Framework and Regulatory Guidance to Perform Safety Assesments for Mining and Mine Remediation Activities

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It all starts here ™

ABSTRACT

This study provided the opportunity to apply the source-receptor-pathway method of solving challenges. The source being the initiation point of the challenge; the pathway, being the routes towards the receptor; and the receptor, being the end point or result of the study. Potential solutions are reverted back to the pathway to be trailed to optimise the effect on the receptor.

This study attends primarily to two challenges. These challenges were identified by the National Nuclear Regulator (NNR). The challenges prevent the optimised protection of the members of the public in the natural occurring radioactive material (NORM) industry. The first being the quantification of the effects of authorised release of liquid and gaseous effluents from on-site operations to off-site locations. New national and international information are considered to enhance the efficiency of methods and criteria applied to optimise the safety of the public. Therefore, it is required to periodically review and improve the acceptance criteria and assessment methodology applied to produce results.

The second operational challenge addressed in this study is the remediation of existing exposure scenarios, such as land radiologically contaminated as a result of historical unregulated actions. Current regulations only make provision for the management of regulated actions. Secondly, because of the nature of the situation, special release criteria needed to be developed to manage these sites, which exceed current generic radiation safety criteria without allowing undue risks to members of the public. The situations for which resolutions are required differ from the current regulated situations. Therefore, a methodology, acceptable to the National Nuclear Regulator, in terms of compliance with the applied principles, was developed as a guide to provide insight in the acceptability of a methodology.

In both situations, public safety assessments and remediation, there are several other systematic hinges in the framework that must be managed before the challenges are adequately dealt with. The first hinge is the legislation that allows the operator to perform specific actions within specified boundaries. To change national legislation is a mammoth task, which is not dealt with in this context. This study, to be effective, needed to demonstrate the inadequacies in existing legislation and what can be done to improve it. The needs identified in this study are now included in proposed new regulations, as it co-insides with a NNR process of updating national standards to be published when processed and approved.

The second hinge in the framework, is all the internal processes at the National Nuclear Regulator that needed to be improved. These processes, include amongst others, development of a remediation framework, development of acceptance criteria, development of authorisation procedures and the development of a review guide for staff of the NNR, etc.

In conclusion, this study improved and made available the following:

- a revised methodology for the determination of the dose to members of the public from radioactive effluents (gaseous and liquid) released into the public domain from planned activities;
- a new methodology for the determination of the dose to members of the public from existing exposure situations;
- criteria for the release of land on existing exposure situations, after remediation from regulatory control;
- the development of a process for the authorisation of existing exposure situations;
- improvement of national regulations on the management of the dose to the public;
- the development of national regulations to manage existing exposure situations;
- tested methodologies, from scenarios compiled, to demonstrate that the assessment methodologies developed, can be effectively applied in practice; and
- a guide document, to be used by the regulator for the review of a safety assessment on the dose to the public, for planned and existing exposure situations, submitted to the regulator for approval.

In addition to the issues addressed in this study, several other challenges, which require further attention, were identified. Some of these issues are as follow:

- the release of legacy sites from regulatory control may require restrictions on future land use; it could, under specific conditions, be impossible to release land that has been remediated to the 0.5 Bq/g exclusion levels, because the modelled doses may exceed 20 mSv/a, especially where Ra-226 is a contaminant; and
- the proposed new regulations address the build-up of radio nuclides in the environment and the ingrowth of progeny, but it is not explicit on the time frames to which provisions for safety should be made;
- plant species to be suitable for commercial or economically viable phytoextraction for radioactively contaminated soils should be further investigated for South African conditions.

KEYWORDS

Remediation, existing exposure scenario, planned exposure scenario, radiation, safety assessment, review guide, mining.

PREFACE AND ACKNOWLEDGEMENTS

It was a bold step in my life to enrol for a PhD at a fairly advanced age. Such a path is a path that asks for a lot of commitment, hard work and dedication. Age usually have the advantage of a bit more maturity and a bit more time to consider things, but it also has disadvantages in the sense that the energy is not as much as it used to be and the thought process has slowed down considerably.

However, I would like to express my gratitude to the National Nuclear Regulator for giving me the opportunity to participate in the process to improve the infrastructure for the protection of the public, which is of prime importance to me.

Secondly, I would like to thank my best friend and partner, for all the indulgence and support, and effort at the end. You made things much more bearable and your assistance made an immense difference.

Lastly, to my Co-Promoter, Dr Dawid de Villiers, you are a man out of a thousand. Thank you for all the motivation and never giving up, for standing by with advice, for long nights spent in review, and all the other things that cannot be mentioned here. It is highly appreciated. This task would never have been completed if it was not for your contributions.

In closure, a life lesson from Isaiah 40: Those who wait upon the Lord will soar like eagles and they will receive strength. One morning we stopped on a little hill to enjoy the environment. At about 50 m above ground level, a pair of eagles was approaching. They were soaring in the wind, no wing movement. We watched them for about 15 minutes. The only visible body parts that moved were the head and the tail. The head moved from left to right to observe the environment, absorbing and carefully considering the information received. With the tail, the worldly challenges were managed by steering the bird through the atmosphere, up, up and away, until it disappeared in the far. Steering with consideration, not fighting. Using the turbulences of life to its advantage.

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GLOSSARY

Action is the use, possession, production, storage, enrichment, processing, reprocessing, conveying or disposal of, or causing to be conveyed, radioactive material; any action, the performance of which may result in persons accumulating a radiation dose resulting from exposure to ionizing radiation; or any other action involving radioactive material (South Africa, 1999b).

Assessment is the process, and the result, of analysing systematically the hazards associated with sources and actions, and associated protection and safety measures, aimed at quantifying performance measures for comparison with criteria (IAEA, 2007a).

Authorised action is an *action* authorised in terms of the National Nuclear Regulator Act (South Africa, 1999b).

Average member of the representative person is the individual receiving the average effective dose or equivalent dose (as applicable) in the representative person.

Collective dose is an expression for the total radiation dose incurred by a population, defined as the product of the number of individuals exposed to a source and their average radiation dose. The collective dose is expressed in person-Sievert (person-Sv) (see collective effective dose) (IAEA, 2007a).

Dose is the sum of the external and internally committed effective dose integrated over the lifetime appropriate to the identified representative person.

Dose constraint is a prospective and source-related restriction on the individual dose arising from the predicted operation of the authorised action which serves exclusively as a bound on the optimisation of radiation protection and nuclear safety (IAEA, 2007a):

(a) to limit the range of options considered in the optimisation process, and

(b) to restrict the doses via all exposure pathways to the average member of the representative person, in order to ensure that the sum of the doses received by that individual from all the controlled sources remains within the dose limit, and which, if found retrospectively to have been exceeded, should not be regarded as an infringement of regulatory requirements but rather as a call for the reassessment of the optimisation of radiation protection.

Dose limit is the value of effective dose or equivalent dose to individuals from actions authorised by a nuclear installation licence, nuclear vessel licence or certificate of registration that must not be exceeded.

Effective dose is the quantity E expressed in the unit $J \cdot kg^{-1}$, termed the Sievert (Sv), defined as the summation of the tissue equivalent doses, each multiplied by the appropriate tissue weighting factor:

$$E = \sum_T w_T \cdot H_T$$

where H_T is the equivalent dose in tissue T and w_T is the tissue weighting factor for tissue T; from the definition of equivalent dose, it follows that:

$$E = \sum_T w_T \cdot \sum_R w_R \cdot D_{T,R}$$

where w_R is the radiation weighting factor for radiation R and $D_{T,R}$ is the average absorbed dose in the organ or tissue T.

Emergency exposure situation is a situation of exposure that arises as a result of an accident, a malicious act, or any other unexpected event, and requires prompt action in order to avoid or reduce adverse consequences.

Equivalent dose is the quantity $H_{T,R}$ expressed in the unit $J \cdot kg^{-1}$, termed the Sievert (Sv), defined as:

$$H_{T,R} = D_{T,R} \cdot w_R$$

where $D_{T,R}$ is the absorbed dose delivered by radiation type R averaged over a tissue or organ T and w_R is the radiation weighting factor for radiation type R; when the radiation field is composed of different radiation types with different values of w_R, the equivalent dose is:

$$H_T = \sum_R w_R \cdot D_{T,R}$$

Exclusion is exclusion from the scope of regulatory control.

Exemption is the determination by the regulator that an action need not be subject to some or all aspects of regulatory control on the basis that the exposure (or potential exposure) due to the action is too small to warrant the application of those aspects.

Ionizing radiation is radiation capable of producing ion pairs in biological material.

Nuclear authorisation is a nuclear installation licence, nuclear vessel licence, certificate of registration or certificate of exemption.

Operational safety assessment is a safety assessment undertaken during operations.

Planned exposure situation is a situation of exposure that arises from the planned operation of a source or from a planned activity that results in an exposure from a source. Since provision for protection and safety can be made before embarking on the activity concerned, associated exposures and their probabilities of occurrence can be restricted from the outset. The primary means of controlling exposure in planned exposure situations is by good design of installations, equipment and operating procedures. In planned exposure situations, a certain level of exposure is expected to occur.

Prior safety assessment is a safety assessment undertaken prior to commencement of operations.

Public is those individuals living off-site.

Reference level is in an emergency exposure situation or an existing exposure situation, the level of dose, risk or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which optimisation of protection and safety would continue to be implemented.

Release is the movement of radioactive material from the site into the environment.

Regulatory Control is the activities performed by the NNR to ensure fulfilling of its objectives as contemplated in Section 2 of the National Nuclear Regulator Act (South Africa, 1999b). The actions refer to the granting of a nuclear authorisation, the assurance of compliance with the conditions of authorisation, and to ensure that provisions for nuclear emergency planning are in place.

Risk is (qualitatively expressed) the probability of a specified health effect occurring in a person or group as a result of exposure to radiation or (quantitatively expressed) a multi attribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with actual or potential exposures relating to quantities such as the probability that specific deleterious consequences may arise and the magnitude and character of such consequences.

Safety assessment is an analysis to evaluate the performance of an overall system and its impact, where the performance measure has a radiological impact.

Site is Authorisation sites as described in the individual nuclear authorisation.

Source term is characteristics and quantity of the radionuclides released to the environment relevant to a safety assessment.

ABBREVIATIONS

AADQ	Authorised Annual Discharge Quantities
ALARA	As Low As Reasonably Achievable
AMAD	Activity Median Aerodynamic Diameter
Bq	Becquerel
CGS	Council for GeoScience
CIP	Carbon-in-pulp
DAFF	Department of Agriculture Forestry and Fisheries
DEA	Department of Environmental Affairs
DMR	Department of Mineral Resources
DSR	Dose to Source Ratio
DWA	Department of Water Affairs
EMRAS	Environmental Modelling for RAdiation Safety
FEPs	Feature, Event and Processes
FOA	Food and Agriculture Organisation of the United Nations
GSR	General Safety Requirements
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiation Protection
LHS	Latin Hypercube Sampling
MODARIA	MOdelling and DAta for Radiological Impact Assessments
NEMA	National Environmental Management Amendment Act, Act No. 62 of 2008
NORM	Natural Occurring Radioactive Material
NNR	National Nuclear Regulator
NNRA	National Nuclear Regulator Act, Act 47 of 1999
OSP	Ore is fed to a Stock Pile
QA	Quality Assurance
RESRAD	RESidual RADioactive computer code

RP	Representative Person
SA	Safety Analysis
SF	Spontaneous Fission
SNSG	Single Nuclide Source Guidelines
SSRP	Regulations in terms of Section 36, read with Section 47 of the National Nuclear Regulator Act (South Africa, 1999b) on Safety Standards and Regulatory Practices
TRS	Technical Report Series of the IAEA
TSF	Tailings Storage Facility
US NRC	United States, Nuclear Regulatory Commission

CHAPTER 1 INTRODUCTION

1.1 Radioactivity and Naturally Occurring Radioactive Material (NORM)

All matter consists of atoms. The atom has a nucleus which contains protons and neutrons. The proton is positively charged and the neutron has no charge. The nucleus is surrounded by negatively charged electrons. When atoms have the same number of protons in the nucleus, but different numbers of neutrons, they are called nuclides of the same atom. An example is uranium-238 (U-238) and uranium-235 (U-235). Both nuclides have 92 protons in the nucleus, but U-238 has 146 neutrons and U-235 has 143 neutrons in their nuclei respectively.

Not all the nuclides are stable. Due to the interaction between the different forces acting on the protons and neutrons, a nucleus with too many neutrons or protons is unstable. All unstable nuclei will spontaneously decay (also called disintegration) to form a nuclide with proton to neutron configuration that is closer to stability (Necsa, 2013). This process of reaching stability through decay is called radioactivity. The energy or particles emitted during the decay process is called radiation. Radiation can be emitted in the form of neutrons, alpha particles, beta particles, neutrinos or gamma rays (UNSCEAR, 2008).

Becquerel (Bq) is the unit of decay. It represents one disintegration per second. The abundance of radioactive material per unit gram of matter is expressed in Becquerel per gram (Bq/g). This is also called the activity concentration or specific activity. The released particle or energy causes radiological damage, in the form of ionisation or excitation, when absorbed in matter. The unit in which absorbed dose is measured, is the gray (Gy). The Gy represents the absorption of 1 joule of energy by 1 kg of matter. Different types of radiation cause different biological effects in tissue. The absorbed dose multiplied by a radiation type weighting factor, converts absorbed dose to equivalent dose, in human tissue, expressed in Sievert (Sv). The annual average dose to humans is about 2.4 mSv (UNSCEAR, 2008). In order to limit biological damage, the dose to a human must be controlled.

South Africa is a country rich in minerals. These reserves are being recovered through different mining processes and then further processed on the surface to extract the monetary valuable substances. The volumes can range from a couple of cubic meters to millions of cubic meters. Many of these natural reserves contain concentrations of a wide variety of radioactive nuclides (radionuclides), each nuclide with a specific half-life and chemical and physical properties. The radionuclide range includes, amongst others, uranium, thorium, protactinium, radium, radon, polonium, lead, bismuth, atrium, etc. The radioactive nuclides contained in the reserves are referred to as naturally occurring radioactive material (NORM) because it is naturally part of the biosphere. The worldwide average activity concentrations of nuclides in soil are as follow: U-238 – 0.033 Bq/g, Ra-226 – 0.032 Bq/g, Th-232 – 0.045 Bq/g, and K-40 – 0.412 Bq/g. Large variations in background soil concentrations have been reported, e.g. 1 Bq/g for U-238 (UNSCEAR, 2008). In the West Rand, a site near the Klerkskraal Dam was used in a 2007 NNR study to determine natural back ground levels for that area. Activity concentrations in soil were measured as follows: U-238 – 0.04 Bq/g, Ra-226 – 0.040 Bq/g and Th-232 – 0.020 Bq/g (NNR, 2007).

In South Africa, many of the gold mines contain NORM. The earth was historically mined for the gold, leaving all the other minerals as waste. Therefore, South Africa has a huge legacy of waste sites that has to be remediated. On the positive side, technology has developed over time and many of these waste sites are currently reworked to, once again, claim valuables from the waste.

Humans and the environment can potentially be harmed when exposed to the radionuclides contained in NORM. The regulatory system in South Africa has set an exclusion level of 0.5 Bq/g for naturally occurring radioactive nuclides of uranium and thorium and their progeny except for radon, 10 Bq/g for potassium-40 in materials that are used in building construction or disposed of and 50 Bq/g for potassium-40 in all other materials (South Africa, 1999a). Below these levels, activities are excluded from regulatory control. If the activity concentration exceeds 0.5 Bq/g, the activities are usually regulated to control the exposure and therefore the dose to workers and the public.

1.2 Objectives

Chapter 2 of the Constitution of the Republic of South Africa (South Africa, 1996a) is concerned with the environment. It states the right of every citizen to, amongst others, a clean and unpolluted environment, protected for future generations through legislation. The IAEA, in the General Safety Requirements, Part 1 on Governmental, Legal and Regulatory Framework for Safety (IAEA, 2010a) in Requirement 2 provides for an unpolluted environment for future generations through the establishment of a framework pride by government. Such a framework should consist of, amongst others, laws and a regulatory framework to protect the current population and future generations from radiation risk through a regulatory body. The regulatory body should establish regulations and criteria and a process of authorisation. It should involve interested parties in decision making. Furthermore, the regulatory body should review and assess activities at facilities, ensure compliance with conditions of authorisation and enforce compliance if so required.

Mining and minerals processing in South Africa involving NORM pose a health risk to citizens. Therefore, it must be authorised and regulated by the National Nuclear Regulator (NNR) in accordance with the requirements of the National Nuclear Regulator Act (South Africa, 1999a). These requirements are contained in the Regulations on Safety Standards and Regulatory Practices (SSRP), which were promulgated in accordance with Section 36 of the NNR Act (South Africa, 2006). Section 3 of the SSRP contains the principal radiation protection and nuclear safety requirements. More specifically, Section 3.3 requires a prior safety assessment before any work may be performed. Section 4 of the SSRP contains requirements applicable to regulated actions. These requirements are more specific and include objectives such as operational safety assessment, controls and limitations on operation, maintenance and inspection programme, staffing and qualification, radiation protection, etc. The NNR is required to develop position papers, requirements and guides to assist licensees (holders of nuclear authorisations) in the preparation of the documentation required for authorisation.

A guide for the assessment of radiation hazards to members of the public from existing and new mining and mineral processing facilities was developed in 1997 (NNR, 1997). This guide was based on guidance retrieved from the International Atomic Energy Agency (IAEA) and other accepted international sources, such as the International Commission on Radiation Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). An example is the Radiation Protection and Safety of Radiation Sources (IAEA, 1996), also known as the IAEA Basic Safety Standards. Since then the national and international regulatory framework for radiation protection has developed significantly with the increase in knowledge and experience. As a result, the IAEA basic safety standards document is currently being replaced with a set of General Safety Requirements documents (GSR-documents) consisting of various subdivisions. For this reason, South Africa, which is a member state of the IAEA and has an obligation to consider the guidance from the IAEA, must also revise and update existing legislation and guidance documentation as well as develop new legislation and guidance as required.

The first objective of this study is therefore to provide a new guidance document that the NNR can distribute amongst holders of nuclear authorisations to update existing public safety assessments for operational facilities. This new guide will also be available as guidance for the safety assessments required for new NORM facilities to be performed as a prior safety assessment. Prior, referring to the safety assessment required before mining or processing operations commences (NNR, 2014a). The guide, Safety Assessment of Radiation Hazard Assessment of the Public from NORM Activities, RG-002 (NNR, 2014a), was finalised and published, as part of this study, in 2014. The document was reviewed internally at the NNR. Thereafter it was distributed for public comment and work shopped with interested parties, after release, as part of the public participation process followed by the NNR. The document was distributed to holders of NNR authorisations. Comments were considered and included as appropriate.

A similar guide for existing exposure situations, such as the Wonderfonteinspruit, where sites are contaminated with radionuclides because of previously unregulated mining activities, is not available at present. A document on regulatory criteria and guidance was developed.

The second objective of this thesis is therefore to expand the existing framework through the improvement of legislation, as applicable, for the regulation of sites contaminated by historical mining and mineral processing activities. This expansion or enhancement of the framework refers to the review and improvement of existing regulations to improve requirements for planned exposure scenarios and include requirements and release criteria for existing exposure scenarios. The licensing process was expanded to include a process for authorisation of existing exposure scenarios. (As part of the improvement process, the following documents were developed and internally approved at the NNR: Plan for Remediation of Contaminated Sites, September, 2014 (NNR, 2014b); Remediation Criteria and Requirements, PP-0018, September 2015 (NNR, 2015); Authorisation Procedure for Remediation of Existing Exposure Scenarios, Final Draft, December 2015, (NNR, 2016b).

In addition to the development of the above-mentioned regulations and guides, the thesis also demonstrates the applicability of the proposed regulatory framework. Applicability is demonstrated by applying the assessment methodologies and criteria to hypothetical sites where the activity concentrations are slightly higher than found in practice. Slightly higher activity concentrations were used to force demonstration of decision making.

Generally, a safety assessment performed from an operator’s perspective, whether it is for a mining and mineral processing operation or a historical contaminated site ear marked for remediation, will be submitted to the NNR for review and authorisation. This review process, per se, is just as important in the protection of human health and the environment as the safety assessment itself. The thesis consequently also contains a guide that was developed for the regulatory review process.

1.3 Structure of the Thesis

Chapter 2 provides an overview of the current national and international status on the methodologies and criteria applied in safety assessments related to NORM facilities and also the remediation of historical sites.

In Chapter 3 the regulatory framework for the regulation of planned and existing exposure situations in the NORM industry in South Africa was discussed. The framework includes the regulatory framework required for the licensing, remediation, and de-licensing of these sites.

In Chapter 4 a new guideline assessment methodology was developed for radiological public safety assessments for NORM facilities. The methodology was developed specific for South African conditions and in accordance with national legislation. This guideline takes into consideration new national and international developments in the field of radiation protection and safety assessment.

In Chapter 5 the safety assessment methodology developed in Chapter 4 for a planned NORM facility, was applied.

In Chapter 6 a new guideline assessment methodology for radiological safety assessments for the remediation of NORM facilities was developed specific for South African conditions and in accordance with national legislation.

In Chapter 7 the safety assessment methodology developed for remediation and the demonstration of compliance with de-licensing criteria as was developed in Chapter 6, was applied.

In Chapter 8 a guide to be used in the review public safety assessments by the NNR was developed. This guide is based on the NNR requirements and safety criteria for the authorisation of NORM facilities to operate within the legislative regime. The review guide will provide staff of the National Nuclear Regulator clear guidance on how to review and assess the adequacy of a safety assessment submitted to obtain an authorisation to operate. The applicability of the review guide is demonstrated, using the assessments conducted in previous chapters as case studies.

In Chapter 9 conclusions were made on the study and potential future work was recommended.

CHAPTER 2 OVERVIEW OF INTERNATIONAL SAFETY ASSESSMENT METHODOLOGIES

Chapter 2 provides an overview of the current international status on the methodologies and criteria applied in radiological safety assessments related to NORM facilities (operational or potentially operational sites) and also the remediation of historical sites (legacy sites). In addition, some of the key terminology used and principles applied in the study are explained in more detail. The terminology explained in this chapter is essential for understanding the context in which the study was performed (e.g. planned exposures versus existing exposures). It also introduces new terms associated with the study, which does not form part of existing framework (e.g. critical group versus representative person).

2.1 Introduction

2.1.1 Authorised sites

An authorised site is an operating site where activities with radionuclides are performed under an authorisation issued by the NNR. Sites are authorised by the NNR following the internal procedures, as set out in PPD-AUT-01 (NNR, 2016b). For mining and minerals processing facilities, a Certificate of Registration is issued to validate authorisation, in terms of Section 22 of the NNR Act (South Africa, 1999a). These also include new sites which are under development for operation. The following applies to an operating site, as far as the public safety assessment is concerned:

- The exposure scenario defined for the safety assessment is referred to as planned exposure scenarios;
- The public safety assessment is performed at off-site locations, on the potential effects of transported radionuclides to these off-site locations, from the operational site;
- Members of the public reside on this site;
- The safety assessment is called a public safety assessment for a planned exposure scenario;
- The public safety assessment is not performed to determine the efficiency of on-site operational activities in relation to the amount of radionuclides released to the environment;

- The safety assessment is performed prospectively to determine the potential hazardous impacts and thereafter control releases to the environment;
- The source of radionuclides originates on-site;
- The radionuclides are transported off-site through the gaseous and liquid pathways; and
- The transportation of radionuclides to the off-site location is a continuous process.

2.1.2 Legacy sites

A legacy site is a site where no operational activities are being performed, i.e. the radionuclide contamination on that site was caused by historical operational activities either on this site or elsewhere. These sites will in future be authorised in terms of the NNR procedure PPD-AUT-02, developed as part of this study (NNR, 2016b). The following applies:

- There is no continuous addition of radionuclides to the site due to operational activities elsewhere;
- Calculations are performed on the exposure due to residential radionuclides;
- The safety assessment is called a public safety assessment for an existing exposure scenario; and
- The safety assessment is usually performed to determine whether remediation is required, and if so also provides detail on the extent of remediation required.

2.2 International Guidance on Public Safety Assessments

2.2.1 The International Commission on Radiation Protection (ICRP)

2.2.1.1 General principles and philosophy of exposure and protection

The ICRP is the most important independent non-governmental organisation that promotes protection against ionizing radiation to members of the public. The ICRP publishes recommendations and guidance documents, which are used as the basis for the science of radiation protection across the world. The NNR applies the ICRP recommendations in its system of protection. Therefore, the South African legislation and safety standards are based on the ICRP recommendations and guidance (ICRP, 2007a).

The ICRP (2007a) defines three types of exposure scenarios, viz. planned exposures, emergency exposures and existing exposures. These are new terms in the South African legislative context. It was previously known as practices, emergency and interventions. Planned exposures refer to the planned activities with sources of radiation, such as nuclear power plants, uranium mining, uranium fuel fabrication, etc. The activities are regulated in countries with established nuclear and radiation programmes. Emergency exposures would typically occur un-planned after an accident or malicious act, where people are exposed to radiation due to the event. The third type of exposure occurs in those situations which existed before actions were regulated. In South Africa, historical environmental contamination caused by un-controlled or un-licensed mining activities, would resort under this category.

Irrespective of the kind of exposure scenario, people and the environment must be protected against the harmful effects of radiation. Therefore, a system of protection was devised. This system of protection is based on three basic principles: justification of exposures, optimisation of protection and implementation of a set of dose limits (ICRP, 2007a). The principle of justification requires that radiation exposure scenarios should do more good than harm. The aim of the optimisation of protection principle is to minimise the chance of exposure, the number of people being exposed and the magnitude of exposures to individuals. Optimisation of exposures should result in keeping doses as low as reasonably achievable (ALARA), taking into consideration economic and social factors. The third principle of protection is the setting of and adherence to dose limits for planned exposure scenarios for workers and members of the public. To assist in the setup of dose limits, the ICRP has divided exposures into three categories, which are occupational exposures, public exposures and medical exposures (ICRP, 2007a). Where public exposures are concerned with normal operating conditions, the concept of a representative person should be applied to identify the individual who receives the highest dose in a year from releases of radioactive material, liquid and gaseous, into the environment (ICRP, 2007a).

The ICRP emphasises the role of optimisation of protection by reducing all exposures to ALARA by implementing dose constraints for planned exposure scenarios and reference levels for emergency and existing exposures (ICRP, 2007a). Dose constraints are proposed on operational control levels, lower than dose limits, below which the dose to the public should be controlled during normal operational activities. Reference levels apply to emergency and existing exposure situations where the dose limit is exceeded. Reference levels are applied on a case-by-case basis whereby exposures are optimised to levels ALARA (ICRP, 2007a). Reference levels also consider residual levels of dose remaining after the activities to remediate have been implemented. For example, reference levels should typically also be applied in remediation activities as applicable to existing exposure scenarios as experienced in South Africa in areas historically contaminated with radionuclides as a result of mining activities.

2.2.1.2 The dose assessment process

The ICRP (2007a) regards a dose assessment as a multi-stage process. In this section a summary of the process is presented. Note, that it is useful to perform the stages separately to maintain order and to verify considerations.

In the first stage, information about the source of radiation is required. This includes the identification of the radionuclides present, as well as the progeny (i.e. decay products) that will grow in. All nuclides present should be identified.

The second stage requires the collection of information about the concentration of radionuclides in the environment. When determining exposure, it is important to include exposure from all the pathways and all the radionuclides that could contribute to the dose. Therefore, information related to both the internal and external exposure pathways should be considered. For external dose assessments, concentrations of radionuclides in air, soil and water are required, or the measured external dose rates in these media should be available. For internal doses, the radionuclide concentrations in food, liquid and air, which may be taken into the body by inhalation, ingestion and absorption through the skin, must be considered.

The third stage of the process would be to collect information on the habits of the persons that could be exposed to the radiation. This would typically include which foods and the quantities thereof are consumed; the time spent indoors and outdoors in the radiation areas, water sources, etc.

The fourth stage is a combination of the radionuclide concentrations with habit (behavioural) data that were selected, based on exposure scenarios defined for the specific analysis. This would constitute the amount of radionuclides being exposed to over a determined timespan. For example, the U-238 content in water is 1 Bq/l and 240 litres of water is consumed per year. Therefore, the total amount of U-238 exposed to per year is 240 Bq.

The fifth stage would entail the conversion of intakes from internal exposures and external exposures into a dose using appropriate dose conversion factors or models. The dose conversion factors for exposure have been derived and are published in ICRP (ICRP, 2012). These conversion factors are also published in the IAEA GSR series of documents (IAEA, 2014a). For example, the dose conversion factor for the ingestion of U-238 for members of the public, expressed as the committed effective dose per unit intake, is expressed in terms of Sv/Bq. Values are given for age ranges. The dose conversion factor for a child, 1 - 2 years old, for the ingestion of U-238, would be 1.2 × 10–7 Sv/Bq (IAEA, 2014a). Therefore, if the child would drink 240 litres of water containing on average 1 Bq/l of U-238, the dose would be (240 Bq × (1.2 × 10–7 Sv/Bq) = 2.88 × 10-5 Sv or 28.8 µSv/a. These calculations can become quite complex when several intake pathways are used for a range of nuclides with their progeny and taking decay into account. In complex situations, models are used to assist in solving the equation.

In the final stage the contributions from external and internal exposure, as applicable to the exposure scenario, would be summed.

2.2.1.3 The representative person

The representative person concept will replace the critical group concept, currently used in the South African legislation (South Africa, 1999a). It is important to include some information on the concept of the representative person in this study to define explicitly the scope of the exposure scenario developed for the specific assessment. Total effective dose to the public cannot be measured directly because some components contributing to the dose are in forms where the direct effect cannot be measured, e.g. the radionuclides contained in foodstuffs. For this reason, the radiological damage effect is estimated using the activity concentrations in the foodstuff, the person’s habitat and a conversion factor. The conversion factor translates the intake quantity of radionuclides to dose. Therefore, in order to quantify the potential exposure of the public, it is necessary to define a hypothetically exposed person or what is called the representative person. The representative person would be the most exposed individual in the reference group (ICRP, 2006).

The dose calculated for the representative person is compared to the dose constraint or dose limit in the case of planned exposure scenarios. In the case of emergency exposure scenarios and existing exposure scenarios, the dose results are compared with the reference level, approved by the regulator on a case-by-case basis (within predefined boundaries of optimisation of exposure).

The characteristics of the representative person are affected by age dependant physiology, dietary information, residential data, use of land, time spent indoors and time spent outdoors, recreational activities, and the like. Consideration must also be given to spatial distribution of radionuclides to determine the highest possible exposures in the assessment. Habit data used (e.g. consumption rates) must be reasonable, sustainable and homogeneous. When considering age differences, age specific dose conversion factors must be used, as defined by ICRP (ICRP, 2012).

2.2.1.4 Exposure time frames, pathways and spatial distribution of nuclides

Dose to the representative person must include exposures from all potential pathways, which include external exposure, inhalation and ingestion from direct exposures, liquid and gaseous discharges (IAEA, 2014a).

The following are new concepts in the South African legislative regime. Time periods, other than the 1-year period for public exposure, has not be implemented and considered in South Africa before. These concepts are as a result of this study and are built into draft Regulations on Nuclear Safety (NNR, 2016c) and also into RG-002 (NNR, 2014a) and Remediation Criteria (NNR, 2015). Dose assessments can be performed prospective or retrospective. Prospective assessments refer to assessments performed to determine the consequences from current and potential future releases, considering potential release rates from a given point or source. Retrospective assessments would be performed from a combination of historical data from the source and some environmental data at a point in time after the release had occurred (IAEA, 2014a).

Time frames are important because the dose is directly related to the period of exposure. When public exposures from normal operations are calculated, the exposure is expressed in terms of dose per annum (IAEA, 2014a). When build-up of long lived nuclides into the environment is considered, cognisance should be taken of the potential build-up of nuclides in the environment over the life-time of the facility. As radionuclides are deposited in the environment and some washed out, a state of equilibrium should be reached, depending on the situation at the facility, after about 30 to 40 years. Therefore, in order to consider equilibrium in the environment, a period of about 40 years should be used (IAEA, 2016a).

Where sites are released from regulatory control, the peak dose should be considered. Peak dose is a concept which is determined by many factors. Peak dose is the maximum dose an individual could be exposed to from all exposure pathways, any time from now, to many years in the future. Peak dose could typically be influenced by the long term dispersion of radionuclides in the ground water pathway and would therefore be important to long lived nuclides (IAEA, 2016a). The United States requires a period of 1 000 years to be considered after closure of a facility to ensure that peak dose is calculated (NUREG, 2016).

Lastly it is important to consider spatial distribution of radionuclides in the environment, caused by various factors, such as atmospheric and liquid dispersion differences over distance; dispersion differences caused by topography and sedimentation; build-up of long lived nuclides and progeny; changes in land-use; etc.

2.2.2 The International Atomic Energy Agency (IAEA)

The IAEA is an international organisation that establishes safety standards for the protection of health and the minimisation of harm caused by the exposure to radioactive material. South Africa is a member state of the IAEA. Member states can apply the standards developed by the IAEA in the regulatory framework for nuclear and radiation safety, as is done in South Africa. Detail on the safety standards will be provided in Chapter 3.

2.2.2.1 Estimating dose to the critical group – Planned scenarios

In 2001, the IAEA developed a safety report describing generic models for use in assessing impacts of discharges of radioactive substances to the environment (IAEA, 2001). This document is currently under review at the IAEA. It will be updated with information developed in the EMRAS (Environmental Modelling for Radiation Safety) and MODARIA (Modelling and Data for Radiological Impact Assessments) working groups, which tested the models with real life scenarios.

In the EMRAS Working Group 2 report, the IAEA developed an environmental impact assessment analysis procedure. The procedure is prospective in nature and produces quantitative results to be used in decision making. A schematic of the process is depicted in Figure 2-1. In brief, it entails the following: Discharges or releases (either liquid or gaseous) from an authorised site to the environment are analysed. The process is as follows:

- Determine the source of radioactive material released to the environment (annual average quantity of each nuclide released);
- Determine the pathway of release (liquid and gaseous dispersion to the soil, plants, animal food, aquatic food, sediment);

- Determine receptor (how is an individual exposed: direct external exposure, inhalation, ingestion); and
- Determine receptor habits and calculate dose from habits and exposures.

These dose results are evaluated against dose limits (a fixed criterion not to be exceeded) or reference levels (a control level, usually below the limit) (IAEA, 2001). This is typically the procedure that would be applied in the public safety assessment for planned scenarios. It will also be used in this study.

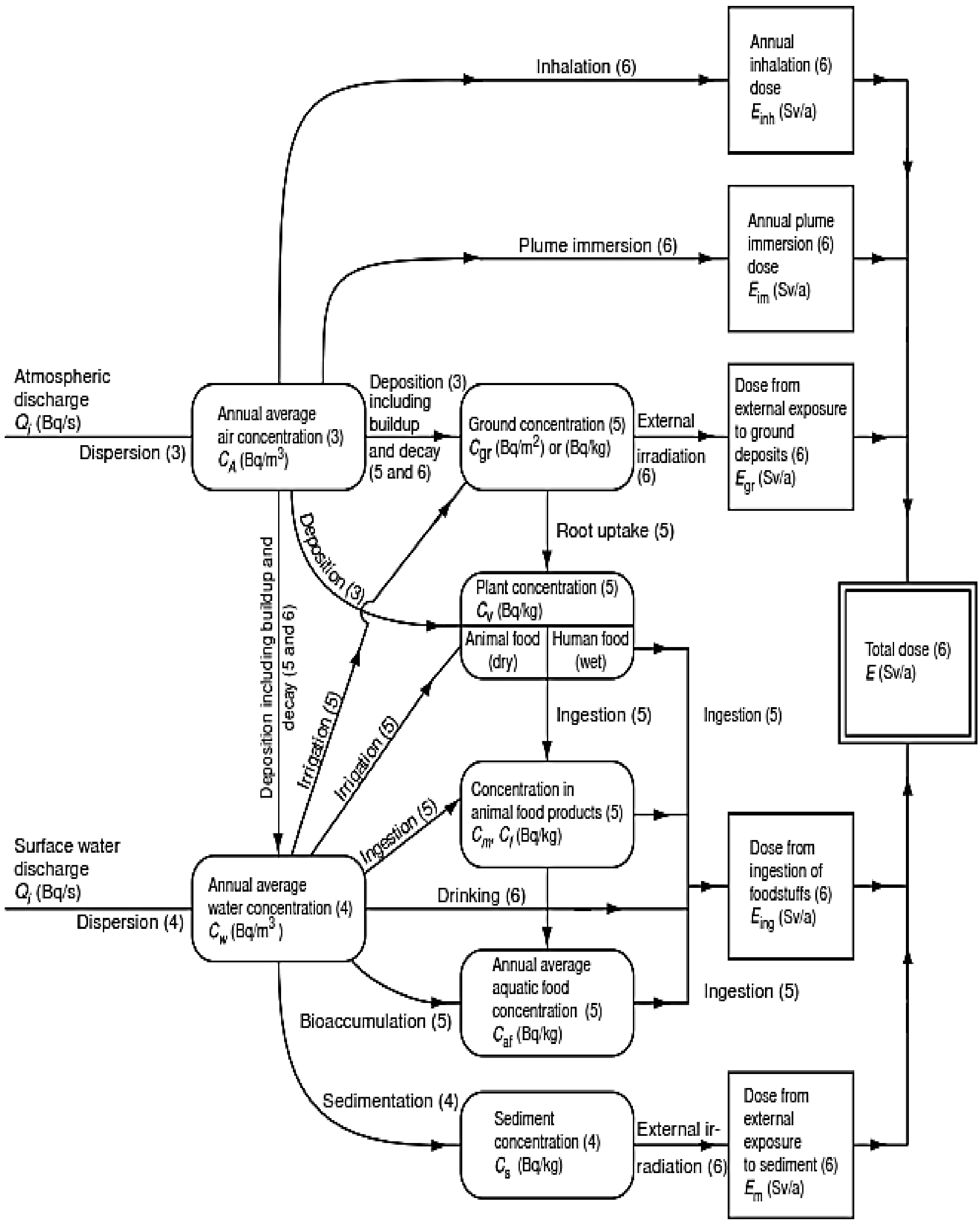

Figure 2-1: IAEA: Assessing Critical Group Doses (IAEA, 2001)

2.2.2.2 Types of safety assessment

The IAEA provides standards and guides based on the needs expressed by the member states. After a project is registered, international experts participate to develop the standard or guide. One such example was the EMRAS project. EMRAS Working Group 2 specifically focused on modelling the transfer of radionuclides from NORM (IAEA, 2016b).

EMRAS Working Group 2 (IAEA, 2016b) identified different types of safety assessments to be performed. For operational facilities, on-site and off-site safety assessments would be performed, with the dispersion of on-site radionuclides as the radionuclide inventory. For legacy sites (existing exposure scenarios) the safety assessment would be based on a detailed site characterisation in order to determine whether remediation is required. If remediation is required, the effects of the remediation strategy adopted should also be assessed. The latter would result in the derivation of radionuclide specific release criteria.

When modelling a site, the best available data should be used. When only limited data is available, a generic or conservative (meaning worst case) model is used. This would result in an overestimation of dose. As more site specific data become available, the safety assessment can be refined and more realistic results can be obtained. For example, a lack of data could result in using a generic water consumption rate of 600 litres per annum from a contaminated borehole. However, in reality 50 % of water consumed, is from a tanker with uncontaminated water. Therefore, safety assessments are always an iterative process where generic data is replaced with site-specific data of a more realistic nature.

The EMRAS Working Group 2 remediation assessment methodology/process is depicted in Figure 2-2. The figure depicts the basic assessment process and where there is an opportunity for the stakeholder and/or public input. The assessment process can be simplified in steps as follows:

- Site characterisation (identification, investigation and setting remediation objectives);
- Establish screening criteria;
- Perform a screening assessment – if results of the screening assessment satisfy the screening criteria, the clean-up criteria can be established. If the screening criteria are not met, more site specific and detailed assessments are required until the screening criteria are satisfied;
- Establish clean-up criteria; and
- Remediate until remediation criteria are met.

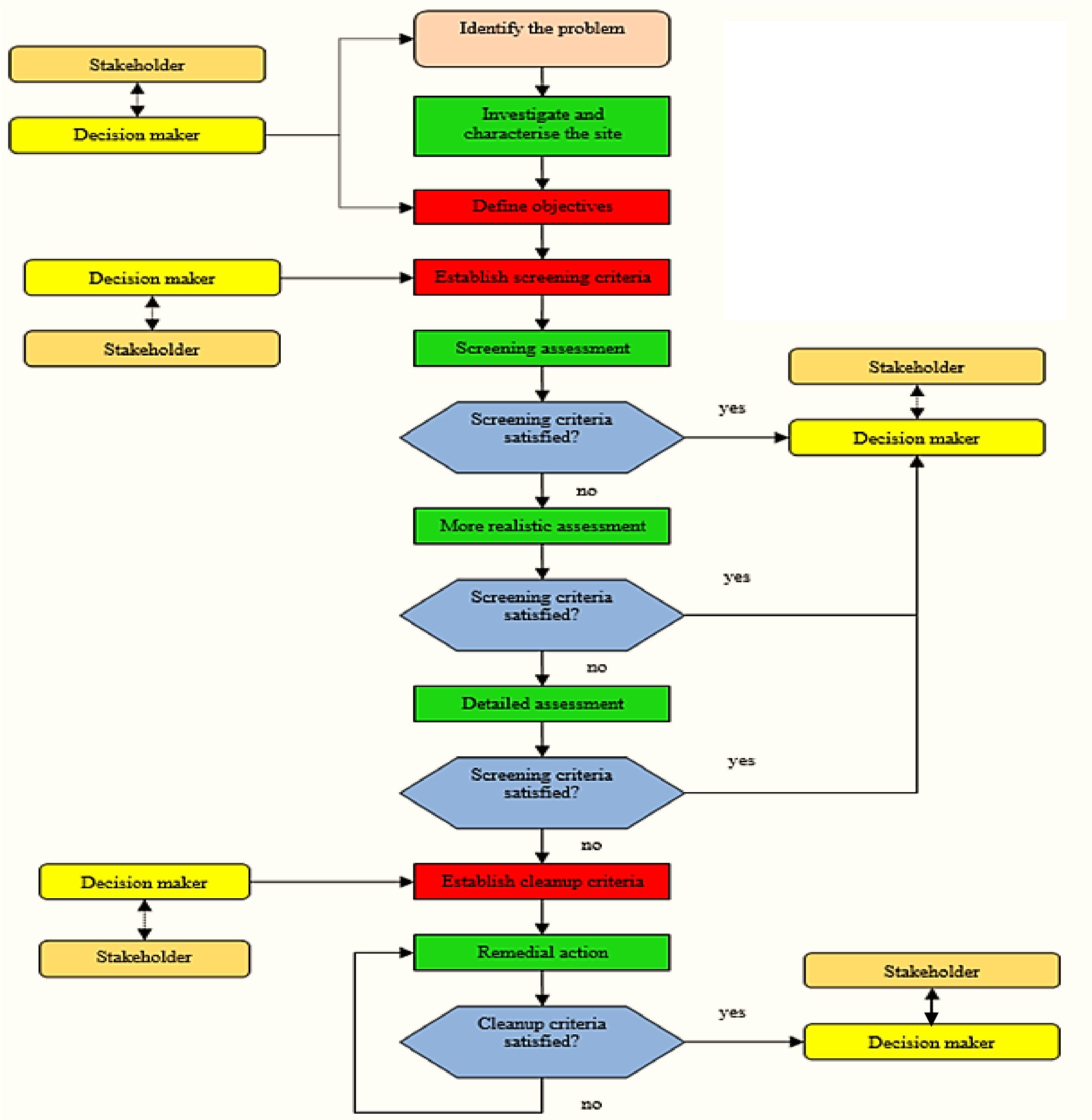

Figure 2-2: The Remediation Assessment Process (IAEA, 2016a)

2.2.3 International and national remediation criteria

In South Africa the principles of justification of actions, optimisation of protective measures and compliance with the dose limits and reference levels, as set by the NNR always apply. Therefore, irrespective of the remediation criteria, exposures must always be kept ALARA.

