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Development of a waste management process for naturally occurring radioactive material in the South African mining industry

by

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Submitted in partial fulfilment of the requirements for the degree
Doctor of Philosophy in Physics

in the

Department of Physics
Faculty of Natural and Agricultural Sciences

UNIVERSITY OF PRETORIA

December 2022

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SUMMARY

Development of a waste management process for naturally occurring radioactive material in the South African mining industry

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Degree:	Doctor of Philosophy Physics
Keywords:	Radiation, NORM, waste

Mining and minerals processing activities interact with an ore body that may contain elevated levels of radionuclides from the uranium and thorium decay series. Furthermore, these isotopes may be concentrated during the beneficiation processes, resulting sometimes in enhanced levels of radioactivity in some of the superfluous residue streams.

While the mining and processing activities contribute significantly to the South African economy and necessary for social upliftment, the waste may cause an impact for hundreds of years due to the radioactivity present and some level of management needs to be introduced or suitability and effectiveness of current measures considered to ensure the prevention of a detrimental legacy.

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Within the South African regulatory framework, the process to manage the disposal of radioactive waste from natural origin is not as well defined as occupational radiation protection for example, hence the need for the development of a radioactive waste management process.

Applying the suggested process, using the data from Palabora Mining Company (PMC), set a structured process that allows the focus on key risks and the optimal use of available resources. The study:

- Demonstrated that the process is aligned with or in some cases gives effect to recommended international principles;
- Create a clear understanding of the potential effective dose to workers and members of the public; and,
- It provided guidance on possible optimisation and thus future focus and improvement.

The study furthermore:

- Justified a rapid screening tool for radioactive waste classification;
- Considered some South African radiation management practices and provided comments as to its suitability; and,
- Identified aspects of further study, such as the need to quantify potential exposure to the ecological systems.

The process can thus form the base for the management of radioactive waste from mining and minerals processing activities post closure.

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RESEARCH OUTPUTS

Journal articles

AJ van der Westhuizen; D de Villiers; J Hondros, J Malherbe; (2022); *Protocol for assessing NORM waste from mining and minerals processing.* (Pending)1

AJ van der Westhuizen; D de Villiers; J Hondros, J Malherbe; (2022); *Assessing the radiological impact from a copper mining and minerals processing facility's NORM waste streams.* ARPS Journal: Radiation Protection in Australasia - V39.No1. May 2022

Conference presentations

Oral presentations

Poster presentations

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LIST OF ABBREVIATIONS

µSv	microSievert, a unit of effective dose
Bq	Becquerel Unit of activity, where becquerel is that quantity of radioactive material in which one atom is transformed per second [1].
$Bq.g^{-1}$	Becquerel per gram Activity per unit mass i.e., concentration of radioactivity.
CNS	Council for Nuclear Safety (Predecessor of the NNR.)
COR	Certificate of Registration
ERA	Environmental risk assessment
EW	Exempt waste
FEPs	Features, events and processes
HLW	High level waste
HMP	Heavy Minerals Plant
Gy	Gray as unit of dose
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate level waste

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LLW	Low level waste
MHSA	Mine Health and Safety Act, No 29/1996
MPRDA	Minerals and Petroleum Resources Development Act, No 28/2002
NEMWA	National Environmental Management: Waste Act, No 59/2008
NORM	Naturally occurring radioactive material(s)
NNR	National Nuclear Regulator (of South Africa)
NNRA	National Nuclear Regulatory Act, No 47/1999
NRWDI	National Radioactive Waste Disposal Institute
NRWDIA	National Radioactive Waste Disposal Institute Act, No 53/2008
PMC	Palabora Mining Company
VLLW	Very low-level waste
VSLW	Very short-lived waste
WMP	Waste management plan

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LIST OF DEFINITIONS

Approach	How to deal with a particular situation in a certain way. (See also “process” and “methodology”.)
Authorisation holder	This is a person or organisation that is involved with a practice/activity or a source within the practice that give rise to radiation risk and is issued an authorisation from a regulatory authority such as the National Nuclear Regulatory of South Africa.
Clearance (IAEA)	A process whereby radioactive material under regulatory control, is removed from that control. (Based on specific activity, the recommendation is 1 $Bq.g^{-1}$ per isotope for naturally occurring radioisotopes.)
Clearance (South Africa)	Material exceeding the exemption level of 0.5 $Bq.g^{-1}$ per isotope, but through a dose assessment can justify that the practice is less than 0.25 $uSv.a^{-1}$ and such a practice can thus be cleared from regulatory control.
Decay chain	Groups of sequentially transforming isotopes [1].
Disposal	Final placement of waste, generally after specific treatment and/or set controls to manage current and future risks.
Dose coefficients	Dose coefficients are broadly defined as a quantity that, when multiplied by a value of either radionuclide intake, air kerma, particle fluence, or environmental radioactivity concentration, will yield an organ equivalent dose or the effective dose to the exposed individual [2].

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Dose constraint	A prospective, source related value of individual dose, applied in a planned exposure situation, above which it is unlikely that protection is optimised for a given source. The value of the dose constraint takes into account the estimated individual dose distribution, with the objective of identifying exposures that warrant specific attention and facilitate optimisation of protection.
Effective dose	Summation of the tissue or organ equivalent doses. (Unit = Sievert and abbreviated as Sv).
Emergency exposure scenarios	Situation of exposure that arises as a result of an accident, malicious act or any other unexpected event, and requires prompt action in order to avoid or reduce adverse consequences.
Equilibrium	It is a state where the activity of the parent isotope is equal to that of the daughter, i.e., the production rate equals the decay rate [1]. (See definition of "Secular equilibrium" below.)
Equivalent dose	Amount of harm caused to a particular organ. (Unit = Sievert)
Exclusion (IAEA)	Any exposure whose magnitude or likelihood is essentially unamenable to control, such as cosmic radiation, 40K in the body and unmodified concentrations of radionuclides in most raw materials, i.e., unamenable to control [3, 4].
Exemption (IAEA)	It is used within the context of practices and sources within practices. A source or practice need not be subjected to some or all aspects of regulatory control on the basis that the exposure and the potential exposure are too small to warrant the

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	application of these aspects or that it is the optimum option for protection irrespective of the actual level of doses or risks.
	For radionuclides of natural origin, exemption of bulk amounts of material is necessarily considered on a case-by-case basis by using a dose criterion of the order of 1 mSv in a year [3, 4].
Exclusion (South Africa)	It is a level below which the radiological content of the material is not of regulatory interest. For South Africa, “Exclusion” is set at 0.5 Bq.g^{-1} per isotope for the NORM isotopes. (See definition of “Clearance” above.)
Existing exposure scenarios	Situation of exposure that already exists when a decision for control is taken, including derivatives from past practices that were never subjected to regulatory control, or subjected to regulatory control but not in accordance with requirements of current standards.
Half-life	It refers to the time the initial number of an isotope is reduced by 50% through radioactive decay. Radioactive decay is logarithmic and unique and constant for a particular isotope [5].
Integrated management system	It is the effective organisation, administration and control by means of an effective management system. This system aims to integrate all elements, including quality, protection of the environment and security, together with economic considerations. It also has to promote a culture of safety and be a quality management system.

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Intervention	To reduce exposure from an existing condition, typically from an accident scenario. In the South African context, specifically RG-0026 and its application in terms of waste management, it is referred to as existing exposure (scenarios).
Isotope	Variations of an element where the variation is due to a different number of neutrons, i.e., the same number of positive electronic charges (protons) and the same extranuclear structure but vary in the number of neutrons [1].
Justification	The process of determining whether a practice is beneficial overall, i.e., whether the benefit outweigh the harm that may result. Also, to consider other harm, such as economic, societal and environmental factors and not only dose.
Limiting reference organisms	Restrictive organism, i.e., most severely affected by the contaminant. (See definition for “Reference organisms” below.)
Methodology	Well-defined (and often formulated) steps to achieve a specific outcome. (See “approach” and “process”.)
NORM	Naturally Occurring Radioactive Material. Where the source of the radiation exposure is the radionuclides from the uranium and thorium decay chains that exists to a varying degree in all matter. These decay chains may not be in secular equilibrium and depending on the process a particular material was subjected to, isotopes may be enhanced or reduced. (Some countries refer to

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	TENORM – Technically enhanced NORM, when equilibrium has been disturbed.)
Order of magnitude	Class or scale or magnitude of any amount where each class contains a value of a fixed ratio, most often 10, for example: • Two orders of magnitude larger is 100 times larger, or; • 1.50E+04 is in the same order of magnitude as 9.32E+04.
Planned exposure scenario	Situation of exposure that arises from planned operations or activities. Provisions for protection and safety are made before starting the activity and the associated exposure can generally be restricted from the start, typically through good design, the right operating procedures, training, right selection of equipment and so forth [6].
Practice / activity	Any human activity that introduces additional sources of radiation or additional exposure pathways, or that modifies the network, so as to increase the exposure or the likelihood of exposure of people.
Process	The general steps proposed for the optimised management of radioactive mine waste as per Figure 3.1-1.
Radiation risk	It is a general term that refers not only to the detrimental health effects of radiation exposure, including the likelihood, but also any other safety risk that might arise from the exposure, presence of radioactive material, or release into the environment.

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RAP / RAPSs	Reference animals and plants.
Reference organism	A series of imaginary entities that provide a basis for the estimation of the radiation dose rate to a range of organisms that are typical, or representative, of a contaminated environment. They are not a direct representation of any identifiable animal or plant species.
RP function	A collective expression of individuals responsible for the development and execution of a radiation protection program and generally consists of a radiation protection monitor, radiation protection officer and radiation protection specialist.
Scenario	A specific possibility. For dose assessments, it is a postulated sequence of events or conditions given rise to a dose to the defined critical group within that scenario.
Secular equilibrium	It occurs where a short-lived daughter isotope has a long-lived parent isotope, i.e., the production rate of the short-lived daughter is equal to its decay rate or simply put, when the activity concentration of decay product(s) is the same as the parent.
Storage	Interim or temporary placement of waste, with final disposal elsewhere or under different conditions and/or controls. Controls may be different than for disposal. (See definition for “Disposal” above.)
Type F materials (Inhalation)	Deposited materials that are readily absorbed into blood from the respiratory tract (fast rate of absorption) [7].

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Type M materials (Inhalation)	Deposited materials that have intermediate rates of absorption into blood from the respiratory tract (moderate rate of absorption) [7].
Waste	A material or a process output that is superfluous, unintended or in addition to the desired output.

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DECLARATION

I declare that this dissertation/thesis, which I hereby submit for the degree PhD to the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

ETHICS STATEMENT

The author, whose name appears on the title page of this dissertation/thesis, has obtained, for the research described in this work, the applicable research ethics approval.

The author declares that s/he has observed the ethical standards required in terms of the University of Pretoria's Code of Ethics for Researchers and the policy guidelines for responsible research.

Signature

Student name: Abraham Jozua van der Westhuizen

Month Year: December 2022

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ACKNOWLEDGEMENTS

My first acknowledgement is to God. He carried me through the difficult times.

A special thanks to my family, especially my wife Martie, for your support and encouragement. You found ways of raising me when we were all facing serious challenges.

I am indebted to my supervisors, Professor Johan Malherbe and Dr Dawid de Villiers. Your enthusiasm and advice were invaluable.

Special thanks to the encouragement, information and advice from my radiation protection colleagues across the globe, with special mention to Dr Jim Hondros and the SHEQ team on site.

My thanks to Dave Turner for your inputs into this document. Your contributions elevated it.

This project could not have been completed without the assistance of Palabora Mining Company. Their approval to continue with the project and permission to utilise company data was invaluable. Special thanks to Johan van Dyk, General Manager SHEQ, and Mr. Han, CEO of Palabora Mining Company in this regard.

This project was not supported by a bursary. Research was done utilising information gathered during the execution of the routine radiation protection program as implemented by Palabora Mining Company since 1993.

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1 INTRODUCTION

1.1 GENERAL

Mankind has always shown a deep interest in the physical domain we found ourselves, seeking growth in our understanding and knowledge of the atomic nature of our world. Around 450 B.C., Leucippus from Greece proposed that matter has an atomic nature. One of his students, thought to be the most famous atomists of his time, Democritus of Abdera proclaimed: "*The only existing things are the atoms and empty space; all else is mere opinion*" [5]. Nevertheless, it was only around 2,000 years later, the beginning of the 19th century that an elementary form of the modern atomic understanding started to develop. It was from this humble origin that the relevance of radiation protection emerged.

A critical point in this timeline was the discovery of radioactivity from uranium by Antoine Henri Becquerel in 1896, interestingly named "radioactivity" by his student, future famous physicist Marie Curie. The understanding of the nature of radioactivity was further evolved in 1897 by Ernest Rutherford when he found that the radioactivity emitted by uranium was complex, in that it emitted "soft" and "hard" rays. (Nowadays we also know that uranium not only emits high (hard) and low (soft) energy gamma rays, but also alpha and beta particles, thus making uranium indeed complex.) Also, extremely relevant to the field of radiation protection was the experimental determination of the law of radioactive decay by Julius Elster and Hans Geitel in 1899, which stated:

$$N_t = N_0 e^{-\lambda t} \qquad \text{[Eq. 1]}$$

Where N_0 is the value of N at time t = 0 and λ is the decay constant equal to $\frac{lin2}{T_{½}}$ and $T_{½}$ is the half-life of the isotope.

Unfortunately, not all discoveries are only benign and the field these discoveries opened up was not without risk to mankind. Soon after these breakthroughs, incidents such as the Radium Dial Watch Painters, (or Radium Girls) between 1917 and 1925 brought some understanding of the potential for harm from radiation to the general public. Jumping forward a further 20 years saw two significant events during the 2nd World War; first in 1942

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was the successful self-staining fission reactor, followed by the first nuclear bomb in 1945. Both were developments with the potential of causing harm on a global scale and suddenly radiation became something to fear.

While there was a general association of such a risk with the nuclear field (sometimes emotionally and sometimes justifiably so) it was only approximately 50 years later (circa 1993) that the attention turned to the mining industry in South Africa as a potential source of a radiation hazard through the very ore body it is extracting. (See Section 2.1.3.1.)

1.2 PROJECT RATIONALE

The mining industry is a vital component of the South African economy, providing means directly to more than 400,000 families and indirectly accepted to be 10 times that number [8]. Nevertheless, mining and its associated beneficiation activities create an array of waste, each with its own characteristics that may include elevated levels of radionuclides. (Elevated when compared with background radiation levels.) These nuclides may have a significant radiological impact(s), not only to the workers, but also the public and environment.

The management of these residues (besides the obvious radioactivity content) differ from nuclear waste in that the responsibility at some point changes ownership (from the mining company to state) and actual closure of the waste generating activity. Some of these residues are left in-situ with an approved management plan, while it is known that others are abandoned afterwards.

It is therefore necessary for government and industry to ensure adequate governance of the impact(s) the industry creates, but also to ensure a balanced approach when dealing with this hazard. The expectation should be that these measures are appropriate in benefit and scale not only during the operational phase of an endeavour, but also for the remnants of these activities once the extraction and beneficiation processes are completed.

South Africa has made significant progress since 1993 in managing the radiation risk posed by sources of natural origin, but there is insufficient national legislative guidance that can direct a mine or Naturally Occurring Radioactive Material (NORM) processing facility in

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the creation of a radioactive waste management strategy to address its legal and moral obligations, especially post closure.

1.3 AIM AND OBJECTIVE

JA Joubert in his 2016 thesis "*Framework and regulatory guidance to perform safety assessments for mining and mine remediation activities*" referenced the constitutional right to a healthy environment and then described a guide to assess radiation hazards to members of the public from mining and minerals processing activities [31]. The objective of that thesis was (a) to provide a new reference document and (b) to expand on the existing regulatory framework. However, it described the work as "*a guide that was developed for the regulatory review process*" and not necessarily as guidance for the operator. The current regulatory framework also does not always guide or assist the operator in making informed decisions.

NORM facilities are unique, with factors such as mineral content, process methodology, site characteristics, diverse waste streams and disposal methodologies potentially different from site to site. A blanket-decision or expression of risk for the waste disposal of a particular NORM site, (or even NORM industry) is thus potentially not appropriate for the level of risk to justify a set remediation or disposal strategy and that the management thereof is therefore not optimised.

Consequently, it necessitates the application of 1st order principles and standards on a unique set of conditions and characteristics in order to quantify the exposure from an endeavour. Based on that outcome, align the defined risk to an appropriate level of remediation or control.

South Africa currently lacks specific templates to follow for the management of NORM waste other than generally defined processes for the management of the radiological risk holistically during the operational phase supported by expressed methods for the safety assessment processes. It is thus necessary to find a way of applying current processes and first principles to define the impact of a multitude of different types of waste. This is particularly applicable to Palabora Mining Company (PMC) as the company has a range of distinctive residue streams, each with its own potential impact.

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In addition, there are other acts and regulations, for example the Mine Health and Safety Act, No. 29/1996 (Mine Health and Safety Act) and National Environmental Management: Waste Act No. 59/2008 (NEMWA) also in play that may hinder or support the optimisation process and thus must be considered.

The objectives of the thesis are thus:

- Defining a practical process (protocol) to classify and thus determine appropriate remediation;
- Consider the alignment with International Atomic Energy Agency guidance / principles to test the appropriateness of the process;
- Apply the process (protocol) using the Palabora Mining Company data;
- Identify or formulate tools to assist in the process;
- Provide arguments for some of the decisions made during the application of the process; and,
- Identify constraints encountered in the application of the process.

Thus, the purpose of this argument is to further develop the process for NORM waste management, utilising the example of the storage and disposal of a copper mine and smelter's various waste stream by using first principles, primarily set by the International Atomic Energy Agency (IAEA) and available national guidance. It is applied to the waste management process from around mine closure to around 500 years into the future, identify possible tools to facilitate the process and possibly identify areas where further developments are necessary.

This proposal and/or process can potentially be used to set the blueprint for a national process in the management of radioactive mine waste post closure.

1.4 DISSERTATION LAYOUT

The thesis will abide by the following arrangement. The first chapter will provide the project rationale and intent, followed (Chapter 2) by a discussion of the fundamental principles of

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radiation protection and the legislative framework. It is to provide the background and reasoning of the process, as expressed in Chapter 3. Chapter 3 will also provide the basic process, formulas and assumptions to be used when executing the process.

Chapter 4 is the application of the process as it relates to Palabora Mining Company (PMC), typically what will be submitted to the regulatory body to demonstrate an appropriate level of radiation safety, including the final classification of the various waste streams found on site. The discussions that follow in Chapter 5 will focus less on the radiation dose and whether the disposal methodology is safe or not but will argue the merit of the suggested process and alignment with international principles. It will further examine some of the decisions to be made through the application of the process and constraints an assessor may encounter. Subsequently, the conclusions reached in Chapter 6 focus primarily on the process and aspects that may impact on the process. It nevertheless confirms the final disposal classification as it is a direct result from the processes followed.

The dissertation lastly (Chapter 7) provides some suggestions for future development and focus as part of a continuous improvement cycle.

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2 FUNDAMENTAL PRINCIPLES AND CONCEPTS

An understanding of some of the basic concepts and principles are necessary to value the justification and ramifications of decisions made with regards to the management of a particular radiation risk and ultimately the most appropriate waste disposal practice.

2.1 RADIATION CONCEPTS

2.1.1 Radioactivity and radiation

Radioactivity is a spontaneous transformation of an unstable nucleus (also referred to as "decay") through the emission of particles and/or electromagnetic radiation (from a defined range) resulting in a new isotope or element [5]. These particles have distinctive properties, each with its own unique influence. To determine the risk (i.e., dose on human and environment) consideration should be given to these characteristics within the framework of the receiving environment.

While there are a host of atomic and subatomic particles, of primary importance for radiation protection when dealing with NORM is alpha radiation, beta radiation and gamma radiation. While the purpose of this thesis is not to investigate or understand the minute details of each particle, it is necessary to grasp some of the fundamentals and specifically those characteristics that will influence the impact or potential protection measures.

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Table 2.1.1-1: Some characteristics and properties of ionising radiation

Parameter	Alpha radiation	Beta radiation	Gamma radiation
Description	Particle, consisting of two protons and two neutrons.	Particle, consisting of an electron.	Electromagnetic wave.
Charge	+2e	-e	0
Range	~10 cm in air.	Few meters in air.	Up to several kilometres.
General	Least penetrative but has significant ionising ability. Readily absorbed by materials and can be stopped by human skin.	More penetrative with reduced ionising ability. Absorbed by denser material in a short distance such as human tissue. Can pass through human skin.	Most penetrative. Require lead shielding to stop.
Primary Hazard	Internal	Not as significant for internal and external dose for most of the organs. Primary hazard of beta radiation is to the lens of the eye and a skin dose.	External and internal.

2.1.2 Expressing exposure

The first step in creating a universal process when dealing with the hazard that is radiation is to quantify the effect of radiation to ensure a common understanding and allow for suitable comparison between different exposure scenarios. This quantification is expressed as dose.

> **Dose**: A measurement of the energy a body absorbed from the radiation and thus indicative of the harm it potentially causes.

Dose is expressed in different categories, the simplest being “absorbed dose”. It represents energy deposited by radiation in a mass and is expressed in “Gray” (Gy) where 1 Gray is defined as 1 joule per kilogram. This unit unfortunately does not provide for the different response body parts have to a value of absorbed radiation, nor account for the difference in

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properties of these particles. It is thus necessary to utilise a unit for protection, design and regulatory purposes that is weighted in this regard. This unit is known as the "equivalent dose" with the unit of "Sievert" (Sv).

$$H_T = \sum_R W_R \ x \ D_{T,R} \qquad \text{[Eq. 2]}$$

H_T	Equivalent Dose in tissue or organ T	Sv
W_R	Radiation Weighing Factor	No unit
$D_{T,R}$	Absorbed dose averaged over the tissue or organ.	Gy

Equivalent dose, while considering the type of radiation, also has its limitation as it represents the impact in terms of a single organ. Further refinement has led to "effective dose", i.e., a dose calculated for the whole body. In essence, it sums up any number of different exposures into a single value of risk (safety assessment).

Table 2.1.2-1: Defining "dose"

Dose = The harm radiation causes.		
Absorbed dose	**Equivalent dose**	**Effective dose**
Amount of radiation deposited in a mass. (Gray = Gy)	Dose that is absorbed by an organ, considering the characteristics of the type of radiation. (Sievert = Sv)	Sum of the Equivalent Doses from individual organs and also considers stochastic effects. (Sievert = Sv)

Establishing the "effective dose" thus allows for a comparative risk determination and evaluation of different scenarios. Since it also considers stochastic effects, it is very suitable for contemplating long-term exposure scenarios, such as the occupational, public, and environmental dose as a result of mining activities.

2.1.3 Naturally occurring radioactive material

2.1.3.1 Abundance and isotopes

Uranium and Thorium are found in abundance, and it is estimated that there are on average 8 parts per million Thorium and 3 parts per million of Uranium present in the earth's crust.

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Naturally occurring radioactive materials, or NORM, are defined as materials that contain isotopes of natural origin, i.e., isotopes from three decay series found in nature, the U-238 decay series, the Th-232 decay series, and the U-235 decay series. These series have in common (other than it being found in nature) isotopes that forms chains of parent-daughter isotopes during decay, usually with the parent and daughter in secular equilibrium, meaning that the daughter isotope has the same activity as the parent isotope due to the very long half-life of the parent isotope. It is also sometimes referred to as TENORM or TENR after the material has been subjected to some form of processing and the equilibrium has been disturbed. (See Section 3.2.3 and the impact it has on "Classification"). The relationship is illustrated by the U-235 decay series below.

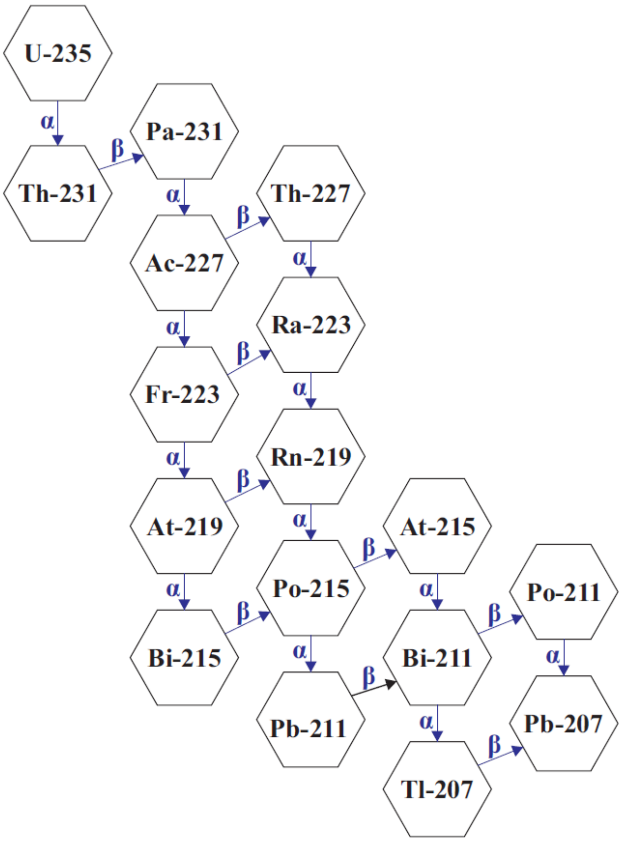

Figure 2.1.3.1-1: U-235 decay series as taken from "Physics of the Atom" [6]

These long half-lives have a particular impact on radiation protection and specifically the management of NORM waste as the level of radiation and thus the dose it will impart will remain at closure levels for hundreds of years.

2.1.3.2 Variable contribution

All isotopes from these naturally occurring decay series emit radiation, but each has its own characteristics and properties thus contributing in varying degrees to the overall impact i.e., effective dose. It is therefore accepted as appropriate to contemplate the exclusion of at least some of the isotopes in the safety assessment process simply because their influence (as a result of their properties or abundance) are considered negligible.

Nevertheless, there is at least one study [9] that offers an alternative view on such a simplistic approach, indicating the need to include at least some of those isotopes generally omitted when doing an environmental risk assessment (ERA). In addition, the South African regulatory authority expects justification for the omission of certain isotopes. It is thus relevant to consider all isotopic contributions before excluding specific isotopes from an assessment process. (Further discussion in this regard is captured in Section 5.4.4 of this document.)

2.1.4 Exclusion, exemption and clearance

Radiation is everywhere, ranging from highly radioactive materials such as radioactive sources or nuclear fuel, to lower levels of radiation from naturally occurring isotopes found in all matter. Some of these sources, such as K-40 in the body or cosmic radiation, are in essence unamenable to control and thus “**excluded**” from a radiation protection regime. Nevertheless, these concepts have different applications in South Africa.

“**Exclusion**” is based on a quantitative value, generally a specific activity set by the relevant regulator for practices and sources within a practice. (Practices to be discussed below.) For South Africa this is set at 0.5 $Bq.g^{-1}$ per isotope for the uranium and thorium decay series. A material with a specific activity less than the exclusion criteria is “**cleared**” from regulatory control. (See Section 2.3.2.2.)

“**Exemption**” refers to the removal from regulatory control of a practice based on the justification provided through a safety assessment. Removal from regulatory control is encompassing including, but not limited to notification, registration or licensing. Simply put,

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if a waste material's radioactive component or specific activity is below the exemption level of 0.25 mSv.a^{-1}, it is "**cleared**" or released from regulatory control.

2.1.5 Practices & interventions

A "**practice**" is any endeavour that adds or cause changes to individuals or groups' exposure or likelihood of exposure, i.e., to limit or control an increase in dose, while an "**intervention**" is defined as an action(s) to decrease existing radiation exposure [10]. In general, interventions are associated with accident scenarios, with the aim of the intervention to put people in a better position in terms of exposure because of the condition.

While the above refers to the broad spectrum of radiation-related activities and processes, applicable to waste management in the South African context are "**planned exposures**" and "**existing exposures**" [21]. A planned exposure situation refers to the introduction of an activity that is planned and expectation is that radiation protection measures should be considered before the introduction of the activity, for NORM typically during feasibility studies and mine planning of proposed ventures. An existing exposure is an activity that commenced before the introduction of regulatory controls.

With due consideration to the definitions of "planned exposure" vis-a-vie "existing exposures", not all NORM practices are easily defined, since both are potentially applicable to a single site and even a single source on a site. As example, a tailings dam with a footprint that was set 30 or more years in the past are expanded to accommodate current mining horisons, still from the same ore body. Such a source thus carries elements of an existing exposure scenario (deposition activities commenced before the onset of regulations) and a planned exposure (current and future deposition).

2.1.6 Contribution(s) from background radiation

Of regulatory interest is the incremental dose from a practice or intervention. However, as stated in Section 2.1.3.1, the isotopes of the uranium and thorium decay series are found everywhere and the radiation contribution from sources other than the specific practice or intervention is referred to as "background". It is therefore necessary to determine the extent

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of background radiation levels and to exclude it from any dose determination. (See Section 3.4 and Section 4.3.5 for further reference to background and how it is applied.)

2.2 LEGISLATING NORM

The impact of NORM was not always considered relevant. Until the early 1990s, radiation protection focussed mostly on radiation from artificial radiation sources and the nuclear fuel cycle. (The nuclear fuel cycle includes uranium mining and nuclear reactors.) Around 1993, a gate monitor in the United Kingdom detected elevated radiation levels in a load of scrap from South Africa. This scrap was then traced to Phalaborwa and ultimately, Palabora Mining Company, a copper mine and smelter. This raised awareness of the potential for radiation risk from sources other than artificial sources and the nuclear fuel cycle and has led to the licensing of NORM facilities in South Africa ever since. Appreciation for the impact of NORM was then enhanced, especially on the international platform, with the issuing of European Union Council Directive 96/29/EURATOM by the European Union in 1996. A key component of the directive was for member states to identify relevant NORM industries in their respective countries and industries such as the phosphate industry, oil and gas industry and the mineral sands industry were then recognised. This significantly raised awareness across the globe and NORM converted from being a localised (United States of America, South Africa) phenomenon to an issue of international concern.

Unfortunately, the concentration of the radionuclides varies significantly from ore body to ore body and the distribution in an ore body is also not homogeneous. Furthermore, once subjected to disruptive and/or intrusive beneficiation processes such as smelting or chemical extraction, the secular equilibrium is disturbed and concentration affected, as illustrated in Figure 2.2-1 below. (Data from reports as reflected in Appendix A.)

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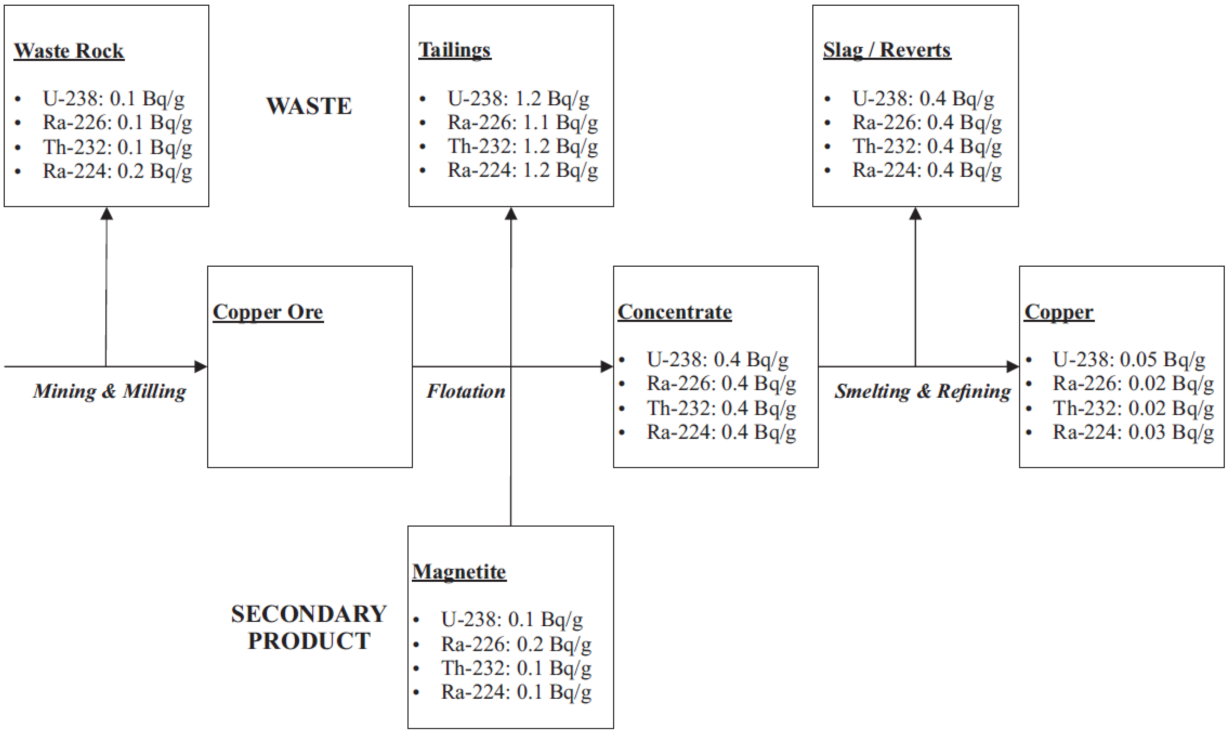

Figure 2.2-1: Average nuclide specific activities of the PMC mining and processing streams

Thus, while clearly a primary contributor to the ultimate expression of risk posed by a particular site, the ore body is but one factor that defines the peril. Other factors, such as mechanisms of beneficiation, site conditions and remediation strategies, also influence the specific activity and thus ultimately the impact posed by storage or disposal. This necessitates the introduction of site-specific assessments and not a generic expression of risk.

