ANNEXURE N8:
PUBLIC DOSE STUDY BY THE NUCLEAR ENERGY COUNCIL OF SOUTH AFRICA

Report on the Radiological Public Hazard Assessment for the Expansion of Rössing Uranium Mine in Namibia, as a Specialist Study for the Phase II SEIA

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1.0 INTRODUCTION

Aurecon South Africa (Pty) Ltd (hereafter referred to as Aurecon) is presently performing a Social and Environmental Impact Assessment (SEIA) for the proposed Expansion of Rössing Uranium Mine [1] (hereafter referred to as Rössing). Necsa has been contracted to perform a Radiological Public Hazard Assessment as a specialist input to the Phase II SEIA. The following document describes the detail and results of the radiological hazard assessment.

2.0 SCOPE OF THE ASSESSMENT

The present Minerals Act [2] of Namibia requires that the holder of a mineral licence shall prepare an Environmental Impact Assessment (EIA). Since the mining activities involve the mining of Naturally Occurring Radioactive Material (NORM), a radiological assessment is to be included as a specialist report in the EIA. Such an assessment mainly addresses the radiological impact of the mine to members of the public that may be exposed. International developments on the radiological impact to non-human species are still in its infancy and will not be considered. The assessment will also not consider the occupational exposure of workers as such exposures will be controlled through the existing occupational Radiation Protection Programme at Rössing [3].

Where required, data from the SEIA scoping report [1], specialist study on the air quality [4] and data from various previous radiological assessments for Rössing [5], [6], [7] will be used.

By nature the process of prospectively assessing radiological risks is an uncertain process since one is trying to predict future conditions, mainly through modelling and extrapolation exercises, using available data. While Rössing has accumulated a vast variety of data over its past operational life, some uncertainties may still remain on the future behaviour of the expanded operations. An aim of the prospective assessment is to also identify the areas of uncertainty and to make proposals for the acquisition and improvement of such data in the environmental monitoring program.

The assessment is performed within a framework of radiation protection and waste management principles and of regulatory requirements, which comprises the assessment context of the study. This is described in Section 3.0.

Section 4.0 summarises the project and site descriptions and provides the information on radiological and radionuclide data that were used to perform the radiological impact assessment.

Due to information uncertainties associated with the future evolution of the site over the time scales of concern, a source-pathway-receptor approach derived from an interaction matrix rather than a formal scenario generation process will be followed to define a limited set of exposure scenarios for dose assessments on the various pathways. The approach followed to develop exposure scenarios has been described before in [5], but is briefly repeated in Section 5.0, together with a description of the pathway dependent scenarios considered in this assessment. A large effort in the assessment was the calculation of the inhalation doses from radon and dust for adult members of the public on a grid basis as determined through air dispersion modelling for the operational phase of the mine. This covered scenarios for the initial and future mine conditions described in [4]. New information for the aquatic pathway has not been provided, and impact from the assessment in [5] was used unchanged, where it was regarded as appropriate.

Section 6.0 is devoted to a deterministic assessment of the radiological impact. First mathematical models are developed and then the deterministic public doses for relevant pathways are assessed as per the defined scenarios. The methodology and assessment of adult inhalation doses on a grid basis are also addressed.

Section 7.0 presents an uncertainty analysis on the atmospheric pathway results, based on data provided in the air quality study [4].

The report is concluded in Sections 8.0, 9.0 and 10.0 with an evaluation of the public impact assessment results, including some general recommendations for additional information to be acquired through the existing environmental monitoring program for possible future assessments. The assessment results will be evaluated against international radiological criteria based on international radiation protection principles [8] and [9]. In addition, in Section 9.2 is an evaluation of the assessment results against the Environmental Impact Criteria presented in Section 3.5.

Section 11.0 presents the referenced documents.

Six appendices are also attached to the report. The scope of work and deliverables as per the sub-consultancy agreement is attached as Appendix A in Section 12.0. Appendix B in Section 13.0 presents a map of the Rössing site and the surrounding environment. Appendix C in Section 14.0 lists the parameters used in or adapted for the deterministic public dose calculations. Appendix D in Section 15.0 contains an Interaction Matrix identifying possible sources and pathways for

Rössing, mainly to assist in scenarios development and to serve as reference for future assessments. Appendix E in Section 16.0 tabulates the activity concentrations of the radionuclides in solid samples provided by Rössing. All the radon and dust concentrations together with the calculated doses for each of the grid points (near-field and far-field) are tabulated in Appendix F (Section 17.0) and Appendix G (Section 18.0) respectively. As these two appendixes contain over 50 000 receptor points (more than a 1000 pages) they are only included in the report that is used for internal purposes, but they are available on request.

3.0 ASSESSMENT CONTEXT

3.1 General

The main purpose of the assessment context is to define the objective, scope and content of the assessment to be performed.

3.2 Purpose and Objective of the Study

A radiological assessment consists of a set of higher level assumptions and constraints that will reflect the regulatory requirements. The assessment context also provides the means, by which the target audience is informed of what is to be included in the assessment, and the justification for these choices. Uncertainties in the prospective assessment are supplemented by assumptions and extrapolations from existing situations. The prospective assessment report is concluded with recommendations for additional measurements in the environmental monitoring program to be used for improving the accuracy during a retrospective review of this hazard assessment to be performed according to regulatory requirements and guidance.

As part of the SEIA, this radiological specialist investigation has the following specific objectives and purpose as stated in the sub-consultancy agreement and in Section 6.5.5 of the Scoping SEIA report [1]:

a. To determine whether a maximum mine expansion will increase public exposure of the critical population at Arandis above the dose constraint of 300 microsieverts per year (see Section 3.4.1 for the motivation) during the operational phase. If required, prevention strategies or mitigation of exposures above the dose constraint will be prescribed. It is assumed that post-closure exposures caused by the maximum expansion will be equal to or lower than the exposure in the operational phase.

b. In addition, the increased exposure to radon in the workplace as a result of the increased production will be assessed.

c. To evaluate the exposure to SEIA criteria specified in [1] and the sub-consultancy agreement and discussed in Section 3.5.

d. To provide input, together with Aurecon, other specialists and Rössing, into possible impact management measures going forward.

3.3 Stakeholders in the Assessment

This assessment is undertaken to provide confidence to various groups of people that the controls currently in place and envisaged will ensure that the impact of the mine does not pose a radiological risk to members of the public. These groups constitute the stakeholders (target audiences) of the assessment. More specifically the stakeholders can be defined as:

a) Rössing management for whom the assessment is being performed,

b) The National Radiation Protection Authority, which as the regulatory body of Namibia, should overlook the process to ensure that the mining and processing activities are performed in accordance with regulatory guidance and requirements provided,

c) The public in the vicinity of the mine as well associated local authorities and

d) Technical, scientific and environmental groups that might have an interest in the approach being followed and the subsequent results.

3.4 Radiological Regulatory Requirements for the Impact Assessment

3.4.1 Regulatory Framework

Radiological protection standards are criteria set to ensure compliance with the basic principles of radiation safety and radioactive waste management. In 2009 the Atomic Energy Act (No. 5 of 2005) was promulgated and the Namibian Atomic Energy Board inaugurated. Thereafter the National Radiation Protection Authority was formed, who is tasked to develop the Regulations for Protection against Ionising Radiation and for the Safety of Radiation Sources and the

Regulations for the Safety and Secure Management of Radioactive Waste. These regulations will be modelled after international standards and together with the Act will provide the legal, regulatory and institutional framework for the management of radiation protection and safety.

However, the mentioned regulations are, to date, still in the development phase [10]. For this reason this document will mainly refer to international standards and recommendations, as contained in IAEA [8], [11], [12] and ICRP [9], [13], [14] publications. Amongst others, these regulations ensure the protection of individual members of the public and their surrounding environment. For this purpose, dose and potential dose limits, dose constraints as well as radon action levels and other appropriate criteria are defined. The basic safety indicator for public impact assessments, is an individual *dose limit*, while for planning purposes, a *dose constraint* at some fraction of the dose limit is used.

The individual dose limit places an upper limit to the dose from all controllable sources to which an individual may be exposed. In assessing the performance with respect to this indicator, all pathways from all the radioactive material or radiation from all practices (excluding medical exposures and natural sources) to the individual must be considered. The recommended dose limit for members of the public is 1 $mSv.a^{-1}$ [8] and [9]. Since the application of dose limits to a single authorized practice has some intrinsic difficulties, the international approach is to use the limit on a case by case basis only, while more generally a source-related dose constraint is applied for optimisation of the impact from a single authorized practice. A value of 300 $\mu Sv.a^{-1}$ is for instance recommended as a constraint for the management of waste from uranium mining [12]. This constraint will also serve as a radiological criterion for the present assessment.

For radon, an action level of 200 to 400 $Bq.m^{-3}$ is used as a criterion level requiring some action to be taken when the level is exceeded [13]. This relates to an annual dose of around 3 to 6 $mSv.a^{-1}$. The action level was, however, only made applicable when radon was regarded as incidental to the mining process and not when the material was mined for its radioactive properties. The latest ICRP recommendations [9] mentions optimization of radon doses below a constraint of 10 $mSv.a^{-1}$, with no distinction between the different products of mining. The ICRP indicated, however, that they are still investigating the exposure to radon. For this assessment the public impact of radon will be evaluated against the public dose limit and constraint mentioned in the previous paragraph but recommendations will also consider the present international uncertainty. The radon doses will hence be evaluated separately and together with the dust inhalation doses.

3.4.2 Assessment Guidance

Broad ICRP guidance on a radiological public hazard assessment is provided in [14]. The IAEA provide broad assessment guidance for mining waste management in [12] and some model guidance in [15]. This report will focus on the scenario development and dose assessment detail, which will be discussed in Section 5.0 and Section 6.0.

3.4.3 Effects in the Future

One of the basic principles for site rehabilitation and the management of the radioactive waste, as associated with mine closure, is that this will be done in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today [11]. This implies that the assessment will include predictions of future impacts. Generally it can also be expected that human technology and society will develop over the time scale of concern. This development is, however, unpredictable. Therefore, it is usual to make some assumptions in order to constrain the range of future human activities that are considered. A common assumption, also made in this study, is that present-day technology, or technologies practised in the past will apply for the complete assessment period.

While predictive results are presented in [4], these cover only the operational phase of the mine. This assessment will hence be restricted to the results of simpler models applicable to the operational phase of the mine.

3.4.4 Safety from Design Optimisation and Control

For a new mine, various site and waste management design options are normally investigated, applying the latest mine engineering practices together with a radiological optimisation exercise. As an existing mine, design optimisation assessments for the Rössing facilities may no longer be a feasible option. In previous radiological assessments (see [5], [6] and [7]) various mitigation options at mine closure have, however, been evaluated by reducing or eliminating the sources affected by each mitigation option. This will only be done if doses are higher than the dose constraint.

3.4.5 Radionuclides Considered in the Assessment

The radionuclides giving rise to the radiological impacts associated with the Rössing operations are those resulting from the U-238, U-235 and Th-232 decay series. The specific radionuclides in these decay series that are of importance to the dose assessment (as they will contribute significantly to the total doses) were selected, where applicable with appropriate half-lives, from [16] and are:

(a) Long-lived alpha (α) emitters: U-238, U-234, Th-230, Ra-226, Po-210, Th-232, Th-228, Ra-224,

(b) Beta (β) emitters: Pb-210, Ra-228 and

(c) Rn-222 (and its short-lived progeny).

In addition, U-235 (α-emitter) with a half-life of 7.04×10^8 years and its daughters (Pa-231, Ac-227 and Ra-223) will also be included in the analysis, but only when these could significantly contribute to doses. Radioactive decay and in-growth should be taken into consideration in predictive assessments, not only to avoid overly conservative results in the case of the slower transport processes, but also to account for the impact of the relevant decay products. This assessment will mainly be based on simple non-predictive models for the atmospheric pathway and will use analytical results provided by Rössing from their extensive database. Where data for some of the above nuclides are missing or regarded as unreliable in the analysis results, extrapolations from indicator nuclides will be performed and justified.

3.4.6 Model Development

Public dose assessment models usually consist of atmospheric, ground- and surface-water transfer models and finally biosphere models to relate the sources of radioactivity and radiation to the amount of radioactivity to which members of the public are exposed through external or internal exposure. Atmospheric modelling is reported on in another specialist report [4]. Aquatic pathway modelling is not performed for this assessment. For evaluation of the results against radiological criteria, overlapping impacts for the aquatic pathway from a previous assessment [5] will be considered if required. Biosphere modelling and the associated radiological assessment will be discussed in Section 6.0.

Ideally, model development within the assessment should be performed through scenario development considering all exposure pathways and all possible present and future conditions. For this assessment, only scenarios relating to normal non-disruptive conditions are considered.

All data used in the assessment are available at Necsa for international review, auditing, quality control and safekeeping.

3.4.7 Critical Groups

Critical groups (redefined in [14] as Representative Individuals) consist of the groups likely to receive the highest exposure and are most likely to be found in the neighbourhood of the sources at the mine. Parameters typical of the critical group locations and expected human actions, behaviour and habits that might have an influence on the assessment are assumed and used in the assessment. These include existing *actual* critical groups that might be influenced by the mining conditions, or *hypothetical* critical groups that might position themselves in areas adjacent to the sources during the period covered by the assessment or be involved in habitual activities that my expose them to radioactivity and radiation originating from mine sources.

Age groups of 0 to 2 years, 2 to 7 years, 7 to 12 years, 12 to 17 years and adults have been used in previous assessments [5]. These groups receive different levels of radiation exposure due to differences in metabolic conditions and behavioural characteristics (e.g. breathing rate). However, to calculate the doses to critical groups in this assessment, the assumption was made that the critical groups consists of adults only. For the atmospheric pathway this assumption generally relates to the most conservative dose. Doses to other age groups can be interpolated through a correction factor deduced and justified from the relative values of input parameters. The correction factor is based on the product of the breathing rate (tabulated in Table 19) and the sum of the dose conversion factors from all the radionuclides (tabulated in Table 20) for the different age groups. Relative to the adult age group is the dose to the other age groups 64%, 70%, 84% and 98% respectively. .

3.4.8 Public Dose Assessment

The basis for any radiological impact assessment consists of site specific data related to the physical, chemical, biological and radiological characteristics of the site. From this perspective a description of site and surrounding environment is needed, as discussed in Section 4.0.

From a description of the operations, site and surrounding environment it would be possible to identify features, events and processes (FEP) related to the mining activities, which could have the potential to expose members of the public to present and future sources of radiation. From such a source-pathway-receptor analysis possible exposure pathways to real and hypothetical critical groups among members of the public can be defined. A formal, systematic scenario generation and justification process from a list of all possible FEP will, however, not be followed. Scenarios have in the past [5] been formulated through the screening of relevant radioactive sources and interacting media, as identified in an interaction matrix, given in Appendix D (see Section 15.0). For this assessment the critical groups are presented as part of the Scope of Work in Section 12.0 and scenarios will be developed based on typical habits also used in the past.

Details on the methodology used in the dose analysis will be provided, including the approaches followed to consider the effects of interacting media in the biosphere and mathematical models used to quantify these effects. The models for environmental transfer in the atmosphere will form part of another specialist report [4]. If required for evaluation of the total impact against radiological criteria, previous results for the aquatic pathway will be used as presented in [5].

3.5 SEIA Criteria for Impact Evaluation

Aurecon has also presented criteria in the Environmental Scoping Report [1] for the evaluation of the environmental impacts in a format involving the ranking various aspects of the impacts. These are presented in Table 1 to Table 5 and their uses are considered in Section 9.2.

Table 1: Assessment criteria for the evaluation of impacts

CRITERIA	CATEGORY	DESCRIPTION
Extent or spatial influence of impact	**National**	Within Namibia
	Regional	Within the Erongo Region
	Local	Mine Licence Area and Mine Accessory Works Area
*** Magnitude of impact (at the indicated spatial scale)**	**High**	Social and/or natural functions and/ or processes are *severely* altered
	Medium	Social and/or natural functions and/ or processes are *notably* altered
	Low	Social and/or natural functions and/ or processes are *slightly* altered
	Very Low	Social and/or natural functions and/ or processes are *negligibly* altered
	Zero	Social and/or natural functions and/ or processes remain *unaltered*
Duration of impact	**Short term** (construction period)	Up to 3 years
	Medium Term	Between 3 and 10 years
	Long Term	More than 10 years after construction

Table 2: Definition of significance ratings

SIGNIFICANCE RATINGS	LEVEL OF CRITERIA REQUIRED
High	• High magnitude with a regional extent and long term duration • High magnitude with either a regional extent and medium term duration or a local extent and long term duration • Medium magnitude with a regional extent and long term duration
Medium	• High magnitude with a local extent and medium term duration • High magnitude with a regional extent and construction period or a site specific extent and long term duration • High magnitude with either a local extent and construction period duration or a site specific extent and medium term duration • Medium magnitude with any combination of extent and duration except site specific and construction period or regional and long term • Low magnitude with a regional extent and long term duration
Low	• High magnitude with a site specific extent and construction period duration • Medium magnitude with a site specific extent and construction period duration • Low magnitude with any combination of extent and duration except site specific and construction period or regional and long term • Very low magnitude with a regional extent and long term duration
Very low	• Low magnitude with a site specific extent and construction period duration • Very low magnitude with any combination of extent and duration except regional and long term
Neutral	• Zero magnitude with any combination of extent and duration

Table 3: Definition of probability ratings

PROBABILITY RATINGS	CRITERIA
Definite	Estimated greater than 95% chance of the impact occurring.
Probable	Estimated 5 to 95% chance of the impact occurring.
Unlikely	Estimated less than 5% chance of the impact occurring.

