuclide analysis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

1. INTRODUCTION

1.1 The Project Area

Sierra Rutile Limited (SRL), a wholly owned subsidiary of Iluka Resources Limited (Iluka), is an existing mining operation located in the Bonthe and Moyamba Districts of the Southern Province of Sierra Leone, 30 km inland from the Atlantic Ocean and 135 km south east (geodesic distance) of Freetown (Figure 1.2). The mine has been in operation for over 50 years and produces rutile, ilmenite and zircon rich concentrate. The SRL operation has an existing Environmental Licence (reference number EPA-SL030) and has undertaken two previous Environmental and Social Impact Assessment (ESIA) studies for their operations in 2001 and an update in 2012 respectively. When these studies where undertaken, the primary mining process was dredge mining (referred to as wet mining). During 2013, SRL commenced a distinct open cast mining operation (referred to as dry mining) as an auxiliary method of ore extraction in conjunction with wet mining. In 2016 a second dry mining operation (Gangama) was commissioned. It is anticipated that, over time, dredge mining will cease and dry mining would be the primary mining method employed.

In 2015 the Environmental Protection Agency of Sierra Leone (EPA-SL) issued a notification to SRL (reference number EPA-SUHA.96/214/a/HNRM), instructing them to undertake an integrated Environmental, Social and Health Impact Assessment (ESHIA) and develop an Environmental, Social and Health Management Plan (ESHMP) for their current and proposed dry and wet mining activities, including the proposed expansion areas. SRK Consulting (South Africa) (Pty) Ltd (SRK) was appointed by SRL to undertake the ESHIA.

The previous ESIA studies did not include the second dry mine expansion and contained limited information on the radiological aspects of operations within SRL mining lease Area 1 (Area 1).The objective of the current study was to assess potential radiation pathways of exposure that relate to SR Area 1 mining; processing; and storage operations, including a dose estimation for the workforce and members of the public.

1.2 Climate

Climate, rainfall and wind data were obtained from the specialist air quality study conducted as part of the ESHIA by SRK Consulting (South Africa) (Pty) Ltd. (SRK, 2017a).

SR Area 1 is characteristically hot and moist during summer and cool and dry in winter. The Inter-Tropical Convergence Zone (ITCZ) influences the climate in the summer period bringing rain and during winter the trade winds dominate bringing a drier climate. Average temperatures are usually greater than 18 °C.

1.2.1 Rainfall

Rainfall is an important parameter with respect to air quality. During the rainy season, air pollution, and more specifically in this case, dust particles, are removed from the atmosphere. Dust emissions are suppressed due to increases in soil moisture content and increased vegetation cover during the rainy season. During the dry seasons, dust emission levels are generally higher.

The average rainfall for Area 1 mineral separation plant (MSP) is estimated to be around 2,800 mm/a; the wet season typically begins in May and ends in November with the highest average monthly rainfall reading of 651 mm (Figure 1.1). The dry season, beginning in December and ending in April, is characterized by low rainfall. The average rainfall during the dry season varies from a minimum of 6 mm in January to a maximum of 97 mm in April.

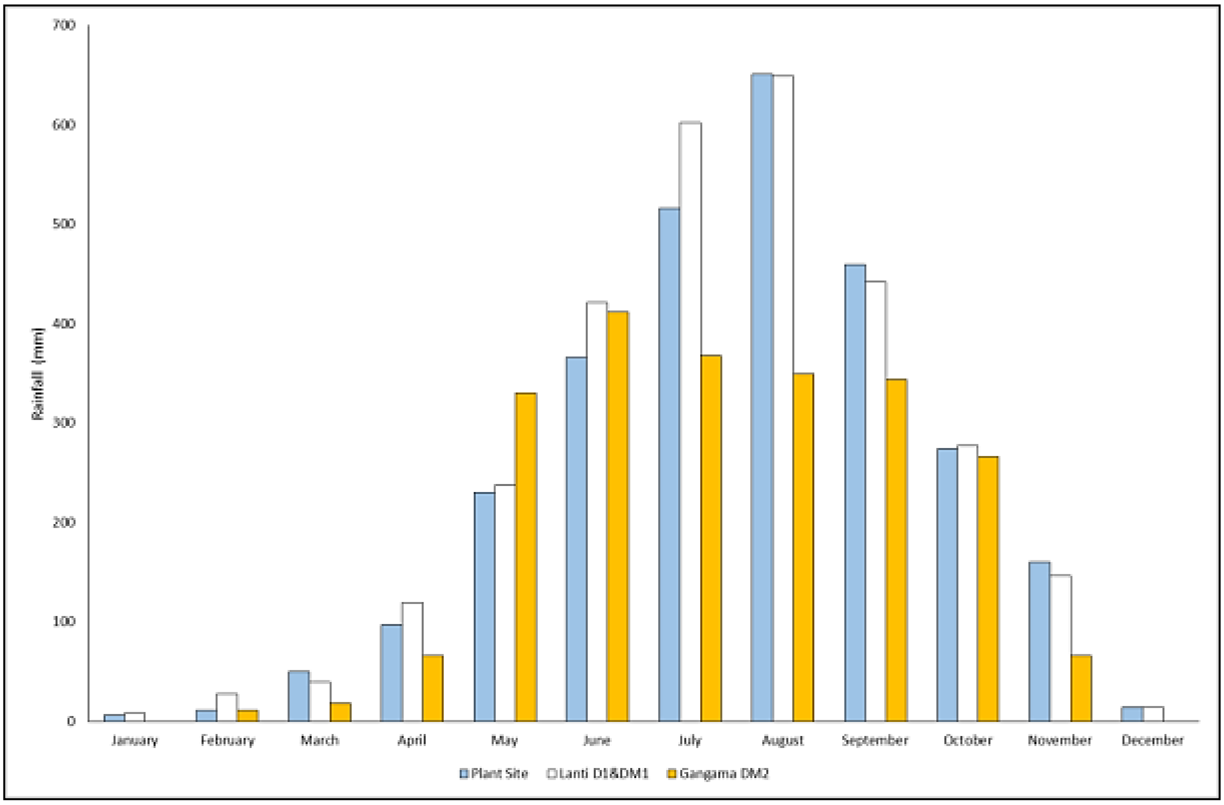


Figure 1.1: Average rainfall for SR Area 1

1.2.2 Wind

Wind speed and direction is an important parameter with respect to air quality as winds can generate dust emissions as well as control the dispersion of an emissions plume. Higher wind speeds result in longer travel distance and dilution of dusts while lower, more stable wind conditions result in shorter travel distance.

The prevailing winds in SR Area 1 are relatively constant throughout the year and dominate from the southwest and west-southwest. The average wind speed as modelled by SRK (2017a) is 2.64 m/s with maximum speeds less than 8.8 m/s.

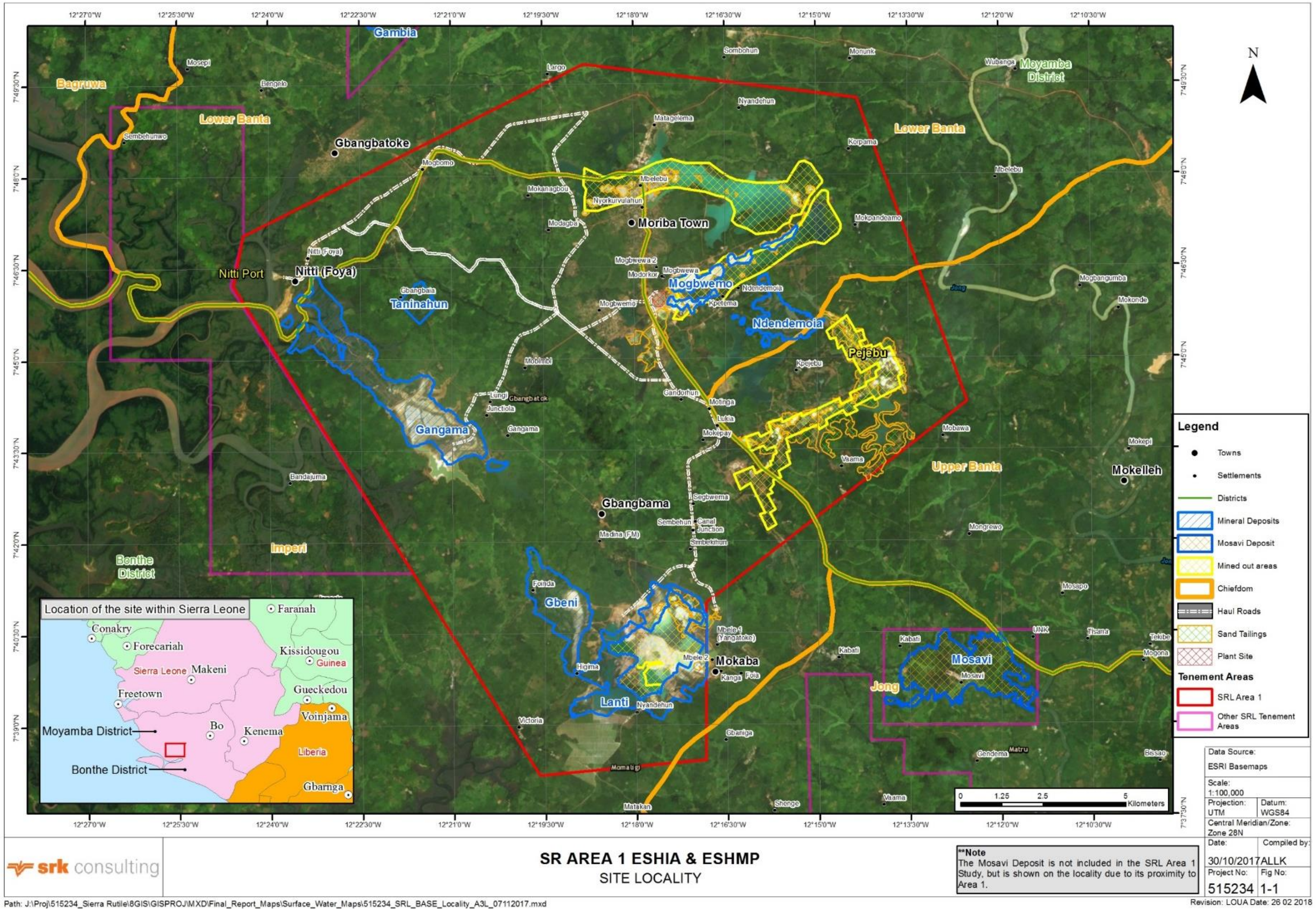


Figure 1.2: Sierra Rutile Limited Area 1 general locality map

1.3 Mineral assemblage

Heavy mineral sands are an important source of titanium minerals; zircon; and rare earth elements within phosphates. The relative abundance of these minerals within a deposit is largely dependent on the geological source.

The main heavy mineral constituents of these sands are the titanium-bearing minerals, predominately ilmenite, but also rutile and leucocoxene, zircon, and the rare earth bearing minerals, monazite and xenotime. The relative proportion of these minerals varies from deposit to deposit, but ilmenite generally contributes by far the largest proportion of the heavy mineral constituents, commonly 50 to 70%. Uranium (U) and thorium (Th) are also present in these minerals. The concentrations of uranium and thorium are generally in trace amounts except for monazite, which typically contains 5% to 7% thorium and 0.1% to 0.3% uranium.

Additional information on the radiological characteristics of minerals contained in mineral sand deposits is given in Appendix 1.

1.4 Operational Overview

SRL's primary operations consist of the Lanti mining operations (dredge and dry mining) and processing facilities (floating and land based concentrators); Gangama dry mining and land based concentrator; the MSP; and the transport and export of product through the Nitti Port facilities (Figure 1.3). The mine additionally maintains an extensive network of ponds; power generation facilities; accommodation; offices; a clinic and roads.

Mining, scrubbing and screening is undertaken at the Lanti dredge, with heavy mineral concentrate (HMC) produced on board the floating concentrator. The dry mines (Lanti and Gangama) produce run of mine ore for their respective concentrators, where de-sliming and primary gravity separation takes place. Separating HMC into the various products is conducted at the MSP.

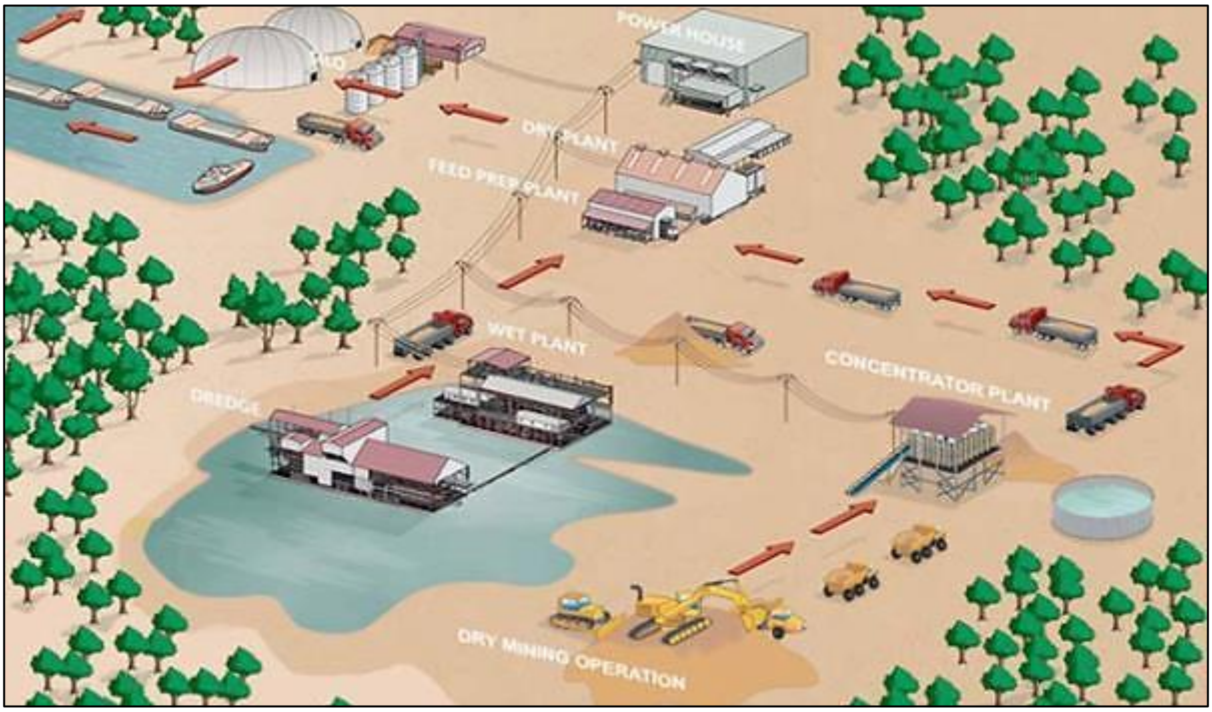


Figure 1.3: Simplified mining operations and processes

At the Lanti dredge (D1), ore is recovered from the mining face with a bucket ladder and routed to primary and secondary scrubbers and screens for separation of oversize material, which is then returned to the dredge pond. Screen undersize material is pumped to the wet concentrator plant (WCP), a floating system that follows behind the dredge. At the WCP, cyclones process the ore to remove the slimes fraction, which is discharged into a separate slimes paddock. The retained material is routed to spiral classifiers (gravity separation) where the heavy minerals (HM) are separated from the barren sands, which is returned to the dredge pond. The HMC is piped to shore for dewatering via two separate cyclone towers: one for low sulphur ore and a second one for high sulphur ore.

Sulphide ores are segregated for the following reasons: sulphur mineralization occurs predominantly in the deeper parts of the Lanti deposit. SRL excavates and segregates the sulphide rich ore during concentration. The process involves monitoring of sulphur levels, excavation of the sulphide rich ore under water, separate stockpiling of the ore and prompt delivery of the high sulphide ore to the MSP for processing. This is for the mining sections of predominantly high sulphur content. For sections of sporadic high sulphide content, SRL blends the high sulphide content ore with low sulphide content materials.

Dry mining at Lanti (DM1) and Gangama (DM2) is conducted through excavation and trucking of ore to mining unit plants where oversize material is separated through scrubbing and screening stages. The undersized material is then routed to the respective WCPs where cyclones process the ore to remove the slimes fraction. The retained material is sent to spiral classifiers for separation of HMC from sands (gravity tails light fraction). Oversize, slimes and sand tailings are all routed back to the mining void for disposal. The separation process in the WCP is a purely physical process, and does not alter the physical form of the individual minerals.

Final HMC is trucked to the Land Plant for separation of individual mineral streams. The Land Plant constitutes a feed preparation plant (FPP), and a dry MSP. In the FPP, a series of attritioners, classifiers, and spirals are used to clean and further upgrade the heavy minerals. Froth flotation is then utilized to remove the sulfide-containing materials, mainly marcasite, but also some pyrite, both of which are iron sulphides. The retained material is further divided into a coarse and fine fraction to serve as feed to the different sections of the dry plant MSP.

At the MSP, the upgraded HMC is processed using a combination of mineral processing techniques where mineral species are separated from one another by exploiting their inherent differences in magnetic susceptibility; surface electrical conductivity; and particle density. While the individual mineral products have strictly controlled chemical specifications, the actual grains of sand are unaltered from their original state. A layout of the process flows for mining, WCPs, FPP and MSP is detailed in Appendix 2.

Rutile and ilmenite concentrates are stored in silos near the MSP prior to haulage to Nitti Port. When sufficient product is available, it is loaded onto barges for transport to ocean-going vessels.

Tailings are produced at several points within the processing circuit. Sulphide tailings are separately stored within a dedicated sulphide tailings dam, and high tension tails (HTT) is stockpiled for potential future sales or blending with zircon containing concentrate. The remainder of the tailings materials are mixed and pumped from the individual circuits to the Total Tailings Facility.

Although the radioactive materials are of natural origin, mining and processing activities concentrate the ore, giving rise to further enhancement of the concentrations of radionuclides in the plant process, product stockpiles and certain tailings streams. The tailings streams include radioactive sands, dusts and possibly also waters containing radioactive suspended solids.

1.5 Sources of radiation at SRL operations

There are two main sources of radiation exposure in mineral sands mining and processing at SRL: man-made sources, i.e. density gauges, which are used in various processes of the operation to determine slurry densities; and naturally occurring radioactive materials (NORM) in the ore, products and tailings.

1.5.1 Man-made radiation: sealed radioactive sources

Various Cesium (Cs-137) density gauges are used at the dredge; dry mining units (Lanti and Gangama); and the MSP for process optimization purposes. Additional sources are stored in a licensed bunker facility for future use/re-use, or for future disposal (Figure 1.4). Sources are classified into five categories: Category 1 sources are potentially the most dangerous and Category 5 sources are the most unlikely to be dangerous. Two types of risks are considered, the risk in handling and being close to a source, and the risk associated with radioactive material being dispersed from a source. It would be highly unlikely for a Category 1 source to contaminate a public water supply to dangerous levels, even if the radioactive material were highly soluble in water. It would be virtually impossible for a source in Caterogy 2 to 5 to contaminate a public water supply to dangerous levels.

Individual sources at SR Area 1 are either Category 4 or Category 5 sources, which are the lowest activity sources in industry (Figure 1.5).

Table 1.1 Categories of sources

Category	Risk in being close to an individual source	Risk in the event that the radioactive material in the source is dispersed by fire or explosion
1	**Extremely dangerous to the person:** This source, if not safely managed or securely protected, would be likely to cause permanent injury to a person who handled it or who was otherwise in contact with it for more than a few minutes. It would probably be fatal to be close to this amount of unshielded radioactive material for a period in the range of a few minutes to an hour.	This amount of radioactive material, if dispersed, could possibly, although it would be unlikely, permanently injure or be life threatening to persons in the immediate vicinity. There would be little or no risk of immediate health effects to persons beyond a few hundred metres away, but contaminated areas would need to be cleaned up in accordance with international standards. For large sources the area to be cleaned up could be a square kilometre or more.
2	**Very dangerous to the person:** This source, if not safely managed or securely protected, could cause permanent injury to a person who handled it or who was otherwise in contact with it for a short time (minutes to hours). It could possibly be fatal to be close to this amount of unshielded radioactive material for a period of hours to days.	This amount of radioactive material, if dispersed, could possibly, although it would be very unlikely, permanently injure or be life threatening to persons in the immediate vicinity. There would be little or no risk of immediate health effects to persons beyond a hundred metres or so away, but contaminated areas would need to be cleaned up in accordance with international standards. The area to be cleaned up would probably not exceed a square kilometre.
3	**Dangerous to the person:** This source, if not safely managed or securely protected, could cause permanent injury to a person who handled it or who was otherwise in contact with it for some hours. It could possibly, although it would be unlikely, be fatal to be close to this amount of unshielded radioactive material for a period of days to weeks.	This amount of radioactive material, if dispersed, could possibly, although it would be extremely unlikely, permanently injure or be life threatening to persons in the immediate vicinity. There would be little or no risk of immediate health effects to persons beyond a few metres away, but contaminated areas would need to be cleaned up in accordance with international standards. The area to be cleaned up would probably not exceed a small fraction of a square kilometre.
4	**Unlikely to be dangerous to the person:** It is very unlikely that anyone would be permanently injured by this source. However, this amount of unshielded radioactive material, if not safely managed or securely protected, could possibly, although it would be unlikely, temporarily injure someone who handled it or who was otherwise in contact with it for many hours, or who was close to it for a period of many weeks.	This amount of radioactive material, if dispersed, could not permanently injure persons.
5	**Most unlikely to be dangerous to the person:** No one could be permanently injured by this source.	This amount of radioactive material, if dispersed, could not permanently injure anyone.

SRL has a radiation management plan (RMP) for sealed radioactive sources (September 2017) detailing the requirements for the safe storage; transport and use of portable and fixed industrial gauges. The purpose of the RMP is to ensure that all practices involving radiation gauges at SRL are conducted as safely as possible and in compliance with the Sierra Leone *Nuclear Safety and Radiation Protection Act 2012.* Compliance with the RMP ensures that the radiation doses to all employees, contractors and visitors are managed appropriately and below the prescribed statutory limits and are as low as reasonable achievable (ALARA). It also ensures that the number of people exposed to radiation, and the likelihood of unexpected exposure to radiation, are minimised.

The Government of Sierra Leone Ministry of Energy Nuclear Safety and Radiation Authority (NSRPA) have issued two Certificates of Registration (licences) for the possession and use of density gauges (Appendix 3).

Table 1.2 SRL Radiation Licenses

Certificates of Registration		
Certificate No	**Provision**	**Validity Period**
APN-USE-0026/16	Authorization for possession and use	12 Months
APN-POS-001/16	Authorization for possession	12 Months

Detailed in these licences, the Licensee is directed to:

- ensure that any personnel, who subsequently may be engaged to operate, install or otherwise deal with the density gauge, have approved training;
- comply with the *Nuclear Safety an Radiation Protection Act 2012*;
- provide prior written notification to the NSRPA of any intension to sell, relocate, install or dispose of the density gauges;
- provide prior written notification to the NSRPA of plans to modify the structure of the premise in any way that may significantly impact on radiation protection and safety; and
- ensure that the installation, service or maintenance of the density gauge on the premises is performed only by personnel authorised by the regulatory authority.

Regular inspections are conducted by the NSRPA to ascertain compliance to license conditions.

Figure 1.4: Storage of gauges at SR Area 1

Figure 1.5: Density gauges in operations

1.5.2 Naturally Occurring Radioactive Material (NORM)

Deposits of mineral sands containing heavy or dense minerals originate from erosion and weathering of rocks and occur as a result of the concentrating effects of wind, ocean currents and wave action. These deposits are enriched through such geological processes in the naturally occurring radionuclides of the uranium and thorium decay chains. The radioactivity is primarily associated with specific minerals within the deposit (e.g. especially monazite and to a lesser extent, zircon). The potential radiation hazard increases with the concentration of these minerals in various products and tailings streams.

Radioactivity in the mineral sands products, especially zircon, can also occur due to incorporation of elemental thorium and uranium into the crystal lattice of the mineral at the time of formation. The amount of monazite in the minerals sands ore typically determines the level of radiation protection that may be necessary. In the deposits within the project area, monazite only occurs in low concentrations (typically <1%). Although the monazite content is relatively low, there exists the potential for exposure significantly in excess of average background levels in mine operations where the mineral sands are extracted and concentrated. Of particular significance from a radiation management perspective is the production of a monazite-rich mineral stream, as in the MSP, and its subsequent disposal in the mine pits.

Radioactive decay of uranium and thorium gives rise to a number of decay products (Appendix 4) as the original atoms change from one element to another as they decay through the emission of radiation, ultimately ending in a stable final atom. In most mineral sands deposits, the uranium and thorium decay chains are in secular equilibrium, which means that the radioactive decay product has the same activity concentration as the parent. If the deposits are subject to chemical treatment processes, then some radionuclides, for example radium, may be separated from their parent radionuclide, thereby disrupting the state of equilibrium. However, such processes are not common in mineral sands processing and the radioactivity contained in the mineral grain remains intact and the chemical availability of radionuclides with respect to water solubility, plant uptake and metabolic behaviour following inhalation or ingestion does not alter from the natural state.

1.5.3 SRL ore

The typical mineral assemblage of the ore in SR Area 1 deposits, as summarized in Table 1.3, consist predominantly of rutile (TiO_2), followed by ilmenite ($FeTiO_3$), and zircon ($ZrSiO_4$) respectively. The orebodies in general have an activity concentration of less than 1 Becquerel per gram (Bq/g) uranium and thorium, thereby not classified as requiring regulation per International Atomic Energy Agency (IAEA) Safety Report Series 49 – Assessing the need for radiation protection measures in work involving mineral sand raw materials standards (2006): “The following values of activity concentration are specified in the Standards as being values below which it is usually unnecessary to regulate, irrespective of the quantity of material or whether it is in its natural state or has been subject to some form of processing:

- 1 Bq/g for uranium and thorium series radionuclides; and
- 10 Bq/g for potassium (40K)”.