2.3 REGULATORY FRAMEWORK

A national regulatory framework can trace its origin back to three main foundations, namely UNSCEAR, ICRP and the IAEA.

- UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation): Sets the basis for radiation protection.
- ICRP (International Commission on Radiological Protection): Sets the philosophical basis for radiation protection and makes recommendations.
- IAEA (International Atomic Energy Agency): Develop practical guidance for nations to adopt.

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While the IAEA output is rarely prescriptive and not normally enforceable unlike national legislation, it generally provides the foundation for the national process that follows.

2.3.1 International guidance: International Atomic Energy Agency

2.3.1.1 Fundamental safety principles (SF-1)

SF-1: Safety Standard- Safety Fundamentals (SF-1) is the keystone document for the management and control of radiation risk and thus central to radioactive waste management [11]. It sets the tone for all requirements to follow, for example, quoting Section 1.1 of SF-1:

> *Radioactivity is a natural phenomenon and natural sources of radiation are features of the environment. Radiation and radioactive substances have many beneficial applications, ranging from power generation to uses in medicine, industry and agriculture. The radiation risks to workers and the public and to the environment that may arise from these applications have to be assessed and, if necessary, controlled.*

It is then further specified that radiation risk refers to (a) harmful health effects or the likelihood thereof and (b) any safety risk including to the environment and its ecosystems as a result of the presence of radioactive material or its release into the environment, both deliberate and accidental. It does not only reference operational impacts but introduces a post-closure responsibility. To quote Section 1.9 of *SF-1: Safety Standard- Safety Fundamentals*:

> *The fundamental safety objective applies to all circumstances that give rise to radiation risk. The safety principles are applicable, as relevant, throughout the entire lifetime of all facilities and activities, – existing and new – utilized for peaceful purposes.*

The document expanded on the definition of "facilities" by including specifically "*...some mining and raw material processing such as uranium mines; radioactive waste management facilities...*". A mining and minerals processing facility such as Palabora Mining Company is thus subjected to the requirements of *SF-1: Safety Standard- Safety Fundamentals* prior to and after closure.

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The following table summarises the IAEA safety fundamentals, identifies the entity responsible for its execution and provides some comments as to the relevance it may have on this study.

Table 2.3.1.1-1: International Atomic Energy Agency safety fundamentals

The fundamental safety objective is to protect people and the environment from harmful effects of ionising radiation.			
No.	**Principle**	**Applicable to:**	**Relevant notes:**
1	Responsible for safety: The prime responsibility for safety must rest with the person or organisation responsible for facilities and activities that give rise to radiation risk.	Authorisation holder / Waste generator	• When reviewing the requirements and specifications, the waste generator is responsible for the safe management of the activity, in this instance the storage and/or disposal of radioactive waste. • This management includes appropriate resources, training and competency, design and maintenance and procedures for the safe control.
2	Role of government: An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.	Regulatory authority	• National Nuclear Regulator • National Radioactive Waste Disposal Institute.
3	Leadership: Effective leadership and management for safety must be established and sustained in organisations concerned with facilities and activities that give rise to radiation risks.	Authorisation holder / Waste generator Regulatory authority	There are several aspects of relevance for any organisation that is responsible for radioactive waste as generated by that facility, for example: • An effective safety management system must be in place. • Human performance must be considered. • Security must be considered. • Safety assessment is necessary.

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The fundamental safety objective is to protect people and the environment from harmful effects of ionising radiation.			
No.	**Principle**	**Applicable to:**	**Relevant notes:**
4	Justification: Facilities and activities that give rise to radiation risks must yield an overall benefit.	Authorisation holder / Waste generator	In general, NORM waste originates from some form of extraction and beneficiation activity and as such there has been some form of justification done for the project to commence. However, when considering disposal or storage options, this principle has to be applied as part of the process.
5	Optimisation: Protection must be optimised to provide the highest level of safety that can reasonably be achieved.	Authorisation holder / Waste generator Regulatory authority	The expectation is the application of the ALARA principle. Achieving this requires safety assessments, not only initially, but also through the facility's lifetime. It also requires a judgement on several other factors while using good practices and common sense.
6	Limitation of risks: Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.	Authorisation holder / Waste generator Regulatory authority	While the regulator plays a role, the burden is at least initially on the authorisation holder to ensure that the dose (or radiation risk) is controlled within specific limits.
7	Protection of present and future generations: People and the environment, present and future, must be protected against radiation risk.	Authorisation holder / Waste generator Regulatory authority	Of significance to NORM waste facilities as: • No significant decrease in radiation levels over a 300-year period. • Significant surface areas affected. Focus on protection of a population of a species. Currently no regulatory obligation to determine the environmental impact. No undue burden on future generations.

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The fundamental safety objective is to protect people and the environment from harmful effects of ionising radiation.			
No.	**Principle**	**Applicable to:**	**Relevant notes:**
8	Prevention of accidents: All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.	Authorisation holder / Waste generator Regulatory authority	The principle relates to a "loss of control", i.e., failures, breaches of security and/or abnormal conditions. It demands "defence in depth".
9	Emergency preparedness and response: Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.	Authorisation holder / Waste generator Regulatory authority	Consideration should be given to reducing the probability and/or severity to ultimately reduce the risk.
10	Protective actions to reduce existing or unregulated radiation risks.	Regulatory authority	From past human activities, i.e., where the development of the tailings dam was not necessarily subjected to current legislative expectations.

From the above, it is necessary to highlight a few issues that will have an impact on the process and template specifically for the management of NORM waste.

- **Principle 1**: The safe management of NORM waste is the responsibility of the waste generator i.e., the holder of a nuclear authorisation. For the South African mining industry, a mining activity must provide for mine closure as part of its "license to operate" (Section 25, 38, 41 and 42 of the Minerals and Petroleum Resources Development Act) [12]. It is also foreseen that at some point, the ownership, or the responsibility for the management of a particular disposed waste such as a tailings dam, will revert to government (Section 43 of the Minerals and Petroleum Resources Development Act) [12]. While it is expected that subsequent closure plans are designed to reduce long-term impact of the environment, it will be necessary to evaluate the closure plans against the criteria set by (a) national radiation legislation and/or (b) the IAEA, since closure plans consider general environmental impacts only.

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- **Principle 2**: While significant in terms of a national regulatory framework, no additional work is required other than setting a template or criteria based on this document, for the rest of the South African mining industry.
- **Principle 3**: This principle talks to an integrated, effective management system. The following demonstrates a typical management system that will ensure an appropriate foundation for the radiation protection program.

Figure 2.3.1.1-1: Basic management system

- **Principle 4**: While not specified, this principle is considered on a macro and micro level. Justification on a macro level for the South African mining industry is generally a simple process, i.e., mining creates necessary jobs in a job-scarce economy. For example, the NORM waste from Palabora Mining Company is the result of more than 50 years of mining, minerals processing and beneficiation, an activity that historically was and still is, (with a neighbouring mine), the backbone of the Ba-Phalaborwa District Municipality's economy. In addition, some of the waste disposal practices, while still being used, commenced long before regulatory control was introduced. On a micro level, it may however be necessary to justify a

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specific storage and/or disposal methodology that is considered, especially when no options are available currently or where a current option breaches one or more other principles, for example Principle 6, Principle 7 and Principle 8 below.

- **Principle 5**: Optimisation for the purposes of this assessment have two distinct applications since a historic tailings dam still in use may be defined as both a practice and intervention. Where there is consideration for a new facility, such an endeavour is a practice. Thus, for this process, the expectation is that there should be some application of common sense, or a decision-making process defined.
- **Principle 6**: Applying the principles will not, in itself, ensure the prevention of harm and as such some limit is necessary to ensure adequate protection for worker, public and environment. It also clearly demands the need for a radiation safety assessment for the activities.
- **Principle 7**: This principle is one of the most significant and applicable tenets. It requires protection not only during the life-of-mine, but also beyond. Due to Palabora Mining Company's location, there is a distinct possibility of post-closure impacts, not only in the neighbouring communities, but also on a pristine habitat, in this instance the Kruger National Park. There is also a possibility of community expansion onto NORM waste sites in the distant future and subsequently, the radiation safety assessment (public and environment), is absolutely necessary to determine the appropriate control regime for these waste streams. This situation is not unique to Palabora Mining Company as a significant number of mines in South Africa are in very close proximity or even inside, communities because of historic developments. Also of key interest is that the expectation is that no "undue burden" should be placed on future generations. This is not only in terms of a radiation dose to a particular population, but also the appropriateness of solutions implemented.
- **Principle 8**: This principle is also one of the drivers for the Palabora Mining Company NORM waste, specifically because of two major possibilities. Firstly, the higher activity material in storage could be subjected to theft and subsequent contamination in a community despite current measures. Secondly, tailings dams, should failure occur, will in the case of Palabora Mining Company may have a significant impact on ecosystems within the Kruger National Park. Of interest, when considering the options for "defence-in-depth", an appropriate management system (Principle 3) is one of the possibilities.

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- **Principle 9**: This principle is considered the “initiator”, as the question on the adequacy of the disposal options led to this study. For PMC, the initial concern was a radiation incident viz. the release of higher activity waste into the community because of criminal activities. However, within the framework of the other principles, such criminal activity is clearly not the only accident scenario applicable, and measures should be considered in advance for possible scenarios such as tailings dam failure and subsequent impact on a pristine ecosystem. Even if all reasonable measures are in place, considering this principle will demonstrate appropriate due diligence from the company.
- **Principle 10**: There are generally 3 different scenarios; the first scenario being when the mining activity commenced and ended before legislation was introduced. Secondly, a situation where a new mine is being developed and thirdly, as is the case with Palabora Mining Company, a mixture of the two. The process to deal with the first and second scenario is generally well understood, but the hybrid scenario still creates significant discussion. It will require careful application of different principles with the expectation that a uniform regime for all waste sources on site may not be possible. (Refer to Section 2.1.5.)

2.3.1.2 Safety requirements and safety guides

The IAEA statute sanctions the development of a system through the creation or acceptance of criteria to protect and/or ensure the safety of human health and the environment. Such a system is complex and in addition to the Safety Fundamentals as described above, is supported by a number of documents that can contribute or needs to be considered in terms of the final waste management solution. Examples of these documents are listed in Table 2.3.1.2-1 below.

Table 2.3.1.2-1: IAEA documents of relevance

Document	**Potential contribution in decision-making process**
GSR Part 3: Radiation Protection and Safety of Radiation Sources – International Basic Safety Standards [3].	General safety requirements are the basis for the protection of people and the environment that **must be met**. It is thus the cornerstone of the occupational-, environmental- and public radiation protection program.

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Document	Potential contribution in decision-making process
RS-G-1.7: Application of the Concepts of Exclusion, Exemption and Clearance [4].	It provides guidelines as to what waste streams can be eliminated from further radiation protection processes and/or consideration. Exclusion, Exemption and Clearance must be demonstrated.
GSG-1: Classification of Radioactive Waste [13].	It is a safety guide, but to a significant extent dictates the direction of the waste management process as it is the first step in determining whether a radiation protection program for a specific mining and minerals processing waste stream is necessary.
SRS-19: Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment.	Provides the foundation for the safety assessments.

2.3.1.3 Graded approach

A graded approach in the management and control of radiation risk is a key aspect of radiation protection and referenced in two of the IAEA safety fundamentals, namely Principle 3 and Principle 5 [11]. To quote:

> Principle 3: Leadership and management for safety
>
> "*...Safety has to be assessed for all facilities and activities, **consistent with a graded approach**...*"
>
> Principle 5: Optimization of protection
>
> "*...To determine whether radiation risks are as low as reasonably achievable, all such risks, whether arising from normal operations or from abnormal or accident conditions, must be assessed (**using a graded approach**) a priori and periodically reassessed throughout the lifetime of facilities and activities.*"

A "**graded approach**" is defined by the IAEA as: "An application of safety requirements that is commensurate with the characteristics of the practice or source and with the magnitude and likelihood of the exposures" [3]. It is thus a process that allows for a varied application of aspects such as control measures (depending on the circumstances) such as potential impacts and consequence of failure. An example of a graded approach is the introduction of an exclusion level, a value below the radiological hazard is considered of insignificant potential and consequence. When applying a graded approach to either existing or planned scenarios, it allows for the regulatory focus to be in a specific area, without

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compromising safety. The detail of such application is captured under Section 2.3.2.5.1 of this document.

2.3.2 South African regulatory framework

South Africa promulgated the Atomic Energy Act in 1948 and through this act, instituted the Atomic Energy Board to oversee the South African uranium industry. Next was the establishment of the Council for Nuclear Safety (CNS) in 1982, but it was only in 1988 that the CNS became the relevant regulatory authority. (Also note that at that time and still today, radiation sources are regulated in terms of the Hazardous Substances Act and controlled by the Department of Health [14].)

In 1999, the promulgation of the National Nuclear Regulatory Act created a new regulatory entity, the National Nuclear Regulator (NNR) that is like its predecessor the CNS, is responsible for amongst others, NORM and at that time, NORM waste [15]. In 2012, through the proclamation of the National Radioactive Waste Disposal Institute Act, the responsibility for radioactive waste moved to National Radioactive Waste Disposal Institute, but the issuing of radiation authorisations still resided with the National Nuclear Regulator [16].

There is thus a dual consideration in terms of the management of NORM waste, i.e., guidance from and working under an authorisation from the National Nuclear Regulator, especially during the operational phase, but ultimately the waste management plan (WMP) authorised in future by the National Radioactive Waste Disposal Institute. (Cooperative governance in this regard is still to be fully defined.)

2.3.2.1 National Nuclear Regulatory Act, No 29/1996

Through the National Nuclear Regulatory Act and supporting Regulations, South Africa is enacting at least some of the IAEA principles, for example it sets the framework for regulatory control and a dedicated regulator, the authorisation / licencing and control of nuclear activities and provision of safety standards [15].

> ***Section 20****. (1) No person may site, construct, operate, decontaminate or decommission a nuclear installation, except under the authority of a nuclear installation licence.*

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> *(3) No person may engage in any action described in section 2(1)(c) other than any action contemplated in subsection (1) or (2), except under the authority of a certificate of registration or a certificate of exemption.* (See Section 4.3.2.4.)

2.3.2.2 Regulations

Critical to the proposed waste management process is "*Regulations in terms of Section 36, read with Section 47, of the National Nuclear Regulatory Act, 1999 (Act No. 47 of 1999), on safety standards and regulatory practices*".

Its relevance is that it sets the "exclusion level" of 0.5 $Bq.g^{-1}$ per isotope for uranium and thorium and their progeny, (except radon) and sets the dose limits and clearance criteria [17].

2.3.2.3 National Nuclear Regulator

The purpose of the Regulator is to control the nuclear industry, not necessarily only those industries that utilises the radioactive properties of the material, but also industries such as mining and minerals processing where the radiation is incidental to the activities. These industries, where the material is not deliberately mined, beneficiated and/or treated for its radioactive properties are often referred to as NORM industries / mines.

Control is achieved through regulations, authorising activities, and setting conditions, requirements (RD documents) and guidance (RG documents) for the authorisation(s), taking cognisance of international treaties and/or guidance from institutions such as the IAEA.

2.3.2.4 Nuclear authorisation

Certificates of Registration (nuclear authorisations) are issued to facilities with materials that are deemed radioactive and may pose a radiation risk in terms of the National Nuclear Regulatory Act, No. 49/1996 by the duly constituted National Nuclear Regulator. Each licence contains a set of licence conditions (registration documents or registration guides), one being for waste management.

2.3.2.5 Registration documents and registration guides

A company that engages in a practice that involves NORM more than the exemption levels is required to have an authorisation called a Certificate of Registration or COR. Such a Certificate of Registration is a "licence to operate" and sets the holder's authorisation

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conditions. The following table summarises these conditions and provides comments with regards to alignment.

Table 2.3.2.5-1: Certificate of Registration conditions

Section	Title	Description	Expectations	Comments
1.1	Scope	Provide the scope or practices authorised.	No further expectations in terms of waste management, unless additional waste practices are introduced that are not part of the current scope.	
1.2	Hazard assessment	Assessments shall be conducted in respect of all operations and activities involving radioactive material.	Safety assessments for all practices.	The process for waste management is risk based, i.e., based on the safety assessment as required in this section.
1.3	Operational limitations	Sets specific limitations in terms of activities that is allowed or not.	• No demolition or disposal without prior approval, supported by a hazard assessment. • Waste with alpha activity of more than 1000 Bq.g-1 shall be stored in a facility approved by the regulator. Decommissioning strategy	The process described in this document supports these limitations set.

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Section	Title	Description	Expectations	Comments
1.4.1	Operational radiation protection: Workforce	Sets the requirements for radiation protection of the workforce.	Guidance provided in: • RD-006: Requirements for the control of radiation hazards: Mining and minerals processing. • RD-011: Requirements for medical surveillance and control of persons occupationally exposed to radiation: Mining and minerals processing. Radiation protection procedure.	The hazard assessment, as required in Section 1.2 of the Certificate of Registration determines the supporting radiation protection program.
1.4.2	Operational radiation protection: Public	Sets the requirements for radiation protection of the public	Guidance provided in: • RD-007: Requirements for the control over radioactive effluent discharges and environmental surveillance: Mining and minerals processing. Radiation protection procedure.	The hazard assessment, as required in Section 1.2 of the Certificate of Registration, determines the supporting radiation protection program.

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Section	**Title**	**Description**	**Expectations**	**Comments**
1.5	Radioactive waste	Sets the requirements for waste management.	Waste management procedure Currently only describes scrap and items for refurbishment.	Limited guidance available for broader waste management.
1.6	Transportation	Sets the requirements for the transportation of radioactive materials	Reference the IAEA document TS-R-1. Transport procedure.	Most NORM materials are exempted from the transport regulations.
1.7	Physical security	Sets expectation for a physical security system that will prevent access to areas containing radioactive materials.	The authorisation holder to provide a description of the physical security measures in place.	This becomes relevant for the storage of high activity material.
1.8	Occurrences	Reference occurrence reporting mechanisms and emergency plans.	Guidance provided in: • RD-012: notification requirements for occurrences: Mining and minerals processing. • RD-008: Requirements for emergency preparedness: Mining and minerals processing	

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Section	Title	Description	Expectations	Comments
1.9	Quality management	Quality management requirements are set.	Guidance provided in: • RD-005: Quality management requirements for activities involving radioactive materials.	This sets the tone for the management system that is referenced. While the IAEA does have a document that describes a system, the National Nuclear Regulator's document is generally well aligned with the ISO 9000 Quality Management System guidelines.

2.3.2.5.1 Interim regulatory guide

An interim regulatory guide for site decommissioning and release of land (*RG-0026: Interim Regulatory Guide – Site decommissioning for planned exposures and remediation of existing exposures for release of land from regulatory control*) is available and do provide some regulatory guidance [21]. The following table summarises critical aspects captured in the document.

Table 2.3.2.5.1-1: Key guidance in RG-0026

Section	Guidance	Comments
1	Reference the National Nuclear Regulator exclusion level of 0.5 Bq.g^{-1} per isotope. See also reference to Section 5.2 of RG-0026 in the table below.	Refer to Section 2.3.2.2. and National Nuclear Regulatory Act [15] and regulations [17].
2	In the scope it refers to requirements for the release of land after decommissioning or remediation.	The concept and intent are broadly aligned with other South African legislation, such as the Minerals and Petroleum Resources Development Act [12].

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Section	Guidance	Comments
5	Release of land from regulatory control after decommissioning in planned exposure situations (currently authorised actions).	This conflicts with the definition of an existing exposure situation, i.e., defined as a situation that exists when the decision is taken. Palabora Mining Company has been generating NORM waste at least 20 – 25 years prior to the establishment of the National Nuclear Regulator but is also a current authorisation holder.
5.1	Release of land from regulatory control if the naturally occurring radioactive nuclides have activity concentrations below the exclusion level, or if not possible, impose restrictions for release for restricted use.	Current technology does not allow the reduction of radionuclide concentrations in bulk NORM waste sources. Thus, the only current option for consideration is to manage the use or exposure.
5.2	Confirm the exclusion level of 0.5 $Bq.g^{-1}$ per isotope	
5.2	Introduce optimisation and the necessity of safety assessments.	
5.2	Release criteria is based on a public dose of 1 $mSv.a^{-1}$.	While the release criteria are set at 1 $mSv.a^{-1}$, a dose constraint is set at 0.25 $mSv.a^{-1}$ for a single site.
6	Introduces justification and optimisation for remedial strategies of existing exposure situations.	
6	Introduces reference levels with a possible range of 1 to 20 $mSv.a^{-1}$.	This provides the opportunity for site specific dose limits and depends on the feasibility of and experience in controlling such exposure.
6	Discussion on site remediation	While the primary intent is to describe site remediation, it does align with the standard management plan steps as set out in Figure 2.3.1.1-1.
6	Occupational exposure	The entity for the remediation and by implication the management of the decommissioned site post closure still need to control occupational exposure of those performing duties on site.

This document is helpful in developing the process, but it requires clarification and support in several areas. Some aspects that require further defining are:

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- The legality of the document after the establishment of the National Radioactive Waste Disposal Institute.
- The role of the National Radioactive Waste Disposal Institute and National Nuclear Regulator in the regulatory process post closure.
- It potentially contradicts itself in the application of its own definitions.
- It does not consider environmental safety assessments and management.
- It is silent on the impact of change of ownership of the site from an authorisation holder to state, and;
- The responsibility and accountability associated with the transfer of specific waste classes from the current authorisation site to a national repository.

2.3.2.6 Summary

South Africa has a comprehensive and structured radiation protection framework applicable to NORM and NORM waste, which can broadly be summarised as follows:

- Activities that involve radioactive material are prohibited if not controlled. (National Nuclear Regulatory Act, Section 4.3.1)
- What is considered "radioactive" is defined. (National Nuclear Regulatory Act, Section 4.3.2)
- This leads to authorisation and a compliance verification process by a dedicated authority. (National Nuclear Regulatory Act, Section 4.3.4)
- Compliance is achieved through a "licence to operate", i.e., authorisation called a "Certificate of Registration" (National Nuclear Regulatory Act, Section 4.3.4.) and;
- With the compliance criteria and guidance provided by the authorisation and supporting documents (National Nuclear Regulatory Act, Section 4.3.5). These "authorisation documents" are based on the IAEA criteria mentioned.

Notwithstanding the above, certain areas have been pointed out (for example in the last portion of Section 2.3.2.5.1) where the regulatory framework requires attention to fully address NORM waste management and control. The following chapter (Chapter 3) will now set a process for NORM waste management by interpreting firstly the national criteria and where it is silent international principles and standards, leading to Chapter 4 where the process is executed using the Palabora Mining Company data.

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3 PROCESS

As alluded to earlier, there are insufficient guidance to the operator of a NORM site that ensures it meet it's legal and moral obligations, hence the need for a structured process. The solution is however, also not restricted to radiation legislation specifically. As expressed in Chapter 2 there are information available to allow for an informed decision by either the regulatory or the operator. However, it is necessary to provide structure to ensure that the various sources of information and guidance are aligned. As important is the realisation that other programs can support a radiation safety management process and it is thus not necessary to manage the hazards in isolation.

3.1 GENERIC PROCESS

In the simplest of terms, the process is to identify the waste disposal options, calculate the risk, apply the risk against radiation management principles and consider strategies to reduce the risk where appropriate. This process is summarised in the following flow diagram.

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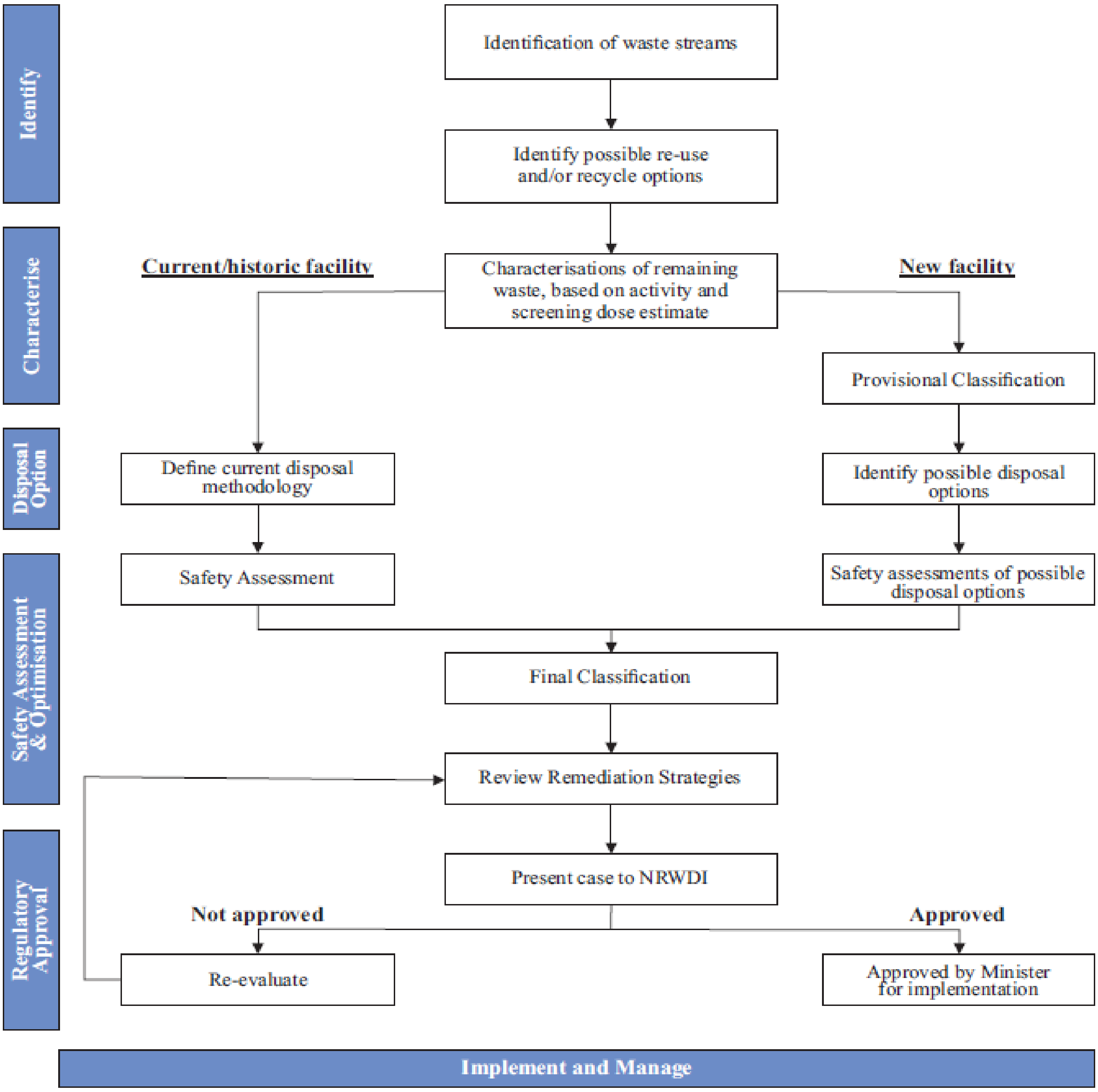

Figure 3.1-1: Suggested NORM waste regulatory process

As seen from the above, key to the process of managing NORM waste is broadly defined as:

- Identifying the waste streams
- Characterise identified streams
- Assess the risk
    - Occupational safety assessment
    - Public safety assessment
    - Environmental safety assessment (This is currently not required, but a likely and recommended future addition.)
- Classify the waste streams

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- Consideration for remediation measures

The following sections will now consider each of the facets in more detail.

3.2 IDENTIFICATION, CHARACTERISATION AND CLASSIFICATION

3.2.1 Identification

The output of process stream(s) that may for the interim or for a significant period after closure be considered superfluous, unintended or in addition to the desired output is classified as a waste. An inferred action in terms of National Environmental Management: Waste Act is the identification of waste streams, since associated regulations require the registration of specific waste activities as contemplated by the act on the national waste database (South Africa Waste Information System) [24]. This would not be possible if a detailed understanding of the waste streams is not available.

While the identification of all waste streams is relevant and a necessary starting point, waste as defined by the National Environmental Management: Waste Act does not automatically infer a radiological response and furthermore, from a radiological protection point of view, not all waste streams require the same attention. (Graded approach.)

3.2.2 Characterisation

All matter contains radioactive nuclides to some degree. Characterisation is the determination of the activity levels to see if a material is considered radioactive or not, i.e., excluded or not from regulatory control.

> The following extract from Regulation 388 of National Nuclear Regulator A [17]:
> *2.1.1 Exclusion of actions*
> *In terms of the provisions of section 2 (2) (b) of the Act, the Act does not apply where, Section 2.1.1.1 the level of radioactivity concentration of each radioactive nuclide in materials is below -*
> *(b) 0.5 Bq per gram for naturally occurring radioactive nuclides of uranium and thorium and their progeny except for radon;*

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Thus, if any of the isotopes of the respective uranium and thorium decay series exceeds 0.5 Bq.g^{-1}, such a material is of regulatory interest and would require a safety assessment. (See also RG-0026 [21].)

A nuclide specific analysis is thus necessary to determine whether a particular mineral waste is subjected to regulatory control and provides fundamental input data for radiological safety assessments.

3.2.3 Classification

The document *GSG-01: General Safety Guide – Classification of Radioactive Waste* from the IAEA sets the guidance for the classification of waste streams within a radiation protection framework [13]. It provides for 6 different waste categories and expected control and/or remediation measures and thus extremely relevant since a graded approach in the management of radiation risk, should be applied. The categories and their basic description can be summarised as follows:

Table 3.2.3-1: IAEA waste categories

Category	Abbreviation	Waste description
Exempt waste	EW	It is excluded from regulatory control based on its activity concentration. (0.5 Bq.g^{-1} per isotope for South Africa and 1 Bq.g^{-1} per isotope generally elsewhere.)
Very short-lived waste	VSLW	Waste that can be stored for a limited period and due to the isotope's very short half live (less than 30 years) can be cleared from regulatory control.
Very low-level waste	VLLW	The activity concentration exceeds the exclusion value, but generally does not need excessive containment or shielding, i.e., disposal in near-surface landfill type facilities that may also contain other types of hazardous waste.
Low level waste	LLW	Waste with a specific activity above exclusion levels and requires more robust isolation and containment for periods of up to a few hundred years. Containment may also be near surface but engineered as it may require shielding during normal handling and transport.
Intermediate level waste	ILW	

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Category	Abbreviation	Waste description
High level waste	HLW	Usually spent nuclear fuel with heat generation. Requires deep geological disposal facilities.

As seen from the above, the basic description of each class does not provide means for a rapid determination of NORM waste, and this may impact on project viability, planning and effective execution. It is thus appropriate to create some means of assisting current NORM facilities or NORM projects to achieve effective compliance.