Table 4: Definition of confidence ratings

CONFIDENCE RATINGS	CRITERIA
Certain	Wealth of information on and sound understanding of the environmental factors potentially influencing the impact.
Sure	Reasonable amount of useful information on and relatively sound understanding of the environmental factors potentially influencing the impact.
Unsure	Limited useful information on and understanding of the environmental factors potentially influencing this impact.

Table 5: Definition of reversibility ratings

REVERSIBILITY RATINGS	CRITERIA
Irreversible	The activity will lead to an impact that is permanent.
Reversible	The impact is reversible, within a period of 10 years.

4.0 SITE AND PROCESS DESCRIPTION

Rössing is a large open pit uranium mine that is located in the Erongo Region in Namibia, South-Western Africa. It is approximately 65 km east north east from the coastal town of Swakopmund and the Atlantic Ocean. The Rössing mining licencing area and accessory works area is bordered by the town of Arandis, approximately 12 km to the north west, and by the incised Khan River valley, approximately 4.5 km to the south-east. Besides the urban areas above, there are also a number of smallholdings located on the lower Swakop River, privately owned farms to the east and designated National Parks in the vicinity of the mine. The expansion of Rössing is part of the general "uranium rush" to the Erongo Region with two other uranium mines already in operation (Langer Heinrich and Trekkopje) and possibly more to follow (e.g. Husab and Areva).

Rössing has been mining and processing uranium since 1976. Mining is undertaken in a conventional open-pit truck and shovel operation conducted in 15 m lifts. The open pit currently measures approximately 3000 m long, 1000 m wide and 370 m deep. The layout of Rössing is depicted in Figure 1 and shows the existing facilities (i.e. Open Pit, Process Plant and Tailings facility and Waste Rock Dumps) and the proposed preferred layout of the expansion facilities (Heap Leach facility, Ripios, Tailings on Tailings facility and expanded Waste Rock Dumps) after the assessment of the social and environmental, technical and financial feasibility of various layout options. The layout options considered different locations of the waste rock dumps, tailings storage facility, acid heap leach facility and ripios disposal area.

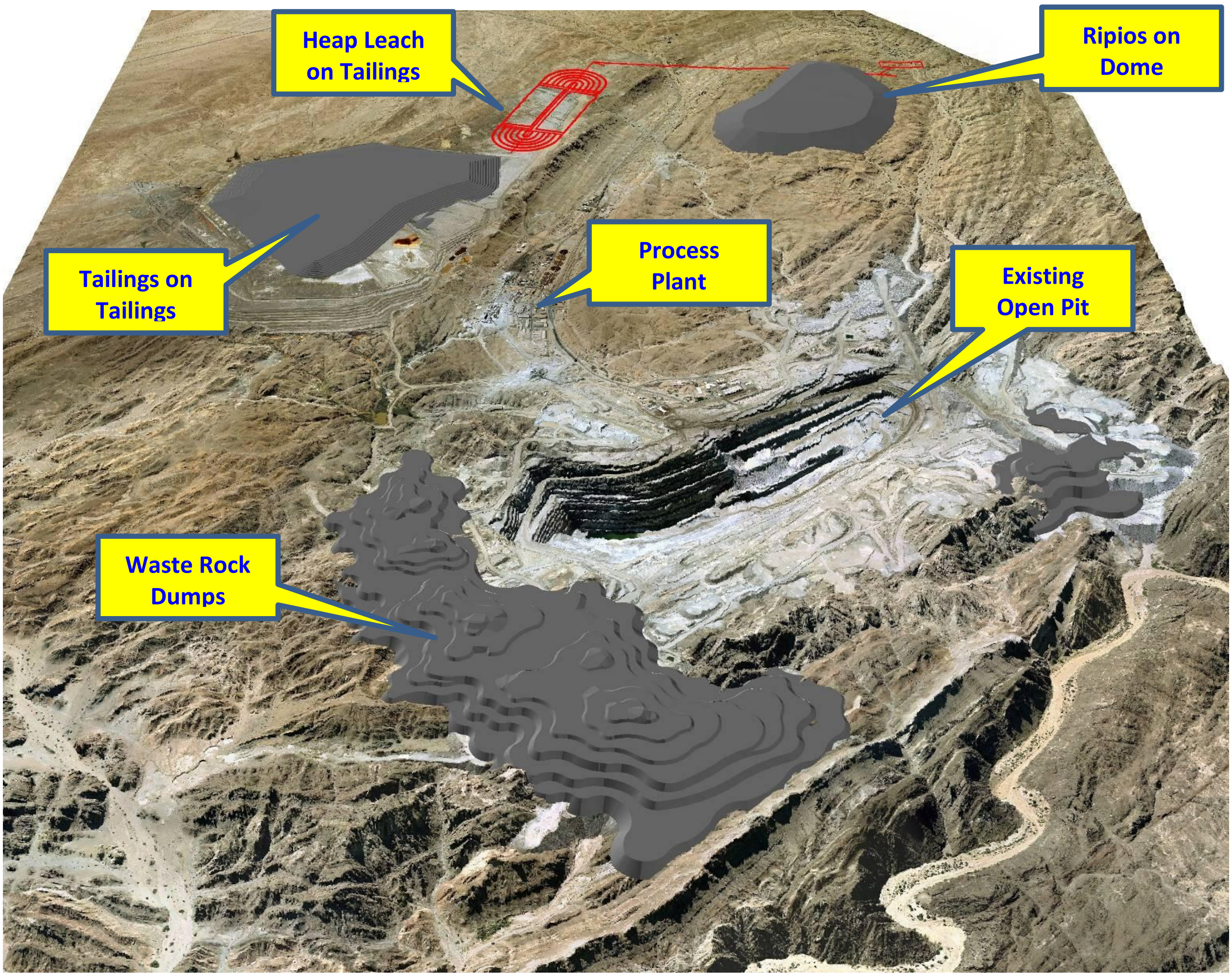

Figure 1: Existing and proposed expansion facilities at Rössing.

Current operations include the mining of the uranium deposits, referred to as the SJ and SK4 mineral deposits, and further processing at the Process Plant through an acid tank leaching process. This process includes crushing, rod-milling and acid leaching followed by solid/liquids separation and tailings disposal at a dedicated tailings site.

The activities for the proposed mine expansion will be located within the existing mining license area of Rössing and will include, in brief, the following:

- *Extension of the current mining activities in the existing SJ open pit* – The same mining method as currently used will be employed to expand the current pit horizontally into different areas:
  - Phase 1 - T10: mining term 2009 to 2010, estimated ore volumes = 24 Mt,
  - Phase 2 - NW : mining term 2008 to 2024, estimated ore volumes = 294 Mt,
  - Phase 3 - SW: mining term 2008 to 2021, estimated ore volumes = 296 Mt.

- *Expanding the waste rock disposal capacity* – The extension of the SJ pit would lead to the disposal of an additional ~250 Mt of waste rock. This will be placed on the existing waste sites, but additional suitable areas were identified to accommodate all waste rock resulting from further future expansion projects or for the consideration of long term implications e.g. seepage control, slope stability, wind and water erosion, rehabilitation of biodiversity, visual intrusion on elevated horizontal lines in the landscape, and emission of dust and radon.

- *Establishment of a new crushing plant* - The proposed new heap leach facility requires crushing of the ore prior to processing, similar to the existing tank leach process, except that it is designed for courser material than the current process. For this reason a new crushing line will to be added, next to and parallel to the existing, to feed the heap leach process. It will provide for a separate coarse ore stockpile and different crushing stages.

- *Expanding the tailings disposal capacit*y – The current tailings dam applies a paddy system with a spigot deposition system whereby coarse ground tailings for dam building are discharged through spigots (open pipe ends), onto the sand wall which is built above the original starter dam. Seepage from the tailings dam is collected in a seepage dam with a plastic-lined wall core. For the expansion the current site will be extended by increasing the height of the support walls, thus allowing the capacity of the tailings facility to extend vertically.

- *Establishment of an acid heap leaching facility* – The facility will be used to recover uranium from low grade ore that is not suitable for the tank leach extraction process. The addition of this process will increase Rössing's U_3O_8 output from 4500 tpa to 8000 tpa. The heap leach plant will be located on the north-eastern extension of the existing tailings storage facility.

- *Establishment of a ripios (spent ore from heap leaching) disposal area* - A separate storage facility will be constructed on the Rössing Dome to accommodate the spent ore tailings (ripios) that originate from the acid heap leach facility.

4.1 Sources to be Considered

The assessment involves only atmospheric emissions from radioactive sources. Detail about the major assumptions to be made is presented in the Scope of Work in Appendix A (Section 12.0). From this the following sources need to be considered:

i. Extension of existing SJ open pit - The average uranium grade in the pit will be similar to the grade in the current pit. Pit walls will emanate radon. Additional ore handling activities (loading and hauling) will create dust. Additional waste rock dumping will create dust.

ii. Expanding the waste rock disposal capacity - Waste rock disposal facilities will be expanded to include additional waste rock. The geometry of the current rock dumps will change and the surface area will increase. The expanded rock dumps will release radon and fugitive radioactive dust.

iii. Establishment of an acid heap leaching facility and a ripios (spent ore from heap leaching) disposal area - A heap leaching facility will be created as described earlier. Uranium grade will be lower than grade in the current open pit. Low-grade ore will be moved from the ROM ore towards the heap leach area. Heap leach rock will be crushed and will generate radioactive dust. Ore handling activities (conveying, stacking and reclaiming) could create dust if dry. The heap will release radon. Particle size distribution will be different from the current run-of-mine ore. The assessment will include the proposed ripios disposal area on the Dome.

iv. Expanding the tailings disposal capacity - Tailings disposal facilities will have to be expanded to receive tailings generated from mining ore at the expanded pit. The geometry of the current tailings facility will extend in a way that the footprint will remain unchanged but that its height will increase to a maximum. Surface area for radon emanation will therefore increase. Fugitive dust will be generated from medium and course tailings and from chemical precipitates. Characteristics of radon and dust generation are unlikely to differ from the current facility.

v. Establishment of new crushing plant - A general increase in production will result in a proportional increase in fugitive radioactive dust generation in the plant area due to ore handling, crushing and roasting of final product, as well as the proposed new process of preparation of heap leach material.

From the information above it is evident that the source terms do not only relate to the sources but also to dust creating natural processes like wind erosion as well as operational processes like mining, ore and waste hauling, ore crushing, and stack emissions during ADU roasting.

4.2 Background Conditions

Enhanced background levels of NORM do exist around the Rössing mine and some of these were considered and discussed in [5]. However, the present assessment uses only modelled dispersion results from sources associated with the mining and processing operations. This represents a conservative estimate from the additional radiation doses above the background. No background corrections are therefore needed since the background was not included in the modelling.

4.3 Radiological Data For Assessment

4.3.1 Radionuclide Concentrations

Rössing has a comprehensive database of radon exhalation rates obtained through direct measurements and of radionuclide concentrations obtained through analyses of solid and water samples collected over many years. From this database the authors selected suitable values for the radon exhalation and radionuclide data to be used for the various sources covered in the atmospheric pathway dispersion modelling and dose assessment in this report. Where radionuclide concentrations were not available it was assumed that these radionuclides were in secular equilibrium with their parent radionuclide, i.e. the particular radionuclide concentration is equal to that of the parent. These chosen values will be discussed hereafter while the defining process of the source terms for each dispersion-modelling exercise is discussed in Section 5.1.2.

As chosen radon exhalation rates were used as source terms in the dispersion modelling exercises reported on in [4], they will not be calculated separately. The values used are tabulated together with the facility area in Table 6. Gravimetric emission rates were, however, used in [4] for dust source terms, which need conversion to nuclide activity concentrations. The nuclide concentrations, chosen from the existing Rössing database, are tabulated in Table 7.

A set of dust samples has also been collected from the various identified sources. The activity concentrations of these samples (tabulated in Section 16.0) will be used for verification of the data in Table 7.

4.4 Human Behaviour Characteristics

The main human behaviours for members of the public, which may be impacted by the mine, are:

- Agricultural activities on farms near and around the mine,
- Working activities close to the Rössing mine (other mines and exploration activities, Arandis airport, visitor and tourist centres) and
- Working and living activities at the Arandis town and Swakopmund.

For this assessment the focus will be on exposure via the radon and dust atmospheric pathways from the mining sources as per the modelled radon and dust concentrations presented in reference [4]. A list of possible receptors forms part of the Scope of Work, and those within the affected area as per the modelling results will be evaluated. These receptors are listed in Section 5.3.2.

Table 6: Radon exhalation rates ($Bq.m^{-2}.s^{-1}$) for the different facility areas, extracted from Rössing database.

Facility	Area	Exhalation Rate
Current tailings storage facility	Tailings Benches	2.19
	Tailings Beaches YZ & Old Beach	1.54
	Tailings Operational Beaches	1.26
Open Pit	Outline of Open Pit Rim	0.773
	Stockpiles	1.54
	Waste	0.472
Rock Dumps	Low Grade	1.16
Plant Area	A	0.974
	B	0.521
	C	1.49
	D	2.10
	E	2.92
	F	4.89
	G	0.961
	H	1.50
	I	0.507
	Coarse Ore Stockpile	1.54
	Fine Ore Stockpile	1.54
Ripios pile	Ripios	0.66
Heap Leach Pad	Heap Leach	1.54

Table 7: Radionuclide concentrations (Bq.g^{-1}) for outdoor airborne dust for various materials, extracted from Rössing database.

Description	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{231}Pa	^{227}Ac	^{223}Ra	^{232}Th	^{228}Ra	^{228}Th	^{224}Ra
ROM Ore	6.28	6.28	6.28	6.28	6.28	6.28	0.29	0.29	0.29	0.42	0.42	0.42	0.00
Tailings	1.46	1.46	1.95	1.95	1.95	1.95	0.07	0.07	0.07	0.16	0.16	0.16	0.00
Fine crushing dust	9.62	9.62	9.62	9.62	9.62	9.62	0.44	0.44	0.44	0.54	0.54	0.54	0.00
Ore in open pit – baseline	3.64	3.64	3.64	3.64	3.64	3.64	0.17	0.17	0.17	0.74	0.74	0.74	0.00
Ore in open pit – expansion	3.31	3.31	3.31	3.31	3.31	3.31	0.15	0.15	0.15	0.68	0.68	0.68	0.00
Waste in open pit - baseline	2.59	2.59	2.59	2.59	2.59	2.59	0.12	0.12	0.12	0.53	0.53	0.53	0.00
Waste in open pit – expansion	2.59	2.59	2.59	2.59	2.59	2.59	0.12	0.12	0.12	0.53	0.53	0.53	0.00
Stacks	1234	1234	0	0	0	0	57	57	57	0	0	0	0.00
Ripios	0.89	0.89	1.19	1.19	1.19	1.19	0.04	0.04	0.04	0.1	0.1	0.1	0.00

5.0 SCENARIO DEVELOPMENT

5.1 Source-Pathway-Receptor Analysis

5.1.1 General

As mentioned before, a generic process will be followed as per the human behaviour characteristics identified in Section 4.4 to identify the existing but also some hypothetical source-receptor-pathway combinations, which will then be analysed as per the detail below.

5.1.2 Sources of Radioactivity

5.1.2.1 Radon Sources

The exhalation of radon from material containing enhanced levels of Ra-226 causes radon sources. Most important is the radon exhalation from the tailings dam, with lower emissions possible from the ripios and waste rock piles and even lesser amounts from the ore stockpiles. The radon exhalation rates will vary for the different sources and over the different mining phases due their size and their Ra-226 concentrations.

5.1.2.2 Dust Sources

Dust sources will also vary depending on the mining phase. The current operations are used as a baseline against which the expanded operations will be evaluated as described in detail in [4]. Gravimetric emission rates for dust sources as related to various mining operations have been calculated for the current as well as the proposed expanded operations for the following source grouping and sub-grouping (see [4] for detail):

- Fugitive Dust Emissions from Materials Handling Operations
  - Tipping

- Fugitive Dust Emissions from Wind Erosion
  - Coarse Ore Stockpile
  - Coarse Ore Stockpile Plume

- Conveyor Plume
- Fine Ore Stockpile
- Fine Ore Stockpile Plume
- Fine Crusher Plume
- Open Pit
- Precipitates
- Rock Dumps
- Stockpiles
- Tailings

- Fugitive Dust Emissions from Vehicle Entrainment
    - Unpaved Roads
    - Paved Roads

- Fugitive Dust Emissions from Dozers and Graders

- Fugitive Dust Emissions from Drilling and Blasting
    - Drilling
    - Blasting

- Fugitive Dust Emissions from Loading Operations

- Fugitive Dust Emissions from Fine Crushing Plant

- Emissions from Stacks

Emissions for the same but expanded sources were assessed for the expansion, while the following additional sources were considered:

- Fugitive Dust Emissions from Wind Erosion
    - Ripios

Considering the sources separately in the dispersion modelling exercise will allow various mitigation options to be considered if required, e.g. if the dose limit or dose constraint is exceeded. These mitigations could be considered during the operational phase of the mine or for rehabilitation at mine closure.

5.1.3 Pathways

5.1.3.1 External Exposure

Experience at other mines indicates that direct external exposure to radiation from mine sources become only important when members of the public are living on areas containing mine ore or residues. While this pathway should be further investigated for post-closure conditions, it is not considered in this prospective assessment as members of the public will not have access to such areas during mine operation. A calculation for a large wall of ore containing 7 $Bq.g^{-1}$ natural uranium indicated that a trivial dose[1] of 10 $\mu Sv.a^{-1}$ will not be exceeded at a distance of 0.5 km from the source. This could hence be used as the limiting distance for permanent public access to the mine sources.

External exposure may also occur from soil contamination due to deposited airborne or waterborne activity. As previously indicated the aquatic pathway is excluded in this assessment. In a previous assessment [5] external exposure to deposition plumes was found to be negligible when compared to inhalation. Deposition plumes may, however, become significant close to stockpiles and tailings dams after many years of operation.