IAEA Safety Standards Series RS-G-1.7 - Application of the Concepts of Exclusion, Exemption and Clearance (2004), sets exclusion levels for naturally occurring radioactivity in bulk materials at 1 Bq/g head-of-chain activity for the uranium and thorium decay chain radionuclides. These values are at the upper end of the world-wide distribution for naturally occurring radioactivity in soils. The activity concentration of 1 Bq/g is currently the internationally-accepted level for defining the scope of regulation for naturally occurring materials containing uranium or thorium.

Ores or mineral concentrates with head-of-chain uranium or thorium activity concentrations less than 1 Bq/g would generally be considered inherently safe (IAEA 2004).

Table 1.3 Typical mineral assemblage of the SRL ore

Mineral assemblage of ore	Typical Abundance (wt%)	Activity Concentration (Bq/g) of constituents (2016 average)
Heavy Mineral Content (HMC)	3 – 5	1.42
Rutile (TiO_2)	1 – 2	0.42
Zircon ($ZrSiO_4$)	~ 0.1	12.18
Ilmenite ($FeTiO_3$)	~ 0.2 – 0.3	1.04
wt% = Weight Percentage		

1.5.4 Heavy Mineral Concentrate

The typical mineral assemblage of HMC produced during primary upgrading of ore at SR Area 1 is summarized in Table 1.4.

Table 1.4 Typical mineral assemblage of SRL HMC

Mineral Assemblage of HMC	Typical Abundance (wt%)
Rutile (TiO_2)	41 – 63
Ilmenite ($FeTiO_3$)	15 – 26
Zircon ($ZrSiO_4$)	3 – 4
Others including: Garnet (Ca, Fe, Mg, Mn)$_3$(Al, Fe, Mn, Cr, Ti, V)$_2$(SiO_4)$_3$; Monazite ((Ce,La,Nd,Th,Y)PO_4); Iron Oxides (Hematite, Goethite, etc.); Pyrite/marcasite (FeS_2); Corundum (Al_2O_3)	7 – 25
wt% = Weight Percentage	

As can be seen from Table 1.4, SRL HMC consists predominantly of rutile, followed by ilmenite and zircon respectively.

1.5.5 SRL products and tailings

Where specific data on the radionuclide content of SRL heavy mineral products is not available, the information from other published data for heavy minerals from other sources may be used to indicate the potential activities in the various process streams. The data in Table 1.5 presents the typical radionuclide content of various heavy minerals extracted from mineral sands Australian operations (Iluka 2005; UPT 1996; WACME 2000).

Table 1.5 Radionuclide concentrations in heavy mineral sand Australian operations

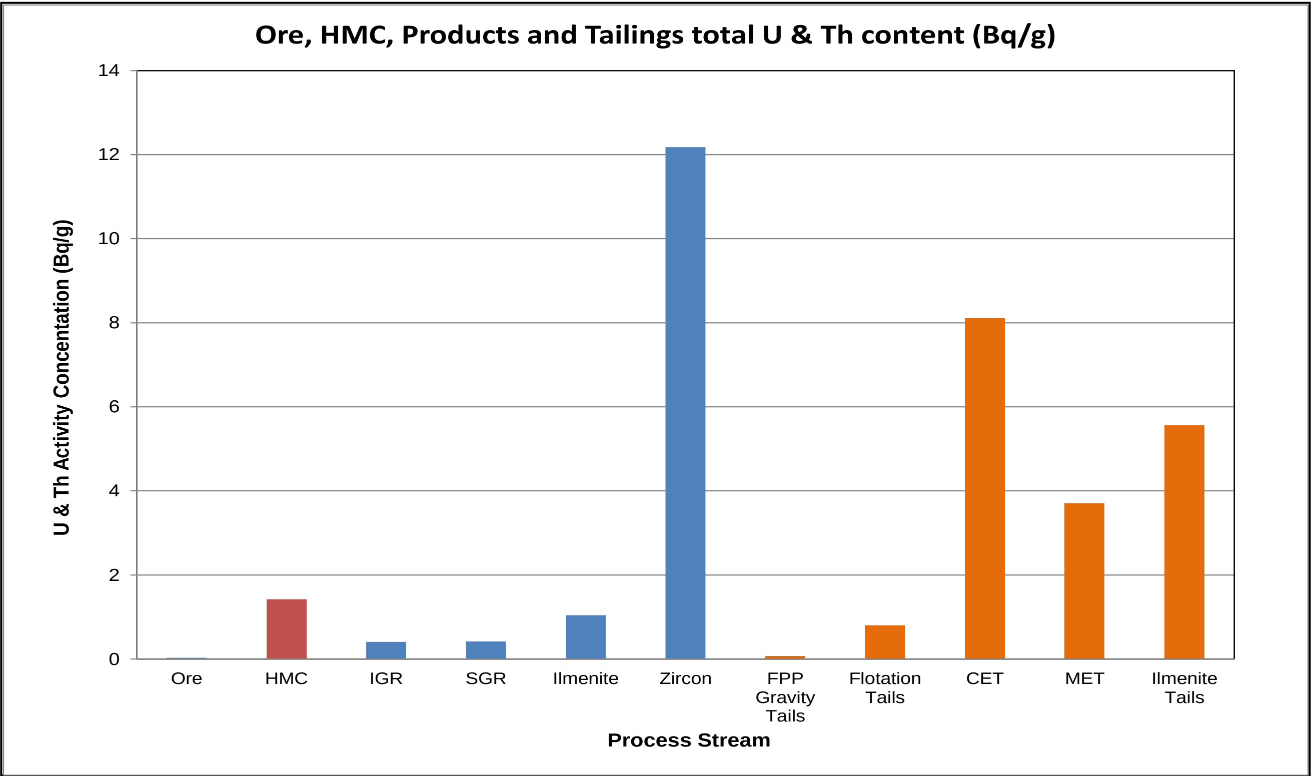
Mineral	Typical mass concentrations (ppm)		Typical activity concentrations (Bq/g)[a]	
	Uranium (U)	Thorium (Th)	Uranium[b]	Thorium[b]
Ilmenite	10-20	50-480	0.12-0.25	0.2-2
Rutile	40-90	40-60	0.5-1.1	0.15-0.25
Zircon	100-300	120-280	1.2-4.0	0.5-1.1
Monazite	1,000-3,000	50,000-70,000	12-40	200-300

Note: (a) Calculated activities using mass/activity relationships of 1 ppm U = 12.4/1000 Bq/g and 1 ppm Th = 4.07/1000 Bq/g.
(b) E xpected: uranium (U-238) and thorium (Th-232) in secular equilibrium with decay products in unprocessed minerals.

Most of the radioactivity associated with heavy minerals is, in particular, due to the presence of significant levels of uranium and thorium in monazite. The content of uranium and thorium in monazite is considerably higher than that of the other minerals. Therefore, in considering the distribution of radioactivity throughout the mining and processing of mineral sands, it is appropriate to focus on the partitioning of monazite at various stages of processing.

In the SR Area 1 operations, monazite is mainly associated with the zircon-rich product; followed by electrostatic tailings; ilmenite tails and ilmenite concentrate respectively and this is reflected in the activity concentrations (Bq/g) as illustrated in Figure 1.6. It has to be noted that the zircon cleaning circuit at the MSP has previously been de-commissioned and the currently produced zircon product therefore contains monazite to a large degree.

Figure 1.6 illustrates the uranium and thorium concentrations in ore, intermediate product (HMC); final products; and tailings streams at SR Area 1.



HMC = Heavy Mineral Concentrate	IGR = Industrial Grade Rutile	SGR = Standard Grade Rutile
FPP = Feed Preparation Plant	CET = Coarse Electrostatic Tails	MET = Medium Electrostatic Tails

Figure 1.6: Uranium (U) and Thorium (Th) levels in process streams

2. PURPOSE AND SCOPE

2.1 Purpose

The purpose of the study is to examine the radiological aspects of SR Area 1 mining and processing operations. The ore body contains minerals enhanced in uranium and thorium, which are concentrated and extracted during mining and processing. In addition a variety of tailings streams containing uranium and thorium are generated. The presence of uranium and thorium in the products, and tailings materials result in the exposure of workers and possibly members of the public to ionizing radiation.

2.2 Scope of Work

The following aspects have been covered within this study:

- review the presence and distribution of radionuclides at SR Area 1 (predominantly NORM);
- review the management of man-made radioactive sources (density gauges) at SR Area 1;
- describe and characterise (where possible) the mineral ore; intermediate materials; products; and tailings associated with SR Area 1 operations;
- assess the potential radiation exposure pathways that relate to SR Area 1 mining and processing operations, including a dose estimation for the workforce and members of the public; and
- recommend a further phase of studies required to improve the understanding and management of any potential radiological impacts.

3. LEGISLATION

Legislation applicable to radiation protection and management at the SRL operations includes:

- *Mines and Minerals Act 2009*;
- Safety in Mining and Milling of Uranium and Other Ores Regulations 2012; and
- *Nuclear Safety and Radiation Protection Act 2012.*

The transport of radioactive materials is controlled by the IAEA Safety Requirements, Regulations for the Safe Transport of Radioactive Material (2012), and the International Maritime Dangerous Goods Code (IMDG Code) (2016). This includes the transport of ores and concentrates which contain natural thorium and uranium radionuclides with a specific activity exceeding 10 Bq/g.

Overarching international guidelines and standards for radiation protection is put forward by the International Commission on Radiological Protection (ICRP) and the IAEA. A detailed description of the different acts is given in Appendix 5.

Other legislation relevant to this study includes:

- the *Environmental Protection Act 2008*;
- the *Mines and Mineral Act 2009*; and
- the *Environmental Protection (Mines and Mineral) Regulations 2013*.

4 DOSE ASSESSMENT METHODOLOGY

4.1 An overview of the dose limitation system

The dose limits recommended by the IAEA are set down in the Basic Safety Standards of the IAEA (2011; Table 4.1). The exposure of individuals must be restricted so that both the total effective dose and the total equivalent dose to relevant organs or tissues do not exceed any of the relevant dose limit specified below.

Occupational exposure

- an effective dose of 20 milli Sieverts per year (mSv/y) averaged over five consecutive years, and of 50 mSv in any single year;
- an equivalent dose to the lens of the eye of 20 mSv per year averaged over 5 consecutive years and of 50 mSv in any single year; and
- an equivalent dose to the extremities (hands and feet) or the skin of 500mSv in a year.

Public exposure

- an effective dose of less than 1mSv in a year;
- an equivalent dose to the lens of the eye of 15mSv in a year; and
- an equivalent dose to the extremities (hands and feet) or the skin of 50mSv in a year.

The occupational dose limit of 20 mSv/y, would apply to those workers who are exposed as a result of working directly with radiation or radioactive materials i.e. occupationally exposed persons. This limit is the sum of all exposures, both from external radiation and the intake of radioactive materials.

Table 4.6 Dose Limits for Occupational Exposed Persons and the Public (IAEA 2011)

Application	Dose Limit Occupational Exposed Person	Dose Limit Members of the Public
Effective dose	20 mSv per year averaged over a period of 5 consecutive calendar years [1,2,3]	1 mSv in a year[4]
Equivalent dose to:		
(a) Lens of the eye	20 mSv per year averaged over a period of 5 consecutive calendar years [1,2,3]	15 mSv in a year
(b) Skin[5]	500 mSv in a year	50 mSv in a year
(c) The hands and feet	500 mSv in a year	No limit specified
The limit apply to the sum of the relevant doses from external exposure in the specified period and the committed dose from intakes in the same period. In this Note, committed dose means the dose of radiation, arising from the intake of radioactive material accumulated by the body over 50 years following the intake (except in the case if intakes by children, where it is the dose accumulated until the age of 70)		
Any dose resulting from medical diagnosis should not be taken into account		
Any dose attributable to normal naturally occurring background levels of radiation should not be taken into account.		
Note 1: With the further provision that the effective dose must not exceed 50mSv in a single year		
Note 2: When a female employee declares a pregnancy, the embryo or fetus should be afforded the same level of protection as a member of the public		
Note 3: When, in exceptional circumstances, a temporary change in the dose limit requirements is approved by the Authority, one of the following conditions applies: (a) The effective dose limit must not exceed 50mSv per year for the period, that must not exceed 5 years, for which the temporary change is approved, and (b) The period for which the 20mSv per year average applies must not exceed 10 consecutive years and the effective dose must not exceed 50mSv in any single year		
Note 4: In special circumstances, a higher value of effective dose could be allowed in a single year, provided that the average over 5 years does not exceed 1mSv per year		
Note 5: The equivalent dose limit for the skin applies to the dose averaged over any 1 square centimeter of skin, regardless of the total area exposed.		

4.2 Potential Exposure Pathways

The mining and processing of heavy mineral ores has the potential to cause elevated radiation exposures of both workers and members of the public during operations and from the management of waste arising from production. Therefore, depending on the level of potential exposures in the industry, certain radiation control measures may be required to provide for an adequate degree of protection for both employees and the public. Appendix 9 provides an introduction to ionizing radiation and pathways of exposure.

In general, radiation hazards to workers arise in the mining and processing of heavy minerals through three principal pathways, namely external irradiation, inhalation and ingestion. The specific potential exposures are, as follows:

- external exposure from the ore body during mining of ores or during separation of heavy minerals, or from stockpiled ore, mineral concentrates, or tailings;
- external exposure during transport of ore or mineral concentrates;
- internal exposure from the inhalation of dusts containing elevated levels of radioactivity;
- internal exposure from the inhalation of radon gas released from minerals during mining or processing operations or from stockpiled materials; and
- direct ingestion of material during handling of ores and heavy mineral concentrates and products.

Potential exposure pathways to members of the public include off-site releases of dusts or radon gas, contamination of food and water supplies due to the migration of radionuclides from the mine site during mining operations or following the disposal of mining tailings (by-products). Radioactivity associated with the various heavy minerals or tailings may also have the potential to be dispersed in the environment during processing operations.

Tables 4.2 and 4.3 summarize the potential relevant pathways of exposure arising from mining and processing activities at SR Area 1, which could have an impact on workers and members of the public respectively.

Table 4.7 Pathways of exposure for Workers from operational sections at SR Area 1

Operational Area	Process Streams	Worker Dose Assessment	
		Relevant Pathways	Occupancy
Dry mining operations (Lanti DM & Gangama DM2) and respective WCPs	Mineral sands ore Oversize material HMC Sand tailings -63 micron Slimes tailings	External gamma	2000 h/y [@]
		Dust inhalation (only HMC)*	2000 h/y [@]
		Inadvertent soil ingestion	N/A (consumption rate as per footnote ^)
Dredge mining operations (Lanti D1) and floating WCP	Mineral sands ore Oversize material HMC Sand tailings -63 micron Slimes tailings	External gamma (some shielding from water will occur as the process is wet)	2000 h/y [@]
		Dust inhalation (HMC as stockpiled on shore)*	2000 h/y [@]
		Inadvertent soil ingestion	N/A (consumption rate as per footnote ^)
MSP & tailings storage area	HMC IGR SGR Ilmenite product Zircon product FPP gravity tails FPP flotation tails CET MET / FET Ilmenite tails	External gamma	2000 h/y [@] (MSP) 1000 [#] h/y (50% tailings area)
		Dust inhalation	2000 h/y [@]
		Inadvertent soil ingestion dose	N/A (consumption rate as per footnote ^)
Nitti Port (product storage and shipment)	IGR SGR Ilmenite product Zircon product	External gamma	2000 h/y [@]
		Dust inhalation	2000 h/y [@]
		Inadvertent soil ingestion dose	N/A (consumption rate as per footnote ^)

* In the WCP, the HMC stockpile is not entirely dry and dust inhalation dose from this stockpile would therefore be an over-estimate

[@] A worker gamma and dust inhalation exposure time of 2000 hours/year (h/y) is assumed: (365 days/y – 52 Sundays – 52 Saturdays – 11 holidays) x 8h/day = 2000 h/y as per internationally accepted value used for worker occupancy

^ Worker soil consumption rate =100 mg/day (ICRP 72); (Ozkaynak et al 2011)

[#] The general workforce at SRL does not work within the tailings storage area. A security guard is stationed at the gate, some distance away from actual stockpiles. Dozer, FEL and truck drivers occasionally in the area are being shielded from external gamma dose to a large extent by their equipment. A reduced occupancy of 1000 h/y (50% of worker occupancy) was thereby selected for worker gamma dose in the area.

HMC = Heavy Mineral Concentrate; IGR = Industrial Grade Rutile; SGR = Standard Grade Rutile
FPP = Feed Preparation Plant; CET = Coarse Electrostatic Tails; MET = Medium Electrostatic Tails

Table 4.8 Pathways of exposure for the Public from operational sections at SR Area 1

Operational Area	Process Streams	Public Dose Assessment	
		Relevant Pathways	Occupancy
Dry mining operations (Lanti DM & Gangama DM2) and respective WCPs	Mineral sands ore Oversize material HMC Sand tailings -63 micron Slimes tailings	The closest communities to DM1 or DM2 is approximately 500 m removed and not close enough to incur a direct gamma dose; and the WCP is a secure area with no access for members of the public	N/A
		Dust inhalation possible for road users and communities in the vicinity	876 h/y (10%) [@]
		Communities not located close enough to DM1 or DM2 to incur a direct soil ingestion dose; and the WCP is a secure area with no access for members of the public	N/A
Dredge mining operations (Lanti D1) and floating WCP	HMC -63 micron Slimes tailings	Gamma dose for public possible from unsecured HMC stockpile (road users) and slimes tailings in TSF	876 h/y (10%) [@]
		Dust inhalation possible for road users and communities in the vicinity	876 h/y (10%) [@]

Operational Area	Process Streams	Public Dose Assessment	
		Relevant Pathways	Occupancy
		Soil ingestion^ dose for public possible from unsecured HMC stockpile (road users) and slimes tailings in TSF	N/A (consumption rate as per footnote ^)
MSP & tailings storage area	HMC IGR SGR Ilmenite product Zircon product FPP gravity tails FPP flotation tails CET MET / FET Ilmenite tails	The MSP and tailings storage areas are secure areas with no access to members of the public to incur external gamma dose	N/A
		Some communities in vicinity of the MSP and tailings storage area (Mogbwemo and KPetema) can incur dust inhalation dose	876 h/y (10%) [@]
		The MSP and Tailings Storage areas are secure areas with no access to members of the public to incur external gamma dose	N/A
Nitti Port (product storage and shipment)	IGR SGR Ilmenite product Zircon product	Nitti Port is a secure area with no access to members of the public to incur a gamma dose	N/A
		Foya village is in the vicinity of Nitti Port. Members of the public can thereby potentially receive dust inhalation doses	876 h/y (10%) [@]
		Nitti Port is a secure area with no access to members of the public to incur a soil ingestion dose	N/A

* In the WCP, the HMC stockpile is not entirely dry and dust inhalation dose from this stockpile would therefore be an over-estimate

^ Inadvertent soil ingestion for adults = 100 mg/day (ICRP 72; Ozkaynak et al 2011); Inadvertent soil ingestion for children = 200 mg/day (Ozkaynak et al 2011; Stanek and Calabrese 1995b)

[@] A public exposure of 876 h/y (10% occupancy: 10/100 x 365 days/y x 24 h/day) is assumed for members of the public using roads in close proximity to sources of radiation

HMC = Heavy Mineral Concentrate; IGR = Industrial Grade Rutile; SGR = Standard Grade Rutile
FPP = Feed Preparation Plant; CET = Coarse Electrostatic Tails; MET = Medium Electrostatic Tails
TSF = Tailings Storage Facility

Radon (Rn-222) is an inert gas produced when radium (Ra-226) decays by alpha emission. Radium is in turn a decay product of the uranium decay series. The potential levels of radon gases in mineral sand mining and separation will depend on the rate at which radon emanates or is released from the ore or mineral product and the level of ventilation in the area where these materials are handled, produced or stockpiled.

The emanation of radon from heavy minerals has been found to be very low (KER 1988). In the open, any radon released from an ore body, or a stockpile, will be rapidly diluted in the atmosphere and dispersed. Therefore it is likely that in open pit mining and associated processing, the radon levels will be comparable to ambient levels and this exposure pathway will not be significant.

Other potential pathways, such as surface or groundwater contamination, are not considered to be of significance as long-term migration of radionuclides from chemically un-altered tailings and other residues disposed of to a mine pit is expected to be minimal. Physical methods are used to separate the heavy minerals in the ore and any mineral tailings returned to pit will not have undergone chemical treatment. Therefore, the monazite will not be altered chemically and there will not be any change in the solubility of uranium and thorium, or the other radioactive elements in the decay series.

It is also known that the radionuclide constituents are highly inert and bound strongly in the mineral structure, when not chemically altered, and it can be concluded that the potential for migration of radioactivity to surface or ground water in the area would be the same as would be with the presence of the ore deposits. Over the long-term any local movement of radionuclides through the groundwater aquifer would be very slow.

The only tailings stream with potential chemical alteration would be the FPP sulphide tailings, containing sulphide minerals, marcasite and pyrite, as this material is acid generating which has the potential to stay acidic in the long term if exposed to oxidizing conditions. From the SRL Water Monitoring Report (Knight Piesold, 2008), it was shown that the supernatant discharge from the coarse sulphide plant tailings outlet pipe into the sulphide plant tailings holding area had radioactivity levels that exceeded the World Health Organization (WHO) guidelines (2008) for gross alpha and gross beta. Process/surface water locations downstream of the Mogbwemo dredge pond however did not exceed WHO guidelines, indicating a minimal impact from these discharge sources.

The SRK (2017b) ESHIA geochemistry characterisation study noted that while the previous studies assessed tailings leachates quality against the WHO guidelines and indicated that aluminium (Al), manganese (Mn), nickel (Ni), cadmium (Cd) and uranium (U) exceeded the guideline limits. The SRK (2017b) study assessed the current tailings leachate quality against Sierra Leonean Environmental Protection (Mines and Minerals) Regulations 2013 "limit at any moment" effluent quality for mining and metallurgic operations and background surface water levels. The findings indicated that all the measured parameters in the leachate from both the primary and secondary process tailings are within the Regulations "limit at any moment" except pH:

- As the primary process tailings are expected to be typically non-acid forming, slightly acidic and non-saline, the bulk of this material is considered to be geochemically unreactive. Due to the low acid sulphate soil and metal leaching (ASS/ML) risk, no special ASS/ML management requirements are recommended except continuation with operational monitoring and testing to detect any unexpected changes that may occur during mining (SRK, 2017b).

- The secondary process tailings, specifically sulphide flotation tailings (SFT), total tailings (TT) and ilmenite tailings (IT), are potentially acid generating (PAG), acidic and non-saline and are likely to present a risk of increased acidity when exposed to oxidising conditions. These materials should continue to be deposited sub-aqueously as is currently done to limit exposure to oxygen. It is recommended that sufficient depth of water cover over the potentially acid generating (PAG) tailings be ensured to prevent re-suspension of tailings by wind or wave action to minimise exposure to potential oxidising conditions (SRK, 2017b).

It is further noted that drinking water is provided by SRL for workers, and that members of the public extract water for drinking purposes from wells in their villages and not from surface water sources. Some villages are also supplied with drinking water from SRL. The location of drinking water wells for the public is far removed from the MSP or tailings storage facility, as the closest community (Mogbwemo) is approximately 500 m from the MSP. Even though members of the public make use of surface water bodies for swimming and bathing, the amount of water accidentally ingested would be minimal. Swimming or bathing by members of the public does not occur in close proximity to the MSP or tailings storage area.

Surface and groundwater monitoring will be included as part of the overall environmental monitoring program. There may be some seasonal and regional variations, and these variations must be taken into account in assessing the possible long-term impacts of mining or mineral processing on the surface and groundwater conditions in the area.

4.3 Potential Exposure Groups

The following groups of individuals may be exposed to radiation resulting from the SR Area 1 operations:

- workers at the mining operations;
- drivers and operators of the mining equipment;
- workers at the WCPs, MSP and Nitti Port;
- workers at the mine site involved in the rehabilitation and MSP tailings disposal operations;
- visitors to the operations;
- contractors; and
- members of the public who live close to the mining and processing operations, or export facilities and product haulage road.

4.4 Dose conversion factors and calculations of dose from potential exposure pathways

Effective dose calculations for individual exposure pathways are dependent on dose conversion factors (DCFs), which are updated by international protection agencies (i.e. ICRP) following outcomes of human and environmental impact studies. Dose conversion factors used, and dose calculations for expected pathways of exposure in the current radiation risk assessment are detailed in Appendix 6.

Limited data is available on the SRL uranium and thorium content of the ore and tailings streams. Routine in-house XRF analysis is done on products and some of the tailings materials but currently, a quality control bench-marking exercise is underway to validate the accuracy of in-house analysis. Initial results from this program have indicated that in-house analysis is biased towards the higher end. Previous studies aimed at characterizing tailings materials have also only evaluated gross alpha (α) and gross beta (β) content; did not analyze for uranium or thorium directly; and did not quantify full decay chain (Appendix 4) radionuclide analysis. To date, no full decay chain radionuclide analysis are available on any of the process streams.

An overview of the radiological characteristics of the ore and processing streams is given in Appendix 1 (those available from analysis). Material radionuclide concentrations were used to estimate potential doses to workers and members of the public from various pathways of exposure. Assumptions about occupancy factors; inhalation rates; dust concentrations in air; particle size of dust etc. (Appendix 6) leads to the estimates of radiation dose summarized in Section 5.

4.5 Gamma measurements taken during the assessment evaluation

Gamma dose rate screening surveys across the SR Area 1 operations; roads; and Nitti Port were undertaken by personnel trained in the use of the RS-125 and RS-220 Super Spectrometers, suitable for measurement of environmental gamma dose rates. An additional survey was conducted to determine background gamma dose (to be subtracted from estimated doses to workers and members of the public) at an area selected for this purpose. Gamma dose rate measurements adjacent to HMC and oversize stockpiles were also conducted as indicative of dose and for estimation of radionuclide content of these materials. Instrument specifications are detailed in Appendix 7. Background dose from various sources that individuals are exposed to during everyday living is detailed in Appendix 8.