3.3 SAFETY ASSESSMENT METHODOLOGY

3.3.1 Occupational safety assessment

RG-0026 requires the control of occupational exposure as if it is a planned exposure situation [21]. See Section 2.3.2.5.1 above.

3.3.1.1 Total effective dose

The following formula is used to determine occupational exposure from radiation.

$$Effective\ Dose = Hp(d) + \sum e(g)_{j.ing}\, I_{j.ing} + \sum e(g)_{j.inh}\, I_{j.inh} \qquad \text{[Eq. 3]}$$

Where:

$Hp(d)$	Equivalent dose from external radiation. (Sv)	Sv
$e(g)_{j.ing}$	Committed effective dose per unit intake via ingestion	$Sv.Bq^{-1}$
$I_{j.ing}$	Activity intakes via ingestion	Bq
$e(g)_{j.inh}$	Committed effective dose per unit intake via inhalation	$Sv.Bq^{-1}$
$I_{j.inh}$	Activity intakes via inhalation	Bq

Ingestion is not that often considered for occupational safety assessments, primarily because mining and minerals processing facilities are required to provide adequate and appropriate eating- and change house facilities for its employees and contractors. (Regulation 5, Mine Health and Safety Act) [30]. Focus is thus on the inhalation risk and the risk posed by

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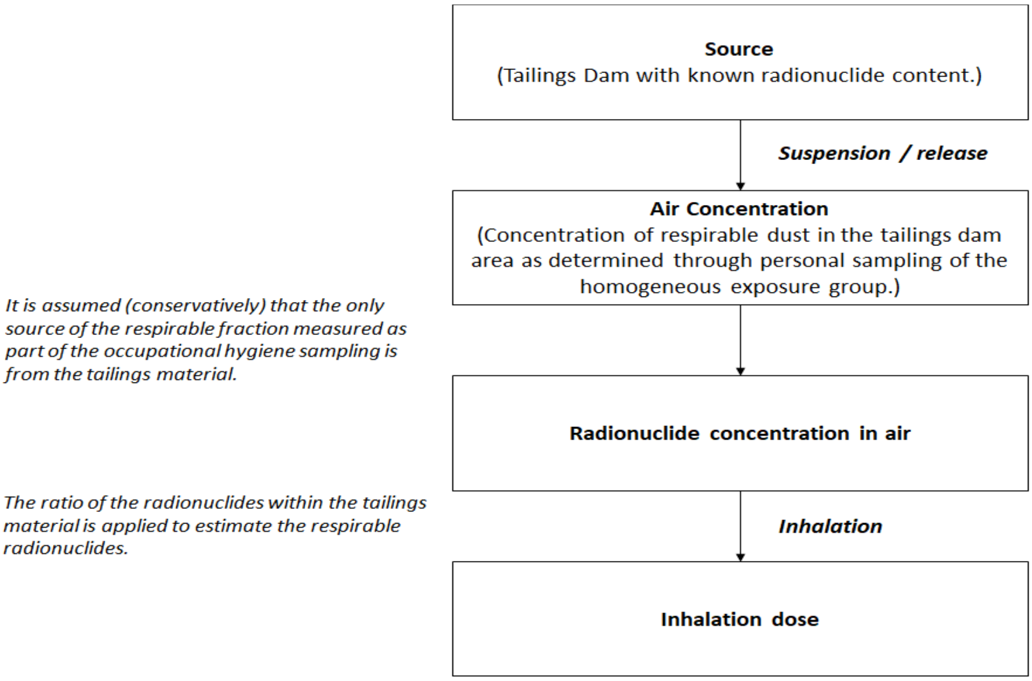
external radiation, but for the purposes of this study, the contribution from ingestion is contemplated.

3.3.1.2 Inhalation dose

The Mine Health and Safety Act also provides potential information sources that may be adapted for use in a risk assessment especially when optimising such determinations. In terms of the requirements for a "*Mandatory Code of Practice for an occupational health program on personal exposure to airborne pollutants*" (promulgated in terms of Section 9 of the Mine Health and Safety Act) a mining operation is expected to determine the concentration of airborne pollutants, including total dust [30]. Knowing the dust load (or air concentration) in a particular area, especially over a period of several years, allows for a better estimate of the concentration of airborne radionuclides and thus inhalation dose. The following figure provide a simplified model for the determination of the inhalation dose. (Detail provided in Appendix B.)



It is assumed (conservatively) that the only source of the respirable fraction measured as part of the occupational hygiene sampling is from the tailings material.

The ratio of the radionuclides within the tailings material is applied to estimate the respirable radionuclides.

Figure 3.3.1.2-1: Determination of inhalation dose

Eq. 3 is then applied, using standard duration of exposure of 2000 hours during routine operations, but reduced significantly after closure. (See Section 3.3.1.4 for detail in respect to duration of exposure below.)

> *Note: The initial air concentration as determined by the occupational hygiene sampling strategy is total respirable dust and needs to be converted to a*

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> *radionuclide concentration in the air. This is achieved by assuming the air concentration at the facility is from the tailings only. The ratio's of radionuclides in the tailings is then applied to the respirable dust concentration to determine the respirable radioactivity concentration. (This is a conservative assessment.) An alternative method is to sample the air concentration above the dam and subject the sample to a nuclide specific analysis. In this instance the first method is used to demonstrate that information for sources other than the radiation program can be used to assist in the estimation the effective dose, i.e. optimisation.*

The above, however, is appropriate only for the operational phase of the mine (including the remediation period) and only becomes a factor again once the cover of the tailings dam starts to deteriorate, i.e., around 100 years after end of life for the facility [18].

Thus, with the operational- and remediation phase part of a standard licence to operate, occupational exposure from a waste management perspective will commence after full implementation of closure measures.

Post closure the suggested inhalation factors are as follows:

- From Closure to 100 years after closure, inhalation is not considered as part of occupational safety assessments.
- From 100 years to 200 years after closure, 25% of the current air concentration as determined by the occupational hygiene program, is utilised.
- From 200 years to 300 years after closure, 30% of the current air concentration as determined by the occupational hygiene program, is utilised.
- From 300 years to 400 years after closure, 35% of the current air concentration as determined by the occupational hygiene program, is utilised.
- From 400 years to 500 years after closure, 40% of the current air concentration as determined by the occupational hygiene program, is utilised.

With the cover in place, the tailings material is not released, and the radionuclides are thus not available for inhalation. Over time, a conservative assumption is that the cover will deteriorate, again exposing tailings for release into the atmosphere. Thus, the initial reduction in air concentration is due to the cover of a tailings facility introduced as part of the remediation measures that gradually deteriorates over time, leading to an increase in the air concentration [18].

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Where a tailings dam is not remediated, the consideration for reduction in the air concentration is generally not appropriate and requires a justification should it be considered.

Duration of exposure is also discussed in Section 3.3.1.4 below.

3.3.1.3 External dose

The cover of the tailings dam will not reduce the external radiation in any meaningful way thus the average dose rate measured during operations is used while the duration of exposure is discussed in Section 3.3.1.4 below. See relevant equations in Appendix B.

3.3.1.4 Duration of occupational exposure

The standard assumption of an exposure period of 2000 hours per year is no longer applicable when dealing with occupational exposure post closure. Occupational exposure will be limited to occasional inspections, sampling and/or maintenance of the remediation measures and not a continuous effort as during the operational phase.

From practical observations it is also known that it is not a single individual that will be responsible for all three activities. Typically, a single individual may be responsible for the inspection and sampling while a dedicated maintenance crew will deal with repair and restoration of the barriers. From site experience it is estimated that the inspection and sampling will probably occur once per month for a 4-hour period or 48 hours (7 working days) per year. It is also considered unlikely that any maintenance activities will exceed 48 hours per year.

The maximum duration of exposure post closure for the determination of the inhalation- and external dose is thus assumed to be 48 hours.

3.3.2 Public safety assessment

RG-0026 requires the control of public exposure, expecting a detailed public safety assessment [21]. See Section 2.3.2.5.1 above. Comprehensive details of the assessment methodology can be found in Appendix B, but the following sections will also reflect on some of the formulas to assist the process narrative.

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3.3.2.1 General

There is software available that can assist with public safety assessments, for example RESRAD (***Res**idual **Rad**ioactivity – Onsite Modelling Software – Argone Laboratory*), but another option is to develop a site-specific algorithm. Such an algorithm may vary significantly in terms of complexity.

To assist with such an algorithm, two critical documents are considered for the basis of such a radiation safety assessment for members of the public. These documents are "*Safety Report Series 19: Generic Models for use in assessing the impact of discharges of radioactive substances to the environment*", (SRS-19), from the International Atomic Energy Agency, and "*RG-002: Regulatory Guide – Safety assessment of radiation hazards to members of the public from NORM activities*", (RG-002), from the National Nuclear Regulator from South Africa [19; 20]. Of the two documents, RG-002 is of primary importance locally as it is a legal document within the South African regulatory framework. Where RG-002 is silent, SRS-19 is utilised as the primary source.

> *Note: The applicable equations are captured in more detail in Appendix B, but the variables, such as isotopic dose conversion factors, consumption ates, duration of exposure or time intervals etc.; is found in SRS-19 and RG-002 [19; 20].*

3.3.2.2 Basic determination

As stated in the section above, an assessment may be conducted through specific and approved software or site-specific algorithms and each method has its own advantages and disadvantages. Preference is often given to software such as RESRAD as the process is generally known and most of the values pre-determined. However, creating a site-specific solution, while more complex, has the advantage of each value and assumptions being known to the assessor and thus creates a better understanding of the accuracy of the outcome. The most basic model is described by the following formula:

$$E = C \text{ x } R \text{ x } DF \qquad \text{[Eq. 4]}$$

Where

E	*Effective dose*	*Sv*

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C	*Concentration*	*Unit depending on specific calculation.*
D	*Dose Conversion Factor*	*Unit depending on specific calculation.*
R	*Rate or exposure period*	*Unit depending on specific calculation.*

From the above:

- The dose conversion factor is given by RG-002 [20] or where no information is provided, SRS-19 [19].
- Consumption rates given by RG-002 or where no information is provided, SRS-19 if no site-specific data is available.
- Generally, the exposure period is known, in this instance as described in Section 3.3.1.4. or provided by RG-002 or SRS-19 if no site-specific data is available.

The key aspect of the calculations is thus to estimate the concentration using as much quality site specific data as possible. The data available in turn determines the level of assumptions to be made and often what process to follow.

> ***An example** is the ingestions of radionuclides through the consumption of fish. If the nuclide specific analysis results for fish are not available, the nuclide specific activity values of the water can be utilised, together with generic transfer factors and consumption values, to ultimately calculate the activity ingestion by humans. This can be further refined by replacing the default consumption values with a community survey to determine regional dietary habits. Within the framework of a graded approach and optimisation, these levels of site-specific information only become necessary where a specific pathway is a noteworthy contributor to a significant effective dose.*

If due care is taken in understanding and considering the assumptions and values used, it should thus theoretically be easier to defend any result obtained through the assessment or identify the most appropriate focal points for optimisation.

To close, the basic assessment is supported by a range of sub routes, referred to as pathways, where these site-specific pathways each contribute to the total effective dose. Each

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pathway's contribution is determined by the concentration that may be inhaled, ingested or resulting from external exposure. The safety assessment needs to consider the concentration not only from the primary pathways, such as inhalation or drinking of water, but also secondary and tertiary contributors. While site specific data is preferable, default values are available to assist in providing a conservative assessment.

3.3.2.3 Pathways

SRS-19 (Section 2.2) suggests an assessment approach for consideration and the transport of the radionuclides through the environment and puts forward the following pathways for consideration [19].

- Inhalation
    - Airborne pollutants (excluding radon)
    - Radon
- External Exposure – Semi-infinite cloud source.
- Ingestion
    - Drinking water
    - Fish
    - Leafy vegetables
    - Root vegetables
    - Fruit
    - Cereal
    - Meat
    - Milk
    - Poultry
    - Eggs

These pathways from source to receptor are best viewed as a flow diagram. To illustrate the contributions and considerations, the following is a view of the pathway that represents the ingestion of vegetables, fruit and cereal.

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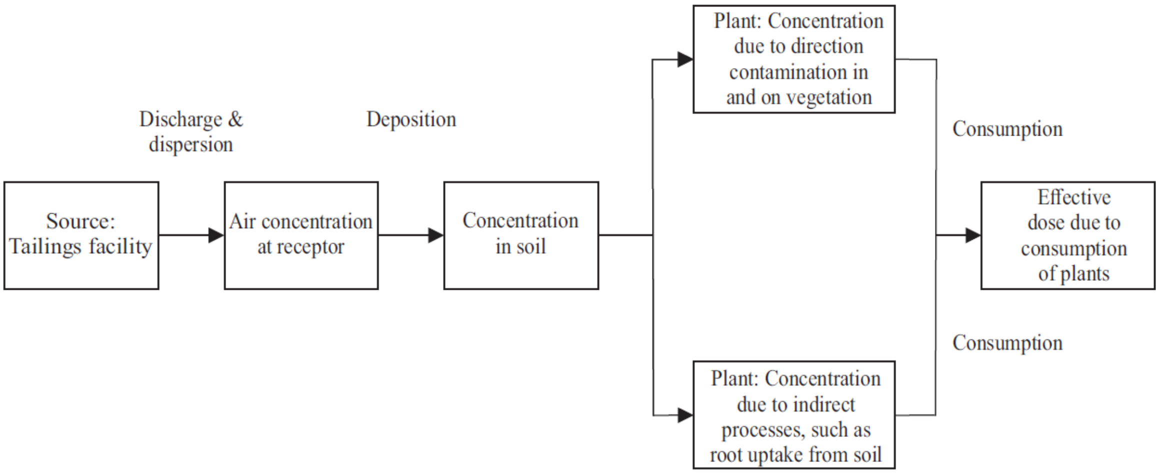

Figure 3.3.2.3-1: Basic pathway from source (tailings facility) to consumption of plants

NORM particles (tailings material) are released from the tailings dam and dispersed through the atmosphere creating a concentration at the receptor. The material is deposited, causing concentration in the plant and ultimately in the human that consumed the plant. The resulting concentration of radionuclides taken up causes a radiation dose.

Dispersion

$$C_A = \frac{P_p Q}{V} \qquad \text{[Eq. 5]}$$

Where:

$C_{A.}$	Radionuclide concentration	Bq.m^{-3}
Q	Average discharge rate	Bq.s^{-1}
V	Volumetric air flow rate at point of release	m^3.s^{-1}
P_p	Fraction of the time the wind blows towards the receptor	dimensionless

For the purpose of this study, an average discharge rate as determined by a study of mine tailings facilities around Gauteng was used. (Studies not published.)

Deposition

Deposition of the air concentration at the receiving environment is then considered as follows:

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$$d_i = (V_d + V_w)C_A \qquad \text{[Eq. 6]}$$

Where:

d_i	Deposition rate	$\mathrm{Bq.m^{-2}d^{-1}}$
$C_{A.}$	Radionuclide concentration	$\mathrm{Bq.m^{-3}}$
$V_d + V_w$	Deposition coefficient (V_T)	$\mathrm{m.d^{-1}}$

Following from the deposition, there is uptake by the plant through two separate processes.

Vegetation - Direct concentration

$$C_{v.i.1} = \frac{d_i \alpha \left[1 - exp\left(-\lambda_{E_i^v} t_e\right)\right]}{\lambda_{E_i^v}} \qquad \text{[Eq. 7]}$$

Where:

$C_{v.i.1.}$	Concentration due to direct contamination on vegetation	$\mathrm{Bq.kg^{-1}}$
A	Interception fraction	$\mathrm{m^2.kg^{-1}}$
d_i	Deposition rate	$\mathrm{Bq.m^{-2}d^{-1}}$
$\lambda_{E_i^v}$	Effective rate constant for reduction of activity concentration	$\mathrm{d^{-1}}$
t_e	Hold-up time between harvest and consumption	d

Vegetation - Indirect concentration

$$C_{s.i.2} = F_v \frac{\left(d_i \left[1 - exp\left(-\lambda_{E_i^s} t_b\right)\right]\right)}{\rho \lambda_{E_i^s}} \qquad \text{[Eq. 8]}$$

Where:

$C_{v.i.2.}$	Concentration of radionuclides due to indirect processes, such root uptake from soil	$\mathrm{Bq.kg^{-1}}$
d_i	Deposition rate	$\mathrm{Bq.m^{-2}d^{-1}}$
$\lambda_{E_i^s}$	Effective rate constant for reduction of activity concentration in the root zone	$\mathrm{d^{-1}}$

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t_b	Duration of discharge	d
P	Standardise surface density for the effective root zone in soil	$kg.m^{-2}$
F_v	Concentration factor for uptake from soil by edible parts of crops	$Bq.kg^{-1}$ plant tissue per $Bq.kg^{-1}$ dry soil

Total vegetation

The two plant pathways are then combined as follows:

$$C_{v.i.} = (C_{v.i.1.} + C_{v.i.2.})exp(-\lambda_t t_h) \quad [Eq. 9]$$

Where:

$C_{v.i.}$	Total concentration of radionuclides in vegetation	$Bq.kg^{-1}$
$C_{v.i.1.}$	Concentration due to direct contamination on vegetation	$Bq.kg^{-1}$
$C_{v.i.2.}$	Concentration of radionuclides due to indirect processes, such root uptake from soil	$Bq.kg^{-1}$
λ_i	Radioactive Decay Constant	d^{-1}
t_h	Hold-up time between harvest and consumption	d

Using $C_{v.i}$ in the formula presented in Section 3.3.2.2 (Eq. 4) the effective dose for the consumption of a particular plant pathway is calculated. This process is then repeated for different plant-based pathways distinguishing between leafy vegetables, root vegetables, fruit, cereal etc, using appropriate transfer- and consumption values for each.

As seen from the above, all the parameters have a significant site-specific value and when conducting a safety assessment, these very specific values are rarely available. It is therefore necessary to make assumptions or use generic values provided by documents such as SRS-119 and RG-02. Generally, these assumptions or generic values are conservative and can be addressed, if necessary, through an optimisation process.

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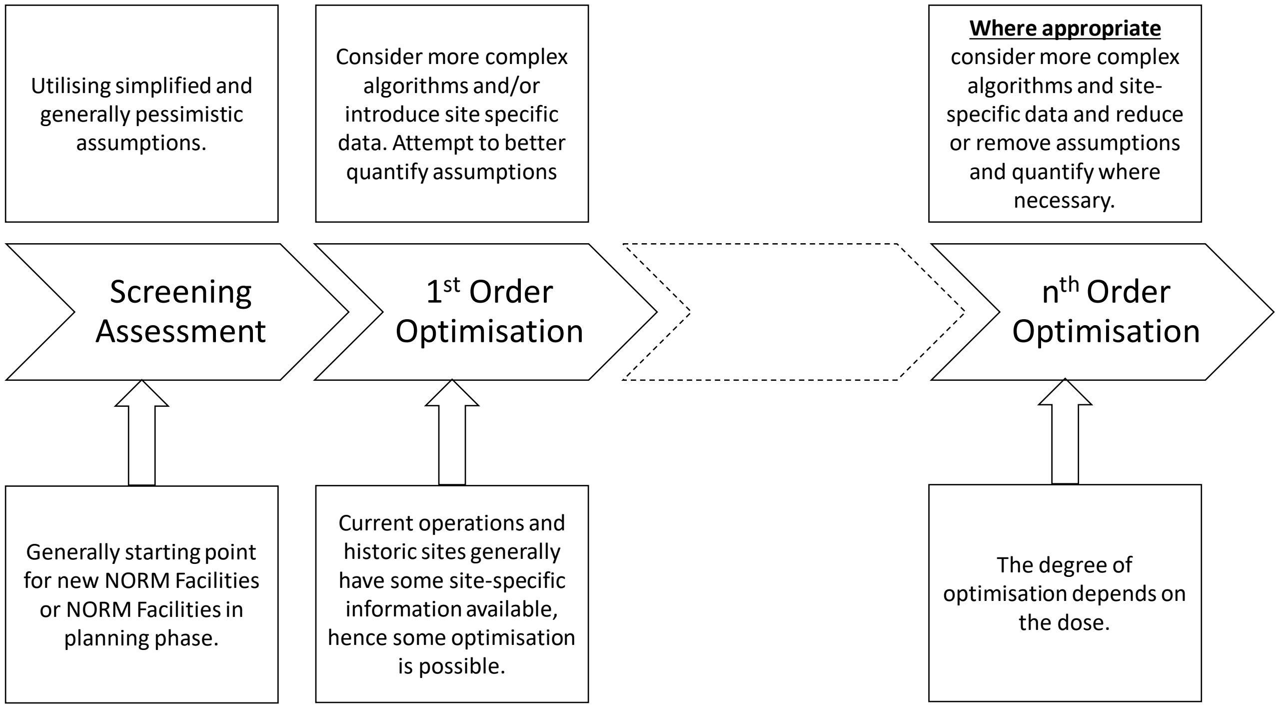
3.3.2.4 Optimisation

Optimisation is required in terms of IAEA Principle 5, where the expectation is to achieve the highest level of safety that can reasonably be achieved, i.e., the ALARA Principle. However, one method for achieving optimisation is to improve assumptions made and reduce, as far as is reasonably achievable, uncertainty associated with an assessment.

Optimisation is very rarely a single process and assessments are often refined and developed over a period of time, as illustrated by the figure below.



Utilising simplified and generally pessimistic assumptions.

Consider more complex algorithms and/or introduce site specific data. Attempt to better quantify assumptions

Where appropriate consider more complex algorithms and site-specific data and reduce or remove assumptions and quantify where necessary.

Generally starting point for new NORM Facilities or NORM Facilities in planning phase.

Current operations and historic sites generally have some site-specific information available, hence some optimisation is possible.

The degree of optimisation depends on the dose.

Figure 3.3.2.4-1: Site assessment and assessment optimisation

Where the nuclide specific analysis indicates a possible exceedance of the exclusion criteria, a screening assessment is necessary. Optimisation at this point is unlikely, but not impossible since it is sometimes feasible to use information from a comparable facility. (See Section 4.3.4.2 as an example.) In addition, the management system (Figure 2.3.1.1-1) drives a continuous improvement cycle. Optimisation will thus develop as the facility and information mature.

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3.3.2.5 Critical groups

Key to the dose assessment, values and assumptions to be used is the determination of key exposure clusters, i.e., critical groups. There are different methods for determining critical groups, for example through scenario development.

However, another option to consider that provides a more realistic outcome is to utilise the mine closure plan mandatory for all authorised mines in terms of the Minerals and Petroleum Resources Development Act [12]. In this document realistic future expectations in terms of land use of a particular mine and minerals processing site are captured and thus appropriate for use as the potential critical groups. Nevertheless, it is unlikely that a true critical group would be the most exposed for all pathways and it is suggested that a true critical group(s) should not be the only consideration. A hypothetical "worst case" should also be included for assessment.

3.3.2.6 Timeframe

It is necessary to demonstrate the suitability and effectiveness of proposed control measures initially but also to find some way of demonstrating continued effectiveness, specifically when determining exposure to members of the public and the environment as captured in Principle 6, Principle 7 and Principle 10 of the IAEA Safety Fundamentals [11].

There is a lack of guidance on appropriate assessment timeframes and this work is suggesting the following specific intervals, i.e., pre-closure, immediately after closure and then at 50-to-100-year intervals.

Table 3.3.2.6-1: Justification for proposed assessment intervals

Timeframe	Represents:
Pre-closure	Limited or no controls established / determination of optimisation
On closure	All controls in place. No deterioration of controls
50 years post closure	End of authorisation holder involvement and start of institutional control
100 years post closure	Deterioration of controls

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Timeframe	Represents:
200 years post closure	Deterioration of controls
300 years post closure	Expected end of institutional control
400 years post closure	Deterioration of controls
500 years post closure	Deterioration of controls

The suggested intervals will demonstrate conditions without waste disposal controls, conditions with uncompromised controls and then the effect of deteriorating controls. Conditions without any controls, i.e., conditions prior to closure and remediation, will also indicate if optimisation is required.

3.3.2.7 Dose limits

The recommended IAEA dose limit of 1 mSv.a^{-1} is also referenced in RG-0026 as the dose limit for planned exposure situations, but in South Africa, an additional dose constraint of 0.25 mSv.a^{-1} is applied due to the public being exposed (potentially) from several different practices (sources).

RG-0026 also introduces differentiation between planned and existing exposure scenarios (Section 2.3.2.5.1) and it further allows for a significantly higher dose limit for existing scenarios. For Palabora Mining Company (PMC) it can be argued that while being a current authorisation holder and practice, PMC is also an existing exposure scenario and as such, a value above 1 and up to 20 mSv.a^{-1} may possibly be considered. The exposure from various scenarios will thus be compared to both 0.25 mSv.a^{-1} and 1 mSv.a^{-1} to demonstrate the potential for broader application of the arguments in this study.

3.3.3 Environmental safety assessment

Currently there is no regulatory expectation to determine the impact of NORM waste on the environment, but there is a broader obligation to ensure radiological impacts on the environment are acceptable. After the Chernobyl accident there have been developments to change the assessment approach to include (or at least consider) the radiological impacts on nature. The ICRP in 2007 stated that it is necessary to consider a wider range of environmental situations irrespective of any human connection with them. It is thus

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considered relevant for inclusion because (a) it will probably become mandatory for South African NORM facilities soon and (b) the mining and processing activities this assessment is based on is up against a pristine environmental conservation area, the Kruger National Park. There is thus a moral obligation to consider the ecological impacts. Since it is also a fundamental principle, it is therefore considered prudent to consider the possible effects radioactive waste may have on the ecology through a radiation safety assessment for the environment.

ERICA is a software program developed to conduct radiological assessments on fauna and flora and adopts a tiered structure, i.e., a graded approach in assessing environmental impacts [22].

Table 3.3.3-1: ERICA approach [22]

Number	Method
Tier 1	• Screening tier. • Based on environmental media concentration limits that will result in a dose rate to the most exposed reference organism equal to the screening dose rate. • Minimal input from the assessor.
Tier 2	• Screening tier. • Calculates dose rates explicitly. • More detailed input from assessor. • Application of uncertainty factors. • Editing of default parameters possible.
Tier 3	• Very detailed. • Requires significant site-specific data and quantification of parameters.

Furthermore, ERICA uses IAEA SRS-19 dispersion models to quantify the source-receptor interface. It is thus aligned with methodology (international and national) for dispersion determination and the methodology used in this study.

There are other computer models available, each with its own advantages and disadvantages, but the purpose of this study is not to comment on the legitimacy and appropriateness of the available software, hence no further comments to be made in this regard other than that

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ERICA is one method to calculate the radiological impacts in a standardised and well recognised manner.

3.4 BACKGROUND RADIATION

Before concluding the discussion on the process to be followed, a final comment on background radiation. Section 2.1.3.1 alluded to the general distribution of uranium and thorium in the earth's crust, but radiation protection generally focussed only on the incremental dose, i.e., the additional dose because of a practice or intervention. Thus, the contribution to effective dose from background radiation needs to be excluded from an assessment process and different methods are available and applied to account for background.

The examples are:

- **External gamma dose**: Consider different areas on the mine site, but areas that do not show remnants of any process or activity. Measure the gamma dose rate at different locations and use the average as a site background.
- **River water**: Measure upstream and downstream from the property. The difference between the values is considered the contribution from the site.
- **Radon**: Measure radon concentration at source and then a radon measurement away from the source. The difference is the contribution from the source only.
- **Groundwater**: Groundwater flow for the Palabora Mining Company site is generally from the tailings facility to the south and southeast, i.e., towards the Selati River. Consider a borehole as a background in other directions and where possible, in a pristine environment.

There are pathways where it is not necessary to correct for background. The following are two examples:

- **Inhalation**: With the concentration above a tailings dam known and applying the nuclide specific activity of the tailings material to the measured concentration, the contribution from other sources is mostly excluded. The dispersion is then calculated using only the source contribution.

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- **Water in the tailings dam**: This water comes directly from the process and is retained inside a basin created by the tailings material. Interaction is thus only with the contaminants and there is no contribution from background sources.

The above are currently used in the radiation protection program for the mine, but some of these methods have constraints that may require further deliberation, as discussed in more detail in Section 5.4.1 and Section 5.4.2.2.

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4 RESEARCH APPROACH

The Palabora Mining Company (PMC) site is ideally suited to test the process as presented. The scope of operations, age and subsequent duration of mining and processing activities of the PMC site present a varied selections of waste disposal routines, with criteria that may hinder or assist in the evaluation of its waste management activities.

- The site in question and subsequent waste management practices are fully established and have been for years.
- The waste streams and associated controlling activities are diverse and the management thereof is determined by aspects such as the process options available and regulatory expectations at the time it commenced but may have change over the years.
- The radiological properties of the material were not initially considered nor were there legislation to govern these properties at least for the first approximately 30 year of the operations.

Subsequently a structured process as described in Chapter 3 is necessary to ensure optimisation of protection, which ideally should occur within the framework of the current management process.

The following sections are broadly grouped according to Figure 3.1-1 (Section 3.1) i.e. (i) introduction, (ii) identification of waste streams, (iii) application of principles of re-use, or re-cycle, (iv) waste characterisation and preliminary classification, (v) safety assessment, (vi) final classification and (vii) a consideration for the remediation strategies currently applied.

4.1 SITE INTRODUCTION

4.1.1 Location

Phalaborwa, meaning “better than the south”, is a town in the Mopani District of the Limpopo Province, approximately 500 km northeast of Johannesburg. The town is supported

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by two major commercial activities, namely mining and eco-tourism, with around 100,000 to 120,000 people living in the Ba-Phalaborwa Municipality.

Figure 4.1.1-1: Aerial rendering of PMC with Ba-Phalaborwa town to the north

4.1.2 History of Palabora Mining Company

In 1868, Karl Mauch discovered the melting of copper by local inhabitants in the Phalaborwa area. This led to copper discoveries circa 1906, followed by the establishment of commercial mining ventures 20 – 30 years later.

The first commercial mining activities commenced with open cast vermiculite mining circa 1938 and phosphate mining in 1951. Palabora Mining Company (PMC) was registered in August 1956, with the project officially launched in 1963 and the first ore crushed in 1965. Furnace activity commenced in 1966, with the first anode cast in February of that year. Also of relevance is the start-up of the Heavy Minerals Plant (HMP) in 1971 used for uranium and heavy minerals recovery. While the Heavy Minerals Plant stopped its operations towards the latter part of the 1990s, Palabora Mining Company remained the main producer and supplier of South Africa’s copper needs and a major exporter of iron in the form of magnetite, a secondary resource generated as part of the copper beneficiation process.

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It is thus safe to say that the mine waste creation and disposal from the described commercial mining and beneficiation processes commenced in 1966.

4.2 WASTE CREATION PROCESSES

4.2.1 Production flow

While there were and are other processes on site that contributes to the overall waste footprint, the copper mining and beneficiation process is the dominant process on site. The following diagram reflects on these activities.