5.1.3.2 Atmospheric Pathway

Meteorological and mechanical processes (e.g. wind speed, wind direction and dispersion) cause radon and dust to be transported from the exhalation and fugitive sources to the receptors.

Details on environmental transfer via the atmospheric pathway are dealt with in [4]. AERMOD and CALPUFF dispersion software were used to model the dispersion of pollutants for the areas that cover the near-field receptors and far-field receptors (see Figure 2) respectively. Information to calculate emissions from fugitive dust sources for current and proposed operations were provided by Rössing personnel. Historical meteorological data for the years 2000-2004 were used for the current study as this data was regarded sufficiently comprehensive for dispersion modelling purposes.

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[1] A trivial dose is a dose that is below what is considered to be significant for this assessment and therefore of no concern (see Section 8.2).

Experience at other mines indicated that the atmospheric pathway is important close to the radon and dust sources. Despite this, the atmospheric pathway will be investigated for critical groups close to and at some distance away from the radon and dust sources discussed in 5.1.2.1 and 5.1.2.2. The pathway will mainly consider inhalation and deposition of dust.

5.1.3.3 Secondary Pathways

At the points of impact at the receptors, the contributions from the atmospheric and aquatic pathways provide source terms for the secondary pathways. It is at these points where the public can get exposed to radiation through secondary transfer via the biosphere. This include, for example, the drinking of contaminated water, eating of food grown on contaminated land (through irrigation or deposition), or eating of livestock (through drinking contaminated water or eating contaminated plants). In a previous assessment [5] secondary ingestion doses due to the transfer of deposited dust to food, was found to be zero and will not be assessed.

5.1.4 Receptors

Specific critical groups will be assessed. These include representatives from the human behaviour characteristics groups identified earlier in Section 4.4 and exposed as per scenario detail presented in Section 5.3.

5.2 Interaction Matrix

An interaction matrix is a useful tool to use in a systematic approach for a source-pathway-receptor analysis. It provides a means to identify the interacting media between sources, pathways and receptors and to represent these in a visual and transparent manner. For this assessment a generic interaction matrix for a typical uranium mine is provided in Section 15.0. Not only does it serve as a guide and tool for model development for the present assessment, but also for future assessments during the operational, closure and post closure phases.

5.3 Critical Groups and Exposure Scenarios

5.3.1 General

A distinction is made between the current situation and the proposed expansion situations each with their respective mining operations that provide the various radon and dust source terms (see Sections 5.1.2.1 and 5.1.2.2) and the exposure scenarios describing the exposure conditions developed for the human receptors. The section below provides detail on the various exposure scenarios as per the source-pathway-receptor analysis described in Section 5.1.

While the assessment only covers the atmospheric pathway, all the pathways are considered in the scenario development below. This is done because the total doses to critical groups should be considered when these are evaluated against radiological criteria. Justifications for the general exclusion of some pathways due to their insignificance are presented in Section 5.1.3 , while other exclusions will be justified in the scenario descriptions. Where significant doses via the aquatic pathways are possible, such doses assessed during a previous assessment [5] will be considered in order to evaluate the possible total dose.

As for the atmospheric pathway assessed doses mainly relate to the inhalation of dust and radon from all the sources during either the current situation and for the proposed expansion situations. Different sources are considered only to evaluate mitigation options if required when the dose limit or dose constraint is likely to be exceeded.

5.3.2 Normal Evolution Condition Scenarios

For this assessment, conceptual models for exposure scenarios are developed for normal evolution conditions of the atmospheric pathway. The scenarios relate to the following 18 receptors identified in the Scope of Work:

a. Khan Mine,
b. Farm Bloemhof,
c. Farm Modderfontein,
d. Farm Geluk,
e. Farm Valencia,
f. Portion 1 of Farm Namibplaas,
g. Farm Trekkopje,

h. Farm Vergenoeg,
i. E-Camp,
j. Arandis Airport,
k. Swakop River Farms,
l. Areva Mine,
m. Swakopmund,
n. Arandis,
o. Valencia Mine and
p. Langer Heinrich Mine.

The receptor locations above are depicted in Figure 2. Scenarios for some of these receptors have been developed and used in previous assessments for Rössing [5], [6], [7]. These scenarios will also be used in the present assessment but will be extended to new receptors in the list above and renumbered. Due to similar human behaviour the same scenario will be applied to more than one receptor, e.g. worker scenarios could apply to workers at various sites. A total of 8 scenarios will hence be considered to cover the 18 receptors above. Illustrative drawings are provided for the various scenario groupings. These indicate all possible routes, however, and the scenario description indicates and justifies the routes and parameters to be considered for each scenario.

Figure 2: Picture of the Rössing region indicating the receptor locations for the scenarios considered, the rectangle indicates the receptors used in the near-field model, while the far-field model include all the others.

5.3.2.1 Scenario 1: Residents of Arandis Town

This scenario will primarily look into exposures via the atmospheric pathway. The critical group is assumed to consist of adults and children of various age groups, exposed to radon and dust emissions from the fugitive sources of the Rössing Uranium mine, which may also deposit in the area. Since no occupation detail are available, a conservative dose will be estimated by dividing the maximum annual exposure time equally between indoor and outdoor conditions (i.e. 4380 $h.a^{-1}$ indoors and 4380 $h.a^{-1}$ outdoors). The people drink uncontaminated water supplied by the Central Namib Water Supply scheme pipeline and may also use this water to irrigate household vegetable gardens. The impact of the aquatic pathways will consequently be disregarded. Scenario 1 is schematically presented in Figure 3. As mentioned in Section 5.1.3.3, the food ingestion pathway will not be assessed for soil containing deposited dust. The food pathway is hence not considered for this scenario.

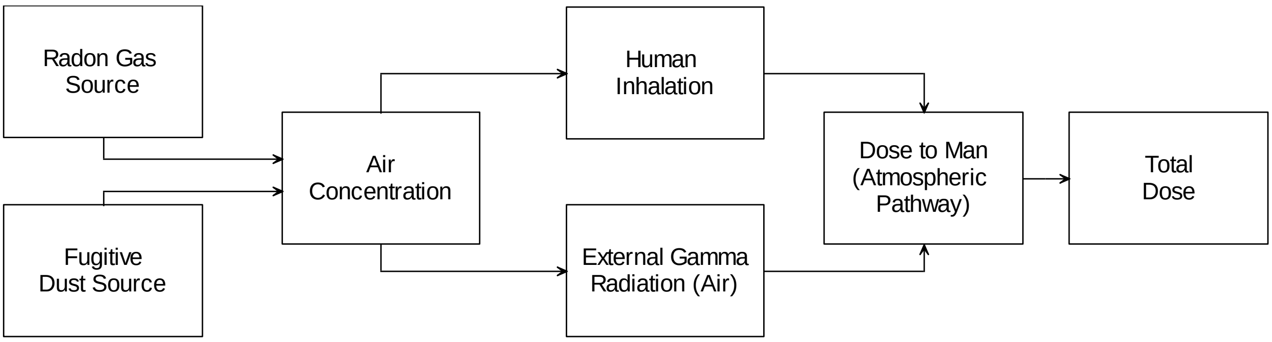

Figure 3: Schematic presentation of Scenarios 1, 2, 3, 4, 7 and 8.

5.3.2.2 Scenario 2: Residents of Arandis Airport

Scenario 2 is similar to Scenario 1, except that the actual critical group is assumed to live and work in the immediate vicinity of Arandis airport. As for Scenario 1, the atmospheric pathway is of primary importance. Since no occupation details are available, a conservative dose will be estimated by dividing the maximum annual exposure time equally between indoor and outdoor conditions (i.e. 4380 $h.a^{-1}$ indoors and 4380 $h.a^{-1}$ outdoors). Scenario 2 is also presented by Figure 3.

5.3.2.3 Scenario 3: Residents Living and Working at the Old Khan Mine Site

Under this scenario, it is assumed that a small community lives and works on the old Khan Mine site. It is assumed that all water at this site originates from the Central Namib Water Supply scheme. As for Scenarios 1 and 2, the atmospheric pathway is hence of primary importance. Since no occupation details are available, a conservative dose will be estimated by dividing the maximum annual exposure time equally between indoor and outdoor conditions (i.e. 4380 $h.a^{-1}$ indoors and 4380 $h.a^{-1}$ outdoors). Residents will obtain their food from Arandis Town. Scenario 3 is also presented by Figure 3.

5.3.2.4 Scenario 4: Working Activities within the E-Camp at Rössing

Scenario 4 includes workers at an office and visitor centre (E-Camp). It is very similar to Scenario 1, except that instead of working within the town of Arandis, it is assumed that some small industries make use of the existing office infrastructure present at Rössing. This scenario therefore assumes a population, living in the town of Arandis, but working (for an average of 2000 $h.a^{-1}$) within the E-Camp at the Rössing mine site. As for Scenarios 1, 2 and 3, the atmospheric pathway is of primary importance. The dose to office workers will be estimated by assuming an exposure time of 2000 $h.a^{-1}$ (100%) indoors. The people drink, however, uncontaminated water supplied by the Central Namib Water Supply scheme pipeline. Scenario 4 is also presented by Figure 3.

5.3.2.5 Scenario 5: Swakop River Smallholdings and Farms

A number of small farms are situated on the north-western bank of the Swakop River downstream from the confluence with the Khan River, through Goanikontes towards Swakopmund. Scenario 5 includes communities at Goanikontes (that is closer to Rössing) and two other farming areas closer to Swakopmund. The farming activities vary but most farmers engage in market gardening (vegetables) and animal products (pig farming, cattle breeding and dairy farming, chicken farming and egg production). The products are mainly sold at small outlets in Swakopmund. Drinking water and water for animal watering is derived from the freshwater pipeline carrying water from the Kuiseb and Omaruru rivers, both unlinked to the Khan and Swakop river catchments in which the mine is situated. Irrigation water is pumped from the Swakop River and used for flood irrigation of vegetables, trees, lucerne, etc. Animals are partly fed with farming products like grass and lucerne. It is assumed that 30 % of the fodder is produced at the farms.

The exposure to and ingestion of irrigated soil by animals and humans and associated food by the farming community will therefore be at 30 % of the parameter values normally used.

In order to carry out the dose assessment for people living at the smallholdings a number of pathways need to be considered and assumptions made. Exposure through the atmospheric pathway would be similar as described in Scenario 6 for Swakopmund. However, the smallholdings are located closer to the mine than Swakopmund itself and exposure to radon and dust might be potentially higher. Exposure through the aquatic pathway could potentially occur via consumed crops, irrigated by contaminated groundwater and consumed animal products (eggs, milk and meat) from animals fed on irrigated fodder. It is assumed that about 50 % of the farmer's diet would be derived from Swakop farm products.

Since no occupation details are available, a conservative dose will be estimated by dividing the maximum annual exposure time equally between indoor and outdoor conditions (i.e. 4380 $h.a^{-1}$ indoors and 4380 $h.a^{-1}$ outdoors). In the past post closure assessment [5] a worst case water quality was assumed mixed (according to hydrogeologically modelled mixing proportions) with natural Khan and Swakop groundwater[2]. These results will be considered to obtain a possible total dose for evaluation against radiological criteria. Scenario 5 is schematically presented in Figure 4.

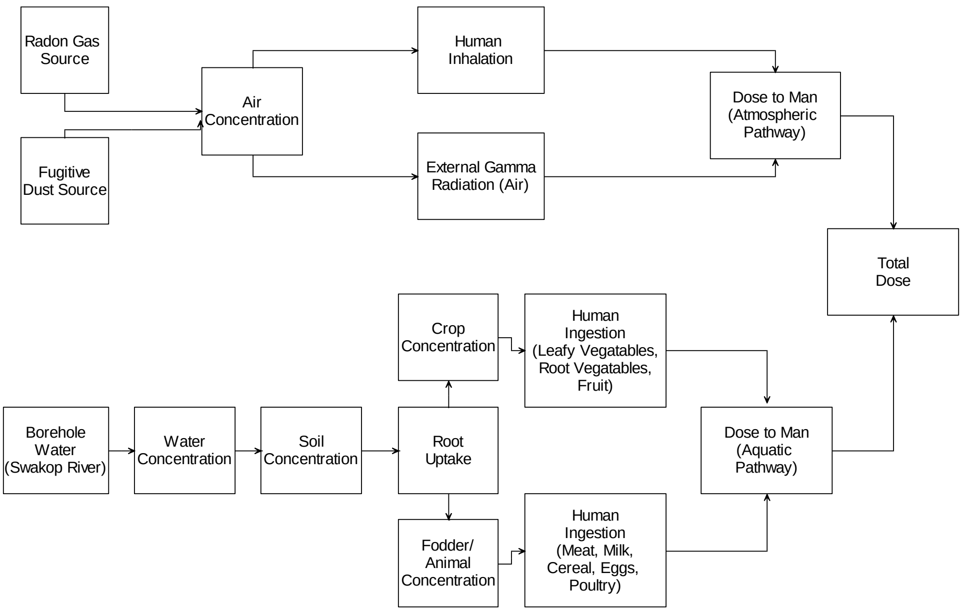

Figure 4: Schematic presentation of Scenario 5.

[2] This is a hypothetical scenario because there are fixed controls in place to prevent this situation.

5.3.2.6 Scenario 6: Residents of Swakopmund

Swakopmund residents could possibly be exposed through the atmospheric and food ingestion pathways. The population drinks water pumped from the supply system of the aquifers of the Omaruru and Kuiseb rivers, which are not linked to the Khan or Swakop River catchments. Food is to a large proportion brought in from South Africa. Only very limited quantities would be sourced from the market gardening done in the vicinity of the town (see Scenario 5). In the assessment 5 % of their food supply will be allocated to this source.

During easterly wind events radon and dust could potentially be dispersed from the mine towards the town. However, it is expected that only very small quantities if any of radon and particulates would reach the area about 60 km downwind from the mine. The incremental additional dose caused by the mine's activities would therefore result from minimal exposure through the atmospheric pathway.

Since no occupation detail are available, a conservative dose will be estimated by dividing the maximum annual exposure time equally between indoor and outdoor conditions (i.e. 4380 $h.a^{-1}$ indoors and 4380 $h.a^{-1}$ outdoors). In the past post closure assessment [5] a worst case water quality was assumed mixed (according to hydrogeologically modelled mixing proportions) with natural Khan and Swakop groundwater[3]. This mixed river water is used for irrigation only. These results will be considered to obtain a possible total dose for evaluation against radiological criteria. Scenario 6 is schematically presented in Figure 5.

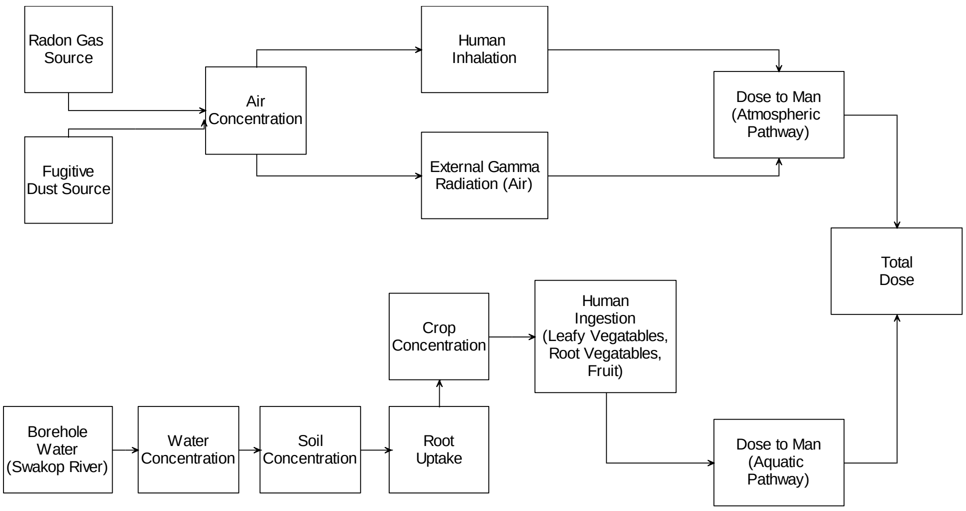

Figure 5: Schematic presentation of Scenario 6.

[3] This is a hypothetical scenario because there are fixed controls in place to prevent this situation.

5.3.2.7 Scenario 7: Working at Mine Sites around Rössing

Scenario 7 includes workers at mine sites around Rössing. These sites include: Areva Mine, Valencia Mine and Langer Heinrich Mine. This scenario is very similar to Scenario 1, except that instead of working within the town of Arandis, it is assumed that the adults work (for an average of 2000 $h.a^{-1}$ outdoors) in industries and centres at various mines located around Rössing. In this Scenario the atmospheric pathway is of primary importance. The people drink, however, uncontaminated water supplied by the Central Namib Water Supply scheme pipeline. Scenario 7 is schematically presented in Figure 3.

5.3.2.8 Scenario 8: Farms around Rössing

A number of small farms are situated on the eastern side of Rössing. These farms include: Vergenoeg, Trekkopje, Namibplaas (Portion 1), Valencia, Bloemhof, Geluk and Modderfontein. While farming activities are similar to those described in Scenario 5, the water used is derived from boreholes that are located on the respective farms. These boreholes are unlinked to the Khan and Swakop river catchments in which the mine is situated. The aquatic pathway is therefore irrelevant to this scenario. The atmospheric pathway is of primary importance and is similar to that of Scenario 2. Since no occupation detail are available, a conservative dose will be estimated by dividing the maximum annual exposure time equally between indoor and outdoor conditions (i.e. 4380 $h.a^{-1}$ indoors and 4380 $h.a^{-1}$ outdoors). Scenario 8 is also presented by Figure 3.