5 RADIATION DOSE ASSESSMENT

5.1 Flow-sheets and dose estimation per operational section

Figures 5.1 to 5.4 display the flow-sheet layout of individual sections of mining and processing at SR Area 1 and indicates feed, intermediates, products and tailings streams. Tables 5.1 to 5.6 summarize the dose assessment detailed results for each operational area for workers and a summary for members of the public.

5.1.1 Radiation Dose Assessment for Workers

Using the material analysis data in Appendix 1 (Table B) and making assumptions about occupancy factors; dust concentrations; and particle size of dust in air, leads to the following estimates of radiation doses, as summarised in Table 5.1. Calculations used for dose estimations are given in Appendix 6.

Table 5.9 Estimated occupational doses for workers

Exposure Pathways	Exposure Time (h/y)	Annual Effective Dose (mSv/y)
Dry Mining operations (Lanti DM1 & Gangama DM2) and WCPs		
External Gamma (combined materials – reconstructed ore [@])	2000 h/y	0.09
External Gamma (HMC only)		1.66
Dust Inhalation (combined materials – reconstructed ore)	2000 h/y	0.009
Dust Inhalation (only HMC)*		0.163
Inadvertent Soil Ingestion (combined materials – reconstructed ore)	N/A (consumption rate as per footnote ^)	$4.2x10^{-5}$
Inadvertent Soil Ingestion (only HMC)		$7.5x10^{-4}$
Dredge Mining operations (D1) and floating WCP		
External Gamma (some shielding from water will occur as the process is wet)	2000 h/y	0.09 [~]
External Gamma (HMC only)		1.66
Dust Inhalation (HMC as stockpiled is on shore)*	2000 h/y	0.163
Inadvertent Soil Ingestion (combined materials – reconstructed ore)	N/A (consumption rate as per footnote ^)	$4.2x10^{-5}$
Inadvertent Soil Ingestion (only HMC)		$7.5x10^{-4}$
MSP & tailings storage area		
External Gamma (combined materials – reconstructed HMC)[+]	2000 h/y (MSP)	1.47
External Gamma (combined tailings)	1000[#] h/y (Tailings area)	1.10
Dust Inhalation (combined materials – reconstructed HMC)	2000 h/y	0.14
Dust Inhalation (combined tailings)		0.21
Inadvertent Soil Ingestion (combined materials – reconstructed HMC)	N/A (consumption rate as per footnote ^)	0.0007
Inadvertent Soil Ingestion (combined tailings)		0.0011
Nitti Port		
External Gamma	2000 h/y	0.74
Dust Inhalation	2000 h/y	0.07
Inadvertent Soil Ingestion	N/A (consumption rate as per footnote ^)	0.0003
* In the WCP, the HMC stockpile is not entirely dry and dust inhalation dose from this stockpile would therefore be an over-estimate		
[~] Overestimate of gamma dose on the dredge and floating WCP as all materials are wet and would be shielded. Largest exposures at dredge would be from density gauges and not NORM		
^ Worker soil consumption rate =100 mg/day (ICRP 72); (Ozkaynak et al 2011)		
[@] Reconstructed ore = recombined activity concentration of ore as made up from the streams into which it is sub-divided at the MUP and WCP, i.e. recombining of oversize + minus 63 micron slimes + gravity sand tailings + HMC (combined per mass ratio)		
+ Reconstructed HMC = recombined activity concentration of HMC as made up from the streams into which it is sub-divided at the FPP and MSP, i.e. recombining of FPP gravity tails + Sulphide flotation tails + HTT + ilmenite tails + IGR + SGR + ilmenite product + zircon product (combined per mass ratio)		
[#]The general workforce at SRL does not work within the tailings storage area. A security guard is stationed at the gate, some distance away from actual stockpiles. Dozer, FEL and truck drivers occasionally in the area are being shielded from external gamma dose to a large extent by their equipment. A reduced occupancy of 1000 h/y was thereby selected for worker gamma dose in the area.		

These dose estimates are based on very conservative parameters, especially for exposure times for each pathway. Dust inhalation doses is further conservative in that a dust loading of 1 mg/m^3 was assumed for calculation purposes and the initial air quality modeling data for the ESHIA (SRK, 2017a) indicated the maximum $PM_{2.5}$ dust loading to be 0.013 mg/ m^3 which is tenfold lower than the assumed value. This dust monitoring was however conducted during the wet season, and additional monitoring during the dry season is required.

5.1.1.1 Mining and Primary concentration at the WCP

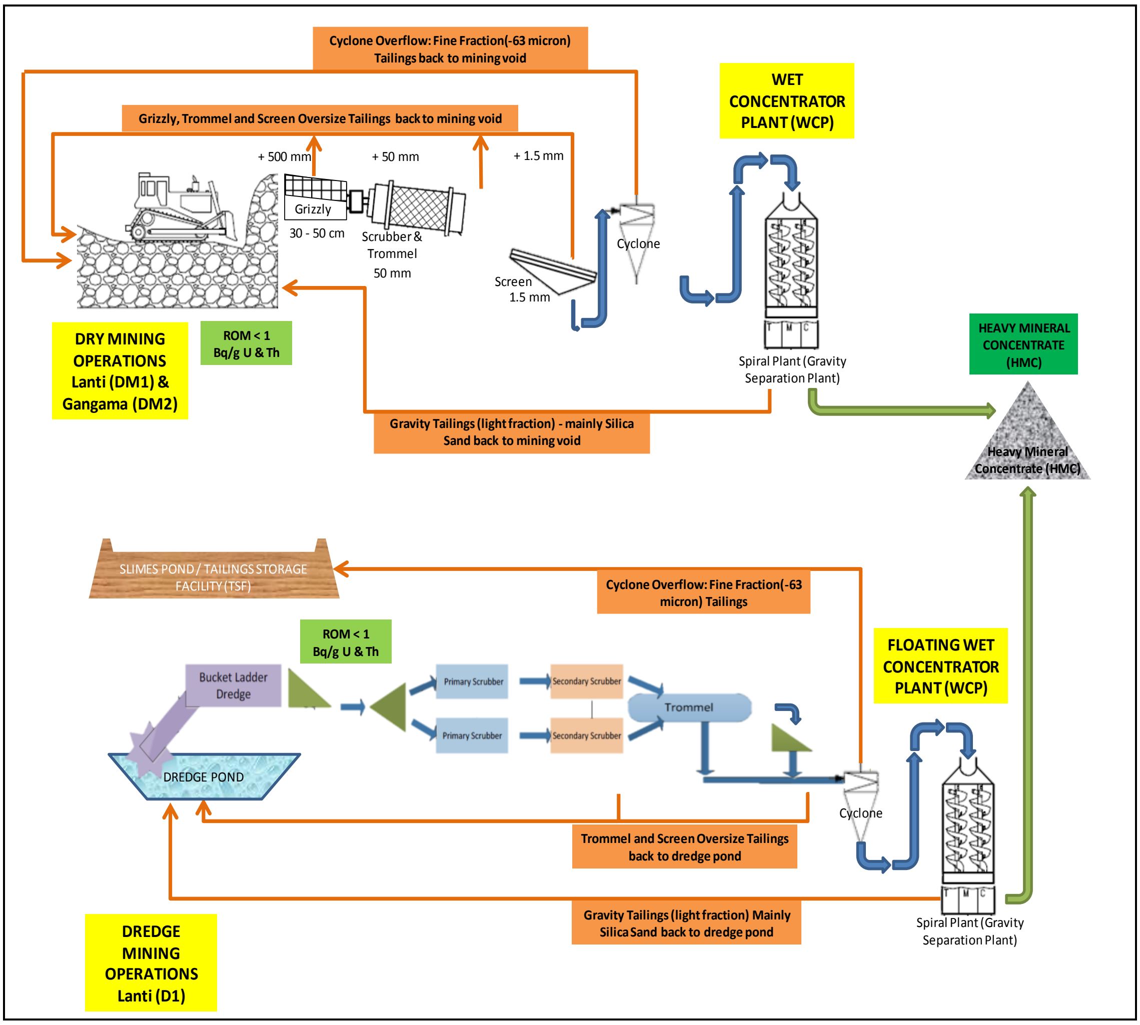


Figure 5.7: Dry (DM1 & DM2) and wet (Dredge D1) mining operations and WCPs

Table 5.10 Dose assessment for Workers at the mines and WCPs

Operational Area	Process Streams	Worker Dose Assessment		
		Relevant Pathways	Annual Dose (mSv/y)	Exposure Time (h/y)
Background gamma (0.06 µSv/h)			**0.12**	2000 h/y
Dry mining operations (Lanti DM1 & Gangama DM2); dredge mining operations (D1) and wet concentrator plants (WCPs)	Mineral sand ore	External Gamma	0.04	2000 h/y
	Primary oversize / secondary oversize		0.03	
	Co-disposed tailing (sand & slimes)		0.02	
	-53 um Fraction (thickener underflow)		0.70	
	Heavy Mineral Concentrate (HMC)		1.66	
	RS-220 measure oversize		0.009	
	RS-220 measure HMC		0.42	
	Reconstructed mineral sand ore		0.09	
	Mineral sand ore (only dry mine)	Dust Inhalation	0.004	2000 h/y
	Primary oversize / secondary oversize (only dry mine)		0.003	
	HMC (dry mines and dredge)		0.163	
	Reconstructed mineral sand ore (only dry mine)		0.009	
	Mineral sand ore	Inadvertent Soil Ingestion	2.10E-05	N/A (consumption rate as per footnote ^)
	Primary oversize / secondary oversize		1.35E-05	
	Co-disposed tailing (sand & slimes)		7.92E-06	
	-53 um Fraction (thickener underflow)		3.85E-04	
	HMC		7.49E-04	
	Reconstructed mineral sand ore		4.19E-05	
	Annual Effective Dose (all pathways) – inclusive of background and derived from reconstructed ore		**0.099**	
	Maximum Annual Effective Dose (all pathways) – inclusive of background and derived from exposure to HMC only		**1.82**	
Annual Dose (mSv/y) = External Gamma Dose (mSv/y) + Dust Inhalation Dose (mSv/y) + Soil Ingestion Dose (mSv/y)				
For the WCP, the Reconstructed mineral sand ore should be the combined products and tailings within the WCP, the Estimated Annual Dose = Annual dose from Reconstructed ore				
Annual Dose (mSv/y) = Average External Gamma Dose from different materials + Average Dust Inhalation Dose from different materials + Average Soil Ingestion Dose from different materials				
Maximum Annual Dose (mSv/y) = Max External Gamma Dose from an individual material + Max Dust Inhalation Dose from an individual material + Max Soil Ingestion Dose from an individual material				
^ Inadvertent soil ingestion for workers = 100 mg/day (ICRP 72; Ozkaynak et al 2011);				

The largest contributing exposure pathway for workers at mining operations is from external gamma when compared to other pathways of exposure. The maximum potential dose that a workers could receive at the WCP is 1.66 mSv/y (excluding background), under the assumption that the individual would stand next to a stockpile of HMC for 2000 h/y; inhale only HMC dust; and ingest only HMC material. This dose would be an over-estimate, as HMC constitutes only 4% of the total material treated through the mine and WCP.

5.1.1.2 Mineral Separation Plant (MSP)

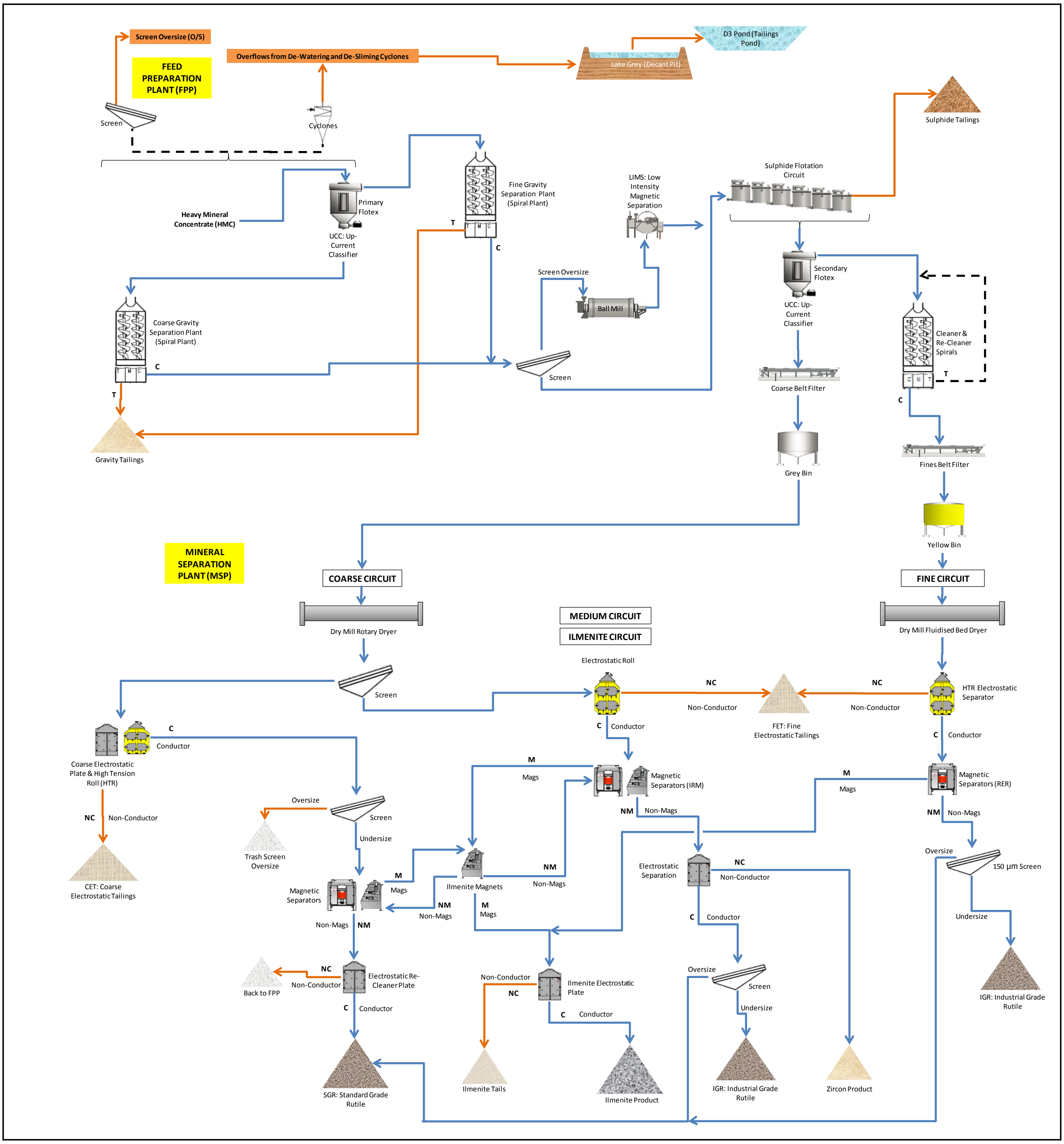


Figure 5.8: Mineral Separation Plant (MSP)

Table 5.11 Dose assessment for Workers the MSP

Operational Area	Worker Dose Assessment			
	Process Streams	Relevant Pathways	Annual Dose (mSv/y)	Exposure Time (h/y)
Background gamma (0.06 µSv/h)			**0.12**	2000 h/y
MSP	Heavy Mineral Concentrate (HMC)	**External Gamma**	1.66	2000 h/y
	Feed Preparation Plant (FPP) gravity tails		0.08	
	Flotation circuit tails (Sulphide tails)		0.97	
	Coarse Electrostatic Tails (CET)		10.28	
	Medium Electrostatic Tails (MET)		4.44	
	Ilmenite Tails (IT)		7.08	
	Industrial Grade Rutile (IGR) product		0.44	
	Standard Grade Rutile (SGR) product		0.45	
	Ilmenite product (IP)		1.25	
	Zircon product		15.02	
	Reconstructed combined HMC feed		1.47	
	Heavy Mineral Concentrate (HMC)	**Dust Inhalation**	0.16	2000 h/y
	Feed Preparation Plant (FPP) gravity tails		0.01	
	Flotation circuit tails (Sulphide tails)		0.09	
	Coarse Electrostatic Tails (CET)		0.94	
	Medium Electrostatic Tails (MET)		0.42	
	Ilmenite Tails (IT)		0.64	
	Industrial Grade Rutile (IGR) product		0.05	
	Standard Grade Rutile (SGR) product		0.05	
	Ilmenite product (IP)		0.12	
	Zircon product		1.41	
	Reconstructed combined HMC Feed		0.14	
	Heavy Mineral Concentrate (HMC)	**Inadvertent Soil Ingestion**	0.0007	N/A (consumption rate as per footnote ^)
	Feed Preparation Plant (FPP) gravity tails		0.0000	
	Flotation circuit tails (Sulphide Tails)		0.0005	
	Coarse Electrostatic Tails (CET)		0.0054	
	Medium Electrostatic Tails (MET)		0.0022	
	Ilmenite Tails (IT)		0.0038	
	Industrial Grade Rutile (IGR) product		0.0002	
	Standard Grade Rutile (SGR) product		0.0002	
	Ilmenite product (IP)		0.0006	
	Zircon product		0.0075	
	Reconstructed Combined HMC Feed		0.0007	
	Annual Effective Dose (all pathways) – inclusive of background and derived from Reconstructed HMC		**1.61**	
	Maximum Annual Effective Dose (all pathways): – inclusive of background and derived from exposure to Zircon product only		**16.44**	
Annual Dose (mSv/y) = External Gamma Dose (mSv/y) + Dust Inhalation Dose (mSv/y) + Soil Ingestion Dose (mSv/y)				
Since HMC should be the combined products and tailings within the MSP, the Estimated Annual Dose = Annual dose from HMC				
Annual Dose (mSv/y) = Average External Gamma Dose from different materials + Average Dust Inhalation Dose from different materials + Average Soil Ingestion Dose from different materials				
Maximum Annual Dose (mSv/y) = Max External Gamma Dose from an individual material + Max Dust Inhalation Dose from an individual + Max Dust Inhalation Dose from an individual				
^ Inadvertent soil ingestion for adults = 100 mg/day (ICRP 72; Ozkaynak et al 2011)				

The largest calculated contributing exposure pathway for workers at the MSP is from external gamma, followed by dust inhalation. It was further shown that the largest dose from an individual material would be incurred from exposure to zircon product, followed by CET and ilmenite tails respectively.

The maximum potential dose for workers at the MSP is 16.32 mSv/y (excluding background), under the assumption that an individual would stand next to an open stockpile of zircon product for 2000 h/y; inhale only zircon dust; and ingest only zircon material. This dose would be an over-estimate, as zircon product constitutes only 0.5% (2016 average) of the total material treated through the MSP. This exposure scenario is also not realistic, as the zircon product is bagged within the MSP directly from the product chute (Figure 5.3) and then stored in an area of the plant with controlled access to workers. Dust liberation and soil ingestion pathways of exposure from zircon product is mitigated through product containment (within bags) and through the compulsory use of dust masks within the area. Gamma exposure is mitigated through limiting the access to the zircon storage area.

Figure 5.9: Zircon bagging at the MSP and storage at D3

The estimated annual dose for workers at the MSP is 1.49 mSv/y (excluding background), and is consistent with radiation doses of Iluka Australian operations, which record annual doses of workers at the MSP, from all exposure pathways, of below 5 mSv/y. The current personal gamma monitoring program conducted at SRL, through measurement of external gamma dose through thermoluminescent dosimeters (TLD badges), has to date not identified any over-exposures for this area.

5.1.1.3 Tailings Storage Area adjacent to the MSP

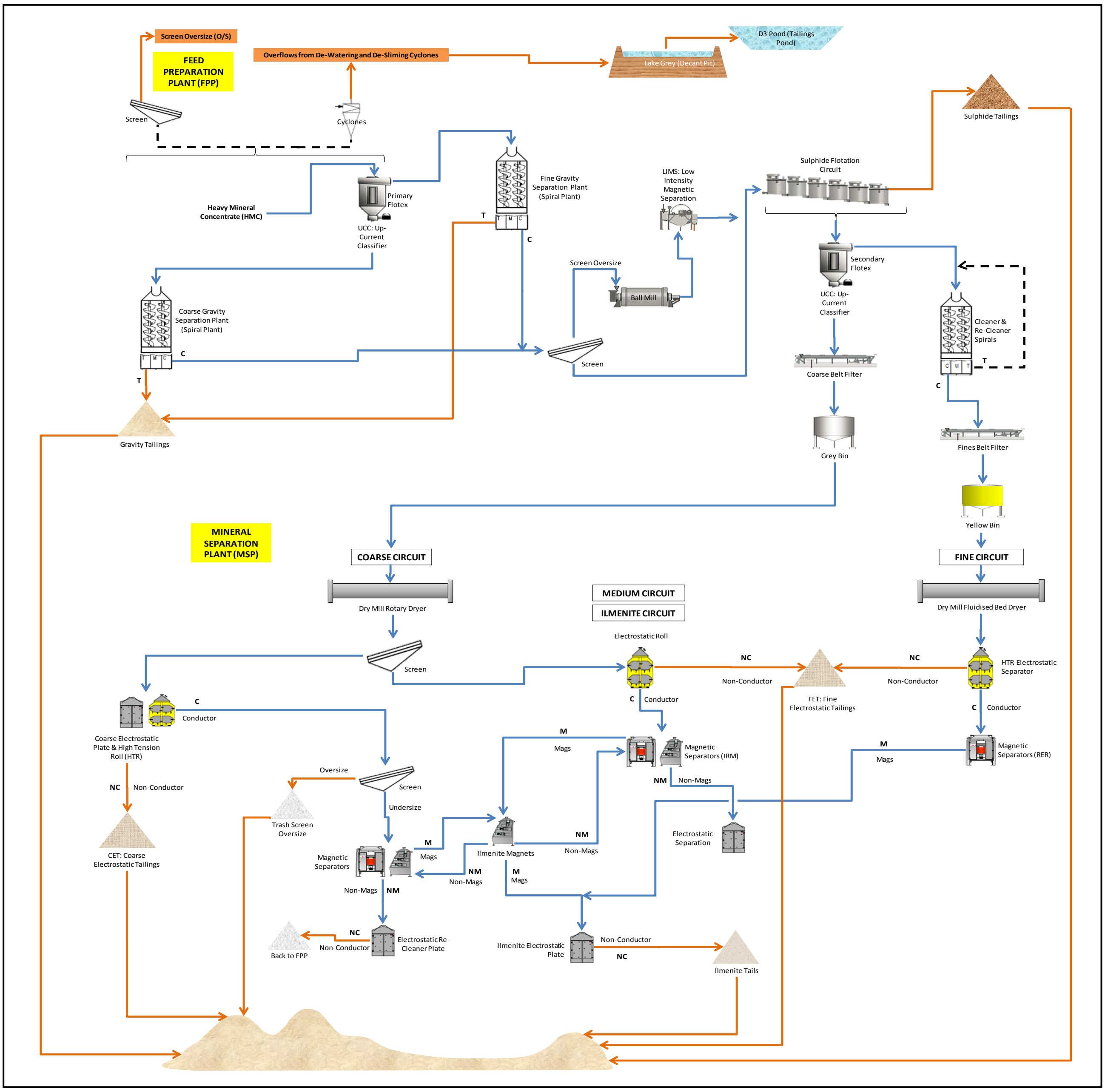


Figure 5.10: Tailings Storage Area

During 2015 and 2016, some of the tailings areas were re-worked to further extract recoverable heavy minerals which were then added to HMC originating from the active mining areas and used as feed to the MSP.

In addition to this, the high tension tailings (HTT; a combination of CET, MET and FET) are sporadically sold dependent upon market demand. This resulted in a marked reduction of the total tailings tonnage currently stored in the tailings storage area adjacent to the MSP. It also resulted in a reduced total material activity concentration (Bq/g U and Th) as the HTT material has an elevated level of uranium and thorium above the remainder of the tailings streams. The dose assessment for workers (Table 5.4), and for members of the public (Table 5.6), is therefore conservative when based on exposures to the reconstructed combined tailings material.

Table 5.12 Dose assessment for Workers at Tailings Storage

Operational Area		Worker Dose Assessment		
	Process Streams	Relevant Pathways	Annual Dose (mSv/y)	Exposure Time (h/y)
Background gamma (0.06 μSv/h)			**0.12**	2000 h/y
Tailings Storage Area adjacent to the MSP	Feed Preparation Plant (FPP) gravity tails	**External Gamma**	0.04	1000 h/y (50%)
	Flotation circuit tails (Sulphide tails)		0.48	
	Coarse Electrostatic Tails (CET)		5.14	
	Medium Electrostatic Tails (MET)		2.22	
	Ilmenite tails (IT)		3.54	
	Reconstructed Combined MSP tailings		1.10	
	Feed Preparation Plant (FPP) gravity tails	**Dust Inhalation**	0.01	2000 h/y
	Flotation circuit tails (Sulphide tails)		0.09	
	Coarse Electrostatic Tails (CET)		0.94	
	Medium Electrostatic Tails (MET)		0.42	
	Ilmenite tails (IT)		0.64	
	Reconstructed Combined MSP tailings		0.21	
	Feed Preparation Plant (FPP) gravity tails	**Inadvertent Soil Ingestion**	0.00004	N/A (consumption rate as per footnote ^)
	Flotation circuit tails (Sulphide tails)		0.0005	
	Coarse Electrostatic Tails (CET)		0.0054	
	Medium Electrostatic Tails (MET)		0.0022	
	Ilmenite tails (IT)		0.0038	
	Reconstructed Combined MSP tailings		0.0011	
	Annual Effective Dose (all pathways) – inclusive of Background and derived from Combined MSP tails		**1.31**	
	Maximum Annual Effective Dose (all pathways) – inclusive of Background and derived from exposure to CET only		**6.09**	
Annual Dose (mSv/y) = External Gamma Dose (mSv/y) + Dust Inhalation Dose (mSv/y) + Soil Ingestion Dose (mSv/y)				
Worker occupancy for gamma exposure assumed 1000 h/y (50% of worker occupancy) as the only individuals exposed is the security guard (some distance away from active tails stockpiles); FEL; Dozer; and Truck Drivers (equipment shielding from gamma radiation).				
Worker estimated annual dose calculated from gamma exposure, dust inhalation and soil ingestion originating from "Reconstructed Combined MSP tailings"				
Maximum Annual Dose (mSv/y) = Max External Gamma Dose from an individual material + Max Dust Inhalation Dose from an individual material + Max Soil Ingestion Dose from an individual material				
^ Inadvertent soil ingestion for adults = 100 mg/day (ICRP 72; Ozkaynak et al 2011)				

The largest calculated contributing exposure pathway for workers at the tailings storage facility is from external gamma, followed by dust inhalation. It was further shown that the largest dose from an individual material would be incurred from exposure to CET, followed by ilmenite tails and medium / fine electrostatic (MET and FET) tails respectively.