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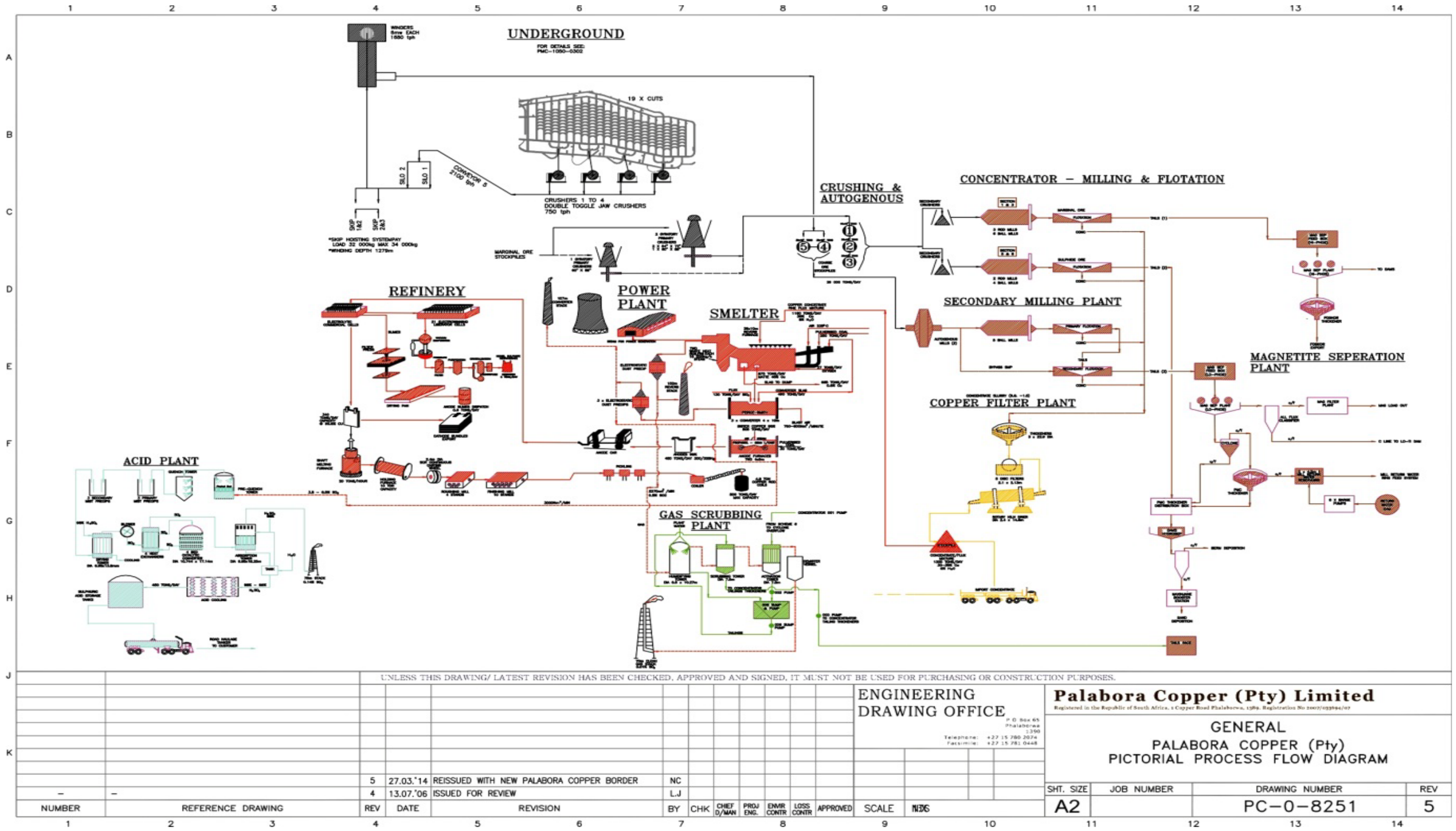

Figure 4.2.1-1: Copper mining, ore processing and beneficiation

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The process activities as described in the flow diagram above consists of mining, crushing and milling, flotation, various stages of smelting and chemical purification, i.e., an electrolytical refinement stage. Secondary mining activities include the opencast mining and beneficiation of vermiculite and hydro-mining of deposited magnetite tailings (a by-product not a waste) generated during the flotation process and stored in stockpiles similar to the tailings. At some stage it was also viable to extract uranium and other heavy minerals as by-products from the process stream.

Each of these stages creates undesirable residues (waste) for example, mining introduces waste rock, the flotation processes the tailings and the Refinery a sludge.

4.2.2 Decommissioning activities

Towards the end of the 1990s, Palabora Mining Company commenced with the decommissioning and dismantling of plants (referred to as the Heavy Minerals Plant) associated with its uranium processing and heavy minerals recovery. Most of the waste generated were dealt with through normal disposal routes after decontamination, but the process did generate some scales and rubble that had to be stored on site due to its elevated radiation levels. (See Table 4.3.4.1-1 for measured dose rates.) To date, no disposal options are available in South Africa, and it remains in storage.

4.2.3 Waste streams

There are numerous waste streams, and a single disposal route is not possible due to the differences in volumes, characteristics and properties of the generated residues, but where possible, the common principles of “reduce, reuse, recycle” are applied. The remainder are either stored or disposed of and the following are typical options available where it is not possible to reuse or recycle:

- Waste rock dumps
- Tailings dams
- Domestic waste disposal site (licenced)
- Hazardous waste storage sites

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Table 4.3.1-1 provides more detail on where it is possible to reduce, reuse or recycle and where not possible, the management option applied.

4.3 IDENTIFICATION, CHARACTERISATION & CLASSIFICATION

Any operation and its associated extraction and beneficiation activities create waste streams and for an operation such as the mining and beneficiation of minerals, these residue streams are numerous and diverse as alluded to in Section 4.2.

Furthermore, not all of these streams have a radiological impact and some of the streams, while relevant radiologically, are not relevant for the purposes of this study, such as scrap.

> **Scrap**: Superfluous metals generally (a) from fabrication or construction activities or (b) used articles from replacement, typically during maintenance or upgrades. Within the production framework these items, (pipes, pumps, valves, chutes etc.), may have surface contamination levels exceeding the public clearance limits for scrap of 0.4 $Bq.cm^{-2}$ for beta/gamma contamination or 0.04 $Bq.cm^{-2}$ for alpha contamination.

The management of scrap is well developed and described within the regulatory framework, with little further advancement required. It is also unlikely that it will remain a source of significant radiological risk post closure, as one of the key components during closure is the removal of unnecessary structures and the recycling of materials where possible. Scrap is a source of value, and it is highly unlikely that that any scrap will remain on completion of site remediation.

4.3.1 Identified waste streams and options

The waste streams and its disposal options are identified through the company's waste management program as captured in MS4.6-STD-514 and listed in Table 4.3.1-1 below [23].

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Table 4.3.1-1: Determination of radiological scrutiny and applicable regulatory framework

Type of waste	Storage	Disposal	Potentially radioactive	Comment
Non-mineral waste	x		No	Domestic waste (typically), but some of these streams may be recycled later as part of the closure process.
		x	No	Not considered within the framework of National Nuclear Regulatory Act [15] or National Radioactive Waste Disposal Institute Act [16]. Materials are generally disposed of on public landfill and/or recycled and regulated through the National Environmental Management: Waste Act [24].
Scrap	x		Yes	Statutory control through the National Nuclear Regulatory Act. Dealt with through the issued Nuclear Authorisation and associated procedures during both the operational phase of the mining activities and then during decommissioning and closure. Material is recycled and will not remain post closure.
Sealed sources	x		Yes	Dealt with through the Hazardous Substances Act during operational phase [14].
Mineral waste • Waste streams will only be in place for a specific period and final disposal will be elsewhere. • Waste streams that are being re-used, re-purposed or converted into a product and by the time of closure, will no longer be on site.	x		No	Waste with no radiological relevance dealt with through the National Environmental Management: Waste Act [24].
	x		Yes	With radiological reference, to be considered in terms of the National Nuclear Regulatory Act and National Radioactive Waste Disposal Institute Act primarily during the operational phase and for a limited period post-closure.
Mineral waste	-	x	No	Waste with no radiological relevance dealt with through the National

Type of waste	Storage	Disposal	Potentially radioactive	Comment
- Waste streams will remain after closure.				Environmental Management: Waste Act [24].
	-	x		With radiological reference, to be considered in terms of the National Nuclear Regulatory Act and the National Radioactive Waste Disposal Institute Act primarily during the operational phase and for a limited period post-closure.

The first few steps of the graded approach are thus to distinguish which material is radiologically meaningful. As seen from the above, a blanket application of radiation protection measures to all waste streams is not an optimised solution and thus a waste of scarce resources. There are waste streams with no radiological relevance that are both disposed of on site or stored for a period before final treatment or disposal elsewhere. These residues are managed through other legislation, specifically the National Environmental Management: Waste Act and do not require any further consideration. Then there are also waste streams with radiological significance, but the impact does not extend post closure and is controlled through the current site authorisation for example scrap.

Further consideration regarding the radioactive content is captured in Sections 4.3.2 and 4.3.3 below.

4.3.2 Provisional screening and categorisation

With a facility in operation since the late 1960s and a mature radiation protection program present, provisional screening and characterisation is a useful step since most of the material has been subjected to a nuclide specific analysis as some stage. (Provisional classification from Table 3.2.3-1.)

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Was this not available, a simple literature study may also provide some indication as to potentially elevated levels of radionuclides, although it should be recognised that the activities across a specific industry may vary by an order of magnitude.

Table 4.3.2-1: Provisional categories and radiological significance

Processing step	Waste streams	Treatment option(s)	Disposal option	Radiologically significant	Provisional classification
Mining	Waste rock	Disposal	Waste dump	Possible	VLLW
Crushing and milling	Waste rock	Disposal	Waste dump	Possible	VLLW
Concentrator	Tailings	Disposal	Tailings dam	Possible	VLLW
	Magnetite	Storage By-product	Tailings dam (Interim) No final disposal required.	Possible	VLLW
Smelter	Reverts	Storage By-product Recycle	Waste dump (Interim) No final disposal required.	Possible	VLLW
	Slag	Storage By-product Recycle	Waste dump (Interim) No final disposal required.	Possible	VLLW
Refinery	Sludge	By-product	No disposal required.	Possible	VLLW
	Copper scrap	Recycle	No disposal required.	Unlikely	-
	Lead	Recycle	No disposal required.	Possible	VLLW
Vermiculite operations	Waste Rock	Disposal	Waste dump	Possible	VLLW
All areas	Scrap	Recycle	Recycling off-site.	Possible	-

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Processing step	**Waste streams**	**Treatment option(s)**	**Disposal option**	**Radiologically significant**	**Provisional classification**
	Domestic	Reduce Recycle Disposal	Domestic waste disposal site	Unlikely	-
	Ash	Storage By-product Recycle	Delisted. Stored on a dump but possibility for re-use.	Possible	VLLW
	Hydrocarbon	Recycle	Recycling off-site.	Unlikely	-
	Hazardous	Disposal	Recycling off-site according to the type of material.	Unlikely	-
	Building rubble	Disposal	Depend on material.	Possible	-
Heavy Minerals Plant demolition waste	Building rubble	Storage	Partial disposal option available in South Africa	Definitely	LLW or ILW
	Scale	Storage	Partial disposal option available in South Africa	Definitely	LLW or ILW

From the table above, a provisional review does indicate possible classification ranging from VLLW to ILW. (See Table 3.2.3-1 for description of waste classifications.) There are also waste streams that may be discarded from the assessment process, such as domestic waste, hydrocarbon waste and some building rubble. It is likely that there will be others (EW), but further characterisation will be needed as indicated in the table.

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4.3.3 Characterisation

Where the tables above served as a first order screening, the radiological significance is quantified through a nuclide specific analysis of the material where it is likely that naturally occurring nuclides may be found in meaningful quantities.

The assays were conducted by an external laboratory, with the methods of analysis referenced in Appendix A. The specific analysis results used (represents sampling over a period of up to 25 years) is also referenced in Appendix A of this document.

The following graph displays the average nuclide specific activity of relevant materials based on the referenced analysis reports.

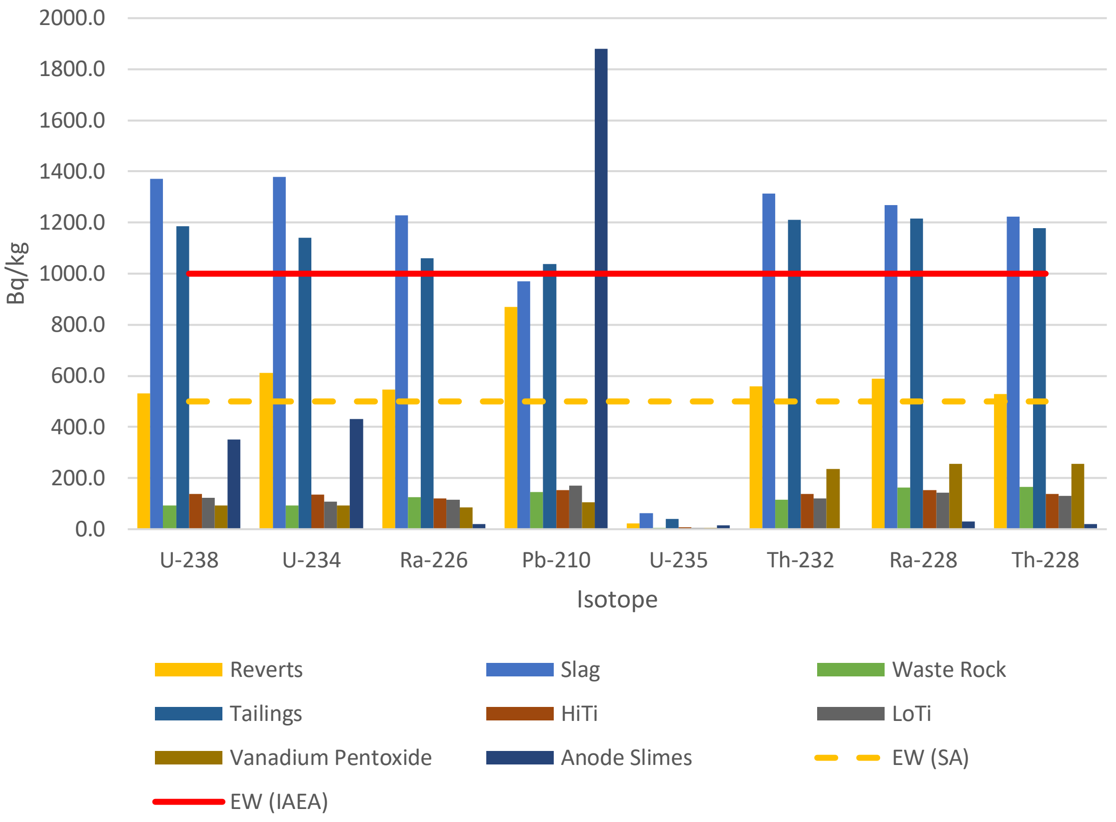

Figure 4.3.3-1: Summary of nuclide specific activities of various waste streams

As seen from the above, reverts, slag and tailings are exceeding the exclusion level of 500 $Bq.kg^{-1}$ (0.5 $Bq.g^{-1}$) for at least some of the naturally occurring isotopes and as such are subjected to the regulatory process. It does, however, not reflect the waste generated by the decommissioning of the Heavy Minerals Plant.

Nuclide specific analysis results are not available for the material from the decommissioning activities, but the dose rate (see Table 4.3.4.1-1) is indicative of a significant radioactive content. It is thus assumed to exceed the exclusion level. The following section discusses this assumption in more detail.

4.3.4 Characterisation of high activity waste from Heavy Minerals Plant

The high activity waste was generated during the decommissioning and dismantling of a heavy minerals plant circa 1999. Some of the generated residues, more aligned with the nuclear fuel cycle, were packed in drums and placed in an interim storage facility on site as there was no permanent waste disposal option available in South Africa. In this instance, a simple screening to classify the material is not an option since the nuclide specific activity data necessary for characterisation is no longer available. As such it will have to be re-sampled, transported and submitted for analysis. Due to the measured external dose levels, this process has to follow the appropriate radiation protection measures including but not limited to, initial dose estimate, application of ALARA principles, IAEA and South African transportation requirements and so forth [25].

It is possible to conduct a screening assessment using available external exposure measurements and information from literature to gain some understanding of risk and thus classification and future requirements.

4.3.4.1 External exposure

The average values were used for external exposure as the available information reflects around 20 years of data collection at locations as indicated in Figure 4.3.4.1 below.

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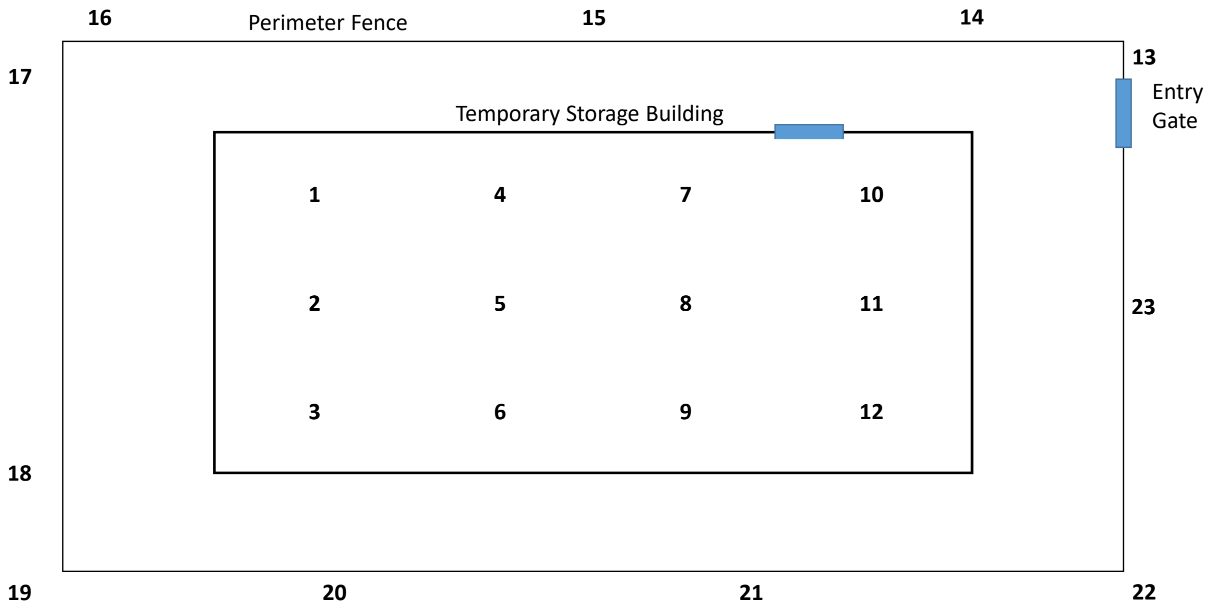

Figure 4.3.4.1-1: Schematic outline of the storage facility with indicated monitoring positions

Please note that the above diagram is not to scale and only indicative of the position where the samples were taken. It does, however, demonstrate the coverage of the area and with the data presented in Table 4.3.4.1-1, provides guidance as to the hazard profile of the facility.

Table 4.3.4.1-1: Dose Rates measured for the temporary storage facility at locations as indicated in Figure 4.3.4.1-1.

Position	Average ($\mu Sv.h^{-1}$)	Standard deviation (Sigma) ($\mu Sv.h^{-1}$)	Coefficient of variation (Standard deviation divided by the mean)	95th percentile ($\mu Sv.h^{-1}$)
1	386.6	63.2	0.2	491.7
2	2471.5	563.5	0.2	3019.4
3	179.8	29.5	0.2	222.7
4	142.1	40.7	0.3	202.8
5	173.2	33.6	0.2	203.9

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Position	**Average (μSv.h^{-1})**	**Standard deviation (Sigma) (μSv.h^{-1})**	**Coefficient of variation (Standard deviation divided by the mean)**	**95th percentile (μSv.h^{-1})**
6	84.3	21.7	0.3	106.0
7	23.1	5.3	0.2	30.3
8	17.4	3.3	0.2	21.0
9	19.7	4.1	0.2	27.2
10	10.6	3.0	0.3	15.1
11	10.3	3.6	0.3	15.1
12	12.4	3.3	0.3	16.2
13	44.7	18.3	0.4	64.0
14	51.0	22.2	0.4	73.9
15	20.6	7.8	0.4	29.4
16	12.2	2.9	0.2	15.3
17	4.1	1.3	0.3	6.1
18	4.1	0.5	0.1	4.6
19	2.4	0.3	0.1	2.8
20	2.9	0.6	0.2	3.7
21	4.7	1.1	0.2	6.5
22	6.6	1.4	0.2	8.2
23	9.5	3.2	0.3	15.2
24	11.2	1.8	0.2	13.6
25	8.2	1.5	0.2	11.0
26	7.4	1.5	0.2	10.0
27	6.6	3.5	0.5	12.3
28	3.5	1.0	0.3	5.0

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Position	**Average (μSv.h^{-1})**	**Standard deviation (Sigma) (μSv.h^{-1})**	**Coefficient of variation (Standard deviation divided by the mean)**	**95th percentile (μSv.h^{-1})**
29	3.3	0.6	0.2	4.2

The above table seems to confirm anecdotal evidence that different types of waste material are present, i.e., significant variation in dose rates observed for different clusters of drums. For the purpose of a standardised waste management process, the following observations:

- It is not appropriate to classify the waste according to the average observed, hence an overall facility dose rate average was not calculated.
- The waste may have different classifications and;
- The different waste classes may require different waste disposal facilities should the principles of justification and optimisation be strictly followed.

The spread of data does not justify the more conservative approach of using the 90th or 95th percentile, as presented by Table 4.3.4.1-1 and illustrated in Figure 4.3.4.1-2 and Figure 4.3.4.1-3 below, using Location 2 and Location 11 as example.

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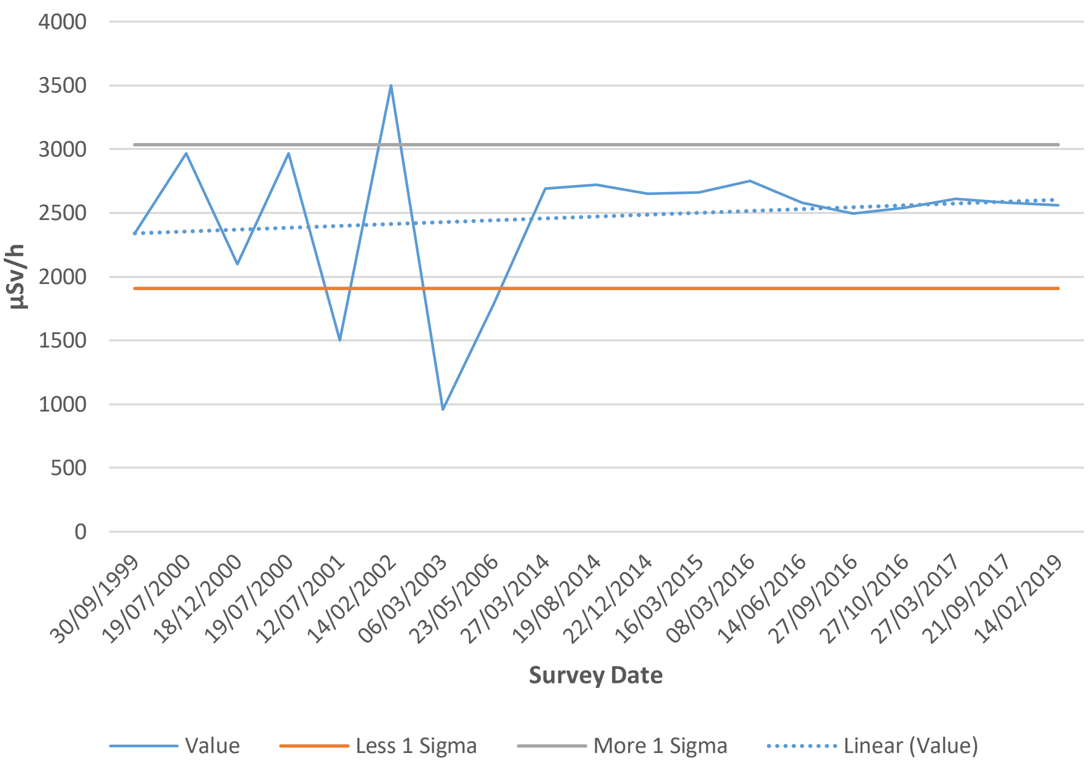

Figure 4.3.4.1-2: Spread of data collected for Location 2

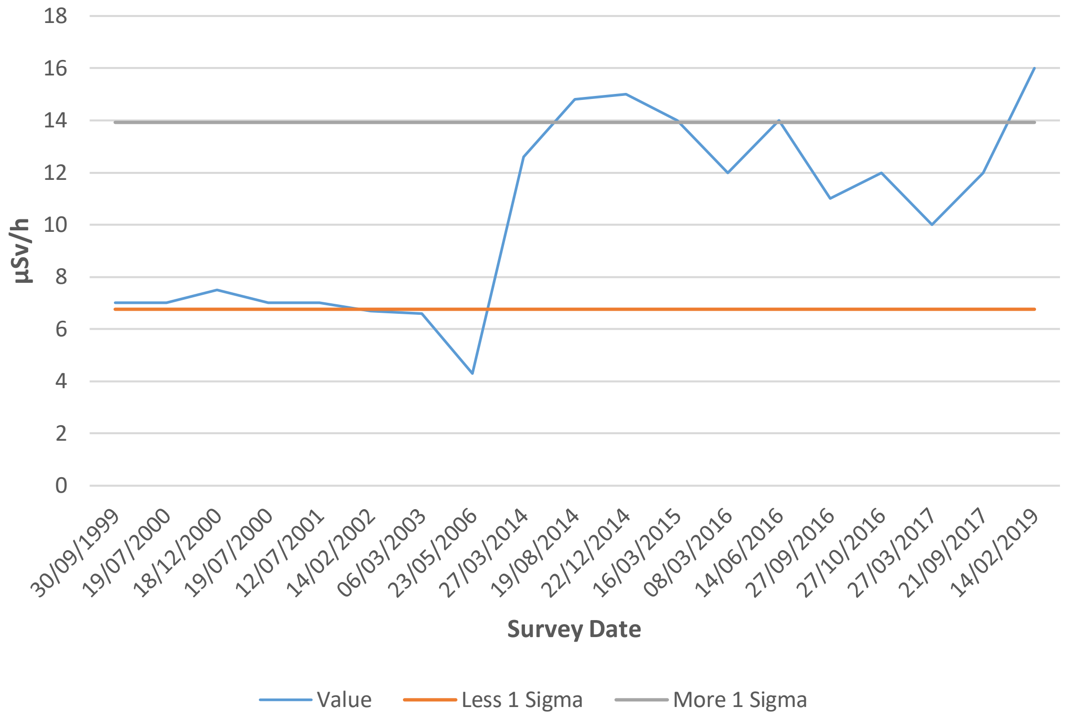

Figure 4.3.4.1-3: Spread of data collected for Location 11

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As seen from the table and two graphs, the coefficient of variation (standard deviation divided by the mean) is less than 1, indicating a low variance, hence the use of average values considered as appropriate.

4.3.4.2 Inhalation dose

Only radon is considered for the inhalation pathway, since the material is enclosed in drums, removing the inhalation of dust from consideration. With the radiological content not known, the inhalation component (radon) was more difficult to determine. Nevertheless, a study conducted at a facility in Brazil is available, allowing for an approximation of the exposure at the Palabora Mining Company (PMC) facility due to some similarities [26]:

- Both are interim storage facilities.
- Both are approximately the same size (Brazil = 17 m x 25 m x 6 m and PMC = 15 m x 30 m x 6 m).
- Both report a mixture of waste including building rubble, sand-like and significant radium-containing waste.
- Same type of containment (drums) used.

Due to similarities observed (and described above), the Brazilian radon concentrations were thus considered appropriate for estimating the radon concentrations in the Palabora Mining storage shed. Thus, no radon sampling was conducted in the Palabora Mining Company shed, but the measured atmospheric concentration levels of the Brazilian facility was used to estimate the radon inhalation dose in the dose assessment. The outcome of the dose assessment is presented in Table 4.4.3.1-1.

4.3.5 Background

A background correction was applied to the following:

- External exposure – Gamma dose rate measurements
- Selati river water
- Radon

Background corrections were not applied to the following:

- Fish (Background levels in fish to be determined.)

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- Groundwater (Background levels of groundwater to be determined.)
- Tailings dam water (As discussed in Section 3.4.)
- Inhalation (As discussed in Section 3.4.)
- Other consumables (As discussed in Section 3.4.)

4.4 ASSESSMENT OF DOSE

4.4.1 Preliminary determination of safety assessment scope

Thus, from Table 4.3.1-1, Table 4.3.2-1 and Figure 4.3.3-1, the scope for each relevant waste stream for the safety assessment is captured in Table 4.4.1-1.

Table 4.4.1-1: Scope of waste stream assessment

Type of waste		**Radioactive**	**Storage**	**Disposal**	**Type of radiation risk/safety assessment**
Area	**Waste stream**				
Concentrator	Tailings	Y		X	• Occupational safety assessment (Operational phase) • Occupational safety assessment (Disposal phase) • Public safety assessment • Environmental safety assessment
	Magnetite	N	X		No assessment required
Smelter	Reverts	Y	X		Occupational safety assessment (Operational phase)
	Slag	Y	X		Occupational safety assessment (Operational phase)
Refinery	Sludge	N	X		N/A
	Copper scrap	N	X		N/A
	Lead	N	X		N/A
Vermiculite Operations	Waste Rock	N		X	N/A

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Type of waste		**Radioactive**	**Storage**	**Disposal**	**Type of radiation risk/safety assessment**
Area	**Waste stream**				
General	Scrap	Y	X		Occupational safety assessment (Not for the purposes of this assessment).
	Domestic	N		X	NA
	Ash	N		X	NA
	Hydrocarbon	N	X		NA
	Hazardous	N	X		N/A
	Building rubble	N		X	N/A
Historic Heavy Minerals Plant	Building rubble	Y	X		• Occupational safety assessment (Operational and storage phase) • Public safety assessment (Operational and storage phase)
	Scale	Y	X		• Occupational safety assessment (Operational and storage phase) • Public safety assessment (Operational and storage phase)

Based on Figure 3.1-1 and subsequent narrative above in Table 4.4.1-1, there are three facilities that require consideration during the operational phase and of these, two waste facilities that necessitate consideration post closure, namely the Heavy Minerals Plant waste and the tailings facility.

For this document, the dose from a source that is excluded from regulatory control (magnetite facility/stockpile) was also assessed for comparison.

4.4.2 Slag

The following table summarises the average nuclide specific activity of the slag. (The average activities are based on the reports and methods referenced in Appendix A.)

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Table 4.4.2-1: Nuclide specific activities of slag

Isotope	Average ($Bq.g^{-1}$)	Maximum ($Bq.g^{-1}$)
U - 238 series		
U-238	1.37E+00	1.62E+00
U-234	1.38E+00	1.63E+00
Ra-226	1.23E+00	1.43E+00
Pb-210	9.69E-01	1.30E+00
U-235 series		
U-235	6.30E-02	7.45E-02
Th - 232 series		
Th-232	1.31E+00	1.53E+00
Ra-228	1.27E+00	1.54E+00
Th-228	1.22E+00	1.45E+00

4.4.2.1 Occupational safety assessment

The following average concentrations were measured for total dust through the occupational hygiene program for airborne pollutants.

Table 4.4.2.1-1: Occupational hygiene monitoring program air concentration for revert homogeneous exposure group

Homogeneous exposure group	Concentration ($mg.m^{-3}$)
Average	6.58E-04
Maximum	1.08E-03

The above data is the total respirable dust concentration as mentioned in Section 3.3.1.2 that is converted into a conservative radionuclide air concentration to use in the inhalation dose determination as per Eq. 10 (Section B.1.1).

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The hygiene monitoring program did not cluster the workers on the slag track as a homogeneous exposure group. However, reverts, a smelter process residue with similar characteristics (including radioactivity content) to slag was used as a likely alternative for the assessment.

Considering various parameters (air concentration, nuclide specific activity and breathing rate or consumption rate) the activity intake is determined and using Eq. 3 for effective dose (Section 3.3.1.1) with dose conversion factors provided by GSR Part 3, occupational exposure is estimated for the operational phase of the facility. This is presented in Table 4.4.2.1-2 [3].

Table 4.4.2.1-2 Occupational exposure from working on the slag track

Description	**Worker dose (mSv.a^{-1})**				
	Inhalation	**Ingestion**	**External dose**	**Radon**	**Total dose**
Dose from average activity (Primary contributors)	1.83E-01	6.17E-03	2.96E+00	2.47E-03	3.15E+00
Dose from average activity (All)	2.56E-01	6.46E-03	2.96E+00	2.47E-03	3.23E+00
Dose from maximum activity (Primary contributors)	3.54E-01	7.63E-03	3.90E+00	9.89E-03	4.27E+00
Dose from maximum activity (All)	4.95E-01	7.97E-03	3.90E+00	9.89E-03	4.41E+00
2008 Worker assessment (Average)	1.14E+00		1.45E+00	0.00E+00	2.59E+00
2008 Worker assessment (Maximum)	1.49E+00		1.88E+00	0.00E+00	3.37E+00
2017 Worker assessment (Average)	5.00E-02		2.88E+00	2.00E-02	2.95E+00
2017 Worker assessment (Maximum)	2.51E-01		2.96E+00	9.20E-02	3.30E+00

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The table above reflects the results of the calculations according to the method described using Eq. 3 for effective dose (Section 3.3.1.1) with dose conversion factors provided by GSR Part 3. (See also Appendix B for the detailed equations.) In addition, it also offers the outcome of previous studies done at the mine, i.e., 2008 [27] and 2017 [28]. The results are comparable, ranging from 2.59 mSv.a^{-1} determined in 2008 to 3.23 mSv.a^{-1} with the current data. The slag track is thus classified as a Supervised Area and no overexposure is anticipated (<20 mSv.a^{-1}).