6.0 RADIOLOGICAL HAZARD ASSESSMENT

6.1 GENERAL

This section involves a deterministic assessment of the radiological impact to the critical groups of each defined exposure scenario, using the conceptual models above together with suitable parameters. This analysis is presented in the sections below.

6.2 Source Term Assessment Methodology

6.2.1 Radon Source Terms

Rössing has made a large variety of experimental measurements on radon exhalation rates and the details about the source sizes and exhalation rates were provided by Rössing. These values (refer to Table 6) were directly imported into the dispersion models [4] and do not form part of the radiological assessment. Radon flux determinations were therefore not needed. The radon modelling was performed for both the current and the proposed future expanded operations.

6.2.2 Dust Source Terms

Gravimetric dust source terms have been calculated for the various sources mentioned in Section 5.1.2.2 and are presented in [4] for both the current and the proposed future expanded operations.

6.3 Assessment of Atmospheric Transfers

The dispersion of pollutants was modelled for the near-field and the far-field using AERMOD and CALPUFF respectively. The near-field consisted of an area covering ~12 km (north-south) by ~14 km (east-west) [4]. This area was divided into a grid with a resolution of ~246 m (north-south) by ~276 m (east-west), and a total of 2 500 receptor points. The AERMOD model simulates ground-level concentrations for each of the receptor grid points. The far-field consisted of an area covering an area ~278 km (north-south) by ~348 km (east-west). This area was divided into a grid with a resolution of ~2km (north-south) by ~2km (east-west), and a total of 24 500 receptor points. The CALPUFF model simulates ground-level concentrations for each of the receptor grid points.

For radon the dispersion modelling covered the combined radon exhalation sources for each of the current and future expanded operations. The modelled radon gas concentration files have been provided to Necsa to assess the inhalation doses from the radon daughters.

For the gravimetric dust emission sources the gravimetric airborne concentration and specific deposition rates have been modelled. For modelling, the sources, mentioned in Section 5.1.2.2 at the current and future expanded operations were grouped as follows [4]:

- *In-pit operations (incl. drilling and blasting) – area sources*
- *Vehicle entrainment – area sources*
- *Materials handling – volume sources*
- *Crushing– volume source*
- *Wind erosion sources – area sources*

The modelled gravimetric airborne concentrations and deposition rates files have also been provided to Necsa to assess the inhalation doses. For this the gravimetric concentrations first needed to be converted to nuclide concentrations. The radionuclide concentrations presented in Table 7 were used for this conversion, while the latest radioanalytical data on samples presented in Appendix E (Section 16.0) will be used for verification.

6.4 Dose Assessment Methodology

6.4.1 Radon Inhalation Pathway

The dose from the exposure to inhaled radon daughters is calculated from modelled indoor and outdoor radon gas concentrations, by multiplication with appropriate conversion factors. For the respective exposure periods refer to Section 5.3.2. The indoor and outdoor concentrations are taken as equivalent, as per modelled outdoor results, although different equilibrium factors with the radon progeny for indoor and outdoor gases are used as per [13] and [20]. The conversion factors for radon are age-independent and will be used as such.

The mathematical model for the calculation of radon is expressed by

$$D_{Radon} = 1.0 \times 10^{3} . \left(Conc_i \, . \, F_i \, . \, T_i + Conc_o \, . \, F_o \, . \, T_o \right) . \, CC_{Rn} \, . \, DC_{Rn} \qquad \text{Eq. 1}$$

where

D_{Radon}	=	Dose from radon exposure	[$\mu Sv.a^{-1}$]
$Conc_i$	=	Indoor radon concentration	[$Bq.m^{-3}$]
F_i	=	Indoor equilibrium factor (0.4)	
T_i	=	Indoor exposure period	[$h.a^{-1}$]
$Conc_o$	=	Outdoor radon concentration	[$Bq.m^{-3}$]
F_o	=	Outdoor equilibrium factor (0.8)	
T_o	=	Outdoor exposure period	[$h.a^{-1}$]
CC_{Rn}	=	Ratio of PAEC and EEC for radon	[$mJ.m^{-3}$ per $Bq.m^{-3}$]

	=	(5.6×10^{-6})	
DC_{Rn}	=	Dose coefficient for radon exposure	$[mSv.h^{-1}$ per $mJ.m^{-3}]$
	=	(1.1 for the public and 1.4 for workers)	

6.4.2 Dust Inhalation Pathway

The dose from the exposure to inhaled radioactive airborne dust is calculated from estimated outdoor dust activity concentrations (also assumed to apply to indoor conditions) by multiplication with appropriate conversion factors. To calculate the inhalation dose from airborne radioactive dust, certain assumptions are required concerning the behaviour of the critical group:

(a) For the respective exposure scenarios and exposure periods refer to Section 5.3.2,

(b) For the adult members of the critical groups from each exposure scenario a breathing rate of 0.93 $m^3 h^{-1}$ [18] was assumed when the scenario refers to non-occupational exposure. This implied 8 hours of sleeping as indicated in Table 19.

(c) For the adult members of the critical groups from each exposure scenario a breathing rate of 1.2 $m^3 h^{-1}$ [21] was assumed when the scenario refers to occupational exposure.

The dose coefficients (in units of $Sv.Bq^{-1}$) for inhalation were taken from [8] and [18]. The mathematical model to calculate the dust inhalation dose from each radionuclide is expressed by:

$$D_{inh,Dust} = 1.0 \times 10^6 . Conc_{Dust} . DC_{inh} . (T_o + SF . T_i) . BR \quad \text{Eq. 2}$$

where

$D_{inh,Dust}$	=	Inhalation dose from radioactive airborne dust	$[\mu Sv.a^{-1}]$
$Conc_{Dust}$	=	Radionuclide concentration in airborne dust	$[Bq.m^{-3}]$
DC_{inh}	=	Nuclide-specific dose coefficient for dust inhalation	$[Sv.Bq^{-1}]$
T_o	=	Annual outdoor exposure period	$[h.a^{-1}]$
T_i	=	Annual indoor exposure period	$[h.a^{-1}]$
SF	=	Indoor shielding factor (taken as 1.0)	-
BR	=	Breathing rate for adult member of the group	$[m^3.h^{-1}]$

6.5 ASSESSMENT

The mathematical models, as detailed in Section 6.4, were developed as interconnecting worksheets on a Microsoft Excel spreadsheet file. By using best estimates of published parameter values (see Appendix C in Section 14.0), deterministic doses were assessed for the atmospheric pathways applicable to the critical group of each normal evolution scenario developed in Section 5.3.2.

In order to evaluate the impact of different mitigation options for the current operations and future expansion, the impact of the different sources needs to be evaluated separately.

6.5.1 Radon Source Contributions

The dispersion modelling for radon did, however, only considered the total exhalation from all sources and hence does not allow an assessment of mitigation options. This may not be important as the mitigation options in [7] were assumed to reduce radon daughter doses by only 4 %. (This figure was derived by evaluating the scenario where the surface of the tailings dam was covered by a layer of mixed waste rock material up to 300 mm deep compared to no covering.)

6.5.2 Dust Source Contributions

For the current and proposed expanded mining operations gravimetric dust concentrations for various sources that are in effect during a particular mining operation were determined separately [4] (refer to Section 5.1.2.2). For the dose assessment various materials that are of importance to the radiological assessment were identified (Table 7) and linked to the different mining operation sources. Refer to Table 8 for these correlations.

Assessment detail and the results are presented in Section 6.6.

Table 8: Various materials linked to mining operation sources during current and expanded operations

Source	Description	Material
C1	Conveyor 1	ROM Ore
C2	Conveyor 2	ROM Ore
C3	Conveyor 3	ROM Ore
CORE	Coarse ore stockpile and plume	ROM Ore
COSRD	Unpaved road along coarse ore stockpile to primary crusher	Fine crushing dust
DAS	Dust-a-side roads	Fine crushing dust
DRBL	Drilling and blasting	Ore in open pit
FCR	Fine crusher	Fine crushing dust
FORE	Fine ore plume	Fine crushing dust
MRD	Main tarred access road	Fine crushing dust
ORE	Materials handling of ore in pit and at crusher	ROM Ore
PIT	In pit	Ore in open pit
PLNTRD	Unpaved roads from tailings dam to coarse ore stockpile	Tailings
SP	Stockpile	ROM Ore
RIPI	Ripios	Ripios
ST_BH	Bag house	Stacks
ST_R	Roaster stacks	Stacks
ST_SC	Scrubber stacks	Stacks
TAIL	Tailings material	Tailings
TAILO	Old tailings material	Tailings
TRD	Roads on tailings dam	Tailings
URD	Unpaved roads in pit and around waste rock dumps	Tailings
WASTE	Waste rock	Waste in open pit

6.6 Results

Dose assessment results for the atmospheric pathway are presented below for all the operations of the two mining phases: *Base Case* and the *Expansion Case*.

6.6.1 Radon Inhalation Pathway

In [4] two different air dispersion models were used to calculate radon dispersion results using measured radon flux values provided by Rössing. A near-field model was used for the receptors close to Rössing (see Figure 1), while a far-field model (also named a regional model) was used for the receptors further away. These models were run for both of the mining phases.

No indoor modelling was performed so it was assumed that the indoor and outdoor concentrations are equal but at equilibrium factors of 0.4 and 0.8 respectively as suggested in [13] and [20]. The applicable radon dispersion results were converted to a dose for an adult member of the public (although radon doses are age-independent) by using Equation 1 and a one year exposure time (i.e. 4380 hours indoors and 4380 hours outdoors). These radon inhalation dose results, indicated as contour plots, are depicted in Figure 6 to Figure 9 for each of the mining phases and sets of receptors. Where applicable the doses for the critical groups were corrected for the correct exposure times as per Exposure Scenarios in Section 5.3.2. As mitigation is not expected to affect radon exhalation significantly, no distinction was made between mitigated and unmitigated conditions. The respective radon inhalation doses to each identified group for the two mining phases are summarised in Table 9.

Table 9: Doses (µSv.a^{-1}) from Radon Inhalation for the different Exposure Scenarios.

Scenario Number	Description	Period Outdoors (h)	Period Indoors (h)	Dose (µSv.a^{-1})	
				Base Case	*Expansion Case*
1	Arandis Town	4380	4380	**19**	**21**
2	Arandis Airport	4380	4380	**37**	**40**
3	Khan Mine	4380	4380	**21**	**24**
4	E-Camp	0	2000	**7.3**	**8.7**
5	Farm Bloemhof	4380	4380	**13**	**15**
	Farm Modderfontein	4380	4380	**7.5**	**8.5**
	Farm Geluk	4380	4380	**7.5**	**9.0**
	Farm Valencia	4380	4380	**25**	**30**
	Portion 1 of Farm Namibplaas	4380	4380	**16**	**20**
	Farm Trekkopje	4380	4380	**16**	**20**
	Farm Vergenoeg	4380	4380	**8.1**	**10**
	Swakop River Farm 1	4380	4380	**10**	**12**
	Swakop River Farm 2	4380	4380	**18**	**21**
	Swakop River Farm 3	4380	4380	**17**	**20**
6	Swakopmund	4380	4380	**3.8**	**4.5**
7	Areva Mine	2000	0	**1.6**	**1.9**
	Valencia Mine	2000	0	**7.3**	**9.1**
	Langer Heinrich Mine	2000	0	**1.3**	**1.5**

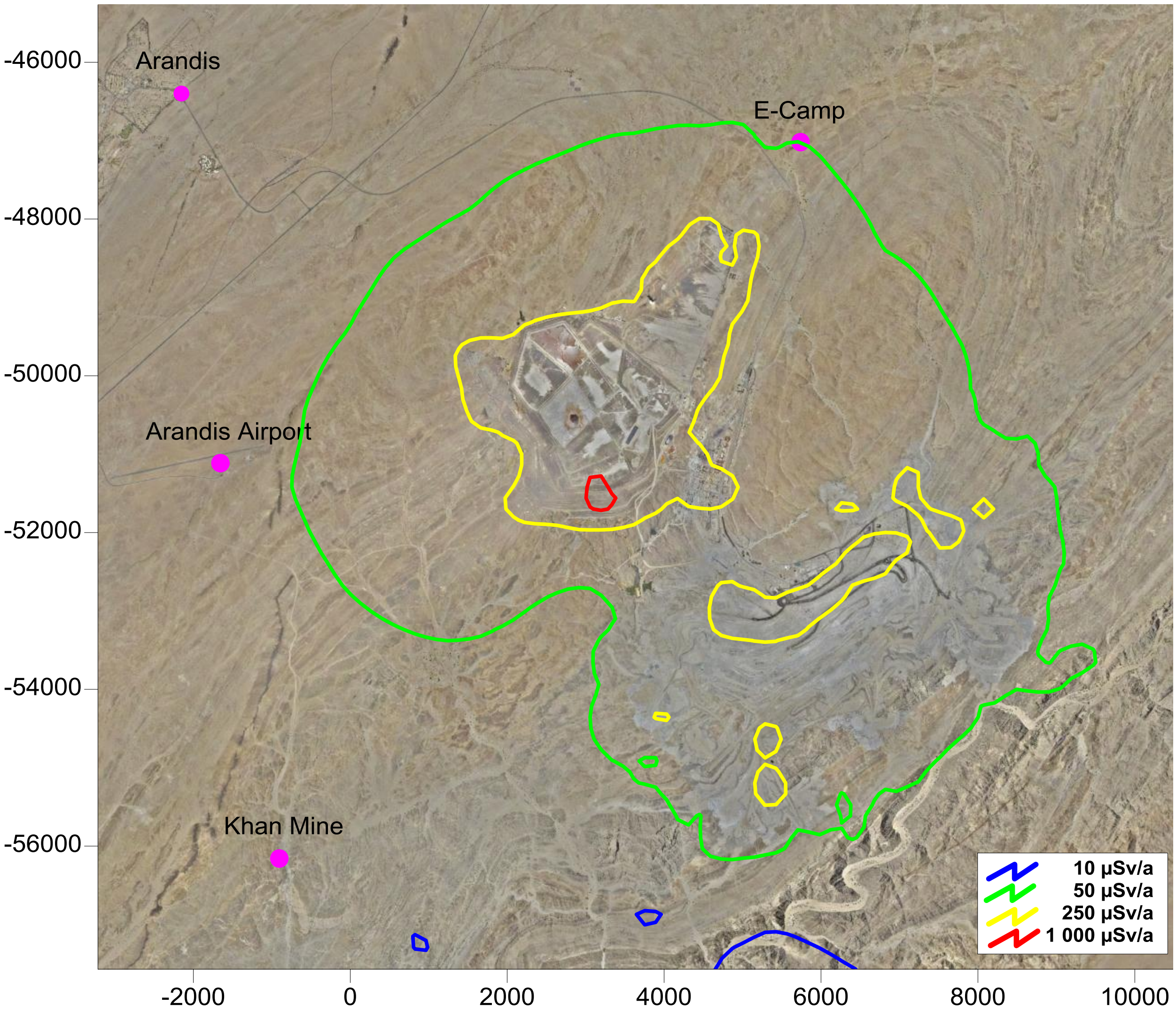

Figure 6: Calculated doses (µSv.a^{-1}) for Radon Inhalation from the *Base Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the near-field receptors.

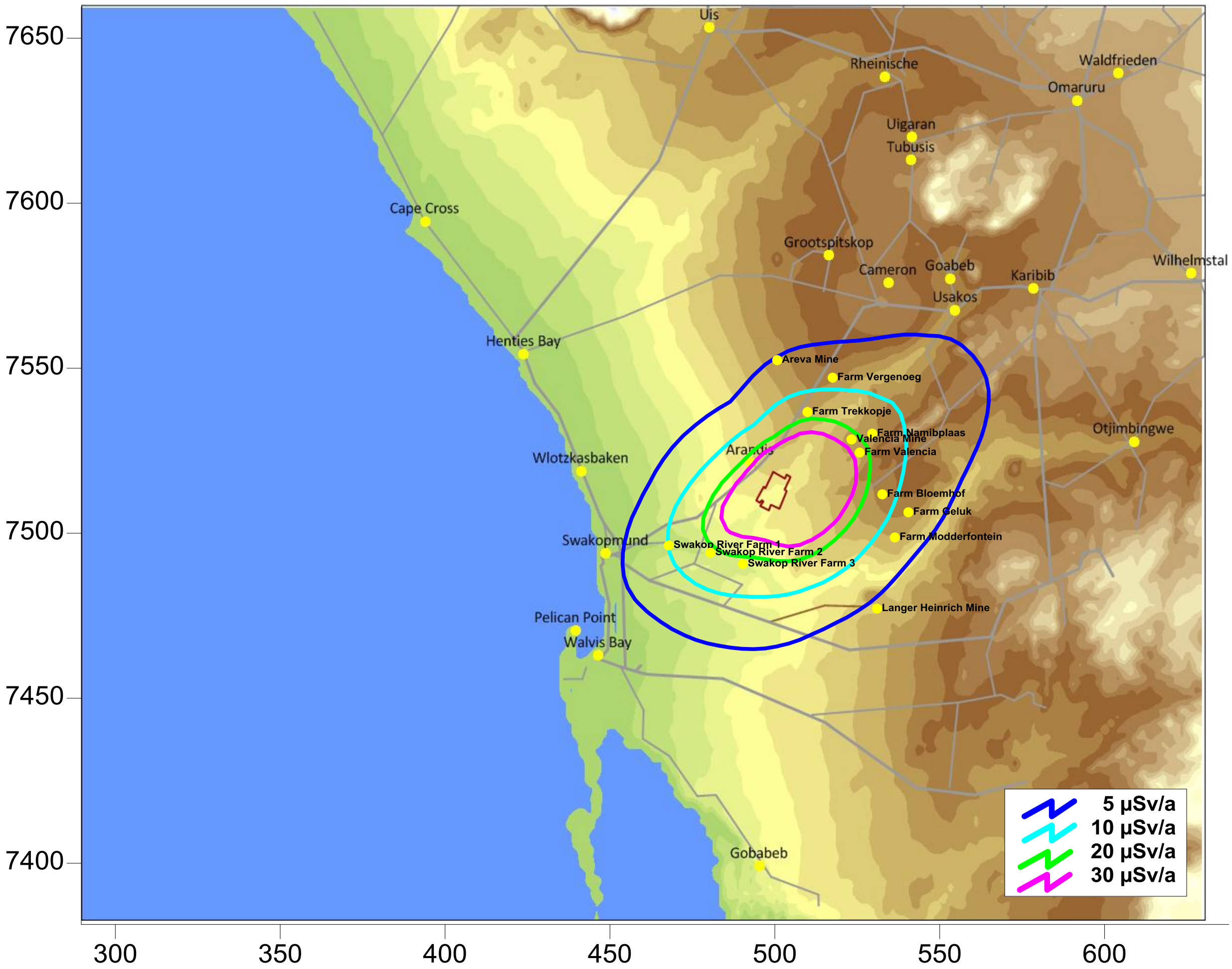

Figure 7: Calculated doses (µSv.a^{-1}) for Radon Inhalation from the *Base Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the far-field receptors.