2.2.3.1 ICRP guidance on remediation criteria

As the dose increases, the likelihood of radiation effects increases. The ICRP has established three bands of exposure, as summarised in Table 2-1, ICRP Reference Levels (ICRP, 2007a). The upper boundary, not to be exceeded, is set at 100 mSv, acute or chronic in a year. (For planned and existing exposures the reference level is usually expressed in mSv/a). Only in extreme situations should a dose exceeding 100 mSv be allowed.

At the bottom end, doses less than 1 mSv, is usually justified if society benefits from the action. The 1 mSv/a is also the normal public dose limit. All public exposures must always be optimised, irrespective of the level of exposure (ICRP, 2007a). The public should be informed of the activities.

The second band, between 1 mSv and 20 mSv, applies to situations where individuals receive direct benefit from the situation, such as workers. In such cases there is usually a surveillance programme in place and individuals are trained (ICRP, 2007a).

The third band, 20 to 100 mSv, applies in unusual and extreme situations of exposure, where reducing the dose will be disruptive. These reference levels would typically apply in emergency situations to reduce exposures (ICRP, 2007a).

In planned exposure situations, the ICRP recommends that public exposures be controlled and optimised under the dose constraint. The ICRP refers to 0.3 mSv/a, and South Africa applies 0.25 mSv/a (ICRP, 2006). Where long-lived nuclides are released, build-up in the environment must be considered.

In existing exposure scenarios, the ICRP recommends that reference levels, set in terms of individual dose, should be used in conjunction with the optimisation process. The reference levels will depend on the (ICRP, 2006) controllability of the source and prevailing economic, social and cultural circumstances. Exposures below the reference level should not be ignored, but assessed to determine whether the situation has been optimised. Reference levels for existing exposure situations should be set typically in the 1 mSv to 20 mSv band of projected dose. Individuals concerned should receive general information on the exposure situation and the means of reducing their doses (ICRP, 2007a).

Table 2-1: ICRP Reference Levels (ICRP, 2006)

Band of Constraint and Reference Levels (mSv)	Characteristics of the Exposure Situation	Radiological Protection Requirements	Examples
> 20 - 100	Individuals exposed by sources that are not controllable, or where actions to reduce doses would be disproportionately disruptive. Exposures are usually controlled by action on the exposure pathways.	Consideration should be given to reducing doses. Increasing efforts should be made to reduce doses as they approach 100 mSv. Individuals should receive information on radiation risk and on the actions to reduce doses. Assessment of individual doses should be undertaken.	Reference level set for the highest planned residual dose from a radiological emergency.
> 1 - 20	Individuals will usually receive benefit from the exposure situation but not necessarily from the exposure itself. Exposures may be controlled at the source or, alternatively, by action in the exposure pathways.	Where possible, general information should be made available to enable individuals to reduce their doses. For planned situations, individual assessments of exposure and training should take place.	Constraints set for occupational exposure in planned situations, comforters and carers of patients treated with radio-pharmaceuticals. Reference level for the highest planned residual dose from radon in dwellings. Abnormally high levels of natural background, stages in post-accident rehabilitation.
1 or less	Individuals are exposed to a source that gives them little or no individual benefits but benefits society in general. Exposures are usually controlled by action taken directly on the source for which radiological protection requirements can be planned in advance.	General information on the level of exposure should be made available. Periodic checks should be made on the exposure pathways as to the level of exposure.	Constraints set for public exposure in planned situations.

2.2.3.2 IAEA guidance on remediation criteria

In the IAEA Safety Standard Series WS-G-3.1 (IAEA, 2007b) document where the remediation process for areas affected by past activities and accidents is described, a generic reference level for aiding decisions on remediation is recommended as an existing annual effective dose of 10 mSv from all sources, including the natural background radiation. A generic reference level for any organ of 100 mSv, could also be established.

The dose to the public cannot be directly measured because of the contribution from several direct and indirect sources. It is therefore modelled (IAEA, 2007b) (this was also built into NNR PP-0018 (NNR, 2015). The modelling can result in derived operational acceptance levels, expressed in terms of activity concentrations (Bq/g or Bq/m^2, or similar), which could be measured and are useful in remediation activities.

The IAEA in GSR Part 3 (IAEA, 2014a), states that the regulatory body shall ensure that a strategy for managing existing exposures is established and implemented. This strategy shall consider the risk associated with such exposures. Sites where the residual dose exceeds the reference levels should be prioritised. The reference levels could range between an effective dose (whole body dose) of 1 and 20 mSv/a as it relates to the representative person.

The IAEA, in TRS 475 (IAEA, 2012), states that reference levels are expressed in terms of an effective dose of 1 – 20 mSv to the representative person. The document also mentions that factors such as ambient activity concentrations in environmental compartments; physical and chemical properties of radionuclides; soil, water, plant and animal characteristics; and farming practices and land use should be considered when evaluating the need for remediation.

2.2.3.3 NNR remediation criteria

Current South African Legislation does not adequately address remediation of existing and emergency exposure situations (South Africa, 1999a). Areas where remediation is required must be brought under NNR authorisation and the applicable safety assessments must be performed.

The NNR is in the process of establishing new regulations (NNR, 2016c), which will be based on the IAEA GSR Part 3 (IAEA, 2014a) and ICRP 103 (ICRP, 2007a). Remediation must always be considered for all activities where the annual effective dose to the representative person exceeds the public dose limit of 1 mSv/a (ICRP, 2007a). Each situation should be evaluated on a case by case basis. A safety assessment must be performed. The safety assessment must consider the principles of justification, optimisation and reference levels. Reference levels between 1 and 20 mSv will be considered by the National Nuclear Regulator. Where exposure situations exceed the public dose limit after remediation, land use restrictions must be motivated and the public informed accordingly. The NNR may consider restricted release of land from existing exposure situations from a reference level that exceeds 1 mSv/a (NNR, 2015).

The aforementioned criteria were derived as a direct result from this study and is contained in NNR document PP-0018 (NNR, 2015). It has partially been implemented in the development of new proposed regulations. It has also resulted in the development of a national remediation strategy, currently being implemented (NNR, 2014b).

2.3 Performing Radiological Safety Assessments

From the previous sections it is clear that performing a radiological safety assessment is the most important part of the process to evaluate the safety of the public. In this process step, all the information gathered, is used to calculate the potential consequence. There are many different ways to get the answer. Some analysts use hand calculations in a spreadsheet, while others use calculation codes developed for this purpose. Some of the codes are available internationally and their characteristics are summarised in Table 2-2 (IAEA, 2001).

In Table 2-2: International Codes Available for Performing Radiological Public Safety Assessments, ten different codes, commonly used internationally, are listed (IAEA, 2016a). The table provides a summary of the scope of the code and the radioactive medium to which it can be applied. The fields of comparison are as follows:

- Model – provides the code name.
- Scope – whether the code can be applied to screening or detailed assessments. Screening assessments usually refer to simple generic models used with limited input parameters. Most input parameters are default. Detailed codes usually refer to codes with sophisticated or refined mathematical models where a variety of inputs are possible. Many of the default values can be changed within specific ranges to allow for site specific analysis.

- Radioactive medium – most models were developed for specific applications. In the medium column, reference is made to the type of application the code can be used for.

Table 2-2: International Codes Available for Performing Radiological Public Safety Assessments (IAEA, 2016a)

Model	Scope	Radioactive Medium
CROM	Screening to detailed	Gaseous and liquid discharges
DandD	Screening	Building and surface soil
DOSDIM+ HYDRUS	Detailed	Surface, near surface
PC-CREAM 08	Detailed	Gaseous and liquid discharge
ReCLAIM	Screening	Contaminated land
RESRAD-OFFSITE	Screening to detailed	Surface, near surface
SATURN	Detailed	Building, surface and near surface
ERICA	Screening to detailed	Dose rates to non-human biota
MICROSHIELD	Detailed	Photon/gamma shielding and dose assessment
AMCARE	Screening	Soil, ground water, surface water and air

This study required an available model that could be applied to NORM sites. The model should also have the following characteristics.

Model on-site and off-site consequences over a prolonged period:

- be able to model radon;
- be able to perform screening as well as detailed assessments;
- be able to model peak dose;
- have been tested on multiple sites;
- have been internationally benchmarked;
- have a feature to perform sensitivity and uncertainty analysis;
- be easily accessible;
- be available to users in South Africa; and
- could, with limited effort, comply with the NNR verification and validation requirements (NNR, 2006).

At the Argonne National Laboratory in the United States of America a set of models were developed under the RESRAD name (RESRAD, 2013). The models qualified for application in this study because they complied with all of the abovementioned criteria and were therefore chosen as application tool. A short training course on the application of the model was attended in the United States of America in 2014 in preparation of using the code in this study.

RESRAD on-site was developed for the U.S. Department of Energy to calculate site-specific RESidual RADioactive (RESRAD) material guidelines as well as radiation doses and excess lifetime cancer risk to a chronically exposed receptor. RESRAD off-site was developed with support of the USA, Nuclear Regulatory Commission (US NRC), (RESRAD, 2009, 2013). RESRAD has a code for on-site and a code for off-site modelling. Both codes have the ability to model nine exposure pathways simultaneously. These are:

- Direct exposure to external radiation from the contaminated soil;
- Internal exposure from inhalation of airborne radionuclides;
- Internal exposure from inhalation of radon progeny;
- Internal exposure from ingestion of:
    - Food produced in contaminated soil and irrigated with contaminated water;
    - Meat and milk from livestock fed with contaminated fodder and water;
    - Drinking water from a contaminated borehole or pond;
    - Fish from a contaminated pond; and
    - Contaminated soil.

The use of the RESRAD codes complies with most of the pre-selected criteria and it also have the following further advantages that were useful for this study (RESRAD, 2013):

- it could be used to derive soil clean-up criteria for contaminated site remediation activities;
- predict future activity concentrations in soil, air, surface water and ground water;
- the model handles a wide range of nuclides, and
- allows users to change the cut-off half-life for setting short-lived daughters in equilibrium with their parent radionuclide.

CHAPTER 3 REGULATORY FRAMEWORK

This Chapter describes the regulatory framework for the regulation of planned and existing exposure situations in the NORM industry in South Africa. The ICRP defines radiological protection regulations or the regulatory framework, as was used in the context of this study, in a broad sense and not limited to the relevant regulations promulgated by government (ICRP, 2007b). The term includes codes of practice, standards and norms, directives and guidance documents. Therefore, the regulatory framework would include the National Nuclear Regulator Act, Act 47 of 1999, the Regulations in terms of Section 36, of the National Nuclear Regulator Act, 1999 (South Africa, 1999a), on Safety Standards and Regulatory Practices (Government Notice R388), and any regulatory requirements, directives, guidance and processes. In this chapter, it was demonstrated what the regulatory framework in South Africa consists of, how it will be improved and how improvements were influenced by international practice.

3.1 Introduction

IAEA safety requirements are not enforceable in any country. It does not form part of the legislative framework unless directly quoted in national legislation. South Africa, as a Member State of the IAEA, participates with all other Member States in compiling the IAEA requirements. The IAEA therefore states that it is desirable for all Member States to adopt and apply IAEA requirements (IAEA, 2014a). The IAEA follows a continuous process of keeping its requirements and recommendations up to date with international trends. The leading and most current set of IAEA standards - Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series no. GSR Part 3, was published in 2014 (IAEA, 2014a), although an interim edition was already available in 2011. GSR Part 3 is aligned with the ICRP 103, the 2007 recommendations (ICRP, 2007a). This means that GSR Part 3 contains the most recent international requirements. In addition to GSR Part 3, the document - Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series no. GSR Part 1, was published in 2010 (IAEA, 2010a). These 2 documents are important to establish a regulatory framework as applicable to this study.

3.2 Current NNR Requirements

The NNR is empowered to provide the regulatory framework, through the NNRA (South Africa, 1999a) to:

- provide for the protection of persons, property and the environment against nuclear damage through the establishment of safety standards and regulatory practices;
- exercise regulatory control related to safety over the siting, design, construction, operation, manufacture of component parts and decontamination, decommissioning and closure of nuclear installations; as well as
- vessels propelled by nuclear power or having radioactive material on board which is capable of causing nuclear damage, through the granting of nuclear authorisations;
- exercise regulatory control over other actions, to which this Act applies, through the granting of nuclear authorisations;
- provide assurance of compliance with the conditions of nuclear authorisations through the implementation of a system of compliance inspections;
- fulfil national obligations in respect of international legal instruments concerning nuclear safety; and
- ensure that provisions for nuclear emergency planning are in place.

In Section 36 of the NNRA, it is stated that the Minister of Energy must, on recommendation of the board of the NNR, make regulations regarding safety standards and regulatory practices (SSRP) (South Africa, 1999a). The SSRP was published in 2006 in the Government Gazette as the Regulations in terms of Section 36, of the NNRA (South Africa, 1999a), on Safety Standards and Regulatory Practices Government Notice R388 (South Africa, 2006). The SSRP has broad, high level, regulations on the following:

- Section 2 – Exclusion, exemption, registration, licensing and clearance;
- Section 3 – Principal radiation protection and nuclear safety requirements;
- Section 4 – Requirements applicable to regulated actions; and
- Section 5 – Decommissioning".

3.2.1 SSRP, Section 2 – Requirements (South Africa, 2006)

Section 2 of the SSRP sets the boundaries for actions to be included or excluded from regulatory control. Section 2 excludes actions from being regulated if the activity concentrations are less than 0.2 Bq/g for artificial radioactive nuclides; 0.5 Bq/g for NORM (applicable to this study); 10 Bq/g for K-40 in building material and 50 Bq/g for K-40 in other material. Furthermore, if the total activity is less than 1 000 Bq, the action is also excluded from regulatory control, (South Africa, 2006).

Where the activity concentration exceeds 0.5 Bq/g, actions can be exempted, without further consideration, if the dose to the public is less than 10 µSv/a and the dose to the population less than 1 person-Sv. For NORM actions the dose criterion is 250 µSv/a. Exemption is justified through a safety assessment.

In addition, actions that exceeded the requirements above can be considered for exemption with further consideration on a case by case basis. This requirement is very vague and difficult to interpret.

Material can be cleared or released from regulatory control if it complies with the exemption criteria. Therefore, not causing a dose to members of the public, exceeding 250 µSv/a, where radionuclides from the NORM industry is concerned.

3.2.2 SSRP, Section 3 – Principal radiation protection and nuclear safety requirements (South Africa, 2006)

The SSRP establishes the primary requirements for radiation protection to be the application of dose and risk limits, optimisation of protection, prior safety assessments, good engineering practises and safety culture.

3.2.3 SSRP, Section 4 – Requirements applicable to regulated actions (South Africa, 2006)

The SSRP requires that for all actions that are regulated, authorisation shall be granted by the NNR after review of an operational safety assessment, which was submitted to justify operational activities. Safety limits and operational control limit, maintenance and inspection requirements are derived from the operational conditions justified in the safety assessment. With regards to the optimisation of protection, a dose constraint of 250 µSv/a is established for the average member of the critical group. Linked to the public dose constraint is a system of Annual Authorised Discharge Quantities (AADQ). The AADQ system allows specific quantities of radionuclides to be released from an action, through the atmospheric and liquid pathways (surface water and underground water) to the environment. The public safety assessment must demonstrate compliance with this requirement.

Section 4 has further high level requirements concerning: radiation dose limits, medical surveillance, dose registers, radioactive waste management, environmental monitoring, transport of radioactive material, physical security, keeping of records, monitoring of workers and radon for occupational exposure.

3.2.4 SSRP, Section 5 – Decommissioning (South Africa, 2006)

Section 5 of the SSRP has high level requirements on authorised actions to make provision for decommissioning from the design phase through to the end-of-life of the action. Financial and human resources must be provided for in advance. A decommissioning strategy must be compiled at the planning phase, prior to operating the facility. At the end-of-life, the action must be decommissioned and decontaminated to levels not exceeding the dose constraint. If these levels cannot be met, restricted land use can be considered on a case-by-case basis. However, the regulations are very vague and there are no detailed requirements for the release of land.

3.2.5 Regulatory requirements and regulatory guides on planned and existing exposure situations

The NNR did not have any additional requirement documents on public exposures nor any requirement documents on existing exposure situations.

The NNR had a guidance document: Guideline on the Assessment of Radiation Hazards to Members of the Public from Mining and Minerals Processing Facilities (LG-1032), (NNR, 1997), which dealt with the exposure of members of the public to effluent releases from mining and mineral processing facilities. This document was out-dated, since it was compiled in 1997 and does not take cognisance of any developments since then.

3.2.6 Conclusion of existing regulations and the regulatory framework

The current regulations contained in the SSRP are all high level requirements. Section 4.5.2.2, for example, states that: “For members of the public, the dose constraint applicable to the average member of the critical group within the exposed population is 0,25 mSv per year specific to the authorised action unless otherwise agreed by the Regulator on a case-by-case basis, taking into account the dose limit specified in Annexure 2 for exposure of members of the public from all sources” (South Africa, 2006). This regulation refers to exposure of the critical group, but it is silent on the “what” and the “how”.

The NNR makes use of a system of requirement documents, which contained more detail on requirements than those contained in the regulations (NNR, 2011). The NNR document, "Requirements for Radiation Dose Limitation: Mining and Minerals Processing (RD-010)" is an example (NNR, 2002c). The requirement documents may further be strengthened by a guidance documents, such as the document, "Guideline on the Assessment of Radiation Hazards to Members of the Public from Mining and Minerals Processing Facilities (LG-1032)" (NNR, 1997). The guidance documents are not license binding, unless included as a condition in the license. However, the guidance documents still form part of the regulatory framework. These documents were out-dated.

The SSRP has no requirements on remediation of existing exposure scenarios.

The SSRP was promulgated in 2006 and it was based on the 1996 IAEA Basic Safety Standards (IAEA, 1996). The IAEA has published new requirements in the General Safety Requirement Series on the regulatory framework (IAEA, 2010a) and GSR Part 3 on the basic safety standards (IAEA, 2014a), which makes the SSRP out-dated.

3.3 Review of IAEA document: GSR Part 1

It is the government's responsibility to regulate safety at a national level by establishing a framework (IAEA, 2010a). This framework should define on the one hand, a set of legal requirements and a body to implement and enforce these requirements, in the form of an Act. On the other hand, the framework should provide the requirements for the industry to comply with, in the form of regulations (IAEA, 2010a). GSR Part 1 provides a framework for member states to follow. It was demonstrated in this chapter, that by implementing the IAEA proposed framework, as appropriate to the country needs, it creates an international environment important to international law and to international commerce (IAEA, 2010a).

3.3.1 Requirements of GSR Part 1 (IAEA, 2010a)

GSR Part 1 has 36 requirements. The requirements deal with three major areas of interest:

- Responsibilities and functions of the Government;
- The global safety regime; and
- Responsibilities and functions of the regulatory body.

Only those requirements applicable to the study were referred to below in relation to the current South African regulatory landscape.

Responsibilities and Functions of the Government

Requirement 1: National Policy and Strategy for Safety

The government should establish a national policy and strategy for safety in accordance with the extent to which radiation and nuclear activities are applied in the country (IAEA, 2010a). The document: "Nuclear Energy Policy for the Republic of South Africa" exist (DME, 2008).

Requirement 2: Establishment of a Framework for Safety

The government should establish and maintain an appropriate governmental, legal and regulatory framework for safety (IAEA, 2010a). The document: "Nuclear Energy Policy for the Republic of South Africa" exist (DME, 2008). This document is referred to, in Section 5, under the Existing Nuclear Energy Governance Framework, established Acts and Policies. The Acts and Policies include the White Paper on Energy Policy (South Africa, 1998c), the Nuclear Energy Act (South Africa,1999b), the National Nuclear Regulator Act (South Africa, 1999a), the Radioactive Waste Management Policy and Strategy (South Africa, 2005), and it refers to Secondary Governance Instruments, which includes, amongst others, the Hazardous Substances Act (South Africa, 1973), the Non-Proliferation of Weapons of Mass Destruction Act (South Africa,1993), the Mine Health & Safety Act (South Africa, 1996b), the Mineral and Petroleum Resources Development Act (South Africa, 2002), the National Environmental Management Act (South Africa, 1998a), the National Water Act (South Africa, 1998b) and the National Energy Regulator Act (South Africa, 2004).

Requirement 3: Establishment of a Regulatory Body

The government, through the legal system, should establish and maintain a regulatory body which is sufficiently staffed with competent resources (IAEA, 2010a). The National Nuclear Regulator has been established and empowered by the NNR Act (South Africa, 1999a).

Requirement 4: Independence of the Regulatory Body

The regulatory body should be independent to make safety related decisions and be functionally separated from entities having responsibilities or interests that could influence its decision making (IAEA, 2010a). The document on NNR regulatory philosophy explains regulatory independence in terms of the National Nuclear Regulator carrying out its mandate that ensures public health from exposures to radiation in accordance with the NNR (NNR, 2011).

Requirement 5: Prime Responsibility for Safety

The prime responsibility for safety shall be assigned to the person or organisation responsible for a facility or an activity (IAEA, 2010b). The prime responsibility for safety lies with the licence holder as is defined in the NNR's regulatory Philosophy (NNR, 2011).

Requirement 6: Compliance with Regulations and Responsibility for Safety

It should be stipulated that compliance with regulations and requirements established or adopted by the regulatory body does not relieve the person or organisation responsible for a facility or an activity of its prime responsibility for safety (IAEA, 2010b). The primary responsibility for safety lies with the holder of a nuclear authorisation (NNR, 2011).

Requirement 7: Coordination of Different Authorities with Responsibilities for Safety within the Regulatory Framework for Safety

Provision shall be made in the regulatory system, where several authorities have responsibilities for safety, for coordination of regulatory functions, avoidance of duplication and conflicting requirements (IAEA, 2010b). The NNR Act, in Section 6 has requirements for co-operative governance (South Africa, 1999a). The NNR document: "Plan for the Remediation of Contaminated Sites", explains the roles and responsibilities of the different regulators in South Africa regarding remediation. This document was developed in 2014, as part of this study, to enhance the regulatory framework on remediation (NNR, 2014b).

Requirement 8: Emergency Preparedness and Response

Holders of nuclear authorisations shall make provision for emergency preparedness and response to respond to nuclear or radiological emergencies (IAEA, 2010b). The NNR Act, in Sections 37 and 38 makes provision for emergency preparedness and response action to be implemented by holders of nuclear authorisations (South Africa, 1999a). The NNR regulatory requirements document, RD-008, Requirements for Emergency Preparedness: Mining and Minerals Processing, exist (NNR, 2002b). The SSRP is being updated (Draft Regulations on General Nuclear Safety), because the requirements in SSRP are broad and vague (NNR, 2016c).

Requirement 9: System for Protective Actions to Reduce Existing or Unregulated Radiation Risks

A system for protective actions to reduce undue radiation risks associated with unregulated sources and contamination from past activities consistent with the principles of justification and optimisation shall be established (IAEA, 2010b). The SSRP is being updated (Draft Regulations on General Nuclear Safety) to include more recent IAEA requirements (NNR, 2016c). The following NNR documents, based on the requirements of the draft Regulations on General Nuclear Safety, were developed as part of making provision for the management of existing exposure situations:

- Funding of Remediation (NNR, 2013);
- Safety Assessment of Radiation Hazard Assessment of the Public from NORM Activities (RG-002), (NNR, 2014a);
- Plan for Remediation of Contaminated Sites (NNR, 2014b);
- Remediation Criteria and Requirements (PP-0018), (NNR, 2015);
- Authorisation Procedure for Remediation of Existing Exposure Scenarios (PPD-AUT-02), (NNR, 2016b); and
- Skills Development Plan for Newly Appointed Staff in the Area of Remediation (PLN-SARA-15-0001), (NNR, 2016d).

Requirement 10: Provision for the Decommissioning of Facilities and the Management of Radioactive Waste and of Spent Fuel

Provisions shall be made for the safe decommissioning of facilities, the safe management and disposal of radioactive waste, and the safe management of spent fuel (IAEA, 2010b). The document Decommissioning of Nuclear Facilities (RD-0026) was developed in 2008 (NNR, 2008a). The SSRP is being updated (Draft Regulations on General Nuclear Safety) to include more recent IAEA requirements (NNR, 2016c).

Requirement 11: Competence for Safety

Provision shall be made for building and maintaining competence for measuring safety of facilities and activities (IAEA, 2010b) SSRP in Section 4.4 contains a very basic requirement (South Africa, 1999a). The document, Skills Development Plan for Newly Appointed Staff in the Area of Remediation, (PLN-SARA-15-0001), (NNR, 2016c), is under development. The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). In addition, the NNR is in the process of establishing a Centre for Nuclear Safety and Security (CNSS), which will draw expertise from all Universities in South Africa to strengthen the knowledge base in the country.

Requirement 12: Interfaces of Safety with Nuclear Security and with the State System of Accounting for, and Control of, Nuclear Material

Within the governmental and legal framework, adequate infrastructural arrangements should be established to interface safety with arrangements for nuclear security and accounting for nuclear material (IAEA, 2010b). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c).

Requirement 13: Provision of Technical Services

Provisions shall be made for technical services for safety, which includes personal dosimetry, environmental monitoring and the calibration of equipment (IAEA, 2010b). There are several accredited service providers in the country, amongst other, the SABS and South African National Accreditation System (SANAS). The NNR is in the process of establishing a radiochemistry laboratory to perform verification analysis on samples from authorised facilities. The laboratory will also be used to quantify the radioactive content in environmental samples for other purposes as required by the NNR.

The Global Safety Regime

Requirement 14: International Obligations and Arrangements for International Cooperation

In order to enhance safety globally, the government shall participate in relevant international initiatives and cooperate as appropriate (IAEA, 2010b). A requirement is included under Section 5 of the NNR Act (South Africa, 1999a).

Requirement 15: Sharing of Operating Experience and Regulatory Experience

Operating experience and regulatory experience shall be analysed and lessons learnt shall be shared (IAEA, 2010b). The SSRP contains a requirement that operational safety assessments must be frequently reviewed and be updated to ensure that it is current (South Africa, 2006). The SSRP is being updated to expand on existing requirements and to include more recent IAEA requirements (NNR, 2016c). The NNR is in the process of establishing a Centre for Nuclear Safety and Security (CNSS), which will draw expertise from all Universities in South Africa to strengthen the knowledge base in the country.

<u>Responsibilities and Functions of the Regulatory Body</u>

Requirement 16: Organisational Structure of the Regulatory Body and Allocation of Resources

Organisational structure of the regulatory body and allocation of resources shall be managed to discharge its responsibilities and perform its functions to commensurate with the radiation risks associated with facilities and activities in the country (IAEA, 2010b). The document, Skills Development Plan for Newly Appointed Staff in the Area of Remediation, (PLN-SARA-15-0001) (NNR, 2016c), is in a draft format. The document, Plan for Remediation of Contaminated Sites (NNR, 2014b), was developed, as part of this study, and contains information regarding staffing and working agreements with institutions of higher education.

Requirement 17: Effective Independence in the Performance of Regulatory Functions

Effective independence in the performance of regulatory functions shall not be compromised (IAEA, 2010b).

Requirement 18: Staffing and Competence of the Regulatory Body

The regulatory body shall employ a sufficiently qualified and competent staff to effectively regulate and perform its functions and its responsibilities (IAEA, 2010b). Section 7 of the NNR Act have regulations regarding staffing of the NNR (South Africa, 1999a). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). The NNR is in the process of establishing a Centre for Nuclear Safety and Security (CNSS), which will draw expertise from all Universities in South Africa to strengthen the knowledge base in the country.

Requirement 19: The Management System of the Regulatory Body

The regulatory body shall have a management system that is aligned with its safety goals (IAEA, 2010b). The management system of the NNR is contained in the document RD-0034 (NNR, 2008b).

Requirement 20: Liaison with Advisory Bodies and Support Organisations

The regulatory body shall obtain technical or other expert professional advice or services as necessary in support of its regulatory functions and responsibilities. The NNR has a signed contract with a technical support organisation and in addition, the NNR is in the process of establishing a Centre for Nuclear Safety and Security (CNSS), which will draw expertise from all Universities in South Africa to strengthen the knowledge base in the country.

Requirement 21: Liaison between the Regulatory Body and Authorised Parties

Formal and informal mechanisms of communication with authorised parties on all safety related issues, shall be established to conduct professional and constructive liaison (IAEA, 2010b). The NNR authorises facilities in accordance with the document PPD-AUT-01 (NNR, 2016a) and for remediation in accordance with procedure PPD-AUT-02 Authorisation Procedure for Remediation of Existing Exposure Scenarios (PPD-AUT-02), (NNR, 2016b).

Requirement 22: Stability and Consistency of Regulatory Control

Stability and consistency of regulatory control must be ensured through formal processes, policies and criteria (IAEA, 2010b). A quality manual and procedures exist.

Requirement 23: Authorisation of Facilities and Activities by the Regulatory Body

Facilities and activities, exceeding exclusion criteria shall be authorised by the regulatory body. The authorisation shall include necessary conditions required for safety liaison (IAEA, 2010b). The NNR authorises facilities in accordance with the document PPD-AUT-01 (NNR, 2016a) and for remediation in accordance with procedure PPD-AUT-02 Authorisation Procedure for Remediation of Existing Exposure Scenarios (PPD-AUT-02) (NNR, 2016b).

Requirement 24: Demonstration of Safety for the Authorisation of Facilities and Activities

Applications for the authorisation of a facility or activity shall submit a demonstration of safety (IAEA, 2010b). The SSRP has requirements for prior safety assessments and for operational safety assessment (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c).

Requirement 25: Review and Assessment of Information Relevant to Safety

The regulatory body shall review and assess the information submitted by the applicant to demonstrate safety to determine compliance with regulatory requirements and the conditions specified in the authorisation, (IAEA, 2010b). The SSRP has requirements for prior safety assessments and for operational safety assessment (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c).

Requirement 26: Graded Approach to Review and Assessment of a Facility or an Activity

Review and assessment of the demonstration of safety for a facility or an activity shall be commensurate with the radiation risks associated with the facility or activity (IAEA, 2010b). The SSRP has requirements for the graded approach to safety assessments (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c).

Requirement 27: Inspection of Facilities and Activities

The regulatory body shall perform inspections of facilities and activities to verify that the authorised party is in compliance with the regulatory requirements and with the conditions specified in the authorisation (IAEA, 2010b). The NNR Act has requirements for compliance assurance (South Africa, 1999a). The NNR has a procedure for compliance assurance (PPD-COM-01), (NNR, 2010).

Requirement 28: Types of Inspection of Facilities and Activities

Inspections of facilities and activities shall include planned and reactive inspections, both announced and unannounced (IAEA, 2010b). The NNR Act has requirements for compliance assurance (South Africa, 1999a). The NNR has a procedure for compliance assurance (PPD-COM-01), (NNR, 2010).

Requirement 29: Graded Approach to Inspections of Facilities and Activities

The frequency and detail of inspections shall be performed in accordance with the radiation risk associated that facility or activity (IAEA, 2010b). The NNR Act has requirements for compliance assurance (South Africa, 1999a). The NNR has a procedure for compliance assurance (PPD-COM-01), (NNR, 2010).

Requirement 30: Establishment of an Enforcement Policy

The regulatory body shall establish and implement an enforcement policy within the legal framework for responding to non-compliance by authorised parties with regulatory requirements or with any conditions specified in the authorisation (IAEA, 2010b). The NNR Act has requirements for enforcement (South Africa, 1999a). The NNR has a procedure for enforcement (PPD-COM-02), (NNR, 2012).

Requirement 31: Requiring of Corrective Action by Authorised Parties

Holders of authorisations shall implement corrective actions after non-compliances have been identified (IAEA, 2010b). The NNR has a requirements document for the mining and mineral processing facilities in RD-005 (NNR, 2002a).

Requirement 32: Regulations and Guides

The regulatory body shall have regulations and guides to specify the principles, requirements and associated criteria for safety (IAEA, 2010b). The NNR has developed a document: Safety Assessment of Radiation Hazards to Members of the Public from NORM Activities, Rev. 0 (RG-002), (NNR, 2014a), as part of this study. There was no safety assessment methodology for sites to be remediated; it was developed during this study. It must be included in a NNR document.

Requirement 33: Review of Regulations and Guides

Regulations and guides should be reviewed as necessary to keep them up to date with due consideration taken of relevant international safety standards and technical standards and of relevant experience gained (IAEA, 2010b). The NNR is in accordance with the NNR Act responsible for standards (South Africa, 1999a).

Requirement 34: Promotion of Regulations and Guides to Interested Parties

Interested parties and the public shall have access to safety regulations and guides and the associated safety criteria (IAEA, 2010b). RG-002 was distributed to holders of nuclear authorisations related mining and minerals processing for comments before it was approved by the NNR in 2014 (NNR, 2014a). In order to promulgate regulations, the regulations are developed internally to the NNR. Thereafter, regulations are approved by the NNR Board and recommended to the Minister of Energy. The Minister of Energy, through a process involving the State Legal Advisor, publishes the draft regulations for comment. After inclusion of the comments, the draft regulations are further processed until promulgated. More information on this process can be found in sections 73 to 82 of the Constitution of the Republic of South Africa, 1996 (South Africa, 1996a), and the relevant Rules of Parliament (See more at: http://www.justice.gov.za/legislation/legprocess.htm#sthash.IhPrF6VN. dpuf).

Requirement 35: Safety Related Records

Records related to the safety of facilities and activities shall be kept by the regulator (IAEA, 2010b). All NNR records are managed in accordance with the records management procedure, (PRO-ICT-01), (NNR, 2009).

Requirement 36: Communication and Consultation with Interested Parties

The regulatory body shall communicate and consult with interested parties and the public about matters related to radiation safety and its decision making processes (IAEA, 2010b). The NNR Act makes provision for public consultation (South Africa, 1999a). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c).

3.4 IAEA: GSR Part 3

GSR Part 3 provides the safety standards in more detail (IAEA, 2014a). Not all the requirements are important to this study. GSR Part 3 requirements are on a level of detail as is currently in NNR requirements documents, a level below the NNR regulations. The content of GSR Part 3 requirement, as adopted, in concept regulations, for South African conditions, is discussed in Section 3.5.

GSR Part 3 (IAEA, 2014a) is concerned with, amongst others, the following requirements:

GSR Part 3: Section 3: Planned Exposure Situations

Requirement 7: Notification and Authorisation

Applications shall be made to the regulator to perform activities with radioactive material (IAEA, 2014a). The NNR Act has requirements on notification and authorisation (South Africa, 1999b). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). The document: Authorisation Procedure for Remediation of Existing Exposure Scenarios (PPD-AUT-02), (NNR, 2016b) was developed, as part of this study.

Requirement 8: Exemption and Clearance

The regulatory body shall determine which activities with radioactive material are to be exempted from some or all of the authorisation requirements and how to clear or remove the action of facilities from regulatory control (IAEA, 2014a). The SSRP has requirements on exemption and clearance (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). The document: Remediation Criteria and Requirements, (PP-0018), (NNR, 2015) was developed, as part of this study, from ICRP criteria (ICRP, 2007a).

Requirement 9: Responsibilities of Registrants and Licensees in Planned Exposure Situations

Holders of nuclear authorisations shall be responsible for protection and safety in planned exposure situations (IAEA, 2014a). The responsibilities of holders of nuclear authorisations, other than requirements for safety assessment, were not specifically dealt with in this study.

Requirement 10: Justification of Practices

Only justified practices shall be authorised by the regulator (IAEA, 2014a). The SSRP has requirements on justification of actions (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). The document: Remediation Criteria and Requirements, (PP-0018), (NNR, 2015) was developed, as part of this study, from ICRP criteria (ICRP, 2007a). Optimisation of protection plays a major role in decision making when reference levels for the release of land, after remediation, is derived.

Requirement 11: Optimisation of Protection and Safety

The regulatory body shall establish and enforce requirements for the optimisation of safety, and holders of nuclear authorisations must ensure that protection and safety is optimised (IAEA, 2014a). The SSRP has requirements on justification of actions (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). The document: Remediation Criteria and Requirements, (PP-0018), (NNR, 2015) was developed, as part of this study, from ICRP criteria (ICRP, 2007a). The safety assessment methodologies developed for public exposure, RG-002 (NNR, 2014) and the safety assessment methodology developed for remediation in this thesis, are both focused on optimisation of protection. Optimisation of protection plays a major role in decision making when reference levels for the release of land, after remediation, is derived.

Requirement 12: Dose Limits

The regulatory body shall establish dose limits and reference levels for occupational exposure and public exposure, and holders of nuclear authorisations shall apply these limits and reference levels (IAEA, 2014a). The SSRP has set dose limits (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). A system of dose limits, dose constraints and reference levels was applied in this study. Reference levels derived for remediation and dose constraints are applied to public dose as a result of authorised release of effluents. The document: Remediation Criteria and Requirements, (PP-0018), (NNR, 2015) was developed, as part of this study, from ICRP criteria (ICRP, 2007a).

Requirement 13: Safety Assessment

The regulatory body shall establish and enforce requirements for safety assessment, and the holders of nuclear authorisations shall conduct an appropriate safety assessment of this facility or activity, prior to operation (IAEA, 2014a). The SSRP has specific requirements on safety assessment (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). This thesis is specifically concerned with the development of safety assessment methodologies for public exposure from authorised releases and public exposure from existing, unauthorised exposure situations.

Requirement 14: Monitoring for Verification of Compliance

Holders of nuclear authorisations shall conduct monitoring to demonstrate compliance with the conditions of authorisation. The regulator shall verify compliance with conditions of authorisation (IAEA, 2014a). The SSRP has specific requirements on verification of compliance (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). This thesis specifically refers to verification of compliance for public exposure from authorised releases and public exposure from existing, unauthorised exposure situations.

Requirement 19: Responsibilities of the Regulatory Body Specific to Occupational Exposure

The regulatory body shall establish and enforce compliance with requirements for occupational safety to ensure that protection and safety is optimised (IAEA, 2014a). The SSRP has specific requirements on verification of compliance (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). Occupational exposures are not dealt with in this thesis. However, there are references to worker safety assessments.

Requirement 31: Radioactive Waste and Discharges

Holders of nuclear authorisations shall establish and implement programmes to ensure that radioactive waste and discharges of radioactive material to the environment are managed in accordance with the conditions of authorisation (IAEA, 2014a). The SSRP has specific requirements on waste management and discharges of radioactive effluent (AADQs) (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). This thesis is explicitly concerned with exposures from discharges to member of the public and the remediation of areas where the environment was contaminated due to uncontrolled activities of waste management in the past. RG-002 (NNR, 2014) and the safety assessment methodology developed for remediation, was developed as part of this thesis.

Requirement 32: Monitoring and Reporting

The regulatory body shall approve and verify compliance with programmes for source monitoring and environmental monitoring compiled by the holders of nuclear authorisations.

Holders shall implement these programmes, monitor compliance and keep records with conditions of authorisation and report to the regulator on the results of compliance (IAEA, 2014a). The SSRP has specific requirements on waste management and discharges of radioactive effluent (AADQs) (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). Monitoring and reporting, as a mechanism of ensuring control, did not form part of this study. However, the NNR document, RG-002 (NNR, 2014) contains some information on the topic.

GSR Part 3: Section 5: Existing Exposure Situations

Requirement 47: Responsibilities of the Government Specific to Existing Exposure Situations

The government shall ensure that existing exposure situations that have been identified are evaluated to determine which occupational exposures and public exposures are of concern from the point of view of radiation protection (IAEA, 2014a). The SSRP does not have requirements on the management of existing exposure situations (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). One of the primary purposes of this study was to develop the framework (regulations, guides and processes) to manage existing exposure situations. It is extensively dealt with in this document.

Requirement 48: Justification for Protective Actions and Optimisation of Protection and Safety

The regulatory body shall ensure that remedial actions and protective actions are justified and that protection and safety is optimised (IAEA, 2014a). The SSRP has specific requirements on optimisation of protection (South Africa, 2006). The SSRP is being updated to include more recent IAEA requirements and to expand the scope of optimisation to include existing exposure situations (NNR, 2016c).