The variances observed are expected as the air concentration for inhalation is dependent on variables such as rainfall, specific activity of material, specific work distribution and so forth.

> Note: A worker will generally have more than one task and these tasks are not necessarily in the same area or under the same conditions. While area air concentration sampling can be used to determine personal exposure, it has the potential of over- or underestimating the dose because of this unpredictability.

The material will be reworked and removed prior to closure and thus will not enter into a disposal phase. An occupational safety assessment post closure is therefore not applicable.

4.4.3 Heavy Minerals Plant demolition residues

4.4.3.1 Occupational safety assessment

The residual material from the dismantling and decommissioning of the Heavy Minerals Plant at Palabora Mining Company is stored in a shed with fencing and access control. The shed has a bunded cement floor with corrugated iron walls and roof. It is located a significant distance from the general operational areas and there is thus limited interaction with the material in this area, with only the Radiation protection function and Security approach this space.

This material is not fully characterised as the analysis conducted during demolition more than 20 years ago is no longer available. It is thus preferable to conduct detailed nuclide specific analysis of the material but, due to the levels measured, the actual sampling and transportation will introduce an additional radiation risk that is not necessary to be incurred

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at this time. (Reasonable assumptions can be made to facilitate the classification and estimate the exposure.) The radiation information that is available consists of external dose rates based on the area surveys conducted between 1999 and 2019 in the locations indicated in Figure 4.3.4.1-1.

4.4.3.1.1 Scenario development

The following scenarios (hypothetical and real) have been identified as the most relevant for the purposes of this study and were developed based on practical experience and discussions with operational personnel.

For these scenarios, only the external pathway is relevant as the materials are stored in sealed drums and the average dose rates are used:

- Heavy Minerals Plant Scenario 1: A person working inside the facility. Duration of exposure is 2000 hours per year. (This is a highly unlikely scenario because the work area is restricted and is provided to understood worst case scenario.)
- Heavy Minerals Plant Scenario 2: Collecting samples from the various containers for nuclide specific analysis. Consideration is given to time spent walking from the main door to the drums, moving between the drums and actual sampling. Duration of exposure is estimated at between 8 and 9 minutes.
- Heavy Minerals Plant Scenario 3: The RP function, from time to time, needs to conduct the area external dose rate surveys. Duration of exposure estimated at 20 minutes per visit.
- Heavy Minerals Plant Scenario 4: Whilst the shed is equipped with alarms, security still visits the area as part of their routine patrol. They do approach the fence to determine if the fence integrity is appropriate and the gate locked. Duration of exposure is estimated at 10 minutes per visit.

Occupational exposure, i.e., equivalent dose from external (penetrating) radiation, is then calculated as the dose rate multiplied by the exposure period [1]. (See also equation in Appendix B, Section B.1.2.) Exposure frequency, considering that it is not always the same RP function or security officer that visit the site, is estimated at a frequency of twice per year for the radiation protection professional and the security officer seventeen times per year.

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Table 4.4.3.1.1-1: Occupational exposure determined for the Heavy Minerals Plant residues.

Heavy Minerals Plant Scenario	Scenario description	Type	Critical group	Estimated effective dose (mSv.a^{-1})
1	Working inside the facility	Hypothetical	General worker	588.5
2	Collection of samples for analysis	Actual	RP function	0.152
3	Routine monitoring	Actual	RP function	0.12
4	Security patrols	Actual	Security	0.02

For current storage and associated exposures observed, the effective dose is less than the exemption value of 0.25 mSv.a^{-1} and thus in compliance with site authorisation conditions. Nevertheless, it is also clear that the material poses potentially a significant radiological risk as illustrated by Heavy Minerals Plant Scenario 1 that considers a hypothetical 2000 working hours per year. The dose rate at certain areas within are sufficiently significant that only 3 hours will cause an exceedance of the public dose limit of 1 mSv.a^{-1}. Thus, the current controls, i.e., access control, fencing, alarms etc, ensure restricted access and thus reduced exposure and, for storage purposes, the measured are deemed appropriate, but may be inadequate should the site be considered as a disposal site.

4.4.3.2 Public safety assessment

The facility can almost be considered a “point source” when compared with a tailings facility. It’s public impact(s), should containment be maintained, would be similar to the occupational exposure since the structure design and containment method do not allow any dispersion of the material off site. The imperative is thus to maintain containment and reduce access and interaction with the material during the storage phase and the placement of the material in a national repository for final disposal if it is not possible to re-work the material for its radiological content.

Should either of the mentioned two options (off-site disposal or re-work material for its radionuclide content) be considered, separate occupational and public safety assessments are to be conducted for the transportation and disposal/rework. While the transportation will probably be done under the authorisation holder’s nuclear authorisation, it is envisaged that

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the disposal at a national repository will be under the under the nuclear authorisation of the disposal facility and probably controlled by the National Radioactive Waste Disposal Institute. (This will require legislative changes in future.)

4.4.4 Tailings facility

The following table summarises the average nuclide specific activity of the tailings. (Refer to Appendix A for analysis reports utilised.)

Table 4.4.4-1: Nuclide specific activities of tailings

Isotope	Average ($Bq.g^{-1}$)	Maximum ($Bq.g^{-1}$)
U - 238 series		
U-238	1.187	1.810
U-234	1.142	1.830
Ra-226	1.061	1.460
Pb-210	1.038	1.320
U-235 series		
U-235	0.040	0.065
Th - 232 series		
Th-232	1.211	1.720
Ra-228	1.216	1.620
Th-228	1.179	1.730

4.4.4.1 Occupational safety assessment

The following average concentrations were measured for total dust through the occupational hygiene program for airborne pollutants. (See Figure 3.3.1.2-1.)

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Table 4.4.4.1-1: Occupational hygiene monitoring program air concentration for homogeneous exposure group associated with the tailings dam

Area	Concentration ($g.m^{-3}$)
Tailings dams (average)	8.23E-04

The above data is the total respirable dust concentration as mentioned in Section 3.3.1.2 that is converted into a conservative radionuclide air concentration to use in the inhalation dose determination as per Eq. 10 (Section B.1.1).

The concentration above, together with the nuclide specific activity, inhalation rate and duration of exposure is then used to determine $I_{j.inh}$ as per Eq. 3 in Section 3.3.1.1.
The external dose rate represents a 5-year sampling period corrected for background and is summarised in the following table.

Table 4.4.4.1-2: Background corrected gamma dose rates for the tailings dam

Number of measurements	Average ($\mu Sv.h^{-1}$)	Maximum ($\mu Sv.h^{-1}$)
469	1.14	2.58

The table above shows a significant variation between the average and maximum. Generally, such variation is not expected, but anecdotal evidence points towards the disposal of material other than run-of-mine tailings that will explain the variation.

The following table summarises the expected dose during the operational phase of the tailings facility using the formula as presented in Section 3.3.1.1 (Eq.3) and a standard occupational exposure period of 2000 hours per year.

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Table 4.4.4.1-3: Occupational exposure from working on tailings during operational phase

Description	Occupational dose ($mSv.a^{-1}$)				
	Inhalation	Ingestion	External	Radon	Total
Dose from average activity (primary contributors)	2.07E-01	5.93E-03	2.29E+00	1.59E-02	2.51E+00
Dose from average activity (all isotopes)	2.65E-01	6.12E-03	2.29E+00	1.59E-02	2.57E+00
Dose from maximum activity (primary contributors)	5.85E-01	8.09E-03	5.16E+00	6.64E-02	5.82E+00
Dose from maximum activity (all contributors)	7.64E-01	8.39E-03	5.16E+00	6.64E-02	6.00E+00
2008 Worker assessment (average) [27]	9.40E-01		1.01E+00	1.06E+00	3.01E+00
2008 Worker assessment (maximum) [27]	9.40E-01		1.99E+00	1.06E+00	3.99E+00
2017 Worker assessment (average) [28]	3.60E-02		2.04E+00	1.20E-02	2.09E+00
2017 Worker assessment (max) [28]	1.08E-01		3.08E+00	6.20E-02	3.25E+00

During the operational phase, the occupational exposure is aligned with the authorisation conditions.

The estimated occupational exposure to the material post closure is again calculated according to Section 3.3.1.1 (Eq.3) and summarised in Table 4.4.4.1-4. (See also Appendix B.) The duration of exposure is no longer 2000 hours per year but reduced to occasional operational activities such as inspections and maintenance. (See Section 3.3.1.4 for a discussion on the duration of exposure for operational activities post closure.)

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Table 4.4.4.1-4: Occupational exposure from working on tailings after operational phase

Period (Years after remediation)	Worker dose ($mSv.a^{-1}$)				
	Inhalation	Ingestion	External	Radon	Total
0 to 100	0.00E+00	1.47E-04	5.49E-02	3.82E-04	5.54E-02
100 to 200	1.59E-03	1.47E-04	5.49E-02	3.82E-04	5.70E-02
200 to 300	1.91E-03	1.47E-04	5.49E-02	3.82E-04	5.73E-02
300 to 400	2.23E-03	1.47E-04	5.49E-02	3.82E-04	5.76E-02
400 to 500	2.54E-03	1.47E-04	5.49E-02	3.82E-04	5.79E-02

As expressed in Eq.3 and Eq.10 in Section B.1.1 and the equation in B.1.2, the occupational dose is a function of time, concentration, inhalation rate, external dose rate and dose conversion factors. The inhalation rate, external dose rate and dose conversion factors remain constant and do not contribute to a variation in effective dose post closure when compared with occupational exposure during the operational phase of the facility. However, the reduced duration of exposure (Section 3.3.1.4) and the diminished air concentration due to the cover material (Section 3.3.1.2) has a significant impact on the occupational effective dose post closure. Despite increasing over a period of 500 years due to loss of cover and thus potential increase in airborne contaminants, the occupational exposure is now significantly below the 0.25 $mSv.a^{-1}$ exemption value, rendering only public and possibly environmental dose of possible importance for future regulatory control.

4.4.4.2 Public safety assessment

The public safety assessment is based on the formula expressed in Section 3.3.2.2, where the effective dose is a function of the concentration, rate of inhalation/ingestion or exposure period and a dose conversion factor. The dose conversion factors, rates and exposure periods are given in SRS-19, RG-002 and ICRP 41 [19; 20; 7]. Pathways from source to human receptor is determined (see Section 3.3.2.3 and example in Figure 4.4.4.2.2-1) using appropriate formulae as expressed in SRS-19, with examples in Section 3.3.2.3 [19].

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4.4.4.2.1 Scenarios

The six specific scenarios (postulated conditions or events) were as identified through the mine closure plan that is most likely to be relevant at some time post closure and thus requires consideration in terms of the impact the waste streams may cause. These scenarios are then subjected to a dose assessment, considering the conditions specifically applicable to them. A further one hypothetical scenario (representing a maximum potential dose) was also defined. The scenarios are based on the potential pathways as identified in Section 3.3.2.3 as it applies to the critical groups as discussed in Section 3.3.2.5. The scenarios and pathways applicable to each scenario is summarised in the following table.

Table 4.4.4.2.1-1: Scenarios and associated pathways for the public safety assessment.

Scenario	Scenario description	Identified pathways
Scenario 1	Subsistence farming primarily to the south of the tailings facility between the facility and the Selati river.	Inhalation – Suspended particulate concentration
		Inhalation – Radon
		Immersion in semi-infinite cloud source
		Ingestion – Water
		Ingestion – Fish
		Ingestion – Leafy vegetables
		Ingestion – Root vegetables
		Ingestion – Fruit
		Ingestion – Cereal
		Ingestion – Meat
		Ingestion – Milk
		Ingestion – Poultry
		Ingestion – Eggs
Scenario 2	Closest current housing to the tailings facility is	Inhalation – Suspended particulate concentration
		Inhalation – Radon

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Scenario	**Scenario description**	**Identified pathways**
	in the town of Phalaborwa.	Immersion in semi-infinite cloud source
Scenario 3	Converting current workshops and/or structures into training facilities and/or light industrial park situated west-southwest of the tailings facility.	Inhalation – Suspended particulate concentration
		Inhalation – Radon
		Immersion in semi-infinite cloud source
Scenario 4	Cultural tourism at a site of cultural significance due east of the tailings facility	Inhalation – Suspended particulate concentration
		Inhalation – Radon
		Immersion in semi-infinite cloud source
Scenario 5	Game management and/or game drives activity by wildlife professionals (field guides). Area east of the tailings facility act as buffer zone to the Kruger National Park but also has potential for game drives.	Inhalation – Suspended particulate concentration
		Inhalation – Radon
		Immersion in semi-infinite cloud source
Scenario 6	Commercial farm between the town to the north and the Selati river / open pit to the south.	Inhalation – Suspended particulate concentration
		Inhalation – Radon
		Immersion in semi-infinite cloud source
		Ingestion – Water
		Ingestion – Fish

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Scenario	Scenario description	Identified pathways
		Ingestion – Leafy vegetables
		Ingestion – Root vegetables
		Ingestion – Fruit
		Ingestion – Cereal
		Ingestion – Meat
		Ingestion – Milk
		Ingestion – Poultry
		Ingestion – Eggs
Scenario 7	Hypothetical – Representing a subsistence farm due east of the tailings facility but utilising groundwater for farming and consumption.	Inhalation – Suspended particulate concentration
		Inhalation – Radon
		Immersion in semi-infinite cloud source
		Ingestion – Water
		Ingestion – Fish
		Ingestion – Leafy vegetables
		Ingestion – Root vegetables
		Ingestion – Fruit
		Ingestion – Cereal
		Ingestion – Meat
		Ingestion – Milk
		Ingestion – Poultry
		Ingestion – Eggs

As seen from the above, the scenarios are a reflection of the potential land use post closure, i.e., eco-tourism and agriculture. Furthermore, while mine closure generally includes the demolition and removal of structures, it is possible that some of the structures may remain and repurposed for example into training venues. To note, not all pathways are applicable to all the scenarios, for example it is appropriate to assume a family living in town will obtain their food from a store, whereas a subsistence farming family will grow most of their food for consumption.

The above scenario development and interaction is best expressed as a flow diagram as per Section 4.4.4.2.2.

4.4.4.2.2 Generic pathways

The following figure represents the pathways considered.

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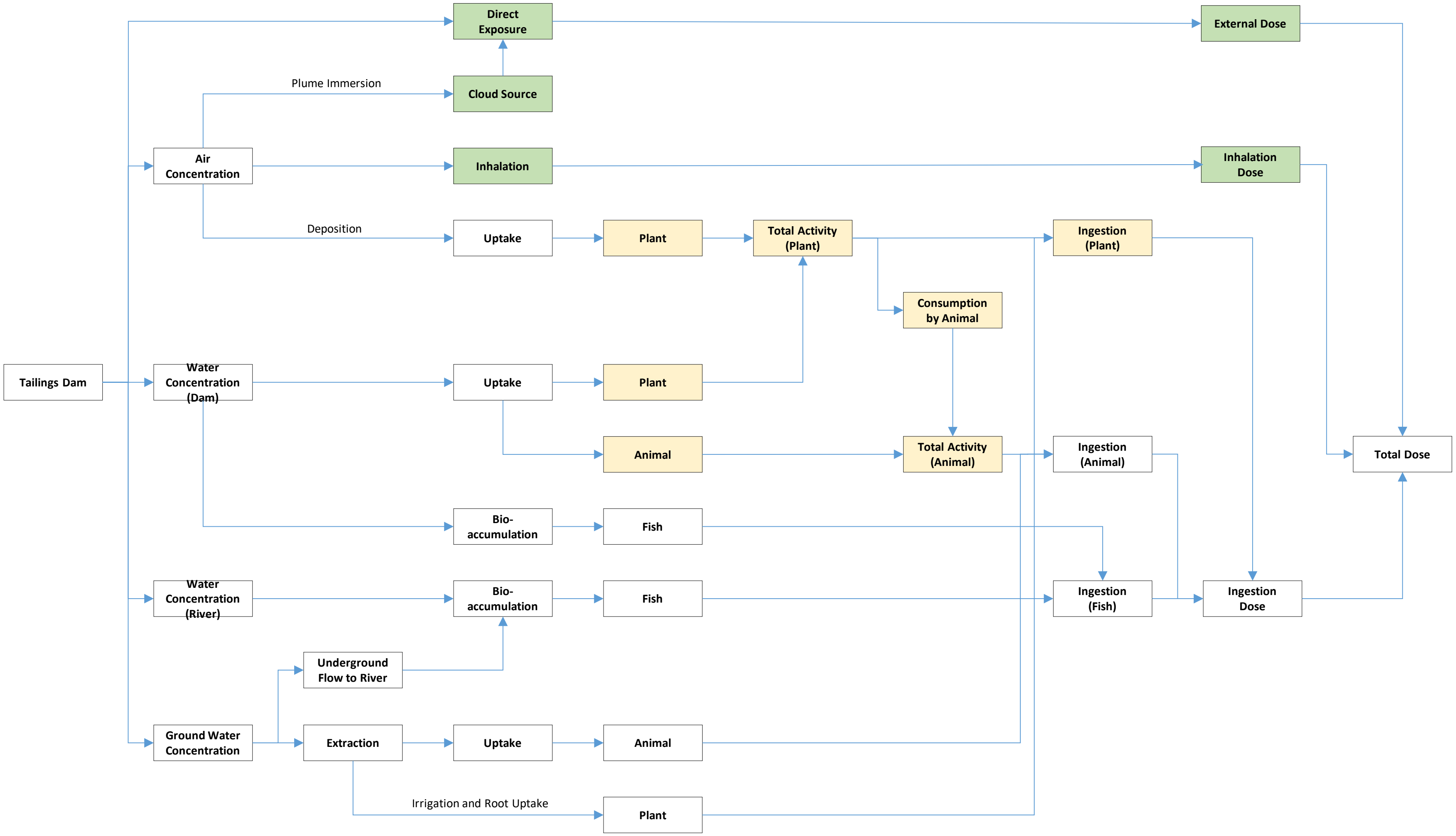

Figure 4.4.4.2.2-1 Generic pathways from source to receptor

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4.4.4.2.3 Screening for optimisation

The effective dose as a result of the conditions prior to closure is presented in the following graph. Each bar represents the annual dose estimate for a specific age group for the different scenarios.

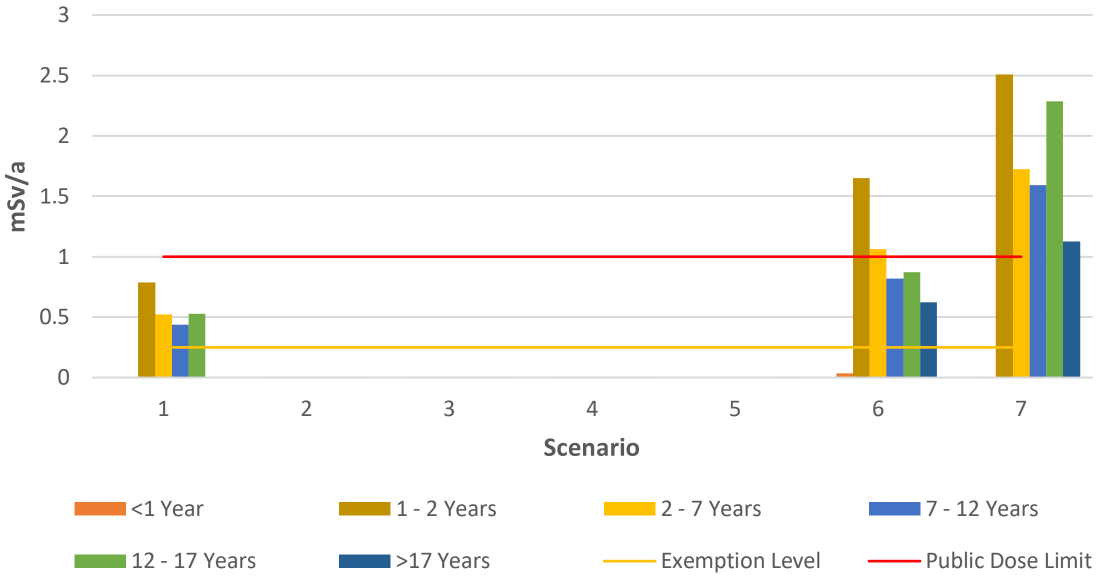

Figure 4.4.4.2.3-1: Determination of exemption and optimisation for the various scenarios

From the above, the most significant pathway is reflected in Table 4.4.4.2.3-1 and the most restrictive age group per scenario (a regulatory expectation) in Table 4.4.4.2.3-2.

Table 4.4.4.2.3-1: Significant pathways

Scenario	Dominant pathway	2nd most dominant pathway
Scenario 1	Milk	Poultry/eggs
Scenario 2	Inhalation	External (cloud source)
Scenario 3	Radon	Dust inhalation
Scenario 4	Radon	Dust inhalation
Scenario 5	Radon	Dust inhalation
Scenario 6	Meat	Milk
Scenario 7	Meat	Milk

The peak dose for each scenario is captured in Table 4.4.4.2.3-2.

Table 4.4.4.2.3-2: Peak dose and associated age group for each scenario

Scenarios													
1		2		3		4		5		6		7	
Peak dose ($mSv.a^{-1}$)	Age group (Years)	Peak dose ($mSv.a^{-1}$)	Age group (Years)	Peak dose ($mSv.a^{-1}$)	Age group (Years)	Peak dose ($mSv.a^{-1}$)	Age group (Years)	Peak dose ($mSv.a^{-1}$)	Age group (Years)	Peak dose ($mSv.a^{-1}$)	Age group (Years)	Peak dose ($mSv.a^{-1}$)	Age group (Years)
8.74E-01	1 – 2	1.73E-04	12 - 17	4.44E-03	>17	7.91E-04	>17	3.21E-03	>17	3.58E-01	1 - 2	2.51E+00	1 -2

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From the graph and tables above, Scenarios 2, 3, 4 and 5 are not subjected to further regulatory concern as their specific activity are less than the exemption level and thus cleared from regulatory concern. Therefore, these four scenarios require no additional optimisation in terms of dose determination or remedial measures within the framework of a graded approach.

In addition to the above, Table 4.4.4.2.3-1 also demonstrates the impact of site-specific characteristics. The same source can have different dominant pathways, depending on the conditions.

Further consideration needs to be given to Scenario 1, Scenario 6 and Scenario 7.

4.4.4.2.4 Scenario 1

Scenario 1 is described as a subsistence farm situated to the south of the tailings facility. As seen from Figure 4.4.4.2.3-1 and Table 4.4.4.2.3-1 above, no remediation will lead to exceedance of the clearance level of 0.25 mSv.a^{-1} and optimisation is required.

It is considered likely that the family satisfies their survival needs from their farming efforts with limited opportunity to sell their produce, but drinking water is obtained from the local service provider. (Groundwater and surface water not suitable for human consumption as per Table 5.4.2.2.6-1.)

The remediation, consisting of covering the tailings facility with a material that has background levels of radiation, will impact on some of the pathways such as inhalation.

The results of the public safety assessment, following the methodology as described in Section 4.4.4.2 and taking cognisance of the remediation, is captured in Figure 4.4.4.2.4-1 below, with the peak dose and associated age group, (as required by the National Nuclear Regulator), provided in Section 4.4.4.2.11 below.

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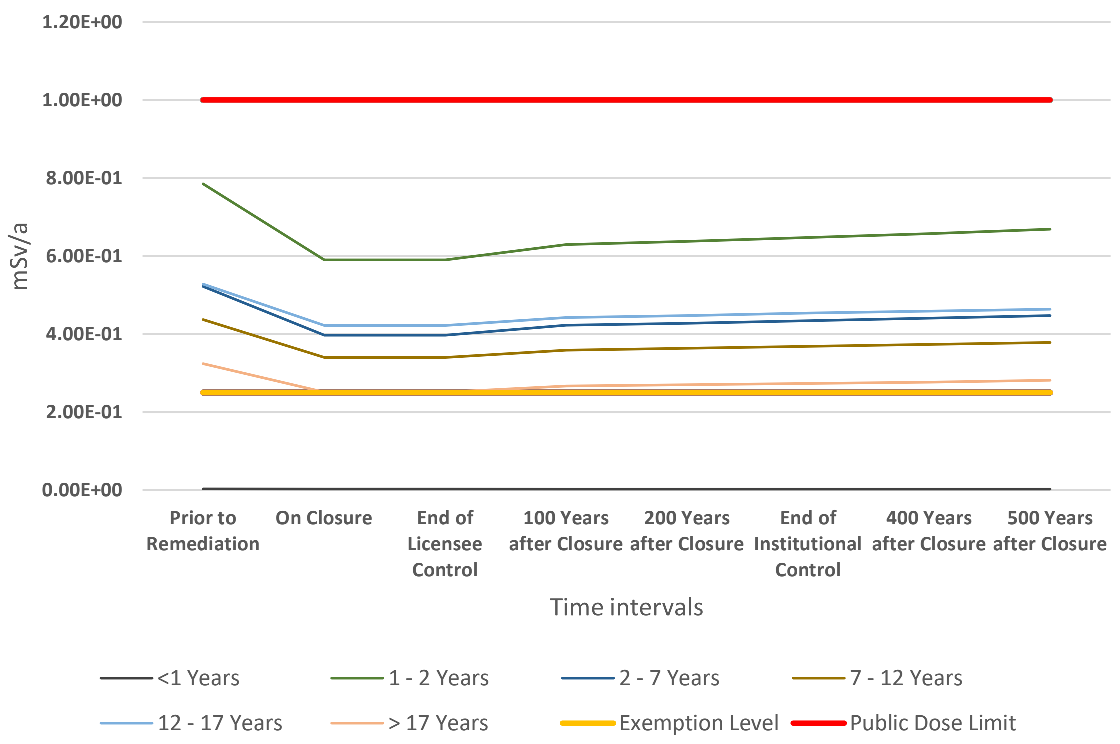

Figure 4.4.4.2.4-1: Subsistence farming south of the tailings facility

For the graph above and applicable to Figure 4.4.4.2.9-1 and Figure 4.4.4.2.10-1, the exemption level refers to the release criteria or dose constraint discussed in Section 3.3.2.7. as it is applied in South Africa and the public dose limit is the upper value as recommended by the IAEA and also referenced in in RG-0026. The 1 mSv.a^{-1} is an indicative value since the tailings facility is an existing exposure situation.

> *Note: The increase in effective dose after the initial decrease is to be expected. Due to the long half-life of uranium and thorium the activity will not reduce over a period of only 500 years. However, the cover of the tailing facility will start to deteriorate after about 100 years [18], thus more tailings material will be released into the atmosphere. This is applicable for all scenarios.*

As seen from the graph, the impact of the tailings facility does not exceed the public dose limit of 1 mSv.a^{-1} for any of the age groups, but it also does not enter into a situation where the facility can be cleared from regulatory control despite the site remediation measures implemented on closure. It would thus remain within the regulatory framework, but the controls would be deemed as adequate.

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4.4.4.2.5 Scenario 2

An effective dose above 0.25 mSv.a^{-1} is very unlikely due to low air concentration of the radionuclides and limited number of potential exposure pathways and is thus not considered further. The peak dose and associated age group is given in Section 4.4.4.2.11.

4.4.4.2.6 Scenario 3

An effective dose above 0.25 mSv.a^{-1} is very unlikely due to low air concentration of the radionuclides and limited number of potential exposure pathways and is thus not considered further. The peak dose and associated age group is given in Section 4.4.4.2.11.

4.4.4.2.7 Scenario 4

An effective dose above 0.25 mSv.a^{-1} is very unlikely due to low air concentration of the radionuclides and limited number of potential exposure pathways and is thus not considered further. The peak dose and associated age group is given in Section 4.4.4.2.11.

4.4.4.2.8 Scenario 5

An effective dose above 0.25 mSv.a^{-1} is very unlikely due to low air concentration of the radionuclides and limited number of potential exposure pathways and is thus not considered further. The peak dose and associated age group is given in Section 4.4.4.2.11.

4.4.4.2.9 Scenario 6

Scenario 6 is described as a commercial farm to the west of the tailings facility. It is safe to assume for a family that resides on a commercial farm that they will obtain most of their foodstuffs from such an operation, but fishing for consumption purposes is unlikely. Drinking water is received from the local service provider. (Groundwater and surface water are not suitable for human consumption as per Table 5.4.2.2.6-1.) As seen from Figure 4.4.4.2.3-1 above, if remediation does not occur, doses more than the clearance level may be incurred, and further optimisation is thus required.

Considering the impact of remediation and subsequent deterioration thereof, the estimated annual dose over a 500-year period is reflected in the graph below, with the peak dose and associated age group presented in Section 4.4.4.2.11.

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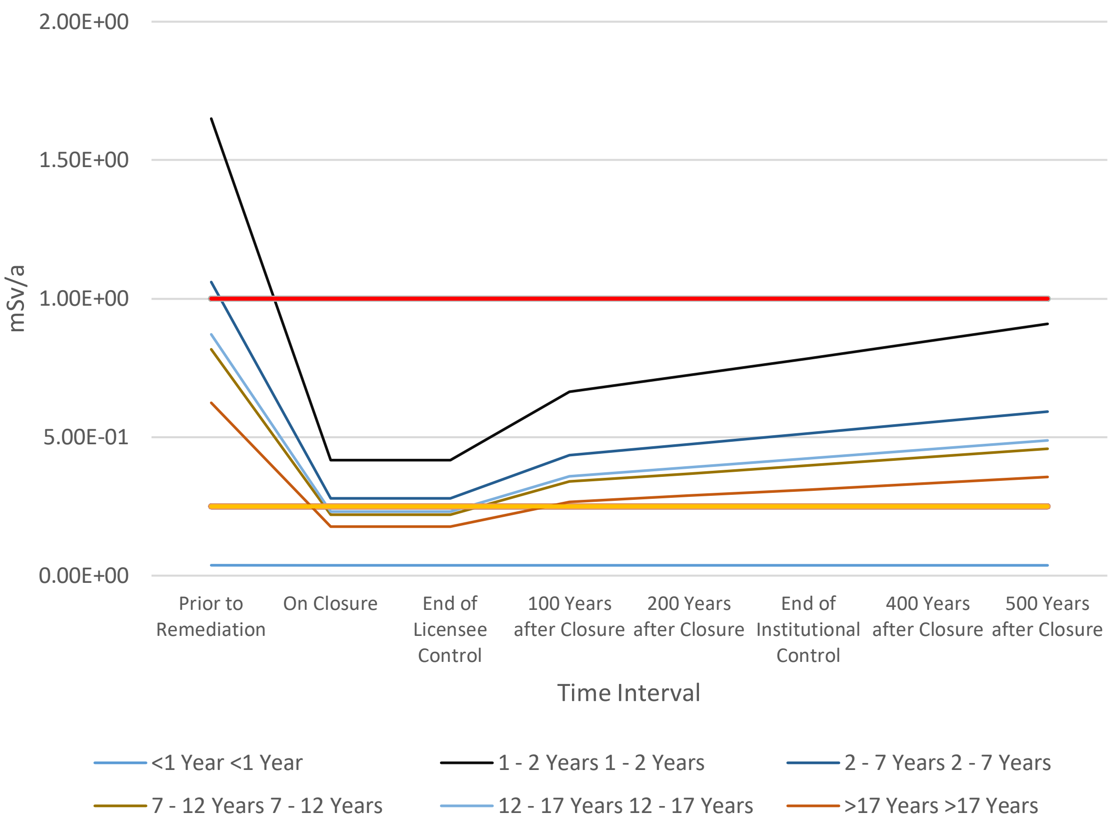

Figure 4.4.4.2.9-1: Commercial farming west of the tailings facility

As with the subsistence farming scenario, Scenario 6 also do not exceed the 1 mSv.a^{-1} limit, but it is above 0.25 mSv.a^{-1} without remediation measures and mostly remains above this clearance level. While the measures are thus appropriate, it would remain within the regulatory framework.