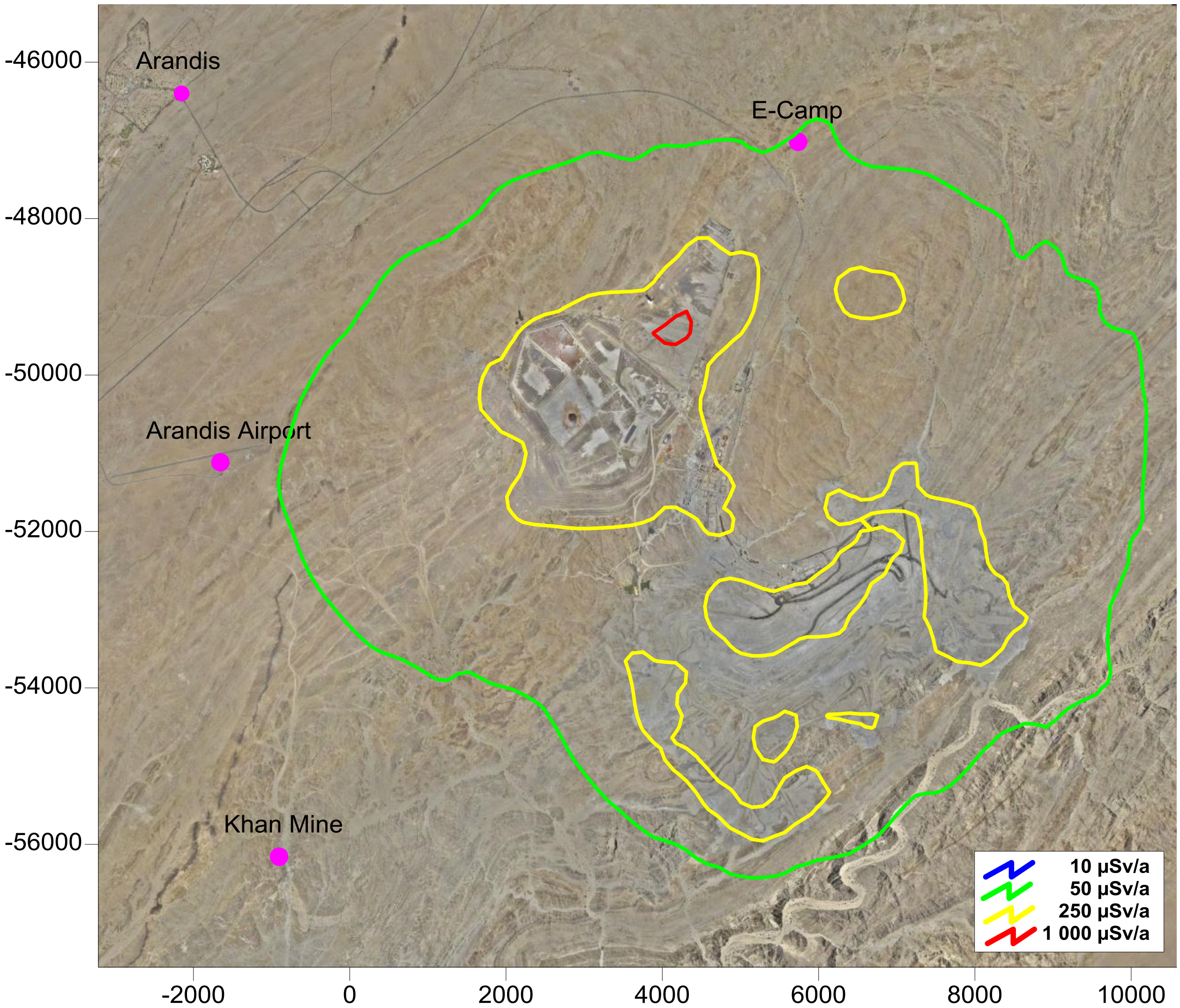

Figure 8: Calculated doses (µSv.a^{-1}) for Radon Inhalation from the *Expansion Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the near-field receptors.

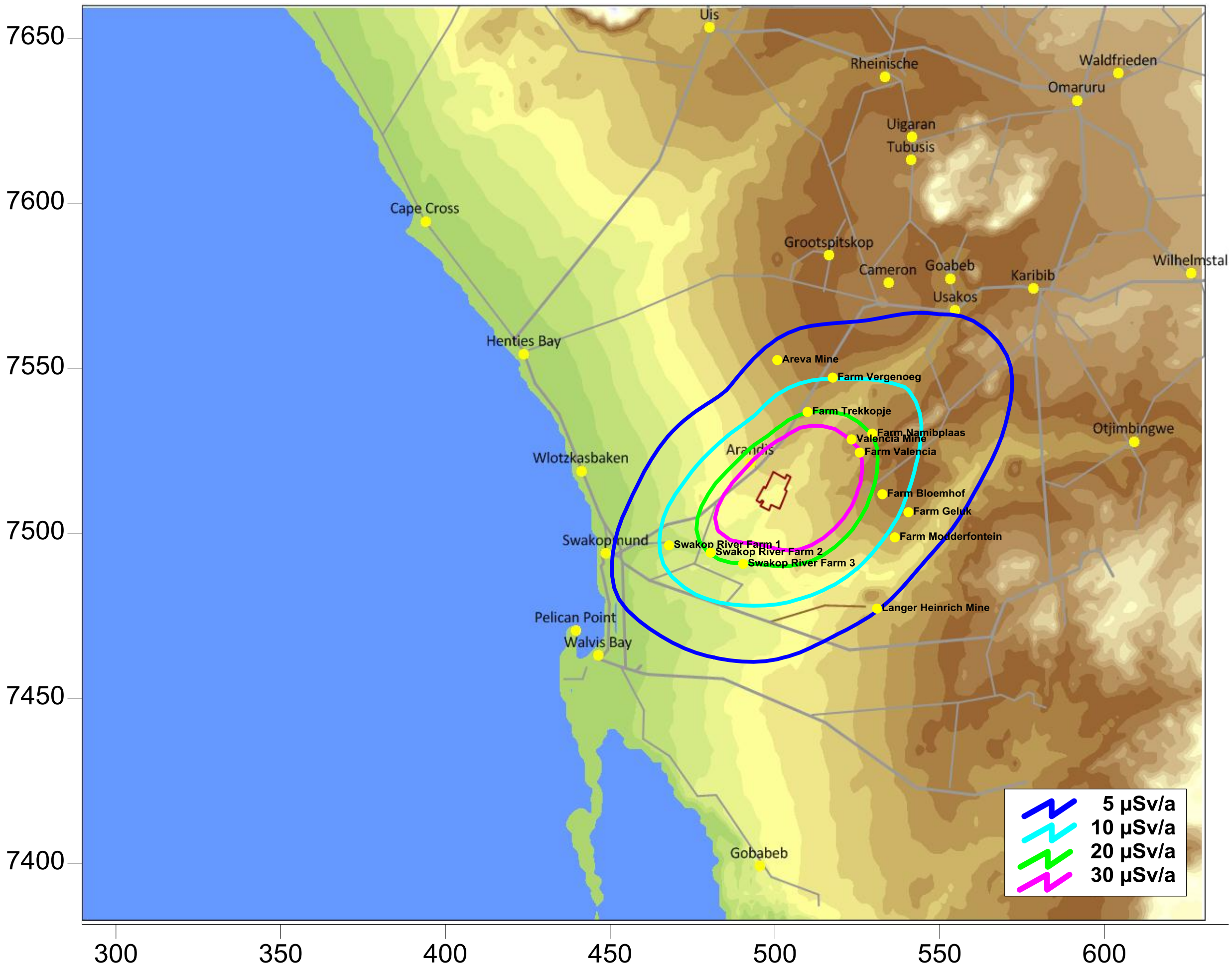

Figure 9: Calculated doses (µSv.a^{-1}) for Radon Inhalation from the *Expansion Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the far-field receptors.

6.6.2 Dust Inhalation Pathway

In [4] two different air dispersion models were used to calculate PM10 dust dispersion results. A near-field model was used for the receptors close to Rössing (see Figure 2), while a far-field model (also named a regional model) was used for the receptors further away. These models were run for each of the various dust sources that are in effect during a particular mining phase. This was done for both mining phases. No indoor modelling was performed so conservative doses were determined by assuming that the indoor concentration are equal to the outdoor concentrations.

The applicable dust dispersion results were converted to a dust inhalation dose (for an adult member of the public) by firstly linking the total radionuclide concentrations of the samples to the mining operation dust source (see Table 8) to obtain a radionuclide concentration. Secondly the concentrations were converted to a dose for an adult member of the public by using Equation 2 with a breathing rate of 0.93 $m^3 \cdot h^{-1}$ and a one year exposure time (that is 4380 hours indoors and 4380 hours outdoors). Hereafter the inhalation doses for all the mining dust sources for a particular mining phase were added to obtain the total dust inhalation dose. This was done for both mining phases. The total PM10 annual adult public dust inhalation dose results, indicated as contour plots are depicted in Figure 10 to Figure 13 for each of the mining phases and sets of receptors. Where applicable, the adult public doses above were next corrected for the various exposure times and inhalation rates as per Exposure Scenarios in Section 5.3.2 to present the annual doses for the various defined critical groups. The respective PM10 dust inhalation doses to each identified group for the two mining phases are summarised in Table 10. Public doses for other age groups relate to the adult doses through conversion to other inhalation rates and dose coefficients (see Appendix C in Section 14.0). Performing such a correction indicates lower doses than for adults for all age groups.

6.6.3 Total dose due to Atmospheric pathway

The total doses to the critical group in each Exposure Scenario due to atmospheric pathways are summarised in Table 11.

Table 10: Doses (μSv.a^{-1}) from Dust Inhalation for the different Exposure Scenarios.

Scenario Number	Description	Period Outdoors (h)	Period Indoors (h)	Dose (μSv.a^{-1})	
				Base Case	*Expansion Case*
1	Arandis Town	4380	4380	**24**	**28**
2	Arandis Airport	4380	4380	**41**	**46**
3	Khan Mine	4380	4380	**123**	**84**
4	E-Camp	0	2000	**8.0**	**11**
5	Farm Bloemhof	4380	4380	**7.0**	**12**
	Farm Modderfontein	4380	4380	**4.0**	**6.8**
	Farm Geluk	4380	4380	**4.1**	**7.0**
	Farm Valencia	4380	4380	**13**	**21**
	Portion 1 of Farm Namibplaas	4380	4380	**8.0**	**13**
	Farm Trekkopje	4380	4380	**7.5**	**12**
	Farm Vergenoeg	4380	4380	**4.0**	**6.5**
	Swakop River Farm 1	4380	4380	**5.0**	**8.0**
	Swakop River Farm 2	4380	4380	**9.5**	**15**
	Swakop River Farm 3	4380	4380	**9.5**	**16**
6	Swakopmund	4380	4380	**1.9**	**3.0**
7	Areva Mine	2000	0	**0.55**	**0.91**
	Valencia Mine	2000	0	**2.6**	**4.5**
	Langer Heinrich Mine	2000	0	**0.55**	**0.89**

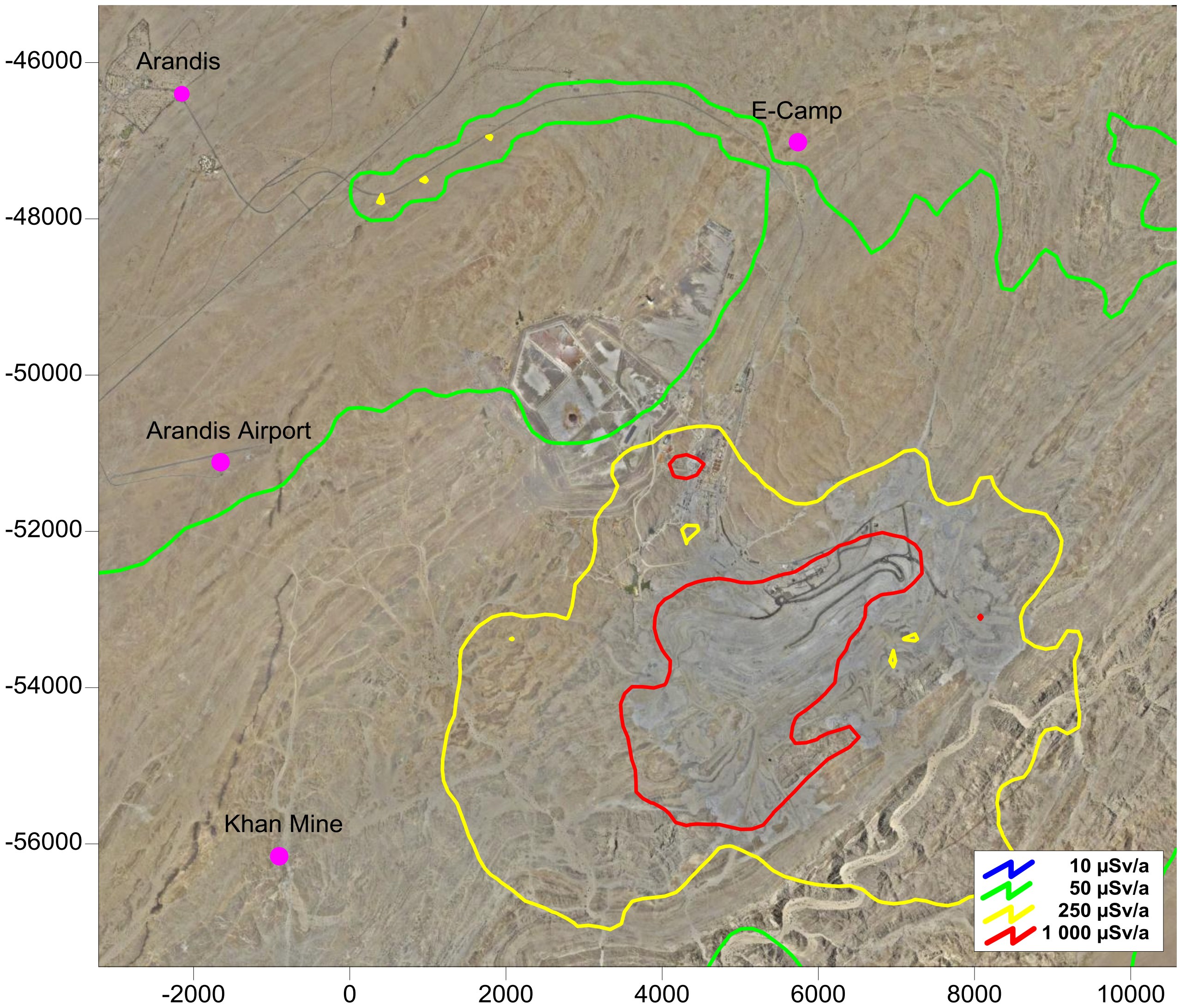

Figure 10: Calculated doses (µSv.a^{-1}) for Dust Inhalation from the *Base Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the near-field receptors.