Requirement 49: Responsibilities for Remediation of Areas with Residual Radioactive Material

The regulatory body shall ensure that a programme is established to identify areas with residual radioactive material; for establishing and implementing remediation programmes and post-remediation control measures. The regulatory body shall also establish a strategy for the management of radioactive waste (IAEA, 2014a). The SSRP is being updated to include more recent IAEA requirements (NNR, 2016c). The following NNR documents were developed as part of making provision for the management of existing exposure situations:

- Funding of Remediation (NNR, 2013);
- Safety Assessment of Radiation Hazard Assessment of the Public from NORM Activities (RG-002), (NNR, 2014a);
- Plan for Remediation of Contaminated Sites (NNR, 2014b);
- Remediation Criteria and Requirements, (PP-0018), (NNR, 2015);
- Authorisation Procedure for Remediation of Existing Exposure Scenarios (PPD-AUT-02), (NNR, 2016b)
- Skills Development Plan for Newly Appointed Staff in the Area of Remediation, (PLN-SARA-15-0001), (NNR, 2016d)

Requirement 50: Public Exposure due to Radon Indoors

The regulatory body shall provide information on levels of radon indoors and the associated health risks and, where required, establish and implement an action plan for controlling public exposure due to radon indoors (IAEA, 2014a). Exposure to radon indoors is not applicable to this study, unless it is directly related to land being remediated.

Requirement 51: Exposure due to Radionuclides in Commodities

The regulatory body shall establish reference levels for exposure due to radionuclides in commodities (IAEA, 2014a). Radionuclides in commodities are not dealt with in this study.

Requirement 52: Exposure in Workplaces

The regulatory body shall establish and enforce requirements for the protection of workers in existing exposure situations (IAEA, 2014a). Exposures in workplaces are not dealt with in this study.

3.5 Draft New General Nuclear Safety Regulations (NNR, 2016c)

In the previous sections, all the inadequacies in existing regulation were highlighted. The NNR has embarked on a process of updating existing regulations contained in the SSRP. The SSRP has been revised and expanded to include existing requirement documents. This study, was partially initiated by the management of existing exposure scenarios in the Wonderfonteinspruit area by the NNR, and could therefore contribute to the expansion of the content of the proposed new regulations. It is important to mention that the current version of the new General Nuclear Safety Regulations is in a draft format and that it has to be processed by the Department of Energy before it will become binding law (NNR, 2016c). Part of this processing includes publishing the regulation for public comment. However, it was identified in the study proposal that this study would provide an opportunity to develop a new national framework for remediation. Therefore, the following sections of draft regulations applicable to this study are included.

Part Five: Safety Assessment (NNR, 2016c)

3. Safety analysis
4. Prior safety assessment
5. Operational safety assessments
7. Periodic safety reviews
8. Worker safety assessments
9. Public safety assessments

Part Six: Radiation Protection, Waste Management and Decommissioning (NNR, 2016c)

2. System of radiation protection
4. Dose limitation
6. Planned exposure situations
7. Existing exposure situations
8. Protection of the environment
10. Record keeping
12. Radioactive waste management
13. Control over radioactive discharges and releases to the environment
14. Decommissioning

The proposed new regulations specify the broad context in which compliance should be demonstrated by specifying the aspects that need to be included (NNR, 2016c). The regulations will eventually be followed by detailed requirement and guides of how to comply. In the previous sections, omissions and shortcomings in existing regulations were identified. In this section, a bit more detail is provided on the proposed improvements to regulations as it is in the current draft version of the Regulations on General Nuclear Safety (NNR, 2016c).

3.5.1 Discussion of draft regulations in part five: Safety assessment (NNR, 2016c)

Prior safety assessment

A safety assessment must be submitted to the NNR and approved by the NNR before any work on a contaminated site may commence (NNR, 2016c). The assessment must be performed prospectively with limited site specific input information. Furthermore, the safety assessment should demonstrate compliance with the fundamental safety criteria and that the necessary control measures and mechanisms can be derived from the safety assessment to ensure safety from exposure to radioactive substances. The safety assessment must include siting and future potential effects:

- releases into the environment from normal operations as well as from accidents;
- a public safety assessment;
- a worker safety assessment;
- future decommissioning;
- emergency planning; and
- nuclear security.

Operational safety assessments (NNR, 2016c)

An operational safety assessment is required as part of keeping the prior safety assessment current, e.g. as more operational information becomes available or operations change due to modifications, process changes and changes to external factors. Changes to operational processes should be reflected in the worker and public safety assessments. This means that the safety assessment process is not a once-off, but an iterative process.

Worker safety assessments (NNR, 2016c)

A prior safety assessment, before any work has commenced, shall determine the average annual effective occupational dose and maximum individual annual effective occupational dose from normal operations and anticipated operational occurrences. These assessments should be updated as operational changes that could affect exposures to the worker occur. Control programmes must also be amended accordingly.

Public safety assessments (NNR, 2016c)

As part of the prior safety assessment, a public safety assessment, which includes non-occupationally exposed workers, visitors to the facility and members of the public in the off-site location could be exposed to on-site activities. In order to perform a public safety assessment, a site characterisation as well as a land use and habitation study is required. All exposure pathways must be analysed and the representative person should be determined. These assessments are also updated when operational changes that may affect exposure changes.

3.5.2 Discussion of draft consolidated regulations on general nuclear safety in Part six: Radiation protection, waste management and decommissioning (NNR, 2016c)

These regulations set out the requirements related to radiation protection, predisposal radioactive waste management, control over radioactive discharges and releases to the environment and decommissioning.

Radiation protection principles (NNR, 2016c)

The principles of justification, optimisation of protection and dose limits for planned exposure scenarios are included in the new proposed regulations (NNR, 2016c). Dose constraints and reference levels, which are very important to this study, are included. In terms of dose constraints for occupational and public exposure, in planned exposure situations, an effective dose of 0.25 mSv per annum, applicable to the authorised action (facility/site), for members of the public, applicable to the representative person, will apply. Reference levels, shall be optimised for existing exposure situations, on a case-by-case basis and approved by the regulator. Optimised and justified reference levels between 1 and 20 mSv per annum will be considered. Dose limits for workers in planned situations have changed to include the new dose to the lens of the eye and the extremities (IAEA, 2014a), (NNR, 2016c).

Radiation protection education, training and information (NNR, 2016c)

New requirements have been established for the training of workers in radiation protection. Qualifications and educational requirements are established. A skills development plan in the area of remediation has been developed (NNR, 2016c). The NNR is also establishing a Centre for Nuclear Safety and Security in collaboration with the largest Universities in South Africa.

Planned exposure situations (NNR, 2016c)

The new proposed regulations consider safety of sources, occupational exposures (which includes monitoring of workers and the workplace), public exposure, and environmental monitoring and reporting requirements.

Existing exposure situations (NNR, 2016c)

Remediation of existing exposure scenarios has been a problem in South Africa for a number of years due to a lack of governing regulations. This study confirmed the gaps in existing regulations and identified other gaps not previously recognised. Information gathered through this study was used in the process of developing the new proposed regulations. The new proposed regulations will now (when approved), allow the authorisation of existing exposure situations to be remediated under the authorisation of the NNR (NNR, 2016c). The proposed new regulations refer to amongst others, reference levels, remedial action plans, public information, post remediation control measures and occupational exposures during remediation. Further to this study, there are issues such as the conditional release of sites from regulatory control for residential use or for industrial use, which are still not included in the revised regulations. These and other issues identified in this study will be fed into the legislative development process at the appropriate time. In addition, the following supplementary documents have been developed:

- Safety Assessment of Radiation Hazard Assessment of the Public from NORM Activities, Pretoria, NNR, (RG-002), (NNR, 2014a).
- Remediation Criteria and Requirements, (PP-0018), (NNR, 2015).

Protection of non-human species (NNR, 2016c)

The new proposed regulations include requirements on the protection of non-human species. These requirements have not filtered through to mining and mineral processing activities in the country as yet. It might be included as research projects in the Centre for Nuclear Safety and Security in collaboration with the largest Universities in South Africa.

Radioactive waste management (NNR, 2016c)

The new proposed regulations include requirements on waste management. These requirements will enhance the 2014 Department of Environmental Affairs (DEA) regulations on environmental management as they exclude radionuclides (South Africa, 2014). Important aspects included in the proposed new regulation, linked to the study and specifically to the waste management during and after remediation, are waste acceptance criteria and waste management plans.

Control over radioactive discharges and releases to the environment (NNR, 2016c)

The new proposed regulations include the requirement on discharges of liquid and gaseous effluent to the environment. These requirements will also enhance the requirements from the DEA, as it focuses on radionuclides, which are excluded from the DEA regulations. Discharges will be calculated for a specific site/facility, taking into account the dose constraint, which is 0.25 mSv per annum from all exposure pathways. The new requirements require environmental surveillance programmes to be established and records submitted to the NNR. Requirements for the representative person as well as the different age groups to be considered are included. These requirements were identified during the execution of this study as being very important in performing public dose assessments. During the compilation of the revised new regulations, it was ensured that the requirements are included in the regulations. These aspects have been included in an NNR regulatory guide: Safety Assessment of Radiation Hazard Assessment of the Public from NORM Activities (RG-002), (NNR, 2014a).

CHAPTER 4 SAFETY ASSESSMENT METHODOLOGY FOR PUBLIC DOSE FROM AUTHORISED NORM FACILITIES

In this Chapter a new guideline assessment methodology for radiological public safety assessments for NORM facilities developed specific for South African conditions and in accordance with National legislation is discussed. This guideline takes into consideration new national and international developments in the field of radiation protection and safety assessment.

It is important to note that this guide was developed, as part of this study, for the sole purpose of quantifying the dose to members of the public. If the requirement was to analyse the performance of mining operations with the purpose of minimisation of releases to the environment, a different approach would have been taken. An example of a methodology to assess system efficiency and performance is the Improved Safety Assessment Methodology for Near Surface Disposal Facilities (ISAM) (IAEA, 2004).

(Note that the safety assessment methodology developed in this Chapter is already in use by the NNR as a guidance document, Safety Assessment of Radiation Hazards to Members of the Public from NORM Activities, RG-002, Revision 0, 2014 (NNR, 2014a). This document was distributed throughout industry for comment and as far as possible, comments were included before the final document was introduced to the mining industry at an open forum.

4.1 Introduction

This new guide was developed, as part of this study, to provide guidance for the safety assessments required for new NORM facilities to be performed as a prior safety assessment. Prior safety assessment, referring to the safety assessment required before mining or processing operations commences. The NNR published the guide in 2014, after it has been through a round of public comments (NNR, 2014a). However, since the publication of RG-002 (NNR, 2014a), there were other developments that require the updating of the guide. One such an example is the reference in RG-002 (NNR, 2014a) to the critical group, where-as this study refers to the representative person (discussed in Chapter 2). The IAEA GSR Part 3 was, at that stage in 2014, also only available in the interim version. Only later in that year, the final version of GSR Part 3 was approved (IAEA, 2014a).

4.2 Assessment Methodology

4.2.1 Overview

Members of the public can be exposed to radiation via external or internal pathways associated with radioactive releases from authorised actions involving NORM (NNR, 2014a). These external and internal sources of radiation exposure in NORM activities include the following nine pathways:

- External exposure from a point or volume source of ionizing radiation from habitat or recreational activities;
- External exposure from a plume of radionuclides in the atmosphere (cloud shine) or in water (water immersion source);
- External exposure from radionuclides on the skin;
- Internal exposure from radionuclides inhaled from the atmosphere;
- Internal exposure from radionuclides in the soil and water ingested through foodstuffs and drinking water;
- Internal exposure from inhalation of short-lived daughters of radon (also thoron for thorium ores) emanated from various sources; and
- Internal exposure from inhalation and ingestion of radionuclides re-suspended from soil and sediment.

The safety assessment process as depicted in Figure 4-1 was developed for this study (NNR, 2014a). The safety assessment process is a generic guideline of how the systematic process should unfold to demonstrate safety of the public around NORM facilities and consists of the following elements:

- Site Description – A description of where the facility or plant is located;
- Process Description – A detailed description of all the activities and processes at the facility or plant, which could result in public exposure;
- Sampling and Analysis – A process through which the isotopic composition and the nuclide specific activity concentration of the radioactive nuclides in the source material on-site is determined;
- Quantify Nuclides On-Site – A detailed description of all the radionuclides present, their quantities, chemical and physical form, decay constants, dose conversion factors, absorption classes and any other relevant information to the safety assessment;

- Source Term Quantification – The quantification, through calculation or modelling, of radioactive nuclides that can be released and dispersed into the environment to contribute to the public dose;
- Exposure Pathways – Identification of all intake and radiation exposure pathways relevant to the safety assessment;
- Representative Person Identification – Identification of all members of the public receiving the highest radiation doses; their habitat, agricultural and social activities that could impact on radiation doses through a source-pathway-receptor analysis and exposure scenario development;
- Assessment Criteria – The dose criteria to members of the public, contained in the legislative and regulatory framework (or criteria for radon concentrations), that should not be exceeded as a result of activities and operations at facilities;
- Public Dose Assessment – A complete dose assessment which should take into account all the exposure pathways and scenarios which requires some form of modelling based on conservative or reasonable assumptions. Results should be validated and uncertainties quantified:
    - Screening Dose Assessment – An initial safety assessment using most likely site specific exposure scenarios and conservative input data. When the results of the screening safety assessment show that the dose to the public (and radon concentrations) are very low compared to assessment criteria, it may not be necessary to further reduce calculational results by using site specific consumption data (IAEA, 2011);
    - Site Specific Dose Assessment – When results of a screening safety assessment exceed specific assessment criteria, then more realistic data and scenarios should be used:
        - Sampling – When a site specific safety assessment is required, more detailed information should be provided on the nuclide compositions and specific operational activities;
        - Analysis – Samples should be analysed at SABS 17025 accredited laboratories, and results should be included in the public dose assessment;
    - Interpretation of Results – The results from the modelling and public safety assessment should be quantified and expressed in radiation dose values and compared with the regulatory criteria. This process should indicate whether any further dose reduction interventions should be considered to comply with the assessment criteria; and

- Public Safety Assessment Report – The assumptions, data, models and calculation results, validations, uncertainties and conclusions should be included in a safety assessment report.

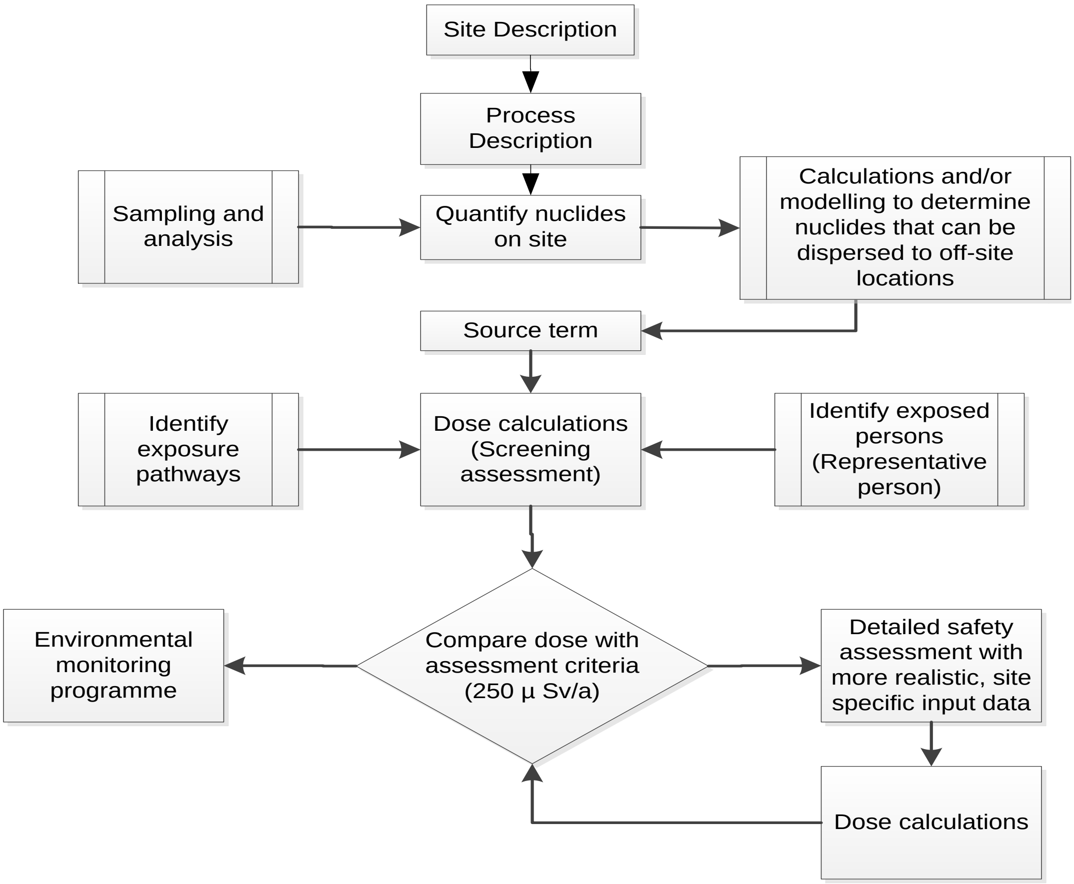

Figure 4-1: Public Safety Assessment Process

4.2.2 Site description and characterisation

The site description and characterisation should provide an overview of all significant sources, possible contaminant migration, dispersion and public exposure pathways (NNR, 2014a). This information will aid in the planning of the assessment, the choice of suitable models and the implementation of a monitoring programme. The following information should be provided for the public safety assessment process:

- General climate description including seasonal variations;
- Geological and hydrological factors as well as topography;
- Biota;

- Historical information on radionuclide contamination levels in the environment e.g. past water surveys, sedimentation surveys, activity concentration in soil and foodstuffs, etc. This could also be obtained from a baseline survey to determine the background conditions against which measurements during the operational phase can be evaluated;
- Radionuclide data from exploration sampling (e.g. ppm U and Th of ore body);
- Input from operational experience and site inspections;
- Experiences from other sites locally and internationally;
- Information from Governmental and other Institutions, such as Department of Water Affairs (DWA), Council for Geoscience (CGS), Department of Agriculture Forestry and Fisheries (DAFF), etc., including studies on site water balance and sampling programmes of non-radioactive materials;
- Studies identifying known points of chemical pollution e.g. identification of ground water plumes and sampling points;
- Identification of water uses and users e.g. municipalities, gardening, irrigation, farmers, use of mine water for drinking purposes, use of mine water for on-site irrigation, export to other users;
- Information on agricultural use of land, soil types, agricultural activities and information such as what type and quantity of food is produced, where the food is being distributed for consumption, etc.;
- Information on the type of settlements, such as informal settlements, housing types, etc.; and
- Demography including information on the population such as ages, gender, eating habits, sources of food, etc.

4.2.3 Process description

The process description should be provided in the public safety assessment to describe the activities and operations at a specific facility that could pose a radiation dose to the public via the relevant pathways. The process description should therefore contain information on all the facilities and the equipment on-site, as well as applications involving NORM. Experiences from other similar facilities, locally and internationally may also be usefully applied and extrapolated, especially for prospective assessments (NNR, 2014a).

4.2.4 Source term

4.2.4.1 Source term characterisation

The location and nature of existing radioactive contamination and the levels of radionuclide concentrations present in the environment should be provided in the safety assessment in the form of or as part of a baseline report. The radioactive nuclides that are associated with the activities of the action with a potential to be released off-site to the environment, including both presently prevailing releases, and future predicted releases, should be determined.

The mode of release, chemical and physical characteristics, as well as the quantities of the radionuclides released, should be determined with the objective of computing the highest annual average dose to the representative person or groups during the operation of the facility or subsequent to closure thereof. Separate source terms should be developed for the airborne and aquatic pathways (NNR, 2014a).

With regard to the development of source terms the following should be described:

a. Airborne pathways:

- Source terms of nuclides in gaseous and particulate releases via various actions (e.g. wind erosion, earth works, material handling, vehicle entrainment, stack releases) including possible upgrading of the nuclide concentrations in fine particles likely to become airborne;
- Physical and chemical properties of substances released;
- Elevation;
- Area and location of release;
- Release velocity;
- Mass flow rate Buoyancy (temperature) when applicable;
- Particle size distribution and activity (AMAD);
- Meteorology and climatology associated with releases; and
- Dispersion of release, deposition and re-suspension at impact location.

b. Aquatic pathways:

- Source term of nuclides released and their radiological, physical and chemical properties;
- Releases into surface water bodies;

- Releases into ground water i.e. leaching and seepage;
- Migration of surface and ground water off the site towards impact location as well as retardation and soil retention of nuclides;
- Extraction via boreholes;
- Chemical and physical characteristics impacting on radionuclide transport processes; and
- Water body dynamics.

4.2.4.2 Progeny and build up in the environment

Radioactive decay should be taken into account in the safety assessment, to account for the impact of the relevant progeny on the radiation doses.

Build-up of radionuclides in the environment due to sedimentation which could be a major contributing factor to radiation doses due to the long lived nature of radioactive nuclides released from NORM related activities should also be included in the safety assessment.

Time frames are important because dose is directly related to the period of exposure. When public exposures from normal operations are calculated, the exposure is expressed in terms of dose per annum (IAEA, 2014a). When build-up of long lived nuclides into the environment is considered, cognisance should be taken of the potential build-up of nuclides in the environment over the life-time of the facility. As radionuclides are deposited in the environment and some washed out a state of equilibrium should be reached, depending on the situation at the facility, after about 30 to 40 years (IAEA, 2016b).

Where sites are released from regulatory control, the peak dose should be considered. Peak dose is a principle which is determined by many factors. Peak dose is the maximum dose an individual could be exposed to from all exposure pathways any time from now up to many years in the future. Peak dose could typically be influenced by the long term dispersion of radionuclides in the ground water pathway and would therefore be important to long lived nuclides (IAEA, 2016b). The United States of America requires a period of 1 000 years to be considered after closure of a facility to ensure that peak dose is calculated (NUREG, 2016).

4.2.5 Exposure pathways

Radiation exposures of the public from NORM activities may arise from the product(s) of a process, from the atmospheric or liquid discharges, from the re-use of by-product material(s) or from the disposal of solid waste(s). The most important routes of radiation exposure of the public are usually external gamma radiation, inhalation and ingestion. Relevant exposure pathways to be taken into account in NORM activities are the following (see Figure 4-2 as illustration):

- External exposure to gamma radiation;
- Internal exposure through dust inhalation;
- Internal exposure through ingestion; and
- Skin contamination (from material deposited directly on the skin).

Figure 4-2 illustrates all the pathways by which an individual may be exposed and should be considered for dose calculations (IAEA, 2001).

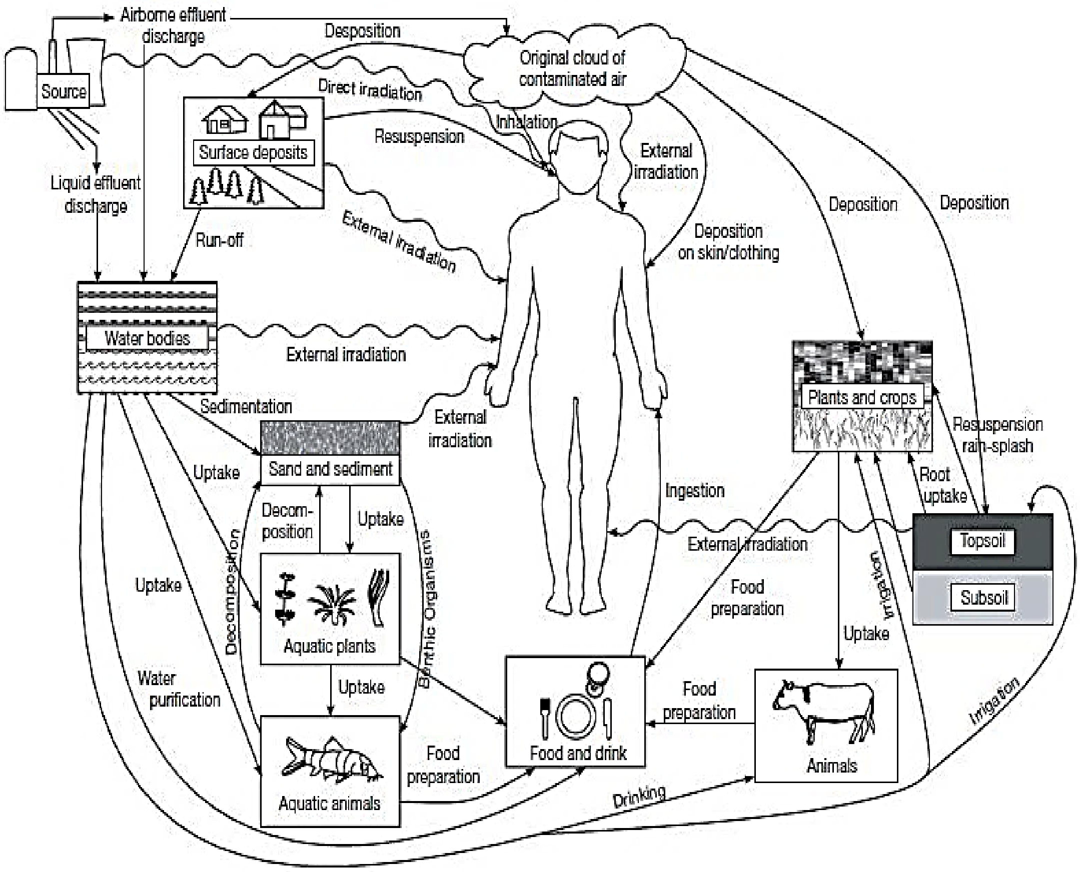

Figure 4-2: Exposure Pathways for Members of the Public (IAEA, 2001)

Factors which may be relevant to the transport of nuclides in the environment, should be addressed in the screening dose assessment, and if necessary, further considered in the model development. These should include the following items which are referred to as FEPs:

Natural FEPs including temporal variation, influencing the following radionuclide transport processes:

- Dust emission through wind erosion;
- Radon exhalation;
- Atmospheric dispersion, deposition and re-suspension;
- Soil erosion and sedimentation through water run-off;
- Surface water (rivers, lakes, wetlands) migration and sedimentation;
- Ground water migration and retardation;
- Water transport through porous media; and
- Nuclide transfer to soil and food chain.

Human activities which may impact on radiation safety:

- Chemical changes by human action;
- Chemical pollution;
- Dam building;
- Land reclamation;
- Ploughing;
- Recycling of solid materials;
- Fertilisation;
- Agricultural activities; and
- Building of roads and buildings with contaminated material.

Radionuclide transport mediated by human action:

- Water extraction;
- Irrigation;
- Water recharge;
- Solid material handling and transport;
- Earth works; and
- Feeding and watering of animals.

Events/processes related to human exposure through:

External exposure:

- Immersion in airborne plume;
- Immersion in surface water;
- Contaminated ground; and
- Contaminated shoreline and sediments.

Internal exposure:

- Inhalation of radioactive gases and particulates; and
- Ingestion of terrestrial and aquatic foods and liquids.

These FEPs are often used in the compilation of an interaction matrix.

4.2.6 Representative person

The representative person is an individual member of the public who is reasonably homogeneous with respect to its exposure for a given radiation source and given exposure pathway and is typical of individuals receiving the highest effective dose (whole body dose) or equivalent dose (organ dose), as applicable, by the given exposure pathway from the given source (ICRP, 2007a). The representative person was discussed in Chapter 2. Therefore, in order to determine the dose to the public, the representative person should be defined and information such as radiation sources, the exposure pathways and the habitat of the individuals in the area around the facility should be provided. Calculations should be performed for the five age groups, as per Table 4-1. The representative person will be selected as a person from the age group with the highest dose.

Age specific dose conversion factors, as contained in ICRP 119 (ICRP, 2012) and consumption rates from the list in Table 4-1 should be used in dose calculations. The consumption rates in Table 4-1 has been derived and are included in RG-002 (NNR, 2014a) from the South African data contained in the Database of the Food and Agriculture Organisation of the United Nations (FOA), Food balance sheets (FOA, 2008).

Table 4-1: Default Annual Consumption Factors

Category	Kg per Year Fresh Weight				
	Adults	15 Year Old	10 Year Old	5 Year Old	1 Year Old
% of Adult	100	85	60	50	40
Water (L/a)	600	510	360	300	240
Soil (kg/a)	0.037	0.03145	0.0222	0.0185	0.0148
Fresh water fish (kg/a)	25	21.25	15	12.5	10
Milk (L/a)	120	102	72	60	48
Beef (kg/a)	30	25.5	18	15	12
Mutton (kg/a)	25	21.25	15	12.5	10
Pork (kg/a)	20	17	12	10	8
Poultry (kg/a)	50	42.5	30	25	20
Eggs (kg/a)	15	12.75	9	7.5	6
Grain (kg/a)	250	212.5	150	125	100

- An average of consumption values was established from international literature which includes values obtained from South African national food balance sheets (FOA, 2008).

In case there is no specific data available for a specific age group, the age group consumption ratios, as a percentage of the adult (1st line in Table 4-1) could be used.

4.2.6.1 Land use

Land use data should be assessed to determine which activities could contribute to the radiation dose and to determine the extent of the respective contributions. The following information should typically be included in the safety assessment:

- land devoted to agricultural uses, its extent, the crops and their yields;
- land devoted to dairy farming, its extent and yields;
- land devoted to industrial, institutional and recreational purposes, its extent and the characteristics of its use;
- bodies of water used for commercial, individual and recreational fishing, including details of the aquatic species fished, their abundance and yield;
- bodies of water used for commercial purposes, including navigation; community water supply, irrigation, and recreational purposes such as bathing and sailing;
- land and bodies of water supporting wildlife and livestock;

- direct and indirect pathways for potential radioactive contamination of the food-chain;
- products imported to or exported from the region which may form part of the food-chain; and
- free foods such as mushrooms, berries and seaweed.

4.2.6.2 Habitation study

A habitation study should be performed to provide data on the habits of the representative person in order to calculate a representative dose due to exposure to radionuclides while in the area of concern. The following type of data should be provided in the safety assessment:

- Quantities of foodstuffs, cultivated in the area, consumed;
- Quantities of livestock or produce from livestock, raised in the area, and consumed;
- Quantities of fish consumed from water bodies in the area of concern;
- Quantities of water, from a contaminated source, consumed;
- Time spent in the area of concern (indoors and outdoors) and time spent elsewhere; and
- Time spent in recreational activities, such as a dam or golf course, or whatever is situated in the area of concern.

4.2.7 Assessment criteria

4.2.7.1 Screening dose assessment

For members of the public, the dose constraint applicable to the average member of the representative person within the exposed population is 250 µSv per annum specific to the authorised action unless otherwise agreed by the NNR on a case-by-case basis, taking into account the dose limit of 1 mSv to exposure of members of the public from all sources. (This value excludes natural background) (NNR, 2016c). Table 4-3 provides the dose criteria for members of the public and the associated actions to be considered by applicants and holders of authorisations in the public safety assessment process (NNR, 2014a).

Table 4-2: Public Safety Assessment Dose Criteria

Screening	Screening Result (µSv/a)	Screening Action	Assessment Outcome
Assumed, conservative input data, sampling and analysis data (optional where applicable)	< 10	No further dose assessment required	Limited release monitoring, environmental monitoring and Quality Assurance (QA) programme
	10 - 100	No further dose assessment required	Appropriate release monitoring, environmental monitoring and QA programme
	100 - 250	No further dose assessment required	Detailed release monitoring, environmental monitoring and QA programme
	> 250	Further assessment required using site specific data, detailed models and data	Plant modification, engineering back fitting and repeat assessment.

When a graded approach for the safety assessment is used and an initial screening assessment is performed with generic habitation data and conservative models, and the dose criterion value of 250 µSv per annum to the representative person is not exceeded, no further safety assessment would be required (NNR, 2014a).

If the result of the safety assessment reveals a dose between 10 and 100 µSv per annum to the representative person, an appropriate release, environmental monitoring and QA programme are required. If the result of the safety assessment reveals a dose between 100 and 250 µSv per annum to the representative person, detailed release monitoring, environmental monitoring and QA programmes are required (NNR, 2014a).

4.2.7.2 Site specific assessment

If the dose criterion of 250 µSv per annum to the representative person is exceeded more detailed and realistic site habitation values (e.g. consumption rates) may be used to improve the reality of the assessment and reduce conservatism (Real consumption rates instead of those specified in Table 4.1. e.g. 50 % contaminated water consumed).

If the result of the safety assessment reveals a dose >250 µSv per annum to the representative person and the assessment was done with realistic habitat, consumption and release data, changes to plant systems and parameters will be required which would lead to a reduction in the amount of activity released to the environment. Build-up in the environment must be taken into account in the safety assessment as well as in the verification programme.

A detailed safety analysis may be performed from the onset, however, conducting an initial screening assessment and the results thereof, should provide useful information on the amount of effort required.

4.2.7.3 Sampling

The surveillance programme should be performed to:

- characterise the source term by sampling and analysis of releases and environmental media;
- provide input for validation of transport models; and
- identify unexpected environmental contamination, transfer routes and pathways.

4.2.7.4 Sample analysis

An analytical method that is capable of performing the measurement at the required sensitivity (usually background level) and accuracy is required (NNR, 2014a).
In general, the main radionuclides from the natural decay series to be analysed, are listed in Tables 4-4, 4-5 and 4-6:

Table 4-3 Th-232 Series (NUREG, 2006)

Parent	Specific Activity (Bq/kg)	Half-Life	Decay Mode	Branching Fraction	Daughter
Th-232	4.10E+06	1.40E+10 y	α	1.00E+00	Ra-228
Ra-228	1.00E+16	5.75 y	β -	1.00E+00	Ac-228
Ac-228	8.30E+19	6.13 h	β -	1.00E+00	Th-228
Th-228	3.00E+16	1.91 y	α	1.00E+00	Ra-224
Ra-224	5.90E+18	3.66 d	α	1.00E+00	Rn-220
Rn-220	3.40E+22	55.6 s	α	1.00E+00	Po-216
Po-216	1.30E+25	0.15 s	α	1.00E+00	Pb-212
Pb-212	5.20E+19	10.6 h	β -	1.00E+00	Bi-212
Bi-212	5.40E+20	60.5 m	β - α	6.40E-01	Po-212
Po-212	6.60E+30	0.30 µs	α		
Tl-208	1.10E+22	3.07 m	β -		

Table 4-4: U-238 Series (NUREG, 2006)

Parent	Spec. Act (Bq/kg)	Half Life	Decay Mode	Branching Fraction	Daughter	Branching Fraction	Daughter
U-238	1.20E+07	4.47E+09 y	SF α	1.00E+00	Th-234		
Th-234	8.60E+17	24.1 d	b -	1.00E+00	Pa-234m	2.00E-03	Pa-234
Pa-234m	2.50E+22	1.17 m	b -IT	1.30E-03	Pa-234	1.00E+00	U-234
Pa-234	7.40E+19	6.70 h	b -	1.00E+00	U-234		
U-234	2.40E+11	2.44E+05 y	A	1.00E+00	Th-230		
Th-230	7.60E+11	7.70E+04 y	A	1.00E+00	Ra-226		
Ra-226	3.70E+13	1.60E+03 y	A	1.00E+00	Rn-222		
Rn-222	5.80E+18	3.82 d	A	1.00E+00	Po-218		
Po-218	1.10E+22	3.05 m	α b -	1.00E+00	Pb-214	2.00E-04	At-218
Pb-214	1.20E+21	26.8 m	b -	1.00E+00	Bi-214		
At-218	9.80E+23	2.00 s	A	1.00E+00	Bi-214		
Bi-214	1.70E+21	19.9 m	b -	1.00E+00	Po-214		
Po-214	1.20E+28	1.64E+02 µs	A	1.00E+00	Pb-210		
Pb-210	2.80E+15	22.3 y	b -	1.00E+00	Bi-210		
Bi-210	4.40E+18	5.01 d	b -	1.00E+00	Po-210		
Po-210	1.50E+17	1.38E+02 d	A				

SF = Spontaneous fission

Table 4-5: U-235 Series (NUREG, 2006)

Parent	Spec. Act (Bq / kg)	Half-Life	Decay Mode	Branching Fraction	Daughter	Branching Fraction	Daughter
U-235	8.00E+07	7.04E+08 y	A	1.00E+00	Th-231		
Th-231	2.00E+19	25.5 h	b -	1.00E+00	Pa-231		
Pa-231	1.70E+12	3.28E+04 y	α	1.00E+00	Ac-227		
Ac-227	2.70E+15	21.8 y	b - α	9.90E-01	Th-227	1.40E-02	Fr-223
Th-227	1.10E+18	18.7 d	α	1.00E+00	Ra-223		
Fr-223	1.40E+21	21.8 m	b -	1.00E+00	Ra-223		
Ra-223	1.90E+18	11.4 d	α	1.00E+00	Rn-219		
Rn-219	4.90E+23	3.96 s	α	1.00E+00	Po-215		
Po-215	1.10E+27	1.78E-03 s	α	1.00E+00	Pb-211		
Pb-211	9.10E+20	36.1 m	b -	1.00E+00	Bi-211		
Bi-211	1.60E+22	2.14 m	α b -	1.00E+00	Tl-207	2.80E-03	Po-211
Tl-207	6.90E+21	4.77 m	b -				
Po-211	3.60E+24	0.52 s	α				

The specific radionuclides to be included in the analysis programme or modelling assessment will vary according to site specific factors (e.g. the uranium and thorium contents of the ores, process materials and wastes) and the specific exposure pathway under examination (gaseous, particulate, liquid and nuclides contained in sedimentation). The exclusion of radionuclides from analysis programmes and modelling assessments must therefore be indicated and justified.

4.2.8 Dose assessment process

4.2.8.1 Scenario development

From the information in Section 4.2.7, real and/or hypothetical exposure scenarios should be developed to define the exposure conditions for the representative person. All sources of radionuclides and all exposure pathways must be considered. The applicable time frames must be considered. If the purpose is to calculate the dose to the representative person, a dose accrued in 1 year is considered. Where build-up in the environment is considered, the point of equilibrium between the annual released fraction, weathering and build-up due to longevity should be considered over the lifetime of the facility. When a facility is considered for release from regulatory control, peak dose, up to about 1 000 years must be considered (NUREG, 2016). Many things can change over a period of 1 000 years; therefore, all plausible scenarios must be considered.

4.2.8.2 Dose calculations

The IAEA has defined models, parameters and dose coefficients which are appropriate for the calculation of age specific doses to the representative person of the public arising from intakes of radionuclides. The representative person will vary according to the site specific scenario. Infants will typically be severely impacted where high milk consumptions are used in milk affected areas. Where maize and meat consumption is high, the 15-year-old or the adult is usually the higher impacted representative person.

When assessing the resulting doses to a defined representative person arising from the internal and external exposure to radionuclides in the environment, the following factors should be considered where appropriate in the assessment:

- The age composition of the representative person and age related metabolic parameters e.g. breathing rates;
- Particle size and activity distribution i.e. AMAD;

- Radionuclide intakes and radionuclide specific dose coefficients;
- Gut uptake factors and lung clearance class (defined by radionuclide chemistry);
- Individual habits affecting exposure e.g. sleeping, activity periods spent indoors and outdoors;
- Culturally appropriate dietary and age specific food and water consumption rates; and
- Gamma shielding factors.

4.2.8.3 Input parameters

For the development of the dose assessment model an interaction matrix which consists of a table indicating all possible elements and parameters in the assessment and interactions between them should be provided.

The interaction matrix should be drawn up as follows:

- List all sources of radioactive material, as identified during the site characterisation process;
- Identify the release and dispersion pathway. Apply the features, events and process list to determine the process that could lead to dispersion;
- Every dispersion process ends at a point of deposition;
- Repeatedly apply the FEP list at the point of deposition until there in no further dispersion possible; and
- The activity concentrations at all dispersion points where human exposure from internal or external sources of radiation is possible (directly or indirectly) should be quantified and translated into a dose to a man from that source at that point. Otherwise an acceptable justification should be provided why a pathway or receptor is not considered (e.g. when similar previous assessments indicated that exposures are negligible).

The following example where the source is a tailings dam is simplified to illustrate the interaction matrix principles:

- The dispersion pathway could be atmospheric and aquatic, therefore both pathways should be further explored. For this illustration only the atmospheric pathway is considered.
- Radioactive nuclides are released through emission and dispersed by wind in the form of particulates;

- Particulates are deposited on soil, and on terrestrial plants;
- The soil and terrestrial plant dispersion pathways should be further evaluated;
- In the case of only soil being assessed, the exposure of the public is affected by spending time on the soil which should be quantified;
- Nuclides in the soil can be further dispersed by re-suspension, ploughing, irrigation, and run off. Each pathway should be considered;
- Ploughing would lead to subsurface activity concentrations of radioactive nuclides, which would be absorbed by the agricultural activities on that land, which could be cattle feed, or fresh produce. The specific pathway should be analysed;
- In the example, root vegetables are produced. The activity in the soil is transferred to the root vegetables, for which a transfer factor (IAEA, 2010a) should be used to quantify the extent of transfer;
- The activity concentration in the edible part of the root should then be quantified. The activity concentration in the root should be multiplied by the human consumption rate and a dose conversion factor, to determine the dose to man; and
- All doses should be summed to determine the total dose to members of the public from a given source.

The use of such a table should facilitate the development of an audit trail of all decisions regarding the screening assessment, the subsequent detailed site specific assessment, and an iterative process towards the final results and conclusions. The interactive matrix is a tool that displays the flow of events in a logical order. At any stage in its development, the interaction matrix could be used to set up a quantitative model for the assessment. The various pathways should then be analysed using computer models, hand calculations or direct measurements as appropriate. Using the example above, the quantitative analysis process could be explained from the following simplified example. The pathway from source to receptor is as follows:

- Radionuclides are dispersed from the tailings facility via atmospheric dispersion to grass;
- Grass is eaten by a cow;
- The cow is milked or slaughtered;
- Meat and milk is consumed by a human, which receives a dose from ingesting the milk or meat; and
- The dose is calculated by multiplying the total quantity of radionuclides ingested over a year with a dose conversion factor to give the dose in Sv/a.

The process above is quantified, step by step, commencing with the activity concentration per nuclide in the tailings facility. Assume, for argument sake, that the tailings contain 1 Bq/g of U-238, 0.03 Bq/g of U-235, 1 Bq/g of U-234, 9 Bq/g of Ra-226 and similar concentrations of the other progeny. The radionuclides dispersed by atmospheric dispersion would be a fraction of the concentration of the radionuclides on the surface of the tailings and a fraction of the Rn released as gaseous nuclides. The dispersed nuclides are deposited on grass, where a fraction is washed to the soil and absorbed by a plant. The cow eats grass, with radionuclide in the external surface as well as radionuclides absorbed in the stem. A fraction of the radionuclides is excreted via milk, urine and faeces, while a fraction is absorbed in the body. Milk and meat, containing derived or measured nuclide activity concentrations, is consumed by a member of the public at a specified rate. The total activity consumed per year in Bq, multiplied by the dose conversion factor for ingestion by a member of the public in Sv/Bq, results in the calculated dose in Sv/a (or µSv/a).