4.4.4.2.10 Scenario 7

As stated earlier, it is unlikely that any one actual scenario will create the highest dose for every pathway, but the summation of the individual highest doses per pathway from different scenarios is also not a reasonable approach for a worst-case scenario. It is not necessarily possible for a specific location or scenario to have the maximum dose for all pathways, for example the predominant wind direction could be in the opposite direction of the groundwater flow. Thus, it would not be possible for a scenario where both the highest possible inhalation dose and water consumption dose is presented. Nevertheless, certain assumptions can be made, such as all fish for ingestion is obtained from the most polluted source.

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For Scenario 7 an unlikely assumption was made that a subsistence type of farming occurs with the water source for farming and human consumption from the most polluted (in terms of its radionuclide content) used in addition to obtaining all their foodstuffs from the impacted soil and vegetation. The influence of water on the various pathways was calculated using the measured nuclide specific activity of the specific borehole, not accounting for any radionuclide loss (reduction in specific activity) due to water purification processes which is unlikely as illustrated in Table 5.4.2.2.6-1 or considering the dilution effect of supplementing the water from other less impacted sources. Dose was then determined as described in Section 4.4.4.2.

Considering the impact of remediation and subsequent deterioration thereof, the estimated annual dose over a 500-year period is reflected in the graph below, with the peak dose and associated age group presented in Section 4.4.4.2.11.

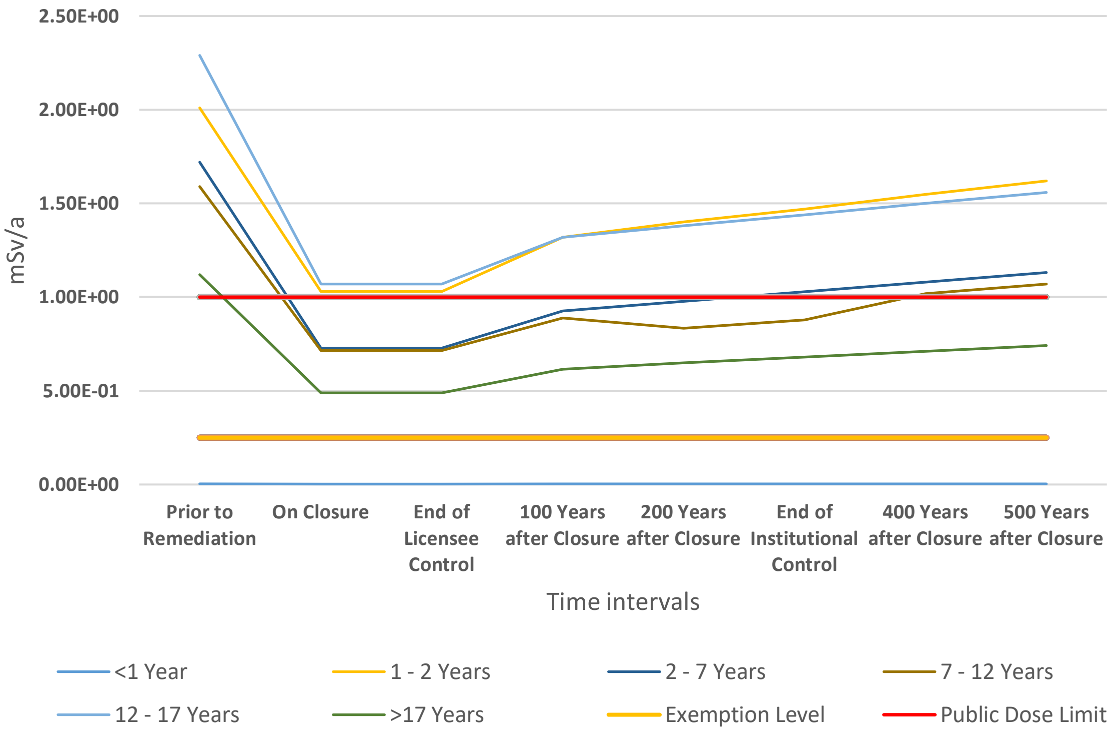

Figure 4.4.4.2.10-1: Subsistence farming south of the facility, using groundwater in agriculture.

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The above graph demostrates the appropriateness of considering worst case scenario as it may highlight particular pathways of concern and a potential focus for future optimisation. In this instance, the contribution from groundwater introduces a consideration that pushes potential exposure above the 1 mSv.a^{-1} limit.

4.4.4.2.11 Peak Dose

The National Nuclear Regulator expects reference to the most significant dose (peak dose) across the relevant age groups. The following table, Table 4.4.4.2.11-1, is a summary of all the peak doses and the associated age group across the scenarios and time intervals to demonstrate the execution of this expectation.

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Table 4.4.4.2.11-1: Peak dose and associated age group for time interval

Scenario	Time interval															
	Prior to closure		On closure		End of licensee control		100 Y after closure		200 Y after closure		300 Y after closure		400 Y after closure		500 Y after closure	
	Peak dose (mSv.a^{-1})	Age group (Years)	Peak dose (mSv.a^{-1})	Age group (Years)	Peak dose (mSv.a^{-1})	Age group (Years)	Peak dose (mSv.a^{-1})	Age group (Years)	Peak dose (mSv.a^{-1})	Age group (Years)	Peak dose (mSv.a^{-1})	Age group (Years)	Peak dose (mSv.a^{-1})	Age group (Years)	Peak dose (mSv.a^{-1})	Age group (Years)
1	8.74E-01	1 - 2	5.90E-01	1 - 2	5.90E-01	1 - 2	6.29E-01	1 - 2	6.38E-01	1 - 2	6.48E-01	1 - 2	6.58E-01	1 - 2	6.68E-01	1 - 2
2	1.73E-04	12 -17	0.00E+00	>17	0.00E+00	>17	3.46E-05	>17	4.33E-05	12 -17	5.19E-05	12 -17	6.06E-05	12 -17	6.92E-05	12 -17
3	4.44E-03	>17	3.64E-03	>17	3.64E-03	>17	3.80E-03	>17	3.84E-03	>17	3.88E-03	>17	3.92E-03	>17	3.96E-03	>17
4	7.91E-04	>17	5.85E-04	>17	5.85E-04	>17	6.27E-04	>17	6.37E-04	>17	6.47E-04	>17	6.57E-04	>17	6.68E-04	>17
5	3.21E-03	>17	2.39E-03	>17	2.39E-03	>17	2.56E-03	>17	2.60E-03	>17	2.64E-03	>17	2.68E-03	>17	2.72E-03	>17
6	1.65E+00	1 - 2	4.17E-01	1 - 2	4.17E-01	1 - 2	6.63E-01	1 - 2	7.24E-01	1 - 2	7.85E-01	1 - 2	8.47E-01	1 - 2	9.08E-01	1 - 2
7	2.51E+00	1 - 2	1.07E+00	12 - 17	1.07E+00	12 - 17	1.32E+00	12 - 17	1.40E+00	1 - 2	1.47E+00	1 - 2	1.55E+00	1 - 2	1.62E+00	1 - 2

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It may initially not be obvious where such a summary add value to the process as described in this study. However, it should be recognised that the age groups differ in eating habits and volumes, physiological aspects and other traits that will impact on the effective dose from a particular waste source. Obvious applications of this information are (a) when optimisation is considered and (b) to determine the most appropriate restricted use opportunity should it become necessary.

4.4.4.3 Environmental safety assessment

A basic environmental assessment (assessing impacts on fauna and flora) was conducted using the ERICA modelling software. (Software is described in Section 3.3.3.) As per the software parameters, the aquatic ecosystem was selected using default data for environmental media concentration limits, occupancy factors and reference organisms thus reducing the variables to the nuclide specific content of the water only.

The results of the Tier 1 screening assessment are reflected in Table 4.4.4.3-1.

Table 4.4.4.3-1: Tier 1 screening assessment for the tailings dam as an aquatic ecosystem

Isotopes	Risk quotient [unitless]	Limiting reference organism
U-234	0.61225	Vascular plant
U-235	0.01835	Vascular plant
U-238	0.3887	Vascular plant
Th-227	21.75	Vascular plant
Th-228	68.04	Vascular plant
Th-230	21	Vascular plant
Th-231	0.8385	Insect larvae
Th-232	2.67	Vascular plant
Th-234	17.25	Insect larvae
Ra-226	22	Insect larvae
Ra-228	0.028	Insect larvae
Po-210	3.45	Insect larvae

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Isotopes	**Risk quotient [unitless]**	**Limiting reference organism**
Pb-210	0.01786	Insect larvae
Sum of Risk Quotient	158.06366	

A first order screening assessment (Tier 1) shows that a dose rate screening value of 10 µGy.h^{-1} is triggered for some of the nuclides. The limiting reference organism is also identified. Since the screening value for some of the isotopes is triggered, a Tier 2 assessment is then suggested by ERICA.

The Tier 2 assessment outcome is presented in Table 4.4.4.3-2.

Table 4.4.4.3-2: Tier 2 screening assessment for the tailings dam as an aquatic ecosystem

Organism	**Total dose rate per organism (µGy h^{-1})**	**Screening value (µGy h^{-1})**
Amphibian	25.9	10
Benthic fish	3.1	10
Bird	26.5	10
Crustacean	5.0	10
Insect larvae	93.6	10
Mammal	8.9	10
Mollusc – bivalve	114.0	10
Mollusc - gastropod	114.0	10
Pelagic fish	3.1	10
Phytoplankton	30.6	10
Reptile	6.0	10
Vascular plant	243.0	10
Zooplankton	88.8	10

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As seen from Table 4.4.4.3-2, a more detailed assessment identified several organisms that will exceed the 10 µGy.h^{-1} screening value, again suggesting that the assessment should escalate, this time to a Tier 3 assessment.

For the purpose of this study, a Tier 3 assessment is not attempted since the detail necessary is not available yet. However, the basic study does indicate that the impact on the environment and associated ecosystems from a NORM waste facility such as a tailings dam cannot be ignored where such a facility will be for final disposal.

4.4.5 Magnetite tailings facility

Since the magnetite tailings material is less than 0.5 Bq.g^{-1} per isotope (as reflected in reports referenced in Appendix A) and thus excluded from regulatory control, an assessment is not necessary. Nevertheless, it is included in this study to allow for an evaluation of some of the conventions followed in South Africa and will form part of the discussions in the next chapter.

The following table summarises the nuclide specific activity for magnetite. (Refer to Appendix A for analysis reports utilised.)

Table 4.4.5-1: Nuclide specific activities of magnetite

Isotope	Average (Bq.g^{-1})	Maximum (Bq.g^{-1})
U - 238 series		
U-238	1.39E-01	1.88E-01
U-234	1.36E-01	1.89E-01
Ra-226	1.20E-01	1.64E-01
Pb-210	1.54E-01	2.22E-01
U-235 series		
U-235	6.40E-03	8.64E-03
Th - 232 series		

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Isotope	Average ($Bq.g^{-1}$)	Maximum ($Bq.g^{-1}$)
Th-232	1.38E-01	1.88E-01
Ra-228	1.52E-01	2.05E-01
Th-228	1.39E-01	1.75E-01

4.4.5.1 Occupational safety assessment

The following average concentrations were measured for total respirable dust through the occupational hygiene program for airborne pollutants.

Table 4.4.5.1-1: Air concentrations measured

Homogeneous Exposure Group	Concentration ($g.m^{-3}$)
Average	6.65E-04
Maximum	1.47E-03

The above data is the total respirable dust concentration as mentioned in Section 3.3.1.2 that is converted into a conservative radionuclide air concentration to use in the inhalation dose determination as per Eq. 10 (Section B.1.1).

The following table summarises the estimated occupational exposure from working on the magnetite dumps during the operational phase of the facility.

Table 4.4.5.1-2 Occupational exposure from working on magnetite stockpiles

Description	Occupational exposure ($mSv.a^{-1}$)				
	Inhalation	Ingestion	External dose	Radon	Total dose
Dose from average activity (primary contributors)	1.97E-02	7.68E-04	1.95E-01	1.93E-02	2.35E-01

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Description	**Occupational exposure (mSv.a^{-1})**				
	Inhalation	**Ingestion**	**External dose**	**Radon**	**Total dose**
Dose from average activity (all)	2.71E-02	7.97E-04	1.95E-01	1.93E-02	2.42E-01
Dose from maximum activity (primary contributors)	5.82E-02	1.06E-03	6.40E-01	2.14E-01	9.13E-01
Dose from maximum activity (all)	8.05E-02	1.10E-03	6.40E-01	2.14E-01	9.35E-01
2008 Worker assessment (average) [27]	3.90E-01		3.80E-01	9.40E-01	1.71E+00
2008 Worker assessment (maximum) [27]	4.65E+00		1.88E+00	1.85E+00	8.38E+00
2017 Worker assessment (average) [28]	1.64E-01		4.11E-01	1.20E-02	5.87E-01
2017 Worker assessment (maximum) [28]	3.83E-01		6.80E-01	6.20E-02	1.13E+00

The average exposure for working on the magnetite dumps ranges from less than 0.25 mSv.a^{-1} to around 1 mSv.a^{-1}, depending on the use of average or maximum nuclide specific activity. It does, however, align with previous studies done in 2008 and 2017 where the doses varied between 0.5 mSv.a^{-}1 and 1.7 mSv.a^{-1}. Using average specific activity values, the magnetite processing areas are not deemed a supervised area. While it is excluded for regulatory control due to its nuclide specific activity, it would not have been exempted, based on dose. This is further discussed in Section 5.4.5.

No further consideration will be given to occupational exposure post closure of the complex since magnetite is not a waste and will be recovered as a product prior to closure.

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4.4.5.2 Public safety assessment

As previously stated, a public safety assessment of the magnetite facility is not necessary since (a) the material is considered a product and will be sold and removed prior to final closure, and (b) it is exempted based on its specific activity.

However, because it approximates certain characteristics of the tailings facility, it was calculated to use for comparative purposes. The methods and processes for determining public exposure is discussed in Section 4.4.4.2 and the scenario descriptions in Section 4.4.4.2.1. Further detail with regards to the equations used is found in Appendix B.

Table 4.4.5.2-1: Public exposure estimate as a result of the magnetite facility

Scenario	Total effective dose ($mSv.a^{-1}$)					
	<1 years	1 - 2 years	2 - 7 years	7 - 12 years	12 - 17 years	Adult (>17 years)
Scenario 1	2.71E-03	6.17E-01	4.14E-01	3.54E-01	4.36E-01	2.62E-01
Scenario 2	7.42E-06	1.24E-05	1.42E-05	1.89E-05	2.23E-05	1.86E-05
Scenario 3	3.64E-03	3.64E-03	3.64E-03	3.64E-03	3.64E-03	3.74E-03
Scenario 4	5.85E-04	5.85E-04	5.85E-04	5.85E-04	5.85E-04	6.12E-04
Scenario 5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.50E-03
Scenario 6	3.73E-02	5.97E-01	3.93E-01	3.06E-01	3.20E-01	2.42E-01

The above is a very conservative approach as it includes the total contributions from radon and fish, two pathways where the magnetite stockpile may have contributed to those pathways' concentration, but if so, to a far lesser degree than the tailings dam. Public dose is in the order of 0.25 $mS.a^{-1}$ to 0.6 $mSv.a^{-1}$ without any form of remediation. The above enhanced the contradiction in that the specific activity is below the exclusion level, but not below the reference level based on dose. This aspect is further discussed in Section 5.4.5.

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4.5 SUMMARY

In summary, applying the process to the residue streams of PMC produced an optimized result.

- Identification: Table 4.3.1-1 provides a detailed profile of the PMC residue streams that includes some optimisation as early as in the first step. (Some of the residue streams such as domestic waste excluded from further consideration.)
- Characterisation: Table 4.3.2-1 further expand on Table 4.3.1-1, supported by the radiological content as presented in Figure 4.3.3-1 (nuclide specific activities). The decommissioning waste is dealt with under Section 4.3.4.
- Safety assessment(s): Safety assessments (occupational and public) were performed on the waste (residue) streams of relevance for the operational phase of the mining activities as well as post closure. For the public safety assessment, the primary driver for post closure radiation risk, 6 probable scenarios were evaluated as well as a worst-case scenario.
- An environmental radiation safety assessment was added (whilst not a current regulatory requirement) to demonstrate the need for future inclusion in the regulatory regime.

The outcome of the assessment now leads to Table 5.2-1, providing a summary of the effective dose, final classification and thus guidance as to the most appropriate remediation measures. Chapter 5 will also expand on the alignment of the process with the IAEA principles, some constraints observed and offer some suggested tools for future use.

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5 DISCUSSION

The hazard of radiation is not a recent phenomenon and sound principles to protect against radiation have been applied in the South African mining industry for nearly 20 years. Still, there are some aspects within this protection framework that is not as well defined as the others for example, waste management. The recent establishment of the National Radioactive Waste Disposal Institute suggests an increased focus in this regard, and it is accepted that change is imminent. Consideration was thus given to the potential practical application of current principles, guidance and available legislation to lend structure, create possible tools for use and raise potential pitfalls going forward. Through the application, observations are also made on the impact of the Palabora Mining Company waste facilities on the occupational, public and environmental sphere within this framework.

5.1 WASTE MANAGEMENT PROCESS

All mining and minerals processing facilities have a variety of residue streams as a result of operational activities and there is a legal and moral imperative to ensure responsible management thereof. However, a single, common treatment and disposal methodology aligned with the management of the most significant hazard is also not appropriate and some form of differentiation is thus necessary to enable an informed decision on the most appropriate treatment response. Such a process or protocol (described in Section 3 and applied in Section 4) is summarised in Figure 5.1 below.

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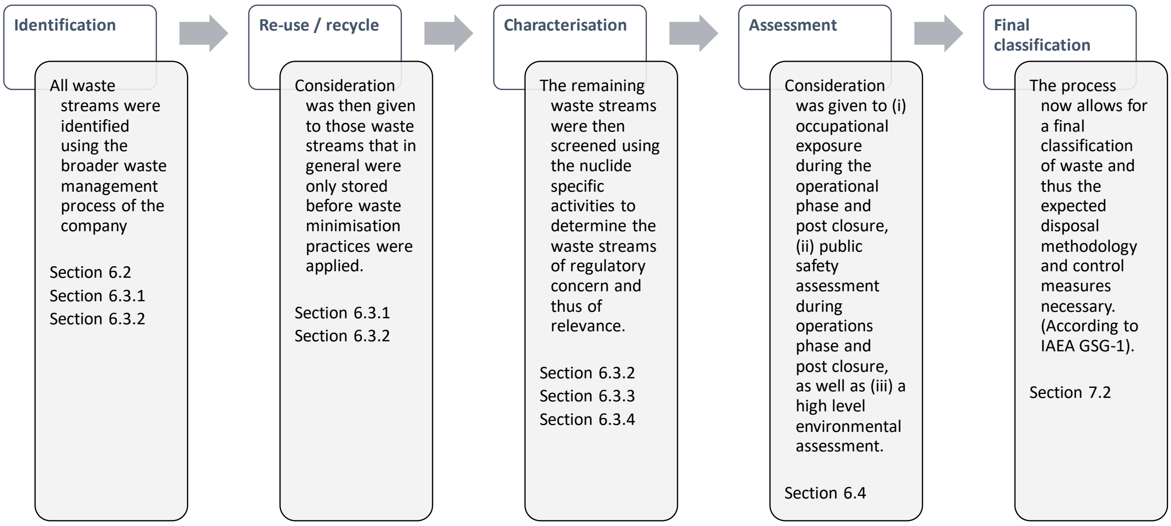

All waste streams were identified using the broader waste management process of the company

Section 6.2
Section 6.3.1
Section 6.3.2

Consideration was then given to those waste streams that in general were only stored before waste minimisation practices were applied.

Section 6.3.1
Section 6.3.2

The remaining waste streams were then screened using the nuclide specific activities to determine the waste streams of regulatory concern and thus of relevance.

Section 6.3.2
Section 6.3.3
Section 6.3.4

Consideration was given to (i) occupational exposure during the operational phase and post closure, (ii) public safety assessment during operations phase and post closure, as well as (iii) a high level environmental assessment.

Section 6.4

The process now allows for a final classification of waste and thus the expected disposal methodology and control measures necessary. (According to IAEA GSG-1).

Section 7.2

Figure 5.1-1: Adherence to the suggested process

As seen from the above, the waste process for NORM waste as defined (using universally accepted waste management and radiation principles) is ordered in such a way that it sets a structured process to define the correct classification of various residue streams found on site. The “tools” or screening techniques allow the focus of the radiation safety assessments to be on very specific scenarios (graded approach) ensuring the future resource utilisation and protection measures are optimised or can be further optimised.

Further discussions on the final classifications are presented in Section 5.2 and 5.4.2.1 below.

5.2 FINAL CLASSIFICATION OF WASTE

As per Figure 5.1-1, the suggested process ends with the final classification for the radioactive waste. With the classification known, GSG-1 now provides guidance (guidance based on broad international experience) of generic remediation strategies that can assist during any of the planning, operational or maintenance phases.

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This is of particular value to the Palabora Mining Company scenario where the waste remediation and treatment measures grew from non-radiation legislation, such as the National Environmental Management: Waste Act or its predecessors. It is necessary to confirm if current practices are aligned with guidance expectations (GSG-1) and while site specific criteria will still play a further role in the optimisation process, this initial comparison confirms broad alignment or not.

The following table is the final output of the various safety assessments reported on in Section 4.1 to Section 4.4 for Palabora Mining Company.

Table 5.2-1: Final classification of waste streams

Waste streams	**Occupational assessment**		**Public assessment**	**Final classification**	**Comments**
	Storage (interim)	**Disposal**	**Disposal**		
Waste rock	Exempted	Exempted	Exempted	EW	Remediation measures appropriate
Tailings	2570 μSv.a^{-1}	~60 μSv.a^{-1}	~250 μSv.a^{-1}	VLLW	Remediation measures appropriate
Magnetite	242 μSv.a^{-1}	Exempted	Exempted	EW	Remediation measures appropriate
Reverts	3230 μSv.a^{-1}	No disposal	No disposal*	VLLW	Classification only during operational phase.
Slag	3230 μSv.a^{-1}	No disposal	No disposal*	VLLW	Classification only during operational phase.
Sludge	Continuously recycled, no final disposal required.				
Copper scrap	Continuously recycled, no final disposal required.				
Lead	Continuously recycled, no final disposal required.				

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Waste streams	Occupational assessment		Public assessment	Final classification	Comments
	Storage (interim)	Disposal	Disposal		
Scrap	Continuously recycled, no final disposal required.				
Ash	Exempted	Exempted	Exempted	EW	Remediation measures appropriate
Building rubble from decommissioned plant	0.152 mSv.a^{-1} (Potential 588.5 mSv.a^{-1})	Partial disposal option available in South Africa	Partial disposal option available in South Africa	LLW or ILW	Some of the waste drums are classified as LLW and some classified as ILW. **Current strategies not suitable for disposal.**
Scale from decommissioned plant.	0.152 mSv.a^{-1} (Potential 588.5 mSv.a^{-1})	Partial disposal option available in South Africa	Partial disposal option available in South Africa	LLW or ILW	Some of the waste drums are classified as LLW and some classified as ILW. **Current strategies not suitable for disposal.**

*While reverts/slag is continuously recycled (similar to sludge, copper scrap and lead) the quantity may cause the material to be on site for a significant period of time, having a measurable impact and hence difference in reporting.

From the table above, the site-specific study supports the temporary classification captured in Table 4.3.2-1. Firstly, it was confirmed that the NORM waste is classified as VLLW if not totally excluded as expected and secondly, it is also confirmed that the scale from the decommissioned plant (with significantly higher radiation levels than other waste types) definitely requires a different disposal option, one that is not currently available in South Africa.

The table highlight another aspect of relevance and that is the potential spread found in the radiation levels of different NORM waste streams. As confirmed in the table, it manifests as four (4) different waste categories, again emphasising the necessity for site specific assessment(s) to optimise the waste management measures post closure. A generic or single solution, based on one category of waste only, may potentially pose a significant radiation risk or onerous and unnecessary controls.

Further discussion in terms of waste classification is made in Section 5.4.2.1 below.

5.3 ALIGNMENT WITH PRINCIPLES

With the process and the application of the process confirmed and applied, it is now necessary to consider the suitability of the process. The purpose of the study was also to determine or set a management process (Reference Figure 5.1-1) that is aligned with national and international practices and guidance. It is thus appropriate to verify if the process addresses or aligns with the most basic of expectations, the IAEA radiation safety principles. The following table (Table 5.3-1) presents an evaluation of the alignment achieved.

Table 5.3-1: Alignment with IAEA safety principles

Agency	Principle	Comment
IAEA	Principle 1: The prime responsibility for safety lies with the organisation responsible for facilities and activities that give rise to radiation risk.	The company has a mine closure plan as per the Minerals and Petroleum Resources Development Act and a nuclear authorisation issued in terms of the National Nuclear Regulatory A. Most of the waste practices are aligned apart from the material from a historic decommissioning activity. The management on site is only an interim solution, i.e., storage, not disposal and disposal options for intermediate level waste material are not readily available in South Africa. (Vaalputs is authorised for disposal of LLW only.) While the prime responsibility lies with the organisation, from a national perspective it is necessary for a national repository to be created where ILW can be disposed of to ensure alignment with Principles 5, 6, 7 and 8.

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Agency	Principle	Comment
IAEA	Principle 2: An effective legal and governmental framework for safety, including an independent regulatory body, must be established, and sustained.	South Africa has both the National Nuclear Regulator and the National Radioactive Waste Disposal Institute to manage and control NORM waste. Most of the fundamentals are referenced in some form of regulatory document or at least inferred, for example the methodology for public safety assessments is captured in RG-002. This document is used extensively in the safety assessment process. The national regulatory framework does require additional detail, for example control mechanisms for the period after closure to the time government assumes responsibility, i.e., initial 50-year period after closure and then the period up to when it is expected that government control also come to end, i.e., from 300 years onwards after closure.
IAEA	Principle 3: Leadership must be effective and management for safety must be established and sustained.	Although not the purpose of this document, the company does have an integrated SHEQ management system that is aligned with international standards such as ISO 14000: Environmental Management Systems. ISO systems in general provides for leadership and accountability, continuous improvement and resources. The standards in general are revised regularly providing a platform that reflects the best practice at that time. It is thus deemed appropriate.
IAEA	Principle 4: The activities that involve NORM must yield a nett benefit.	In general, NORM waste originates from some form of extraction and beneficiation activity and as such there has been some form of justification done for the project to commence. Mining activities, especially in the rural areas, play a significant role in economy. However, when considering disposal or storage options, this principle has to be applied as part of the process. The evaluation of future land-use scenarios as part of the process does create an opportunity to evaluate and influence future decisions and thus creates an opportunity to ensure an informed decision regarding nett benefit.

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Agency	Principle	Comment
IAEA	Principle 5: Protection must be optimised.	Optimisation is both a target, for example setting and using an exclusion level of 0.5 Bq.g^{-1} per isotope and a continuous process. This study is part of such a continuous improvement process and demonstrates not only mechanisms for optimisation but optimise certain aspects in, for example the safety assessment process. The principle is thus addressed but it can never be considered permanently achieved. Political, social, environmental, etc. changes may require future interventions and optimisation.
IAEA	Principle 6: No individual bears an unacceptable risk of harm.	The radiation safety assessments demonstrated that the effective dose is for most instances so low that it is exempted from regulatory control and at current levels still below the dose limit.
IAEA	Principle 7: People and the environment, present and future, must be protected against radiation risk.	With current information available, the dose assessments do not show undue risk even when considering the degradation of some of the remediation measures. Nevertheless, it should be recognised that the appetite for risk may change in future, and it is foreseen that this will require re-evaluation in future. What is currently lacking within the regulatory framework is due consideration for the environment. It is thus classified as partially achieved, but the change is required and regulatory level, not with the person responsible for the practice. This is applicable to the broader international spectrum as well.
IAEA	Principle 8: All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.	The principle relates to a “loss of control”, i.e., failures, breaches of security and/or abnormal conditions. This was not fully considered as part of this document.
IAEA	Principle 9: Measures in place for emergency preparedness and response for nuclear or radiation incidents.	The radiation levels, with the exception of the residues from the decommissioning activities, and based on safety assessments, are unlikely to create a scenario of overexposure. Nevertheless, no further considerations are given to specific emergency scenarios, such as tailings dam failure or uncontrolled intrusion into the storage facility housing the ILW.

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Agency	Principle	Comment
IAEA	Principle 10: Protective actions to reduce existing or unregulated radiation risks.	There is alignment with this expectation. This study is a consideration and evaluation of a historic and current source of NORM material that may impact on the health and wellbeing of people and/or the environment.

From the table above is it clear that this study is a necessary component in the alignment of NORM waste management with the international principles of radiation protection or, in some instances, a demonstration that these principles are met.

5.4 CONSTRAINTS, ALTERNATIVES & TOOLS

It is stated in several sections of this thesis that some of the aspects of radiation protection and regulation are well defined and entrenched within the South African mining activities, but at the same time it was also iterated that NORM waste management is not as well defined as other branches. It was thus expected that this study would bring to the fore aspects that requires additional thought or at least bring about suggestions for simplification. The sections to follow will discuss various topics in this regard, with the aim of creating dialogue and ultimately the best way forward for South Africa.

5.4.1 Dose limitations

It is not a simplistic process to define a public dose limit for the Palabora Mining Company site. The IAEA suggests a dose limit of 1 mSv.a^{-1} for members of the public which is widely accepted internationally. While South African legislation similarly refers to a dose limit for members of the public of 1 mSv.a^{-1}, a dose constraint of 0.25 mSv.a^{-1} is generally applied for current authorised actions [21]. The argument put forward (which do have merit) is that mine clusters close to the communities may lead to a condition whereby more than one authorisation holder impacts on a specific critical group and the combined exposure then lead to an exceedance of the 1 mSv.a^{-1} criteria. The dose constraint is thus applied to manage these occurrences.

Nevertheless, the dose limits / constraints referenced above are set for "practices" (current operations), but some mining and minerals processing facilities (such as Palabora Mining

Company) have been in operation for a significant number of years and the bulk of the waste facilities were developed prior to the introduction of national legislation and protection. It is thus argued that the definition for "interventions" or "existing exposure scenarios" applies to Palabora Mining Company and subsequently with a potential dose limit of 20 $mSv.a^{-1}$ set for interventions as found internationally. With Palabora Mining Company's waste disposal sites having elements of both a "practice" and an "intervention", a potential third classification or option and thus dose limit may be necessary.

It is argued that the answer lies with "justification" and "optimisation" since it applies to both "practices" and "interventions". The solution proposed is to set site-specific dose limits or reference levels for the mining complex, based on a cost benefit analysis and technology available (ALARA / optimisation). The waste management process proposed in this document supports and is aligned with such an approach.

Furthermore, through the safety assessments the process also provided the level of detail necessary to gain an understanding of specific pathways that will or will not support dose reduction.

> **As example:**
> The tailings dam is a historic activity that is also a functioning ecosystem and through the assessment it is known what the ingestion contribution from fish is to the total dose in the most likely exposure scenarios. However, with current technology and cost the purification of the tailings dam water to the extent that it will reduce the radioactive contaminants in the water and thus in the fish will be exorbitant and perhaps not even possible. It is thus unlikely that any measures introduced reactively can reduce the contribution of fish to the effective dose. Focus should then be on aspects that can be controlled, and consideration is then given to a more appropriate site-specific dose constraint provided all measures have been optimised and justified and the dose limit for intervention is not exceeded.

In summary, the Palabora Mining Company site is partially aligned with definitions of both a practice and an intervention. It is thus appropriate to use the principles of justification and optimisation to derive a site-specific dose constraint or dose limit and the process and

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associated radiation safety assessments as described allows for an informed decision in this regard.

5.4.2 Tools & criteria

The process followed is theoretically simple and should have posed few constraints during execution. However, several questions came to the fore that were not specifically within the objective of this study or alternatively an opportunity emerged for the development of a tool to assist with future assessments.

The following sections will discuss these viewpoints in more depth and offering suggestions for future consideration.