The maximum potential dose for workers at the tailings storage facility is 5.97 mSv/y (excluding background), under the assumption that an individual would stand next to a stockpile of CET for 1000 h/y; inhale only CET dust for 2000 h/y; and ingest only CET material. This dose would be an over-estimate, as CET constitutes only 2.8% (2016 average) of the total tailings material stored in the area. It has to be noted that the only individuals exposed to gamma radiation at the tailings storage area are the security guards, which are some distance away from the tailings stockpiles; FEL and dozer operators; and truck drivers. Mobile equipment operators would have some shielding provided by the machinery.

The estimated annual dose for workers at the tailings storage facility is 1.19 mSv/y (excluding background). The current personal gamma monitoring program (TLD badges) conducted for security guards at the tailings storage area, has to date not identified any over-exposures.

5.1.1.4 Nitti Port

Figure 5.11: Nitti Port product storage and shipment

Table 5.13 Dose assessment for Workers through potential exposure pathways at Nitti Port

Operations Evaluated	Process Streams	Worker Dose Assessment		
		Relevant Pathways	Annual Dose (mSv/y)	Exposure Time (h/y)
Background gamma (0.06 µSv/h)			**0.12**	2000 h/y
Nitti Port (Product storage and shipment)	Industrial Grade Rutile (IGR) product	**External Gamma**	0.44	2000 h/y
	Standard Grade Rutile (SGR) product		0.45	
	Ilmenite product (IP)		1.25	
	Zircon product		15.02	
	Reconstructed Combined MSP products		0.74	
	Industrial Grade Rutile (IGR) product	**Dust Inhalation**	0.05	2000 h/y
	Standard Grade Rutile (SGR) product		0.05	
	Ilmenite product (IP)		0.12	
	Zircon product		1.41	
	Reconstructed Combined MSP products		0.07	
	Industrial Grade Rutile (IGR) product	**Inadvertent Soil Ingestion**	0.0002	N/A (consumption rate as per footnote ^)
	Standard Grade Rutile (SGR) product		0.0002	
	Ilmenite product (IP)		0.0006	
	Zircon product		0.0075	
	Reconstructed Combined MSP products		0.0003	
	Annual Effective Dose (all pathways) – inclusive of Background and derived from Combined Products		**0.81**	
	Maximum Annual Effective Dose (all pathways) – inclusive of Background and derived from exposure to Zircon product only		**16.44**	
Annual Dose (mSv/y) = External Gamma Dose (mSv/y) + Dust Inhalation Dose (mSv/y) + Soil Ingestion Dose (mSv/y)				

Worker estimated annual dose calculated from gamma exposure, dust inhalation and soil ingestion originating from "Reconstructed Combined MSP Tailings"
Maximum Annual Dose (mSv/y) = Max External Gamma Dose from an individual material + Max Dust Inhalation Dose from an individual material + Max Soil Ingestion Dose from an individual material
^ Inadvertent soil ingestion for adults = 100 mg/day (ICRP 72; Ozkaynak et al 2011)

The largest calculated contributing exposure pathway for workers at Nitti Port is from external gamma, followed by dust inhalation. It was further shown that the largest dose from an individual material would be incurred from exposure to zircon product, followed by ilmenite. The maximum estimated dose for workers at Nitti Port is 16.3 mSv/y (excluding background), under the assumption that an individual would stand next to an open stockpile of zircon product for 2000 h/y; inhale only zircon dust; and ingest only zircon material. This dose would be an over-estimate, as zircon product constitutes only 0.7% (2016 average) of the MSP products and is only transported to Nitti Port when shipments are due (i.e. not permanently stored at the port). The estimated annual dose for workers at Nitti Port is 0.69 mSv/y (excluding background), as calculated from exposure to reconstructed MSP products.

5.1.2 Radiation Dose Assessment for members of the Public

Using the material data in Appendix 1 and making assumptions about occupancy factors, dust concentrations and particle size of dust loads to the estimates of radiation doses for members of the public is summarised in Table 5.6.

Table 5.6 Estimated doses to members of the Public

Exposure Pathways	Exposure Time (h/y)	Age Group	Annual Effective Dose (mSv/y)
Dry Mining operations (Lanti DM1 & Gangama DM2) and WCPs			
Closest community about 500 m from dry mining plants, thereby not close enough to incur a direct gamma dose and the WCP is a secured area with no access for the public	N/A		
Dust inhalation possible for road users and communities in the vicinity (combined materials – mineral sand ore)	876 h/y (10%) @	Adult	0.003
		15 years	0.003
		10 years	0.002
		5 years	0.002
		1 year	0.001
Closest community about 500 m from dry mining plants, thereby not close enough to incur a direct soil ingestion dose and the WCP is a secured area with no access for the public	N/A		
Dredge Mining operations (D1) and floating WCP			
Gamma dose for public possible from HMC stockpile (road users on foot), but direct access to the stockpile now restricted	876 h/y (10%) @	0.73	
Gamma dose for public possible from unsecured slimes tailings in TSF (road users on foot)		0.31	
Dust inhalation possible for road users and communities in the vicinity of HMC stockpile	876 h/y (10%) @	Adult	0.051
		15 years	0.049
		10 years	0.040
		5 years	0.029
		1 year	0.022
Dust inhalation possible for road users and communities in the vicinity of slimes tailings in TSF		Adult	0.019
		15 years	0.019
		10 years	0.015
		5 years	0.011

Exposure Pathways	Exposure Time (h/y)	Age Group	Annual Effective Dose (mSv/y)
		1 year	0.008
Soil ingestion dose for public possible from unsecured HMC stockpile (road users on foot), but direct access to the stockpile now restricted	N/A (consumption rate as per footnote ^)	Adult	0.0009
		15 years	0.0019
		10 years	0.0022
		5 years	0.0027
		1 year	0.0035
Soil ingestion dose for public possible from unsecured in vicinity of slimes tailings in TSF (road users on foot)		Adult	0.0004
		15 years	0.0009
		10 years	0.0011
		5 years	0.0013
		1 year	0.0017
MSP & Tailings Storage Area			
The MSP and tailings storage areas are secure areas with no access to members of the public to incur external gamma dose	N/A		
Some communities in vicinity of the MSP (Mogbwemo and Kpetema) can incur dust inhalation dose from combined material (reconstructed HMC). Closest community approximately 500m from MSP	876 h/y (10%) @	Adult	0.0008
		15 years	0.0018
		10 years	0.0021
		5 years	0.0025
		1 year	0.0033
Some communities in vicinity of the tailings storage area (Mogbwemo and KPetema) can incur dust inhalation dose from combined tailings. Closest community approximately 500m from MSP		Adult	0.064
		15 years	0.061
		10 years	0.050
		5 years	0.036
		1 year	0.028
The MSP and tailings storage areas are secure areas with no access to members of the public to incur soil ingestion dose	N/A		
Nitti Port			
Nitti Port is a secure area with no access to members of the public to incur a gamma dose	N/A		
Foya is the only village in the vicinity of Nitti Port, but at a distance in excess of 1 km. Members of the public can thereby potentially receive dust inhalation doses from combined products	876 h/y (10%) @	Adult	0.0004
		15 years	0.0008
		10 years	0.0010
		5 years	0.0012
		1 year	0.0015
Nitti Port is a secure area with no access to members of the public to incur a soil ingestion dose	N/A		

* In the WCP, the HMC stockpile is not entirely dry and dust inhalation dose from this stockpile would therefore be an over-estimate

@ A public exposure of 876 h/y (10% occupancy: 10/100 x 365 days/y x 24 h/day) is assumed for members of the public using roads in close proximity to sources of radiation

^ Inadvertent soil ingestion for adults = 100 mg/day (ICRP 72; Ozkaynak et al 2011); Inadvertent soil ingestion for children = 200 mg/day (Ozkaynak et al 2011; Stanek and Calabrese 1995b)

The highest calculated dose that a member of the public could receive from any of the operations evaluated, is from external gamma exposure to HMC. This dose rate, when added to dust and soil ingestion doses, is still below the public dose limit of 1 mSv/y.

It is therefore concluded that no high radiation exposure risk to members of the public exist for mining and processing activities at SR Area 1.

5.1.3 Gamma screening level surveys

During 2017, gamma screening level surveys were conducted of the SRL operational areas, roads and storage facilities (e.g. Nitti Port). Measurements were conducted with the RS-125 Serial No 2711 and RS-220 Serial No 6327. From the surveys it was shown that areas with the highest gamma radiation exposure are the MSP; the tailings storage area; and Nitti Port. This confirms the outcome of the radiation dose assessment for the workforce (Figure 5.6).

Figure 5.12: Gamma screening level surveys of Area 1

5.2 Radiation Dose Assessment for Fauna and Flora

Just as ionizing radiation affects humans, it may affect other living organisms. This may lead to effects in the environment, impacting individuals, populations, species and whole ecosystems. Such effects, which arise from the biological effects of ionizing radiation in wildlife, are referred to as environmental effects.

Environmental effects may include:

- increase morbidity (or reduce fitness) of individuals within populations;
- increase mortality; and
- reduce reproduction success (reduced number of offspring caused by reduced fertility or other factors).

To protect people, dose or dose rate limits may be specified and dose reduction strategies implemented, so as to remove the risk of acute effects. With regards to wildlife, the objective is to prevent or reduce the frequency of deleterious radiation effects, such as those that cause morbidity, early mortality or reduce reproductive success to a level where they would have a negligible impact of the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems (ICRP, 2008).

More recently, there has been increasing awareness of the potential vulnerability of the environment and the need to be able to demonstrate that it is protected against the effects of industrial pollutants, including radionuclides, for example the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) publication: Fundamentals for Protection of Ionizing Radiation (2014).

Plants and animals may be exposed to ionising radiation in the environment from different sources, and under different types of exposure situations. In all of these, factors affecting the doses received will vary enormously.
Various assessment tools are available for the radiological assessment of the environment. One of the readily available assessment tools is called ERICA (Environmental Risk from Ionizing Contaminants Assessment) that predicts the risk to reference animals and plants from ionizing radiation. The initial or Tier 1 ERICA assessment is used for screening out sites or materials giving rise to negligible risk of the populations of non-human species being affected by the presence of the ionizing radiation, i.e. radionuclide activity concentrations present (terrestrial, marine and freshwater environments) that could not result in dose to non-human species above the screening value of 10 µGy per hour. This screening value is the dose rate assumed to be environmentally safe.

The pragmatic approach to determine actual risk to biota would be to consider the existing databases (FASSET, ERICA, UNSCEAR, ICRP and PROTECT) on effects in terms of bands of dose within which certain effects have been noted, or might be expected, and then to select a band to serve as what is termed a 'derived consideration reference level' (DCRL). A DCRL can therefore be considered as a band of dose rate within which there is likely to be some chance of deleterious effects of ionizing radiation occurring to individuals of that type of species.

It is proposed to conduct such an ERICA assessment for SRL once all processing materials have been characterized in terms of full radionuclide analysis.

6. TRANSPORT OF RADIOACTIVE MATERIAL

HMC is hauled from Lanti (dry mine and dredge) and Gangama (dry mine) to the MSP and non-commercial tailings are back-loaded to the mine for final disposal into mine voids. Some of the high tension tailings (HTT) are sold and transported to Nitti Port, but some might be discarded along with other tailings streams into the mining voids. MSP products are hauled to Nitti Port for loading onto barges and eventually onto ocean going vessels.

The transport of radioactive materials is controlled by the IAEA Safety Requirements - Regulations for the Safe Transport of Radioactive Material (2012), and the International Maritime Dangerous Goods Code 2016 (IMDG Code). This includes the transport of ores and concentrates which contain natural thorium and uranium radionuclides with a specific activity exceeding 10 Bq/g.

For the purposes of transport, some of these materials may be exempt from the requirements of the IAEA Transport Regulations (2012), and the IMDG Code. The exempt concentrations for both uranium and thorium are 1 Bq/g. However, there is an additional clause that applies to the transport of materials containing natural uranium and thorium, where processing of the material is not for extraction of the radioactive elements. Under this criterion, heavy mineral sand products or tailings may be exempt from the transport regulations if they have an activity concentration of thorium and uranium of less than 10 Bq/g.

As per Appendix 1, only two products have activity concentrations potentially in excess of 10 Bq/g and these are the zircon product and the electrostatic tails (CET, MET and FET also known as HTT). Currently, these two products are combined in ratios as to result in material activity concentrations below 10 Bq/g for transport purposes.

In the potential event that zircon or HTT are classified as radioactive for the purposes of transport, SRL shall ensure that radioactive classification, packaging, labelling and placarding of trucks comply with the IAEA Transport Regulations. The Radiation Management Plan for transport will be adhered to in respect of the following:

- all reasonable steps are taken to stow and secure any package in a freight container or on a vehicle;
- any radiation monitoring or personal dose assessment requirements as outlined in the RMP are complied with; and
- the NSRPA are notified immediately of any accident involving the transport vehicle and loss of containment of radioactive materials.

7. CONTROL MEASURES

Control methods or actions proposed for the site to ensure that radiation doses are maintained as low as reasonably achievable (Table 7.1). Radiation monitoring conducted to ensure control measures are adequate is discussed in Section 8.

Table 7.1 Proposed control measures for radiation exposure at SR Area 1

Exposure Pathways	Proposed Control Measures
Mining Operations	
Exposure to gamma radiation from ore body	Establish site security and signage to restrict unauthorized access.
Inhalation of radioactive dust	Implement a Traffic Management Plan for the mine.
	Evaluation of dust suppression suitable for nuisance and environmental dust control.
	Progressive establishment of vegetation on restored surfaces and minimizing the area of exposed surfaces.
	Use mining equipment with enclosed cabins.
	Monitor environmental dust on site and at boundaries.
Processing plants (mining unit plant [MUP], pre-concentrator plant [PCP] and WCP)	
Inhalation or ingestion of radioactive dust	Enforce good personal hygiene practices (e.g. no eating, drinking or smoking without first washing hands when been in contact with the material. If visibly contaminated, wash down shoes, etc.).
	Keep HMC stockpile moist by continuous discharge of wet HMC as wet processing results in low dust emissions.
Exposure to gamma radiation from HMC stockpile.	Locate HMC stockpile away from the site office.
	Ensure low occupancy rate by FEL operators.

Exposure Pathways	Proposed Control Measures
Transport to and from MSP	
Exposure to gamma radiation from bulk HMC *(Note that HMC is below exemption limits for IAEA Transport Regulations).*	Ensure tailgates seal effectively on trucks transporting HMC and that HMC is suitably moist to prevent distribution of the material into the environment and potentially exposing members of the public to dust inhalation and external gamma exposure.
	Minimize exposure time of the driver on the road. The radiation dose received is however limited by separation distance between the driver and the load as well as by shielding of the truck.
Exposure to gamma radiation from bulk mineral tailings from the MSP.	If possible, blend MSP tailings with low radioactivity sand tailings to reduce overall radionuclide concentrations.
	Minimize exposure time of the driver on the road. The radiation dose received is however limited by separation distance between the driver and the load as well as by shielding of the truck.
	Transport materials in accordance with the IAEA Transport Regulation requirements for Low Specific Activity Materials (LSA I) and surface contaminated objects (SCO) and ensure that load is securely contained to prevent environmental contamination in case of an accident.
Disposal of tailings and residues at mine site	
Exposure to gamma radiation from bulk tailings materials and inhalation of radioactive dust.	Management of activity via a Safe Work Procedure or as per the RMP for NORM, which specifies any special protective measures.
	Limited exposure due to only a small volume of mining by-products requiring disposal.
	Establish a monitoring program.
Unauthorized release of mineral sands tailings to public leading to exposure to gamma radiation and inhalation of radioactive dust.	No release of tailings or products without assessment of implications.
Radon/thoron exposure of members of the public	
Emanation of thoron/radon gas from stockpiled or deposited minerals.	Ensure open storage, wet concentrate and natural ventilation which will quickly dilute any thoron/radon gas emanated from the mine site. Consequently, it is anticipated that the radon levels would be close to natural background levels for Area 1.
	Cover deposited tailings minerals with low radioactivity fill.
Radionuclides in surface or groundwater	
Potential contamination of surface or groundwater by radionuclides	Monitor radium and other radionuclide levels in groundwater during each phase of mining and processing.
Site Rehabilitation	
Exposure to gamma radiation from restored landforms.	Compare baseline gamma dose rate survey with post-mining levels.

8. RADIATION MONITORING AND DOSE ASSESSMENT

8.1 Monitoring program objectives

The main purpose of radiation monitoring of personnel is to collect relevant exposure data for health protection. The primary radiological hazard associated with mineral sands mining and processing is chronic exposure to elevated levels of external radiation and airborne radioactivity from the material. The consequential health risk therefore depends upon the average exposure received by an individual worker over the course of their working life (i.e. the total radiation dose).

8.2 Monitoring strategy

The radiation monitoring program consists of two different assessment components, consisting of 'routine' and 'operational' measurements. Routine monitoring is to be performed with the objective to determine and assess the range and distribution of exposures for different work categories (usually these are referred to as homogeneous exposure groups). Results of this monitoring when compared with baseline data can be used for determining acceptability of exposures and the need for further investigative sampling and additional controls.

Multiple exposure measurements are necessary to precisely estimate an individual's yearly exposure. Due to the large number of staff normally involved in mining operations it is reasonable to monitor various operations rather than to track an individual's exposure. Individuals will be assigned to work category groups where the exposures are expected to be similar. The group mean exposure will then be assigned to all workers within the group, irrespective of whether an individual worker has been sampled or not during the monitoring period.

It is important that sufficient exposure data is collected, across the various work categories, in order to make robust statistical analyses and conclusions. The optimum number of measurements required will be related to the levels or concentrations measured. For example, for dust monitoring, the number of samples will depend on the concentration of airborne radioactive contaminants and their variability. A greater number of samples are required for work categories where exposures are a significant fraction of derived air concentration limits and/or the variability in exposures is substantial. In other words, the work categories with the potential to record significant airborne radioactivity concentrations will be sampled at greater frequency.

'Operational' monitoring is usually performed to identify the specific sources and tasks that pose the greatest potential exposures in a workplace. The results serve as a basis to devise the most appropriate and efficient control strategies, and to assist in task characterisation or engineering performance assessment. Sampling times are adjusted to reflect process cycle or task times. Operational sampling will be undertaken as determined by the SRL appointed Radiation Safety Officer (RSO). It is important that the routine monitoring program is based on random collection procedures, and unbiased monitoring and analytical techniques. The use of non-random collection procedures (e.g. sampling only "worst cases" or during discrete campaigns of a few days every quarter), and operational monitoring results, will not be used for routine exposure assessments.

It is important that the radiation monitoring program remain dynamic and subject to ongoing review and adjustment in light of exposure trends.

8.3 Designated workers

The intensity of radiation monitoring, and the techniques utilised will vary depending on an individuals expected annual dose. Employees can be split in to two groups namely 'designated' and 'non-designated' employees.

'Designated employees', for the purpose of the radiation monitoring program, are those workers who are classed as 'occupationally exposed persons', i.e. those likely to receive a radiation dose in excess of 1 mSv/y. For this group of employees it is important, where practicable, to undertake measurements that rely on personal measurements.

'Non-designated employees', for the purpose of this monitoring program, are those occupationally exposed employees whose work requires only minor exposure to radiation and are unlikely to exceed an annual dose of 1 mSv/y. Site employees whose work involves no direct exposure to radiation should be included in this category. For this group, radiation monitoring will be less frequent, and rely heavily on area monitoring results.

It is expected that most employees who work at the site will be non-designated employees. However, approximately 12 months of individual assessment with personal passive dose meters will be required to accurately categorise designated and non-designated employees.

A broad summary of the elements of the monitoring strategy for both designated and non-designated employees are provided in Table 8.1.

Table 8.14 Summary of approach to monitoring for designated and non-designated employees

Exposure Pathway	Hazard	Monitoring Method	
		Non-designated Employees	Designated Employees
Inhalation	Long-lived alpha emitters in dust	Area sampling using low or medium flow-rate air samplers. The average exposure for the work category is obtained using a random sampling regime, in which multiple measurements are collected over the monitoring period (usually a year) from representative work areas.	Personal sampling using low flow-rate portable air samplers. The average exposure is determined for each designated work category (each category representing a relatively uniform exposure group). A random sampling regime, in which many measurements are collected from various designated workers over the monitoring period (usually a year), is used.
Inhalation	Radon/ thoron	Area sampling using continuous monitors (e.g. track etch detectors) or single gross alpha measurements.	Area sampling using continuous monitors (e.g. track etch detectors) or single gross alpha measurements
External radiation	Gamma rays	Combination of passive area dose meters and dose rate measurements using a survey meter with suitable sensitivity and energy response. Doses are assessed by multiplying radiation dose rates in various areas of the site with occupancy factors.	Personal passive dose meters. The integrated radiation dose over the exposure period is sum of the personal-issue dose meter results over the period.

8.4 Radiation monitoring program

The operational radiation monitoring program for SR Area 1 is summarised in Table 8.2. The frequency of monitoring has not been included and will be determined as soon as reasonably achievable.

IAEA Safety Standards Series No. RS-G-1.7 (IAEA 2004), Application of the Concepts of Exclusion, Exemption and Clearance states that “the intensity of monitoring should be matched to the exposures potentially received. It is common practice to ‘designate’ employees who are likely to receive significant doses (for example, greater than 5 mSv/y). Such designated employees are then monitored more intensively (including, where appropriate, personal monitoring), and their doses are assessed individually. Non-designated employees will then be monitored less intensively, and their doses assessed as an average of their relevant workgroup(s)”.

Table 8.15 Operational radiation monitoring for SR Area 1

Radiation parameter	Item/site monitored	Method/equipment and/or radiation measured
Personal dose Hp(10)	Designated employees	Personal passive dose meters.
	Non-designated employees	Combination of area passive dose meter results, monitoring of Ambient Dose Equivalent Rate using suitable dose rate monitor (e.g. energy-compensated GM) and occupancy factors.
Absorbed gamma dose rate in air – SR Area	Designated locations	Combination of area passive dose meter results and monitoring of Ambient Dose Equivalent Rate using suitable dose rate monitor (e.g. energy-compensated GM).
Airborne radioactivity (dust) - Personal	Designated employees	Personal air sampling using portable, low-flow (2 LPM) pumps. Determination of activity concentration using alpha counting.

Radiation parameter	Item/site monitored	Method/equipment and/or radiation measured
	Non-designated employees	Area air sampling using medium-flow pumps. Determination of activity concentration using alpha counting.
Airborne radioactivity (dust) – Off-site locations	Site boundary at locations where environmental PM_{10} dust measurements are taken	Positional air sampling using high volume samplers. Determination of activity concentration using alpha counting and gamma ray spectrometry.
Radon & thoron gas concentrations – Off-site locations	Upwind and downwind locations in vicinity of closest residences to mining and operational areas	Track etch detectors – combination system to measure both radon (Rn-222) and thoron (Rn-220).
Surface contamination – on-site	Crib rooms, control rooms, change rooms in all areas; fixed and mobile plant	Visual inspection, contamination monitoring, and wipe tests or equivalent for transferable contamination.
Surface contamination – off-site removal	Materials/plant removed from site.	Inspection and logging by RSO or Iluka staff prior to clearance.
Particle size (AMAD) determinations	Work areas	Air sampling through a cascade impactor. Alpha counting of stage substrates and statistical determination of AMAD.
Radioactivity content of HMC, saleable products, MSP by-products/tailings and slimes	Concentrate, product and waste streams	Analysis of uranium and thorium content by ICPMS or other suitable technique (conversion of ppm to Bq/g^{-1})
Radionuclides in groundwater	Selected groundwater monitoring bore sites (based on pre- operational survey)	Analysis of radium (Ra-226, Ra-228) by scintillation counting by external laboratory.

In regard to the monitoring program there are several additional operational considerations, namely:

- Surveys of the ambient dose equivalent rate in air will consist of a series of measurements that adequately cover the regularly occupied locations of the areas under consideration, with typical and peak values being recorded. For gamma surveys, a portable hand-held survey meter with suitable sensitivity and energy response will be held at about 1 m from ground/floor level.
- For personal air sampling, employees will be assigned to relatively uniform exposure groups, to the extent practical, and the average exposure for the group will be determined by applying appropriate statistical analysis techniques to the measured airborne radioactivity concentrations. Assignment of personal air samplers will be on a rotational basis to ensure a spread of monitoring results on individuals within a work category.
- Personal sampling for airborne radioactivity will be undertaken in accordance with the assumed best practice procedure for inhalable dust monitoring as specified in Australian Standard AS-3640 – *Workplace atmospheres – Method for sampling and gravimetric determination of inhalable dust*.
- The sampling strategy for personal air sampling will include sampling on night shifts as well as during the day. Sample start times will be varied to ensure adequate coverage of all operational duties carried out throughout the shift.

Positional air samples will be usually taken for engineering control purposes or to assess the impact of changes to process conditions or control technology. As such, the frequency of measurement is left to the professional judgement of the RSO.

8.5 Radiation monitoring equipment

Table 8.3 provides a list of typical equipment that will be used to give effect to the monitoring program described in Section 8.4.