When performing hand calculations, the radionuclide transfer from medium to medium (E.g. grass to soil to cow to milk) and eventually the dose is calculated step by step, taking cognisance of decay and build-up of progeny. Hand calculations can be speed up by using spreadsheets with pre-programmed algorithms, where all the individual calculations are automated. Alternatively to calculations for the transfer of radionuclides in the environmental compartments, environmental media could be sampled to reduce uncertainties and then be used in calculations to quantify dose. Sampling and analysis is a costly exercise and usually the analyses are performed at reduced costs without compromise of the outcome. The choice of method is therefore often driven by the availability of analysis results and costs. These factors should, however not affect the accuracy of the analysis.

In addition to the above, regulatory approved computer models can be used to assess exposures. Conservative parameters should be used in the models in the initial phases of the assessment. Depending on the assessment results obtained, progressive refinement, including uncertainty analysis, as described later, should be necessary to achieve the necessary confidence levels.

4.2.8.4 Atmospheric emissions and dispersion modelling

Atmospheric discharges should include both gaseous and particulate releases from volume, area and point sources which may be chronic long term releases (e.g. slime dams) or acute short term releases (e.g. in-plant roaster discharges). Atmospheric emissions should be calculated or determined for various natural or human activities causing such emissions (e.g.

wind erosion, earth works, material handling and vehicle entrainment). Radon exhalation rates should also be calculated or determined for sources containing enhanced levels of Ra-226. Thoron exhalation rates may only be required if the material has high thorium and hence Ra-224 contents like monazite (NNR, 2014a). The following types of sources should be addressed, using different models or modelling options to calculate emissions due to natural and human processes:

Point sources including:

- Upcast ventilation shafts; and
- Metallurgical processes e.g. stack releases, roaster discharges.

Volume and area sources including:

- Slime dams;
- Pyrite and calcine dumps;
- Open pit operations;
- Waste rock dumps;
- Ore stockpiles;
- Contaminated sites, rehabilitation and demolition activities; and
- Dry evaporation dams.

Concentrations of atmospheric releases decrease with distance from the source due to their movement downwind, advection and dilution and dispersion. Information to predict radionuclide concentrations at the location of the representative person should be used in calculations such as:

- Source type;
- Radionuclide characteristics;
- Site topography;
- Site climate and wind patterns; and
- Distance of the representative person receptor from the point of source.

As part of the screening assessment, a straight line Gaussian plume model may be used, provided the terrain is fairly flat. A rationale should be provided for modelling assumptions used with regard to:

- Atmospheric stability categories;
- Topographical effects; and
- Deposition parameters.

In the absence of wind rose data, the conservative approach should be adopted whereby it may be assumed that the wind blows directly towards the representative person at all times under worst case dispersion conditions.

Due to the considerable heights of tailing dams and waste dumps these should be modelled as volume sources rather than area sources. Alternatively, a conservative approach of assuming that the total emission is from a point source at the shortest distance between the source edge and the receptor, could be used.

4.2.8.5 Ground water modelling

Within a site there may be areas where significant releases of radionuclides from surface sources into the underlying ground water occur. Potential sources on sites include seepage and/or run off from waste rock, slime dams, evaporation pans, re-charging operations and from other material stockpiles e.g. calcine, pyrite. Polluted ground water plumes may spread off the site into surrounding aquifers used by the public (NNR, 2014a).

Where such plumes have been identified, the rate of movement and the extent of the plume movement should be quantified as this may indicate aquifers potentially contaminated by radionuclides.

Potential release points of contaminated surface water to ground water should be identified for each site and then quantitatively assessed through a combination of modelling and monitoring at available boreholes and surface seepage points e.g. at the bottom of tailing dams or springs.

Where pollution plumes are identified, the primary purpose of modelling should be to predict rates of migration and interactions with potential representative persons in the long term. Ground water pollution plumes should be identified e.g. through sampling of available on and off-site boreholes and potential user groups should be identified by hydro census. A list of commonly available codes that can be used for multiple analyses is provided in Table 2-2.

4.2.8.6 Surface water modelling

The radionuclide source terms for modelling should be defined by an initial water sampling programme at critical points within the water balance based on a mixture of grab and composite samples. The radionuclide concentrations obtained should be entered directly into the transport model.

In the screening assessment it should be conservatively assumed that the nuclide concentrations in surface water at the first point of public access equals the concentration at the point of release except if justification for a less conservative approach can be provided. A list of commonly available codes that can be used for multiple analyses is provided in Table 2-2.

4.2.8.7 Re-suspension of suspended radionuclides

The activity concentration of re-suspended radionuclides should be included in dose calculations as the concentration of suspended and deposited radionuclides in sediments and on soil may become re-suspended when being disturbed which in turn may cause higher doses to members of the public.

4.2.8.8 Transfer factors

In assessing the safety from releases of radionuclides into the environment, mathematical models are used in which the pathways of radionuclides from the release point to humans are quantitatively described by transfers between "environmental compartments" (e.g. from soil to pasture to cattle to humans). The radionuclide transfer between these compartments is usually described by transfer parameters (IAEA, 2010a). In South Africa, there is very little site specific information available on transfer factors. Therefore, we rely heavily on internationally available data such as those contained in the IAEA Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments (Technical Reports Series No. 472) (IAEA, 2010a). These values are specified per nuclide for various transport media, e.g. the transfer of uranium from soil to milk in loam soils and were chosen from the upper ends of ranges of available data (IAEA, 2010a). Hopefully site specific values will be developed for specific South African sites as the Centre for Safety and Security gathers momentum. Site specific values would provide more realistic data and reduce conservatism in calculations. Site specific data would also contribute to better understanding of the transfer of radionuclides in the environment, especially where there are large uncertainties.

In simple models these transfer parameters represent the ratio of concentrations of a radionuclide in two compartments under equilibrium conditions (referred to as the Concentration Factor Method). In more complex dynamic models, an attempt is made to represent the time dependent movement of radionuclides between the various environmental compartments i.e. the model is a conceptual approximation of the kinetics of the real system.

Simple equilibrium models have been well described and documented and default values are available for many of the transfer parameters (IAEA, 2010a). The Concentration Factor Method is adequate for many situations involving chronic releases of long lived radionuclides where equilibrium can be assumed in view of the timescales involved. Although it is usually sufficient in screening assessments to consider average conditions over prolonged periods, the combined effects of transient high release rates and unfavourable environmental situations involving substantial variations in release rates should be considered.

In contrast the parameters used in dynamic models (referred to as the Systems Analysis Method) tend to be model and site specific and their values depend on the assumptions used in establishing the model. Two types of transfer parameters should be used in models:

- Individual Parameters: These describe the transfer from one discrete environmental compartment to another e.g. from cattle feed or pasture to cattle; and
- Aggregated Parameters: These describe transfer via a complete chain of parameters e.g. the aggregated transfer parameter relating to radionuclide activity deposited on the soil surface to the concentration in the meat of grazing animals. This approach applies particularly to herds of cattle which do not receive additional feed or water from outside the area. In natural ecosystems this is an advantage as neither the individual transfer parameters to the various parts of the animal diet nor the animal diets themselves are well known.

The default transfer factors, as contained in RG-002 (NNR, 2014a), should be used in public safety assessments, except if other parameters can be justified in more realistic and site specific situations.

4.2.8.9 Dose coefficients

Dose coefficients from the latest version of the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources should be used (IAEA, 2014a). These values are the only internationally accepted values.

4.2.8.10 Time scales and seasonal variations

The safety assessment should ensure equitable protection of both current and future generations and this will involve balancing greater certainty for shorter time periods with increasing uncertainty over longer time periods. The time scale of interest for an assessment is a function of the nature of the operational plant/facility/system and the external influences on it, and the longevity of the radionuclides involved. Therefore, the time scales of an assessment should be justified on a case-by-case basis (ICRP, 2007a).

In view of the fact that many of the processes involved in the migration of radioactive material through the environment (e.g. sedimentation in rivers, uptake into the food chain) are transient processes, the peak or plateau values should be determined in the safety assessment. In this regard the assessment process should determine the highest annual dose to the representative person or groups during the operation of the facility and should adequately account for the influence of seasonal factors (ICRP, 2007a).

In addition to seasonal factors, consideration should also be given to abnormal weather conditions such as infrequent heavy rainfall and floods. A separate assessment should be prepared to assess the dose to the public under these conditions. Both assessed dose and frequency should be considered in the framework of a dose assessment.

4.2.8.11 Manual methods

Where dose calculations are performed manually, a spreadsheet is a handy tool to prevent duplication and it expedites the rate at which calculations are performed. An example of the use of a spreadsheet is referred to in Section 4.2.8.3. The mathematical formulations used in the spreadsheets should be presented in the safety assessment reports. The spreadsheets should be systematically developed while the lay-out should also be described in the safety report as to supplement its review. Results should be captured in tables and included in safety assessment reports.

4.2.8.12 Codes and software

There are various codes commercially available in the market. When codes are used, their validation and verification by the user is required and subsequent verification and acceptance by the NNR of the specific code is required in accordance with NNR requirements for verification and validation (NNR, 2006). More detail on some of the codes available was given in Chapter 2 where the use of RESRAD for this study was justified. An example of the use of codes is referred to in Section 4.2.8.3.

4.2.8.13 Quality assurance

The NNR quality assurance requirements should be applied to the public safety assessment process (NNR, 2008b). The NNR requirements on the integrated management process are based on International Standards Organisation (ISO) systems. The applicant or holder of an authorisation should identify and document the processes needed for the quality management programme with regards to Radiation Protection and determine the sequence and interaction of these processes, ensure the availability of resources and information necessary to support the operation and monitoring of these processes, monitor, measure and analyse these processes, and implement actions necessary to achieve planned results and continual improvement.

The public safety assessment should cover elements such as the control of documents; control of records; managements responsibilities; radiation protection function; design and development; control of monitoring and measuring devices; measurement, analysis and improvement; internal audits; continual improvements; corrective actions; and preventative actions.

4.2.9 Sensitivity analysis

Sensitivity Analysis (SA) is the study of how a specific input parameter would affect the output of a model (numerical or otherwise), e.g. variations in the wind speed in an air dispersion model (NNR, 2014a). For low wind speeds, the deposition of radionuclides is expected to be closer to the point of release, resulting in higher activity concentrations and therefore a higher dose to the exposed person. Sensitivity, therefore refers to how sensitive the results are to small changes in the input parameter. The extent to which sensitivity analyses are applied will depend on the amount of conservatism applied in each safety assessment and has to be justified on a case-by-case basis (IAEA, 2001).

A sensitivity analysis should be provided in the safety assessment process which includes:

- Supporting the decision making or the development of recommendations for decision makers (e.g. testing the robustness of a result);
- Enhancing communication from modellers to decision makers (e.g. by making recommendations more credible, understandable, compelling or persuasive);
- Increasing the understanding or quantification of the system (e.g. understanding relationships between input and output variables); and
- Modelling of development (e.g. searching for errors in the model).

4.2.10 Uncertainty analysis

Uncertainty in the assessment methodology arises from possible departures of the real situation from the assumptions outlined in the assessment context. For example, when the surface activity of a sample is measured in a counting apparatus. The uncertainty can be expressed in terms of, amongst other, the mean uncertainty or the standard deviation. The mean deviation, z, from the true value is calculated as the sum of the outputs, x, divided by the number of observations, n, and would be expressed as $z = x \pm n$. More on the application of uncertainties in RESRAD in Section 5.10 and Section 7.9. Although analytical methods are widely used, rigorous testing to quantify uncertainty under all potential conditions of model application should be provided. The extent to which uncertainty analyses are applied will depend on the amount of conservatism applied in each safety assessment and has to be justified on a case-by-case basis (IAEA, 2001).

The calculation method should present a detailed derivation of the uncertainty bounds to be associated with important results. The modelling should provide a realistic calculation of any particular phenomenon to a degree of accuracy compatible with the current state of knowledge of that phenomenon. The neglect or simplification of any phenomenon should not be treated by including a deliberate pessimism or bias, but should form part of an assessment of the overall modelling uncertainty.

In arriving at the overall calculated uncertainty all sources of uncertainty, including scaling uncertainties and uncertainties associated with initial and boundary conditions should be taken into account. The methodology used to combine the various sources of calculation uncertainty should be described and justified. Judgments concerning dominant phenomena and key models should be clearly stated and justified. For each parameter, which is judged to be of particular significance to the derivation of the overall uncertainty, justification should be provided for the assumed uncertainty distribution of that parameter.

4.2.11 Interpretation of results

A step-wise iterative procedure should be used to assess the representative person's doses and should focus on those aspects of the assessment that could give the highest doses. The initial assessment should be performed with conservative data. The assessment result should be benchmarked against the predetermined dose criterion. If the dose criterion is not exceeded, the level of detail in the assessment is acceptable. When the dose criterion is exceeded, a more detailed assessment should be conducted, using more realistic data. An iterative process should be repeated until the most realistic data and site specific data is used. If these results still exceed reference levels, physical actions should be implemented to reduce the source term and limit exposure scenarios.

CHAPTER 5 APPLICATION OF THE SAFETY ASSESSMENT METHODOLOGY TO A NORM FACILITY

Chapter 5 contains the practical application of the safety assessment methodology developed in Chapter 4 for planned situations, as applied to a NORM facility. This assessment methodology has the following steps (as outlined in Chapter 4):

- Site description;
- Assessment context;
- Source term development;
- Receptor definition;
- Exposure scenarios;
- Models;
- Assessments;
- Uncertainty analysis;
- Sensitivity analysis;
- Results; and
- Conclusions.

5.1 Site Description

Fictitious data is used as input into the public safety assessment, although it is based on real-life examples of operational facilities. Real mine data was not used because of permission issues to be obtained from the specific mines that were approached.

In brief, the mining and on-site operational processes are outlined. Ore is mined from the subsurface and fed directly into an enclosed (meaning that if dust is generated it is not released into the public domain) metallurgical processing plant. Excess ore is stored on a Stockpile (OSP). When there is no feed to the metallurgical plant from the mine, Ore is fed from the stockpile. At the processing plant, the ore is crushed and processed to extract gold as primary product, through a Carbon-In-Pulp (CIP) adsorption process. The processed material is taken to the gold plant, where gold is extracted. Solids from the leach process are washed to remove gold and cyanide and then disposed on a Tailings Storage Facility (TSF). Residue from the CIP process is screened to recover loaded carbon and is either pumped to a backfill plant or a TSF. Uranium is also recovered chemically at the processing plant. The process is depicted in Figure 5-1. Uranium is recovered from the pulp using sulphuric acid.

The sulphuric acid neutralises the carbonate minerals and dissolves the uranium. The solution is treated with a redox agent to create an ion. Uranium is extracted through an ion exchange resin.

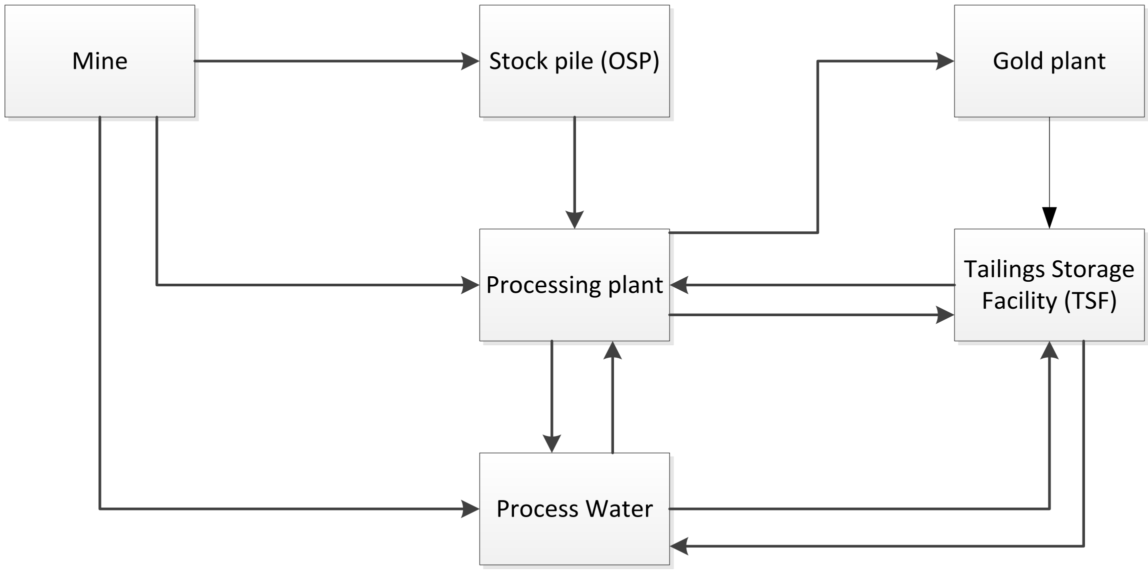

Figure 5-1: The Basic On-Surface Mining Processes

All facilities are on-surface facilities. The OSP, the TSF and some of the connecting roads can cause a spread of radionuclides to the off-site public domain. These operational activities were chosen for further analysis. Radionuclides are released from the on-site operations to the off-site location through atmospheric, on-surface wash-off and sub-surface ground water dispersion processes.

5.2 Assessment Context

5.2.1 Assessment requirements

In the assessment context die purpose and scope of the analysis is defined. In this study a radiological assessment was performed to primarily demonstrate the practical application of the assessment methodology developed in a previous chapter. The methodology is applied to demonstrate how a NNR license holder will have to demonstrate compliance with NNR off-site public safety assessment criteria. The assessment focuses on the quantification of consequences to the representative person, rather than on the functioning of the mining activities in order to reduce potential dispersible radioactive material.

The public dose limit in South Africa is 1 mSv/a to the representative person. A dose constraint of 0.25 mSv/a to the representative person, from all operator associated activities, is applied by the NNR as the compliance criteria. The basis for setting the dose constraint at 0.25 mSv/a is that it is assumed that there could be four operators in the same area who could simultaneously contribute to environmental pollution and expose the representative person. In demonstrating compliance with regulatory criteria, the operators should consider all on-site operations that could lead to off-site exposures. The atmospheric, surface water and ground water pathways should be analysed to determine off-site radionuclide concentrations. The summed exposure effects of inhalation, ingestion and external radiation, from all the sources at the off-site location should be determined. Compliance with the regulatory criterion is demonstrated when present and future exposures from environmental released, to the representative person, does not exceed the 0.25 mSv/a criteria. Therefore, the dose constraint becomes a dose limit.

Important principles such as *minimisation of exposure*, *minimisation of burden on future generations* and *polluter pays* principles are important to adhere to. The safety assessment is therefore, first and foremost performed to evaluate the safety of the representative person. When compliance with criteria is demonstrated, release to the environment must be optimised. The analysis should clearly identify the important release pathways, because the principle of control at source should be applied to optimise exposures to the representative person. Long term issues to be considered are build-up of nuclides in the environment and ground water migration of nuclides. Extended periods of typically 40 years, or even longer, should be considered. Finally, the assessment is performed to identify the content of the environmental verification surveillance programme.

5.2.2 Physical and hydrological site characterisation

It is important to define up-front which assessment tool will be used to perform the assessment. The equipment, or model, must be able to analyse all sources of contamination and all pathways of release dispersion. The model will require inputs in a specific format. RESRAD off-site, Version 2.6 was used as model in this study (RESRAD, 2007).

The RESRAD ground water model calculates nuclide transport in the ground water from the primary zone to a borehole, in different homogeneous layers. The layers or zones consist of a cover layer, a primary contaminant layer, an unsaturated zone and a saturated zone, as in Figure 5-2.

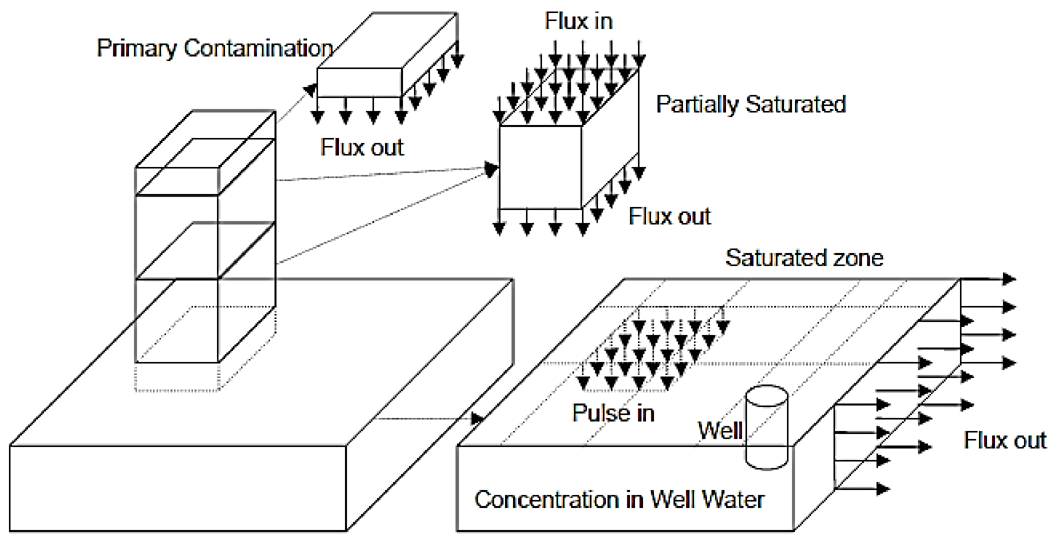

Figure 5-2: Conceptualisation of Ground Water Transport in RESRAD-OFFSITE (RESRAD, 2007)

To determine the rate of transport specified properties such as density, porosities, hydraulic conductivity, dispersivities and hydraulic gradient must be known. The processes considered in the transportation of nuclides are, the losses and gains resulting from radiological transformations, advective transport by water as it flows through the porous medium and dispersive transport caused by concentration gradients (RESRAD, 2007). Ground water movement can be a slow process and is difficult to quantify from surface data. Primarily default values were used, because it correlated quite well with values used in specialist studies in South Africa and neighbouring countries.

Radionuclides are washed off from the source material through processes of leaching and rain. Surface wash-off is gathered in a surface water body, from which water is used for human and animal consumption, irrigation of crops and other domestic uses. The quantities and ratios used was a combination of default values and South African values (NNR, 2014a).

To calculate atmospheric dispersion, RESRAD uses a Gaussian plume with an effective stack height, which is based on a chronic area source release. Nuclides are transported by wind to off-site locations where it is deposited on the surface and absorbed by the ground and plants or eaten by animals. The model makes terrain height adjustments and can calculate wet and dry depositions (RESRAD, 2007). Rainfall and wind directions are required as input parameters. An average rainfall of 600 mm/a, which is close to the actual rainfall in the Johannesburg area and a single wind direction was used in the model. A wind frequency file, from regional Gauteng meteorological data, could have been prepared as a more realistic representation of atmospheric conditions. If a wind frequency file was used as input, dose impacting in different wind directions would have been calculated. This would have changed the dose effect drastically since wind from one direction assumes deposition at one location for a year. This is an example where realistic data together with wind dispersion would have reduced exposure results considerably.

Nuclides accumulate in the environment due to the transportation through ground water, surface wash-off or atmospheric dispersion. Where the nuclides are deposited, the interaction between the nuclides and the environment is considered through several sets of internationally used transfer factors (IAEA, 2010a). Inputs are required with regard to the farming activities (livestock, fresh produce and soil types), usually obtained from a land use survey. Most of the information required above was collected as part of the environmental impact assessment through specialist studies. In this study a combination of RESRAD default values and RG-002 values were used (RESRAD, 2007, NNR, 2014a).

5.3 Source Term Development

In this section, the quantities and types of radionuclides that could be dispersed to the environment was considered and quantified. It is important to include the progeny of the nuclides released in the assessment. The facilities under consideration are the OSP, the road and the TSF. The OSP and the road have similar characteristics in the sense that the source term, consists primarily of nuclides in concentrations as they appear in nature. The TSF have varying activity concentrations because of the operational processes applied in the gold and/or uranium processing operations. TSFs usually also contains large volumes of waste collected from previous less effective processes. Therefore, the source terms chosen for the two different types of operations are tabulated in Table 5-1. RESRAD (2007) does not make provision for all the progeny.

Natural uranium contains by weight 99.275 % U-238, 0.719 % U-235 and 0.0057 % U-234 (IRSN, 2012). The specific activities of the uranium isotopes are: U-238 – 1.24E4 Bq/g, U-235 – 8.00E4 Bq/g and U-234 – 2.3E8 Bq/g. The specific activity of U-nat (natural uranium, the sum of U-238, U-235 and U-235) is therefore for 1 g of natural uranium and without taking into account radioactivity of decay products, the chemical element is distributed as follows:

Nuclide	% Abundance	Specific Activity (Bq/g)	Bq/mg of U-nat
U-238	99.275	1.24E+04	1.23E+01
U-235	0.719	8.00E+04	5.75E-01
U-234	0.0057	2.30E+08	1.31E+01
U-nat			2.60E+01

UNSCEAR reported U-238, in its natural state (background values), in soil to have average concentrations of about 40 Bq/kg (0.04 Bq/g) (UNSEAR, 2008). Uranium concentration in milled ore and tailings as well as associated total mass and mass of produced U for different gold mines of the West Rand and Far West Rand vary between 13 mg/kg (338 Bq/g) at West Rand Consolidated mines to 443 mg/kg (11518 Bq/g) at Western Areas, with an average of 126 mg/kg (3276 Bq/g) (Winde, 2010). Brenck in his study for the NNR (NNR, 2007), sampled 38 sites in the Wonderfonteinspruit Area. His sample's U-238 content varied between 0.027 ± 3 Bq/g to 10 000 ± 800 Bq/g. The Brenck sites were environmental samples and not necessarily tailing samples. Activity concentrations used by De Villiers and De Beer et al. (Necsa, 2010a) in calculations of public doses, varied between 0.41 Bq/g and 9 Bq/g. The source term used in this study, in Table 5-1, was compiled to be in a similar range as that used by De Villiers and De Beer (Necsa 2010a).

Table 5-1: Nuclide Specific Source Terms per Scenario

	Operation		
Exposure Duration	**OSP[1]** 3.00E+01	**TSF[2]** 3.00E+01	**Road[3]** 3.00E+01
	Basic Radiation Dose Limit 2.50E-1 (mSv/a) from All Sources		
Nuclide	**Activity Concentration (Bq/g)**		
Ac-227	4.00E-01	4.00E-01	4.00E-01
Pa-231	4.00E-01	4.00E-01	4.00E-01
Pb-210	4.60E+00	9.00E+00	4.60E+00
Po-210	4.60E+00	9.00E+00	4.60E+00
Ra-226	4.60E+00	9.00E+00	4.60E+00
Ra-228	2.80E-01	6.00E-01	2.80E-01
Th-228	2.80E-01	6.00E-01	2.80E-01
Th-230	4.60E+00	9.00E+00	4.60E+00
Th-232	2.80E-01	6.00E-01	2.80E-01
U-234	4.60E+00	1.00E+00	4.60E+00
U-235	4.00E-01	3.00E-02	4.00E-01
U-238	4.60E+00	1.00E+00	4.60E+00

The total activity used in the assessment is linked to the activity concentration as a function of the operation size. In this study the operations modelled were defined as volume sources. The dimensions used were: OSP - 200 000 m^3; Road – 1 m^3; and TSF – 200 000 m^3.

5.4 Receptor Definition

The public exposed to potential sources of radiological contamination is referred to as the receptor. The representative person is derived from the receptor. Only three age groups are considered, being the 1-year-old, the 10-year-old and an adult. The representative person would be calculated to be the most exposed person from the three different age categories. (The person receiving the highest dose.) Decision making will be based on the highest dose to the most exposed person, therefore the representative person. Mines are mostly in rural areas, therefore the areas adjacent to the mine are defined by primarily farming activities. The representative person lives on the land and will remain there for the next 30 years. He lives in a house about 500 m from the TSF. There is a delay in food consumption after harvest. Drinking water and household water are obtained at 50 % from the borehole and 50 % from the surface water body. Under normal circumstances the prevailing conditions will be used to determine the receptor location and habitat. Site specific conditions, such as distances from the sources of contamination, etc. will be considered.

Livestock producing meat and milk is watered from surface water and the borehole. Land is irrigated from the borehole and the surface water.

Food consumed and where it comes from, is tabled in Table 5-2.

Table 5-2: Food Consumption Rates per Age Group

Food	1 Year Old	10 Year Old	Adult
Drinking water; 50 % Surface water; 50 % borehole water	240	360	600
Fish consumption (kg/a); 50 % from affected area	2.16	3.24	5.4
Other aquatic food (kg/a); 50 % from affected area	0.36	0.54	0.9
Non-Leafy vegetables consumption (kg/a); 50 % from affected area	64	96	160
Leafy vegetable consumption (kg/a); 50 % from affected area	5.6	8.4	14
Meat consumption (kg/a); 50 % from affected area	25.2	37.8	63.0
Milk consumption (L/a); 100 % from affected area	36.8	55.2	92
Soil ingestion (g/a)	14.6	21.9	36.5

For the screening assessment, a standard set of public activities were defined. These include, a person living on the off-site, farming with livestock and fresh produce. The person consumes all the products from his farm. Time spent indoors and time spent at the different farming activities were considered.

ICRP 101 proposes three age groups (ICRP, 2006) in the definition of the representative person. The ICRP proposed age groups, 1-year-old, 10-year-old and adult were used in the assessment. For each age group there is a unique set of dose conversion factors, consumption rates, inhalation rates and time spent at different locations, taken from RG-002 (NNR, 2014a).

5.5 Exposure Scenarios

The exposure scenarios were developed from all of the above mentioned input parameters. In order to calculate a dose, a known radioactive activity concentration for each nuclide at a given location was determined. The activity concentration was multiplied by the habit of the representative person and the dose conversion factor for each nuclide to produce dose. The exposure is then the sum of internal as well as external pathways from all nuclides. The most exposed person, or representative person is thus identified as the person receiving the highest dose. Decision making is based on the highest dose.

RESRAD makes provision for nine different exposure pathways (RESRAD, 2007), which are, direct external exposure from contamination in soil; inhalation of dust particulates; inhalation of radon and short lived progeny; ingestion of water; plant-derived food; meat; milk; aquatic food; and incidental ingestion of soil. Radon inhalation by a person positioned on top of the primary contaminant was excluded, because we modelled the dose to off-site locations.

A rural resident farmer scenario was developed to model exposure to the representative person in order to apply conservancy. The farmer is self-sufficient and produces all his food needs locally on the off-site area. He lives on the farm. The agricultural activities consist of land and pastures, from which the produce are ingested; a surface water body and a borehole provides for watering of vegetation and consumption. The surface waterbody also contains fish for consumption. Time is spent indoors and outdoors. It is also assumed that aquatic food from the off-site surface body is consumed. If the residential farmer scenario results in doses higher than the off-site public exposure assessment criteria when conservative input data was used in a screening calculation, more realistic data, such as real time occupancies and real actual consumptions of foodstuffs could be used to reduce dose to portray reality. If all the reality checks were made and the assessment criteria still exceed the dose constraint, the source term should be reduced until the dose constraint is met. The dose constraint should include build-up in the environment. The principle of optimisation of protection should be applied throughout the whole process, considering costs.

5.6 Models

It was mentioned earlier that there are different ways of performing a safety assessment. The use of mathematical models for the determination of ground water movement, surface water movement and atmospheric movement of radionuclides in the environment remains an option to be used. In this study the approach of a source-pathway-receptor is followed. The source is identified; it is dispersed into the environment where an individual, the representative person is exposed. The content of the model will be determined by the site specific conditions and must be compiled to suite a specific set of conditions.

In practice there are several approaches to these types of safety assessments. Applying a code is a predictive method, which could be applied to new mining operations. As data becomes available, the analysis should be repeated to refine the outcome. Most of the mining authorisations issued were issued for operational facilities with large amounts of historical plant and environmental data. Therefore, the general approach to safety assessments is to use available data and deterministically evaluate public exposures with the use of spreadsheets.

Several codes were evaluated, amongst others, PC CREAM, AMBER, NORMALYSA, GENII, Hotspot, Rascal, PC Cosyma, etc. The code, RESRAD-OFF-SITE was used as a tool to perform the assessment (RESRAD, 2007), because it is readily available, it can model NORM, it has internationally been benchmarked, it can be used for detailed studies, many of the important input parameters can be altered to input local values, and it has sensitivity and uncertainty capabilities. The process followed is one of several available. The assessment was performed from generic criteria and therefore qualifies as a screening assessment. If the assessment criteria are exceeded, an iterative process, with site specific and more realistic data, would have to be performed.

The models used by RESRAD (RESRAD, 2007), are not discussed in detail, however there are references to specific details throughout the study as was considered necessarily. The ground water transport model mathematically determines the volume of connected moisture-filled pores and the soil in contact with the pores; it considers the partitioning of nuclides between the water and solid phases of the soil; quantities of nuclides in a unit volume of soil; changes in quantities of nuclides stored in the elemental volume due to radiological transformation; changes in quantity of nuclides stored in the elemental volume due to advective transport; changes in the quantity of nuclides in the elemental volume due to longitudinal dispersion. The ground water transport model further considers concentration of nuclides in the mobile pores and immobile pores; retardation factors; pore water velocity and dispersivities.

The atmospheric transport model is based on the Gaussian plume model for dispersion. The model considers, for surfaces based operations, an effective release height (surface heat transfer influenced); plume rise; relative terrain height adjustments; and the wind power-law. Furthermore, the model considers plume reflections and chronic releases (over a period of 1 year); it uses an area sources model (exposed surface); and corrections are made for depletion. The model also considers wet and dry depositions; mixing heights, meteorological conditions (annual average used in this study, not joint frequencies) and buoyancy induced dispersion.

5.7 Assessments

The primary purpose of the assessment in this study was to demonstrate the methodology. However, a safety assessment for an operating operation, or a planned situation must demonstrate compliance with the public dose criteria, or the dose constraint, as in this case. If the safety assessment reveals that the operation does not comply with the requirements, physical or engineered barriers will have to be implemented to reduce public exposure.

RESRAD can only analyse one source at a time. Therefore, various runs had to be performed for each of the operational activities identified that could result in public exposure. The activities identified were the stockpile, a road and a tailings storage operation. ICRP 103 has identified three age groups for the representative person, viz. 1-year-old, 10-year-old and adult (ICRP, 2006). RESRAD can only perform runs for a single age group at a time (RESRAD, 2007). Therefore, for each source three runs had to be performed. The public dose was calculated from the sum of the exposures from all the pathways.

5.8 Results

A residential rural farmer scenario was used to model the exposure of the representative person. The safety assessment demonstrated that the operational activities of the stockpile, the tailings storage facility and the road, at the mine, can be operated within the 0.25 mSv/a off-site exposure criterion set by the NNR, if only one year of exposure was considered.

All the results are contained on the attached CD. This includes the twelve runs performed, the RESRAD user manual and a copy of the code RESRAD Off-site, Version 2.6, 2010 User's manual for RESRAD-OFFSITE, Version 2, NUREG/CR-6937, Environmental Science Division, Argonne National Laboratories, 2007.

Table 5-3: Modelled Annual Dose per Age Group

Operation	Effective Dose (mSv/a)
OSP 1 year old	6.928E-02
TSF 1 year old	1.353E-01
Road 1 year old	2.001E-05
Total	**2.046E-01**
OSP 10 year old	3.357E-02
TSF 10 year old	6.539E-02
Road 10 year old	1.035E-05
Total	**9.897E-02**
OSP Adult	2.581E-02
TSF Adult	5.014E-02
Road Adult	8.229E-06
Total	**7.596E-02**

The results reveal that the maximum dose, for the mine, for the specific scenarios identified, is ascribed to the 1-year-old age group. The dose is 2.046E-01 mSv/a, which complies with the regulatory criteria. However, before the end of the first year, the dose exceeds 2.50E-1 mSv/a, which is not acceptable.

There is a further requirement that build-up in the environment should be considered. Table 5-4 reveals again that the 1-year-old group is exposed to the highest peak accumulative dose of 5.81E-1 mSv/a (that is 581 µSv/a). The highest dose contribution, of 3.84E-01 mSv/a, was from the TSF at 22.6 years. The assumption was made that 22.6 years later, a 1-year-old would receive 3.84E-01 mSv/a if the 1-year-old would be exposed in a similar manner than a 1-year-old today. The peak effective dose exceeds the dose constraint of 2.50E-1 mSv/a as indicated in Table 5-4. Therefore, intervention is required, either in the form of more realistic input data or in the form of reduction in the source term or a combination of the two methods.

To develop a spreadsheet to perform maximum or peak dose, for exposures from all pathways, considering all available nuclides and their progeny and build-up in the environment, to verify and validate results, and to perform sensitivity and uncertainty analysis, to the extent that RESRAD performs these calculations, would have required many man hours and expertise in various fields. That does not include the compilation of a user's manual.

Table 5-4: Build-Up of Modelled Annual Dose per Age Group

t (Years)	0	0.5	1	5	10	30	50
OSP 1 Year Old	6.928E-02	1.188E-01	1.494E-01	1.960E-01	1.969E-01	1.969E-01	1.968E-01
TSF 1 Year Old	1.353E-01	2.318E-01	2.916E-01	3.823E-01	3.841E-01	3.840E-01	3.840E-01
Road 1 Year Old	2.001E-05	2.284E-05	1.785E-05	1.207E-06	6.544E-07	5.853E-07	5.503E-07
Total 1 Year Old	**2.046E-01**	3.506E-01	4.410E-01	5.783E-01	**5.810E-01**	5.809E-01	5.808E-01
OSP 10 Year Old	3.357E-02	5.695E-02	7.142E-02	9.343E-02	9.391E-02	9.411E-02	9.418E-02
TSF 10 Year Old	6.539E-02	1.109E-01	1.391E-01	1.819E-01	1.829E-01	1.833E-01	1.834E-01
Road 10 Year Old	1.035E-05	1.146E-05	9.004E-06	9.194E-07	5.884E-07	5.270E-07	4.971E-07
Total 10 Year Old	9.897E-02	1.679E-01	2.105E-01	2.753E-01	2.768E-01	2.774E-01	**2.776E-01**
OSP Adult	2.581E-02	4.351E-02	5.446E-02	7.112E-02	7.149E-02	7.162E-02	7.165E-02
TSF Adult	5.014E-02	8.450E-02	1.058E-01	1.381E-01	1.388E-01	1.391E-01	1.392E-01
Road Adult	8.229E-06	9.009E-06	7.174E-06	1.047E-06	7.603E-07	6.772E-07	6.256E-07
Total Adult	7.596E-02	1.280E-01	1.603E-01	2.092E-01	2.103E-01	2.107E-01	**2.109E-01**

Table 5-5: Peak Effective Dose

Scenario	Peak Dose (mSv/a)	Time (Year)
TSF 1 year old	3.84E-01	22.6
OSP 1 year old	1.97E-01	21.6
Road 1 year old	4.96E-07	87.5

The results presented in Table 5-5 were obtained from a screening analysis. In order to evaluate results, the contribution of all the exposure scenarios must be summed. If the results of the screening analysis did not exceed regulatory requirements, no further analysis would have been required. However, the screening criteria was exceeded for the TSF, therefore more detailed and realistic analysis was required.

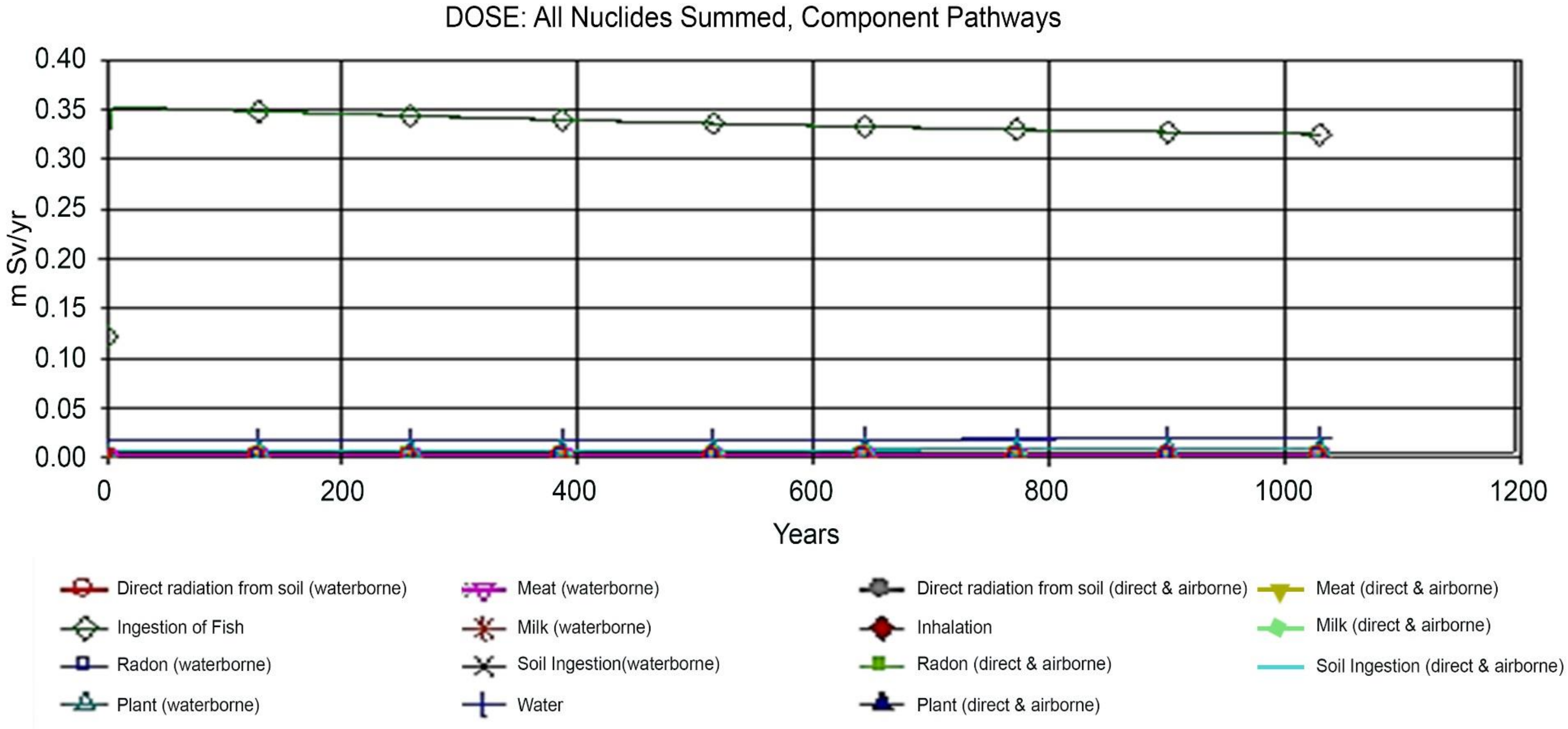

Figure 5-3: TSF – Build-Up Dose from all Pathways

From Figure 5-3, it is evident that the dose for the TSF with aquatic foods peaked at about 3.5E-1 mSv/a. In order to refine calculations, more realistic data should be used. Therefore, the reality of aquatic food intake should be reviewed to reduce dose.