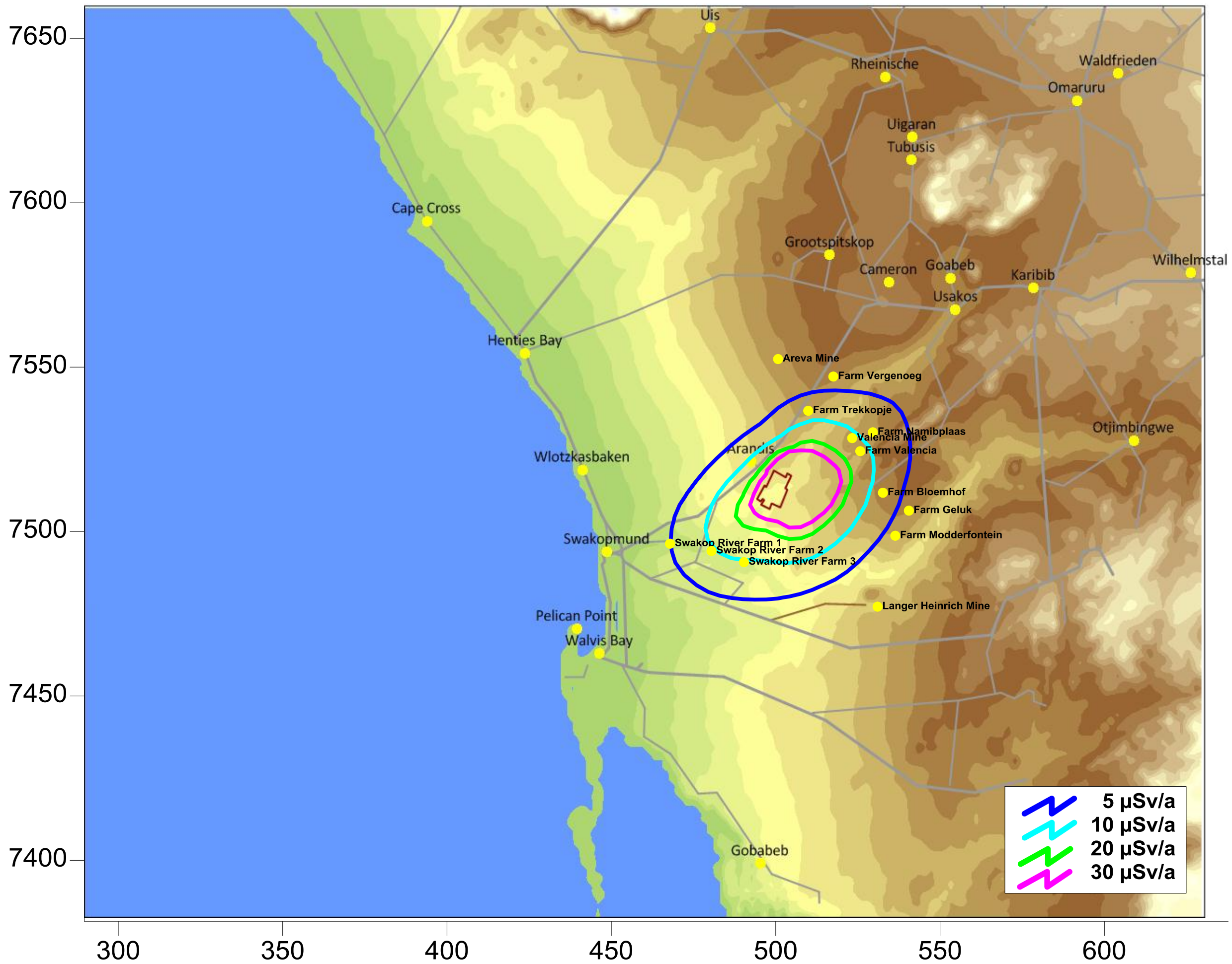

Figure 11: Calculated dose rates (µSv.h^{-1}) for Dust Inhalation from the *Base Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the far-field receptors.

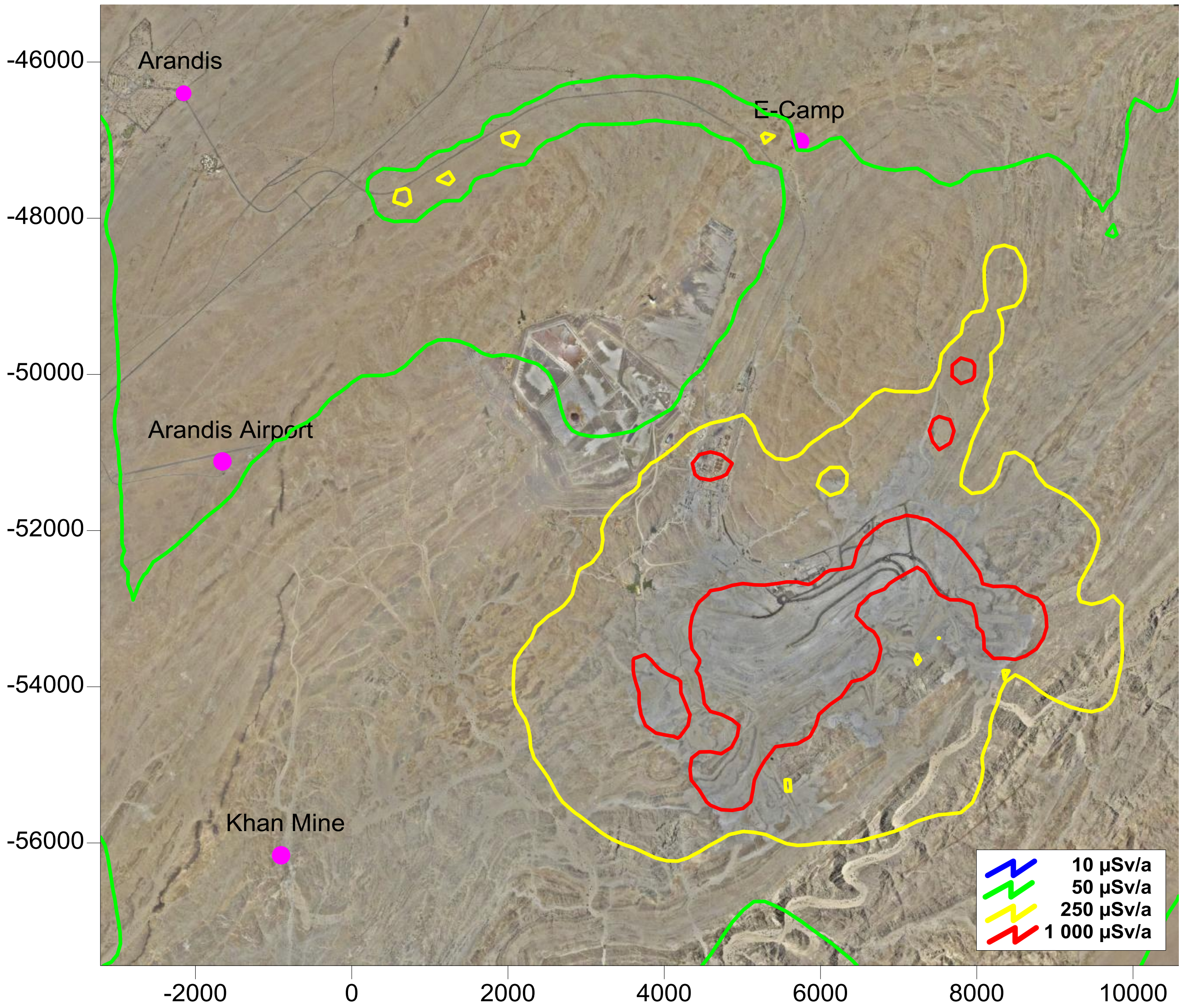

Figure 12: Calculated dose rates (µSv.h^{-1}) for Dust Inhalation from the *Expansion Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the near-field receptors.

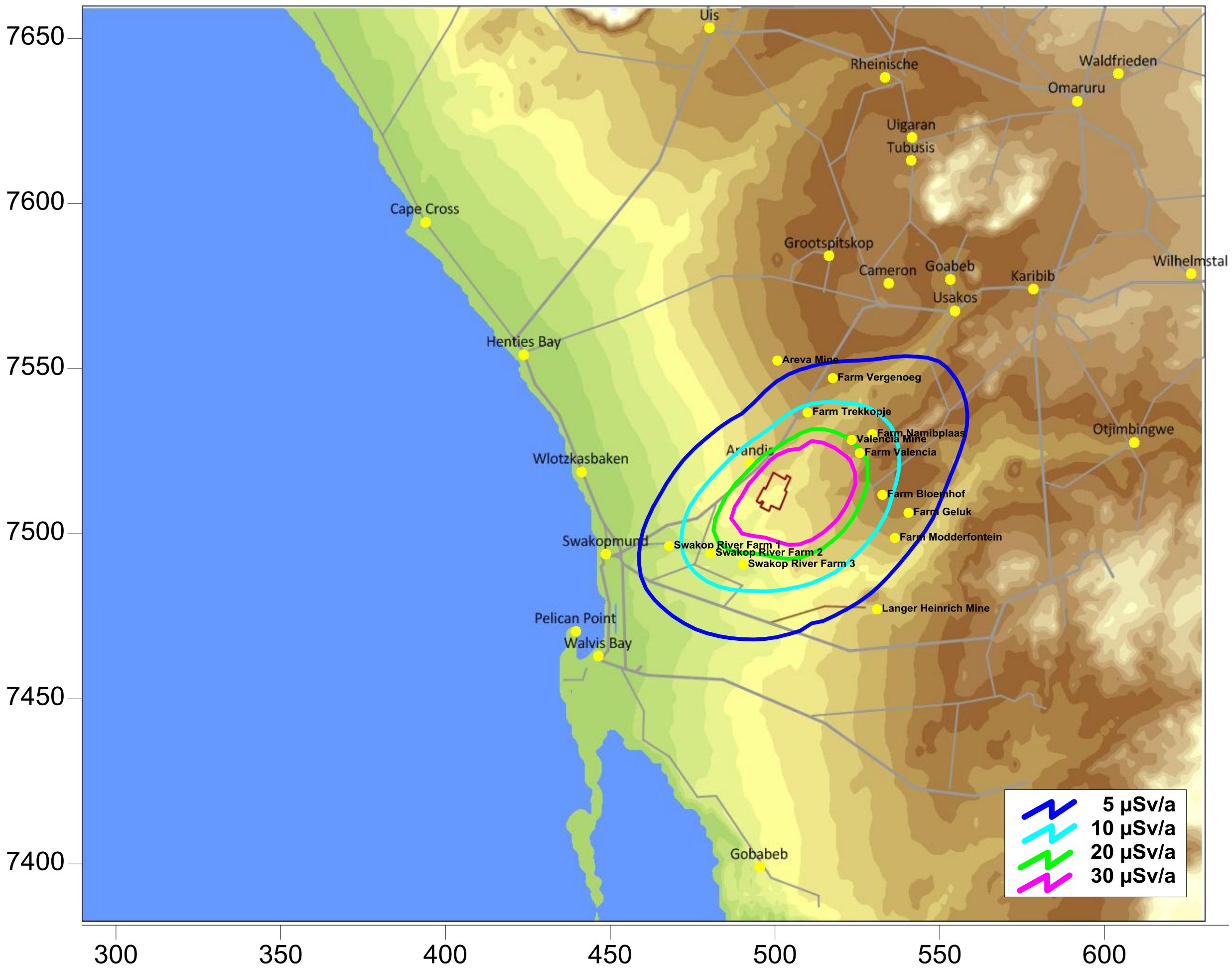

Figure 13: Calculated dose rates (µSv.h^{-1}) for Dust Inhalation from the *Expansion Case* for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors) at the far-field receptors.

Table 11: Total Doses (µSv.a^{-1}) from the Atmospheric Pathways for the different Exposure Scenarios.

Scenario Number	Description	Period Outdoors (h)	Period Indoors (h)	Dose (µSv.a^{-1})	
				Base Case	*Expansion Case*
1	Arandis Town	4380	4380	**43**	**49**
2	Arandis Airport	4380	4380	**78**	**86**
3	Khan Mine	4380	4380	**144**	**108**
4	E-Camp	0	2000	**15**	**20**
5	Farm Bloemhof	4380	4380	**20**	**27**
	Farm Modderfontein	4380	4380	**12**	**15**
	Farm Geluk	4380	4380	**12**	**16**
	Farm Valencia	4380	4380	**38**	**51**
	Portion 1 of Farm Namibplaas	4380	4380	**24**	**33**
	Farm Trekkopje	4380	4380	**24**	**32**
	Farm Vergenoeg	4380	4380	**12**	**17**
	Swakop River Farm 1	4380	4380	**15**	**20**
	Swakop River Farm 2	4380	4380	**28**	**36**
	Swakop River Farm 3	4380	4380	**27**	**36**
6	Swakopmund	4380	4380	**5.7**	**7.5**
7	Areva Mine	2000	0	**2.2**	**2.8**
	Valencia Mine	2000	0	**9.9**	**14**
	Langer Heinrich Mine	2000	0	**1.9**	**2.4**

6.7 DOSES FROM AQUATIC PATHWAY

Doses from aquatic pathways have not been assessed as part of the present project as no new information for such an assessment is available. Instead results from a post-closure assessment in 2002 [5] are presented below as an indication of possible doses from aquatic sources under post-closure conditions for both the current and expanded operations. These results relate to doses for Scenario 5 and Scenario 6 described in Sections 5.3.2.5 and 5.3.2.6. They were extracted from Table 13 and Table 14 of [5], and are presented in Table 12. They were assessed through a simple mixing model for seepage water from the tailings dam into the Khan River and subsequently into the Swakop River. They assume groundwater control operations would continue after mine closure and be discontinued only in subsequent years, when groundwater flows have reduced to such an extent that mixed major element water quality satisfies priority use criteria for the Khan River water (stock watering).

Table 12: Age-dependent public doses assessed for the aquatic pathways in [5]

Pathway	Doses (μSv.a^{-1}) for Farming on Smallholdings					Doses (μSv.a^{-1}) for Residents of Swakopmund				
	1 year	5 year	10 year	15 year	Adult	1 year	5 year	10 year	15 year	Adult
Doses from water consumption	0	0	0	0	0	0	0	0	0	0
Doses from external exposure to irrigated soil	17	17	17	17	17	0	0	0	0	0
Doses from ingestion of irrigated soil	4	3	2	3	0	0	0	0	0	0
Doses from milk consumption	12	7	7	8	2	4	3	2	3	1
Doses from beef consumption	1	1	2	2	1	0	1	1	1	1
Doses from goat meat consumption	0	1	1	1	1	0	0	0	0	0
Doses from poultry consumption	0	0	0	0	0	0	0	0	0	0
Doses from egg consumption	0	0	0	0	0	0	0	0	0	0
Doses from grain and cereal consumption	4	3	3	5	2	0	0	0	1	0
Doses from leafy vegetable consumption	3	2	2	4	1	0	0	0	0	0
Doses from root vegetable consumption	13	9	11	20	5	1	1	1	2	0
Total doses from all ingestion pathways	**54**	**43**	**45**	**60**	**29**	**5**	**5**	**4**	**7**	**2**

7.0 UNCERTAINTY ANALYSIS

Uncertainties can only be extracted in a limited way from information in [4] in as far as modelling was performed with weather information for various years and from the uncertainties associated with the radionuclide concentrations in the dust and the variation in the exhalation rates of radon sources. The analysis hereof is discussed below. ICRP dose conversion factors and inhalation rates are regarded as internationally accepted fixed values [14], hence no uncertainty association.

7.1 ATMOSPHERIC PATHWAY

7.1.1 Uncertainties in the Radon Dose Assessment

The total uncertainty in the Radon Dose Assessment consists of a contribution from the uncertainty in the annual variation in the weather information (σ_W) and a contribution from the variation in the exhalation rates (σ_E) used in the characterisation of the radon sources.

The radon dispersion data received from Airshed Planning Professionals (Pty) Ltd was modelled based on 2004 weather information and the different radon exhalation rates applicable to the radon sources. The uncertainty in the weather information was estimated by modelling additional radon dispersion data for the inner receptors using weather information for the years 2000, 2001, 2002, 2003 and 2004 and calculating the respective doses for the Scenarios 1 to 4. As a first order approximation it was assumed that the data (like many other data sets from natural processes) will fit a normal distribution. The uncertainty in the data could therefore be determined by the calculation of the standard deviation, σ_W.

Airshed Planning Professional (Pty) Ltd also provided the exhalation rates used in the modelling. The values ranged from 0.472 – 4.89 $Bq.m^{-2}.s^{-1}$ for the different sources. With a standard deviation of 1.00 $Bq.m^{-2}.s^{-1}$ and an average exhalation rate of 1.51 $Bq.m^{-2}.s^{-1}$ the assumption was made that the uncertainty in the exhalation rates (σ_E) is equal to 67% of the mean value of the doses for the different years.

The total standard deviation σ_{Radon} was estimated for each assessed dose from the standard deviations σ_E and σ_W as per equation below,

$$\sigma_{Radon} = \sqrt{\sigma_E^2 + \sigma_W^2} \quad \text{Eq. 3}$$

Furthermore, maximum radon doses considered as representing the upper 95% confidence level were calculated by adding the mean and 1.96 standard deviations of the respective scenarios. All the 2010 and 2013 radon inhalation doses are lower than their respective upper confidence levels. This means that the assessed data for the *Base Case* and *Expansion Case* are usable as it falls within the boundaries of the distribution. The doses, standard deviations and upper confidence levels for the two mining phases are summarised in Table 13 and Table 14.

7.1.2 Uncertainties in the Dust Dose Assessment

The total uncertainty in the Dust Dose Assessment consists of a contribution from the uncertainty in the annual variation in the weather information (σ_W) and a contribution from the uncertainty in the radioanalytical data (σ_R) used in the characterisation of the source terms.

The dust dispersion data was modelled based on 2004 weather information. To estimate the uncertainty in the weather information a similar approach to that of the radon uncertainty was adopted. Dust inhalation doses for Scenarios 1-4 were determined using weather information for the years 2000, 2001, 2002, 2003 and 2004. As with the radon doses, it was assumed that the dust doses form a normal distribution. Standard deviations (σ_W) were calculated and taken as the uncertainty in the annual variation in weather information.

As discussed earlier, Table 8 summarises the links between the dust sources and the radionuclide concentrations extracted from the Rössing data base. However uncertainties for the latter were not provided. In a few cases it was possible to calculate standard deviations from the provided lists of concentrations in the data base used to determine the average values in Table 8. The average standard deviation was 46% and the assumption was made that the radionuclide uncertainty σ_R is therefore equal to 46% of the mean value of the doses for the different years.

An estimate of the total standard deviation σ_{Dust} was obtained for each assessed dose from the standard deviation σ_R and the standard deviation σ_W as per equation below.

$$\sigma_{Dust} = \sqrt{\sigma_R^2 + \sigma_W^2} \quad \text{Eq. 4}$$

Table 13: Doses, standard deviations, mean values and maximum doses for all the Scenarios used for the determination of the uncertainty in the Radon Dose Assessment for the *Base Case*.