Table 8.16 List of typical equipment for radiation monitoring

Monitoring Equipment	Purpose
Personal radiation monitors	Personal radiation dose -$H_p(10)$
Hand held radiation monitor with appropriate energy compensated detector	Area gamma monitoring - H*(10)
High volume air sampler with PM10 size selection	Environmental dust concentration measurement. Filtered dust samples are analyzed for gross alpha activity.
Portable air sampling pumps	Personal dust concentration measurements. Filtered dust samples are analyzed for gross alpha activity.
Inhalable dust sampling heads with filters	For use with portable air sampling pumps and measurement of dust concentration
Bubble tube or equivalent accepted calibration service	Flow rate verification for personal air sampling pumps
Alpha counting chamber with solid state detector and counter/time	Gross alpha counting of filtered dust samples
Inductively Coupled Plasma Mass Spectrometry (ICPMS) – laboratory instrument	Analysis of thorium and uranium content of bulk mineral samples
Track etch detectors	Assessment of radon/ thoron gas concentrations in air.

All equipment used for the radiation monitoring program will be maintained and calibrated in accordance with Australian or International standards.

8.6 Investigation levels

Investigation and reporting will be implemented when monitoring indicates any unusually high or unexpected results for a measured radiation parameter. The investigation may reveal a previously undetected source of radiation or a practice that has changed since done previously. The investigation may also reveal an erroneous assessment or an issue with the monitoring technique. The investigation levels that will be used for SR Area 1 are outlined in Table 8.4.

Table 8.17 Investigation levels for the radiation monitoring program

Radiation Parameter	Investigation Level	Comment
1. Area Monitoring		
1.1 Site Boundary	>0.5 µSv/h	If not previously identified
1.3 Any Area	>5 µSv/h	If not previously identified
2. Personal External Exposure Monitoring		
2.1 Designated Worker	>2.0 mSv in a quarter	Assessed from personal radiation monitor
3. Personal Internal Exposure Monitoring		
3.1 Designated Worker	>1 mSv in a quarter	Assessed from air sampling
4. Airborne Radioactivity		
4.1 Total Alpha Activity on personal air sample	>4.0 Bq/m^3 for shift sample	Four times derived air concentration limit ~ 0.5 mSv
4.2 Total Alpha Activity on personal air samples	4 consecutive samples >1.0 Bq/m^3	Indicates potential for significant exposure
4.3 Total Alpha Activity	>Mean + 3 std deviations	Work category mean
5. Airborne Dust		
5.1 Inhalable dust on personal air samples	>10 mg/m^3	Statutory limit for dust concentration

8. CONCLUSIONS

Limited data is available on the uranium and thorium content of the ore and tailings streams at SR Area 1. Routine in-house XRF analysis is done on products and some of the tailings materials but currently, a quality control bench-marking exercise is underway to validate the accuracy of in-house analysis. Previous studies aimed at characterizing tailings materials have only evaluated gross alpha (α) and gross beta (β) content and to date, no full decay chain radionuclide analysis are available on any of the process streams.

Available analysis was used to estimate potential doses to workers and members of the public from relevant pathways of exposure. In the absence of suitable environmental data, assumptions about occupancy factors; inhalation rates; dust concentrations in air; dust particle size etc., were used to estimate radiation dose. It has to be noted however that the dose assessment is conservative in estimation, as the initial indications from the quality control benchmarking evaluation confirmed that the SRL in-house XRF thorium and uranium analysis are biased towards the higher end. Dust inhalation doses is further conservative in that a dust loading of 1 mg/m^3 (corresponding to a high dust loading) was assumed for calculation purposes and the initial air quality modeling data for the ESHIA (SRK, 2017a) indicated the maximum $PM_{2.5}$ dust loading to be 0.013 mg/ m^3 which is tenfold lower than the assumed value. This dust monitoring was however conducted during the wet season, and monitoring for the dry season is still required.

From the dose assessment conducted across all the operational sites at Area 1, it was determined that the largest contributing exposure pathway for workers is from external gamma, followed by dust inhalation. Inadvertent soil ingestion dose was shown to be a negligible contributor to total dose.

The estimated dose to workers at mining and wet concentrator plants (WCP) operations was shown to be 0.1 mSv/y.

At the mineral separation plant (MSP) it was determined that the largest dose from an individual material would be incurred from exposure to zircon product. The zircon product however only constitutes 0.5% of the total material treated through the MSP; is bagged directly from the product chute (to mitigate dust exposure); and stored in an area of the plant with controlled access to workers, thereby limiting gamma exposure. The estimated annual dose for workers at the MSP is 1.49 mSv/y (excluding background), which is consistent with radiation doses of Iluka Resources Limited (Iluka) Australian operations, which record total annual doses below 5 mSv/y. The current personal gamma monitoring program conducted at SRL (TLD badges) to date has shown that doses are in line with those predicted from the dose assessment.

At the tailings storage area, it was determined that the largest dose from an individual material would be incurred from exposure to coarse electrostatic tails (CET). This dose would however be an over-estimate, as CET constitutes only 2.8% of the total tailings material stored in the area. Further to this, the only individuals exposed to radiation dose at the tailings storage area are the security guards which control access to the area (some distance away from the actual tailings stockpiles); front-end-loader (FEL) operators; dozer operators and truck drivers (some shielding provided by the machinery). The estimated annual dose for workers at the tailings storage is 1.19 mSv/y (excluding background) and the current personal gamma monitoring program conducted at SRL (TLD badges) to date have shown that doses are in line with those predicted from the dose assessment.

At Nitti Port, it was determined that the largest worker dose from an individual material would be incurred from exposure to zircon, followed by ilmenite. The estimated annual dose for workers at the Port is however 0.69 mSv/y (excluding background), as calculated from exposure to “reconstructed MSP products”.

All doses calculated for the workforce is an order of magnitude below the annual dose limit of 20 mSv/y, and in line with doses measured at Iluka Australian operations.

The estimated total dose for members of the public on roads or in villages close to dry mining; wet mining; WCP operations; MSP and Tailings operations; and close to Nitti Port is below the public exposure limit of 1 mSv/y.

Gamma screening level surveys conducted of the SRL operational areas, confirmed that the areas with the highest gamma radiation exposure are the MSP; the tailings storage area; and Nitti Port.

The emanation of radon from heavy minerals has been found to be very low (KER 1988). In the open, any radon released from an ore body or a stockpile will be rapidly diluted in the atmosphere and dispersed. It is therefore likely that in open pit mining and associated processing, the radon levels will be comparable to ambient levels and this exposure pathway is not considered to be significant for workers or members of the public. It is however recommended to measure radon levels in air as part of the baseline surveys.

Other potential pathways of exposure, such as from the ingestion of surface or groundwater by members of the public, are not expected to be significant, but would nonetheless need on-going monitoring and assessment.

Knight Piesold (2008) indicated that the supernatant discharge from the coarse sulphide plant tailings outlet pipe (un-diluted process stream) had radioactivity levels that exceeded the WHO guidelines for gross alpha and gross beta. Process / surface water locations downstream of the Mogbwemo dredge pond however did not exceed WHO guidelines, indicating a minimal impact from these discharge sources.

SRK (2017b) geochemistry characterization study further concluded that all the measured parameters in the leachate from both the primary and secondary process tailings are within the Sierra Leonean Environmental Protection (Mines and Minerals) Regulations 2013 “limit at any moment”, except for pH. The findings indicated that:

- “As the primary process tailings are expected to be typically non-acid forming, slightly acidic and non-saline, the bulk of this material is considered to be geochemically unreactive. Due to the low acid sulphate soil and metal leaching (ASS/ML) risk, no special ASS/ML management requirements are recommended except continuation with operational monitoring and testing to detect any unexpected changes that may occur during mining.
- The secondary process tailings, specifically sulphide flotation tailings (SFT), total tailings (TT) and ilmenite tailings (IT), are potentially acid generating (PAG), acidic and non-saline and are likely to present a risk of increased acidity when exposed to oxidising conditions. These materials should continue to be deposited sub-aqueously as is currently done to limit exposure to oxygen. It is recommended that sufficient depth of water cover over the potentially acid generating (PAG) tailings be ensured to prevent re-suspension of tailings by wind or wave action to minimise exposure to potential oxidising conditions”.

Further to this, drinking water for workers and some communities surrounding the MSP, is provided by SRL. Members of the public also extract water for drinking purposes from wells in their villages and usually not from surface water sources. The location of drinking water wells for the public is far removed from the MSP or tailings storage facility. Even though members of the public make use of surface water bodies for swimming and bathing, such activities do not occur in close proximity to the MSP or tailings storage area. The amount of water accidentally ingested during swimming should be minimal.

Surface and groundwater monitoring will be included as part of the overall environmental monitoring program. There may be some seasonal and regional variations, and these variations must be taken into account in assessing the possible long-term impacts of mining or mineral processing on the surface and ground water conditions in the area.

To investigate the risk of radiation exposure to fauna and flora, a preliminary ERICA assessment has been conducted, the results of which demonstrated that modelled dose rates for all fauna species exposed to process materials at SR Area 1 are below the threshold dose rate of 10 μGy/h. For mine

Slimes tailings (cyclone overflow); HMC; MSP tailings and MSP products, flora species (with the exception of trees) are above the screening dose level. Lichen and Bryophytes are the most sensitive organisms, followed by Grasses and Shrubs respectively.

Based on Derived Concentration Reference Levels (DCRLs), flora species potentially only show effects of reduced reproductive success at levels of 10 – 100 mGy/day (equivalent to 417 to 4170 μGy/h). Preliminary DCRL's are set at 1 – 10 mGy/day (equivalent to 42 to 417 μGy/h), but at these levels, no effects to populations have yet been proven. For mine slimes tailings; HMC; MSP Tailings and MSP Products, Lichen and Bryophyte dose rates are in excess of 42 μGy/h, but still well below 417 μGy/h.

It has to be noted however that mineral sand tailings, as present around dredge ponds and active mining areas, are well sorted, with minimal fine particles present (with the exception of the slimes tailings which is the – 63 micron material fraction from the wet concentrator plant and mainly consistent of clay phases). Sand tailings have very low nutrient and water holding capacity and are unable to sustain plant growth.

It can therefore be concluded that the activity concentration levels contained within mine sand tailings, or areas contaminated with HMC; MSP tailings or products should not have a significant effect on fauna and flora populations present.

9. RECOMMENDATIONS

Limited data is available on the uranium and thorium content of the ore and tailings streams at SR Area 1. To further estimate potential doses to workers and members of the public from relevant pathways of exposure, a baseline monitoring program will be established for the SR Area 1 operations. This will result in more accurate predictions of the potential doses to workers and the public. The baseline monitoring program should include the determination of the following within the project area:

- the radionuclide concentrations in soil across the current (and future) project areas through the soil profile;
- the radionuclide concentrations in tailings across the current project areas. Full radionuclide analysis of selected tailings streams for future human health and biota modeling purposes;
- the absorbed (radiation) gamma dose rates in air across the current (and future) project areas;
- the radon (Rn-222) and thoron (Rn-220) concentrations in the air;
- the groundwater radionuclide concentrations (incl. U, Th, Ra-226, Ra-228, gross alpha and beta);
- the surface water radionuclide concentrations (incl. U, Th, Ra-226, Ra-228, gross alpha and beta); and
- the long lived alpha activity (LLAA) in airborne dust.

It is also proposed to conduct an ERICA assessment (biota modelling) once processing materials have been characterized in terms of full radionuclide analysis.

10. REFERENCES

- Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) (2014). Fundamentals for Protection of Ionizing Radiation
- Australian Standard AS-3640 – Workplace atmospheres – Method for sampling and gravimetric determination of inhalable dust.
- Graell Ltd. (2017). Sierra Rutile Project Area 1 Environmental, Social and Health Impact Assessment: Hydrogeological Study. Report No. 515234/Hydrogeology.
- Iluka Resources Limited (2005). Material Safety Data Sheets, http://www.iluka.com.au/
- Iluka Resources Limited (2006). Northern Murray Basin Project Ouyen Area, North-Western

Victoria: Radiation Assessment, March 2006

- International Atomic Energy Agency (IAEA) (2004). Safety Standards Series No. RS-G-1.7 Application of the Concepts of Exclusion, Exemption and Clearance
- International Atomic Energy Agency (IAEA) (2006). Safety Report Series 49 – Assessing the need for radiation protection measures in work involving mineral sand raw materials standards.
- International Atomic Energy Agency (IAEA) (2012). Safety Requirements - Regulations for the Safe Transport of Radioactive Material.
- International Atomic Energy Agency (IAEA) (2011) Basic Safety Standards
- International Commission on Radiological Protection (ICRP) (2008). Environmental Protection – the Concept and Use of Reference Animals and Plants. ICRP Publication 108. Ann. ICRP 38 (4-6).
- International Commission on Radiological Protection (ICRP) (2012). Compendium of Dose Coefficients based on ICRP Publication 60. ICRP Publication 119. Ann. ICRP 41(Suppl.)
- International Maritime Dangerous Goods Code (2016).
- KER 1988. Kerrigan, G.C., *Thoron Emanation from Monazite*, Radiation Protection in Australia, Vol. 6, 63-64, 1988.
- Sierra Rutile Limited (2017). SRLRM001 - Sealed Radioactive Sources Radiation Management Plan.
- Knight Piesold (2008). Sierra Rutile Limited Water Monitoring Report.
- SRK Consulting (South Africa) (Pty) Ltd. (2017a). Sierra Rutile Project Area 1 – Environmental, Social and Health Impact Assessment: Specialist Air Quality Impact Assessment.
- SRK Consulting (South Africa) (Pty) Ltd. (2017b). Sierra Rutile Project Area 1 – Environmental, Social and Health Impact Assessment: Geochemistry Characterization of Selected Residues.
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2000). Exposures from Natural Radiation Sources. UN, New York.
- Hewson, G.S. and Upton, H. (1996) Operational and Regulatory Aspects of the Management of Radioactive Wastes Arising from Mineral Sands Processing. Radiation Protection in Australia. Volume 14(3), 60-67.
- Western Australia Chamber of Minerals and Energy (WACME) (2000) Best practice in radioactive waste management guidelines in the Western Australian mineral sands industry. January 2000 revision.
- World Health Organization (WHO) (2008) Guidelines for Drinking Water Volume 1: Recommendations. 3rd Edition.
- Fauna and Flora Radiation Risk Assessment through ERICA modelling at SR Area 1

APPENDIX 1 – RADIOLOGICAL CHARACTERISTICS OF SR AREA 1 PROCESSING STREAMS

Limited data is available on the uranium and thorium content of the ore and tailings streams. Routine in-house XRF analysis is done on products and some of the tailings materials but currently, a quality control bench-marking exercise is underway to validate the accuracy of in-house analysis.

Previous studies aimed at characterizing tailings materials have also only evaluated gross alpha (α) and gross beta (β) content; did not analyze for uranium or thorium directly; and did not quantify full decay chain radionuclide analysis. To date, no full decay chain radionuclide analysis are available on any of the process streams.

Specific activity or activity concentration (Bq/g) values are calculated for thorium and uranium using the following conversion factors:

Th (Bq/g) = Th (ppm) x 4.059 / 1000
U (Bq/g) = U (ppm) x 12.441 / 1000

The conversion factors for uranium and thorium from ppm to Bq/g are calculated as follows (conversion factors are provided in Table 5):

Specific Activity (SA) = λN (Bq/g)

Where λ = decay constant (s^{-1}) = ln 2 / $t_{1/2}$ = 0.693 / $t_{1/2}$
$t_{1/2}$ = half live of nuclide (s)
N = number of atoms (g^{-1}) = N_A / A
N_A = Avogadro Constant = number of atoms in one mole = 6.023 x 10^{23} atoms
A = Atomic weight of nuclide in one mole

Table A: U-238 and Th-232 Specific Activity Conversion Factors

Nuclide	Atomic Mass (A)	Half-life of individual		Decay Constant	Specific Activity Conversion Factor
	gram / mole	Years	sec	λ = ln 2 / $T_{1/2}$ (s)	
U238	238.03	4.47 billion	1.40903E+17	4.92E-18	12.441
Th232	232.04	14.05 billion	4.43081E+17	1.56E-18	4.059

The Table below summarizes indicative U and Th concentration ranges as per in-house XRF analysis, extracted from limited data sets in 2017 as well as the yearly data from 2016 where available. The accuracy of these results is dependent on the outcome of the quality control benchmarking evaluation where duplicate samples have been analyzed through at accredited external laboratories. As indicated, the tonnage and constituency of the ilmenite tails is highly variable and currently poorly defined.

Table B: Product and tailings radionuclide concentrations in SRL operations

Process Stream	U (Bq/g)			Th (Bq/g)			Th & U	U (ppm)			Th (ppm)			
	Average	Min	Max	Average	Min	Max	Bq/g	Average	Low	High	Average	Low	High	Comments
Mining and Wet Concentrator Plants (WCP's)														
D1 HMC	0.26	0.19	0.41	0.77	0.51	1.20	1.03	21	15	33	190	126	295	Nov 2017 daily assay data
DM1 HMC	0.22	0.17	0.26	0.73	0.49	1.54	0.95	18	14	21	180	120	379	
DM2 HMC	0.25	0.17	0.34	1.21	0.56	2.18	1.46	20	14	27	299	139	536	
Total HMC	**0.47**	**0.25**	**1.62**	**0.94**	**0.81**	**2.03**	**1.42**	**38**	**20**	**130**	**231**	**200**	**500**	**2016 Annual Data**
Feed Preparation Plant (FPP)														
FPP gravity tails	0.02	0.01	0.04	0.04	0.03	0.06	0.07	2	1	3	11	8	16	Dec 2017 daily assay data
Flotation circuit tails	0.21	0.15	0.31	0.59	0.19	1.26	0.80	17	12	25	145	47	311	Froth samples taken from individual cells
Dry Plant Mineral Separation Plant (MSP)														
Coarse E Tails	1.2	0.9	1.5	7.0	4.1	11.7	8.1	93	74	118	1718	999	2887	Nov 2017 daily assay data. These streams are combined to form Zircon Concentrate
Medium E Tails	0.9	0.6	1.1	2.7	1.6	3.7	3.7	75	52	92	673	402	912	
Scavenger HTRS NC (Tails)	1.0	0.6	1.4	2.0	0.6	4.0	3.1	81	50	109	505	136	985	
Scavenger Plate NC (Tails)	1.1	0.8	1.4	2.7	0.7	4.8	3.8	89	64	110	659	177	1176	
Ilmenite tails		0.12	1.24		1.62	8.12			10	100		400	2000	Highly variable and data is indicative only
Combined Coarse and Medium E Tails	**10.6**	**4.0**	**49.8**	**10.7**	**1.9**	**17.7**	**21.3**	**850**	**320**	**4000**	**2640**	**460**	**4350**	**2016 Annual Data**
IGR product	0.21	0.19	0.26	0.23	0.10	0.22	0.44	17	15	21	56	25	53	2017 shipment assays
SGR product	0.22	0.17	0.31	0.26	0.21	0.32	0.48	18	14	25	63	52	79	
Ilmenite product	0.32	0.16	0.57	0.79	0.50	1.03	1.11	26	13	46	195	124	253	
IGR product	**0.23**	**0.12**	**0.34**	**0.18**	**0.08**	**0.27**	**0.41**	**18**	**10**	**27**	**45**	**19**	**68**	**2016 Annual Data**
SGR product	**0.22**	**0.07**	**0.30**	**0.20**	**0.10**	**0.34**	**0.42**	**17**	**6**	**24**	**50**	**25**	**84**	**2016 Annual Data**
Ilmenite product	**0.27**	**0.08**	**1.71**	**0.77**	**0.48**	**1.30**	**1.04**	**22**	**6**	**138**	**189**	**118**	**321**	**2016 Annual Data**
Zircon product	**2.55**	**0.29**	**5.10**	**9.63**	**0.27**	**38.46**	**12.18**	**205**	**23**	**410**	**2373**	**67**	**9475**	**2016 Annual Data (Bag Analysis)**

The Radiological Implications of the Mining and Processing Operations

Although the radioactive materials are of natural origin, mining and processing activities concentrate the ore, giving rise to further enhancement of the concentrations of radionuclides in the plant process, stockpiles and certain tailings streams. The tailings streams include radioactive sands, dusts and possibly also waters containing radioactive suspended solids. The presence of radionuclides in such ores has the following major radiological implications:

- occupational exposures of workers;
- potential exposure of members of the public living in nearby villages or utilizing roads adjacent to stockpiles or tailings storage areas; and
- waste management and environmental impacts.

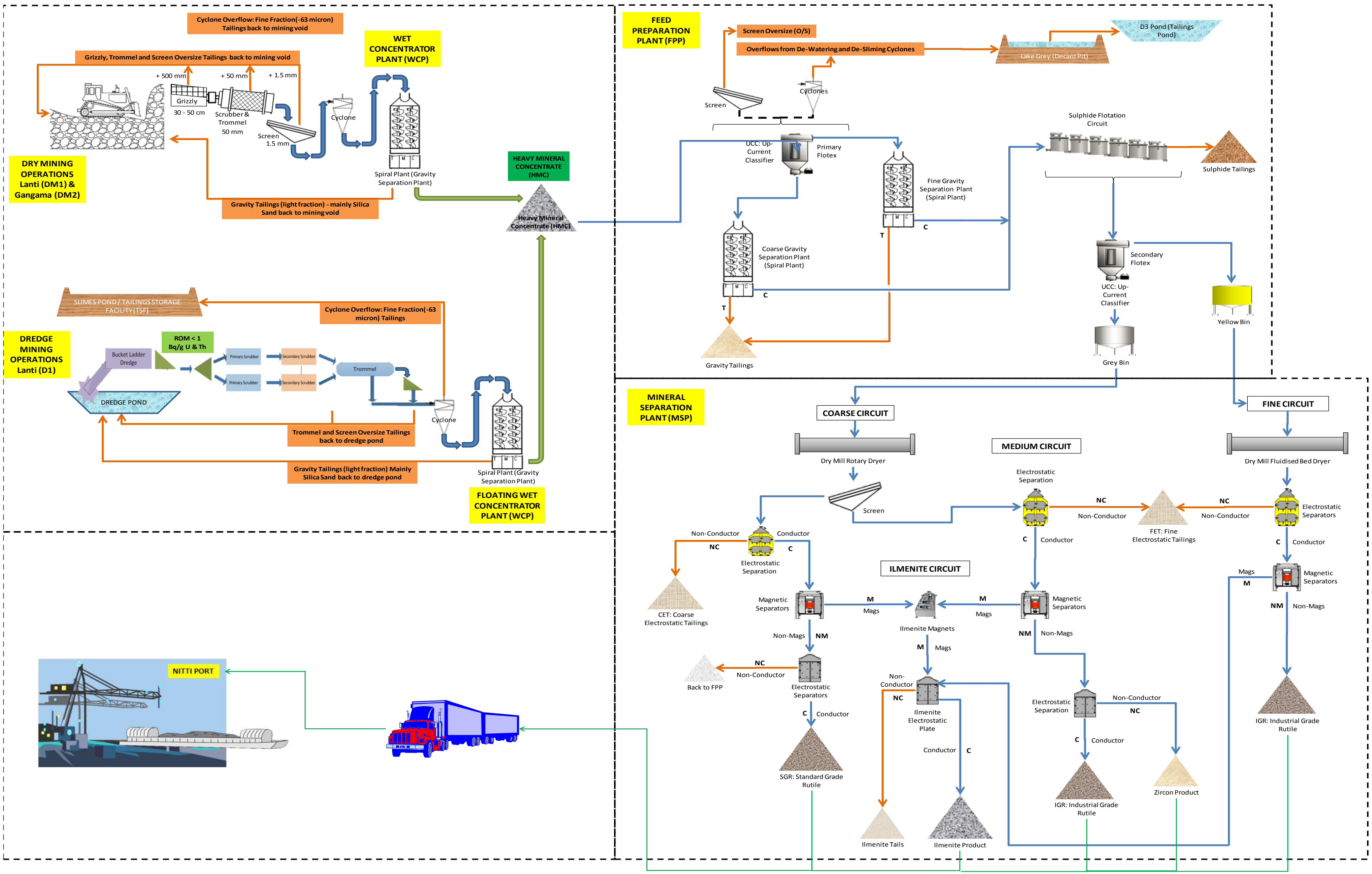
Potential exposure pathways of workers and members of the public living near to the site comprise the following:

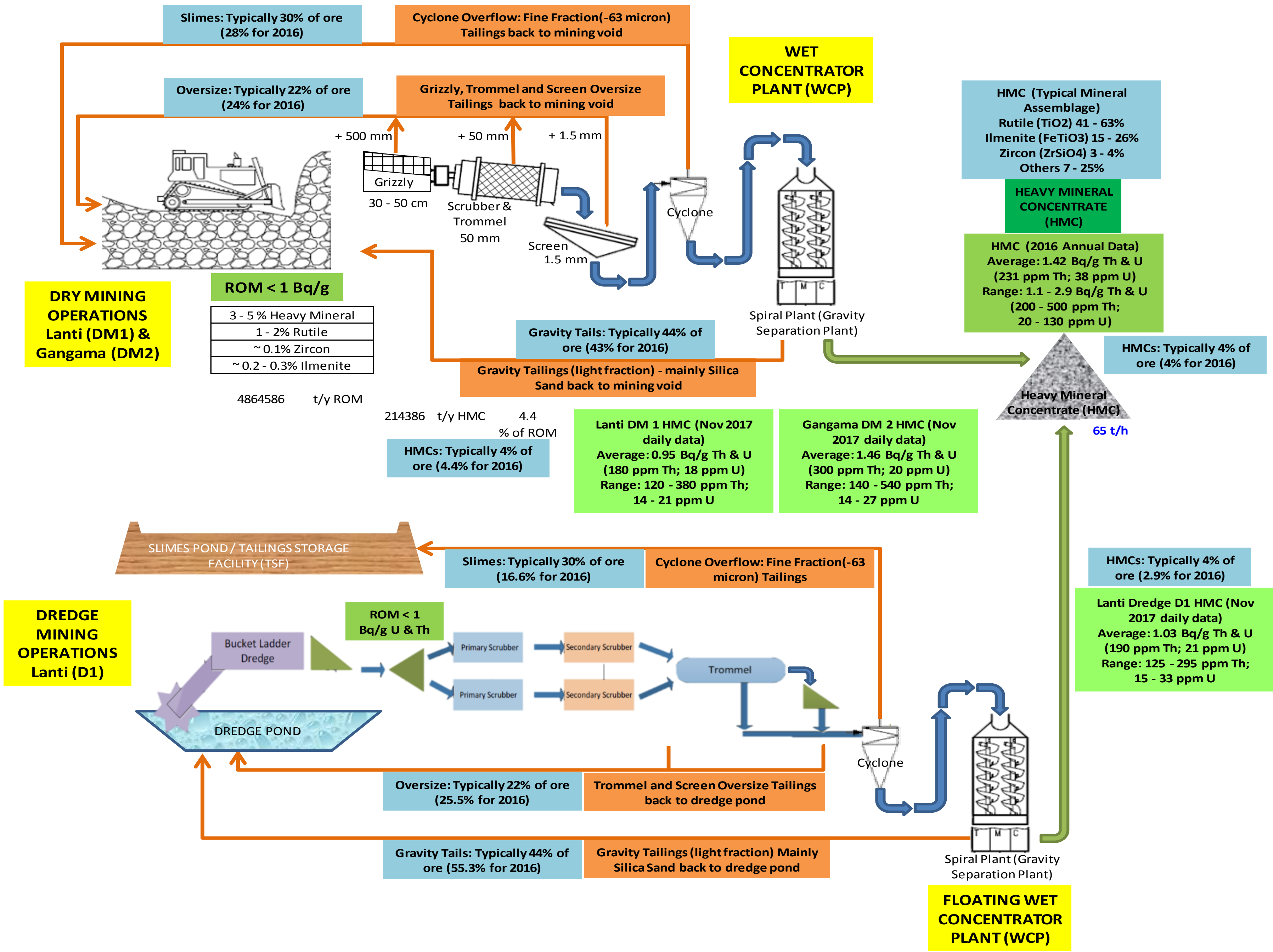
- external gamma irradiation from the gamma emitting radionuclides;
- inhalation of radioactive radon gas;
- inhalation of radioactive dusts containing long lived alpha emitters of the uranium and thorium decay chains;
- ingestion of water and foods containing radionuclides; and
- inadvertent soil ingestion (hand-to-mouth).