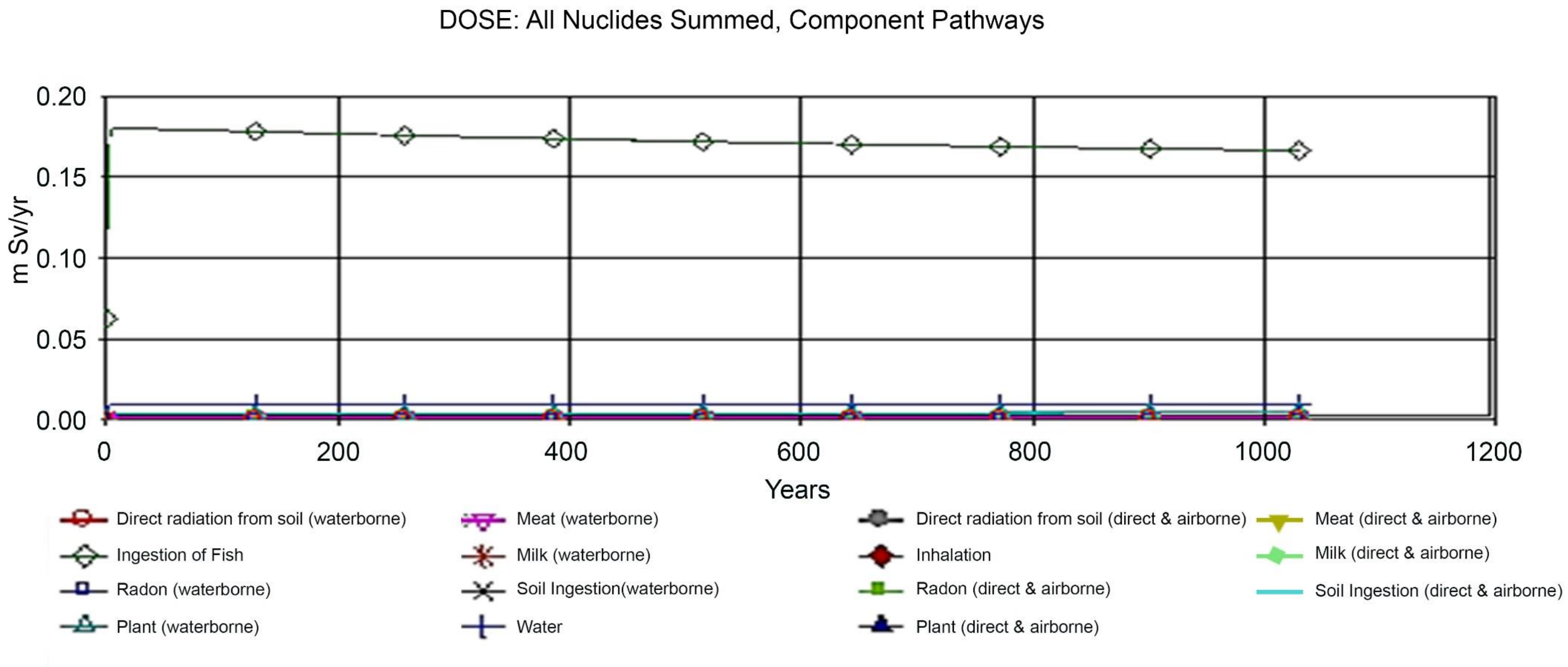

Figure 5-4: OSP – Build-Up Dose from All Pathways, Excluding Fish

Both Figures 5-3 and 5-4 revealed that the consumption of aquatic foods is, by far, the most dominant contributor to the dose. In order to refine calculations, more realistic data should be used. Therefore, the reality of aquatic food intake should be reviewed to reduce the dose.

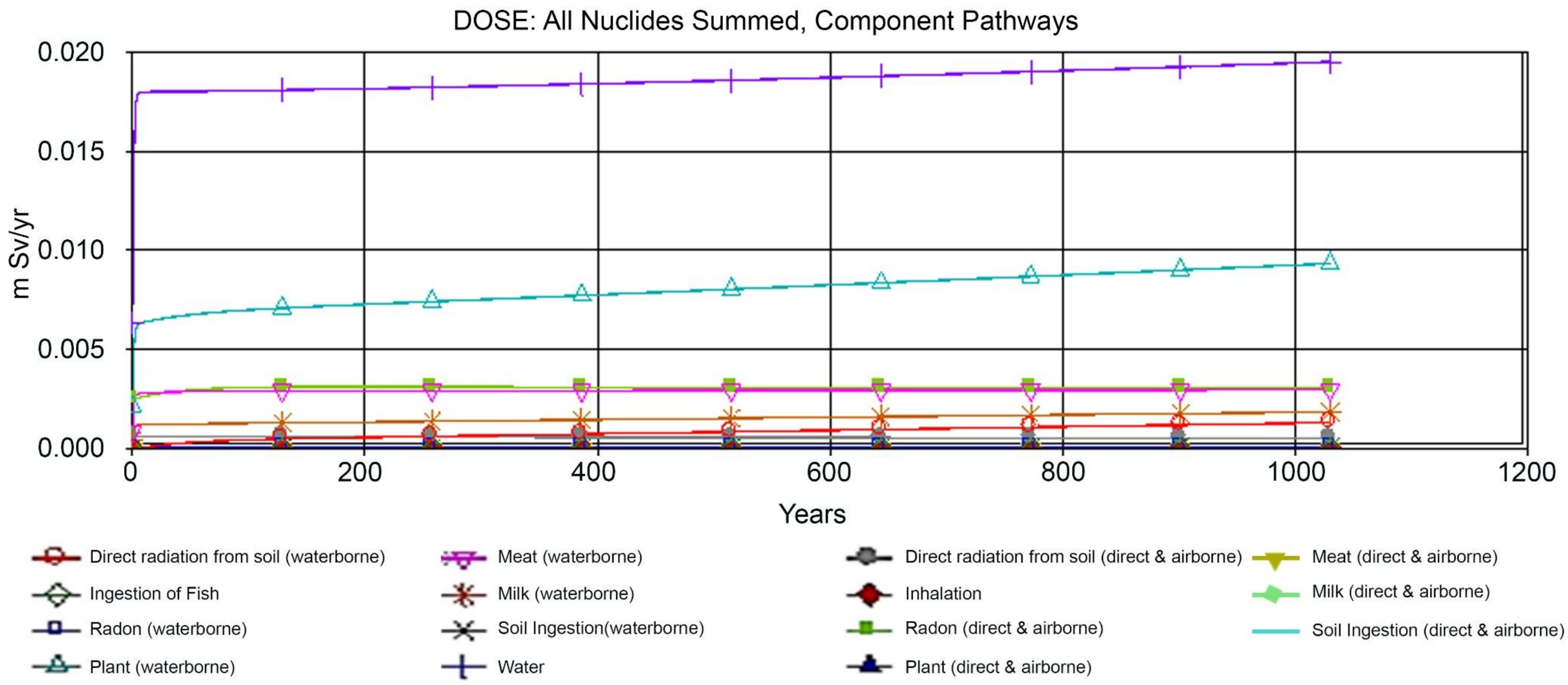

Figure 5-5: TSF – Build-Up Dose from All Pathways, Excluding Fish

If the consumption of aquatic foods were to be eliminated, as indicated in Table 5-6, there is a continuous build-up of the dose for 1 000 years to a maximum value of **5.884E-02** mSv/a. It is therefore evident that if the consumption of aquatic foods is removed from the food chain, the mine would be in compliance with regulatory requirements. However, if the principle of optimisation is applied, actions should also be taken to reduce the run-off of contaminants to the environment. The question is however; will aquatic food be consumed from the source in the scenario (fish in the surface water body) within the following 1 000 years.

Table 5-6: Dose, Without Aquatic Foods at Time T=0 and T=Max Dose

Operation	Dose t (0) (year)	Max Dose (mSv/a)	Time at Max Dose (Year)
OSP 1 year old	6.785E-03	1.985E-02	1.030E+03
TSF 1 year old	1.313E-02	3.899E-02	1.030E+03
Road 1 year old	2.989E-06	2.989E-06	0.000E+00
Total	**1.992E-02**	**5.884E-02**	

5.9 Sensitivity Analysis

The analysis was performed on the TSF for exposures to a 1-year-old on water consumption of 240 l/a. The aquatic food pathway was switched off. The deviations in consumption rates were 1.5 times more and 1.5 times less.

Ra-226 is the biggest contributor to the dose. The sensitivity analysis in Figure 5-6 reveals that the dose increases with increased consumption and decreases with decreased consumption. The dose from similar consumption rates decreases with time as Ra-226 decays, the sensitivity of the dose to the consumption rate seems to be directly proportional to the intake. As the intake increases, the dose increases and as the intake decreases, the dose decreases.

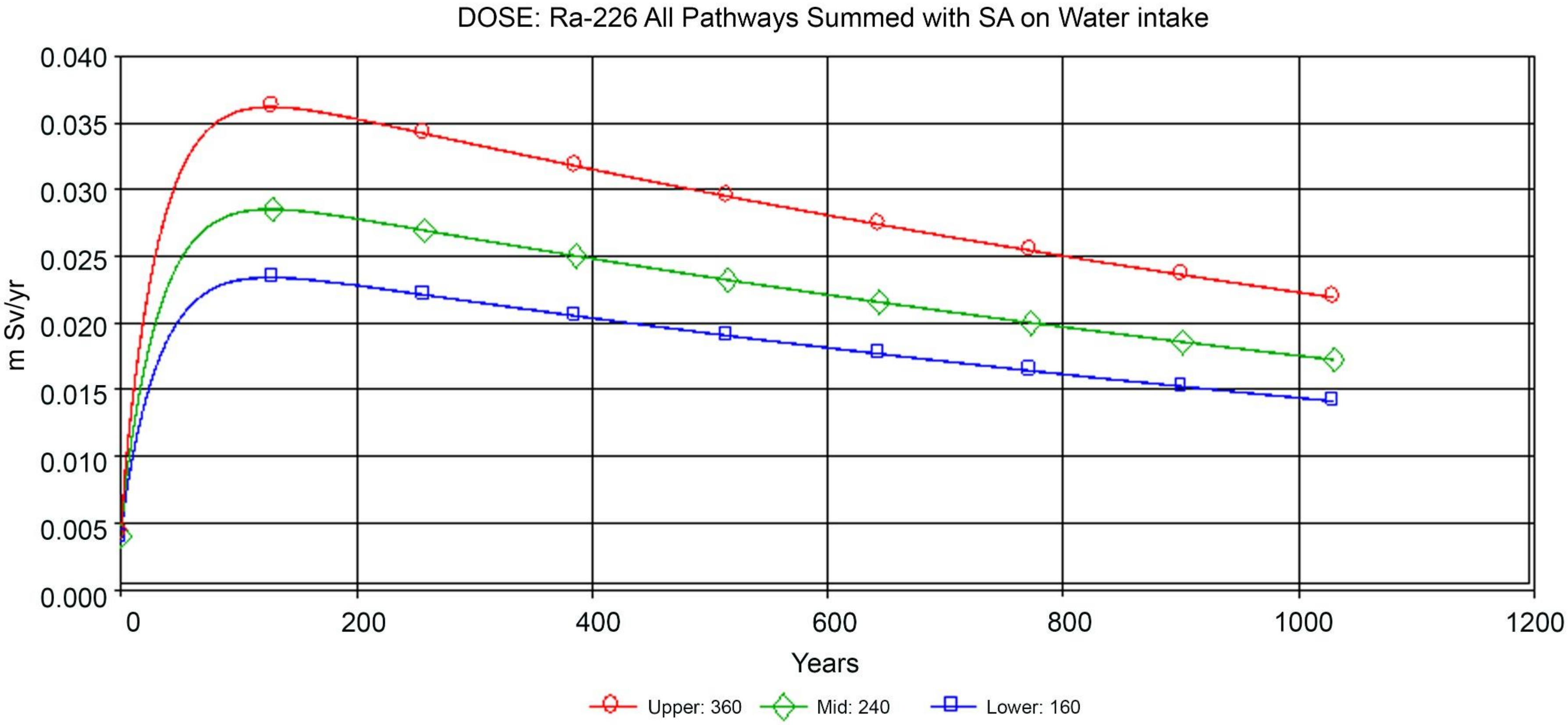

Figure 5-6: Sensitivity of Dose to Varying Water Intakes

5.10 Uncertainty Analysis

The uncertainty analysis was performed on the TSF for exposures to a 1-year-old on water consumption of 240 l/a. The RESRAD off-site code, Version 2.6 was used for the modelling. The aquatic food pathway was switched off. In this study, uncertainty analysis was performed to demonstrate the methodology. Uncertainty analysis could also have been performed for almost all the parameters that have an input option. Therefore, an uncertainty analysis was only performed on the consumption of water, which was the pathway contributing the most to the dose (RESRAD, 2007). Other parameter, which has an influence on the analysis, such as the water dispersion pathway and the time frame up to peak dose, would also have revealed interesting results.

The input parameter was the consumption of water at a rate of 240 l/a. There were 100 observations performed on the input parameter. The sampling technique applied was Latin Hypercube sampling (LHS). In the LHS technique, the distribution is divided into equally probable segments, equal in number to the desired number of observations. Then a value is picked at random from each segment according to the probability density function within that segment. This ensures that the sample covers the entire range of the distribution, even when the number of samples is relatively small. After the code obtains the required number of samples for each input parameter, it produces the probabilistic set of inputs. The code sampled consumption from .001 to 6.015 times the consumption rates.

The results of the uncertainty analysis are tabulated in Table 5-7. For each nuclide of the specific pathway, uncertainty is expressed in terms of a minimum, maximum, average and standard deviation value. The values are repeated for peak time, peak dose and dose at selected intervals.

Table 5-7: Peak Dose per Nuclide at Different Time Intervals

Nuclide (j)	Peak Time Years	Peak Dose mSv/a	DOSE(j,t), mSv/a				
			t= 0.00E+00	1.00E+01	3.00E+01	5.00E+02	1.00E+03
Ac-227							
Min	3.02E+00	1.83E-04	8.52E-05	1.51E-04	7.91E-05	1.87E-11	1.67E-18
Max	3.02E+00	1.34E-03	5.46E-04	1.10E-03	5.76E-04	1.36E-10	1.22E-17
Avg	3.02E+00	4.80E-04	2.04E-04	3.95E-04	2.07E-04	4.89E-11	4.37E-18
Std	0.00E+00	1.96E-04	7.83E-05	1.61E-04	8.44E-05	2.00E-11	1.78E-18
Pa-231							
Min	1.38E+02	2.81E-04	3.05E-05	1.39E-04	2.11E-04	2.57E-04	2.24E-04

Max	1.39E+02	1.93E-03	1.85E-04	9.22E-04	1.43E-03	1.76E-03	1.54E-03
Avg	1.39E+02	7.05E-04	7.02E-05	3.41E-04	5.26E-04	6.44E-04	5.62E-04
Std	0.00E+00	2.80E-04	2.62E-05	1.33E-04	2.08E-04	2.56E-04	2.24E-04
Pb-210							
Min	3.02E+00	1.40E-02	4.13E-03	1.17E-02	6.35E-03	2.84E-09	4.85E-16
Max	3.02E+00	9.06E-02	2.77E-02	7.54E-02	4.05E-02	1.77E-08	3.03E-15
Avg	3.02E+00	3.37E-02	1.02E-02	2.81E-02	1.51E-02	6.67E-09	1.14E-15
Std	0.00E+00	1.30E-02	4.00E-03	1.08E-02	5.80E-03	2.53E-09	4.32E-16
Po-210							
Min	0.00E+00	1.28E-03	1.27E-03	7.66E-11	1.01E-26	0.00E+00	0.00E+00
Max	5.03E-01	8.14E-03	8.14E-03	4.63E-10	6.08E-26	0.00E+00	0.00E+00
Avg	2.68E-02	3.04E-03	3.04E-03	1.76E-10	2.31E-26	0.00E+00	0.00E+00
Std	1.13E-01	1.17E-03	1.17E-03	6.57E-11	0.00E+00	0.00E+00	0.00E+00
Ra-226							
Min	1.26E+02	2.01E-02	3.77E-03	9.03E-03	1.46E-02	1.65E-02	1.24E-02
Max	1.28E+02	1.07E-01	6.59E-03	3.92E-02	7.37E-02	8.83E-02	6.62E-02
Avg	1.27E+02	4.26E-02	4.50E-03	1.68E-02	2.98E-02	3.50E-02	2.62E-02
Std	3.89E-01	1.48E-02	4.80E-04	5.13E-03	1.00E-02	1.22E-02	9.15E-03
Ra-228							
Min	2.01E+00	6.29E-04	2.38E-04	3.64E-04	3.51E-05	8.10E-30	7.01E-45
Max	3.02E+00	2.63E-03	1.14E-03	1.29E-03	1.16E-04	2.40E-29	7.01E-45
Avg	2.52E+00	1.14E-03	4.70E-04	6.02E-04	5.59E-05	1.22E-29	7.01E-45
Std	1.08E-01	3.40E-04	1.54E-04	1.57E-04	1.38E-05	0.00E+00	0.00E+00
Th-228							
Min	0.00E+00	4.37E-04	4.37E-04	1.29E-05	9.38E-09	0.00E+00	0.00E+00
Max	5.03E-01	5.83E-04	5.74E-04	2.38E-05	1.72E-08	0.00E+00	0.00E+00
Avg	3.35E-03	4.73E-04	4.73E-04	1.57E-05	1.14E-08	0.00E+00	0.00E+00
Std	4.09E-02	2.34E-05	2.31E-05	1.86E-06	1.32E-09	0.00E+00	0.00E+00
Th-230							
Min	1.03E+03	8.24E-03	1.96E-04	4.78E-04	5.86E-04	4.63E-03	8.07E-03
Max	1.03E+03	4.27E-02	1.18E-03	3.29E-03	3.79E-03	2.43E-02	4.18E-02
Avg	1.03E+03	1.71E-02	4.50E-04	1.20E-03	1.41E-03	9.69E-03	1.67E-02
Std	0.00E+00	5.85E-03	1.68E-04	4.78E-04	5.45E-04	3.35E-03	5.73E-03
Th-232							
Min	1.03E+03	7.37E-03	3.25E-05	7.63E-04	1.22E-03	4.15E-03	7.20E-03
Max	1.03E+03	2.92E-02	1.86E-04	3.30E-03	4.89E-03	1.63E-02	2.85E-02
Avg	1.03E+03	1.30E-02	7.20E-05	1.41E-03	2.16E-03	7.28E-03	1.27E-02
Std	0.00E+00	3.70E-03	2.61E-05	4.30E-04	6.23E-04	2.07E-03	3.61E-03
U-234							
Min	8.05E+00	1.80E-05	6.69E-06	1.75E-05	1.75E-05	1.68E-05	1.79E-05
Max	1.03E+03	1.19E-04	4.26E-05	1.19E-04	1.18E-04	1.12E-04	1.14E-04
Avg	1.42E+02	4.37E-05	1.59E-05	4.36E-05	4.35E-05	4.12E-05	4.27E-05
Std	3.43E+02	1.72E-05	6.10E-06	1.72E-05	1.71E-05	1.61E-05	1.64E-05
U-235							
Min	1.03E+03	8.27E-07	2.05E-07	5.56E-07	5.84E-07	7.31E-07	8.23E-07
Max	1.03E+03	5.33E-06	1.30E-06	3.66E-06	3.71E-06	4.62E-06	5.30E-06

Avg	1.03E+03	1.99E-06	4.87E-07	1.36E-06	1.39E-06	1.73E-06	1.97E-06
Std	0.00E+00	7.65E-07	1.87E-07	5.28E-07	5.31E-07	6.60E-07	7.60E-07
U-238							
Min	8.55E+00	1.97E-05	7.28E-06	1.95E-05	1.97E-05	1.78E-05	1.57E-05
Max	5.03E+01	1.33E-04	4.73E-05	1.33E-04	1.32E-04	1.18E-04	1.04E-04
Avg	2.58E+01	4.87E-05	1.76E-05	4.86E-05	4.87E-05	4.35E-05	3.84E-05
Std	9.80E+00	1.92E-05	6.81E-06	1.92E-05	1.91E-05	1.70E-05	1.50E-05
ΣALL							
Min	1.03E+03	2.80E-02	1.02E-02	2.27E-02	2.31E-02	2.56E-02	2.79E-02
Max	1.03E+03	1.39E-01	4.63E-02	1.25E-01	1.25E-01	1.31E-01	1.38E-01
Avg	1.03E+03	5.65E-02	1.95E-02	4.90E-02	4.94E-02	5.27E-02	5.63E-02
Std	0.00E+00	1.88E-02	6.14E-03	1.73E-02	1.74E-02	1.79E-02	1.88E-02

ΣAll = total dose summed for all nuclides

Table 5-8: Comparison of Modelled Results for TSF with Uncertainty Results

	Dose mSv/a)						Ratios
Dose	Dose at t=0	Std	D + Std	D - Std	Time (Years)	Modelled D	
Min	1.02E-02	6.14E-03	1.63E-02	4.06E-03	1.03E+03		7.77E-01
Max	4.63E-02	6.14E-03	5.24E-02	4.02E-02	1.03E+03	1.31E-02	3.53E+00
Avg	1.95E-02	6.14E-03	2.56E-02	1.34E-02	1.03E+03		1.49E+00
	Dose at t=Max						
Min	2.80E-02	1.88E-02	4.68E-02	9.20E-03	1.03E+03		7.18E-01
Max	1.39E-01	1.88E-02	1.58E-01	1.20E-01	1.03E+03	3.90E-02	3.57E+00
Avg	5.65E-02	1.88E-02	7.53E-02	3.77E-02	1.03E+03		1.45E+00

Table 5-8 contains the comparison between the normally modelled dose in the last column and the results of the uncertainty modelled dose in Columns 2 to 5. Column 3 displays the standard deviation (Std). In Column 4 the standard deviation was subtracted from the uncertainty dose. In Column 5 the standard deviation was added to the uncertainty modelled dose. The time of the peak dose is given in Column 5. Column 6 contains the ratios of the uncertainty modelled dose to a normally modelled dose.

It was found that the time of the peak dose remained constant at 1.03E+03 years.

When comparing the modelled dose with the uncertainty dose at t=0, it is found that the normally modelled dose (1.31E-02 mSv/a) has a value between the minimum (1.02E-02 mSv/a) and the average (1.95E-02 mSv/a), with the average uncertainty dose exceeding the modelled dose. When the standard deviations are considered, the upper and lower bounds of the minimum modelled uncertainty dose ((4.06E-03 to 1.63E-02) mSv/a) overlap with the normally modelled dose (1.31E-02 mSv/a). When the standard deviations are considered, the upper and lower bounds of the average modelled uncertainty dose ((2.56E-02 to 1.34E-02) mSv) exceeds the normally modelled dose (1.31E-02 mSv/a). This translates to the conclusion that when the uncertainties are considered in accordance with LHS, the normally modelled dose is probably too low.

When comparing the modelled peak dose with the uncertainty peak dose, it is found that the normally modelled peak dose (3.90E-02 mSv/a) has a value between the minimum (2.80E-02 mSv/a) and the average (5.65E-02 mSv/a) modelled uncertainty dose, with the average uncertainty dose exceeding the modelled dose. When the standard deviations are considered, the upper and lower bounds of the minimum uncertainty modelled dose ((4.68E-02 to 9.20E-03) mSv) overlaps with the normally modelled dose (3.90E-02 mSv/a). However, the upper and lower bounds of the average modelled uncertainty dose ((7.53E-02 to 3.77E-02) mSv) also overlaps with the normally modelled dose (3.90E-02 mSv/a). This translates to the conclusion that when the uncertainties are considered in accordance with LHS, the normally modelled dose is probably too low.

However, when comparing the ratios of the uncertainty modelled dose to the normally modelled dose, we find that the gap difference in ratios between the doses at time t=0 (3.53 - .777 = 2.75) and at a time where the dose reaches its peak (3.57 - 0.718 = 2.85), increases over time. As time advances, the probable minimum doses decrease and the probable maximum doses increase. It can therefore be concluded that the model results over time are probably more uncertain at both the upper and lower ends. However, it seems as though the margin of uncertainty at the lower end increases more that at the upper end.

5.11 Conclusions

A public radiological safety assessment was performed for an unidentified mine considering a stockpile, a road and a tailings facility as sources of radionuclides. The radionuclides are dispersed though the atmospheric, surface water and ground water pathways. The representative person is a person, 1-year-old, who was exposed under a self-sufficient residential farming scenario. The maximum dose, from Table 5-4, for all the pathways at time t=0 2.046E-01 mSv/a and the maximum peak dose after about 22 years of operation is 5.81E-01 mSv/a. If the aquatic food from the surface water body is removed, the maximum dose at t=0 is 1.99E-02 mSv/a and at peak, 1 030 years further, the maximum dose was modelled as 5.88E-02 mSv/a. There are 2 conclusions to be drawn from these results.

- When all possible exposure pathways are considered for a site, it is likely that the public dose calculated on an annual basis, can exceed the dose constraint of 250 µSv/a. It is therefore important to consider site specific input data when the analysis is performed; and
- The long term effect of the build-up of nuclides in the environment and delayed effects because of slow dispersion via the water pathway was revealed when the peak dose, which is built into the proposed new regulations, becomes a consideration for compliance with dose constraints. There are many solutions to be considered to resolve this issue, amongst others, strict control at the source and restricted future land-use.

It was demonstrated in Figure 5-6 that the accrued dose is more or less proportional to the intake of radionuclides as far as water consumption is concerned.

When applying uncertainty analysis, it was found, in Table 5-8, that model results over time are probably more uncertain at both the upper and lower ends. However, it seems as though the margin of uncertainty at the lower end increases more that at the upper end.

It is evident from the safety assessment that the methodology developed can be applied effectively to normal operating conditions also known as planned operating scenarios. The results compare favourably with similar exercises performed elsewhere at the end of the 1st operating year (Necsa, 2010b and Necsa, 2012). The methodology also demonstrates that the application of the graded approach or the iterative assessment process has clear and positive advantages.

CHAPTER 6 SAFETY ASSESSMENT METHODOLOGY FOR REMEDIATION

Chapter 6 contains a new guideline assessment methodology for radiological safety assessments for the remediation of NORM facilities developed specific for South African conditions and in accordance with National legislation.

6.1 Introduction

Historically mining and mineral processing activities were not regulated by the National Nuclear Regulator, resulting into radiological contamination from mine water discharges, the diffuse emissions of seepage and runoff from slime dams and other activities. National legislation with regards to Natural Occurring Radioactive Material (NORM) was established in the late 1980. Due to the nature of the problem, legislation was implemented in phases. It was important to initially control active operations to reduce immediate environmental contamination. This process is well established and regulated. Now it is time to start regulating legacy sites, which are not under operation, but was contaminated with radionuclides during historical unauthorised practices. These unauthorised exposure situations are referred to as existing exposure situations.

In Chapter 3, the regulatory framework was discussed. Chapter 4 dealt with the safety public safety assessment methodology for operational sites. This chapter contains the safety assessment methodology for existing exposure situations. It was developed, as part of this study, considering the requirements contained in ICRP 101 (ICRP, 2006), ICRP 103 (ICRP, 2007a), IAEA GSR Part 3 (IAEA, 2014a), and the draft General Nuclear Safety Regulations (NNR, 2016c), which is under development at the NNR.

6.2 Requirements for Remediation

It was established in Chapter 2 that two types of assessments will be performed for existing exposure situations. The safety assessments are public safety assessments and worker safety assessments. Public safety assessments will be performed, at minimum, prior to decision making of whether remediation is required and after remediation has been completed. The latter process will be a repetition of the initial assessment, just using the results of the radionuclide distribution after remediation as input to the assessment. The last assessment will be performed to demonstrate that the remediation was successful and that the site can be released from regulatory control. This does not exclude in between assessments if so required.

The worker safety assessments, on the other hand, are required to determine the type and extent of protective action required to ensure that exposure from remediation activities are minimised. The worker safety assessment is applicable to the period of authorisation during which remediation activities will be applied. The worker safety assessment will identify and quantify sources of potential exposure. Efforts will be focused on eliminating or at least reducing exposure to potential radioactive material to minimise exposure during remediation. Workers will be registered as radiation workers and a radiation worker safety programme will be implemented. This programme consists of a workplace surveillance programme, a worker surveillance programme and a medical surveillance programme. However, the worker safety assessment falls beyond the scope of this study.

6.2.1 Requirements for the public safety assessments

A comprehensive site characterisation is required through sampling and analysis. All sources of radiological contamination will be identified. All pathways of exposure will be identified. The reference person will be identified for a subsistence farmer exposure situation (NNR, 2015). A land-use survey will be performed to determine the habitat, agricultural and social activities that could impact on radiation doses.

The subsistence farmer scenario would require an analysis of the following exposures, as applicable to the site (RESRAD, 2007):

- External gamma exposure;
- Inhalation;
- Plant ingestion;
- Meat ingestion;
- Milk ingestion;
- Aquatic foods;
- Drinking water; and
- Soil ingestion.

If compliance with remediation release criteria cannot be demonstrated, a safety assessment can be performed for scenarios that could motivate a restricted release of the site. Restricted release refers to restrictions being imposed on future use of the land. These scenarios would lay restrictions on the use of the land and the time spent on the premises. The restrictions should be enforced by law, for which South African legislation does not at present make provision. An expansion of the regulations should be considered. Two examples of scenarios for restricted release are included in the text following. The scenarios are for the urban resident and for industrial use.

In the urban resident scenario, the following would be considered:

- External gamma from the soil and water;
- Inhalation of dust;
- Ingestion of some fruit and vegetables produced on the land;
- Ingestion of the soil; and
- 8 760 hours per annum exposure time, minus the time spent indoors.

In the industrial exposure scenario, the following exposure pathways will be considered:

- External gamma from the soil, with a surface cover over it;
- Inhalation from dust; and
- 2 000 hours per annum exposure time.

6.2.2 Requirements for the worker safety assessments

The prior safety assessment shall determine the average and maximum annual effective occupational dose from normal operations and anticipated operational occurrences. The safety assessment shall demonstrate that adequate measures, including design provisions where required, are in place to control the radiation exposure of workers within the occupational dose limits of 20 mSv per annum. Protection must be optimised and the magnitude of individual doses, the number of people exposed and the likelihood of exposures being incurred have all been kept ALARA, economic and social factors taken into account. The worker safety assessment is not included in the scope of this study.

6.2.3 Remediation criteria

Remediation must always be considered for all the sites where the annual effective dose to the representative person exceeds the public dose limit of 1 mSv/a. Each situation should be evaluated on a case-by-case basis based on the results of a safety assessment, considering the subsistence farmer scenario (NNR, 2015). The safety assessment should identify the peak dose and should be performed over an extended period of up to 1 000 years (NUREG, 2016). Evaluation of the need for remediation should be based on the principles of justification, optimisation and reference levels. Reference levels between 1 and 20 mSv will be considered by the NNR (ICRP, 2007a). Where exposure situations still exceed the public dose limit (1 mSv/a) after remediation, land use restrictions must be motivated and the public informed accordingly. The National Nuclear Regulator may consider a restricted release of land from existing exposure situations using a reference level of twice annual natural background, that is in the region of 5 mSv/a, with the appropriate justification and appropriate measures to inform the public (NNR, 2015).

6.2.4 Remediation strategies

In order to develop technical solutions for the remediation of dispersed environmental contamination, input from various scientific and engineering disciplines, including health sciences, chemistry, physics, geology, microbiology and environmental engineering are necessary. It is also necessary to include information on the political, social and economic context. The issues of the proactive actions of regulators and the public perception will also come into play (IAEA, 2014b). While attempting to reduce residual contamination over large areas, factors such as dose, cost, public perception and anxiety, and minimal disturbance to the environment should be taken into account (IAEA, 2012). The overarching objective of the operation must be to remove or reduce the source term, or prevent the likelihood of exposure to a harmful dose. A generic process map for decision making and technology assessment is given in Figure 6-1 (NNR, 2014b).

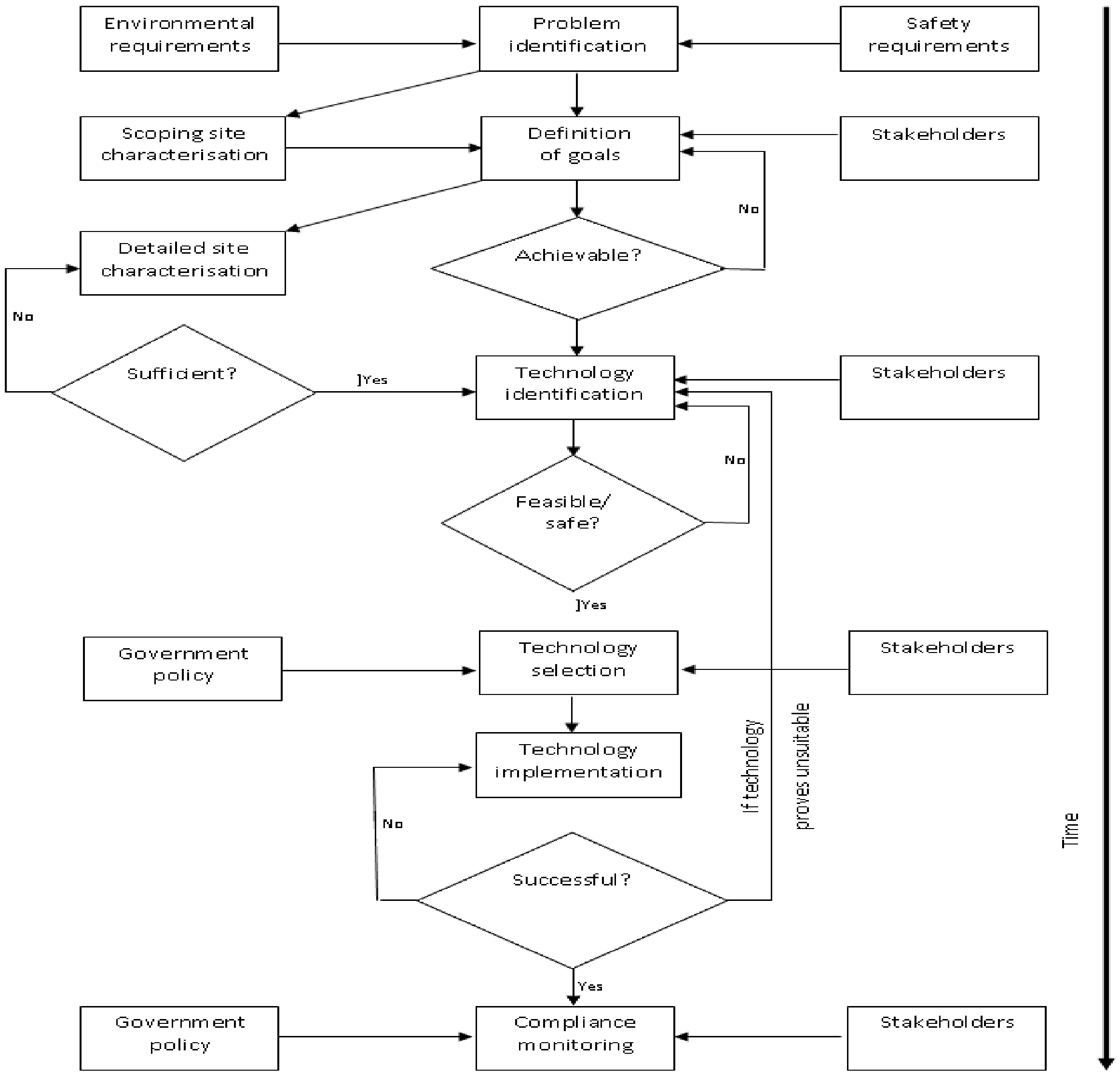

Figure 6-1: Process Map for Decision Making

Figure 6-1 was developed, as part of this study, to establish a process to be followed when remediation and specifically the technology applied to remediate is to be considered (NNR, 2014b). The process is basically a 6 step process. The process flows as follows:

- **Problem Identification** – a site is identified as a potential existing exposure scenario because it the in-situ conditions seems to be in conflict with regulatory safety requirements and environmental laws;
- **Definition of Goals** – the site must be radiologically characterised, using a screening analysis. During this process, all stakeholders are afforded the opportunity to comment on the process. If the site requires remediation, a detailed safety assessment is prepared;
- **Technology Identification** – remediation goals are identified and Nuclide Specific Guidelines (NSGs) are derived. Technologies applicable to the situation are evaluated;

- **Technology Selection –** The best available technology is identified for the task at hand. Different technologies (see Section 6.2.5 for examples), are analysed to determine the most effective application. This forms part of the site safety assessment required for submission to the NNR to obtain an authorisation to remediate;
- **Technology Implementation –** the technology is applied to the contaminants, while the efficiency is continuously measured. If the technology does not comply with efficiency requirements, the situation may require a re-assessment; and
- **Monitoring for Compliance –** before the site can be released from regulatory control, the holder has to compile a completion of remediation report, to be submitted to the NNR. This report includes a detailed monitoring to demonstrate compliance with the NSG, developed prior to commencement with remediation. The NNR verified compliance with a similar, but smaller in scale monitoring programme. If the site complies with the NSG criteria, it could be released from regulatory control.

6.2.5 Remediation technologies

The most popular remediation technologies applied around the world are summarised as follows (IAEA, 2014b):

- **Chemical Extraction (Ex situ) –** Disposal of contaminated soil is the option that has been most widely used to date. This involves the separation or extraction of contaminants. It would rely on the required substitution of the removed material with clean top soil. It may not be viable in the case of large volumes of contaminated soil;
- **Surface and Ground Waters: Pump and Treat –** Large quantities of ground water are pumped and stored in a suitable nearby location. Sediment is then removed and similarly heavy metals can be separated or extracted by chemical processes;
- **Natural Attenuation –** This method relies on the capacity of natural media (rocks, soils, sediment and ground water) to retard contaminant migration. This however will require adequate monitoring owing to the evolution of natural systems with time and our incomplete understanding of natural processes at a site;
- **Alternative Land Uses –** When extensive areas have been contaminated, many of the discussed remediation methods may be too expensive to carry out or too intrusive. Alternative uses of the land may need to be considered (for example if the land was used for agricultural purposes). These may range from considering uses such as a parkland or eco-tourism;

- **Phytostabilisation** – Involves the development of a stable and permanent vegetation cover that reduces the risk of erosion of contaminated soil and thus reducing waterborne and dust-borne exposure pathways. This technique may also change the mobility of toxic elements by reducing concentration in the soil matrix;
- **Phytoextraction** – The use of plants to remove contaminants from the environment and concentrate them in above ground plant tissue. It requires that the target radioelement be available to the plant root, absorbed by the root and trans-located from the root to the stem. Uranium removal: Free UO_2^{2+} is the uranium species most readily taken up and translocated by plants. It may require soil amendments that increase the availability of the uranium complexation;
- **Chemical Processes: Co-Precipitation** – Radionuclides present at very low mass concentrations can nevertheless form solid phases by co-precipitation in mineral lattices. A useful example for NORM materials is the high selectivity shown by radium for barite. This may however involve establishing geochemical controls for the migration of radioelements in the field;
- **Excavation and Landfills** – Removal of the top layer of soil. The thickness is determined through sampling and analysis. The use must be justified from a radiological safety perspective, in terms of the dose to the representative person; and
- **In Situ Soil Vapour Extraction Treatment** – The physical removal of volatile compounds from the unsaturated zone through vapour extraction boreholes or air injection boreholes. Vacuum blowers produce a motive force to induce airflow through the soil. Volatiles are typically adsorbed on to activated carbon.
- **Reactive Barriers** - A passive, in situ technology that emplaces the reactive media in the subsurface designed to intercept a contaminant plume, provide a flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals down-gradient of the barrier.

6.2.6 Prioritisation of remediation

Priority shall be given to those groups for whom residual dose exceeds the reference level. These people will be relocated to a site, which complies with free living requirements. This essentially implies that the site of relocation will have to be declared as contamination free to be considered as a site for relocation. Interim safety measures may be required to render the site safe until remediation activities are to be implemented (NNR, 2015).

Sites that are considered for remediation would require to be characterised prior to decision making. The characterisation will be used as input into a screening safety assessment. Radiological prioritisation will be determined in accordance with the results of the screening as given in the Table 6-1. Category A will receive priority consideration for remediation (NNR, 2015).

Table 6-1: Site Categorisation Table

Annual effective dose	Site Categorization
➢ 20 mSv/a	A
5 – 20 mSv/a	B
1 – 5 mSv/a	C
250 µSv/a – 1 mSv/a	D

Further prioritisation is required. Other factors required would include the following (NNR, 2015):

- Socio-economic considerations;
- Deployment of available remediation techniques;
- Availability of scientific data required for the site characterisation;
- Potential impacts of adjoining properties and protection of the environment;
- Availability of funds; and
- Inputs from interested and affected communities.

6.2.7 Management of remediation

Remediation activities must be authorised. For authorisation a public safety assessment and a worker safety assessment is required (NNR, 2014b). A detailed remediation plan must be established. Remediation techniques should be identified and evaluated before implementation. After completion of remediation the site radiological survey should be completed and the public safety assessment repeated to demonstrate compliance with the approved release criteria. Close-out measurements to demonstrate compliance should be included in the report to the NNR. The NNR will verify measurements and release the site from regulatory control (NNR, 2014b).