• Waste classification tool:	Justification of a decision-making tool (Section 5.4.2.1)
• Optimisation:	Application of a fundamental principle (Section 5.4.2.2)
• Remediation practices:	Impact of specific activities (Section 5.4.2.3)
• Environmental consideration:	Application of a fundamental principle (Section 5.4.3)
• Inclusion / exclusion of isotopes:	Justification of a national decision (Section 5.4.4)
• Setting an exclusion level:	Justification of a national decision (Section 5.4.5)

5.4.2.1 Rapid waste classification tool

GSG-1 does provide the necessary guidance to classify radioactive waste and the guidance note presents a combination of inferred specific activity, descriptive parameters and effective dose for final classification [13]. While technically accurate and appropriate, a comprehensive safety assessment may not be appropriate for planning and regulatory purposes and a simplified means of rapid classification is generally more desirable. For such a simplification, a flow diagram for waste classification is proposed based on the IAEA guidelines to provide a simple screening instrument using nuclide specific activities of NORM or other rapid means of activity determination where possible.

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The following sections are based on an interpretation of GSG-1, provide justification for the proposed tool, and also support the waste classification in Section 5.2.

5.4.2.1.1 EW

Legislation generally provides for clear guidance in terms of exclusion. The broader international community accepts 1 $Bq.g^{-1}$ per isotope, while South Africa use 0.5 $Bq.g^{-1}$ per isotope. The specific activity level for EW is thus set on 0.5 $Bq.g^{-1}$ per isotope for the naturally occurring isotopes.

5.4.2.1.2 VSLW

This criterion is also uncomplicated to justify. A simple nuclide specific analysis should provide the necessary information regarding isotope content and thus decay rates. If the material is made up of short-lived isotopes that is exceeding 0.5 $Bq.g^{-1}$ per isotope but will in 30 years be less than 0.5 $Bq.g^{-1}$ per isotope, it is classified as VSLW. The type of containment will depend on the physical properties, activity, type of radiation emitted and so forth. Containment is then seen as “Storage” as it will be released as exempted waste in 30 years.

5.4.2.1.3 VLLW

In the IAEA system, VLLW is defined as waste with activity concentrations slightly above exclusion levels. When defining VLLW, GSG-1 specifically refence NORM waste from mining and minerals processing and suggests defining acceptance criteria but cautioned that criteria will depend on site specific conditions. It also suggests one or two orders of magnitude above the exempt criteria.

Furthermore, from the assessment in Chapter 4 and further discussed in Chapter 5, waste with a specific activity of around 1 $Bq.g^{-1}$ per isotope creates a radiation risk of around 1 $mSv.a^{-1}$. Considering historical mining residues may be managed with a dose up to 20 $mSv.a^{-1}$, it is suggested that an upper limited of around 10 $Bq.g^{-1}$ per isotope for NORM waste to be considered for VLLW. This is both aligned and conservative.

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It should be remembered that the 10 Bq.g^{-1} per isotope is a suggested classification value and the final controls as appropriate only justified through a site-specific assessment process against the dose limits imposed by the regulator.

5.4.2.1.4 LLW and ILW

With the range of VLLW from 0.5 Bq.g^{-1} per isotope to 10 Bq.g^{-1} per isotope and high-level waste material as defined in Section 5.4.1.5, it is safe to suggest criteria for LLW and ILW. As recommended by GSG-1 and combined with the decision of VLLW, the following is set for LLW and ILW provided it does not trigger the criteria for HLW.

- LLW = >10 Bq.g-1 per isotope, but dose rate < 2 mSv.h-1
- ILW = >10 Bq.g-1 per isotope and dose rate > 2 mSv.h-1

5.4.2.1.5 HLW

Generally spent nuclear fuel and not found with NORM mining and minerals processing facilities. The activities exceed 10^4 TBq.m^{-3} and it also generates significant quantities of heat.

5.4.2.1.6 Rapid screening tool

Based on the arguments in Section 5.4.2.1.1 to Section 5.4.2.1.5, the following flow diagram (based on GSG-1) was developed to assist in the classification of waste.

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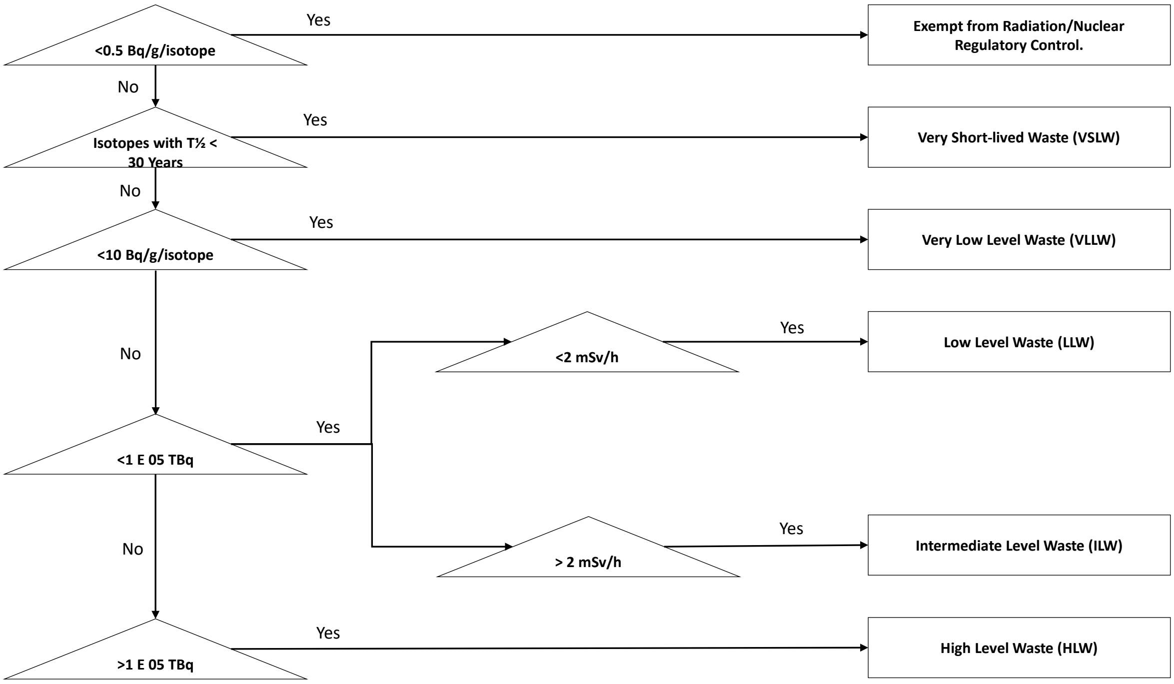

Figure 5.4.2.1.6-1: NORM waste management classification decision tree

As seen from the above, the outcome presents a rapid means of determining the class of radioactive waste and thus broadly what the remediation measures should be. This should assist with current site evaluations and in the planning of future developments.

5.4.2.2 Optimisation

5.4.2.2.1 General

Protection must align with the ALARA principle but also required is a “graded approach” when applying radiation protection measures. A “graded approach” by definition requires appropriate action according to the magnitude of the risk. The onus is thus placed on the determination of the effective dose, and it cannot be said that ALARA is achieved if the dose is grossly over- or underestimated.

Even though presented as an “interim regulatory guide”, RG-0026 in Sections 5.2, 6 and 7(3) supports the arguments for justification and optimisation, as well as site specific dose limits, called “reference levels”.

The challenge is that achieving regulatory compliance does not necessarily mean that ALARA (optimisation) has been achieved. It only demonstrates adherence to Principle 6

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(Section 2.3.1.1). On the other hand, it is also difficult to describe or uphold ALARA beyond a legislative constraint as it depends on a number of variables such as the availability of technology, financial means of the entity responsible for the waste and so forth. Regular reviews (risk assessments, control measures, evaluation of possible appropriate remediation technologies etc.) will at least demonstrate a consideration for continuous improvement and compliance.

Nevertheless, this study has highlighted several areas where further optimisation would be appropriate and of immediate value.

5.4.2.2.2 Initial optimisation

From Figure 3.3.2.4-1 in Section 3.3.2.4, the prospect is to apply some form of optimisation even in the most basic of calculations when dealing with a facility that has been in existence for some years. Some site-specific data is generally available even if only from the mandatory occupational hygiene- or environmental management programs.

Thus, the outcome of the assessments as presented in Section 4 already includes some optimisation, for example, (a) using the occupational hygiene air pollutant concentrations for the occupational inhalation dose determination, (b) for the public safety assessment including radioactive decay of the various isotopes, or (c) utilising actual fish analysis results for the fish ingestion pathway and (d) site weather information.

5.4.2.2.3 Peak dose

Furthermore, Section 4.4.4.2.11 reflects a summary of the peak doses per age group for each scenario associated with the tailings facility. This data as stated, also provides potential opportunities for optimisation. As example, Scenario 2, 3, 4 and 5 provides an effective dose less than 0.25 $mSv.a^{-1}$, while the other three scenarios, Scenario 1, 6 and 7 less than 20 $mSv.a^{-1}$. Thus, if the tailings facility is classified as a planned exposure scenario (practice) and not as an existing exposure scenario (intervention), restricted release with land use corresponding the activities defined in Scenario 2, 3, 4 and 5 post closure would be appropriate.

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5.4.2.2.4 Radon

The simplest method is to take a measurement at the receptor and then a background measurement at a suitable location. The difference is then accepted as the contribution from the practice. For the purposes of this study, a similar assumption was made where a concentration measured in town was subtracted from the radon concentration above the source. This method is very conservative as it does not consider the dilution during dispersion and is currently considered appropriate by the National Nuclear Regulator as part of the company's public monitoring program.

Nevertheless, it fails to allow for dilution during dispersion and it possibly introduces an additional significant overestimation of the effective dose as it does not consider the contribution from other practices that emit radon. Furthermore, geological formations, especially in the Phalaborwa area, may cause significant variation in natural radon concentrations. The single-source model is thus not suitable once refinement of the effective dose determination becomes necessary.

It thus creates an opportunity to re-evaluate the method for establishing the contribution from a single practice within a complex. The suggested method is not based on the difference between source and receptor but more complex:

- Define radon background.
- Model dispersion of the radon plume and not rely on measurements.

The above will be of value for scenarios such as Scenario 7 where the effective dose is above 1 $mSv.a^{-1}$. Accuracy in the contribution from radon may change the approach in applying the available resources to manage the exposure.

5.4.2.2.5 Fish

The assumption was made that the fish received its nuclide activity from a single source and the dose determined though the net activity contribution i.e., the difference in activity concentration from fish caught at the incoming and exit points from the site. This remains a very conservative assumption since the activity present in the water is not from a single source, i.e., the tailings dam, but from all practices in the complex. This approach is generally

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considered appropriate for the purposes of site management during the operational phase of the nuclear authorisation holder where all sources will contribute to the impact the operations causes. Nevertheless, on closure the site is remediated leaving only the tailings facility as the existing practice. There should thus be a reduction in the impact on water and water resources which is not considered now since current analysis results are utilised. Furthermore, the impact of a mineral-rich environment, i.e., background and background dose, needs to be understood and quantified.

It is thus necessary to fully define the aquatic interactions and ecosystems in order to better understand the contribution from a single source, i.e., the tailings dam, still within the framework of a graded approach. This is even more applicable when considering the environmental impact of waste's radioactive component.

5.4.2.2.6 Impact of water purification

It can be argued that in a worst-case scenario (such as Scenario 7) the impact of water purification should not be considered. It is a valid argument in instances where water quality is at least fit for human consumption or used in agriculture, although not necessarily of drinking water standard. However, in Phalaborwa, the groundwater quality is so poor that it was determined not fit for human and animal consumption as early as the 1940s. The table below (Table 5.4.2.2.6-1) compares some of the water quality parameters of the borehole used in this assessment with the South African national water standards. Without a comparative analysis it is assumed that the water quality is a combination of the poor background quality and contributions from the operational activities.

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Table 5.4.2.2.6-1: Some parameters reflecting groundwater chemistry as obtained from the groundwater monitoring program

Description	**Total dissolved solids**	**Conductivity**	**pH**	**Ca**	**Mg**	**Na**	**K**	**SO_4**	**Cl**	**F**
Average	2230	295	7.6	144	151	350	7.6	774	293	0.8
Drinking Water Standard	1000	150	6 - 9	80	70	400	100	400	600	3.5
Agricultural Standard	540	-	6.5 - 8.4	-	-	460	-	-	350	15

As demonstrated above, total dissolved solids exceed both the national drinking water and agriculture standards (shown red) while other contaminants such as calcium (shown in orange) exceeds at least the drinking water standard. It is thus appropriate to expect the water to be subjected to some form of purification before being fit for purpose, especially human consumption.

It is also appropriate to accept that standard water purification practices may impact on the radionuclide content of the water and potentially reducing the specific activity available for consumption. In support of this statement, consider the work that has been done in Poland on the treatment of mine water and specifically water rich in radium [29]. This study reported on two types of mine water; a type with the isotopes of radium and barium present and a second with the ions of radium and sulphates. They found that while different remediation

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measures are necessary (specifically for the sulphate-rich water) a reduction of about a factor 5 was observed for Ra-226 and a factor 8 for Ra-228.

The above does introduce another complexity (suggesting another site-specific component) namely the potential impact of water chemistry. Also, water purification may introduce a new practice that will require justification and the appropriate occupational and potential waste safety assessment(s).

To conclude, while purification of water from the boreholes is unlikely for the immediate future, consideration needs to be given to the impact of such a practice as it remains a future possibility due to potential water scarcity.

5.4.3 Environmental assessment

The environmental assessment included is very robust and the purpose was not to present a detailed and defendable assessment of the ecological impact of the tailings facility. The purpose was to provide a very basic demonstration of such an approach using default parameters of ERICA.

The assessment demonstrated that the reference screening dose rate level of 10 μGy.h^{-1} used by ERICA is exceeded for some of the reference organisms in both the Tier 1 (Table 4.4.4.3-1) and Tier 2 (Table 4.4.4.3-2) estimation. The software did recommend a detailed evaluation (Tier 3), but the necessary data was not readily available. To obtain such information will require a detailed and comprehensive study on its own and since the environmental assessment is not mandatory (nor the purpose of this study) the Tier 3 was not further considered.

In addition to the aspects associated with the system, the screening assessment does introduce an unexpected phenomenon. As indicated, it appears to exceed an internationally utilised reference value and the expectation is therefore a severely impacted ecosystem. Yet, the tailings pond is teeming with wildlife (especially on a macro level) ranging from birds and fish to crocodile and hippopotamus. It thus appears necessary not only to focus on the

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system and software, but also on an ecological level to fully quantify and qualify the impact on the environment.

Nevertheless, even such a robust evaluation does provide some value within the broader framework of this study, namely:

- Depending on the screening value, a NORM tailings facility may have a meaningful impact on eco-systems as illustrated by the Tier 1 and Tier 2 evaluation, but;
- It will be necessary to set screening limits nationally as part of legislative development.

5.4.4 Isotopes for consideration

5.4.4.1 Impact of inclusion / exclusion of isotopes

There are different paths followed when considering nuclides for inclusion in radiation safety assessments, for example, some exclude the U-235 series while others use all possible isotopes of the three naturally occurring decay series or justifying the use (or not) of specific isotopes.

According to RG-002, isotopes to consider for analysis may vary as a result of the specific activity content, pathway under investigation, type of waste and so forth. It also provides reference to the main isotopes i.e., U-238, U-234, Th-232, Th-230,Th-228, Ra-228, Ra-226, Ra-224, Po-210 and Pb-210. Rn-222 and Rn-220 are also included in the list. Furthermore, the National Nuclear Regulator in RG-002 also provides transfer factors and transfer coefficients for Pb, Po, Ra, Th and U [20]. It is thus generally assumed that these isotopes mentioned for analysis are the main isotopes for consideration, further referred to in this document as the “primary isotopes”. To establish if this assumption is appropriate, the contribution of these isotopes was compared to the contribution of all isotopes in relation to the total dose from the occupational and public safety assessments of the tailings facility. The contribution of radon (both isotopes) was excluded for a number of reasons, primarily because its impact is determined by a different assessment process as a result of its gaseous state and secondly, a specific tailing dam’s contribution to measured radon is difficult to fully quantify due to the uncertainty associated with background.

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This comparison is presented in the following table. (Of note, the timeframe used for the comparison is for conditions prior to remediation.)

Table 5.4.4.1-1: Impact of using all or some of the isotopes for safety assessments

Description	Assessment type	Age group	Estimated dose ($mSv.a^{-1}$)		Variation (%)
			All isotopes	Primary isotopes	
Tailings Dam	Occupational	>17 years	2.71E-01	2.13E-01	21%
Slag Track	Occupational	>17 years	2.63E-01	1.89E-01	28%
Magnetite Dam	Occupational	>17 years	2.79E-02	2.04E-02	27%
Scenario 1	Public	<1 year	2.82E-04	2.09E-04	26%
		1 - 2 years	7.79E-01	7.51E-01	4%
		2 - 7 years	5.17E-01	4.96E-01	4%
		7 – 12 years	4.33E-01	4.11E-01	5%
		12 - 17 years	5.23E-01	4.93E-01	6%
		>17 years	3.20E-01	3.07E-01	4%
Scenario 2	Public	<1 year	5.66E-05	4.20E-05	26%
		1 - 2 years	9.48E-05	7.09E-05	25%
		2 - 7 years	1.09E-04	8.35E-05	23%
		7 – 12 years	1.46E-04	1.14E-04	22%
		12 - 17 years	1.73E-04	1.38E-04	20%
		>17 years	1.44E-04	1.17E-04	19%
Scenario 3	Public	<1 year	1.21E-05	9.01E-06	26%
		1 - 2 years	2.04E-05	1.52E-05	25%
		2 - 7 years	2.34E-05	1.79E-05	23%
		7 – 12 years	3.14E-05	2.45E-05	22%
		12 - 17 years	3.72E-05	2.97E-05	20%

Description	Assessment type	Age group	Estimated dose (mSv.a^{-1})		Variation (%)
			All isotopes	Primary isotopes	
		>17 years	8.03E-04	6.49E-04	19%
Scenario 4	Public	<1 year	9.34E-08	6.93E-08	26%
		1 - 2 years	1.57E-07	1.17E-07	25%
		2 - 7 years	1.80E-07	1.38E-07	23%
		7 – 12 years	2.41E-07	1.88E-07	22%
		12 - 17 years	2.86E-07	2.29E-07	20%
		>17 years	2.06E-04	1.66E-04	19%
Scenario 5	Public	<1 year	0.00E+00	0.00E+00	-
		1 - 2 years	0.00E+00	0.00E+00	-
		2 - 7 years	0.00E+00	0.00E+00	-
		7 – 12 years	0.00E+00	0.00E+00	-
		12 - 17 years	0.00E+00	0.00E+00	-
		>17 years	8.20E-04	6.63E-04	19%
Scenario 6	Public	<1 year	2.63E-04	1.95E-04	26%
		1 - 2 years	1.61E+00	1.57E+00	2%
		2 - 7 years	1.02E+00	9.98E-01	3%
		7 – 12 years	7.80E-01	7.51E-01	4%
		12 - 17 years	8.34E-01	7.91E-01	5%
		>17 years	5.87E-01	5.70E-01	3%
Scenario 7	Public	<1 year	1.09E-03	3.12E-04	61%
		1 - 2 years	2.51E+00	1.49E+00	40%
		2 - 7 years	1.72E+00	1.02E+00	40%
		7 – 12 years	1.59E+00	9.62E-01	39%
		12 - 17 years	2.28E+00	1.41E+00	38%

Description	**Assessment type**	**Age group**	**Estimated dose ($mSv.a^{-1}$)**		**Variation (%)**
			All isotopes	**Primary isotopes**	
		>17 years	1.12E+00	6.65E-01	41%
Average variation (Occupational)					25%
Average variation (Public)					21%
Average variation (Total)					22%

As seen from the above, on average between 4% and 40% of the dose is not considered if selective isotopes are used with the most significant variation occurring within the estimation of public dose.

It is thus necessary to identify those isotopes that may be significant in terms of a radiation safety assessment and to achieve that desired outcome a simple process of preservation is followed. As a first step, the most affected pathways are identified (Section 5.4.4.2) and as a second step, the major contributors to dose within that particular pathway are identified (Section 5.4.4.3).

5.4.4.2 Pathways of relevance

As stated above, further comparison was then made between the contribution of the primary isotopes and all isotopes for the different pathways of the public safety assessments. The impact then expressed as percentage and the results are summarised in Table 5.4.4.2-1.

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Table 5.4.4.2-1: Variation between using primary isotopes vs all isotopes for a safety assessment

Description	<1 year	1 - 2 years	2 - 7 years	7 - 12 years	12 - 17 years	>17 years
Scenario 1						
Inhalation (Air concentration)	26%	25%	23%	22%	20%	19%
Fish	-	21%	25%	31%	41%	28%
Leafy vegetables	-	58%	60%	59%	51%	55%
Root vegetables	-	36%	38%	38%	32%	34%
Cereal	-	34%	37%	41%	41%	35%
Fruit	-	43%	45%	46%	41%	41%
Meat	-	1%	1%	1%	1%	1%
Milk	-	4%	4%	5%	5%	4%
Poultry	-	0%	0%	0%	0%	0%
Eggs	-	1%	1%	1%	1%	1%
Scenario 2						
Inhalation (Air concentration)	26%	25%	23%	22%	20%	19%
Scenario 3						
Inhalation (Air concentration)	26%	25%	23%	22%	20%	19%
Scenario 4						
Inhalation (Air concentration)	26%	25%	23%	22%	20%	19%
Scenario 5						
Inhalation (Air concentration)	-	-	-	-	-	19%
Scenario 6						
Inhalation (Air concentration)	26%	25%	23%	22%	20%	19%
Fish	-	21%	25%	31%	41%	28%
Leafy vegetables	-	31%	34%	39%	41%	33%
Root vegetables	-	31%	34%	39%	40%	33%

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Description	**<1 year**	**1 - 2 years**	**2 - 7 years**	**7 - 12 years**	**12 - 17 years**	**>17 years**
Cereal	-	31%	34%	39%	40%	33%
Fruit	-	31%	34%	39%	40%	33%
Meat	-	0%	0%	0%	0%	0%
Milk	-	6%	7%	9%	12%	7%
Poultry	-	1%	1%	1%	2%	1%
Eggs	-	1%	1%	1%	2%	2%
Scenario 7						
Inhalation (Air concentration)	71%	71%	71%	70%	70%	69%
Drinking water (Ground)	-	30%	32%	32%	31%	31%
Fish	-	9%	11%	11%	9%	18%
Leafy vegetables	-	87%	14%	17%	23%	17%
Root vegetables	-	74%	74%	71%	67%	71%
Cereal	-	85%	86%	83%	77%	85%
Fruit	-	84%	84%	82%	77%	81%
Meat	-	40%	38%	34%	31%	38%
Milk	-	46%	45%	42%	38%	45%
Poultry	-	35%	35%	35%	35%	35%
Eggs	-	18%	19%	20%	22%	21%

It is clear that for certain pathways, the use of all isotopes or not is significant as demonstrated by the percentage variation. It is important to note that the external exposure from immersion in a semi-infinite cloud source is negligible in terms of the total dose and therefore irrelevant whether a particular isotope is excluded or not.

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5.4.4.3 Isotopes of relevance

To preserve the most significant isotopes contributing to the total dose from a specific pathway, the isotopes doses of each relevant pathway were ranked from the highest to the lowest and the Top 10 summarised in Table 5.4.4.3-1.

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Table 5.4.4.3-1: Ranked contributors to total dose

Scenario	Pathway	1	2	3	4	5	6	7	8	9	10
1	Inhalation	Th-230	Ac-227	Pa-231	Th-232	Th-228	Po-210	Pb-210	U-234	U-238	U-235
	Fish	Po-210	Pb-210	Ac-227	Ra-228	Pa-231	Ra-226	Th-230	U-234	U-238	Th-232
	Leafy vegetables	Pb-210	Ra-226	Po-210	Ra-228	Th-230	U-234	U-238	U-235	Ac-227	Pa-231
	Root vegetables	Ra-226	Pb-210	Po-210	Ra-228	Th-230	U-234	U-238	U-235	Ac-227	Pa-231
	Cereal	Po-210	Pb-210	Ra-226	Th-230	Ra-228	U-234	U-238	U-235	Ac-227	Pa-231
2	Inhalation	Th-230	Ac-227	Pa-231	Th-232	Th-228	Po-210	Pb-210	U-234	U-238	U-235
3	Inhalation	Th-230	Ac-227	Pa-231	Th-232	Th-228	Po-210	Pb-210	U-234	U-238	Ra-226
4	Inhalation	Th-230	Ac-227	Pa-231	Th-232	Th-228	Pb-210	Pb-210	U-234	U-238	U-235
5	Inhalation	Th-230	Ac-227	Pa-231	Th-232	Th-228	Pb-210	U-234	Po-210	U-238	U-235
6	Inhalation	Th-230	Ac-227	Pa-231	Th-232	Th-228	Po-210	Pb-210	U-234	U-238	U-235
	Fish	Po-210	Pb-210	Ac-227	Pa-231	Ra-228	Ra-226	Th-230	U-234	U-238	Ra-223
	Leafy vegetables	Po-210	Pb-210	Ra-226	Th-230	Ra-228	U-234	U-238	U-235	Ac-227	Pa-231
	Root vegetables	Po-210	Pb-210	Ra-226	Th-230	Ra-228	U-234	U-238	U-235	Ac-227	Pa-231

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Scenario	Pathway	1	2	3	4	5	6	7	8	9	10
	Cereal	Po-210	Pb-210	Ra-226	Th-230	Ra-228	U-234	U-238	U-235	Ac-227	Pa-231
	Fruit	Po-210	Pb-210	Ra-226	Th-230	Ra-228	U-234	U-238	U-235	Ac-227	Pa-231
7	Inhalation	Th-230	Po-210	U-234	U-238	Ra-226	Pb-212	Bi-212	Th-231		
	Drinking water	U-234	Po-210	U-238	Ra-226	Th-230	Pb-212	Th-231			
	Fish	Pb-210	Po-210	Ra-228	Ra-226	Th-230	Th-232	Th-228	U-234	U-238	Ra-224
	Leafy vegetables	Ra-226	U-234	Po-210	U-238	Th-230	Pb-212	Th-231	Bi-212		
	Root vegetables	Ra-226	Po-210	U-234	U-238	Th-230	Th-231	Pb-212	Bi-212		
	Cereal	Ra-226	Po-210	Th-230	U-234	U-238	Th-231	Pb-212	Bi-212		
	Fruit	Ra-226	U-234	Po-210	U-238	Th-230	Th-231	Pb-212	Bi-212		
	Meat	Po-210	Ra-228	Ra-226	U-234	U-238	Pb-210	Th-230	Th-232	Th-228	Ra-224
	Milk	Po-210	Ra-228	Ra-226	Pb-210	U-234	U-238	Ra-224	Th-230	Th-232	Th-228
	Poultry	Po-210	U-234	U-238	Ra-226	Pb-210	Ra-228	Th-230	Th-232	Ra-228	Ra-224
	Eggs	Po-210	U-234	U-238	Th-230	Ra-226					

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Contemplating the above, it is clear that the following isotopes (sometimes excluded because they are not considered isotopes of relevance) also appears to contribute meaningfully to the effective dose of this public safety assessment:

- U-238 Series: No additional isotopes of relevance.
- U-235 Series: U-235; Th-231; Ac-227; Pa-231; Ra-223
- Th-232 Series: Pb-212; Bi-212

Thus, considering only the perceived "primary" isotopes when assessing dose may lead to a significant misrepresentation of the impact from mining activities and as demonstrated underestimating it significantly, in some instances by more than 30%. While there may be others, two of the primary reasons for this finding are:

- Site specific processes impact each element differently (depending on the physical and chemical properties of the element) leading to daughter isotopes not in secular equilibrium with the parent isotope, and;
- Dose conversion factors showing a significant variance thus a lesser specific activity may have a significant impact.

It is thus difficult to justify in advance which isotopes can be excluded from an assessment without potentially influencing the outcome of such assessment. The use of primary isotopes exclusively should only be considered if the aim is a rapid screening assessment and subsequently any form of optimisation attempted should include all isotopes or at least as many isotopes as possible. This recommendation is supported by a study [9] done in Canada that reached a similar conclusion. Considering theoretical and site-specific data for environmental assessments, they found that the outcome contradicts the common perception that the contribution from U-235 is negligible and also suggested areas of potential focus to fully understand the findings.

Current commercial analysis techniques, however, do not analyse all isotopes directly and different methods are used to incorporate the contribution from each isotope in the decay chain, for example:

- Allocate the measured parent specific activity to the subsequent daughter isotopes individually; or

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- Add the dose conversion factors for the intermediate nuclides to an “effective” dose conversion factor to multiply with the parent specific activity.

Both options are basically the same and assume equilibrium between the parent and subsequent daughters, but the advantage of the first option is that it is immediately obvious which isotope and thus element is significant in terms of total dose which in turn could be relevant when deciding on the most appropriate optimisation route. It was thus the path followed in this assessment.

5.4.5 Justification of EXCLUSION criteria

Where the IAEA suggests 1 Bq.g^{-1} per isotope as an exclusion level, South Africa utilises 0.5 Bq.g^{-1} per isotope. The process described herein could potentially be used to determine if the South African criteria is an overestimation of the risk and hence potentially not aligned with the ALARA principle. To test the hypothesis, a comparison was made between the impact from the tailings dam (around 1 Bq.g^{-1} per isotope) and the magnetite stockpile (around 0.1 Bq.g^{-1} per isotope) for Scenarios 1 - 6. Scenario 7 was excluded as it is considered a hypothetical scenario where the assumptions made could skew the outcome.

This comparison was also found not to be simplistic, since some of the pathways are based on nuclide specific activity measurements with potential contribution from multiple sources/practices, for example the inhalation of radon and the consumption of fish. Removing these pathways, the impact from the remainder of the pathways were then compared and reflected in Table 5.4.5-1, where the estimated effective dose from the exempted material is presented as a percentage of the non-exempt material dose.

Table 5.4.5-1: Comparative ratio between exempt and non-exempt material

Description	<1 years	1 - 2 years	2 - 7 years	7 - 12 years	12 - 17 years	>17 years
Scenario 1	13%	77%	78%	80%	82%	79%
Scenario 2	13%	13%	13%	13%	13%	13%
Scenario 3	13%	13%	13%	13%	13%	13%
Scenario 4	-	-	-	-	-	13%

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Description	**<1 years**	**1 - 2 years**	**2 - 7 years**	**7 - 12 years**	**12 - 17 years**	**>17 years**
Scenario 5	-	13%	13%	13%	13%	13%
Scenario 6	13%	35%	34%	34%	34%	35%

Table 5.4.5-1 shows variations ranging from 13% to 82%. For the two scenarios that represent more comprehensive assessments (more relevant pathways) and should thus provide the most accurate representation, the results are inconclusive. For Scenario 1, there is little difference (about 20%) between the non-exempted and exempted material but, for Scenario 6, the difference is more significant, i.e., in the order of about 65%. The following table considers the doses incurred from the exempted material, following the effective dose determination for members of the public as expressed in Appendix B.

Table 5.4.5-2: Impact on Public from Exempt Material

Description	**<1 years**	**1 - 2 years**	**2 - 7 years**	**7 - 12 years**	**12 - 17 years**	**>17 years**
Scenario 1	3.70E-05	5.59E-01	3.74E-01	3.21E-01	4.01E-01	2.37E-01
Scenario 2	7.42E-06	1.24E-05	1.42E-05	1.89E-05	2.23E-05	1.86E-05
Scenario 3	1.59E-06	2.67E-06	3.05E-06	4.07E-06	4.80E-06	1.03E-04
Scenario 4	1.23E-08	2.05E-08	2.34E-08	3.13E-08	3.69E-08	2.65E-05
Scenario 5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.06E-04
Scenario 6	3.45E-05	5.54E-01	3.52E-01	2.66E-01	2.79E-01	2.02E-01

As seen from the above, the impact from exempt material (magnetite) is in the order of 0.25 mSv.a^{-1} to 0.5 mSv.a^{-1}. It's effect (effective dose) thus falls broadly within the same range as material with a nuclide specific activity of 1 Bq.g^{-1} per isotope (tailings), i.e., between 0.25 mSv.a^{-1} and 1 mSv.a^{-1}.