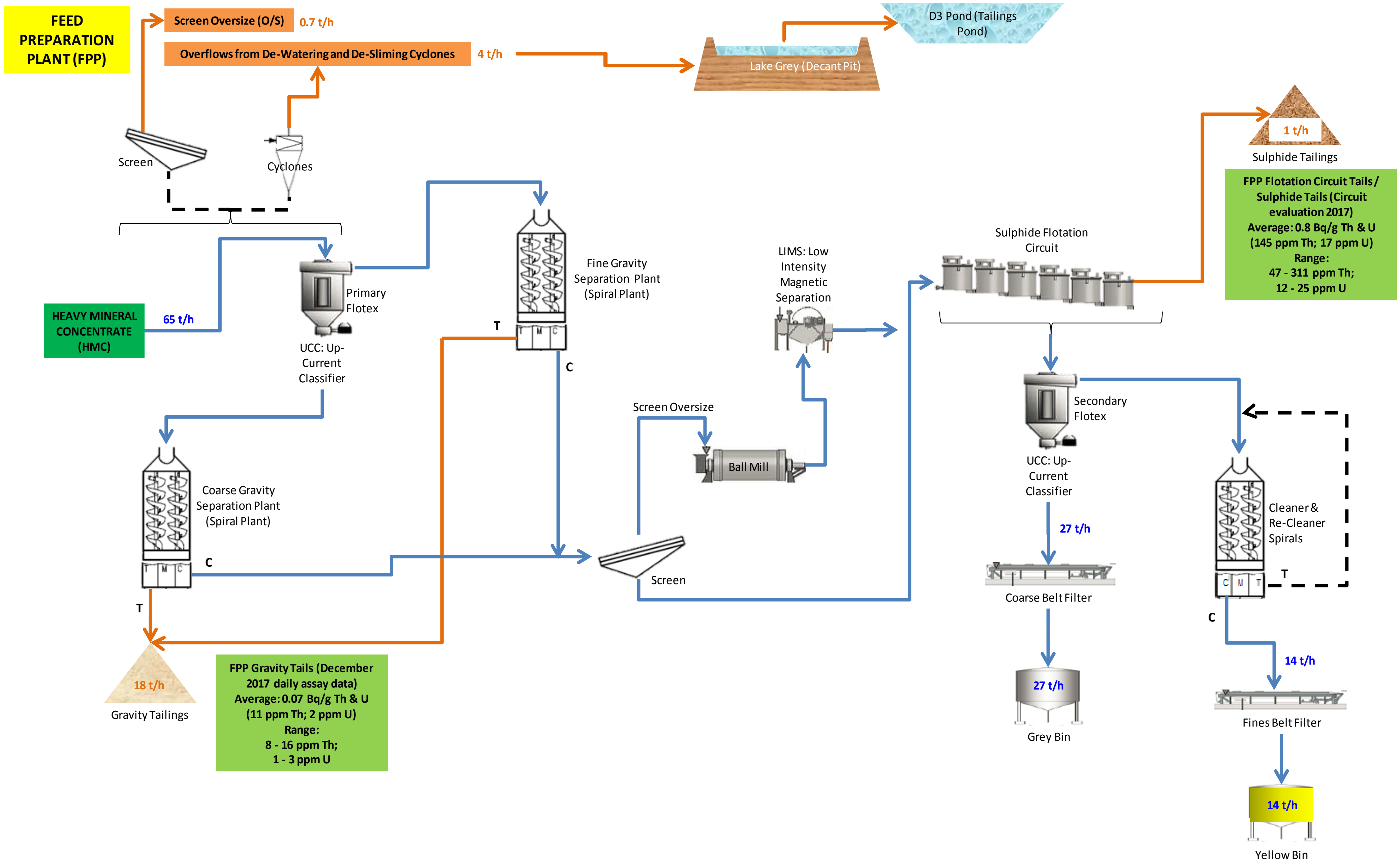
In addition, the operational areas may experience accumulation of tailings and product materials resulting in elevated radiation levels around the processing facility, along the transport routes and at Nitti Port.

Potential exposure pathways to members of the public include off-site releases of dusts or radon gas, contamination of food and water supplies due to the migration of radionuclides from the mine site during mining operations, transport or following the disposal of tailings. Radioactivity associated with the various heavy minerals or tailings may also have the potential to be dispersed into the environment during processing operations.

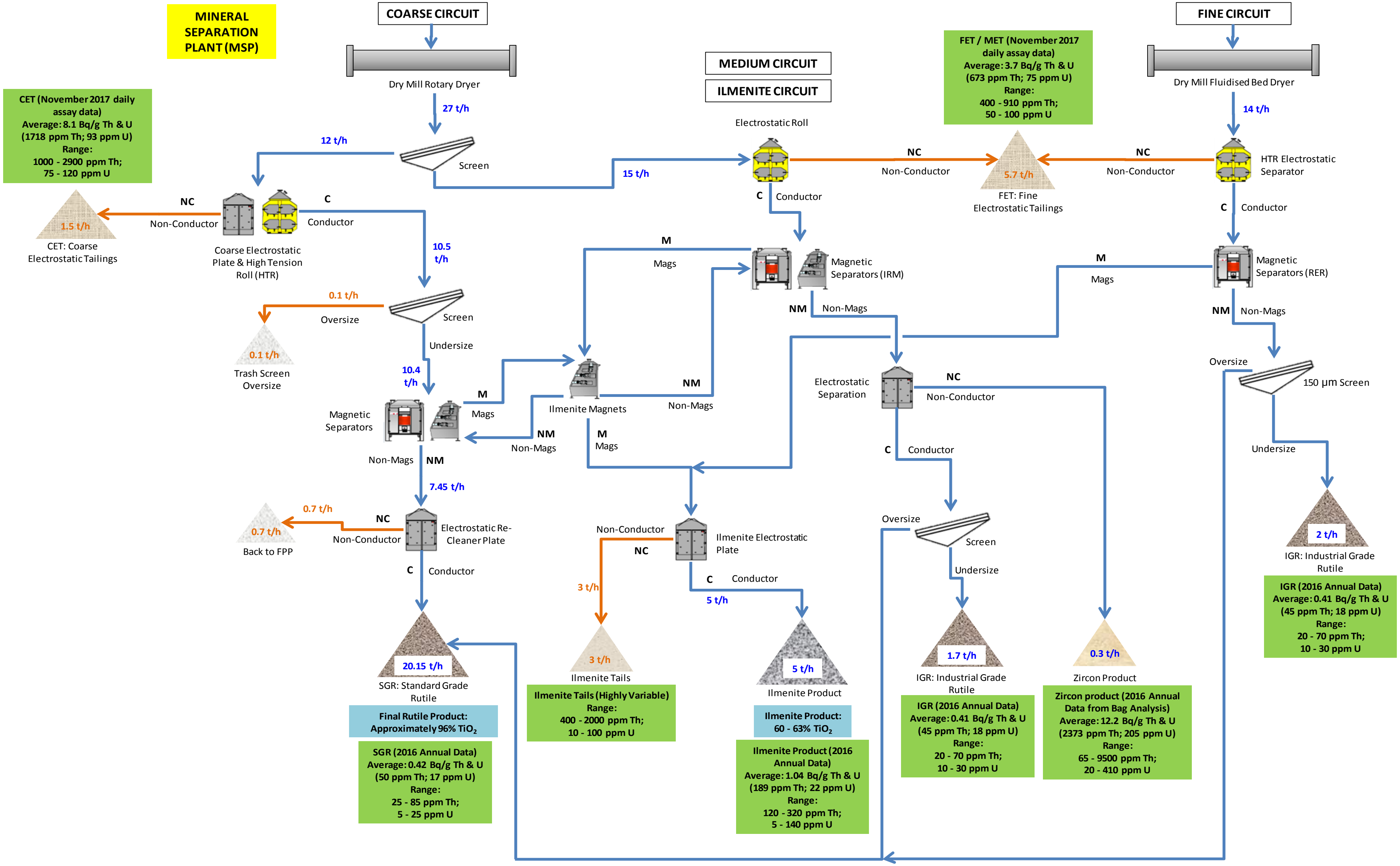
APPENDIX 2 –SR AREA 1 PROCESS OVERVIEW AND RADIONUCLIDE DISTRIBUTIONS




Slimes: Typically 30% of ore (28% for 2016)
Cyclone Overflow: Fine Fraction(-63 micron) Tailings back to mining void
WET CONCENTRATOR PLANT (WCP)
Oversize: Typically 22% of ore (24% for 2016)
Grizzly, Trommel and Screen Oversize Tailings back to mining void
HMC (Typical Mineral Assemblage) Rutile (TiO2) 41 - 63% Ilmenite (FeTiO3) 15 - 26% Zircon (ZrSiO4) 3 - 4% Others 7 - 25%
+ 500 mm
+ 50 mm
+ 1.5 mm
Grizzly
30 - 50 cm
Scrubber & Trommel
50 mm
Screen
1.5 mm
Cyclone
HEAVY MINERAL CONCENTRATE (HMC)
HMC (2016 Annual Data) Average: 1.42 Bq/g Th & U (231 ppm Th; 38 ppm U) Range: 1.1 - 2.9 Bq/g Th & U (200 - 500 ppm Th; 20 - 130 ppm U)
DRY MINING OPERATIONS Lanti (DM1) & Gangama (DM2)
ROM < 1 Bq/g
3 - 5 % Heavy Mineral
1 - 2% Rutile
~ 0.1% Zircon
~ 0.2 - 0.3% Ilmenite
Spiral Plant (Gravity Separation Plant)
Gravity Tails: Typically 44% of ore (43% for 2016)
Gravity Tailings (light fraction) - mainly Silica Sand back to mining void
HMCs: Typically 4% of ore (4% for 2016)
Heavy Mineral Concentrate (HMC)
65 t/h
4864586 t/y ROM
214386 t/y HMC 4.4 % of ROM
HMCs: Typically 4% of ore (4.4% for 2016)
Lanti DM 1 HMC (Nov 2017 daily data) Average: 0.95 Bq/g Th & U (180 ppm Th; 18 ppm U) Range: 120 - 380 ppm Th; 14 - 21 ppm U
Gangama DM 2 HMC (Nov 2017 daily data) Average: 1.46 Bq/g Th & U (300 ppm Th; 20 ppm U) Range: 140 - 540 ppm Th; 14 - 27 ppm U
SLIMES POND / TAILINGS STORAGE FACILITY (TSF)
Slimes: Typically 30% of ore (16.6% for 2016)
Cyclone Overflow: Fine Fraction(-63 micron) Tailings
HMCs: Typically 4% of ore (2.9% for 2016)
Lanti Dredge D1 HMC (Nov 2017 daily data) Average: 1.03 Bq/g Th & U (190 ppm Th; 21 ppm U) Range: 125 - 295 ppm Th; 15 - 33 ppm U
DREDGE MINING OPERATIONS Lanti (D1)
Bucket Ladder Dredge
ROM < 1 Bq/g U & Th
Primary Scrubber
Secondary Scrubber
Primary Scrubber
Secondary Scrubber
Trommel
DREDGE POND
Cyclone
Oversize: Typically 22% of ore (25.5% for 2016)
Trommel and Screen Oversize Tailings back to dredge pond
Gravity Tails: Typically 44% of ore (55.3% for 2016)
Gravity Tailings (light fraction) Mainly Silica Sand back to dredge pond
Spiral Plant (Gravity Separation Plant)
FLOATING WET CONCENTRATOR PLANT (WCP)



FEED PREPARATION PLANT (FPP)
Screen Oversize (O/S)
0.7 t/h
Overflows from De-Watering and De-Sliming Cyclones
4 t/h
D3 Pond (Tailings Pond)
Lake Grey (Decant Pit)
Screen
Cyclones
1 t/h
Sulphide Tailings
FPP Flotation Circuit Tails / Sulphide Tails (Circuit evaluation 2017)
Average: 0.8 Bq/g Th & U
(145 ppm Th; 17 ppm U)
Range:
47 - 311 ppm Th;
12 - 25 ppm U
Fine Gravity Separation Plant (Spiral Plant)
Primary Flotex
LIMS: Low Intensity Magnetic Separation
Sulphide Flotation Circuit
HEAVY MINERAL CONCENTRATE (HMC)
65 t/h
UCC: Up-Current Classifier
T
C
Screen Oversize
Ball Mill
Secondary Flotex
UCC: Up-Current Classifier
Coarse Gravity Separation Plant (Spiral Plant)
Cleaner & Re-Cleaner Spirals
27 t/h
Screen
Coarse Belt Filter
C
T
T
C
18 t/h
Gravity Tailings
FPP Gravity Tails (December 2017 daily assay data)
Average: 0.07 Bq/g Th & U
(11 ppm Th; 2 ppm U)
Range:
8 - 16 ppm Th;
1 - 3 ppm U
27 t/h
Grey Bin
14 t/h
Fines Belt Filter
14 t/h
Yellow Bin



MINERAL SEPARATION PLANT (MSP)
COARSE CIRCUIT
Dry Mill Rotary Dryer
27 t/h
12 t/h
Screen
15 t/h
CET (November 2017 daily assay data)
Average: 8.1 Bq/g Th & U
(1718 ppm Th; 93 ppm U)
Range:
1000 - 2900 ppm Th;
75 - 120 ppm U
NC
Non-Conductor
1.5 t/h
CET: Coarse Electrostatic Tailings
Coarse Electrostatic Plate & High Tension Roll (HTR)
C
Conductor
10.5 t/h
0.1 t/h
Oversize
Screen
0.1 t/h
Trash Screen Oversize
Undersize
10.4 t/h
Magnetic Separators
M
Mags
NM
Non-Mags
Non-Mags
NM
7.45 t/h
0.7 t/h
NC
0.7 t/h
Back to FPP
Non-Conductor
Electrostatic Re-Cleaner Plate
C
Conductor
20.15 t/h
SGR: Standard Grade Rutile
Final Rutile Product: Approximately 96% TiO_2
SGR (2016 Annual Data)
Average: 0.42 Bq/g Th & U
(50 ppm Th; 17 ppm U)
Range:
25 - 85 ppm Th;
5 - 25 ppm U
MEDIUM CIRCUIT
ILMENITE CIRCUIT
Electrostatic Roll
C
Conductor
M
Mags
Magnetic Separators (IRM)
NM
Non-Mags
Ilmenite Magnets
NM
Non-Mags
M
Mags
Non-Conductor
NC
Ilmenite Electrostatic Plate
3 t/h
3 t/h
Ilmenite Tails
Ilmenite Tails (Highly Variable)
Range:
400 - 2000 ppm Th;
10 - 100 ppm U
C
Conductor
5 t/h
5 t/h
Ilmenite Product
Ilmenite Product: 60 - 63% TiO_2
Ilmenite Product (2016 Annual Data)
Average: 1.04 Bq/g Th & U
(189 ppm Th; 22 ppm U)
Range:
120 - 320 ppm Th;
5 - 140 ppm U
FET / MET (November 2017 daily assay data)
Average: 3.7 Bq/g Th & U
(673 ppm Th; 75 ppm U)
Range:
400 - 910 ppm Th;
50 - 100 ppm U
NC
Non-Conductor
5.7 t/h
FET: Fine Electrostatic Tailings
NC
Non-Conductor
Electrostatic Separation
NC
Non-Conductor
C
Conductor
Oversize
Screen
Undersize
1.7 t/h
IGR: Industrial Grade Rutile
IGR (2016 Annual Data)
Average: 0.41 Bq/g Th & U
(45 ppm Th; 18 ppm U)
Range:
20 - 70 ppm Th;
10 - 30 ppm U
0.3 t/h
Zircon Product
Zircon product (2016 Annual Data from Bag Analysis)
Average: 12.2 Bq/g Th & U
(2373 ppm Th; 205 ppm U)
Range:
65 - 9500 ppm Th;
20 - 410 ppm U
FINE CIRCUIT
Dry Mill Fluidised Bed Dryer
14 t/h
HTR Electrostatic Separator
C
Conductor
M
Mags
Magnetic Separators (RER)
NM
Non-Mags
Oversize
150 µm Screen
Undersize
2 t/h
IGR: Industrial Grade Rutile
IGR (2016 Annual Data)
Average: 0.41 Bq/g Th & U
(45 ppm Th; 18 ppm U)
Range:
20 - 70 ppm Th;
10 - 30 ppm U

APPENDIX 3 – SRL RADIATION LICENCES

APN-USE-0026/16:

N.S.R.P.A

GOVERNMENT OF SIERRA LEONE
MINISTRY OF ENERGY
NUCLEAR SAFETY AND
RADIATION PROTECTION AUTHORITY
38th Liverpool Street Freetown Sierra Leone
Email: josiekongo@yahoo.com
Tel: +23276610754

UNITY FREEDOM JUSTICE

INS-IND-N-00013
F-IND-00026/16

AUTHORISATION FOR POSSESSION AND USE

9th December 2016

ADDRESS OF FACILITY
ACCESS BANK BUILDING
30 SIAKA STEVEN STREET
FREETOWN

NAME OF RESPONSIBLE PERSON
DESMOND G WILLIAMS

NAME OF FACILITY
SIERRA RUTILE LIMITED

PURPOSE OF CERTIFICATE
POSSESSION AND USE OF DENSITY GUAGE

The following Cs 137 moisture density gauges at the lanti DM1, gangama DM 2, wet plant, dredge and MSP sites authorized for possession and use are listed below:

Radioisotopes	Quantity	Serial Number
Cs 137	Thirty Eight (38)	B 191, B 200, B 269, B 426, B 992, B 993, B 2105, B 2113,B 2114,B 2125, B 2126, B 4670,B 4677, B 4678, B 4679, B 4680, B 4692, B 4693 F 387, F 388 F 516, F 617, F 835, F 837, F 838, F 839, F 836, NH 457, NH 481, NU 776, NU 784, NU 807 M 356 S 779 30213917, 30213918

AUTHORIZED USERS

The Licensee is directed to ensure that any personnel, who subsequently may be engaged to operate, install, maintain or otherwise deal with the moisture density gauge, have approved training in accordance with Licensees Radiation Protection Programme approved by the Board.

REGISTRATION CONDITIONS

The Licensee is directed to:

- comply with the Nuclear Safety and Radiation Protection Act,2012
- provide prior written notification to the Nuclear Safety and Radiation Protection Authority of any intention to — sell, relocate, install, or dispose of the moisture density gauge (by any means); of plans to modify the structure of the premises in any way that may significantly impact on radiation protection and safety;
- Ensure that the installation, service or maintenance of the moisture density gauge on the premises is performed only by personnel authorized by the regulatory authority.

The License is approved
Deputy Chief Radiation Protection Officer

Date 9th December 2016

This Authorization must be displayed in a prominent public location within the premise

CERTIFICATE NUMBER: APN-USE-0026/16 **EXPIRY DATE: 9TH DECEMBER 2017.**

APN-POS-001/16:

GOVERNMENT OF SIERRA LEONE
MINISTRY OF ENERGY
NUCLEAR SAFETY AND
RADIATION PROTECTION AUTHORITY
38th Liverpool Street Freetown Sierra Leone
Email: josiekongo@yahoo.com
Tel: +23276610754

N.S.R.P.A

UNITY FREEDOM JUSTICE

INS-IND-N-00013
F-IND-00026/16

AUTHORISATION FOR POSSESSION

9th December 2016

ADDRESS OF FACILITY
ACCESS BANK BUILDING
30 SIAKA STEVEN STREET
FREETOWN

NAME OF RESPONSIBLE PERSON
DESMOND G WILLIAMS

NAME OF FACILITY
SIERRA RUTILE LIMITED

PURPOSE OF CERTIFICATE
POSSESSION OF DENSITY GUAGE

The following Cs 137 moisture density gauges stored in the Bunker are authorised for possession

Radioisotopes	Quantity	Serial Number
Cs 137	Thirteen (13)	B 53, B 939, B 991, B 1190, B 2104, B 2106, B 5532 F 402 S 226 102, 81391, 21507719

AUTHORIZED USERS

The Licensee is directed to ensure that any personnel, who subsequently may be engaged to operate, install, maintain or otherwise deal with the moisture density gauge, have approved training in accordance with Licensees Radiation Protection Programme approved by the Board.

REGISTRATION CONDITIONS

The Licensee is directed to:

- comply with the Nuclear Safety and Radiation Protection Act,2012
- provide prior written notification to the Nuclear Safety and Radiation Protection Authority of any intention to — sell, relocate, install, or dispose of the moisture density gauge (by any means); of plans to modify the structure of the premises in any way that may significantly impact on radiation protection and safety;

The License is approved ....
Deputy Chief Radiation Protection Officer

Date 9th December 2016

This Authorization must be displayed in a prominent public location within the premise.

CERTIFICATE NUMBER: APN-POS-001/16	**EXPIRY DATE: 9TH DECEMBER 2017.**

APPENDIX 4 – URANIUM AND THORIUM

Radiological Characteristics of Minerals containing Uranium and Thorium

The radiological characteristics and properties of uranium and its decay chain radionuclides are complex, as it comprises a mixture of elements and isotopes with significantly different chemical properties. This can have a strong influence on its potential health hazards (Mekisich, M 1988), (UNSCEAR 2000), (Carter, 1983), (Carter *et al* 1993).

Uranium ore as it is found in nature contains three uranium isotopes and eleven major decay products. These decay products comprise a wide variety of elements with different radiological and chemical properties. In the undisturbed ore the activity concentration of the parent ^{238}U and ^{235}U radionuclides are in secular equilibrium with their main decay products. Secular equilibrium refers to the state where each radionuclide in a piece of ore has the same activity concentration per gram. For example if the ^{238}U activity concentration in the ore is 1 Bq/g[1] the activity concentration of each decay product (e.g. ^{234}U' ^{230}Th, and ^{226}Ra) will also be 1 Bq/g[1].

Under secular equilibrium conditions the activity concentrations of the decay chain radionuclides in the ore will be equal; however the physical mass of each radionuclide per gram of ore is not the same. The half-lives of the decay products are all significantly shorter than the parent ^{238}U radionuclide and as a result the masses of the daughter nuclides in secular equilibrium with 1 gram of ^{238}U are therefore very small. In the uranium decay chains the parent radionuclides will contribute the majority of the mass per gram of 100% uranium ore.

The half-lives of the radionuclides of the uranium decay chain range from 1.3 minutes (^{210}Tl) to 4.5 billion years (^{238}U). The longer lived radionuclides found in the tailings (e.g. ^{238}U, ^{234}U, ^{230}Th, and ^{226}Ra) will therefore persist in the tailings for many millions of years into the future.

The Uranium Decay Chain

The ^{238}U decay chain comprises fourteen discrete decay steps to stable lead (^{206}Pb) (Refer to Figure below). Each decay step will result in the emission of ionizing radiation (alpha or beta particles or gamma photons, or some combination) with characteristic energies and probabilities of emission.