6.2.8 Environmental sampling and analysis

In the following section environmental sampling and analysis are discussed as it plays a very important role in site characterisation.

Sampling programmes should be conducted with the following objectives (NNR, 2014a):

- To characterise the source term by sampling and analysis of releases and environmental media;
- To provide input for validation of transport models;
- To identify unexpected environmental contamination, transfer routes and pathways;
- Depending on the results obtained and the requirements of the transport models used, the monitoring programmes should be amended from time to time;
- A background or reference site should be required when historical practices have been performed in the area that may have contributed to the increase in radionuclides in the environment;
- The quality of the sampling programme should be assured;
- The analytical method should be capable of performing the measurement at the required sensitivity (usually background level) and accuracy;
- In general, the main radionuclides to be analysed for can be categorised as follows:
    - Long lived alpha emitters: $_{238}$U, $_{234}$U, $_{230}$Th, $_{226}$Ra, $_{210}$Po; $_{232}$Th, $_{228}$Th, $_{224}$Ra;
    - Beta emitters: 210Pb, 228Ra; and
    - 222Rn and 220Rn (and their progeny);
- The specific radionuclides to be included in the analysis programme or modelling assessment will vary according to site specific factors (e.g. the uranium and thorium contents of the ores, process materials and wastes) and the specific exposure pathway under examination (gaseous, particulate, liquid, and nuclides contained in sedimentation). The exclusion of radionuclides from analysis programmes and modelling assessments must therefore be indicated and justified;
- Sampling can be performed for a screening analysis where limited information is required; or
- Sampling can be performed for a detailed safety assessment where nuclide specific data is required;
- To define an appropriate subsistence farmer scenario for the representative person;
- To provide information during the different stages of remediation regarding the efficiency of the remediation technologies applied; and

- At the end of remediation to verify efficiency of the applied remediation technologies and to verify compliance with release criteria.

6.3 The Public Safety Assessment Methodology for Remediation

The public safety methodology for planned situations, as discussed in Chapter 4, differs from the assessment methodology applied to existing exposure situations. For existing exposure situations, there are no operational activities that could lead to further dispersion of the deposited radionuclides. Therefore, the safety assessment methodology applied for remediation, will follow the same basic principles as followed in the safety assessment methodology for planned situations. The safety assessment methodology for remediation, will be an iterative process, being a repeat of the initial safety assessment after the remediation activities have been completed. The revised final safety assessments will use the radionuclide activity concentrations, obtained from the post-remediation surveys. The safety assessment process is depicted in Figure 6-2 and further discussed in the following paragraphs.

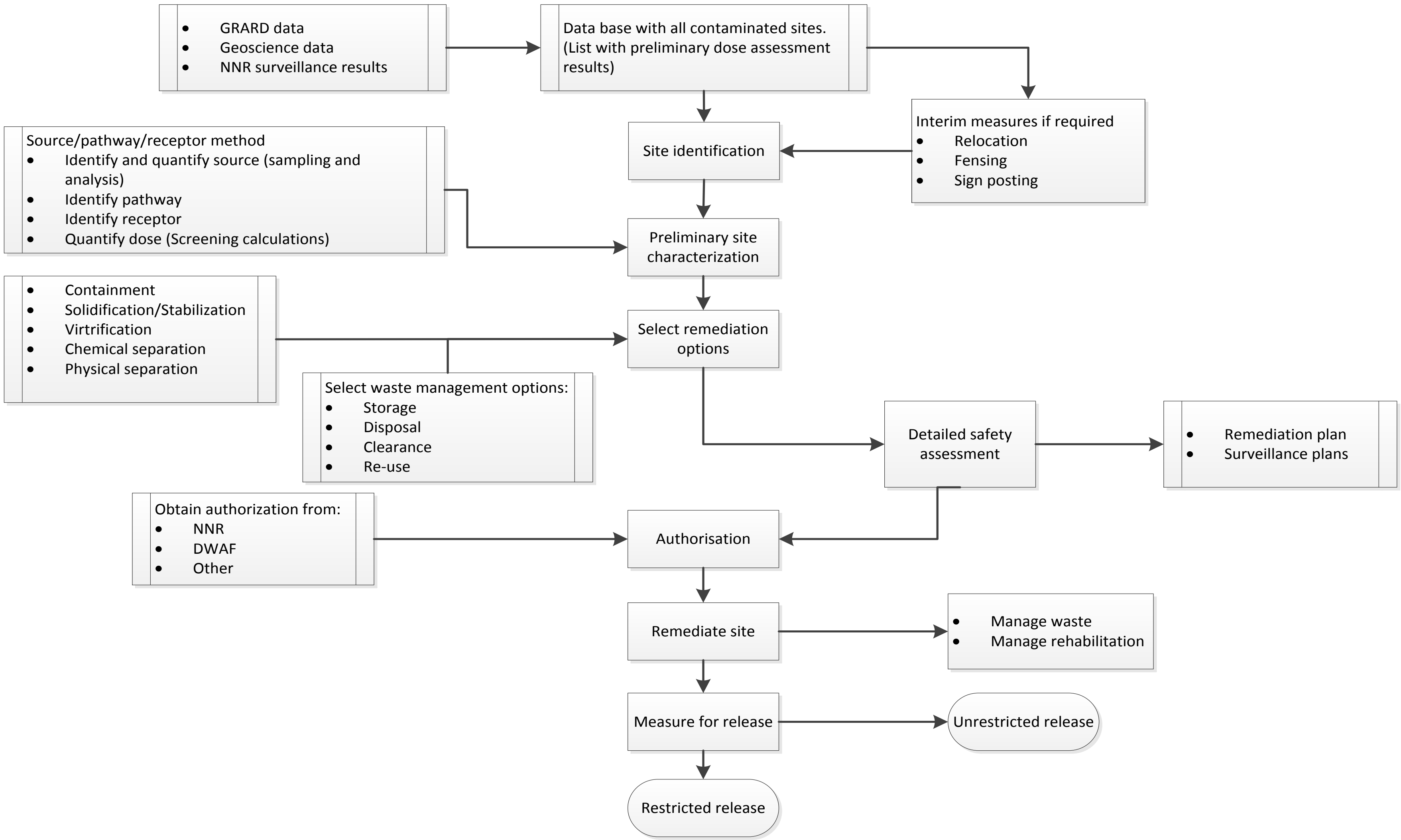

Figure 6-2: Public Safety Assessment Methodology for Remediation

6.3.1 Safety assessment process description

6.3.1.1 Site identification

The site is identified from multiple sources of information that currently exists in the country. A database of radiologically contaminated sites will be compiled from information using available national sources such as the Department of Mineral Resources database, database from Council for Geoscience, studies from universities, reports available from Water Research Commission, etc. In addition to these resources, the NNR will embark on a process of national radionuclide mapping to fill in the knowledge gaps. The starting point for remediation would most probably be a site in the Wonderfonteinspruit area in Gauteng, where the processes and criteria can be tested (NNR, 2014b).

6.3.1.2 Preliminary site characterisation

A survey is performed to obtain the required site and area information (see also Section 6.2.8). The site characterisation should identify and quantify the nature of the contamination as an input to the selection of the appropriate remediation technology. A public safety assessment is performed as discussed in Section 6.2. The source-pathway-receptor method is used to model the dose to the representative person from a subsistence farmer scenario, similar to the method defined in Chapter 4. The dose assessment is performed to establish the maximum exposure for a year at the time of assessment. In addition, the peak dose should also be determined. The results of the safety assessment will be evaluated against the 1 – 20 mSv/a criteria from Section 6.2. Nuclide specific reference levels should be determined in aid of the choice of remediation technology (NNR, 2014b).

6.3.1.3 Select site remediation option

Remediation is never a simple process. Remediation of radiologically contaminated land cannot be done in isolation from other contaminants. It is therefore crucial to have a team of experts of a wide range of areas together to define a remedial plan. Some of the most common, current solutions have been mentioned in Section 6.2.5. From a radiological point of view, it is important to define the remediation technology and model the efficiency of the process to determine whether the site would comply with release criteria after completion of remediation. Final sampling and analysis will be required to verify the efficiency of the claimed technology before the land is released from regulatory control (NNR, 2014b).

6.3.1.4 Authorisation of remedial activities

The national process for authorisation of existing exposure situations has not been established. The different authorities are working towards the establishment of such a process. With regards to general environmental pollution at derelict and ownerless sites, the newly promulgated Act 25 of 2014, National Environmental Management Laws Amendment Act, 2014, Government Gazette publication no. 37713, (South Africa, 2014) ascribes the responsibility for managing the environmental remediation, to the Department of Mineral Resources (DMR). The application for an authorisation to remediate will now be made at one point. DMR will distribute the application to remediate to all the other authorities, who will respond back through DMR to the applicant. However, the DMR responsibility, excludes radionuclides, for which a separate authorisation will be required through the NNR. At sites where remediation is required and the owner can be identified, steps will be taken against the owner to prevent further pollution (NNR, 2014b).

The NNR has also established its own processes for the authorisation of remediation on NORM sites (NNR, 2015). After the remediation technology, from the previous section, has been selected and the nuclide specific soil concentration levels have been derived, the public safety assessment, discussed earlier in this chapter, is performed and submitted to the NNR for authorisation. The NNR will approve the application and grant the authorisation with specific conditions that must be complied with. These conditions would include, amongst others, a radiation protection programme, an environmental surveillance programme, a waste management programme and requirements for the close-out of remediation (NNR, 2014b).

6.3.1.5 Remediate site

Once the remediation activities have been authorised, the specified remediation technology or combination of technologies is applied. The NNR, and other authorities, will continuously provide oversight to ensure compliance with conditions of authorisation (NNR, 2014b).

6.3.1.6 Measure for release

Another detailed site survey is required at the end of the remediation actions (NNR, 2014b). This survey again is a detailed survey performed nuclide specific to verify compliance with the nuclides specific release criteria that has been identified in the initial remediation safety assessment. Although the results of the safety assessment were expressed in dose, a nuclide specific analysis should have been performed to determine the relative contributions of the radionuclides present in the contaminated media. Release criteria could then easily be expressed in terms of nuclide activity concentrations in media, for example the uranium-238 concentration (Bq/g) in soil.

6.3.1.7 Release site

The final step in the remediation process would be to release the site from regulatory control. If the site can comply with the release criteria for a subsistence farmer scenario, the site is released without restrictions for use as the owner pleases. If the site cannot comply with the release criteria, further safety assessments are required (see Section 6.2).

Safety assessments can be performed for other restricted use scenarios, such as the residential and industrial occupational scenarios. However, as mentioned earlier, current legislation in South Africa does not permit this as yet. These options should be further investigated (NNR, 2014b).

CHAPTER 7 APPLICATION OF THE SAFETY ASSESSMENT METHODOLOGY FOR REMEDIATION

Chapter 7 contains the application of the safety assessment methodology developed for remediation and the demonstration of compliance with de-licensing criteria, as was developed in Chapter 6. This chapter demonstrates adherence to important principles such as justification and optimisation of exposure and minimisation of a burden on future generations. Other aspects investigated include the identification of the important exposure pathways, the long term in-growth of progeny and the associated effects.

7.1 Site Description

The site is called Site A, for the purpose of this study. A background site, Site B was also modelled. The site used to be a mining site, more specific a tailings facility, which was abandoned after the mine has been worked out. In the meantime, the land was occupied by persons for residential purposes. The assessment was performed to determine whether remediation is required and if so, to what extent.

7.2 Assessment Context

7.2.1 Assessment requirements

The assessment was performed using the following evaluation criteria:

- Determine peak dose over an extended period for a subsistence farmer scenario (NNR, 2015);
- > 5 mSv/a remediate (NNR, 2015);
- 1 – 5 mSv/a – annual public information sessions to explain the hazards of exposure to radionuclides and make recommendations regarding limiting exposure to the pathways most contributing to the dose (NNR, 2015); and
- Always apply optimisation/ALARA (NNR, 2015).

RESRAD on-site, Version 6.5 was used to model the dose to a representative person for a subsistence farmer scenario, as was stated in Section 6.2.1 (RESRAD, 2007; NNR, 2015).

7.2.2 Physical and hydrological site characterisation

The set of parameters used, were selected to enable ground water migration analysis using a credible code. Before the code would be accepted for use in South Africa, it would have to be demonstrated to comply with the validation and verification requirements of the NNR (NNR, 2006). RESRAD has been validated by the code developers for a wide range of uses, which provides its credibility (RESRAD, 2007). RESRAD on-site required the following site parameters as input to model the hydrological transportation of radionuclides for which mostly default values were used, as applicable (RESRAD, 2007):

- Surface area of 1 000 000 m2, thickness 2 m, volume 2 000 000 m^3;
- The contamination was recently placed, no credit for historical dispersion;
- No soil cover over the contaminated zone;
- The density of the contaminated zone is 1.5 g/cm^3;
- The erosion rate is 1.000E-03 m/a;
- Total porosity is 4.000E-01;
- Field capacity is 2.000E-01;
- Hydraulic conductivity 1.000E+01 m/a;
- B parameter 5.300E+00;
- Average annual wind speed 2.000E+00 m/s;
- Humidity in air – not used;
- Evapotranspiration coefficient – 5.000E-01;
- Precipitation – 1.000E+00 m/a;
- Irrigation – 2.000E-01 m/a;
- Irrigation mode – overhead;
- Runoff coefficient – 2.000E-01;
- Watershed area for nearby stream or pond – 1.000E+06 m^2;
- Accuracy for water/soil computations – 1.000E-03;
- Density of saturated zone – 1.500E+00 g/cm^3;
- Saturated zone total porosity – 4.000E-01;
- Saturated zone effective porosity – 2.000E-01;
- Saturated zone field capacity – 2.000E-01;
- Saturated zone hydraulic conductivity – 1.000E+02 m/a;
- Saturated zone hydraulic gradient –2.000E-02;
- Saturated zone b parameter – not used;
- Water table drop rate – 0.000E+00 m/a;

- Borehole pump intake depth (m below water table) – 1.000E+01;
- Model: Non-dispersion (ND) or Mass-Balance (MB) – ND; and
- Well pumping rate – 2.500E+02 m3/a.

7.3 Source Term Development

The same source term, as used in Chapter 5, was copied into Table 7-1 for this application. This source term is aligned in terms of activity concentration, with values found by UNSCEAR (UNSCEAR, 2008), Winde (Winde, 2010), NNR (NNR, 2007) and de Villiers (Necsa, 2010a). A fairly high activity of concentrations was used in the assessment to allow for assessment criteria to be exceeded. Exceeding the assessment criteria; allowed for the demonstration of further phases of assessment that would be required if the initial screening assessment would not be adequate (NNR, 2014a). The exposure duration is 50 years and the dose limit was 1 mSv/a (South Africa, 2006). A dose limit of 1 mSv/a was chosen, because that is the current public dose limit and by applying ALARA, optimisation of protection would be achieved. However, the 1 to 20 mSv/a criteria (ICRP, 2006) was applied in the solution.

Table 7-1 (in the last column) contains nuclide specific activity concentrations, typically in the range reported by De Villiers (Necsa, 2012). Background values are usually subtracted from site values to normalise the results and to have a value comparable with natural background. Background sites are extremely difficult to found in the Wonderfonteinspruit area due to the extent of historic radioactive contamination and the random dispersion of nuclides over a period of time. To obtain representatively, it would be required to perhaps use samples at specified depths in the soil. This however, is a matter for a different discussion.

Table 7-1: Nuclide Specific Source Terms for Remediation

Nuclide	Site A (Bq/g)	Background Site (Bq/g)
Ac-227	4.00E-01	1.81E-03
Pa-231	4.00E-01	1.81E-03
Pb-210	9.00E+00	5.90E-02
Po-210	9.00E+00	5.90E-02
Ra-226	9.00E+00	4.21E-02
Ra-228	6.00E-01	2.47E-02
Th-228	6.00E-01	2.30E-02
Th-230	9.00E+00	3.93E-02
Th-232	6.00E-01	2.28E-02
U-234	1.00E+00	3.96E-02
U-235	3.00E-02	1.81E-03
U-238	1.00E+00	3.93E-02

The total activity used in the assessment was linked to the activity concentration as a function of the contaminated zone size. In this study the operations modelled, were defined as volume sources. The dimensions of the tailings storage facility are 1E+06 m^2 and 2 m thick, which results in a volume of 2E+06 m^3.

7.4 Receptor Definition

The public exposed to potential sources of radiological contamination was referred to as the receptor or the representative person. Three age groups were used in the assessment to identify the most exposed group or representative person (ICRP, 2006). The analysis was performed over an extended period to determine peak dose. Where extended analysis periods, such as 1 000 years are applied (NUREG, 2016), the exposure scenario should be conservative. The NNR requires a demonstration of the dose to the representative person for a subsistence farmer scenario (NNR, 2015). It is common for people in certain areas of South Africa to live in informal settlements on any piece of vacant land, even on tailings facilities, such as the Tudor Shaft area, close to Krugersdorp (NNR, 2007). However, if land is released for unrestricted use, it should be available for any type of use; therefore, the subsistence farmer scenario is the preferred scenario (NNR, 2007). Mines are mostly in rural areas; therefore, the areas adjacent to the mine are defined by primarily farming activities. The representative person lives on the land and will remain there for the next 50 years. All the activities are located on the primary source of contamination. The areas occupied by the farming activities are tabulated in Table 7-2.

Table 7-2: Areas Occupied in Farming Scenario

Activity	Surface area (m^2)
Primary contaminant	1 000 000
Fruit, grain, non-leafy vegetables	1 000
Leafy vegetables	1 000
Pasture	4 000
Grain	4 000
Dwelling	1 000

The amount of food consumed and the ratio from the affected area are tabulated in Table 7-3 (NNR, 2014a). (The food consumption rates were developed for a generic application under South African conditions in safety assessments for all types of facilities. The consumption rates are, however captured in the document, RG-002, for mining purposes, which was work performed for inclusion in Chapter 4 (NNR, 2014a).

Table 7-3: Food Consumption Rates per Age Group (NNR, 2014a)

Food	1 Year Old	10 Year Old	Adult
Fish consumption (kg/a); 50 % from affected area	2.16	3.24	5.4
Drinking water; 50 % Surface water; 50 % borehole water	240	360	600
Fish consumption (kg/a); 50 % from affected area	2.16	3.24	5.4
Other aquatic food (kg/a); 50 % from affected area	0.36	0.54	0.9
Non-leafy vegetables consumption (kg/a); 50 % from affected area	64	96	160
Leafy vegetable consumption (kg/a); 50 % from affected area	5.6	8.4	14
Meat consumption (kg/a); 50 % from affected area	25.2	37.8	63.0
Milk consumption (L/a); 100 % from affected area	36.8	55.2	92
Soil ingestion (g/a)	14.6	21.9	36.5

Other input information used during RESRAD modelling is as follows (NNR, 2014a):

- Inhalation rate 1-year-old – 1.928E+03 m^3/a;
- Inhalation rate 10-year-old – 5606 m^3/a;
- Inhalation rate Adult – 8400 m^3/a;

- Mass loading for inhalation – 1.000E-04 g/m^3;
- Exposure duration – 5.000E+01 a;
- Shielding factor, inhalation – 4.000E-01;
- Shielding factor, external gamma – 7.000E-01;
- Fraction of time spent indoors – 5.000E-01;
- Fraction of time spent outdoors (on site) – 2.500E-01; and
- Shape factor flag, external gamma – 1.000E+00.

Assumptions were made to suite the evaluation of a piece of land to be used, after remediation, as land suitable for subsistence farming, as required in the NNR document, RG-002, (NNR, 2014a). These assumptions regarding land use are as follows:

- Contamination fraction of drinking water – 1.000E+00;
- Contamination fraction of household water – 1.000E+00;
- Contamination fraction of livestock water – 1.000E+00;
- Contamination fraction of irrigation water – 1.000E+00;
- Contamination fraction of aquatic food – 5.000E-01;
- Contamination fraction of plant food – 0.500E+00;
- Contamination fraction of meat – 1.000E+00;
- Contamination fraction of milk – 1.000E+00;
- Livestock fodder intake for meat – 6.800E+01 kg/d
- Livestock fodder intake for milk – 5.500E+01 kg/d;
- Livestock water intake for meat – 5.000E+01 l/d;
- Livestock water intake for milk -– 1.600E+02 l/d; and
- Livestock soil intake – 5.000E-01 kg/d.

For the screening assessment, a standard set of public activities was defined. These include, a person living and farming on the primary area of contamination, farming with livestock and fresh produce. The person consumes all the products from his farm. Time spent indoors was considered as well as time spent on different farming activities (NNR, 2014a).

ICRP 101 proposes three age groups (ICRP, 2006) in the definition of the representative person. The ICRP proposed age groups, 1-year-old, 10-year-old and adult were used in the assessment. For each age group there is a unique set of dose conversion factors, consumption rates, inhalation rates and time spent at different locations (NNR, 2014a).

7.5 Exposure Scenarios

The exposure scenarios were developed from all of the above mentioned input parameters. A rural resident farmer scenario was developed to model exposure to the representative person, thus to assess the suitability of land for use after completion of remediation. The farmer is self-sufficient and produces all the food he needs locally on the site. He lives on the farm. The agricultural activities consist of land and pastures, which are ingested; a surface water body and a well for watering and consumption. Time is spent indoors and outdoors. Peak doses were also calculated. Decision making was based on the results of the peak dose. The calculation of the peak dose would evaluate future use of the land. The Nuclear Regulatory Commission in the United States of America requires a period of 1 000 years to be considered in safety assessments where land is to be cleared from regulatory control (NUREG, 2016)

All the possible pathways considered by RESRAD were selected for the analysis, to allow for the release of land under any circumstance possible over the next 1 000 years, as follows:

- External gamma exposure;
- Inhalation:
- Plant ingestion;
- Meat ingestion;
- Milk ingestion;
- Aquatic foods;
- Drinking water; and
- Soil ingestion.

7.6 Models

The RESRAD on-site model within the RESRAD on-site, Version 6.5 code was used to perform the assessment (RESRAD, 2009). The assessment, based on the source-pathway-receptor approach, applies to the specific site only and cannot be applied to any other site, because each site has specific characteristics. Where the soil type differs, for example, the migration rates of nuclides in that medium will differ and affect the rate and quantities of nuclide migration. The assessments were performed from generic criteria and therefore qualify as a screening assessment, to illustrate the principle. Where the assessment criteria were exceeded, an iterative process with site specific and more realistic data, was performed.

7.7 Results

There were several assessments performed on Site A. The discussion of the results is divided into a screening analysis and a refined analysis. A safety assessment was also performed for a background site.

7.7.1 Radiological safety analysis

The analysis was performed for three age groups, being 1-year-old, 10-year-old and adult (ICRP, 2006). The results of the safety assessment appear in Table 7-4. It was found that at time t=0, the adult would receive a dose of 258 mSv/a, the 10-year-old, 291.6 mSv/a and the child, 385.9 mSv/a. Therefore, the 1-year-old becomes the representative person, which is important for decision making. The dose peaks at time=913 years at 8.023E+03 mSv/a. In addition, also in Table 7-4, a safety assessment was performed with activity concentrations specified in Table 7-1 for a background site for a 1-year-old. The dose at time t=0 years was 2.55 mSv/a, and the maximum dose of 37.31 mSv/a was obtained at time t=897 years. The background should be subtracted from the modelled value to obtain a corrected value. However, the modelled results demonstrated that the background value also exceed the assessment criteria (20 mSv/a) after a 100 years (for this specific scenario.).

Table 7-4: Modelled Annual Dose per Age Group – Selected Site

Age Group	Effective Dose (mSv/a)						
Time (a)	**0**	**1**	**10**	**30**	**100**	**300**	**1 000**
1-year-old [Rem 1]	3.86E+02	5.21E+02	7.36E+02	1.23E+03	2.78E+03	5.73E+03	7.99E+03
10-year-old [Rem 10]	2.92E+02	3.52E+02	4.48E+02	6.67E+02	1.36E+03	2.66E+03	3.65E+03
Adults [Rem Adults]	2.58E+02	3.04E+02	3.76E+02	5.40E+02	1.06E+03	2.03E+03	2.76E+03
Reference site [Rem1BGr]	2.55E+00	3.41E+00	4.43E+00	6.65E+00	1.34E+01	2.69E+01	3.72E+01

The results obtained from the modelling were displayed over a period of 1 000 years as is required by the UN NRC (NUREG, 2016). Extracted from the same set of results, was the information displayed in Table 7-5. The values in Table 7-5 merely portray the peak dose values. It is interesting to note that peak doses appear at different times, varying from 897 years to 913 years. The decline in the effective dose from peak to 1 000 years can clearly be seen when comparing the results in Tables 7-4 and 7-5.

Table 7-5: Peak Dose – Selected Site

Age group	Peak Dose (mSv/a)	Time (a)
Rem 1 year [Rem 1]	8.023E+03	913
Rem 10 year old [Rem 10]	3.666E+03	903
Rem Adult [Rem Adult]	2.774E+03	895
Reference site [Rem1BGr]	3.731E+01	897

7.7.2 Pathway and source analysis

The dose clearly exceeds the remediation criteria, which results in further analysis. The next step in the process would be to determine the source of contamination and the nuclide contributing to the dose. The results for the dose from all nuclides, via all pathways have been graphically displayed in Figure 7-1. From the graph, which displays the contribution of parent nuclides, it is clear that the highest contribution comes from Ra-226 (79.1 %), followed by Pb-210. However, from Table 7-7, results of water dependent pathways, we can see that there is a 20.73 % contribution from Th-230. Both these nuclides are progeny from U-238. Interestingly, the activity concentration of both these nuclides were high from the input data, therefore the effect was not only due to ingrowth of progeny. The long period leading to the peak dose can be ascribed to radionuclide transportation in ground water to the surface water body.

Ra-226 is the nuclide that has the largest contribution to the dose. If the Ra-226 initial activity concentration was reduced from 9 Bq/g (Figure 7-1) to 1 Bq/g (Figure 7-2), to test the dose reduction effect, it would have resulted in a dose of 212.5 mSv/a at time t=0 years and peak at 2 492 mSv/a at t = 1 000 years from 486 mSv/a at T=0 years to 6 350 mSv/a at t=1 000 years. That would have resulted in reduction ratios of 0.437 at t=0 and 0.392 at t=1 000 years. Therefore, even reducing the initial activity concentration 9 times would have still resulted in an exceedance of the dose criteria. The efficiency of removal of a single nuclide must be seen in relation to the total contribution of all nuclides. It is also clear that the efficiency of nuclide reduction is less effective over a long period of time because of the presence of the parent nuclides, U-238.

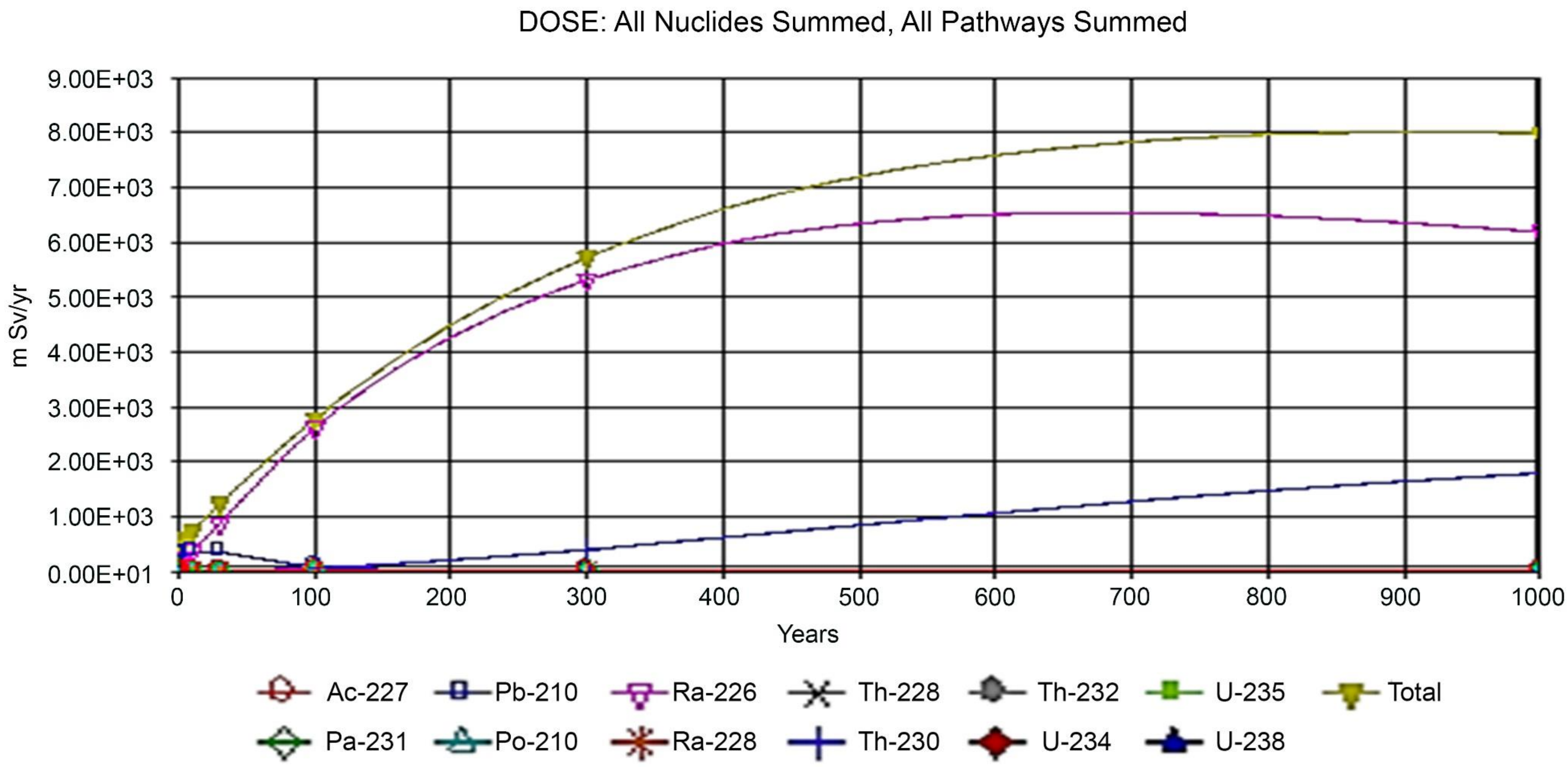

Figure 7-1: Dose from All Nuclides Summed

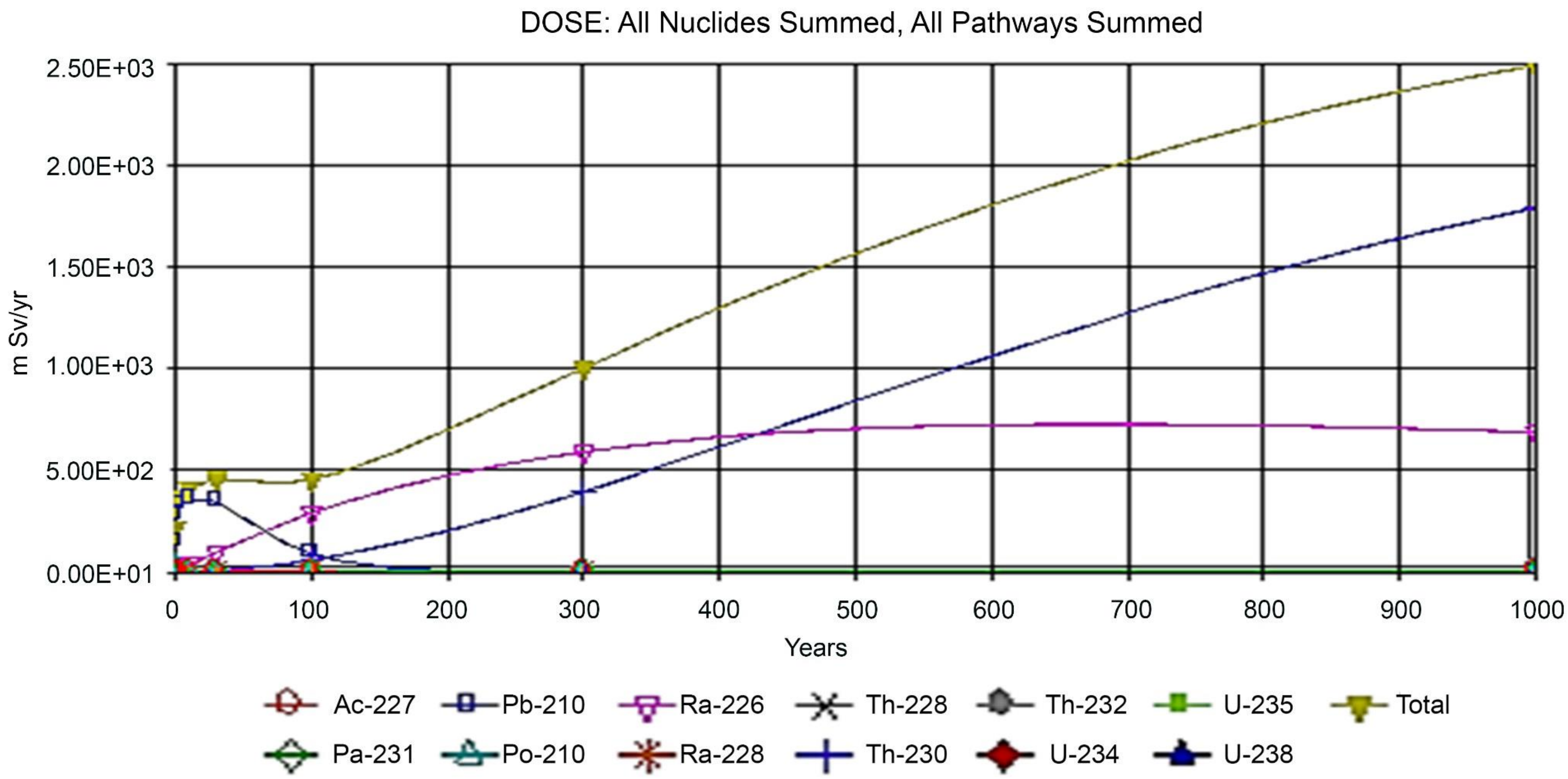

Figure 7-2: Dose from All Nuclides Summed, Ra-226 Input 1 Bq/g

It is interesting to note that the majority of the dose results from Ra-226 with ingrowth of Th-230. Both of these nuclides fall in the half-life category 10 – 10 000 years in Table 7-6.

Table 7-6: Half-Life Categories of Radionuclides

Half-Life	Nuclides
➢ 10 000 years	Th-232, U-238, U-234, U-235
100 years – 10 000 years	Th-230, Ra-226,
1 years – 100 years	Ra-228, Th-228, Pb-210
Days	Ra-224,
Hours, minutes, seconds	Ac-228, Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208 Th-234, Pa-234, Rn-222, Po-218, Pb-214, At-218, Bi-214, Po-214, Bi-210, Po-210

When examining the water dependent exposure pathway, Table 7-7, it was found that the majority of the dose, at peak dose, 913 years, could be attributed to the consumption of fish, or aquatic foods (7 210 mSv/a or 89.82 %) and then from drinking water (614 mSv/a or 7.65 %). A screening value 1 mSv/a was set as selection criteria to determine whether remediation at that source would be required. It was found that all the water dependent pathways exceeded the screening value, even with complete elimination of these foodstuffs. Therefore, remediation at all the sources would be required to release the site from regulatory control. This is tabled and graphically displayed in Table 7-7. (Run Rem1. 2015 on CD).

Table 7-7: Dose, All Pathways, Water Dependent at Peak Dose, 913 Years

Radio-	Water		Fish		Radon		Plant		Meat		Milk		All Pathways	
Nuclide	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.
Ac-227	5.96E-15	0	4.69E-15	0	0.00E+00	0	3.93E-16	0	8.86E-18	0	3.46E-17	0	1.12E-14	0
Pa-231	2.75E+00	0.0003	1.89E+00	0.0002	0.00E+00	0	1.81E-01	0	4.22E-02	0	1.36E-02	0	4.91E+00	0.0006
Pb-210	2.85E-10	0	3.43E-09	0	0.00E+00	0	2.87E-11	0	3.51E-11	0	5.15E-12	0	3.79E-09	0
Po-210	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Ra-226	**4.86E+02**	**0.0605**	**5.73E+03**	**0.7137**	**9.33E-01**	**0.0001**	**4.89E+01**	**0.01**	**5.91E+01**	**0.01**	**8.90E+00**	**0.0011**	**6.35E+03**	**0.791**
Ra-228	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Th-228	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Th-230	1.25E+02	0.0156	1.48E+03	0.1841	2.41E-01	0	1.26E+01	0	1.52E+01	0	2.29E+00	0.0003	1.66E+03	0.2073
Th-232	6.52E-02	0	2.51E-02	0	1.59E-08	0	4.01E-03	0	1.06E-03	0	2.47E-03	0	7.24E+00	0.0009
U-234	1.98E-01	0	1.08E+00	0.0001	1.89E-04	0	1.62E-02	0	1.17E-02	0	4.24E-03	0	1.32E+00	0.0002
U-235	7.12E-03	0	2.96E-03	0	0.00E+00	0	4.70E-04	0	7.92E-05	0	9.64E-05	0	1.10E-02	0
U-238	1.01E-01	0	1.04E-02	0	1.84E-07	0	6.90E-03	0	6.96E-04	0	2.40E-03	0	1.23E-01	0
Total	**6.14E+02**	**0.0765**	**7.21E+03**	**0.8982**	**1.17E+00**	**0.0001**	**6.17E+01**	**0.01**	**7.44E+01**	**0.01**	**1.12E+01**	**0.0014**	**8.02E+03**	**1**

The results for the water in-dependent analysis are tabulated in Table 7-8. The largest dose contributions to the representative person is attributed to inhalation of radon (33.6 mSv/a or 0.42 %) from living on the contaminated site and from ingesting plant based foods (12.3 mSv/a or 0.15 %) harvested from the contaminated site. Once again, compared to the screening criteria of 1 mSv/a the resultant dose exceeds the criteria in all pathways, except for the inhalation pathway. Therefore, all sources would require remediation.

Table 7-8: Dose, All Pathways, Water In-Dependent, at Peak Dose, 913 Years

Radio-	Ground		Inhalation		Radon		Plant		Meat		Milk		Soil	
Nuclide	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.	mSv/a	fract.
Ac-227	1.66E-17	0	1.94E-18	0	0.00E+00	0	5.19E-17	0	4.42E-19	0	1.52E-18	0	2.37E-18	0
Pa-231	5.94E-03	0	7.30E-04	0	0.00E+00	0	2.54E-02	0	3.82E-03	0	4.97E-04	0	1.04E-03	0
Pb-210	9.06E-16	0	6.90E-16	0	0.00E+00	0	2.30E-12	0	9.15E-13	0	1.20E-13	0	1.25E-13	0
Po-210	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Ra-226	1.24E+00	0.0002	9.95E-04	0	1.18E+01	0.0015	2.69E+00	0	7.52E-01	0	1.58E-01	0	1.03E-01	0
Ra-228	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Th-228	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
Th-230	2.28E+00	0.0003	4.31E-02	0	2.16E+01	0.0027	4.77E+00	0	1.27E+00	0	2.75E-01	0	2.12E-01	0
Th-232	1.54E+00	0.0002	5.89E-03	0	1.89E-01	0	4.76E+00	0	2.69E-01	0	3.37E-01	0	4.67E-02	0
U-234	5.74E-04	0	4.46E-05	0	5.41E-03	0	1.73E-03	0	3.48E-04	0	1.56E-04	0	1.22E-04	0
U-235	1.86E-04	0	1.92E-06	0	0.00E+00	0	5.31E-05	0	6.69E-06	0	3.38E-06	0	3.59E-06	0
U-238	1.19E-03	0	2.81E-05	0	3.29E-06	0	5.68E-04	0	3.77E-05	0	8.24E-05	0	7.68E-05	0
Total	5.07E+00	0.0006	5.08E-02	0	**3.36E+01**	0.0042	**1.23E+01**	0	2.29E+00	0	7.71E-01	0.0001	3.62E-01	0

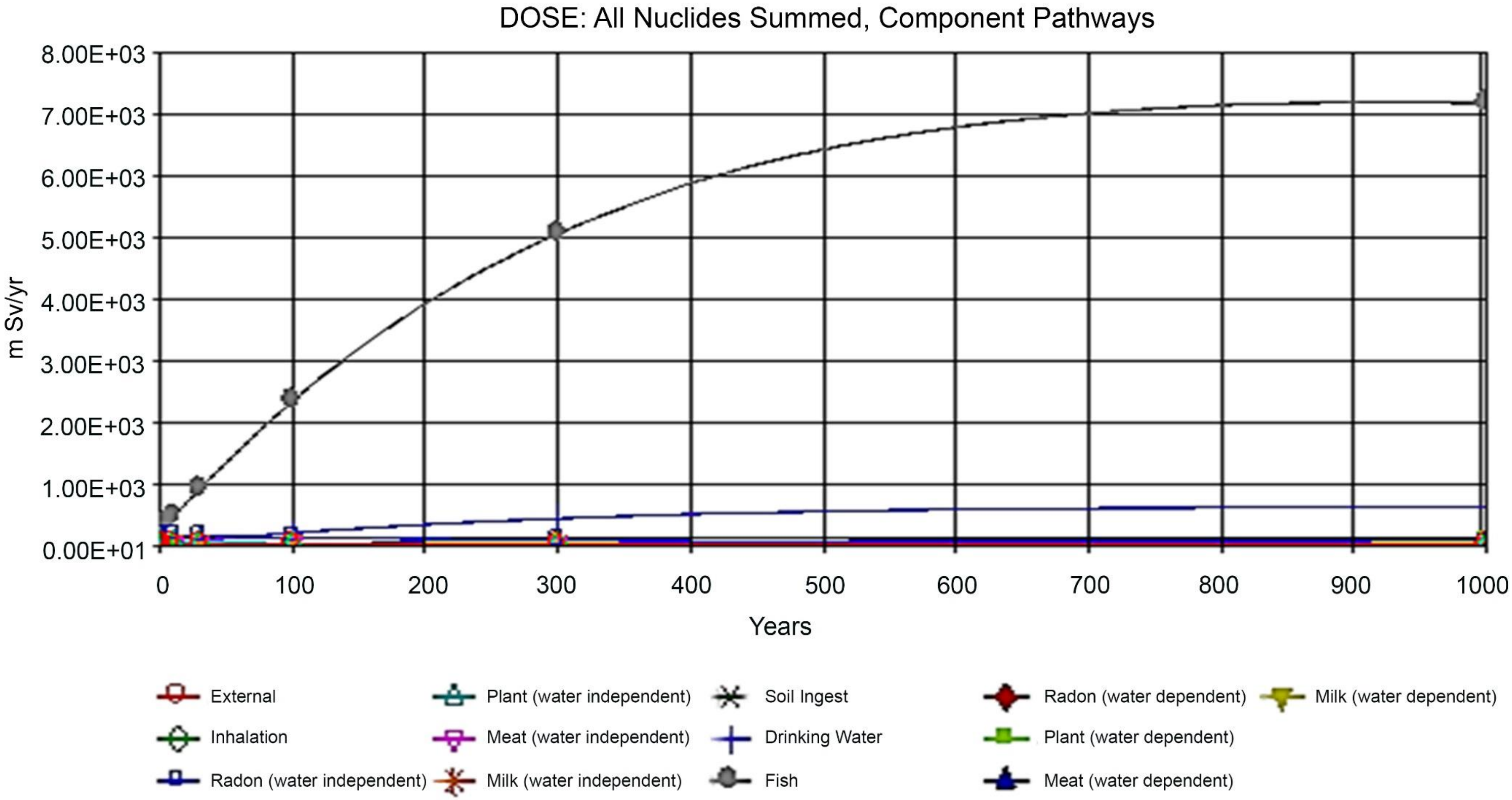

Figure 7-3: All Nuclides Summed: Component Pathways

Figure 7-3 shows that the consumption of fish (aquatic food), by far (89.8 %), has the biggest effect on the dose to the representative person. This is followed by water independent radon. If the dose contribution from fish consumption, 7 210 mSv/a, is subtracted from the total dose, 8 020 mSv/a, the result would be 817 mSv/a. Although the analysis has clearly identified the most sensitive food pathways, remediation would still be required. However, the screening analysis reveal valuable information regarding the specific nuclides and the specific consumption pathways to be managed when source term reduction was applied and may be important at later stages in the management process of remediation. Once again, it must be remembered that the results of this analysis is just as good as the input figures and the efficiency of the calculational tool. This emphasises the fact that the calculational tool should be validated and verified in accordance with the requirements established by the NNR (NNR, 2006).