It further allows for a disconnect in the regulations between exclusion and exemption in that as demonstrated above, exempt material may not achieve the exclusion criteria. This conundrum is resolved by stating that one **or** the other can be applied, but it does support the argument for site specific dose constraints.

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The outcome is thus inconclusive and additional investigations are necessary for a possible change from 0.5 $Bq.g^{-1}$ to 1 $Bq.g^{-1}$ as the exclusion level for the South African regulatory framework.

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6 CONCLUSIONS

The right to a healthy environment is enshrined in the South African constitution, further enhanced by the basic principles set by the International Atomic Energy Agency. [31, 11] However, little guidance has been given to the practical application of legislation to the operator (especially post closure) to ensure that these legal and moral obligations are met.

Subsequently, a basic process was set (using national and international guidance) and applied to the Palabora Mining Company residue streams. This allowed for appropriate focus on and ultimately classification of the most relevant waste streams, ensuring a balanced process in managing the radiological hazard posed by the naturally occurring radionuclides. Palabora Mining Company is highly suitable for such an application as it has mature waste management activities (historic and current) that tested the hypothesis (as set in Chapter 3) on various levels.

Through the application of this study on such an arrangement it was clear that generic assumptions and decisions with regards to the management of NORM waste is inadequate as site-specific variables play a major role in the impact these waste management activities create. It also became clear that the constraints encountered, or questions raised may be relevant on a national or even international scale. The same applies to the suggested tools that were developed.

To summarise, the objectives of the thesis are thus:

- Defining a practical process (protocol) to classify and thus determine appropriate remediation. (Section 6.1)
- Consider the alignment with International Atomic Energy Agency guidance / principles to test the appropriateness of the process. (Section 6.2)
- Apply the process (protocol) using the Palabora Mining Company data (Section 6.3, Section 6.4)
- Identify or formulate tools to assist in the process. (Section 6.1; Section 6.4, Section 6.5)

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- Provide arguments for some of the decisions made during the application of the process. (Section 6.5)
- Identify constraints encountered in the application of the process. (Section 6.5)

The following sections provide short summaries of the conclusions reached.

6.1 WASTE MANAGEMENT PROCESS

The process generated is a structured process that can be applied to current and future practices as it:

- Follows a clear hazard identification, risk determination and quantification process;
- Provides waste classification aligned with international guidance and in the process a rapid waste classification screening tool is presented (Section 6.3 below);
- Gives guidance that aids optimisation and quantification of risk (Section 6.4, 6.5 and 6.6 below) and;
- Is well aligned with IAEA first principles (Section 6.2 below).

6.2 ALIGNMENT WITH FIRST PRINCIPLES

The process followed generally aligns with the first principles of the IAEA and it largely sets the tone for international best practice. The alignment is broadly summarised as follows:

- **Principle 1**: Generally aligned, but South Africa needs to develop an Intermediate Level Waste Site for disposal of some NORM waste.
- **Principle 2**: Generally aligned. South Africa does have two regulatory bodies that specifically focus on aspects of radioactive waste. What requires attention is a strategy after operations come to an end in terms of enforcement of closure remediation criteria and then maintaining it as a responsible entity after 50 years.
- **Principle 3**: Aligned. This process does take into account management accountability and responsibility within a framework of an integrated management system.
- **Principle 4**: Mining activities provide much needed work in a relatively poor part of the country and thus to the benefit of the broader community. The principle should

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also be applied when making a final decision regarding disposal of the historic waste stream from the heavy minerals plant demolition.

- **Principle 5**: Aligned, but optimisation is an evolving process and there may be an expectation to adjust measures to account for changes in political, social and technological developments.
- **Principle 6**: Aligned. Expected doses are in the order of 0.25 mSv.a-1 to 1 mSv.a-1 with remediation measures intact.
- **Principle 7**: Aligned. Expected doses are in the order of 0.25 mSv.a-1 especially in the first 100 years. However, where remediations measures deteriorate, it can increase to around 1 mSv.a-1.
- **Principle 8**: Not considered as part of this study.
- **Principle 9**: Considered to be partially aligned especially since a worst-case scenario was introduced. It does require additional work, especially within the framework of accident scenarios. (See Principle 8.)
- **Principle 10**: This study provides guidance on the evaluation of the effectiveness of remediation measures and is thus a tool to ensure alignment with this principle.

6.3 DOSE LIMITS – COMPLIANCE

It is challenging to issue a definitive statement regarding the waste facilities' compliance to dose criteria post closure within the current regulatory framework. It exceeds the South African dose constraint of 0.25 mSv.a^{-1} set for practices as described in Section 3.3.2.7 of the document, but internationally it would generally be considered acceptable (around 1 mSv.a^{-1}).

Furthermore, it is also argued that the waste activities are not a pure practice (Section 5.4.1) hence the dose constraint should not apply. It is suggested that a site-specific dose limit is set. Such a step will align the different principles, supporting legislation and should encourage the maintenance of remediation measures by allowing appropriate focus on the remediation that can be controlled. The outcome of any future radiation safety assessments will then be compared with the revised limit or constraint.

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There is one exception and that is the residues from the historic demolition activities that is currently in storage. While the dose limits are not exceeded, it is not contemplated that this material should be kept indefinitely (disposed of), and a national repository is envisaged for ILW to ensure a safe and controlled final disposal for this category of waste.

6.4 FINAL DISPOSAL CLASSIFICATION

Following the classification guidelines presented by the IAEA, the NORM waste is predominantly classified as VLLW. This classification is generally endorsed by the site-specific assessments and remediation measures employed by Palabora Mining Company appropriate for final disposal. However, it is not appropriate to automatically assume NORM waste is VLLW without a site-specific assessment or evaluation, as the remnants from a historic demolition activity demonstrated that at least some of the waste streams can be LLW or even ILW, requiring additional engineering and management controls for disposal.

6.5 CONSTRAINTS, ALTERNATIVES AND TOOLS

6.5.1 Optimisation

Optimisation is a combination of ensuring effective and cost-effective protection measures but must also include attempts to reduce the uncertainty associated with the dose determination introduced by an overly conservative assumptions, lack of validated and quality site specific data and so forth. This study was not a pure theoretical assessment as it introduced critical sets of measured data such as the weather information, air concentration above the dams, nuclide specific analysis of receptor environments, etc. The remediation measures were also considered in the assessment and as such it represents a fair reflection of impact of the site. Some optimisation has thus been introduced, but the process also identified areas for further optimisation, such as a radon study.

It is thus envisaged that regular reviews will introduce the outcome of these studies, consider new technology and potential changes to societal expectations and bring about change in the control measures where appropriate, i.e., continuous optimisation. This process should

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typically be captured in the regulatory framework, especially how it will be dealt with above 50 years when the site handed over to the regulatory authority to manage.

6.5.1.1 Practice or intervention

The Palabora Mining Company activities align to the definitions of both a practice and intervention, creating a situation where the dose limit of the site can be debated. The study has shown that if optimisation is applied, it is appropriate to justify a site-specific dose limit or dose constraint. Furthermore, the justification of this site-specific dose constraint is possible should the process be followed.

6.5.2 Isotopes for consideration

Utilising only some of the isotopes for an assessment is appropriate for a rapid screening evaluation of the risk. Where optimisation of the dose becomes relevant, so too does the need to include isotopes of all three of the naturally occurring radioactive decay series. Standard practice of utilising the nuclide specific activity of the nearest measured isotope is then appropriate.

6.5.3 Justification of EXCLUSION criteria

This assessment could not conclusively demonstrate that a relaxation of the exclusion level of 0.5 $Bq.g^{-1}$ per isotope to 1 $Bq.g^{-1}$ per isotope is justified. More work is required in this regard.

6.5.4 Rapid screening tool

To assist with the classification of radioactive waste during planning, auditing or when rapid decision-making is appropriate, a screening tool (Figure 5.4.2.1.6-1) was developed.

6.5.5 Environmental assessments

The ERICA software does indicate that a tailings facility may exceed at least the internationally utilised referenced screening limit of 10 $\mu Gy.h^{-1}$. Without legislation or guidance in this regard (national and international) it is difficult to predict the potential impact this may have in future on site remediation and control measures. However, the

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development of radiological environmental legislation for South Africa should be considered as urgent due to the complexities and subsequent impact on a possible timeline to set such criteria.

6.5.6 Site-specific criteria

This study has demonstrated that a generic assessment or pre-determined criteria are not appropriate when considering complex mining and minerals processing activities. Differences in critical groups, background, different extraction processes, age of the site and so forth all contribute to site-specific criteria, aspects that need to be considered for an optimised process and for the justification of decisions made.

6.6 SUMMARY

The quantitative and qualitative process ensured a structured process that is aligned with or will ensure alignment with international and national expectations. While the process in itself is a tool, the waste classification decision tree further assists in this regard. The outcome is the successful classification of the radioactive waste streams and a comprehensive estimate of effective dose both occupational and public due to radioactive waste.

The process demonstrates opportunities for optimisation at various stages of the assessment process, while providing justification for key decisions made, for example the justification to use all isotopes in an assessment process.

Finally, the structured process allowed for the identification of constraints and areas of further study, as summarised in Section 7 of this document.

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7 RECOMMENDATIONS

This document brought to the fore a significant number of questions, constraints and/or concerns that could form the basis of further study and/or development. In no particular order:

- The IAEA definition of a "practice" only refers to human exposure. With the developments in the determination of an "environmental impact", it is suggested that consideration be given to include it in the definition as well. While this is an issue of international interest, the system is not as prescriptive as to exclude inclusion in national legislation.
- In line with accepting the consideration for an environmental impact, develop local standards aligned with international practices for environmental radiation protection.
- The contribution of radon from various practices in and around Phalaborwa needs to be quantified. The current practice of determining the net difference between concentration at source and receptor as the radon contribution from that source is not appropriate and potentially disproportionately conservative. In this instance it is advised that radon distribution modelling be considered to estimate radon contribution.
- It is expected that most of the South African mining and minerals processing waste will follow a similar pattern as found at Palabora Mining Company. It is therefore likely that most of the waste will be classified as VLLW, and it is thus suggested that a wider range of minerals be evaluated to determine if the suggested 10 Bq.g-1 upper limit as a screening activity for VLLW is appropriate.
- A disposal site for NORM ILW in South Africa is required. With uranium extraction activities common or at least historically common as a co-process of gold extraction, it is unlikely that Palabora Mining Company is the only site with other extraction processes that may lead to elevated levels of radiation, especially with scales and residues. It is thus recommended that a national repository be created for disposal should the current Vaalputs facility not be suitable to also receive ILW.

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- This study did not consider accident scenarios. It is suggested that a set of potential scenarios are created and considered specifically to ensure consideration for Principles 8 and 9 of *SF-1: Safety Standard- Safety Fundamentals*.
- As part of the environmental monitoring program as generated by the public safety assessment, various biota is collected for nuclide specific analysis. Where possible, determine site specific transfer coefficients, KD factors and bioaccumulation factors from these data to optimise the risk model. (See Section 3.3.2.1 of this document.)
- Conduct a detailed study utilising various site-specific scenarios and associated data to determine the most appropriate exclusion level for NORM management in South Africa.
- Consider revising RG-0026 and align with regulatory developments. Give due consideration for management of NORM waste post closure. (See Section 2.3.2.5.1 for more detail.)
- Introduce continuous optimisation in a regulatory waste management framework post closure.

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APPENDIX A

The nuclide specific analysis was conducted by an external laboratory, (RadioAnalysis), from NECSA. The laboratory is currently a SANAS accredited laboratory, but it is not clear when the laboratory achieved accreditation. Since some of the analysis dates back to 1994, no reference to the laboratory accreditation nor specific method reference number is thus given. The following table, Table A-1 summarises the analysis methodologies followed by the laboratory.

Table A-1: Laboratory analysis methods for solids and liquids

Parameter	Method
Solid samples	
Gross alpha activity	Gross alpha/beta analysis
Gross beta activity	Gross alpha/beta analysis
Uranium	Neutron activation analysis
Thorium	Neutron activation analysis
Ra-226	Gamma spectrometry
Ra-228	Gamma spectrometry
Th-228	Gamma spectrometry
Pb-210	Low energy gamma spectrometry
Liquid samples	
Gross alpha activity	Gross alpha/beta analysis
Gross beta activity	Gross alpha/beta analysis
Uranium	Alpha spectrometry
Thorium	Alpha spectrometry
Radium	Alpha spectrometry
Po-210	Alpha spectrometry
Pb-210	Alpha spectrometry

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The following table, Table A-2, provides the required reference to the analysis results used in the assessment of risk as described in this document.

Table A-2: Laboratory reference numbers for nuclide specific analysis used in this study

Material	Laboratory reference number	Date of report
Production		
Tailings	RA-06765	30/12/2005
	RA-09413	27/11/2008
	RA-12937	27/07/2012
	RS2018-3064-01	20/12/2018
Magnetite	RA-06765	30/12/2005
	RA-09413	27/11/2008
	RA-12937	27/07/2012
	RA-07712	05/09/2012
	RS2015-1119-02	04/11/2015
	RS2018-3064-01	20/12/2018
Waste Rock	RA-09413	27/11/2008
	RA-12937	27/07/2012
	RS2017-1880-01	24/08/2017
	RS2018-3064-01	20/12/2018
Slag / Reverts	RA-12937	27/07/2012
	RA-07712	05/09/2012
	RS2015-1119-02	04/11/2015
	RS2018-3064-01	20/12/2018
Anode Slimes	RA-12624	06/06/2012
	RA-07712	05/09/2012
	RS2015-4261-02	31/05/2016

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Material	Laboratory reference number	Date of report
	RS2018-3064-01	20/12/2018
Environment		
Soil	RS2015-3954-01	30/03/2016
Waste Rock Dump Seepage Water	RA-16079-02	22/09/2014
	RS2015-1118-02	30/01/2015
Borehole B06	RA05839	22/10/2004
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Borehole B11	RA01166-1	06/05/1997
	RA01252/3	30/06/1997
	RA01410	30/10/1997
	RA01469	31/10/1997
	RA05839	22/10/2004
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015

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Material	Laboratory reference number	Date of report
	RS2018-3065-01	14/12/2018
Borehole B12	RA05839	22/10/2004
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Borehole B16	RA05839	22/10/2004
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
Borehole B20	RS2018-3065-01	14/12/2018
Borehole B22	RA01166-1	06/05/1997
	RA01252/3	30/06/1997
	RA01410	30/10/1997
	RA01469	31/10/1997
	RA05839	22/10/2004
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009

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Material	Laboratory reference number	Date of report
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Borehole B24	RA01166-1	06/05/1997
	RA01252/3	30/06/1997
	RA01410	30/10/1997
	RA01469	31/10/1997
	RA05839	22/10/2004
	RA-09412	03/04/2009
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Surface water: Selati In	RA159	1/07/1994
	RA403-1	10/1995
	RA05839	22/10/2004
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Surface water: Selati out	RA159	1/07/1994
	RA403-1	10/1995
	RA05839	22/10/2004

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Material	Laboratory reference number	Date of report
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Surface water: Olifants River	RA159	1/07/1994
	RA05839	22/10/2004
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Wastewater: Tailings dam (RWTD)	RA159	1/07/1994
	RA403-1	10/1995
	RA05839	22/10/2004
	RA 06645	09/12/2005
	RA-07754	21/12/2007
	RA-08692	22/09/2008
	RA-09412	03/04/2009
	RJ2009-0433	30/03/2010

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Material	**Laboratory reference number**	**Date of report**
	RA-13845-01	24/07/2013
	RS2015-1118-02	30/01/2015
	RS2018-3065-01	14/12/2018
Fish	RA403-1	10/1995
	RA159	1/07/1994

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APPENDIX B

The following basic calculations support the processes within the document.

$$E = C \text{ x } R \text{ x } DF \qquad \text{[Eq.4]}$$

Where

E	Effective dose	Sv
C	Concentration	Unit depending on specific calculation.
DF	Dose Conversion Factor	Unit depending on specific calculation.
R	Rate or exposure period	Unit depending on specific calculation.

B.1.1 Occupational Exposure

$$Effective\ Dose = Hp(d) + \sum e(g)_{j.ing}\, I_{j.ing} + \sum e(g)_{j.inh}\, I_{j.inh} \qquad \text{[Eq.3]}$$

Where:

$Hp(d)$	Equivalent dose from external radiation [3]	Sv
$e(g)_{j.ing}$	Committed effective dose per unit intake via ingestion	$Sv.Bq^{-1}$
$I_{j.ing}$	Activity intakes via ingestion	Bq
$e(g)_{j.inh}$	Committed effective dose per unit intake via inhalation	$Sv.Bq^{-1}$
$I_{j.inh}$	Activity intakes via inhalation	Bq

But:

- Ingestion dose is not considered since lunchrooms are available to employees and contractors, and;
- External dose rate is measured.

B.1.2 Inhalation

$$E_{inh} = \sum_i C_{Ai} R_{inh} DCF_i \qquad \text{[Eq. 10]}$$

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Where:

E_{inh}	Annual effective dose from inhalation [27; 28]	$Sv.a^{-1}$
C_{AI}	Concentration of nuclide I (See Section 3.3.1.2)	$Bq.m^{-3}$
R_{inh}	Inhalation rate [30]	$m^3.a^{-1}$
DCF_i	Committed effective dose per unit intake via inhalation [3]	$Sv.Bq^{-1}$

As example:

The U-238 specific activity of tailings is 1.187 Bq.g^{-1}, but the air concentration of respirable dust in the area is 0.0008232 g.m^{-3} (8.23E-04 g.m^{-3}) as determined by the occupational hygiene monitoring program. The inhalation rate of an adult is 1.2 m^3.h^{-1} and duration of exposure is accepted as 2000 working hours per annum. The dose conversion factor is 5.8E-07 Sv.Bq^{-1}. The isotope contribution to the total effective inhalation dose is therefor:

= 1.187 Bq.g^{-1} x 0.0008232 g.m^{-3} x 1.2 m^3.h^{-1} x 2000 h x 5.80E-07 Sv.Bq^{-1}

= 1.36E-03 mSv.a^{-1}

B.1.2. External gamma dose rate

External gamma dose rate is measured directly with duration of exposure the only other determining factor. Eq. 4 thus translate to the following:

$$E_{Ext} = E_{EDR}t$$

Where:

E_{Ext}	Effective dose from external gamma radiation	$Sv.a^{-1}$
E_{EDR}	External dose rate (measured)	$Sv.h^{-1}$
t	Duration of exposure for the year [20]	h

B.2 PUBLIC EXPOSURE

The public exposure is more complex, with various pathways ultimately determining the effective dose to members of the public. It is therefore appropriate to express these pathways in a flow diagram. (See Section 4.4.4.2.2 and Figure 4.4.4.2.2-1.)

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B.2.1 External dose

The following flow diagram is an extraction for Figure 4.4.4.2.2-1, emphasising the external dose path.

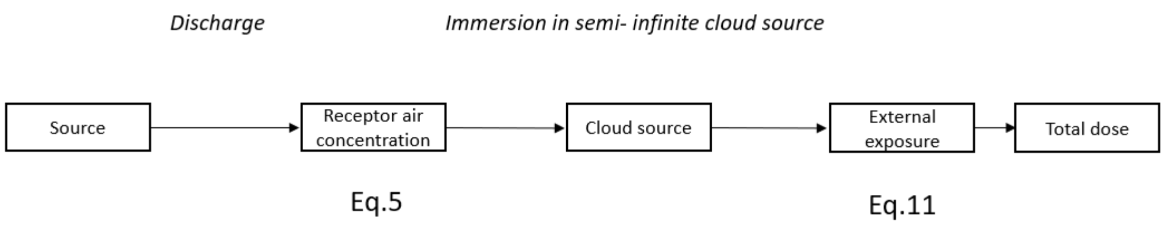

Figure B.2.1-1: Determination of effective dose from external exposure to members of the public

$$C_A = \frac{P_p Q}{V} \qquad \text{[Eq. 5]}$$

Where:

$C_{A.}$	Radionuclide concentration [19]	Bq.m^{-3}
Q	Average discharge rate	Bq.s^{-1}
V	Volumetric air flow rate at point of release [19]	m^3.s^{-1}
P_p	Fraction of the time the wind blows towards the receptor – Obtained from the Palabora Mining Company weather data	dimensionless

For the purpose of this study, an average discharge rate as determined by a study of mine tailings facilities around Gauteng was used. (Studies not published.)

$$E_T = \sum_i h_i C_{Ai} t \qquad \text{[Eq. 11]}$$

Where:

E_t	Effective dose from all isotopes [32]	Sv
h_i	Coefficient for air submersion for isotope *i* [32]	Sv per Bq.s.m^{-3}
C_{Ai}	Radionuclide concentration for isotope *i*	Bq.m^{-3}
t	Duration of exposure	s

B.2.2 Inhalation

The determination of the inhalation contribution to effective dose is similar to the determination of the occupational inhalation dose (Eq. 3 and Eq. 10) but an added step is necessary, i.e., Eq. 5.

B.2.3 Ingestion

The following flow diagram is an extraction for Figure 4.4.4.2.2-1, emphasising the effective dose from ingesting food and / or water:

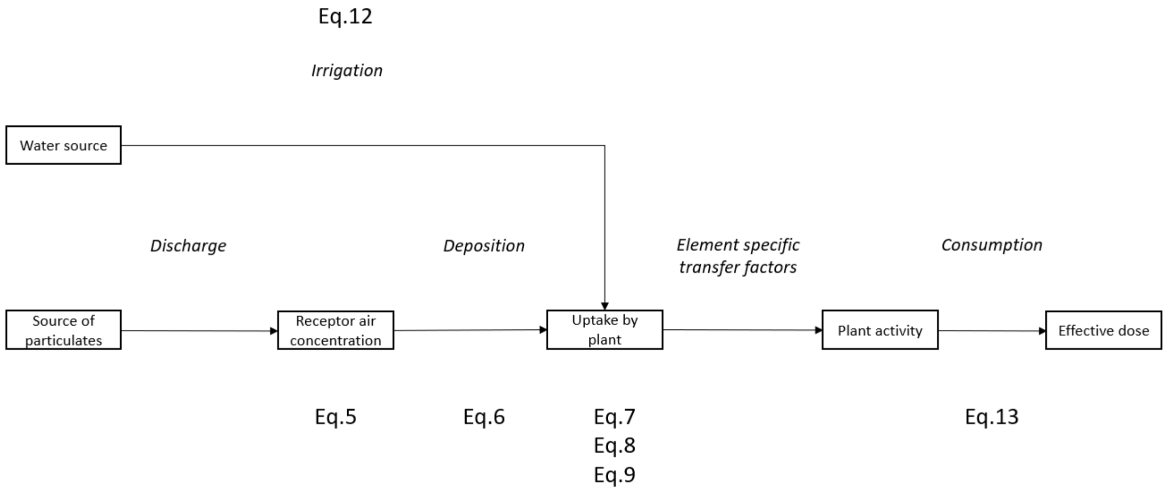

Figure B.2.3-1: Determination of effective dose from ingestion (fruit, vegetables, cereals) to members of the public

$$E_{ing.p} = C_{p.i} H_p DF_{ing} \qquad [Eq.13]$$

Where:

$E_{ing.p}$	Annual effective dose from consumption of nuclide *i* in foodstuff *p* [19]	Sv.a^{-1}
$C_{p.i.}$	Concentration of radionuclide *i* in foodstuff *p*.	Bq.kg^{-1}
H_p	Consumption rate for foodstuff *p* [19; 20]	kg.a^{-1}
DF_{ing}	Dose coefficient for ingestion of radionuclide *i* [19; 20]	Sv.Bq^{-1}

Discharge

The ingestion dose commences with the discharge of air particulates from the source, resulting in an air concentration of radioactive isotopes at the receptor (expressed by Eq. 5) that is then deposited.

Deposition

Deposition of the air concentration at the receiving environment is then considered as follows:

$$d_i = (V_d + V_w)C_A \qquad \text{[Eq. 6]}$$

Where:

d_i	Deposition rate	Bq.m^{-2}d^{-1}
$C_{A.}$	Radionuclide concentration	Bq.m^{-3}
$V_d + V_w$	Deposition coefficient (V_T) [19]	m.d^{-1}

Following from the deposition, there is uptake by the plant through two separate processes.

Vegetation - Direct concentration

$$C_{v.i.1} = \frac{d_i \alpha\left[1 - exp\left(-\lambda_{E_i^v} t_e\right)\right]}{\lambda_{E_i^v}} \qquad \text{[Eq. 7]}$$

Where:

$C_{v.i.1.}$	Concentration due to direct contamination on vegetation	Bq.kg^{-1}
A	Interception fraction	m^2.kg^{-1}
d_i	Deposition rate	Bq.m^{-2}d^{-1}
$\lambda_{E_i^v}$	Effective rate constant for reduction of activity concentration	d^{-1}
t_e	Hold-up time between harvest and consumption	d

Vegetation - Indirect concentration

$$C_{s.i.2} = F_v \frac{\left(d_i\left[1-exp\left(-\lambda_{E_i^s} t_b\right)\right]\right)}{\rho \lambda_{E_i^s}} \qquad \text{[Eq. 8]}$$

Where:

$C_{v.i.2.}$	Concentration of radionuclides due to indirect processes, such root uptake from soil	Bq.kg^{-1}
d_i	Deposition rate	Bq.m^{-2}d^{-1}
$\lambda_{E_i^s}$	Effective rate constant for reduction of activity concentration in the root zone	d^{-1}
t_b	Duration of discharge	d
P	Standardise surface density for the effective root zone in soil	kg.m^{-2}
F_v	Concentration factor for uptake from soil by edible parts of crops	Bq.kg^{-1} plant tissue per Bq.kg^{-1} dry soil

Total vegetation

The two plant pathways are then combined as follows:

$$C_{v.i.} = (C_{v.i.1.} + C_{v.i.2.})exp(-\lambda_t t_h) \qquad \text{[Eq. 9]}$$

Where:

$C_{v.i.}$	Total concentration of radionuclides in vegetation	Bq.kg^{-1}
$C_{v.i.1.}$	Concentration due to direct contamination on vegetation	Bq.kg^{-1}
$C_{v.i.2.}$	Concentration of radionuclides due to indirect processes, such root uptake from soil	Bq.kg^{-1}
λ_i	Radioactive Decay Constant	d^{-1}
t_h	Hold-up time between harvest and consumption	d

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Irrigation may also contribute to the radionuclide uptake of the plant or animal, depending on the source of irrigation. For Scenarios 1 – 6 it was assumed that the source of water is from a utilities service provider, unaffected by the mining and minerals processing activities. Scenario 7 however, assumes irrigation from a borehole that is affected by the tailings facility, hence needs to be considered for the determination of effective dose.

$$d_i = C_{w.i} I_w \qquad \text{[Eq.12]}$$

Where:

$d_{.i.}$	Deposition rate	$Bq.m^{-2}d^{-1}$
$Cw_{.i.}$	Concentration of nuclide i in water.	$Bq.kg^{-1}$
I_w	Average irrigation rate	$m^3.m^{-2}.d^{-1}$

The deposition rate due to irrigation is then applied, using Eq.7, Eq.8 and subsequently Eq.9 again.

B.2.4 Secondary food

Secondary food refers to food (meat, milk, poultry, eggs) where there is first an uptake by the animal feed (Eq.9) and then a differential uptake by the animal. The following flow diagram is an extraction for Figure 4.4.4.2.2-1, emphasising these pathways.

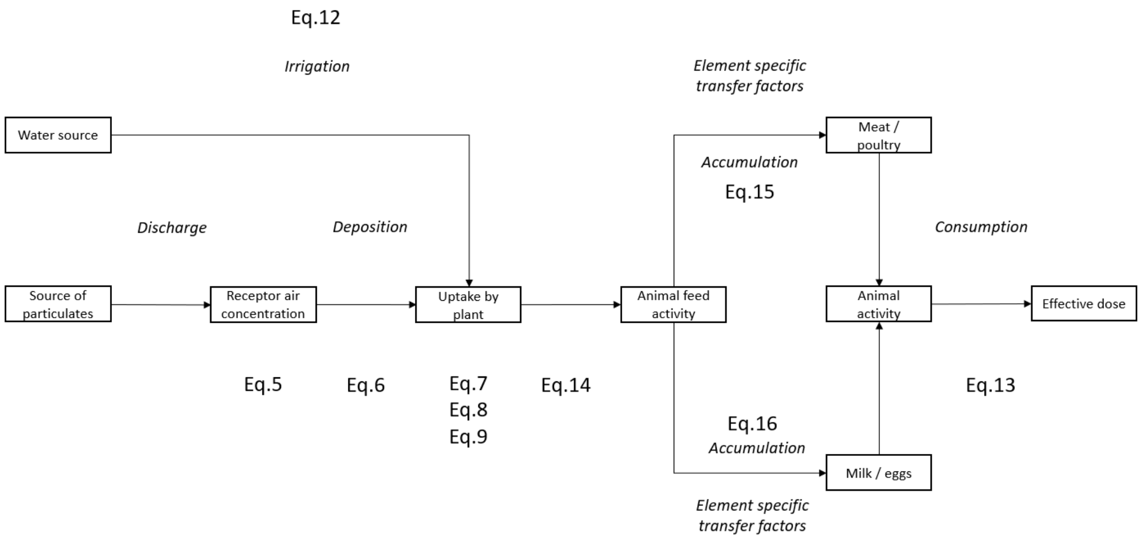

Figure B.2.4-1: Determination of effective dose from ingestion (meat, milk, poultry, eggs) to members of the public

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$$C_{a.i} = f_p C_{v.i} + \left(1 - f_p\right) C_{p.i} \qquad \text{[Eq.14]}$$

Where:

$C_{a.i.}$	Concentration of radionuclide *i* in animal feed [19]	$\mathrm{Bq.kg^{-1}}$
$C_{w.i.}$	Concentration in pasture [Eq.9]	$\mathrm{Bq.kg^{-1}}$
$C_{p.i.}$	Concentration in stored feeds [Eq.9]	$\mathrm{Bq.kg^{-1}}$
f_p	Fraction of the year the animals consume fresh pasture	dimensionless

From the above, the basic equation for the concentration of radionuclides in meat is the following:

$$C_{f.i} = F_m\left(C_{a.i} Q_f + C_{w.i} Q_w\right) exp\left(-\varphi_i t_f\right)$$

Where:

$C_{f.i.}$	Concentration of radionuclide *i* in animal flesh [19]	$\mathrm{Bq.kg^{-1}}$
F_m	Fraction of animal's daily intake of a radionuclide that appears in each kg of flesh [19; 20]	$\mathrm{d.kg^{-1}}$
$C_{a.i.}$	Concentration of nuclide *i* in animal feed [Eq.14]	$\mathrm{Bq.kg^{-1}}$
$C_{w.i.}$	Concentration of nuclide *i* in water	$\mathrm{Bq.m^{-3}}$
Q_f	Amount of feed consumed by the animal per day [19; 20]	$\mathrm{kg.day^{-1}}$
Q_w	Amount of water consumed by the animal per day [19; 20]	$\mathrm{m^3.day^{-1}}$
φ_i	Rate constant for radioactive decay of radionuclide *i*	$\mathrm{d^{-1}}$
t_f	Time between slaughter and human consumption [19]	d

Similarly for milk or eggs:

$$C_{m.i} = F_m\left(C_{a.i} Q_f + C_{w.i} Q_w\right) exp(-\varphi_i t_m)$$

Where:

$C_{m.i.}$	Concentration of radionuclide *i* in milk [19]	$\mathrm{Bq.L^{-1}}$
F_m	Fraction of animal's daily intake of a radionuclide that appears in each litre of milk [19; 20]	$\mathrm{d.L^{-1}}$

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$C_{a.i.}$	Concentration of nuclide *i* in animal feed [Eq.14]	Bq.kg^{-1}
$C_{w.i.}$	Concentration of nuclide *i* in water	Bq.m^{-3}
Q_f	Amount of feed consumed by the animal per day [19; 20]	kg.day^{-1}
Q_w	Amount of water consumed by the animal per day [19; 20]	m^3.day^{-1}
φ_i	Rate constant for radioactive decay of radionuclide *i*	d^{-1}
t_f	Time between collection and human consumption [19]	d

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