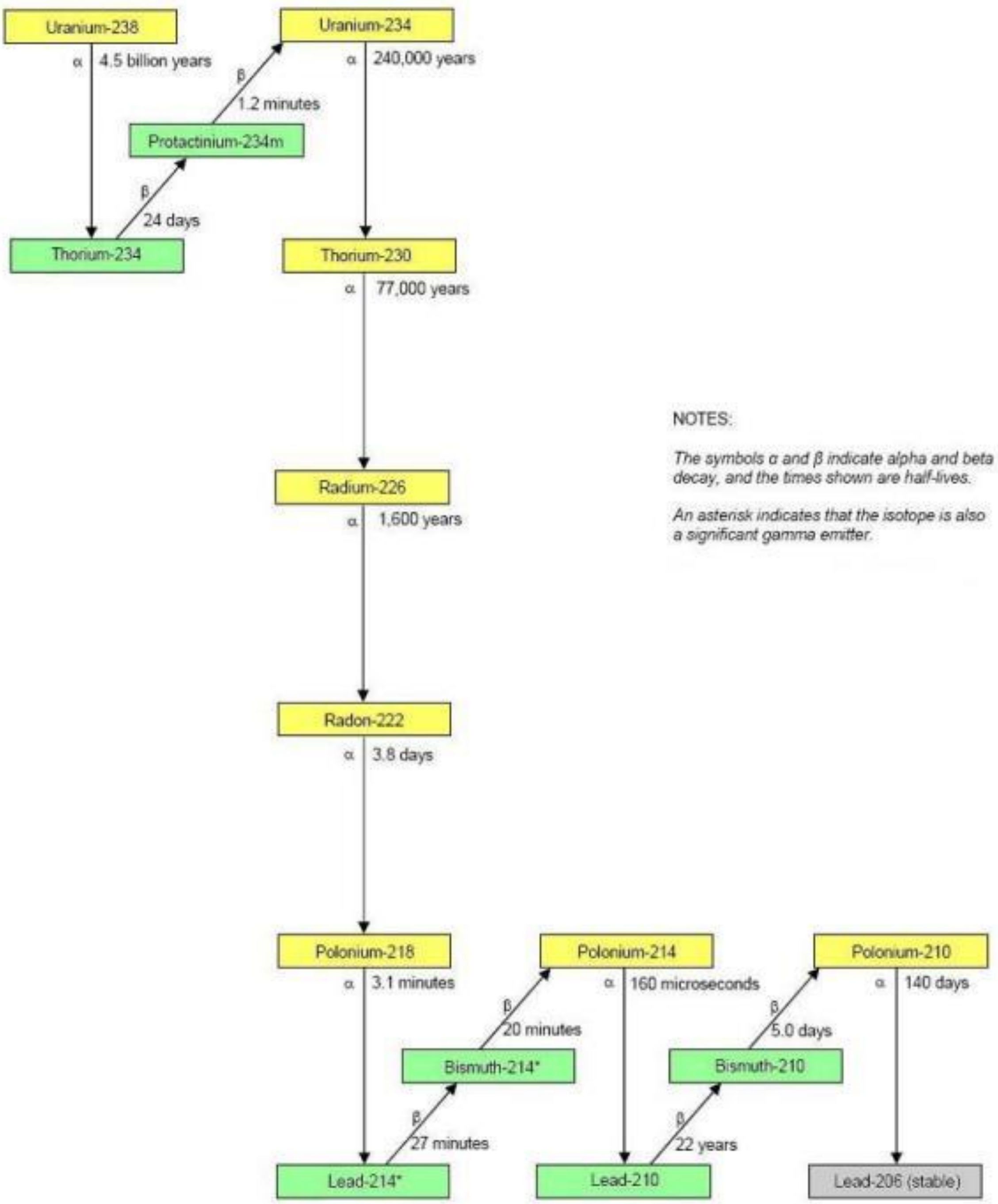
The majority of the radionuclides in the chain have relatively short half-lived; only five radionuclides have half-lives exceeding one year; these are referred to as "long lived radionuclides"

The half-lives of the long lived radionuclides of the ^{238}U Decay Chain are provided in the table below.

Table C: The Half-Lives of the Long Lived Radionuclides of the ^{238}U Decay Chain

Radionuclide	Half-Life (Years)
U-238	$4.51x10^{9}$
U-234	$2.45x10^{5}$
Th-230	$7.80x10^{4}$
Ra-226	$1.60x10^{3}$
Pb-210	21

As a result of the very long half-lives these radionuclides will persist, if released into the environment, for a very long time, and if incorporated into the body they will remain until death.

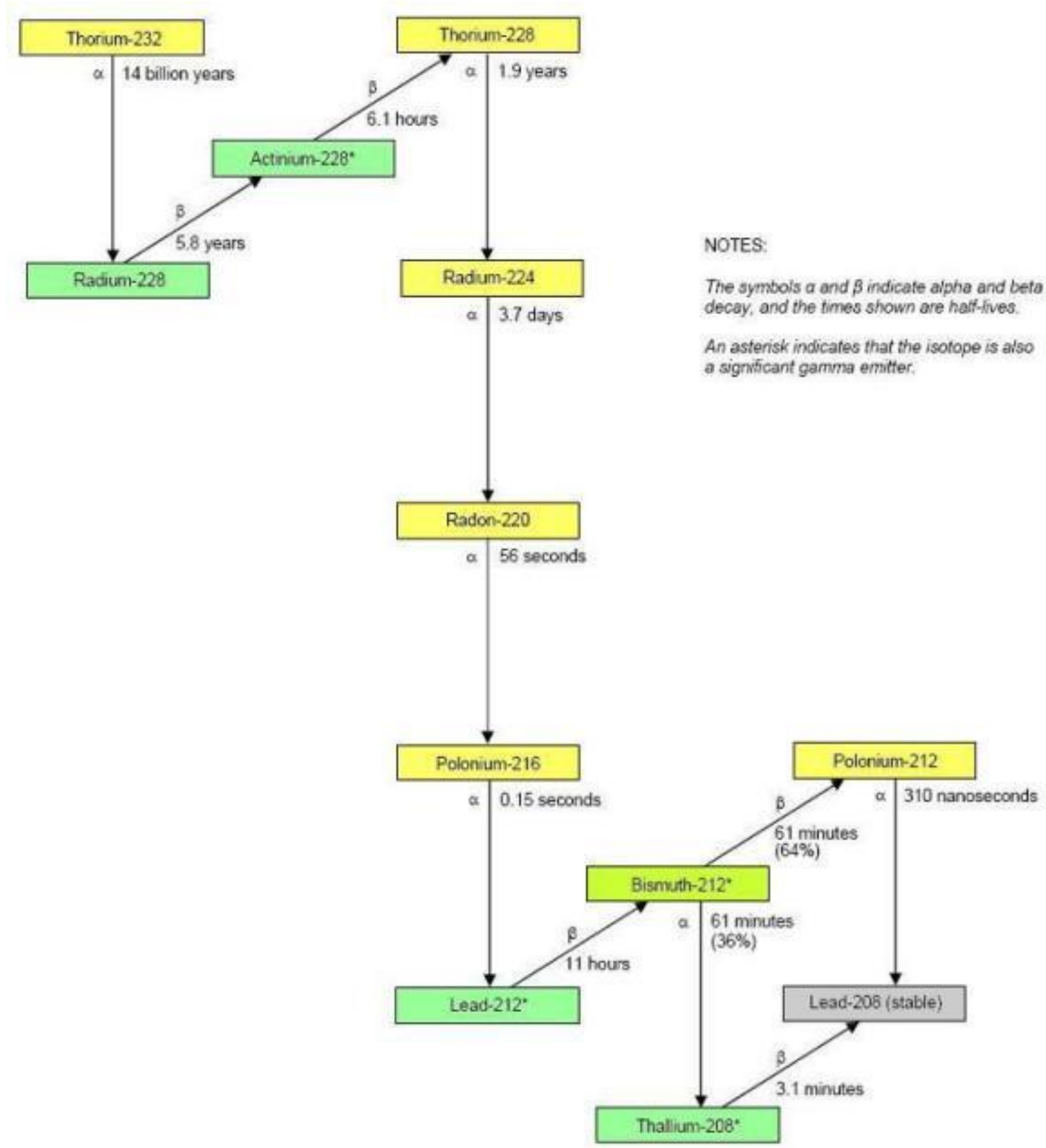


^{238}U Decay Chain

The Thorium Decay Chain

The parent ^{232}Th decays to stable ^{208}Pb through ten decay steps (Refer to Figure below). With the exception of the parent radionuclide ^{232}Th (half-life 1.41×10^{10} years) the daughter half-lives are all less than 7 years. ^{228}Th and ^{228}Ra have half-lives measured in years (1.9 to 6.7 years respectively). The remaining radionuclide half-lives range from nanoseconds to 10.64 hours.

There are seven radionuclides, which decay primarily through alpha emission. The most important long-lived alpha emitters of radiological significance are ^{232}Th and ^{228}Th. The ^{224}Ra radionuclide with a half-life of 3.64 days is not usually included as a long lived alpha emitter when unsupported by ^{232}Th, however if incorporated into the body is has some radiological significance. Thoron gas (^{220}Rn) decays producing a number of short lived alpha emitters which are of radiological significance (^{216}Po, ^{212}Bi and ^{212}Po) when inhaled.



^{232}Th Decay Chain

References:

- Alara Consultants cc, Ranobe Mine Project, Southwest Region, Madagascar, Volume 13: Radiation Assessment, January 2013
- Mekisich, M. (1988) The Health Physics of Uranium. MSc Thesis. Pretoria Technicon.
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), (2000). Exposures from Natural Radiation Sources. UN, New York.
- Carter, M.W. (1983) Derived Limits for Occupational Exposure to Uranium Mine and Mill Dusts in the Air and on Surfaces. Radiation Protection Dosimetry. 4 (1) 27-31. Oxford University Press.
- Carter, M.W., Burns, P. and Munslow-Davies (1993) Development of a Revised Radiotoxicity Hazard Classification. Radiation Protection Dosimetry. 46: (1) 37-43. Oxford University Press.

APPENDIX 5 – LEGISLATION

Mines and Minerals Act 2009

The *Mines and Minerals Act 2009* (MM Act) replaced the *Mines and Minerals Act 1994*. The provision of this Act relates to exploration, and mining of radioactive minerals. The issues and provisions dealing with radiation management forms an integral part of the Act and are covered in Part XIII of the Act.

A "radioactive mineral" means a mineral which contains by weight at least one twentieth of one percent (0.05 per centum) of uranium (U) and thorium (Th) or any combination of it (500 ppm U & Th), and includes but not limited to:

- monazite sand and other ore containing thorium; and
- carnotite, pitchblende and other ores containing uranium.

500 ppm U and Th would represent an activity concentration range of 2 Bq/g (all Th) to 6.2 Bq/g (all U). A radioactive material in accordance with the IAEA would be material containing an activity concentration (or specific activity) of 1 Bq/g.

Section (123)(1) of the Act states that "No person shall explore for or mine or treat or possess or export or import or otherwise dispose of any radioactive mineral except under and in accordance with the terms and conditions of a permit granted by the Minister".

The Act has recently been supplemented by the Safety in Mining and Milling of Uranium and Other Ores Regulations 2012.

Safety in Mining and Milling of Uranium and Other Ores Regulations 2012

The Regulations apply to intrusive exploration, siting of construction; operation and decommissioning of mining and processing of uranium; and processing of heavy mineral sands; mining and processing of rare earth elements; mining ores other than uranium and heavy mineral sands; production of oil and gas; manufacture of titanium dioxide pigment; the phosphate industry; the zircon and zirconium industry; production of tin, tantalum, copper, aluminum, iron and steel and geothermal generation.

Section 3 of the Regulations stipulates the following:

"For the purpose of these Regulations, a radiation protection plan shall include:

- identification of sources of ionising radiation, associated exposure pathways and assessment of radiation risk;
- the design, engineering and administrative controls to optimise protection measure and ensure compliance with the established dose limits;
- the health and safety training program, that includes radiation protection, for workers;
- a medical health surveillance program, that responds to the potential health and safety risk posed by the activities; and
- arrangements for monitoring, reviewing, reporting and recording the radiation exposure for workers."

"A waste management program shall include:

- categorisation of all waste and identification of associated management systems;
- characteristics of all waste streams including tailings, waste rock and industrial waste;
- consideration of radiological and non-radiological hazards, feasible management options (including backfill into mine workings);
- a description of the design and schedule for the construction, operation and decommissioning of the waste management system including handling, transport, temporary storage and final disposal and a risk assessment of and justification for selected management options; and
- safety assessment of waste management including accidental situations and long term safety."

Section 10 of the Regulations stipulates that “results of decommissioning activities should include radiation surveys and environmental monitoring”.

Section 11 of the Regulations requires that:

- all movement of mineral ores subject to the transport regulations are in accordance with the regulations in respect to packaging, signage and documentation; and
- ensure that all tailings from ores are monitored for radioactive contamination and safely disposed of in the appropriate manner.

In summary, the Regulations requires a Radiation Management Plan (RMP) and a Radiation Waste Management Plan (RWMP) detailing the protection of workers, members of the public and the environment from harmful effects of radiation exposures arising from mining or mineral processing and from the waste resulting from these activities.

Nuclear Safety and Radiation Protection Act 2012

The *Nuclear Safety and Radiation Protection Act 2012* provides for the establishment of the Nuclear Safety and Radiation Protection Authority to exercise regulatory and supervisory control for the beneficial and peaceful uses of radioactive substances and their applications, including licensing, inspection and enforcement throughout Sierra Leone, to provide adequate protection to the public, workers and the environment against the harmful effects of radiation.

Section 1(a) (b) of the Act provides for the meaning of exemption level, namely “exemption level” means:

- a quantity of radioactivity below 3.7 kilo Becquerel;
- a specific radioactivity below 74 Becquerel per gram.

Section 5(2) (i) (ii) of the Act states that “This Act shall apply to every source of ionizing radiation above the exemption level other than:

- radioactive substances found in nature; and
- sealed sources or any apparatus or devices containing a sealed source where the dose rate at 10 cm from the source does not exceed 1 micro Sievert per hour (1 uSv/h) and the source activity does not exceed the exemption level.”

Section 30(1) of the Act also prohibits any person that manufactures, produce, posses, use, import (or cause to be imported), export (or cause to be exported), dispose, lease or deal in any radioactive substance or device emitting ionising radiation unless that person holds a licence issued by the Authority under this Act.

In summary, the Act only applies to radioactive sealed sources that contain a level of radioactivity above 3.7 kilo Becquerel (kBq) and dose rates at 10cm from the source above 1 uSv/h.

SRL has two Certificates of Registration (i.e. licenses) for the possession and use of density gauges (as issued by the Government of Sierra Leone Ministry of Energy Nuclear Safety and Radiation Protection Authority (NSRPA)):

- Authorization for possession and use (APN-USE-0026/16; validity: 9 Dec 2016 - 9 Dec 2017)
- Authorization for possession (APN-POS-001/16; validity: 9 Dec 2016 – 9 Dec 2017)

IAEA Standards and Safety Guides:

The IAEA Safety Guides recommend actions, conditions or procedures for meeting the IAEA's Safety Requirements, and reflect current internationally accepted principles and recommended practices. Three interrelated Safety Guides provide guidance on meeting the requirements of the Basic Safety Standards for occupational radiation protection:

- The Safety Guide on Occupational Radiation Protection (IAEA Safety Standards Series No. RS-G-1.1, 1999) provides general guidance on the establishment of an effective radiation protection programme for occupational exposure;
- The Safety Guide on Assessment of Occupational Exposure due to External Sources of Radiation (IAEA Safety Standards Series No. RS-G-1.3, 1999) provides guidance on conducting assessments of occupational exposure to external sources of radiation; and
- The Safety Guide on Assessment of Occupational Exposure Due to Intakes of Radionuclides (IAEA Safety Standards Series No. RS-G-1.2, 1999) provides guidance on conducting assessments of intakes of radioactive materials arising from occupational exposure.

A further Safety Guide on *Occupational Radiation Protection in the Mining and Processing of Raw Materials*, (IAEA Safety Standards Series No. RS-G-1.6, 2004), provides more specific recommendations and guidance on meeting the requirements for the establishment of occupational RMPs in the mining and processing of raw materials.

A Safety Guide on *Application of the Concepts of Exclusion, Exemption and Clearance* (IAEA Safety Standards Series No. RS-G-1.7, 2004) provides important quantitative guidance on the application of the concept of exclusion to exposures arising from naturally occurring radioactive material.

APPENDIX 6 - DOSE ASSESSMENT CALCULATIONS AND CONVERSION FACTORS

Radiation dose limits apply to the sum of relevant doses from external exposure in the specified period (e.g. for a calendar year) and the relevant committed doses from intakes of radionuclides (e.g. via inhalation or ingestion) in the same period. The period for calculating the committed dose to workers is 50 years (i.e. the dose is the total dose that will be received over the 50 years following the intake).

The total effective dose for workers will be calculated according to the following formula:

$$E_T = H_P(d) + h_{RD} \cdot I_{RD} + h_{RnP} \cdot I_{RnP} + h_{TnP} \cdot I_{TnP}$$

Where: $H_P(d)$ is the personal dose equivalent from gamma radiation during the year (mSv).

- h is the committed effective dose per unit exposure or intake and
- *RD* refers to radioactive dust
- *RnP* refers to radon (Rn-222) progeny
- *TnP* refers to thoron (Rn-220) progeny
- I is the exposure or intake in the case of radioactive dust, expressed as Bq of gross alpha activity, or, in the case of radon or thoron progeny, as $mJ \cdot hm^{-3}$

For intake of radioactive dust, the relative activities of thorium and uranium series radionuclides need to be established in order to derive the appropriate dose conversion factors.

Effective dose calculations for individual exposure pathways are dependent on conversion factors, which are updated by international protection agencies following outcomes of human and environmental impact studies. The current investigation considered publications from the following agencies and regulatory bodies:

- ICRP (International Commission on Radiological Protection);
- IAEA (International Atomic Energy Agency);
- ARPANSA (Australian Radiation Protection and Nuclear Safety Agency);
- DMP (Government of Western Australia – Department of Mines and Petroleum Resources Safety (Formerly: Department of Industry and Resources));
- MIAC (Government of Western Australia – Mining Industry Advisory Committee (Formerly MOSHAB (Government of Western Australia - Mines Occupational Safety and Health Advisory Board));
- DER (Government of Western Australia - Department of Environment Regulation).

Selected conversion factors per exposure pathway and dose calculations used in the current assessment are summarized below:

The following tables detail the conversion factors selected for use within the Contamination Remediation Project CRP (conducted at Iluka Australia operations during 2014 and 2015) for the exposure pathways of external gamma, radon and thoron inhalation, dust inhalation, and water and soil ingestion. Calculations used to determine dose rates from each exposure pathway are also provided.

External gamma

External gamma dose can be measured through either personal monitoring or area monitoring. Personal monitoring is a requirement for “controlled” operational areas with Naturally Occurring Radioactive Material (NORM) sources giving rise to radiation doses in excess of 5 mSv/y. Personal monitoring is conducted through the use of TLD badges (thermoluminescent dosimeters) and area monitoring with either the RS-125; RS-220 or the RadEye PRD. A Gray (unit of absorbed dose) to Sievert (unit of equivalent dose) conversion of 1 is adopted for calculation of equivalent dose.

External gamma dose rate calculation

Bq/g U x 1000 g/kg x 0.43 (nGy/h per Bq/kg) x 1 µGy / 1000 nGy x 1 µSv / 1 µGy + Bq/g Th x 1000 g/kg x 0.666 (nGy/h per Bq/kg) x 1 µGy / 1000 nGy x 1 µSv / 1 µGy = µSv / h

Where 0.43 and 0.666 nGy/h per Bq/kg = Air Kerma gamma dose rate in air at 1 meter from a homogenous plane of material containing uranium and thorium respectively (Beck H, de Planque G (1968)).

Even though the air kerma conversion factors for U and Th assume an unlimited radioactive source with a homogenous distribution of uranium and thorium throughout the source, these conversion factors were used to calculate gamma dose rate for a person standing one meter away from a stockpile of material. The calculated dose rate would therefore be conservative, as a stockpile of material is a finite amount.

Inhalation of radon, thoron and progeny

Table D summarizes the effective dose to unit exposure conversion factors for radon (Rn-222), thoron (Rn-220) and their progeny.

Table D: Dose conversion factors for radon, thoron and progeny

Conversion	Conversion Factor	
	Radon-222	Radon-220
From radon progeny exposure to effective dose	1.4 mSv per mJ.h.m^{-3}	0.48 mSv per mJ.h.m^{-3}
From radon exposure to effective dose	3.1 x 10^{-6} mSv per Bq.h.m^{-3}	3.6 x 10^{-5} mSv per Bq.h.m^{-3}
Note: Thoron = Rn-220 {another isotope of radon, but only called "thoron" due to being part of the Thorium decay chain}		

Dust Inhalation

Table E summarizes the dose conversion factors per particle size (AMAD) for lung absorption type S for the workforce, and Table F summarizes dose conversion factors per age group for members of the public for an AMAD of 1 µm.

Table E: Dose conversion factors for the workforce from dust inhalation

Nuclide	Lung absorption type	Conversion Factor (Sv / Bq) per AMAD particle size			
		1 µm	3 µm	5 µm	10 µm
U-238	S	7.3 x 10^{-6} *	7.1 x 10^{-6}	5.7 x 10^{-6} *	3.5 x 10^{-6}
Th-232	S	2.3 x 10^{-5} *	1.7 x 10^{-5}	1.2 x 10^{-5} *	8.1 x 10^{-6}
Th-232 in Secular equilibrium with progeny				4.82 x 10^{-5}	IAEA 1996
* Value also from ICRP 119					

Table F: Dose conversion factors for members of the public from dust inhalation

Nuclide	Lung absorption type	Conversion Factor (Sv / Bq)					
		Age Range					
		< 1 y	1 – 2 y	2 – 7 y	7 – 12 y	12 – 17 y	> 17 y
U-238	S	2.9 x 10^{-5}	2.5 x 10^{-5} *	1.6 x 10^{-5} #	1.0 x 10^{-5} @	8.7 x 10^{-6} ^	8 x 10^{-6} +
Th-232	M	8.3 x 10^{-5}	8.1 x 10^{-5} *	6.3 x 10^{-5} #	5 x 10^{-5} @	4.7 x 10^{-5} ^	4.5 x 10^{-5} +
* Value also from ICRP 119 – 1 year							
# Value also from ICRP 119 – 5 years							
@ Value also from ICRP 119 – 10 years							
^ Value also from ICRP 119 – 15 years							
+ Value also from ICRP 119 - Adult							
Age < 1 y is also termed infants in some of the guidelines; Age > 17 y is also termed adults in some of the guidelines							
AMAD = Activity Median Aerodynamic Diameter							
Lung absorption Type F = Fast absorption							
Lung absorption Type M = Medium absorption							
Lung absorption Type S = Slow absorption							

Dust inhalation dose

Worker Dose Assessment

In terms of exposure to radioactivity in airborne dust, the worker dose can be estimated using the following assumptions:

Table G: Calculation parameters used for dust inhalation dose for Workers

Parameter	Value
Breathing rate	1.2 m^3/ h
Airborne dust concentration	1 mg/m^3
Median particle size of the dust	5 µm
Exposure time	2000 hours per year
Dose coefficient for thorium-232 in secular equilibrium with other radionuclides in the series	4.82 x 10^{-5} Sv/Bq (IAEA 1996)

Calculation for worker dust inhalation dose:

Bq/g (Th & U) x 1 mg/m^3 (dust loading in air) x 1g / 1000mg x 1.2 m^3/h (breathing rate) x 2000 h/y (occupancy) x 0.0482 mSv/Bq (DCF)

Public Dose Assessment:

In terms of exposure to radioactivity in airborne dust, public dose can be estimated using the following assumptions:

Table H: Calculation parameters used for dust inhalation dose for Workers

Parameter	Value
Breathing rate	As per Table I for various age groups
Airborne dust concentration	1 mg/m^3
Median particle size of the dust	5 µm
Exposure time	Varying
Dose coefficient for thorium-232 in secular equilibrium with other radionuclides in the series	As per Table F for Th-232

Table I: Breathing rates for members of the public

ICRP 119 Age Group	Inhalation Rate (m^3/h)
3 months	0.12
1 year	0.22
5 years	0.37
10 years	0.64
15 years	0.84
Adults	0.92

Calculation for members of the public dust inhalation dose:

Bq/g (Th & U) x 1 mg/m^3 (dust loading in air) x 1g / 1000mg x selected breathing rate per age group m^3/h x selected exposure time h/y x DCF mSv/Bq

Breathing rates selected are in accordance with the International Commission on Radiological Protection (ICRP) publication ICRP 101. It is also assumed that the radionuclide content in the dust is the same as that in the respective mineral sand ore, intermediate, product or tailings material (Appendix 1, Table B).

An airborne dust loading of 1 mg/m^3 is consistent with a heavy dust loading in the air. This level of airborne dust is very conservative in that it is most unlikely that these conditions would be maintained over the total year. It is further conservative in that 6 months of the year in Sierra Leone is the rainy season (average annual rainfall of ~ 3 m – see section 1.2.1 and Figure 1.1) during which dust liberation is minimal. Annual dose from dust inhalation for workers and members of the public can thereby effectively be reduced by 50% as a more realistic scenario.

Water, Food and Soil Ingestion

Dose conversion factors for water and soil ingestion are identical for each radionuclide. Table J summarizes the dose conversion factors for the workforce, and Table K summarizes dose conversion factors per age group for members of the public.

Table J: Dose conversion factors for the workforce from ingestion

Nuclide	Absorption type	Conversion Factor (Sv / Bq) ICRP 119
U-238	M	7.6×10^{-9}
Th-232	S	9.2×10^{-8}
Ra-228	M	6.7×10^{-7}
Th-228	S	3.5×10^{-8}
Th-230	S	8.7×10^{-8}
Ra-226	M	2.8×10^{-7}
Pb-210	F	6.8×10^{-7}
Po-210	F	2.4×10^{-7}
U-235	M	8.3×10^{-9}
Pa-231	M	7.1×10^{-7}
Th-227	S	8.4×10^{-9}

Table K: Dose conversion factors for members of the public from ingestion

Nuclide	Conversion Factor (Sv / Bq) Age Range					
	1 – 2 y	2 – 7 y	7 – 12 y	12 – 17 y	> 17 y	ICRP 119 Adult
U-238	1.2×10^{-7} *	8×10^{-8} #	6.8×10^{-8}@	6.7×10^{-8} ^	4.5×10^{-8} +	4.5×10^{-8} +
Th-232	4.5×10^{-7} *	3.5×10^{-7} #	2.9×10^{-7}@	2.5×10^{-7} ^	2.3×10^{-7} +	2.3×10^{-7} +
Ra-228	5.7×10^{-6} *	3.4×10^{-6} #	3.9×10^{-6}@	5.3×10^{-6} ^	6.9×10^{-7}+	6.9×10^{-7} +
Th-228	3.7×10^{-7} *	2.2×10^{-7} #	1.4×10^{-7}@	9.4×10^{-8} ^	7.2×10^{-8} +	7.2×10^{-8} +
Th-230	3.1×10^{-7} #	2.4×10^{-7}@	2.2×10^{-7} ^	2.1×10^{-7} +	4.1×10^{-7}	2.1×10^{-7} +
Ra-226	6.2×10^{-7} #	8×10^{-7}@	1.5×10^{-6} ^	2.8×10^{-7} +	9.6×10^{-7}	2.8×10^{-7} +
Pb-210	2.2×10^{-6} #	1.9×10^{-6}@	1.9×10^{-6} ^	6.9×10^{-7} +	3.6×10^{-6}	6.9×10^{-7} +
U-235	1.3×10^{-7} *	8.5×10^{-8} #	7.1×10^{-8}@	7.0×10^{-8} ^		4.7×10^{-8} +
Pa-231	1.3×10^{-6} *	1.1×10^{-6} #	9.2×10^{-7}@	8.0×10^{-7} ^		7.1×10^{-7} +
Th-227	7.0×10^{-8} *	3.6×10^{-8} #	2.3×10^{-8}@	1.5×10^{-8} ^		8.8×10^{-9} +
* Value also from ICRP 119 – 1 year						
# Value also from ICRP 119 – 5 years						
@ Value also from ICRP 119 – 10 years						
^ Value also from ICRP 119 – 15 years						
+ Value also from ICRP 119 - Adult						
Age < 1 y is also termed infants in some of the guidelines; Age > 17 y is also termed adults in some of the guidelines						
Lung absorption Type F = Fast absorption						
Lung absorption Type M = Medium absorption						
Lung absorption Type S = Slow absorption						

For most exposure pathways, conversion factors were adopted from ICRP Publication 119 - Compendium of Dose Coefficients based on ICRP Publication 60, 2012. This publication contains the latest (2012) factors with corrections to previous publications following most recent human health studies with specific focus on infants.