7.7.3 Deriving nuclide specific dose/source ratios

The parent nuclide and progeny principal radionuclide contributions are tabled in Table 7-9. [Rem 1 A summary report, 2015]. For some nuclides, (Pa-231, U-235, U-238), there are 2 sets of data provided in Table 7-9, because the initial input activity concentration (Bq/g) reflects a state of equilibrium as would be expected in nature. The Dose to Source Ratio (DSR) is of particular importance when evaluating the radionuclide input contribution relative to the resultant dose from that nuclide. Ra-226, in particular, from the water dependent pathway, causes the highest resultant dose. In Table 7-9, it can be seen that the DSR for Ra-226 is also the highest (21.7 at t=0). Therefore, when radionuclide specific release criteria are set, the DSR is a strong indicator. DSR is a ratio, which is time dependent. The relative contributions of Ac-227 can be interpreted, from Table 7-9, as having a short term impact (DSR at t=0 is 1.45E+00 and DSR at 1 000 a = 7.79E-16), relative to Ra-226. The Ac-227 impact decreases, whereas the Ra-226 impact, increases over time (2.17E+01 at t=0, versus 6.88E+02 at t=1 000 years). The DSR is important in selecting a long or short term solution for the release of land. Where the results reveal long term build-up in the environment, the site may be released, considering remedial actions such as phytostabilisation or phytoextraction. It was calculated by Cerne for an ideal plant species to be suitable for commercial or economically viable phytoextraction of Ra-226 from soil contaminated with uranium, the Ra-226 accumulation in the shoots should at least be 10 times that of the Ra-226 concentration in the soil (Cerne, 2012). Perhaps this avenue could be further explored for South African conditions.

Table 7-9: Dose/Source Ratios Summed Over All Pathways

Parent Nuclide	Progeny		Calculation Time (a)			
(i)	(j)	Fraction	0.00E+00	3.00E+01	3.00E+02	1.00E+03
			Dose/Source Ratios (mSv/a)/(Bq/g)			
Ac-227	Ac-227	9.86E-01	4.40E-01	2.38E+00	1.67E-03	7.15E-16
Ac-227	Th-227	9.86E-01	8.08E-02	3.29E-02	5.43E-06	2.44E-18
Ac-227	Ra-223+D	9.86E-01	9.33E-01	4.83E-01	1.39E-04	6.09E-17
Ac-227	ΣDSR(j)		1.45E+00	2.90E+00	1.82E-03	7.79E-16
Ac-227+D	Ac-227+D	1.38E-02	6.62E-03	3.36E-02	2.35E-05	1.01E-17
Ac-227+D	Ra-223+D	1.38E-02	1.52E-02	8.85E-03	3.42E-06	1.45E-18
Ac-227+D	ΣDSR(j)		2.18E-02	4.25E-02	2.69E-05	1.15E-17
Pa-231	Pa-231	9.86E-01	6.91E-01	9.21E-01	2.10E+00	9.72E-01
Pa-231	Ac-227	9.86E-01	8.36E-03	2.71E+00	1.73E+01	6.95E+00
Pa-231	Th-227	9.86E-01	1.22E-03	5.41E-02	7.88E-02	2.31E-02
Pa-231	Ra-223+D	9.86E-01	1.22E-02	7.37E-01	1.68E+00	5.87E-01
Pa-231	ΣDSR(j)		7.13E-01	4.42E+00	2.12E+01	8.53E+00
Pa-231	Pa-231	1.38E-02	9.67E-03	1.29E-02	2.94E-02	1.36E-02
Pa-231	Ac-227+D	1.38E-02	1.25E-04	3.84E-02	2.44E-01	9.78E-02
Pa-231	Ra-223+D	1.38E-02	2.10E-04	1.27E-02	3.87E-02	1.43E-02
Pa-231	ΣDSR(j)		1.00E-02	6.40E-02	3.12E-01	1.26E-01
Pb-210	Pb-210	1.00E+00	1.41E+00	6.88E-01	3.55E-04	1.88E-13
Pb-210	Bi-210	1.00E+00	6.46E-02	8.29E-02	1.06E-04	6.72E-14
Pb-210	Po-210	1.00E+00	1.48E+01	3.78E+01	4.53E-02	2.84E-11
Pb-210	ΣDSR(j)		1.63E+01	3.85E+01	4.57E-02	2.87E-11
Po-210	Po-210	1.00E+00	3.98E+00	3.53E-22	0.00E+00	0.00E+00
Ra-226	Ra-226	1.00E+00	1.97E+01	1.82E+01	9.31E+00	2.20E+00
Ra-226	Rn-222+D	1.00E+00	1.75E+00	1.68E+00	9.90E-01	3.71E-01
Ra-226	Pb-210	1.00E+00	2.67E-02	1.19E+00	4.32E+00	4.50E+00
Ra-226	Bi-210	1.00E+00	1.41E-03	1.73E-01	1.38E+00	1.63E+00
Ra-226	Po-210	1.00E+00	2.44E-01	7.49E+01	5.75E+02	6.79E+02
Ra-226	ΣDSR(j)		2.17E+01	9.62E+01	5.91E+02	6.88E+02
Ra-228+D	Ra-228+D	1.00E+00	9.42E+00	2.57E-01	1.97E-15	0.00E+00
Ra-228+D	Th-228	1.00E+00	5.89E-02	1.24E-02	4.83E-17	0.00E+00
Ra-228+D	Ra-224+D	1.00E+00	2.86E-01	6.76E-02	3.78E-16	0.00E+00
Ra-228+D	ΣDSR(j)		9.77E+00	3.37E-01	2.39E-15	0.00E+00
Th-228	Th-228	1.00E+00	2.89E-01	5.49E-06	0.00E+00	0.00E+00
Th-228	Ra-224+D	1.00E+00	1.62E+00	2.93E-05	0.00E+00	0.00E+00
Th-228	ΣDSR(j)		1.90E+00	3.48E-05	0.00E+00	0.00E+00
Th-230	Th-230	1.00E+00	2.43E-02	2.42E-02	2.42E-02	2.40E-02
Th-230	Ra-226	1.00E+00	4.24E-03	2.50E-01	1.78E+00	2.94E+00

Th-230	Rn-222+D	1.00E+00	3.76E-04	2.29E-02	1.73E-01	3.31E-01
Th-230	Pb-210	1.00E+00	4.09E-06	8.39E-03	3.71E-01	1.44E+00
Th-230	Bi-210	1.00E+00	1.91E-07	9.99E-04	9.87E-02	4.65E-01
Th-230	Po-210	1.00E+00	2.66E-05	4.35E-01	4.15E+01	1.94E+02
Th-230	ΣDSR(j)		2.89E-02	7.41E-01	4.39E+01	1.99E+02
Th-232	Th-232	1.00E+00	2.65E-02	2.65E-02	2.65E-02	2.64E-02
Th-232	Ra-228+D	1.00E+00	5.38E-01	9.73E+00	9.96E+00	9.88E+00
Th-232	Th-228	1.00E+00	2.59E-03	3.32E-01	3.44E-01	3.43E-01
Th-232	Ra-224+D	1.00E+00	1.18E-02	1.75E+00	1.81E+00	1.81E+00
Th-232	ΣDSR(j)		5.79E-01	1.18E+01	1.21E+01	1.21E+01
U-234	U-234	1.00E+00	1.65E-02	4.26E-02	1.80E-01	9.09E-02
U-234	Th-230	1.00E+00	1.16E-07	6.36E-06	4.26E-05	6.91E-05
U-234	Ra-226	1.00E+00	1.27E-08	3.38E-05	2.05E-03	8.49E-03
U-234	Rn-222+D	1.00E+00	1.12E-09	3.10E-06	2.10E-04	1.16E-03
U-234	Pb-210	1.00E+00	1.58E-10	8.85E-07	5.94E-04	9.36E-03
U-234	Bi-210	1.00E+00	5.58E-11	1.20E-07	1.80E-04	3.28E-03
U-234	Po-210	1.00E+00	2.25E-08	5.12E-05	7.48E-02	1.36E+00
U-234	ΣDSR(j)		1.65E-02	4.27E-02	2.58E-01	1.47E+00
U-235	U-235	9.86E-01	1.31E-01	1.46E-01	2.20E-01	9.41E-02
U-235	Th-231	9.86E-01	5.94E-03	5.80E-03	4.05E-03	1.16E-03
U-235	Pa-231	9.86E-01	6.68E-06	5.94E-04	1.34E-02	1.99E-02
U-235	Ac-227	9.86E-01	6.44E-08	9.07E-04	9.82E-02	1.45E-01
U-235	Th-227	9.86E-01	7.99E-09	2.02E-05	4.50E-04	4.82E-04
U-235	Ra-223+D	9.86E-01	2.01E-05	1.42E-03	1.32E-02	1.08E-02
U-235	ΣDSR(j)		1.37E-01	1.55E-01	3.49E-01	2.71E-01
U-235	U-235	1.38E-02	1.84E-03	2.05E-03	3.08E-03	1.32E-03
U-235	Th-231	1.38E-02	8.32E-05	8.11E-05	5.66E-05	1.62E-05
U-235	Pa-231	1.38E-02	9.35E-08	8.31E-06	1.87E-04	2.78E-04
U-235	Ac-227+D	1.38E-02	7.02E-10	1.28E-05	1.38E-03	2.04E-03
U-235	Ra-223+D	1.38E-02	1.34E-09	4.59E-06	2.20E-04	2.98E-04
U-235	ΣDSR(j)		1.92E-03	2.15E-03	4.93E-03	3.95E-03
U-238	U-238	5.40E-05	8.19E-07	2.12E-06	8.97E-06	4.54E-06
U-238	U-238	1.00E+00	1.52E-02	3.93E-02	1.66E-01	8.42E-02
U-238	Th-234+D	1.00E+00	2.37E-02	2.40E-02	1.16E-02	1.94E-03
U-238	U-234	1.00E+00	1.89E-08	3.67E-06	1.53E-04	2.51E-04
U-238	Th-230	1.00E+00	1.14E-13	2.71E-10	1.54E-08	5.69E-08
U-238	Ra-226	1.00E+00	5.15E-11	3.41E-09	5.45E-07	6.35E-06
U-238	Rn-222+D	1.00E+00	1.27E-11	6.59E-10	5.83E-08	9.58E-07
U-238	Pb-210	1.00E+00	1.88E-10	9.26E-09	2.23E-07	9.19E-06
U-238	Bi-210	1.00E+00	7.02E-11	3.23E-09	7.20E-08	3.25E-06
U-238	Po-210	1.00E+00	2.78E-08	1.41E-06	3.01E-05	1.34E-03
U-238	ΣDSR(j)		3.88E-02	6.33E-02	1.78E-01	8.77E-02

7.7.4 Deriving single nuclide soil guidelines

RESRAD has the capability to derive a set of Single Nuclide Soil Guidelines (SNSG), as tabulated in Table 7-10. Single nuclide soil guidelines refer to a soil guideline per nuclide, which is the activity concentration per nuclide, in Bq/g. This activity concentration is linked to the remediation release criteria, which must be satisfied for the site to be released from regulatory control, in this case, 1 mSv/a.

Table 7-10: Single Radionuclide Soil Guidelines G(i,t) in Bq/g for 1 mSv/a

	Time (a)			
Nuclide	**t= 0.000E+00**	**3.00E+01**	**3.00E+02**	**1.00E+03**
	Single Radionuclide Soil Guidelines (SNSG) (Bq/g)			
Ac-227	6.78E-01	3.40E-01	5.43E+02	*2.676E+12
Pa-231	1.38E+00	2.23E-01	4.66E-02	1.16E-01
Pb-210	6.16E-02	2.60E-02	2.19E+01	3.49E+10
Po-210	2.51E-01	*1.663E+14	*1.663E+14	*1.663E+14
Ra-226	4.61E-02	1.04E-02	1.69E-03	1.45E-03
Ra-228	1.02E-01	2.97E+00	*1.009E+13	*1.009E+13
Th-228	5.25E-01	2.88E+04	*3.032E+13	*3.032E+13
Th-230	3.46E+01	1.35E+00	2.28E-02	5.03E-03
Th-232	1.73E+00	8.45E-02	8.24E-02	8.30E-02
U-234	6.06E+01	2.34E+01	3.88E+00	6.81E-01
U-235	7.19E+00	6.37E+00	2.82E+00	3.64E+00
U-238	2.57E+01	1.58E+01	5.62E+00	1.14E+01

***At specific activity limit**

These values are nuclide specific, which when applied to each nuclide in the mixture of nuclides in the contamination zone, will result in a dose exceeding the dose limit. However, the relative contribution of the dose to the representative person must be taken into consideration and also the ratio of radionuclides presents as primary contaminants in the contamination zone. An interesting observation is that for Ra-226, the NSG is 0.00138 Bq/g, which is significantly below the NNR exclusion level of 0.5 Bq/g. This would result, for this specific scenario, that the land would probably not be released from regulatory control after remediation when the subsistence farmer scenario is applied, because of the following: From Table 7-1, Ra-226 has an activity concentration of 9 Bq/g. The background Ra-226 concentration is 0.0421 Bq/g, resulting in a corrected activity concentration of about 8.96 Bq/g. The single nuclide guideline value is 0.00138 Bq/g (Table 7-11). Divide the residual activity concentration by the single nuclide guideline value (8.96/0.00138) to get a clean-up ratio of about 6 490. The single nuclide concentration value is also (0.0421/0.00138) a factor of about 30 below background.

In Table 7-11, the RESRAD Nuclide Specific Soil Guide (NSG) were given, linked to the Dose/Source Ratio (DSR). These values are scenario specific and have been derived from the input source term per exposure pathway for a dose limit of 1 mSv/a. The DSR x NSG column in the table is merely the product of the DSR and the NSG to demonstrate that the dose does not exceed the annual dose limit of 1 mSv per nuclide.

An interesting observation is that some of these NSGs are below the natural background, e.g. Pb-210, Ra-226, and Th-230. Most of the NSGs are even below the specific activity value of 0.5 Bq/g to bring activities under regulatory control.

Table 7-11: Summed DSR and NSG at 1 mSv/a Reference Level

Nuclide	Initial Concentration (Bq/g)	DSR	NSG (Bq/g)	Background (Bq/g)
Ac-227	4.00E-01	3.06E+00	3.26E-01	1.81E-03
Pa-231	4.00E-01	2.60E+01	3.85E-02	1.81E-03
Pb-210	9.00E+00	4.18E+01	2.39E-02	5.90E-02
Po-210	9.00E+00	3.98E+00	2.51E-01	5.90E-02
Ra-226	9.00E+00	7.27E+02	1.38E-03	4.21E-02
Ra-228	6.00E-01	9.77E+00	1.02E-01	2.47E-02
Th-228	6.00E-01	1.90E+00	5.25E-01	2.30E-02
Th-230	9.00E+00	1.99E+02	5.03E-03	3.93E-02
Th-232	6.00E-01	1.22E+01	8.22E-02	2.28E-02
U-234	1.00E+00	1.47E+00	6.81E-01	3.96E-02
U-235	3.00E-02	6.16E-01	1.62E+00	1.81E-03
U-238	1.00E+00	2.27E-01	4.40E+00	3.93E-02

***Kept at original input value**

A similar exercise was performed to model NSG values at 20 mSv/a. The results are displayed in Table 7-12. Comparing the Ra-226 NSG for a reference level of 1 mSv/a versus the NSG for 20 mSv/a, at peak dose, ± 0.00138 vs. 0.0284. This value is still significantly below the 0.5 Bq/g exclusion level used in South African legislation. Comparing the 20 mSv/a NSG (Table 7-12) with the background value for Ra-226 (Table 7-1) (0.0421 vs. 0.0284) the clean-up ratio is about 1.5. This is still below background, but more achievable.

Table 7-12: Summed NSG at 20 mSv/a Reference Level and Background

Nuclide (i)	Initial (Bq/g)	NSG(t=0) (Bq/g)	NSG(t=1 000) (Bq/g)	Background (Bq/g)
Ac-227	4.00E-01	6.51E+00	*2.676E+12	1.81E-03
Pa-231	4.00E-01	7.69E-01	1.63E+00	1.81E-03
Pb-210	9.00E+00	4.78E-01	4.75E+10	5.90E-02
Po-210	9.00E+00	5.02E+00	*1.663E+14	5.90E-02
Ra-226	9.00E+00	2.75E-02	2.84E-02	4.21E-02
Ra-228	6.00E-01	2.05E+00	*1.009E+13	2.47E-02
Th-228	6.00E-01	1.05E+01	*3.032E+13	2.30E-02
Th-230	9.00E+00	1.01E-01	1.08E-01	3.93E-02
Th-232	6.00E-01	1.64E+00	1.66E+00	2.28E-02
U-234	1.00E+00	1.36E+01	1.52E+01	3.96E-02
U-235	3.00E-02	3.24E+01	5.46E+01	1.81E-03
U-238	1.00E+00	8.80E+01	1.63E+02	3.93E-02

*At specific activity limit

7.7.5 Calculated dose at 0.5 Bq/g and at background

The calculations for the subsistence farmer scenario were repeated for different activity concentrations. The highest original activity was that of Ra-226, P0-210, Pb-210 and Th-230 at 9 Bq/g. To reduce the activity concentration to 0.5 Bq/g, the original activity concentration (9.0 Bq/g) was divided by 18. This process was repeated for all the nuclides in the input list. (Run Rem1.5. 2015 on CD). In addition, a run was also performed for the background site for a 1-year-old (Run Rem1BGr. 2015 on CD). The activity concentrations used for the background site was typical to that which is expected in the Gauteng area. The results demonstrated that it was very difficult to reach the NSG values calculated in the previous section, since most of these values are below natural background values. The input results are tabulated in Table 7-13. It must, however, be emphasised that the results from each scenario is specific to that scenario.

Table 7-13: Source Term Remediated to 0.5 Bq/g

Nuclide	Original Input (Bq/g)	Original Input/18 (Bq/g)	Background (Bq/g)
Ac-227	4.00E-01	2.22E-02	1.81E-03
Pa-231	4.00E-01	2.22E-02	1.81E-03
Pb-210	9.00E+00	5.00E-01	5.90E-02
Po-210	9.00E+00	5.00E-01	5.90E-02
Ra-226	9.00E+00	5.00E-01	4.21E-02
Ra-228	6.00E-01	3.33E-02	2.47E-02
Th-228	6.00E-01	3.33E-02	2.30E-02
Th230	9.00E+00	5.00E-01	3.93E-02
Th-232	6.00E-01	3.33E-02	2.28E-02
U-234	1.00E+00	5.56E-02	3.96E-02
U-235	3.00E-02	1.67E-03	1.81E-03
U-238	1.00E+00	5.56E-02	3.93E-02

The RESRAD model was run with reduced activity concentration levels, as tabulated in Table 7-14. The results are compared with the results of the original pre-remediation activity concentrations. The modelled dose results are still much higher than the 1 mSv/a to 20 mSv/a remediation criteria. The results verified the "difficult to release" statement made in Section 7.7.3 to release a site from regulatory control after remediation when the subsistence farmer scenario is applied, because the NSGs are, in some cases, far below 0.5 Bq/g, which is the NNR exclusion criteria (South Africa, 2006).

Table 7-14: Comparison of Dose Assessments with Pre-Remediation Activities Concentrations and Activity Concentrations Reduced to 0.5 Bq/g

Action	Original Input	Remediation Factor 18 Applied	Background
Dose at time t=0 (mSv/a)	3.86E+02	2.14E+01	2.554E+00
D-Max (mSv/a)	8.01E+03	4.46E+02	3.731E+01
Time where dose is maximum (a)	913	913	897
Exposure time t (a)	50	50	50

7.7.6 Other options to reduce dose

The surprising results revealed by the modelling in Section 7.7.4 will dictate an in-depth investigation into the exclusion requirements of 0.5 Bq/g currently applied in South Africa. If these results were obtained from the specific scenario, it might be applicable to other instances as well. It is recognised that the results of the analysis are scenario specific. Clearance and exemption levels are discussed in ICRP 103 and ICRP 104 (ICRP, 2007a and 2007b). It is the general consensus that NORM waste and exposures from NORM should be treated differently from artificial nuclides (Hunter, 2013). In the case of the world renowned German Wismut sites, the site was released for restricted use (Lersow, 2006). Therefore, there are other options to be explored in the meantime. The results from analyses of this scenario, which can be seen as a screening assessment, allow for the options to demonstrate the application of the assessment methodology (see Figure 6-1) when the initial screening does not demonstrate compliance with the remediation criteria. These include the following:

- Reviewing the farmer input data and apply a more realistic scenario; and/or
- Define and apply different land-use scenarios.

7.7.7 Review the farmer scenario

The current farmer scenario is based on a person living on the previously contaminated tailings dam. The main dose contribution is from eating fish from the run-off water and drinking water. Keeping the remediated activity concentration values, the farmer scenario was remodelled, removing the consumption of fish and water drinking pathways and using the source term down-scaled from the original input values to the highest activity concentration being 0.5 Bq/g, as shown in Table 7-15.

Table 7-15: Reduced Source Term to 0.5 Bq/g

Nuclide	Activity Concentration
Pa-231	2.20E-02
Pb-210	5.00E-01
Po-210	5.00E-01
Ra-226	5.00E-01
Ra-228	3.30E-02
Th-228	3.30E-02
Th-230	5.00E-01
Th-232	3.30E-02
U-234	5.56E-02
U-235	1.67E-03
U-238	5.50E-03

Table 7-16: Total Dose after Remediation, No Fish, No Drinking of Water

Time (a)	0.00E+00	3.00E+01	3.00E+02		1.00E+03
Total Dose (mSv/a)	1.31E+01	1.32E+01	1.27E+01		1.10E+01

The results in Table 7-16 revealed that after removal of the ingestion of the water pathway and the removal of the consumption of aquatic foods, or fish, the site is ready for release from regulatory control for restricted use (see Figure 6-2). However, the site deed will have to be amended to permanently prohibit certain excluded activities from being performed on this land.

7.7.8 Modelling the residential scenario

In Chapter 6, it was suggested that different scenarios should be considered for the release of sites after remediation. The source term used in Section 7.7.6 was used and the resident scenario, from Chapter 6 was used as input to the model as follows:

- External gamma from the soil and water;
- Inhalation of dust;
- Ingestion of some fruit and vegetables produced on the land; and
- Ingestion of the soil.

Table 7-17: Modelling Results for a Residential Scenario after Remediation

Time (a)	0	10	30	300	1 000
Dose (mSv/a)	3.267E+00	3.420E+00	3.506E+00	4.280E+00	4.355E+00

The dose at time t=0 is 3.267 mSv/a, Table 7-17. The maximum dose or peak dose of 4.496 mSv/a will be reached at 624 years. The site can then be released in terms of the proposed new remediation release criteria of between 1 and 20 mSv/a (NNR, 2015), which applies to the immediate and peak dose as modelled.

7.7.9 Modelling the industrial scenario

In the industrial exposure scenario (see Chapter 6), the following exposure pathways will be considered:

- External gamma from the soil, with a surface covering it; and
- Inhalation from dust.

Table 7-18: Modelling Results for an Industrial Scenario after Remediation

Time (a)	0	10	30	300	1 000
Dose (mSv/a)	9.715E-01	9.706E-01	9.290E-01	5.545E-01	2.704E-01

The immediate dose of 0.915 mSv/a and the peak dose of 0.927 mSv/a were reached at t=0.1 378 years. According to this scenario, the site can be released in terms of the proposed new 1 – 20 mSv/a criteria (NNR, 2015).

7.8 Sensitivity Analysis

A sensitivity analysis was performed to build confidence in the results from the analysis performed (NNR, 2014a), on the consumption of fruit, vegetables and grain consumption pathway only, to demonstrate the principle. The analysis was performed after the ingestion pathways of aquatic foods and drinking water were removed. The response to the variation in consumption, 1.5 times above and 1.5 times below the value used in the assessment, was used. Results as per Figures 7-4 to 7-8.

In Figure 7-4 where the ingestion dose is plotted for fruit, vegetables and grain consumption, the dose values follow almost a straight line (with a slight negative slope). When the consumption rate is reduced, the line remains almost parallel to the original line. Therefore, reducing intake will almost produce linear dose reduction results.

Increasing the consumption, Figure 7-4, on the other hand, shows that food consumed from the same land, would in 200 - 300 years from now, result in a higher dose per portion at the higher consumption ratio. This is due to the movement of nuclides in the soil as a result of ground water movement. Peak dose is modelled between 200 and 300 years at around 16 mSv/a. Therefore, the dose is more sensitive at higher consumption rates over time. Lower consumptions do not seem to affect the accrued dose.

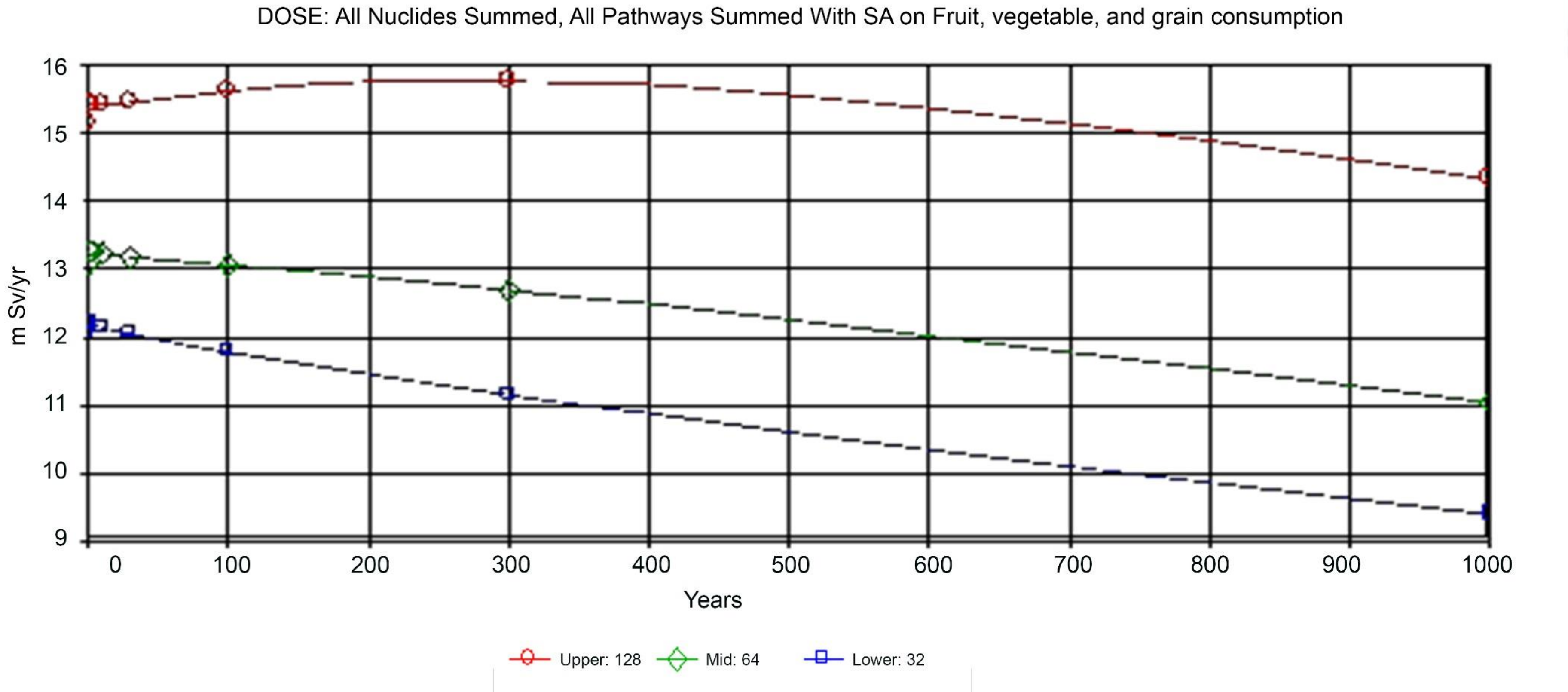

Figure 7-4: Sensitivity Analysis on Fruit, Vegetables and Grain Consumption: All Nuclides

Ra-226 is the radionuclide that has the largest influence on the dose, because it has the highest dose to source ratio. Other factors that may have an influence is that it has a specific activity of 3.7E10 Bq/g and a half-life of 1 600 years. It is an alpha emitter. The dose conversion factor is 2.24E-07 Sv/Bq (NUREG, 2006). It is interesting to see that with higher consumption rates; the peak dose moves further into the future. For 1.5 times the consumption rate, the peak dose will be received after 100 years. For lower consumptions, the peak dose will move to 60 or 70 years.

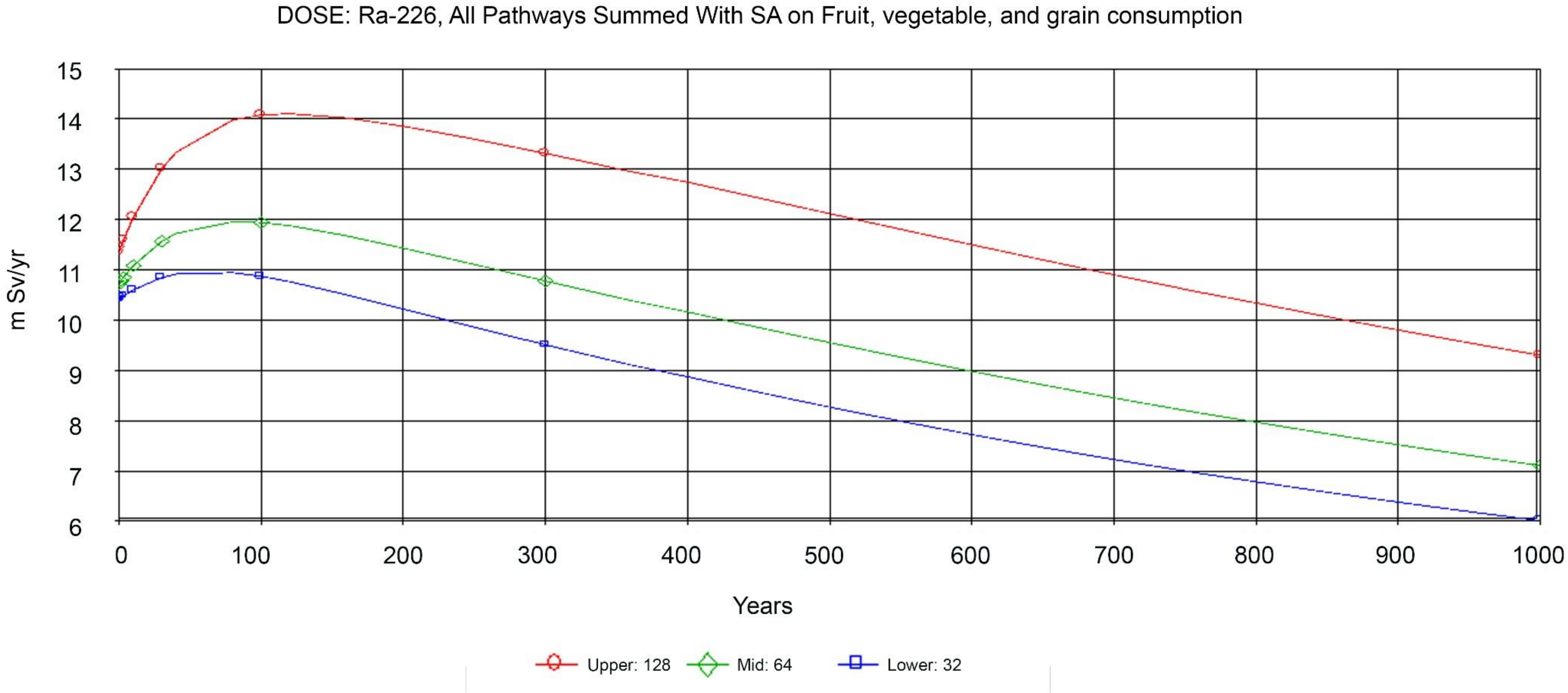

Figure 7-5: Ra-226 Consumption Rate Influence

Pa-231, U-235 and U-238 have long half-lives of 3.28E4, 7.04E8 and 4.47E9 years respectively. The peak dose remains at more or less the same time in the future. There is a constant decrease in the dose from the consumption of food over a period of time. The dose decreases gradually over time. There is a change in pattern at around 750 years, where there is a sharp decrease in the dose. This is due to the distance of the contamination zone parallel to the aquafer. If the parallel distance is shortened from 100 m to 10 m, the change in slope moves from 750 years to 200 years. Therefore, it is linked to the water dependent pathway.

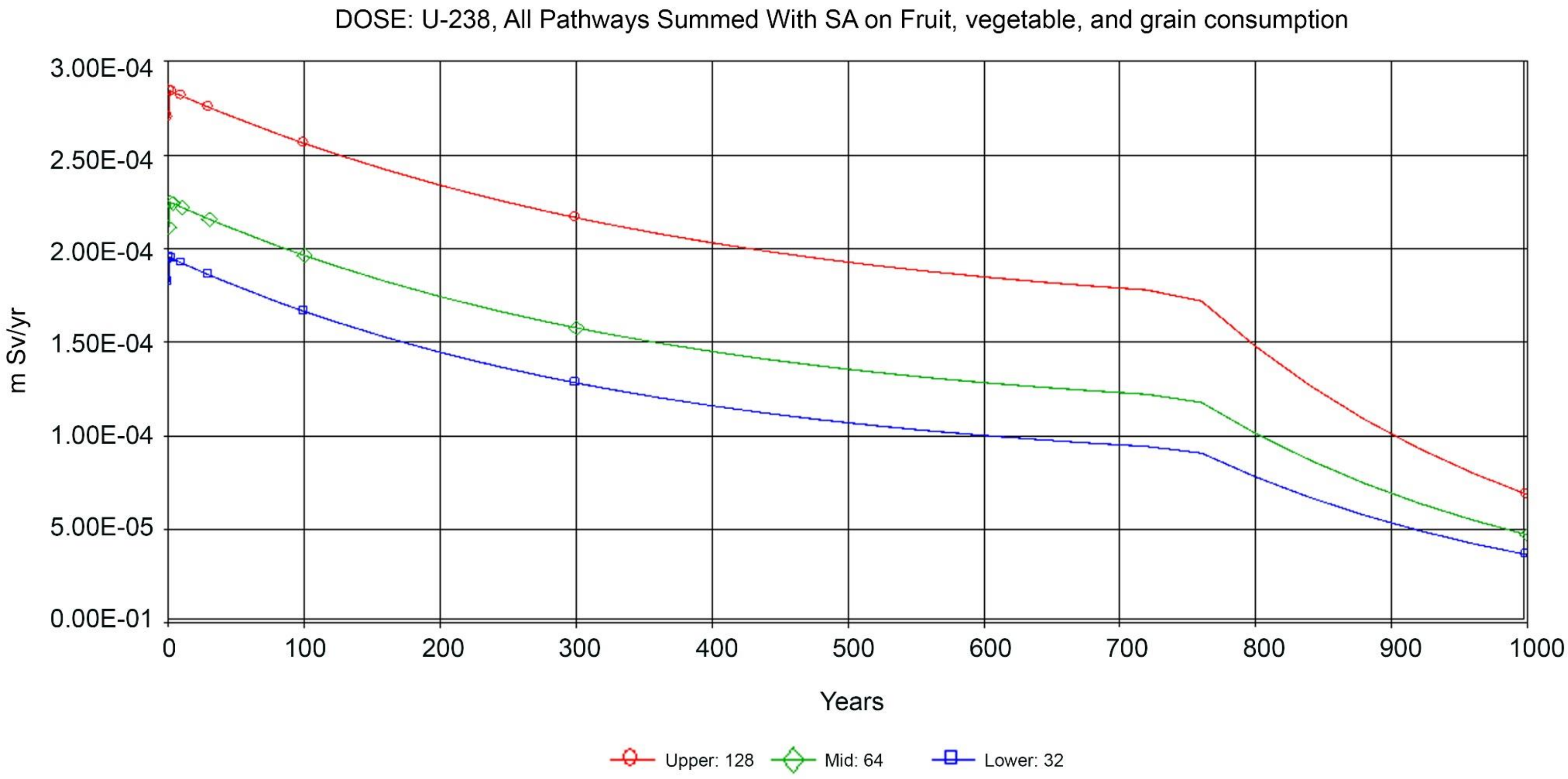

Figure 7-6: U-238 Sensitivity Analysis

Another interesting phenomenon is that shown in Figure 7-7 for Th-230. Th-230 has a half-life of 7.70E+04 years. It is clear from Figure 7-7 that after 1 000 years, Th-230 has not reached its peak dose yet. As consumption increases, the dose increases over time as the nuclide grows into equilibrium with the parent, U-238.

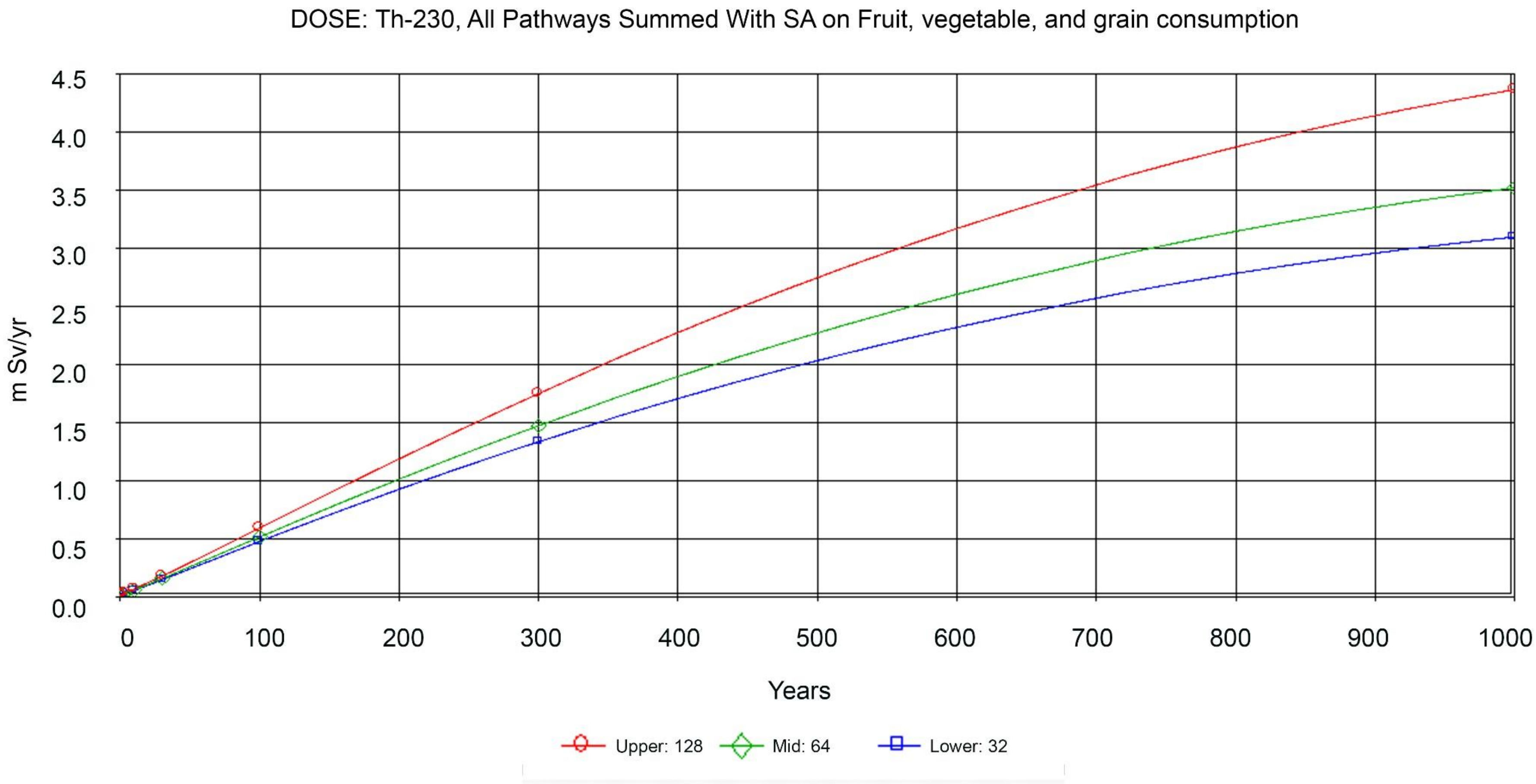

Figure 7-7: Sensitivity of Th-230

Although Ac-227, in Figure 7-8, has a lesser contribution to the dose, the sensitivity analysis revealed an interesting combination of some of the other nuclides. The half-life is 6.13 h. No activity concentration was specified initially. There is ingrowth of Ac-227 up to about 100 years, where the peak dose can also be seen. At peak dose, higher consumption rates have a larger effect on the dose. The dose effect difference deceases with time. The same drop in the dose is seen around 700 years, similar but a bit earlier than with U-238.