Scenario Number	Description	Dose ($\mu Sv.a^{-1}$)						Std Dev	Mean Value	Maximum Dose ($\mu Sv.a^{-1}$)
		2000	2001	2002	2003	2004	2010	σ	μ	μ + 1.96 σ
1	Arandis Town	23	17	20	16	13	19	12	18	42
2	Arandis Airport	43	25	38	43	27	37	25	35	84
3	Khan Mine	15	21	21	23	25	21	14	21	49
4	E-Camp	6.8	7.2	8.6	6.5	6.1	7.3	4.8	7.0	16

Table 14: Doses, standard deviations, mean values and maximum doses for all the Scenarios used for the determination of the uncertainty in the Radon Dose Assessment for the *Expansion Case*.

Scenario Number	Description	Dose ($\mu Sv.a^{-1}$)						Std Dev	Mean Value	Maximum Dose ($\mu Sv.a^{-1}$)
		2000	2001	2002	2003	2004	2013	σ	μ	μ + 1.96 σ
1	Arandis Town	27	19	24	19	15	21	15	21	49
2	Arandis Airport	50	29	42	48	31	40	28	40	95
3	Khan Mine	19	24	24	26	27	24	16	24	56
4	E-Camp	8.3	8.8	11	7.8	7.8	8.7	5.9	8.7	20

Furthermore, maximum dust inhalation doses considered as representing the upper 95% confidence level were calculated by adding the mean and 1.96 standard deviations of the respective scenarios. All the 2010 and 2013 dust inhalation doses are lower than their respective upper confidence levels. This means that the assessed data for the *Base Case* and *Expansion Case* are usable as it falls within the boundaries of the distribution. The doses, total standard deviations and upper confidence levels for the two mining phases are summarised in Table 15 and Table 16.

7.2 AQUATIC PATHWAY

Uncertainties in aquatic pathway doses are discussed in [5], but are mainly based on variations in analytical data, while the uncertainty related to the simple mixing model used was not addressed. This model represents only a very simple modelling exercise of the flow behaviour of effluent, hypothetically mixed into the Khan River water and neglect major effects in the transport behaviour of the radionuclides in the water and soil. As this will force the results to the conservative side it may overestimate the aquatic doses considerably. No attempt will hence be made to assess uncertainties for the aquatic pathway results, and the values will merely be used in a qualitative way.

The aquatic pathway only relates to the Scenarios 5 and 6 involving small holdings or farms down the Swakop River and inhabitants of Swakopmund. Total doses from radon and dust for these two scenarios were less than 60 $\mu Sv.a^{-1}$. Aquatic doses for these scenarios in [5] range from 2 to 7 $\mu Sv.a^{-1}$ for *residents of Swakopmund* and 29 to 60 $\mu Sv.a^{-1}$ for the *farmers at the Smallholdings*. No radon and dust uncertainties were assessed for these scenarios, but if one uses the total uncertainty that were evaluated for e.g. Arandis (as a conservative estimate) for both the atmospheric and aquatic pathways, the maximum total dose with the aquatic pathway included is still less than the dose constraint of 300 $\mu Sv.a^{-1}$.

Table 15: Doses, total standard deviations, mean values and maximum doses for all the Scenarios used for the determination of the uncertainty in the Dust Dose Assessment for the *Base Case*.

Scenario Number	Description	Dose ($\mu Sv.a^{-1}$)						Total Std Dev	Mean Value	Maximum Dose ($\mu Sv.a^{-1}$)
		2000	2001	2002	2003	2004	2010	σ_T	μ	$\mu + 1.96\ \sigma_T$
1	Arandis Town	**25**	**21**	**23**	**19**	**18**	**24**	**10**	**21**	**41**
2	Arandis Airport	**46**	**28**	**44**	**37**	**29**	**41**	**19**	**37**	**74**
3	Khan Mine	**140**	**83**	**110**	**127**	**83**	**123**	**56**	**109**	**219**
4	E-Camp	**6**	**8**	**9**	**7**	**5**	**8**	**4**	**7**	**14**

Table 16: Doses, standard deviations, mean values and maximum doses for all the Scenarios used for the determination of the uncertainty in the Dust Dose Assessment for the *Expansion Case*.

Scenario Number	Description	Dose ($\mu Sv.a^{-1}$)						Total Std Dev	Mean Value	Maximum Dose ($\mu Sv.a^{-1}$)
		2000	2001	2002	2003	2004	2010	σ_T	μ	$\mu + 1.96\ \sigma_T$
1	Arandis Town	**25**	**22**	**25**	**20**	**16**	**28**	**11**	**22**	**42**
2	Arandis Airport	**46**	**32**	**44**	**39**	**30**	**48**	**19**	**38**	**75**
3	Khan Mine	**88**	**57**	**67**	**78**	**56**	**88**	**35**	**69**	**137**
4	E-Camp	**9**	**10**	**12**	**9**	**7**	**11**	**5**	**9**	**18**

8.0 DISCUSSION OF RESULTS AND RECOMMENDATIONS

8.1 Radiation Management Program

The draft regulations of the National Radiation Protection Authority (NRPA) [10], mentioned in Section 3.4.1, require that an authorization application must be accompanied by a Radiation Management Program that, among other requirements, addresses in particular the following:

- all relevant information relating to the impact of the practice on public interests,
- the results of all assessments, including environmental impact assessments and studies that have been carried out in respect of the practice concerned as well as reports of those assessments and studies when the application is for disposal of radioactive waste or storage of radioactive sources for long periods,
- particulars of the impact of the practice on private interests, including the interests of affected landowners and holders of other rights and interests in land.

While this report deals with the impact of radioactive sources at Rössing on the surrounding public and other interests, it relates mostly to the operational phase of the mine. Long-term (e.g. post-closure) requirements as well as general radioactive waste management requirements are not particularly addressed. Rössing compiled a radioactive waste management program in this regard that addressed the long-term (e.g. post-closure) and other management requirements such as the segregation and categorization of radioactive waste and submitted it to the NRPA.

8.2 Evaluation Against radiological criteria

The following radiological criteria are considered in the discussion below:

b) Doses below10 µSv.a^{-1} are regarded as trivial and of no concern.

c) Doses below 300 µSv.a^{-1} are regarded as below a source constraint (for the Rössing Mine), ranked as a low risk only needing low priority attention in terms optimization to keep doses As Low as Reasonably Achievable (ALARA).

d) Doses between 300 $\mu Sv.a^{-1}$ and 1000 $\mu Sv.a^{-1}$ are regarded as below the public dose limit, but of medium risk as they are above the source constraint and need medium priority attention for optimization to keep doses As Low as Reasonably Achievable (ALARA).

e) Doses above 1000 $\mu Sv.a^{-1}$ are above the public dose limit, of high risk, and need high priority in terms of attention for reduction to below the public dose limit.

As mentioned in Section 3.4.1, the radon and dust inhalation pathways will be evaluated separately and combined against the criteria above.

8.2.1 Radon Inhalation

The assessed doses due to Radon Inhalation are summarised in Table 9. These doses are age independent and also apply to children.

For the *Base Case* radon inhalation doses are trivial (smaller than 10 $\mu Sv.a^{-1}$) for the people at the mines Langer Heinrich, Valencia and Areva, the workers at the E-Camp, the residents of Swakopmund and the residents of the farms Modderfontein, Geluk and Vergenoeg. The radon doses are low for the residents of Arandis (19 $\mu Sv.a^{-1}$), the Arandis Airport (37 $\mu Sv.a^{-1}$), the Khan Mine (21 $\mu Sv.a^{-1}$), the residents of the Swakop River Farms 1, 2, 3 (10 $\mu Sv.a^{-1}$, 18 $\mu Sv.a^{-1}$ and 17 $\mu Sv.a^{-1}$ respectively) and the residents of the farms Bloemhof (13 $\mu Sv.a^{-1}$), Valencia (25 $\mu Sv.a^{-1}$), Namibplaas (16 $\mu Sv.a^{-1}$) and Trekkopje (16 $\mu Sv.a^{-1}$). No measures are hence recommended to safeguard the public at the mentioned locations.

The radon inhalation doses for the *Expansion Case* are higher than for the *Base Case*. The radon inhalation doses are trivial (smaller than 10 $\mu Sv.a^{-1}$) for the people at the mines Langer Heinrich, Valencia and Areva, the workers at the E-Camp, the residents of Swakopmund and the residents of the farms Modderfontein and Geluk. The radon doses are low for the residents of Arandis (21 $\mu Sv.a^{-1}$), the Arandis Airport (40 $\mu Sv.a^{-1}$), the Khan Mine (24 $\mu Sv.a^{-1}$), the residents of the Swakop River Farms (12 $\mu Sv.a^{-1}$, 21 $\mu Sv.a^{-1}$ and 20 $\mu Sv.a^{-1}$ respectively) and the residents of the farms Bloemhof (15 $\mu Sv.a^{-1}$), Valencia (30 $\mu Sv.a^{-1}$), Namibplaas (20 $\mu Sv.a^{-1}$), Trekkopje (20 $\mu Sv.a^{-1}$) and Vergenoeg (10 $\mu Sv.a^{-1}$). No measures are hence recommended to safeguard the public at the mentioned locations.

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The assessed doses for both mining phases are below the 300 $\mu Sv.a^{-1}$ source constraint, even with the addition of the uncertainty.

In Section 6.5.1 it is mentioned that mitigation options would reduce radon inhalation doses with only 4%. If this is applied it would leave the radiological criteria grouping for the respective locations as it is.

8.2.2 Dust Inhalation

The assessed doses due to Dust Inhalation are summarised in Table 10. These doses represent the most conservative assessments in terms of age since they were calculated for adults i.e. doses to children would be lower than indicated.

For the *Base Case* dust inhalation doses are trivial (smaller than 10 $\mu Sv.a^{-1}$) for the people at the mines Langer Heinrich, Valencia and Areva, the workers at the E-Camp, the residents of Swakopmund, the residents of the Swakop River Farms 1, 2, 3 and the residents of the farms Bloemhof, Modderfontein, Geluk, Namibplaas, Trekkopje and Vergenoeg. The dust inhalation doses are low for the residents of Arandis (24 $\mu Sv.a^{-1}$), the Arandis Airport (41 $\mu Sv.a^{-1}$), the Valencia Farm (13 $\mu Sv.a^{-1}$) and the Khan Mine (123 $\mu Sv.a^{-1}$). Although the dose at the Khan Mine was over 100 $\mu Sv.a^{-1}$ it is still lower than the dose constraint. No measures are hence recommended to safeguard the public at the mentioned locations.

The dust inhalation doses are higher for the *Expansion Case* then for the *Base Case* except for the Khan Mine which has a lower dose. The dust inhalation doses are trivial (smaller than 10 $\mu Sv.a^{-1}$) for the people at the mines Langer Heinrich, Valencia and Areva, the residents of Swakopmund, the residents of the Swakop River Farm 1 and the residents of the farms Modderfontein, Geluk and Vergenoeg. The dust inhalation doses are low for the residents of Arandis (28 $\mu Sv.a^{-1}$), the Arandis Airport (46 $\mu Sv.a^{-1}$), the residents of the farms Bloemhof (12 $\mu Sv.a^{-1}$), Valencia (21 $\mu Sv.a^{-1}$), Namibplaas (13 $\mu Sv.a^{-1}$), Trekkopje (12 $\mu Sv.a^{-1}$), the residents of the Swakop River Farms 2 (15 $\mu Sv.a^{-1}$)and 3 (16 $\mu Sv.a^{-1}$), the workers at the E-Camp (11 $\mu Sv.a^{-1}$) and the Khan Mine (84 $\mu Sv.a^{-1}$). No measures are hence recommended to safeguard the public at the mentioned locations.

The assessed doses for both mining phases are below the 300 $\mu Sv.a^{-1}$ source constraint, even with the addition of the uncertainty. Mitigation options were hence not assessed. It was also observed that in Post Closure conditions the only dust sources remaining would be the tailings dam, Ripios and waste rock dumps. If only these dust sources are used for the dose assessment the resulting doses would be in the order of 1% of the doses mentioned in this section.

8.2.3 Total Dose for Atmospheric Pathways

The total doses due to Dust Inhalation and Radon Inhalation are summarised in Table 11. These are all below the 300 µSv.a^{-1} source constraint, even with the addition of the uncertainty.

In a recent completed Strategic Environmental Assessment for the Central Namib Uranium Rush [22] the annual average total dose from all sources (i.e. exposure from background, medical and mining sources) received by residents of Arandis (taken as the worst case scenario) is derived as 2.29 mSv.a^{-1}. If the background dose of 1.97 mSv.a^{-1} [22] is subtracted a person would receive a dose of 0.32 mSv.a^{-1} from all mining and medical sources, including the existing Rössing sources. However, even when adding the maximum dose assessed in this report as an additional mining source, a person would still receive less than the 1 mSv.a^{-1} dose limit.

8.3 Data Verification

The radionuclide concentrations of the various materials (as tabulated in Table 7) were compared to the latest radioanalytical data (tabulated in Section 16.0). This was performed by linking the various materials to all the possible experimental data sets e.g. *Ore in open pit* is linked to *Open pit bench ore*. Refer to Table 17 for these correlations. Where more than one set of data is applicable the average radionuclide concentration was used for the comparison. These concentrations are tabulated in Table 18.

The average radionuclide concentrations used in this report compare well with the latest radioanalytical data, taking into account the uncertainty that can be in the order of 46%. Only in the case of the *Ore in the open pit* is the analysis data for the uranium radionuclides in the order of a factor of 3 higher and for the radium a factor of 2 higher than the used values. Compared to the data base of values this sample can be seen as an outlier and the area where it was sampled should be verified with more samples before it can be used to raise a concern.

Table 17: Various materials linked to the latest radioanalytical data

Material	Experimental Data
ROM Ore	Primary crusher conveyor Coarse ore stockpile conveyor P stockpile Coarse ore stockpile
Tailings	Tailings sample coarse Tailings sample intermediate
Fine crushing dust	Fine ore conveyor spillage Fine ore stockpile Fine crushing plant
Ore in open pit	Open pit bench ore
Waste in open pit	None
Stacks	None
Ripios	Tailings proposed heap

Table 18: Average radionuclide concentrations ($Bq.g^{-1}$) for various materials, derived from the latest radioanalytical data

Description	^{238}U	^{234}U	^{226}Ra	^{210}Pb	^{235}U	^{232}Th	^{228}Ra	^{228}Th
ROM Ore	6.87	6.93	5.26	-	0.32	0.23	0.20	0.18
Tailings	0.84	0.84	4.87	6.28	0.04	0.14	0.14	0.12
Fine crushing dust	5.21	5.26	5.20	-	0.24	0.21	0.19	0.14
Ore in open pit	10.3	10.4	6.20	-	0.48	0.35	0.17	0.19
Ripios	1.09	1.09	1.55	-	0.05	0.09	0.17	0.16

9.0 EVALUATION AGAINST SEIA CRITERIA

9.1 ICRP APPROACH TO RISK

The ICRP has estimated the probability of a fatal cancer by relying mainly on studies of the Japanese survivors of the atomic bombs and their assessment by bodies such as UNSCEAR and BEIR. The ICRP uses the term detriment to represent the combination of the probability of occurrence of a harmful health effect and a judgement of the severity of that effect. The many aspects of detriment make it undesirable to select a single quantity to represent the detriment and the ICRP has therefore adopted a multi-dimensional concept. Nonetheless, the ICRP presents in its latest publication [9] risk coefficients for a whole population (meaning not age-dependent) as 0.055 per 1 Sievert of exposure for fatal cancer and 0.002 per 1 Sievert of exposure for heritable effects. This means that for the highest dose of 144 $\mu Sv.a^{-1}$, as assessed in this report, it is likely that there will be 8 fatal cancers per million people exposed and 3 people with heritable effects per 10 million people exposed i.e. the possibility is very low. For the area of Rössing's influence this means that for the highest assessed dose of 144 $\mu Sv.a^{-1}$ not even one person of the ~ 100 000 members of the public, that live in the vicinity of Rössing, is expected to develop fatal cancer or heritable effects due to the operations of Rössing. i.e. the possibility is very low.

9.2 SEIA RISKS

Based on the tables given in Section 3.5 and the results of this assessment the following evaluations can be done.

The EXTEND of the risks is within the *Regional Category*. The Criteria for ranking the MAGNITUDE of impacts and PROBABILITY (of exposure to impacts) are based on the ICRP proposed data. Should a person contract cancer the MAGNITUDE is high as it can lead to fatality. However the probability of obtaining fatal cancer is linked to the dose risk coefficient and the dose received. In the case of Rössing the dose is regarded as low (below or close to a trivial level). For this reason the MAGNITUDE is taken as *Low* and the PROBABILITY taken as *Unlikely* (less than 1 in a 100 000). The DURATION is taken as *Long Term* as it could remain post-closure. The CONFIDENCE is taken as *Certain* and the REVERSIBILITY RATING as *Irreversible* if a person contract cancer.

Using the above mentioned indicators and the fact that the assessed doses are all below the dose constraint, the SEIA SIGNIFICANCE risks for dust and radon to members of the public for all the Exposure Scenarios are hence regarded as **"Low"** not requiring immediate attention. The same finding applies to the planned future expansion as the assessment does not present any significant increase in the radiological risks due to dust and radon inhalation.

10.0 FINAL CONCLUSION AND RECOMMENDATIONS

The outcome of this public dose assessment indicated that, for the identified critical groups as per the defined exposure scenarios, the doses received from the relevant sources of exposure during the proposed mining operations for the various mining phases are trivial to low i.e. resulting doses are lower than the dose constraint of 300 $\mu Sv.a^{-1}$.

There seems to be no significant difference between the impacts of the *Base Case* and the *Expansion Case*.