Table L: Recommended Values for Daily Soil, Dust, and Soil + Dust Ingestion Rates (mg/day)

Table 5-1. Recommended Values for Daily Soil, Dust, and Soil + Dust Ingestion (mg/day)

Age Group	Soil[a]				Dust[b]		Soil + Dust	
	General Population Central Tendency[c]	General Population Upper Percentile[d]	High End Soil-Pica[e]	High End Geophagy[f]	General Population Central Tendency[g]	General Population Upper Percentile[h]	General Population Central Tendency[c]	General Population Upper Percentile[h]
6 weeks to <1 year	30				30		60	
1 to <6 years	50		1,000	50,000	60		100[i]	
3 to <6 years		200				100		200
6 to <21 years	50		1,000	50,000	60		100[i]	
Adult	20[j]			50,000	30[j]		50	

[a] Includes soil and outdoor settled dust.
[b] Includes indoor settled dust only.
[c] Davis and Mirick (2006); Hogan et al. (1998); Davis et al. (1990); van Wijnen et al. (1990); Calabrese and Stanek (1995).
[d] Özkaynak et al. (2011); Stanek and Calabrese (1995b); rounded to one significant figure.
[e] ATSDR (2001); Stanek et al. (1998); Calabrese et al. (1997b; 1997a; 1991; 1989); Calabrese and Stanek (1993); Barnes (1990); Wong (1988); Vermeer and Frate (1979).
[f] Vermeer and Frate (1979).
[g] Hogan et al. (1998).
[h] Özkaynak et al. (2011); rounded to one significant figure.
[i] Total soil and dust ingestion rate is 110 mg/day; rounded to one significant figure it is 100 mg/day.
[j] Estimates of soil and dust were derived from the soil + dust and assuming 45% soil and 55% dust.

Inadvertent Soil Ingestion dose

Worker Dose Assessment:

In terms of exposure to hand-to-mouth ingestion of soils, the worker dose can be estimated using the following assumptions:

Table M: Calculation parameters used for soil ingestion dose for Workers

Parameter	Value
Daily soil ingestion rate	100 mg/day (Ozkaynak et al 2011)
Exposure time	2000/8760 x 365 days/y = 83.3 days/year
Soil Ingestion conversion factor for thorium-232	9.2×10^{-5} mSv/Bq
Soil Ingestion conversion factor for uranium-238	7.6×10^{-6} mSv/Bq

Calculation for worker inadvertent soil ingestion dose: $D_{Ing\text{-}soil} = Conc_{soil} * DCF * CR$

Where:
$Conc_{soil}$ = Soil activity concentration (Bq/g)
DCF = Dose Conversion Factors (mSv/Bq)
CR = Consumption rate (mg/day)

Bq/g Th x 100 mg/day (adult ingestion) x 1g / 1000mg x 83.3 days/y x 9.2×10^{-5} mSv/Bq +
Bq/g U x 100 mg/day (adult ingestion) x 1g / 1000mg x 83.3 days/y x 7.6×10^{-6} mSv/Bq

Public Dose Assessment:

In terms of exposure to hand-to-mouth ingestion of soils, the public dose can be estimated using the following assumptions:

Table N: Calculation parameters used for soil ingestion dose for Workers

Parameter	Value
Daily soil ingestion rate for adults	100 mg/day (Ozkaynak et al 2011)
Daily soil ingestion rate for children	200 mg/day for Children (Ozkaynak et al 2011; Stanek and Calabrese 1995b)
Exposure time	876/8760 x 365 days/y = 36.5 days/year
Soil Ingestion conversion factor for thorium-232	As per Table K (mSv/Bq)
Soil Ingestion conversion factor for uranium-238	As per Table K (mSv/Bq)

Calculation for public inadvertent soil ingestion dose: $D_{Ing\text{-}soil} = Conc_{soil} * DCF * CR$

Adult Soil Ingestion
Bq/g Th x 100 mg/day (adult ingestion) x 1g / 1000mg x 36.5 days/y x DCF (Th) mSv/Bq +
Bq/g U x 100 mg/day (adult ingestion) x 1g / 1000mg x 36.5 days/y x DCF (U) mSv/Bq

Children Soil Ingestion (various ages)
Bq/g Th x 200 mg/day (adult ingestion) x 1g / 1000mg x 36.5 days/y x DCF per age group (Th) mSv/Bq + Bq/g U x 200 mg/day (adult ingestion) x 1g / 1000mg x 36.5 days/y x DCF per age group (U) mSv/Bq

References:

- International Commission on Radiological Protection (ICRP) (2012). ICRP Publication 119 - Compendium of Dose Coefficients.
- International Commission on Radiological Protection (ICRP) (1994) Publication 66 – Human respiratory tract model for radiological protection.
- International Commission on Radiological Protection (ICRP) (2006) Publication 101 – Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and the Optimization of Radiological Protection: Broadening the Process
- Beck H, de Planque G (1968) - The radiation field in air due to distributed gamma-ray sources in the ground. HASL-195, Environmental Measurements Laboratory, U.S. Department of Energy, New York

APPENDIX 7 – RS-125 SPECIFICATIONS

1.1 MAIN FEATURES

- **RS-125 = 2x2" (6.3cu ins)** Sodium-Iodide detector provides High sensitivity performance due to the large xtal. Energy response from 30 keV-3000keV.
- **RS-230 = 2x2" (6.3cu ins)** BGO detector provides typically 3x equivalent performance over comparably sized Sodium-Iodide detectors.
- Full ASSAY capability with data in **%K and ppm U and Th.**
- **no radioactive sources required for proper operation**
- **USB** connection for data retrieval
- **Bluetooth** support for data transfer
- Large easy to read **5 digit display** updated at 1/sec – giving a wide dynamic range, no overflow, no range controls. Graphic display LCD with white backlight with automatic dimming - 128 x 64 pixels, 28 x 60mm size
- Simple **ONE BUTTON OPERATION** – no parameter setups required for normal operation
- Fast response, easy-to-hear **AUDIO** at 20/sec sampling making source location easier and eyes free
- **512K** memory standard on older units – **4M** standard on newer units (512K memory units can be upgraded if required)
- New design state-of-the art electronics with advanced CPU/spectrometer capability
- Special rugged design, robust aluminum casting construction with a heavy duty "**Rubberized**" outer coat which works as a shock absorber and provides thermal isolation.
- Outer coating gives a **good grip even when wet**, is simple to maintain and permits easy decontamination if required.
- Well balanced, easy to hold and designed for **one hand operation**
- **RUGGEDISED** integrated carrying handle
- **Full IP66 weatherproofing** – short term water immersion and fully dust protected
- **Rechargeable battery kit** supplied including NiMH battery pack module (4xAA) batteries, Universal Charger (110/220VAC) and a 12V cigarette lighter charge cable.
- Typical **8+ hour** battery life at 15^0 C on NiMH batteries
- Size 10.2" x 3.2" x 3.6" – 4.4lbs **<u>with batteries</u>** (259x81x91mm – 2Kgs : RS230=2.2Kgs)
- Operational Temperature range **-20 to 50 degrees** Celsius (display is the limit)
- Spare battery module for "**instant**" replacement
- **Protective boot** with carry straps (supplied standard with 2008 units but available as an option for older units)

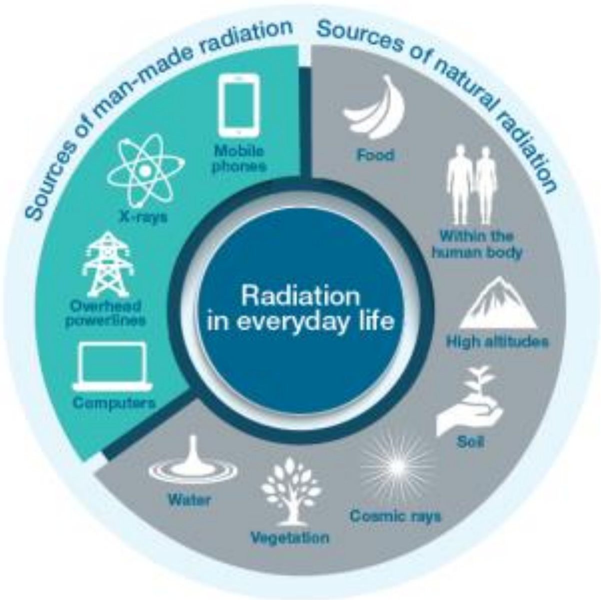
N.B. see Section 5 for summary of new software system changes. Note that this manual incorporates all changes in the current release

OLDER UNITS HAD A SIDE CARRY HANDLE BUT THIS HAS BEEN DISCONTINUED ON 2008 UNITS AS THE RUGGEDISED CARRY HANDLE MADE THIS UNNECESSARY

NOTE: USERS ARE REMINDED THAT THE RS-125, IN COMMON WITH OTHER SIMILAR INSTRUMENTS, USES A Sodium-Iodide CRYSTAL AS THE DETECTOR (the RS-230 uses a BGO detector). THESE CRYSTALS ARE FRAGILE AND EVEN THOUGH THE UNIT HAS BEEN RUGGEDISED FOR FIELD USE, GREAT CARE SHOULD BE TAKEN TO AVOID ABUSING THE INSTRUMENT AS THE VERY EXPENSIVE CRYSTAL IS <u>NOT COVERED UNDER WARRANTY</u>

APPENDIX 8 – NATURAL BACKGROUND RADIOACTIVITY AND RADIATION

Radiation is part of everyday life. Everyone and everything is exposed to radiation. Humans receive background radiation dose from natural sources, including cosmic radiation from space, radioactivity in rocks and soils (terrestrial), in water and oceans, and in the air, as well as radioactivity within the human body (i.e. potassium and carbon in bones and blood). Background radiation is also received from man-made sources (e.g. medical x-rays, televisions, smoke detectors, mobile phones and radiopharmaceuticals).



(Source: Iluka Natural occurring radiation and mineral sands factsheet; www.iluka.com)

Sources of natural and man-made radiation

Exposure to radiation is either from direct exposure to a source of radiation outside the body (external exposure from e.g. medical x-ray, or gamma dose from standing next to a stockpile of HMC), or from ingestion and inhalation of radioactive materials (internal exposure). Radioactivity which occurs naturally in soils; water; livestock and vegetation could be ingested by a human receptor as food, whilst other forms of radiation, such as radon (radioactive gas) and dust are inhaled. Worldwide, the natural background radiation dose to an individual is about 2.4 mSv per year (mSv/y) (IAEA 2004), but some countries' average dose from natural background is in excess of 10 mSv/y, the variation of which would depend on the nature of the surrounding geology; altitude above sea level, local diet etc.

Ionizing radiation with an activity concentration of 1 Becquerel per gram (Bq/g) is the internationally accepted level for defining a material as radioactive. Material activity concentrations less than 1 Bq/g, is not classified as radioactive and considered to be inherently safe if the source of the radionuclides is insoluble or immobile.

External sources (e.g. the gamma emitting radionuclides in surface soils) irradiate the body with gamma photons, whereas the main internal hazard is the incorporation of radioactive materials into the body through ingestion or inhalation. Once incorporated, the radionuclides may be distributed in the body and could irradiate living tissues by alpha and beta particle emission.

References:

- International Atomic Energy Agency (2004). Safety Guide on Occupational Radiation Protection in the Mining and Processing of Raw Materials RS-G-1.6
- Iluka Resources Limited. Natural occurring radiation and mineral sands factsheet. www.iluka.com

APPENDIX 9 – PATHWAYS, RADIOACTIVITY AND IONISIZING RADIATION

Potential exposure pathways of workers and members of the public living near to the site comprise the following:

- external gamma irradiation from the gamma emitting radionuclides;
- inhalation of radioactive radon gas;
- inhalation of radioactive dusts containing long lived alpha emitters of the uranium and thorium decay chains; and
- inadvertent soil ingestion (hand-to-mouth).

Inhalation of long-lived alphas in dust

Alpha emitters present no external hazard as the primary hazard arising from alpha emitters occurs when they are inhaled or ingested. Many alpha emitters of the uranium and thorium decay chains are long-lived alpha emitters and continue to irradiate the body over the individual's lifetime. The most important long-lived alpha emitters in terms of the exposure of workers and the public are U-238; U-234; Th-230; Ra-226; Po-210; Th-232; and Th-228. Dry and dusty operations will result in the re-suspension of alpha emitting dusts into the air.

The Dredge D1 and WCP operations at the FPP and at the MSP have a low potential for dust generation as a large proportion of the material treated is processed under wet conditions. Dry operations with a potential for dust generation will occur in the dry mining areas (Lanti DM1 and Gangama DM2) and the dry sections of the MSP.

Engineering and PPE controls are required to mitigate occupational inhalation exposures in the dry process areas of the MSP in order to maintain the workers exposures as low as reasonably achievable. This is accomplished through a dust extraction system and compulsory wearing of dust masks.

Ingestion of long-lived alphas in soils, water and foods

The primary radiological hazards arising from beta particles are associated with external exposure to the skin surface and the inhalation of dusts containing beta emitters e.g. Pb-210, Ra-228. In heavy minerals mining and processing operations a limited amount of beta exposure to the skin will occur. No specific administrative or engineered measures to control beta exposure are required provided that adequate controls are implemented over the individual's exposure to alpha inhalation and gamma dose rates.

External Radiation Exposure

Some of the radionuclides of the U-238 and Th-232 decay chains are strong gamma emitters. The strength of the gamma radiation fields is dependent on the radionuclide activity concentration in the materials as well as the quantity of the material in the vicinity. Areas in which enhanced gamma radiation fields may be encountered at Area 1 include the following:

- HMC stockpiles;
- MSP product and tailings stockpiles;
- Areas of the MSP and Nitti Port containing concentrated streams of monazite, as well as accumulations of the process materials.

The generic methods of protection against gamma radiation fields include limiting the time of exposure, maintaining a distance from the source of gamma radiation and engineered controls such as the use of shielding e.g. concrete bunkers and bins for the collection of the high activity concentrates and tails.

Half-Life

A characteristic of all radionuclide atoms is that they emit ionizing radiation and spontaneously decay forming an atom of another element. Each radionuclide has a characteristic rate of transformation referred to as the decay constant. The half-life refers to the period of time in which it takes half the atoms of a radionuclide to decay into another type radionuclide.

For example the half-life of ^{226}Ra is 1,600 years. A tailings facility at mine closure that contains ^{226}Ra will have half the original amount of ^{226}Ra remaining in the tailings after a period of 1,600 years has elapsed.

After four half-lives (6400 years), approximately 6% of the original ^{226}Ra inventory will remain in the tailings. After 10 half-lives (16,000 years) have elapsed approximately 1% of the original ^{226}Ra inventory will remain in the tailings.

Dose and Dose Rate

A radiation dose (more correctly referred to as the effective dose) is a measure of the radiation energy absorbed by the body during a defined time period. The unit of effective dose is referred to as the Sievert. Results are reported in millisieverts (mSv) and microsieverts (µSv) per hour or per year.

In the control of radiation hazards it is necessary to know the rate at which radiation is received.

The relationship between dose, dose rate and time is:

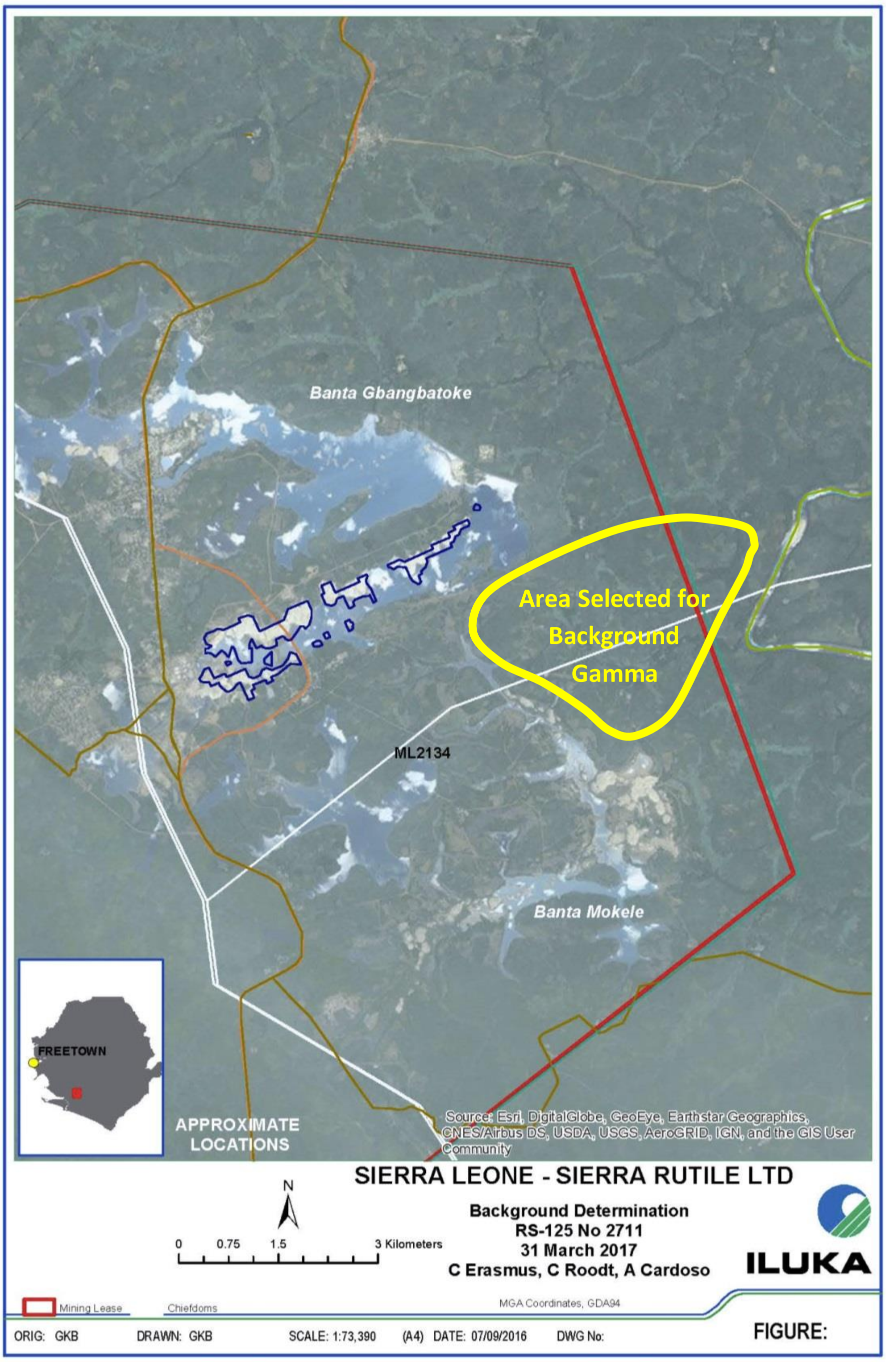
Dose = dose rate x time

For example if a worker is exposed to a dose of 2 microsieverts in one hour, the dose rate is 2 $\mu Sv.h^{-1}$.

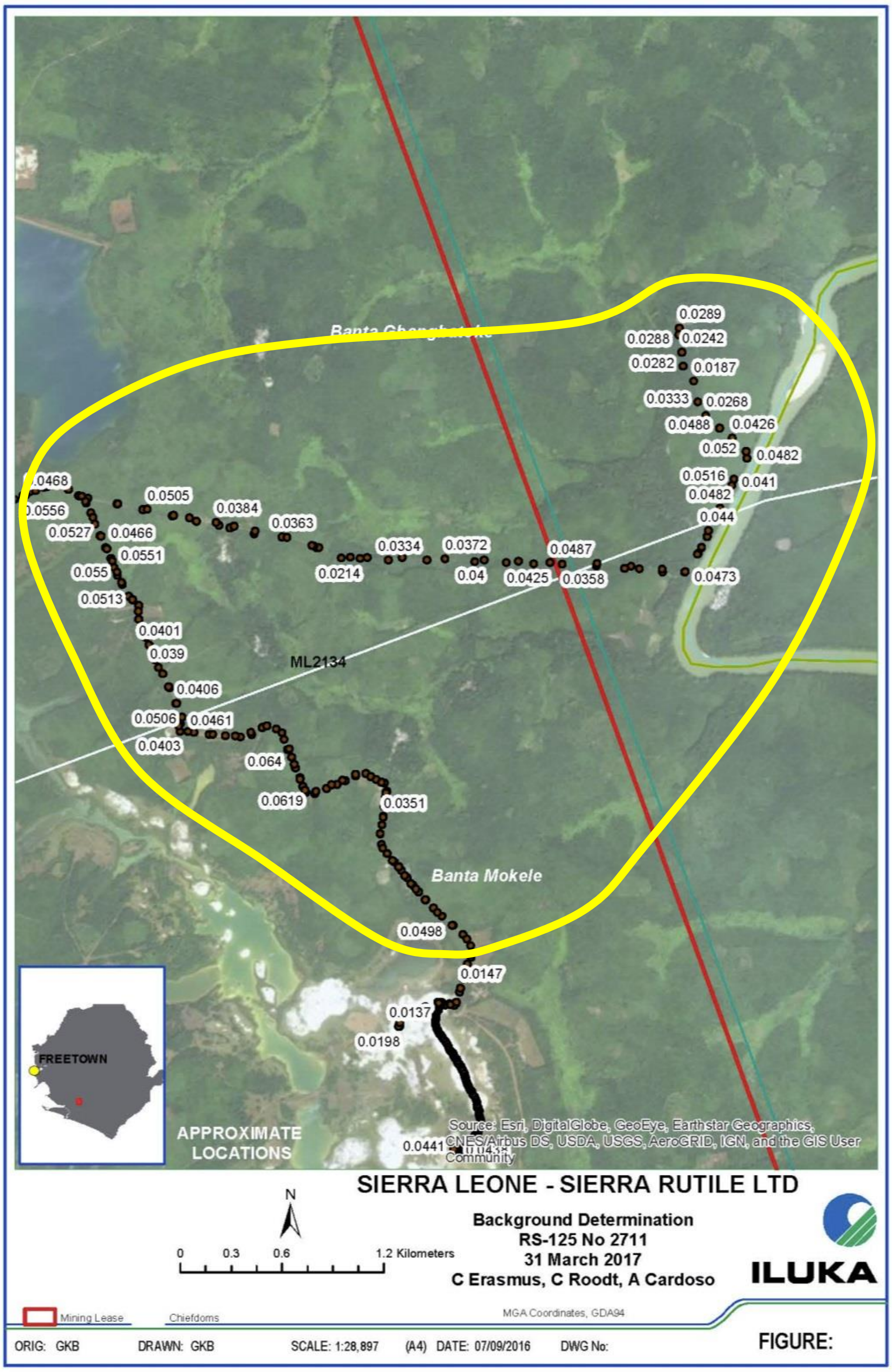
APPENDIX 10 – SR AREA 1 BACKGROUND GAMMA RADIATION

Background is generally determined by undertaking pre-operational gamma dose rate surveys at the proposed operational sites. In the instance that no pre-operational gamma surveys were conducted (as is the case for SR Area 1), an area needs to be selected which is unaffected by mining operations, similar in characteristics, and within close proximity to serve as background location.

The File Note: “Background gamma level assessment for SRL, April 2017”, provides a summary of measured gamma levels at a selected background location for SRL Area 1 (Figures below). Measurements were conducted with the RS-125 Serial No 2711 and determined a background gamma level of 0.06 µSv/h.



Area identified as unaffected by mining operations for the determination of background gamma radiation levels



Gamma radiation levels over an area selected to be unaffected by mining operations for background determination

Data statistics of the area selected to be unaffected by mining operations at SRL for background determination

Statistics	Hourly Dose (µSv/h) as measured by RS-125 (No 2711)
Average	0.043
Min	0.019
Max	0.069
Stdev	0.010
90th Percentile	0.056
95th Percentile	0.059
Count	93

Ninety three (93) data-points were selected from an area east of the Land-Plant (MSP) and historic Mogbwemo mining activities. This area was assumed to be unaffected by mining activities as it is still overgrown with forest vegetation and partially outside of the mining area boundary. From the survey data, the average hourly dose rate is 0.04 µSv/h with a 90^{th} Percentile of 0.06 µSv/h and a 95^{th} Percentile of 0.06 µSv/h. It was recommended that the 95^{th} Percentile value (international best practice) of 0.06 µSv/h be adopted for background gamma levels of SRL.

References

- Sierra Rutile Limited (2017). File Note: Background gamma level assessment for Sierra Rutile Ltd. Internal document not for publication.