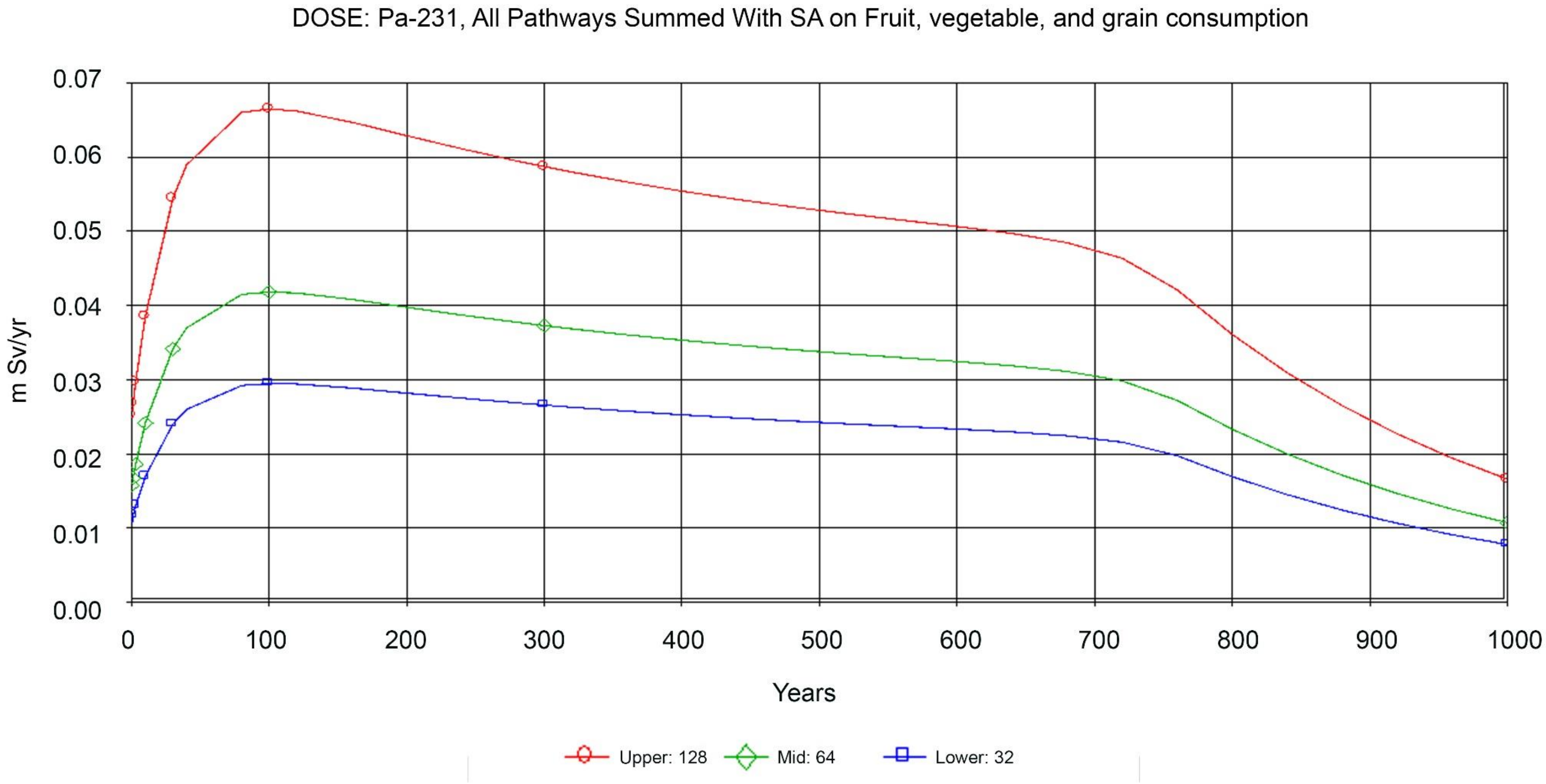

Figure 7-8: Sensitivity of Ac-227

In summary, the sensitivity of the dose to the consumption of food seems to be directly proportional to the intake. Graphical dose patterns are characterised by the half-life of the nuclide.

7.9 Uncertainty analysis

In RESRAD, the uncertainty and probabilistic analysis can be used to study a variation in the prediction and the importance of each individual parameter when a number of parameters are varied simultaneously over their likely range. An uncertainty analysis can be performed on almost all the input parameters in the RESRAD code. In this study, uncertainty analysis was performed to demonstrate the methodology. An uncertainty analysis was therefore only performed on the consumption of fruit, vegetables and grain, which was the pathway contributing the most to the dose (RESRAD, 2007).

The sampling technique applied was LHS. In the LHS technique, the distribution is divided into equally probable segments, equal in number to the desired number of observations. A value is then picked at random from each segment according to the probability density function within that segment. This ensures that the sample covers the entire range of the distribution, even when the number of samples is relatively small. After the code obtains the required number of samples for each input parameter, it produces the probabilistic set of inputs. The input parameter was the consumption of fruit, vegetables and grain at a rate of 64 kg/a. There were 500 observations performed per input parameter. The values chosen by the code was a minimum of 135 kg/a; an average of 178 kg/a and maximum of 318 kg/a.

The results are tabulated in Table 7-20 and in Table 7-19. In Table 7-19, the minimum, maximum and average times and doses for the sum of all the nuclides from Table 7-20 were extracted into Column 2. Column 4 contains the Time-Average and Dose-Average ratio. At the maximum probable values for the dose, the D-Avg ratio is 1.24, where-as at the maximum time of peak dose, the T-Avg ratio is smaller at 1.18. Therefore, the uncertainty ratio for the dose is larger than for time, which could be interpreted that the probability for over estimating a dose increases over time. The T-Avg ratio for the probable minimum peak time is 0.668, where-as the D-Avg ratio at the minimum probable peak dose is 0.814. This point to larger uncertainties with regard to the dose at the bottom end of uncertainty.

The 5th column of Table 7-19 represents the Time-Std ratio and the Dose-Std ratios. At the time where the probability for peak dose is at its minimum, the Time-Std ratio, 0.122, compares well with the Dose-Std ratio of 0.121.

In Table 7-19, the 6th column, the Minimum-Maximum ratio in time, 0.566, and in dose, 0.659 are given. These ratios are both high, which indicate large uncertainties with regard to the probabilities of predicting peak dose and the time of peak dose. From this ratio, it seems as though the time predictions of peak dose are more uncertain than the predictions of the peak dose itself.

Table 7-19: Uncertainty of Peak Dose of All Nuclides Ratios

Time	t=max	Std	T-Avg Ratio	Std Ratio	Min-Max Ratio
Min	2.76E+02	3.38E+01	6.68E-01	1.22E-01	5.66E-01
Max	4.88E+02	3.38E+01	1.18E+00	6.93E-02	
Avg	4.13E+02	3.38E+01		8.18E-02	
Peak Dose	**D=max**	**Std**	**D-Avg ratio**	**Std ratio**	
Min	1.62E+01	1.96E+00	8.14E-01	1.21E-01	6.59E-01
Max	2.46E+01	1.96E+00	1.24E+00	7.97E-02	
Avg	1.99E+01	1.96E+00		9.85E-02	

Table 7-20: Uncertainty of Peak Dose per Nuclide

Nuclide (j)	Peak Time	Peak Dose	t= 0.00E+00	mSv/a 3.00E+01	3.00E+02	1.00E+03
Ac-227						
Min	1.18E-01	5.32E-02	5.09E-02	1.99E-02	3.07E-06	1.39E-18
Max	3.46E-01	1.04E-01	9.83E-02	3.84E-02	6.00E-06	2.71E-18
Avg	3.05E-01	7.53E-02	7.17E-02	2.80E-02	4.36E-06	1.97E-18
Std	6.82E-02	1.23E-02	1.11E-02	4.32E-03	6.83E-07	3.08E-19
Pa-231						
Min	9.87E+01	7.01E-02	2.65E-02	5.74E-02	6.18E-02	1.75E-02
Max	1.00E+02	1.34E-01	5.10E-02	1.10E-01	1.18E-01	3.28E-02
Avg	9.93E+01	9.82E-02	3.73E-02	8.05E-02	8.63E-02	2.42E-02
Std	3.04E-01	1.50E-02	5.70E-03	1.23E-02	1.30E-02	3.57E-03
Pb-210						
Min	1.13E+00	3.34E+00	2.85E+00	1.63E+00	7.39E-04	3.78E-13
Max	1.29E+00	6.41E+00	5.64E+00	3.02E+00	1.25E-03	6.19E-13
Avg	1.20E+00	4.68E+00	4.07E+00	2.24E+00	9.65E-04	4.84E-13
Std	3.61E-02	7.17E-01	6.50E-01	3.26E-01	1.20E-04	5.61E-14
Po-210						
Min	0.00E+00	3.44E-01	3.44E-01	2.65E-24	0.00E+00	0.00E+00
Max	0.00E+00	5.24E-01	5.24E-01	4.07E-24	0.00E+00	0.00E+00
Avg	0.00E+00	4.23E-01	4.23E-01	3.27E-24	0.00E+00	0.00E+00
Std	0.00E+00	4.19E-02	4.19E-02	3.31E-25	0.00E+00	0.00E+00

Ra-226						
Min	1.22E+02	1.44E+01	1.14E+01	1.32E+01	1.37E+01	9.62E+00
Max	2.00E+02	2.05E+01	1.31E+01	1.70E+01	2.03E+01	1.53E+01
Avg	1.56E+02	1.71E+01	1.22E+01	1.49E+01	1.66E+01	1.21E+01
Std	1.79E+01	1.42E+00	3.82E-01	8.75E-01	1.54E+00	1.33E+00
Ra-228						
Min	0.00E+00	5.83E-01	5.83E-01	1.71E-02	6.97E-17	0.00E+00
Max	0.00E+00	1.17E+00	1.17E+00	3.22E-02	1.31E-16	0.00E+00
Avg	0.00E+00	8.42E-01	8.42E-01	2.37E-02	9.65E-17	0.00E+00
Std	0.00E+00	1.38E-01	1.38E-01	3.53E-03	1.42E-17	0.00E+00
Th-228						
Min	0.00E+00	6.97E-02	6.97E-02	1.21E-06	0.00E+00	0.00E+00
Max	0.00E+00	8.55E-02	8.55E-02	1.34E-06	0.00E+00	0.00E+00
Avg	0.00E+00	7.66E-02	7.66E-02	1.27E-06	0.00E+00	0.00E+00
Std	0.00E+00	3.67E-03	3.67E-03	3.20E-08	0.00E+00	0.00E+00
Th-230						
Min	1.00E+03	4.49E+00	2.21E-02	1.84E-01	1.79E+00	4.49E+00
Max	1.00E+03	6.68E+00	3.96E-02	2.38E-01	2.51E+00	6.68E+00
Avg	1.00E+03	5.45E+00	2.98E-02	2.07E-01	2.10E+00	5.45E+00
Std	0.00E+00	5.12E-01	4.07E-03	1.26E-02	1.67E-01	5.12E-01
Th-232						
Min	8.50E+01	6.68E-01	3.46E-02	6.52E-01	6.68E-01	6.66E-01
Max	8.70E+01	1.29E+00	6.98E-02	1.26E+00	1.29E+00	1.29E+00
Avg	8.60E+01	9.42E-01	5.00E-02	9.18E-01	9.41E-01	9.39E-01
Std	4.16E-01	1.45E-01	8.21E-03	1.42E-01	1.45E-01	1.45E-01
U-234						
Min	7.53E+02	3.34E-03	1.56E-03	1.60E-03	2.04E-03	3.15E-03
Max	7.54E+02	5.63E-03	3.06E-03	3.12E-03	3.69E-03	5.09E-03
Avg	7.54E+02	4.34E-03	2.22E-03	2.27E-03	2.77E-03	4.00E-03
Std	2.02E-01	5.34E-04	3.51E-04	3.54E-04	3.83E-04	4.52E-04
U-235						
Min	0.00E+00	2.52E-04	2.52E-04	2.36E-04	1.58E-04	5.57E-05
Max	0.00E+00	2.98E-04	2.98E-04	2.85E-04	2.30E-04	9.71E-05
Avg	0.00E+00	2.72E-04	2.72E-04	2.58E-04	1.90E-04	7.39E-05
Std	0.00E+00	1.07E-05	1.07E-05	1.13E-05	1.68E-05	9.64E-06
U-238						
Min	5.82E-01	2.93E-04	2.78E-04	2.84E-04	2.25E-04	7.17E-05
Max	6.02E-01	4.47E-04	4.31E-04	4.39E-04	3.78E-04	1.27E-04
Avg	5.91E-01	3.61E-04	3.45E-04	3.52E-04	2.92E-04	9.62E-05
Std	3.96E-03	3.60E-05	3.56E-05	3.62E-05	3.57E-05	1.30E-05
ΣALL						
Min	2.76E+02	1.62E+01	1.54E+01	1.58E+01	1.62E+01	1.48E+01
Max	4.88E+02	2.46E+01	2.08E+01	2.17E+01	2.42E+01	2.33E+01
Avg	4.13E+02	1.99E+01	1.78E+01	1.84E+01	1.97E+01	1.85E+01
Std	3.38E+01	1.96E+00	1.24E+00	1.38E+00	1.86E+00	1.99E+00
ΣALL is total dose summed for all nuclides						

7.10 Conclusions

The following conclusions can be derived from the content of Chapter 7:

- The study revealed (as in Table 7-4) that the 1-year age group is the most sensitive to the dose from sites that require remediation. The 1-year-old therefore is regarded as the reference person. The dose to the reference person is used in decision making.
- In Table 7-5 it was shown that a site with background nuclide concentration, some even below regulatory exclusion levels after a screening analysis, will be difficult to be released from regulatory control under the full residential farmer occupancy scenario. Therefore, if such a scenario might develop, the flow diagram in Figure 6-1 indicates alternative options to be followed. Several options were shown in this chapter.
- It was shown in Figure 7-2 that Ra-226 is the biggest contributor towards the dose, from this scenario. Ra-226 is also the nuclide that places the biggest restriction on the possible release of sites from regulatory control. The model has the ability to single out a specific nuclide, which allows a selection of more remediation options as was indicated in Chapter 6.
- The water dependent pathway is the most restrictive pathway in terms of a dose and the peak dose was reached after 913 years, according to results in Table 7-7. Release to water pathways should therefore be carefully managed, taking cognisance of the remediation technologies discussed in Chapter 6.
- The importance of the derivation of NSGs was demonstrated in Section 7.7.4. The use of NSGs is very important as derived from remediation release criteria.
- The use of NSGs emphasises the importance of detailed, nuclide specific sampling and analysis after completion of remediation for the demonstration of compliance with remediation criteria.
- It was shown in Sections 7.7.7 and 7.7.8, that future restricted land-use may be required to release sites from regulatory control after remediation.
- Sensitivity analysis in Section 7.8 was limited to the consumption of vegetables and grain. It can be concluded that for larger ingestion rates, there may be a slightly higher than proportional sensitivity in the dose.
- There are large uncertainties in terms of the modelling probability of the time of peak dose and the peak dose itself, because of the many variables in the modelling parameters, as is evident from Table 7-19.
  - Many safety people would say “it is better to err towards safety”. This approach is very costly in SA. Therefore, when screening shows non-compliance, the follow-up detailed

assessments should use realistic data as the consequences (for especially land release) might be dire in terms of loss of land for agriculture etc.

- It can be concluded that the safety assessment developed in Chapter 6 and applied in Chapter 7 can effectively be implemented as an analysis tool for the assessment of sites that needs to be remediated.

CHAPTER 8 GUIDE FOR REGULATORS FOR REVIEW OF SAFETY ASSESSMENTS

Chapter 8 contains a guide to be used in the review of public safety assessments by the National Nuclear Regulator. This guide is based on the NNR requirements and safety criteria for the authorisation of NORM facilities to operate within the legislative regime (NNR, 2014a; 2014b; 2015) and a summary of the work in the previous chapters. The review guide will provide staff of the NNR clear guidance on how to review and assess the adequacy of a safety assessment submitted, to obtain an authorisation to operate. The applicability of the review guide is demonstrated, using the assessments conducted in previous chapters as case studies.

8.1 Purpose and Scope

The purpose of this chapter is to provide the employees of the NNR with a guide to perform reviews on public radiological assessments submitted by the holders of nuclear authorisations. The guide is provided in the form of a checklist. The scope of the review guide is limited to activities performed with Natural Occurring Radioactive Material (NORM). The guide is based on the information contained in Chapters 4 - 7 of this study. The guidance developed here can be applied to both radiological public safety assessments at mining sites and to sites to be remediated.

The safety assessment was divided into several sections or areas of review. For each area of review, a scope will be defined and an acceptance criteria provided (NNR, 2014a, 2014b, 2015). The areas of review are as follow:

- Site description;
- Assessment context;
- Source term development;
- Receptor definition;
- Exposure scenarios;
- Models;
- Dose assessment;
- Uncertainty analysis;
- Sensitivity Analysis;
- Results; and Conclusions.

When reviewing the submission from the holder the following generic aspects should be kept in mind, as indicated in Table 8-1.

Table 8-1: Generic Aspects to be Considered

Point of Interest	Comment
The safety assessment and the supporting documents must adequately address the site/facility/plant/mine under review	
Statements made, must be suitably justified, traceable and clear	
Supporting documentation must be referenced/available on request	
Site and environmental studies will usually be performed as specialist studies	
Sufficient data and information must be provided so that the calculations can be verified independently	

8.2 Site Description

The site description and process description is a two-step process. The site description should provide an overview of the physical location of the site and its surroundings. The process description should identify all the potential sources that could result in releases to the environment from normal operating conditions (see Tables 8-2 and 8-3).

8.2.1 Site location and surroundings

Table 8-2: Site Location and Surrounds to be Considered

Item	Comment
Does the submission adequately describe the site in terms of site location? • The distance from the closest towns or cities • The province • The latitude and longitude of the site • A map of the geographical location	
Is there specialist studies or detailed information included on the following: • The description and quantification of the surface run-off water • The geological and hydrological factors, as well as topography • The general climate description including seasonal variations • The biota presents in the area	

• A baseline radiological environmental characterisation. (The historical information on radionuclide contamination levels in the environment e.g. past water surveys, sedimentation surveys, activity concentration in soil and foodstuffs, etc.) • The radionuclide data from exploration sampling (e.g. ppm U and Th of ore body) • Input from operational experience and site inspections • Experiences from other sites locally and internationally • Information from Governmental and other Institutions, such as the Department of Water Affairs (DWA), Council for Geoscience (CGS), Department of Agriculture Forestry and Fisheries (DAFF), etc., including studies on site water balance and sampling programmes of non-radioactive materials • Studies identifying known points of chemical pollution e.g. identification of ground water plumes and sampling points • Identification of water uses and users e.g. municipalities, gardening, irrigation, farmers, use of mine water for drinking purposes, use of mine water for on-site irrigation, export to other users • Information on agricultural use of land, soil types, agricultural activities and information such as what type and quantity of food is produced, where the food is being distributed for consumption, etc. • Information on the type of settlements, such as informal settlements, housing types, etc. • Demography, including information on the population such as ages, gender, eating habits, sources of food, etc.	

8.2.2 Process description

Table 8-3: Process Description Considerations

Item	Comment
Is the following adequately described and included: • The nature of the business; • A site plan with a broad process flow diagram; • An identification and quantification of all potential and significant sources of radionuclides on-site; • A detailed process description of the areas where radionuclides are present; • A detailed description of radionuclide migration on-site and off-site;	

8.3 Assessment Context

In the assessment context the purpose and scope of the analysis/submission is defined. References are made to the applicable legislation and standards which will determine the interpretation of the results of the study in Table 8-4.

Table 8-4: Assessment Context Considerations

Item	Comment
References for acceptance criteria (NNR criteria overrides all other criteria. International references may be used in the absence of NNR criteria): • Was the NNR Act and regulations used as assessment criteria? • Were any other acceptance criteria used in the assessment? • Was the use of any other criteria properly justified?	

The acceptance criteria in Table 8-5 should be applied as public radiological dose assessments criteria.

Table 8-5: Public Safety Assessment Dose Criteria

Screening	Screening Result (μSv/a)	Screening Action	Assessment Outcome
Assumed, conservative input data, sampling and analysis data (optional where applicable)	< 10	No further dose assessment required	Limited release monitoring, environmental monitoring and QA programme
	10 - 100	No further dose assessment required	Appropriate release monitoring, environmental monitoring and QA programme
	100 - 250	No further dose assessment required	Detailed release monitoring, environmental monitoring and QA programme
	> 250	Further assessment required using site specific data, detailed models and data	Plant modification, engineering back fitting and repeat assessment

The remediation action related to the dose assessment criteria, as a guideline is included in Table 8-6.

Table 8-6: Remediation Action Table

Dose (µSv/a)	Action
< 250	Acceptable
250 – 1 000	Apply optimisation; public information
1 000 – 5 000	Apply optimisation; repeated annual public information sessions; demarcation of areas of primary concern; consider cost effective remediation solutions
5 000 – 20 000	Apply optimisation; repeated annual public information sessions; demarcation of areas of concern; remediation of areas of primary concern; consider the substitution of affected food and water from contaminated area; restrictions on land-use as appropriate
> 20 000	Consider temporary or permanent relocation of occupants; remediate; public information sessions; demarcate all areas of concern; restrict use of contaminated zones.

The Remediation dose criteria for the prioritisation of sites purely on the basis of the dose, is given in Table 8-7. The order of priority decreases from A, alphabetically downwards to D. Sites C and D may be considered for release without active remediation.

Table 8-7: Remediation Prioritisation Criteria

Annual effective dose	Site Categorization
➢ 20 mSv/a	A
5 – 20 mSv/a	B
1 – 5 mSv/a	C
250 µSv/a – 1 mSv/a	D

8.4 Source Term Development

The mode of release, chemical and physical characteristics, as well as the quantities of the radionuclides released, should be determined with the objective of computing the highest annual average dose to the representative person or groups during the operation of the facility or subsequent to closure thereof. Separate source terms should be developed for the airborne, surface run-off and aquatic pathways (see Table 8-8).

Table 8-8: Source Term for Radiological Public Safety Assessment Considerations

Item	Comment
Were the following process steps included? • Identification of on-site processes that contains radionuclides; • Identify the specific nuclides available for dispersion – the whole range and the abundance (ppm or Bq/g); • Identify the whole range of progeny; • Physical and chemical properties of the radionuclides released; • Particle size distribution and activity (AMAD); • Quantify the amount of radionuclides available for dispersion (leach rates, release rates and frequencies, etc.); • Identification of the potential dispersion pathway (atmosphere, surface run-off, ground water).	

8.5 Receptor Definition

The receptor or the representative person is an individual member of the public who is reasonably homogeneous with respect to its exposure to a given radiation source and given exposure pathway. It is typical of individuals receiving the highest effective dose (whole body dose) or equivalent dose (organ dose), as applicable, by the given exposure pathway from the given source. In order to determine the dose to the public, the representative person should be defined and information such as radiation sources, the exposure pathways and the habitat of the individuals in the area around the facility should be provided. The following are guidelines or default values. Deviations from these values should be justified.

8.5.1 Consumption rates

Generic consumption rates from Table 8-9 should be used in screening dose calculations. The consumption rates in Table 8-9 have been derived from the South African data contained in the Database of the Food and Agriculture Organisation of the United Nations, Food balance sheets (NNR, 2014a). If any other consumption rates are used, a justification is required. The age groups specified in Table 8-9 should be considered in the safety assessments.

Table 8-9: Default Annual Consumption Factors

Category	Adults	15 Year Old	10 Year Old	5 Year Old	1 Year Old
% of Adult	100	85	60	50	40
Water (L/a)	600	510	360	300	240
Soil (kg/a)	0.037	0.03145	0.0222	0.0185	0.0148
Fresh water fish (kg/a)	25	21.25	15	12.5	10
Milk (L/a)	120	102	72	60	48
Beef (kg/a)	30	25.5	18	15	12
Mutton (kg/a)	25	21.25	15	12.5	10
Pork (kg/a)	20	17	12	10	8
Poultry (kg/a)	50	42.5	30	25	20
Eggs (kg/a)	15	12.75	9	7.5	6
Grain (kg/a)	250	212.5	150	125	100

8.5.2. Land use

Land use data should be assessed to determine which activities could contribute to the radiation dose and to determine the extent of the respective contributions. The information in Table 8-10 should typically be included in the safety assessment.

Table 8-10: Land Use Considerations

Item	Comment
The following aspects should be detailed: • The land devoted to agricultural use, its extent, the crops and their yields; • The land devoted to dairy farming, its extent and yields; • The land devoted to industrial, institutional and recreational purposes, its extent and the characteristics of its use; • The bodies of water used for commercial, individual and recreational fishing, including details of the aquatic species fished, their abundance and yield; • The bodies of water used for commercial purposes, including navigation; community water supply, irrigation and recreational purposes, such as bathing and sailing; • The land and bodies of water supporting wildlife and livestock; • The direct and indirect pathways for potential radioactive contamination of the food-chain; • The products imported to or exported from the region which may form part of the food-chain; • The free foods such as mushrooms, berries and seaweed.	

8.5.3 Habitation study

A habitation study should be performed to provide data on the habits of the representative person in order to calculate a representative dose due to exposure to radionuclides while in the area of concern (see Table 8-11).

Table 8-11: Habitation study considerations

Item	Comment
The following type of data should be provided in the safety assessment: • The quantities of foodstuffs, cultivated in the area, consumed; • The quantities of livestock or produce from livestock, raised in the area, and consumed; • The quantities of fish consumed from water bodies in the area of concern; • The quantities of water, from a contaminated source, consumed; • The time spent in the area of concern (indoors and outdoors) and time spent elsewhere; and • The time spent in recreational activities, such as a dam or golf course, or whatever is situated in the area of concern.	

8.6 Exposure Scenarios

Radiation exposures of the public from NORM activities may arise from the product(s) of on-site processes, from the atmospheric or liquid discharges or from surface run-off, from the re-use of by-product material(s) or from the disposal of solid waste(s). The most important routes of radiation exposure of the public are usually external gamma radiation, inhalation and ingestion. Exposure scenarios for the radiological safety assessment of the public and for remediation would be similar (refer to Table 8-12).

Table 8-12: Exposure Scenario Considerations

Item	Comment
In defining the scenario, the following pathways should have been considered: • Exposure from internal (inhalation and ingestion) or external sources of radiation; • External radiation from contaminated soil; • Inhalation of contaminated dust; • Inhalation of Radon and short lived progeny; • Ingestion of water, food and soil.	

8.6.1 Rural resident farmer scenario

The primary case would be a self-sufficient resident farmer-survivalist (NNR, 2015) who produces all the food to meet his dietary needs in the affected area. All exposure pathways identified in Table 8-13 would be active.

Table 8-13: Rural Resident Farmer Scenario

Exposure Pathway	Where Contamination is			
	Dwelling	Agricultural Land & Pasture	Surface Water Body	Borehole
External gamma from accumulation in soil or water	Y	Y	N	NA
Inhalation of dust blown in from primary contamination	Y	Y	N	NA
Inhalation of radon from primary contamination	N	N	N	NA
Inhalation of radon from water used at home	NA	NA	N	N
Ingestion of vegetables, fruit and grain	NA	Y	NA	NA
Ingestion of meat	NA	Y	NA	NA
Ingestion of milk	NA	Y	NA	NA
Ingestion of aquatic food	NA	NA	Y	NA
Ingestion of soil	Y	Y	NA	NA
Ingestion of water	NA	NA	Y	Y

NA = not applicable; Y = Yes; N = No

8.6.2 Urban resident scenario

It is likely that the meat, milk, and aquatic food pathways would be inactive and that input appropriate for the location of the affected area would be used to model the urban resident scenario.

Table 8-14: Urban Resident Scenario

Exposure Pathway	Where Contamination is			
	Dwelling	Agricultural Land & Pasture	Surface Water Body	Borehole
External gamma from accumulation in soil or water	Y	NA	N	NA
Inhalation of dust blown in from primary contamination	Y	NA	N	NA
Inhalation of radon from primary contamination	N	NA	N	NA
Inhalation of radon from water used at home	NA	NA	N	N
Ingestion of vegetables, fruit, and grain	Maybe	NA	NA	NA
Ingestion of meat	NA	NA	NA	NA
Ingestion of milk	NA	NA	NA	NA
Ingestion of aquatic food	NA	NA	Maybe	NA
Ingestion of soil	Y	NA	NA	NA
Ingestion of water	NA	NA	Maybe	Maybe

8.7 Models

The radiological safety assessment process is an iterative process. The process begins with generic conservative inputs. If the assessment criteria are exceeded, some generic input data is replaced with site specific realistic data.

Table 8-15: Model Considerations

Aspect	Comment
Assessment types: • Screening assessment • Site specific assessment	
For atmospheric dispersion the following items are important: • The source terms of nuclides in gaseous and particulate releases via various actions (e.g. wind erosion, earth works, material handling, vehicle entrainment, stack releases) including possible upgrading of the nuclide concentrations in fine particles likely to become airborne; • The physical and chemical properties of substances released; • The elevation of the release; • The area and location of the release; • The release velocity; • The mass flow rate, buoyancy (temperature) when applicable; • The particle size distribution and activity (AMAD); • The meteorology and climatology associated with releases; • The dispersion of release, deposition and re-suspension at impact location.	
Liquid effluent dispersion: • The source term of nuclides released and their radiological, physical and chemical properties; • The releases into surface water bodies; • The releases into ground water i.e. leaching and seepage; • The migration of surface and ground water off the site towards the impact location as well as retardation and soil retention of nuclides; • The extraction of water via boreholes or surface water bodies; • The chemical and physical characteristics impacting on radionuclide transport processes; • The water body dynamics.	
Progeny and build up in the environment must be considered	
Peak dose must be calculated	
The time period of exposure considered must be extended up to peak dose	
The nuclides to be considered are tabled in Table 8-16	
Timespan of the assessment – up to peak dose	

8.7.1 Nuclides to be considered

Tables 8-16 to 8-18 contain the nuclides in the primary decay series. All the nuclides should be included in the safety assessment. Screening out of nuclides is not recommended, especially if the assessment is performed over a long period. There may be variations due to operational activities on the site. Variations should be substantiated with nuclide specific sample results. If radon can be associated with operational activities, e.g. tailing dams, should be added to the off-site dose and not be treated separately.

Table 8-16: Th-232: Series (NUREG, 2006)

Parent	Spec. Act Bq/kg	Half Life	Decay Mode	Branching Fraction	Daughter
Th-232	4.10E+06	1.40E+10 y	α	1.00E+00	Ra-228
Ra-228	1.00E+16	5.75 y	β -	1.00E+00	Ac-228
Ac-228	8.30E+19	6.13 h	β-	1.00E+00	Th-228
Th-228	3.00E+16	1.91 y	α	1.00E+00	Ra-224
Ra-224	5.90E+18	3.66 d	α	1.00E+00	Rn-220
Rn-220	3.40E+22	55.6 s	α	1.00E+00	Po-216
Po-216	1.30E+25	0.15 s	α	1.00E+00	Pb-212
Pb-212	5.20E+19	10.6 h	β -	1.00E+00	Bi-212
Bi-212	5.40E+20	60.5 m	β - α	6.40E-01	Po-212
Po-212	6.60E+30	0.30 us	α		
Tl-208	1.10E+22	3.07 m	β -		

Table 8-17: U-238: Series (NUREG, 2006)

Parent	Spec. Act (Bq/kg)	Half Life	Decay Mode	Branching Fraction	Daughter	Branching Fraction	Daughter
U-238	1.20E+07	4.47E+09 y	SF α	1.00E+00	Th-234		
Th-234	8.60E+17	24.1 d	b -	1.00E+00	Pa-234m	2.00E-03	Pa-234
Pa-234m	2.50E+22	1.17 m	b -IT	1.30E-03	Pa-234	1.00E+00	U-234
Pa-234	7.40E+19	6.70 h	b -	1.00E+00	U-234		
U-234	2.40E+11	2.44E+05 y	α	1.00E+00	Th-230		
Th-230	7.60E+11	7.70E+04 y	α	1.00E+00	Ra-226		
Ra-226	3.70E+13	1.60E+03 y	α	1.00E+00	Rn-222		
Rn-222	5.80E+18	3.82 d	α	1.00E+00	Po-218		
Po-218	1.10E+22	3.05 m	α b -	1.00E+00	Pb-214	2.00E-04	At-218
Pb-214	1.20E+21	26.8 m	b -	1.00E+00	Bi-214		
At-218	9.80E+23	2.00 s	α	1.00E+00	Bi-214		
Bi-214	1.70E+21	19.9 m	b -	1.00E+00	Po-214		
Po-214	1.20E+28	1.64E+02 μs	α	1.00E+00	Pb-210		
Pb-210	2.80E+15	22.3 y	b -	1.00E+00	Bi-210		
Bi-210	4.40E+18	5.01 d	b -	1.00E+00	Po-210		
Po-210	1.50E+17	1.38E+02 d	α				

Table 8-18: U-235 series (NUREG, 2006)

Parent	Spec. Act (Bq / kg)	Half Life	Decay Mode	Branching Fraction	Daughter	Branching Fraction	Daughter
U-235	8.00E+07	7.04E+08 y	α	1.00E+00	Th-231		
Th-231	2.00E+19	25.5 h	b -	1.00E+00	Pa-231		
Pa-231	1.70E+12	3.28E+04 y	α	1.00E+00	Ac-227		
Ac-227	2.70E+15	21.8 y	b - α	9.90E-01	Th-227	1.40E-02	Fr-223
Th-227	1.10E+18	18.7 d	α	1.00E+00	Ra-223		
Fr-223	1.40E+21	21.8 m	b -	1.00E+00	Ra-223		
Ra-223	1.90E+18	11.4 d	α	1.00E+00	Rn-219		
Rn-219	4.90E+23	3.96 s	α	1.00E+00	Po-215		
Po-215	1.10E+27	1.78E-03 s	α	1.00E+00	Pb-211		
Pb-211	9.10E+20	36.1 m	b -	1.00E+00	Bi-211		
Bi-211	1.60E+22	2.14 m	α b -	1.00E+00	Tl-207	2.80E-03	Po-211
Tl-207	6.90E+21	4.77 m	b -				

8.8 Dose Assessment Process

In the section on dose assessment, the source term, Representative Person (RP), exposure scenarios and models are brought together. This results in the modelling or calculation of the dose of the RP under specific conditions, with certain assumptions. The results are evaluated against the assessment criteria and a decision is made (NNR, 2014a).

Table 8-19: Dose Assessment Process Considerations

Aspect	Comment
The following input parameters should be used: • The ICRP, (ICRP, 2012), has published a set of dose coefficients for inhalation, ingestion and external exposures, for workers and for members of the public, for a range of age groups; • Age groups (at least) 1-year-old, 10-year-old and adult; • Particulate size public – 5 µm; • Transfer factors from IAEA (IAEA, 2010a); • Time scales – linked to peak dose.	
Manual methods of dose calculations: • Calculations must be reproducible; • Inputs must be referenced and traceable and available to NNR.	
Codes and Software: • Codes must be validated and verified in accordance with RD-016. (NNR, 2006).	
Quality Assurance: • The submission should comply with the requirements of RD-005. (NNR, 2002a).	
Sensitivity analysis: • A sensitivity analysis should be applied to aspects having a major influence on the dose results.	
Uncertainty Analysis: • Uncertainty analysis should be performed on aspects having a major effect on dose results.	

CHAPTER 9 SUMMARY AND CONCLUSIONS

9.1 Summary and Conclusions

The title of this study is Framework and Regulatory Guidance to Perform and Review Radiological Public Safety Assessments for Mining and Mine Remediation Activities. It is concerned with the radiological safety assessment on NORM activities within the legal framework provided to regulate these activities. It deals both with operating NORM activities and with legacy sites.

Chapter 2 provides an overview of the current national and international status on the methodologies and criteria applied in safety assessments related to NORM facilities and also the remediation of historical sites. The methodology developed and applied in this study follows a similar logical pattern and is suitable for South African conditions and fits into the South African legal framework.

Chapter 3 contains the regulatory framework for the regulation of planned and existing exposure situations in the NORM industry in South Africa. The NNR is responsible for the development of the regulatory framework. After developing the framework, it is proposed to the Minister on Energy, who, after processing it, endorses the regulations as legally binding.

The framework includes the regulatory framework required for the licensing, remediation, and de-licensing of these sites. The existing regulations are inadequate in terms of detail and content. Proposed new regulations, currently under development, were discussed. The proposed revised regulations explicitly include sections on existing exposure situations, which was previously lacking. The proposed new regulations are based on the latest IAEA trends as contained in the General Safety Requirement series being developed internationally. These regulations have been adopted for South African conditions.

Chapter 4 contains a new guideline assessment methodology for radiological public safety assessments for NORM facilities developed specific for South African conditions and in accordance with proposed new national regulations. This guideline takes into consideration new national and international developments in the field of radiation protection and safety assessment. Principles such as critical group have been replaced with a representative person. There is inconsistency in the industry in applying safety assessment methodologies. This work should provide more detailed guidance on how a safety assessment should be performed. The safety assessment methodology developed, also provides guidance on the scope of analysis required to demonstrate safety of the public.

Chapter 5 contains the practical application of the safety assessment methodology developed in Chapter 4 for a planned NORM facility. The methodology was applied, by using the RESRAD model for off-site safety assessments. Dispersion of radionuclides from an operating facility, such as a mine, was modelled. A tailings storage facility, a stock pile and a road were used as sources of radionuclides. The radionuclides were dispersed into the environment through atmospheric, surface run-off and ground water pathways. A rural farming situation was used to define the exposure situation. The modelling was performed for 1-year-old, 10-year-old and adult age groups. The 1-year-old group received the highest dose and was therefore used to define the representative person.

The methodology was applied successfully and demonstrated that releases to the environment from operating facilities will have to be controlled very carefully not to exceed regulatory dose constraints.

Chapter 6 contains a new guideline assessment methodology for radiological safety assessments for the remediation of NORM facilities developed specific for South African conditions and in accordance with proposed new national regulations. Remediation is an existing problem in South Africa, which is to be addressed as a matter of urgency. An assessment methodology, similar to the public radiological safety assessments was developed. The methodology applied to operational facilities commences with a source term from whence there is dispersion of radionuclides into the environment. For remediation, the source of contamination is already there. The quantification of the source term is reliant on a detailed radiological characterisation of the area. The representative person lives on the land and a residential rural farmer situation is used to determine exposure to a member of the public.

Remediation criteria, between 1 and 20 mSv/a was set as the acceptance criteria in this study. The existing South African regulations do not make provision for criteria for remediation. This new criteria, was developed as part of this study and included in newly developed framework documentation developed by the National Nuclear Regulator and also in the proposed new regulations.

Chapter 7 contains the application of the safety assessment methodology developed for remediation and the demonstration of compliance with de-licensing criteria as developed in

Chapter 6. Modelling was performed with the RESRAD on-site version 6.5. Typical activity concentration found in a tailings storage facility was used to characterise the contamination zone. A residential rural farming situation was modelled for age groups 1-year-old, 10-year-old and adult. The 1-year-old received the highest dose and was used as the representative person.

The study revealed amazing results. Doses were much higher than expected. Peak dose was reached at a point around 1 000 years in the future. Activity concentration ratios of the radionuclides present were pro rata scaled down to 0.5 Bq/g. The results of modelling demonstrated that even at these low levels, the 20 mSv/a acceptance criteria could easily be exceeded. The implementation of single nuclide soil guidelines was investigated, but that revealed activity concentrations below natural background for certain nuclides, which was unrealistic to achieve. In finding a solution to remediate to acceptably low levels, it was found that alternative exposure situations and restricted land use should be implemented.

Chapter 8 contains a guide to be used in the review public safety assessments by staff of the NNR. The content of this chapter must therefore be translated into a working internal document at the NNR on how to review and assess the adequacy of a radiological public safety assessment submitted by an operator to obtain an authorisation, in terms of the NNR Act, to operate a facility. In developing the guide, provision was made for it to be used for operational facilities, as well as for sites to be remediated.

9.2 Future work identified

9.2.1 It was identified in this study, when the remediation methodology was applied, that the release of legacy sites from regulatory control may require restrictions on future land use. The proposed new regulations do not address this aspect as yet. Sections on restricted release of land after remediation should be included.

9.2.2 Current and proposed new regulations do not make provision for the implementation of the required remedies to release land from regulatory control resulting in restricted land use. Before the proposed new regulations are adopted, amendments should be included to manage restricted future use of land released after remediation.

9.2.3 It was demonstrated in this study that it is sometimes impossible to release land that has been remediated at the 0.5 Bq/g exclusion levels, because the modelled doses may exceed 20 mSv/a. It would be worthwhile doing a detailed study on the application of remediation technologies and how to meet the acceptance criteria for releasing sites from regulatory control. Much more work is required in this regard.

9.2.4 The proposed new regulations address the build-up of radio nuclides in the environment and the ingrowth of progeny, but it is not explicit on the time frame to which provisions for safety should be made. The study revealed that, for certain situations where remediation was applied, the dose to the public can increase for prolonged periods, exceeding 1 000 years. More clarity should be provided in the regulations or guidance documents provided by the NNR.

9.2.5 It was calculated by Cerne for an ideal plant species to be suitable for commercial or economically viable phytoextraction of Ra-226 from soils contaminated with uranium, the Ra-226 accumulation in the shoots should at least be 10 times of the Ra-226 concentration in soil (Cerne, 2012). Perhaps this avenue should be further explored for South African conditions.

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