Uncertainty analysis was difficult to perform since no uncertainty values for the dust source terms were available. The approach taken may have overestimated the total uncertainty in the assessment. However, the derived maximum dust inhalation doses and radon doses still remained lower than the dose constraint.

The radioanalytical results used in this assessment is generally in good agreement with the latest radioanalytical results of single samples presented in [19], taking the assumed 46% uncertainty into account. It is however good practise to use a database of values to determine an average value than rely solely on one set of data, due to the possibility of outliers. As a result of this large uncertainty it is suggested that the on-going monitoring and surveillance program of radon and dust concentrations be used to verify the findings of this assessment, especially in the area where the *Ore in the open pit* [19] sample was taken. These measurements will also be used to improve the accuracy during a retrospective review of this hazard assessment to be performed according to regulatory requirements and guidance.

The Necsa assessment was performed taking cognisance of specific critical groups. The scenarios may, however change with time. Rössing should therefore continuously study possible movement of people into the area that could influence the outcome of the studied scenarios. It is recommended to review, on an on-going basis, the validity of the identified critical group(s) and re-define these if changes are noticed.

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12.0 APPENDIX A: SCOPE OF SUB-CONSULTANCY SERVICES

12.1 INTRODUCTION

The potential impact of radiological exposure on the public will be assessed by means of collating available information and extrapolating predicted dispersion of radioactive material by means of modelling. The public dose assessment will be informed by modelling of emissions through the atmospheric pathway.

The purpose is to determine whether a maximum mine expansion will increase public exposure of the critical group above the dose constraint of 300 micro Sieverts per year during the operational phase and post closure. If required, prevention strategies or mitigation of exposures above the dose constraint will be prescribed.

In addition, the increased exposure to Radon in the workplace as a result of the increased production, will be assessed.

12.2 SCOPE OF WORK

The work will consist of considering public exposure at a number of receptor locations through the atmospheric pathway (radioactive dust and radon). The future scenarios to be assessed are the operational phase of Rössing Uranium's maximum expansion scenario taking all the above developments into account, and the post closure scenario. The scope of work is broken down into two phases.

The first phase, for which a proposal is requested under this cover, should consider public exposure at a number of receptor locations through the atmospheric pathway (radioactive dust and radon).

The work considers the operational phase of the planned expansion scenario, as well as the post closure scenario. The purpose is to determine whether a maximum expansion will increase public exposure of the critical group above the dose constraint. Should this be the case, development will need to be constrained or managed in a way to prevent or mitigate exposures above the dose constraint. It is assumed that post closure exposures caused by the maximum expansion will be equal to or lower than the exposure in the operational phase. This will be assessed and included in the reporting.

The dose constraint to be used is 300 micro Sieverts per year. A stochastic approach should be adopted in the assessment and the significance of the change in exposure caused by the additional dose compared to background dose should be determined. The radon background will need to be remodelled. A sensitivity analysis should be carried out in order to understand which potential mitigation alternatives would result in the most significant dose reduction. The extent of the stochastic treatment as well as the sensitivity and uncertainty analysis will depend on the extent of such analyses performed on the dispersion results and may require only expected and conservative doses to be determined.

The work does not include an assessment of the aquatic pathway as no modelling data is available for this exercise.

12.2.1 Receptor location and assessment scenario

The receptor locations to be assessed are:

a. Khan Mine,
b. Farm Bloemhof,
c. Farm Modderfontein,
d. Farm Geluk,
e. Farm Valencia,
f. Portion 1 of Farm Namibplaas,
g. Farm Trekkopje,
h. Farm Vergenoeg,
i. E-Camp,
j. Arandis Airport,
k. Swakop River Farms,
l. Areva Mine,
m. Swakopmund,
n. Arandis,
o. Valencia Mine and
p. Langer Heinrich Mine.

The workplace exposure to radon will be based on current radon monitoring on the mine and increased proportionally with increased production rate. The operational phase of the maximum expansion scenario will have a number of sources of radon and radioactive dust:

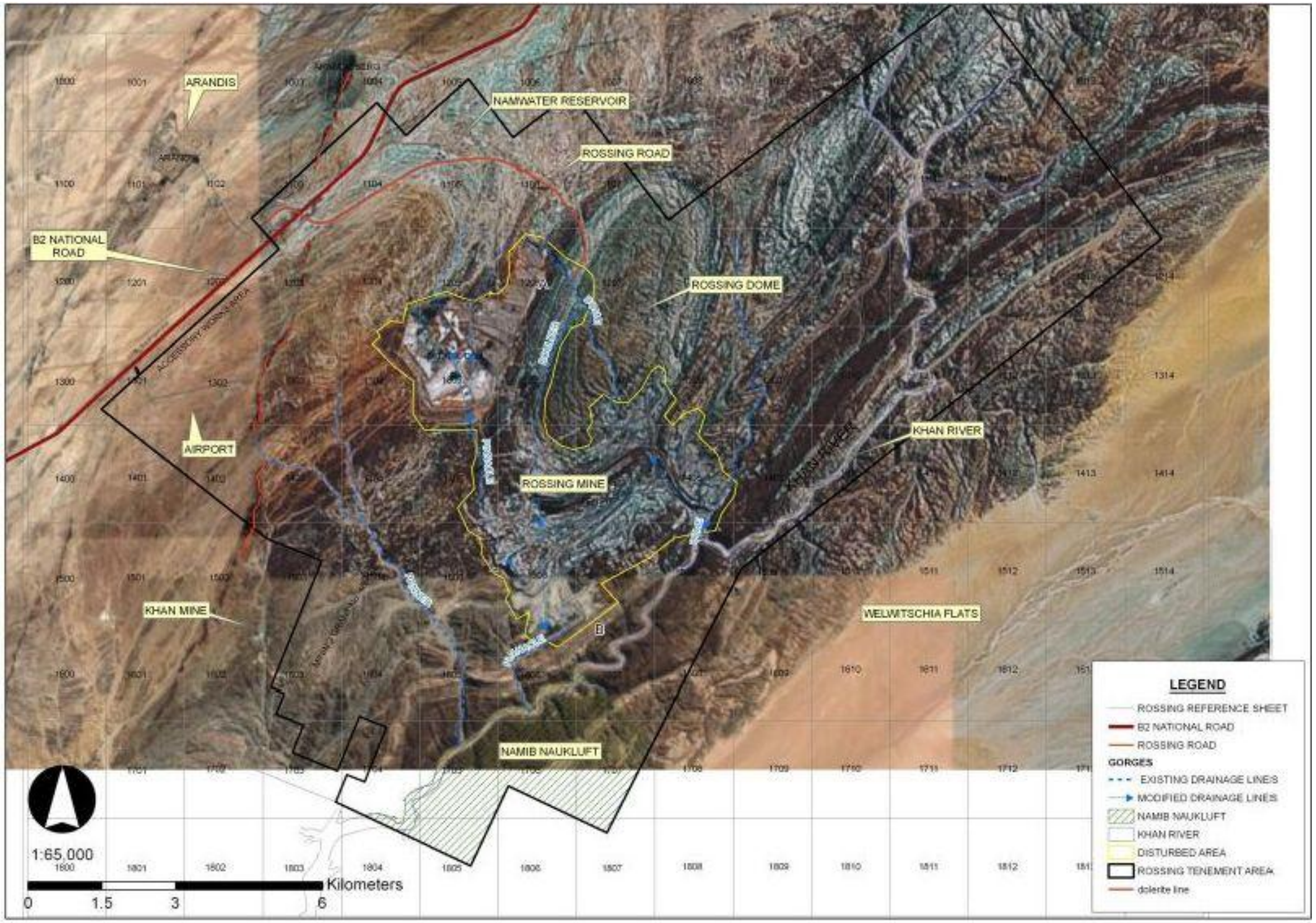
- Extension of the current mining activities in the existing SJ open pit;
- Expanding the waste rock disposal capacity;
- Establishment of a new crushing plant;
- Expanding the tailings disposal capacity;
- Establishment of an acid heap leaching facility; and
- Establishment of a ripios (spent ore from heap leaching) disposal area.

12.2.2 Deliverables

In order for the results to be incorporated into mine planning and for the work to be reviewed by independent third parties, the following deliverables are required:

1) A report including a stochastic assessment and a sensitivity analyses and sufficient illustrations for the reviewers to understand the input parameters (such as dust generation and meteorological conditions) and sources for the model. The report must contain appendices with tables of all data used; and
2) A set of digital maps showing receptor locations, source geometry and iso-dose contours for the maximum expansion scenario on the locally used survey grid system (LO15).
3) An assessment of risk of exceedances of relevant standards and potential adverse human health impacts is to be undertaken and included in the report to the Consultant.

13.0 APPENDIX B: MAP OF RÖSSING SITE AND THE SURROUNDING ENVIROMENT



14.0 APPENDIX C: DOSE ASSESSMENT PARAMETERS

Table 19: Calculation of daily-inhaled volumes for different age groups.

Type of Activity	Age = 0 – 2 a			Age = 2 - 7 a			Age = 7 - 12 a			Age = 12 - 17 a			Adults		
	T	B	T*B	T	B	T*B	T	B	T*B	T	B	T*B	T	B	T*B
Sleep	14.00	0.15	2.10	12.00	0.24	2.88	10.00	0.31	3.10	10.00	0.42	4.20	8.00	0.45	3.60
Sitting	3.33	0.22	0.73	4.00	0.32	1.28	4.67	0.38	1.77	5.50	0.48	2.64	6.00	0.54	3.24
Light exercise	6.67	0.35	2.33	8.00	0.57	4.56	9.33	1.12	10.45	7.50	1.38	10.35	9.75	1.50	14.63
Heavy exercise	-	-	-	-	-	-	-	-	-	1.00	2.92	2.92	0.25	3.00	0.75
Total per day	24		5.17	24		8.72	24		15.32	24		20.11	24		22.22
Avg. per hour	**0.22**			**0.36**			**0.64**			**0.84**			**0.93**		
T = Hours per day , B = Inhalation rate (m^3 h^{-1}) as per ICRP-71 Table 6															

Table 20: Dose coefficients (Sv.Bq^{-1}) to calculate inhalation doses for the public impact assessment

Only the radionuclides in the decay series that will contribute significantly to the total doses were selected and are listed below.

Age Group	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Pa-231	Ac-227	Ra-223	Th-232	Ra-228	Th-228	Ra-224
0 – 2	2.5E-05	2.9E-05	3.5E-05	2.9E-05	1.8E-05	1.4E-05	6.9E-05	2.0E-04	2.4E-05	5.0E-05	4.8E-05	1.3E-04	9.2E-06
2 – 7	1.6E-05	1.9E-05	2.4E-05	1.9E-05	1.1E-05	8.6E-06	5.2E-05	1.3E-04	1.5E-05	3.7E-05	3.2E-05	8.2E-05	5.9E-06
7 – 12	1.0E-05	1.2E-05	1.6E-05	1.2E-05	7.2E-06	5.9E-06	3.9E-05	8.7E-05	1.1E-05	2.6E-05	2.0E-05	5.5E-05	4.4E-06
12 – 17	8.7E-06	1.0E-05	1.5E-05	1.0E-05	5.9E-06	5.1E-06	3.6E-05	7.6E-05	1.1E-05	2.5E-05	1.6E-05	4.7E-05	4.2E-06
Adults	8.0E-06	9.4E-06	1.4E-05	9.5E-06	5.6E-06	4.3E-06	3.4E-05	7.2E-05	8.7E-06	2.5E-05	1.6E-05	4.0E-05	3.4E-06
Workers	5.7E-06	6.8E-06	7.2E-06	2.2E-06	1.1E-06	2.2E-06	1.7E-05	4.7E-05	5.7E-06	1.2E-05	1.7E-06	3.2E-05	2.4E-06

Report on the Radiological Public Hazard Assessment for the Expansion of Rössing Uranium Mine in Namibia, as a Specialist Study for the Phase II SEIA

15.0 APPENDIX D: GENERIC INTERACTION MATRIX

1.1 Tailings dam	2.1 X	3.1 X	4.1 X	5.1 X	6.1 X	7.1 Wind erosion	8.1 Exhalation	9.1 Run-off	10.1 Water erosion	11.1 Seepage	12.1 X	13.1	14.1 External exposure	15.1	16.1 External exposure	17.1 External exposure
1.2 X	2.2 Plants and stacks	X	X	X	X	7.2 Stack emissions	8.2 Stack emissions	9.2 Liquid discharges	X	X	X	X	X	X	X	17.2 X
1.3 X	X	3.3 Rock dumps	X	X	X	7.3 Weat-her. /Mech	8.3 Exhalation	9.3 Run-off	10.3 Water erosion	8.3 Seepage	X	X	X	X	X	17.3 External exposure
1.4 X	X	X	4.4 Open pit	X	X	X	8.4 Exhalation	X	X	X	X	X	X	X	X	17.4 External exposure
1.5 X	X	X	X	5.5 Waste sites	X	X	8.5 Exhalation	9.5 Run-off	X	8.5 Seepage	X	X	X	X	X	17.5 External exposure
1.6 X	X	X	X	X	6.6 Stock piles	7.6 Wind erosion	8.6 Exhalation	9.6 Run-off	X	8.6 Seepage	X	X	X	X	X	17.6 External exposure
1.7 X	X	X	X	X	X	7.7 Dust	X	X	X	X	12.7 Deposition	X	14.7 Inhalation	X	16.7 Inhalation	17.7 Inhalation
1.8 X	X	X	X	X	X	X	8.8 Radon	X	X	X	X	X	14.8 Inhalation	X	16.8 Inhalation	17.8 Inhalation
1.9 X	X	X	X	X	X	X	X	9.9 Surface water	10.9 Settling	11.9 Infiltration	12.9 Irrigation	13.9 Uptake	14.9 Uptake	15.9 Uptake	19.9 Drinking	17.9 Drinking
1.10 x	X	X	X	X	X	X	X	9.10 Flood resus-pension	10.10 Sediments	8.10 Flow and transport	X	13.10 Uptake	14.10 Uptake	15.10 Uptake	16.10 Uptake	17.10 External exposure
1.11 X	X	X	X	X	X	X	X	9.11 Decanting	X	11.11 Ground-water	12.11 Irrigation	X	X	X	16.8 Drinking	17.11 Drinking
1.12 X	X	X	X	X	X	X	X	9.12 Flood resus-pension	X	X	12.12 Soil	X	X	15.12 Uptake	X	17.12 X
1.13 X	X	X	X	X	X	X	X	X	X	X	X	13.13 Aquatic plants	14.13 Con-suption	X	16.13 Con-sumption	17.13 X
1.14 X	X	X	X	X	X	X	X	X	X	X	X	X	14.14 Aquatic animals	X	16.14 Con-sumption	17.14 Con-sumption
1.15 X	X	X	X	X	X	X	X	X	X	X	X	X	X	15.15 Terrestrial plants	16.15 Con-sumption	17.15 Con-sumption
1.16 X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	16.16 Terrestrial animals	17.16 Con-sumption
1.17 X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	17.17 Humans

16.0 APPENDIX E: ACTIVITY CONCENTRATIONS ($Bq.kg^{-1}$) OF NUCLIDES IN SOLID SAMPLES

Not all radionuclides of concern were analysed. For these omitted it was assumed that these radionuclides were in secular equilibrium with their parent radionuclide, i.e. the particular radionuclide concentration is equal to that of the parent.

Field code	Primary Crusher Conveyor			Coarse Ore Stockpile Conveyor			Fine Ore Stockpile Conveyor Spillage			Open Pit Bench Ore			P Stackpile		
Lab code	RJ2010-0016X001			RJ2010-0016X002			RJ2010-0016X003			RJ2010-0016X004			RJ2010-0016X005		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA
^{238}U	8640	90	1.4	5950	60	1.3	4520	50	1.3	10300	100	1.4	7630	80	1.3
^{234}U	8710	90	1.4	6000	60	1.3	4560	50	1.3	10400	100	1.4	7690	80	1.4
^{226}Ra	8410	150	100	2640	80	110	5210	100	100	6200	110	98	4470	90	81
^{235}U	398	4	0.063	274	3	0.061	208	2	0.060	476	5	0.063	351	4	0.062
^{232}Th	280	4	4.3	193	3	3.9	172	3	3.6	346	5	4.4	284	4	3.8
^{228}Ra	347	55	160	127	38	120	171	45	140	167	38	120	110	40	130
^{228}Th	172	39	130	177	28	89	114	32	110	192	24	77	155	26	89
^{40}K	793	156	460	909	160	460	1070	150	400	1330	150	390	953	139	390
Gross alpha	110000	4000	2900	53000	3000	2800	50100	2900	2600	89700	3900	2900	51100	2900	2600
Gross beta	25800	400	530	24100	400	380	19400	300	370	27000	400	480	18200	300	380

Field code	Coarse Ore Stockpile			Fine Ore Stockpile			Tailings Prosposed Heap			Tailings Sample Coarse			Tailings Sample Intermediate		
Lab code	RJ2010-0016X006			RJ2010-0016X007			RJ2010-0016X008			RJ2010-0016X009			RJ2010-0016X010		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA
^{238}U	5260	50	1.3	4110	40	1.4	1090	10	1.4	630	8	1.4	1040	10	1.4
^{234}U	5300	50	1.3	4150	40	1.4	1090	10	1.4	635	8	1.4	1050	10	1.4
^{226}Ra	5510	110	98	3730	80	86	1550	40	50	2070	40	60	7660	140	120
^{210}Pb	Not analysed			Not analysed			Not analysed			Not analysed			6280	140	270
^{235}U	242	2	0.061	189	2	0.063	50.0	0.5	0.063	29.0	0.3	0.063	47.9	0.5	0.063
^{232}Th	166	2	3.9	154	2	3.0	88.0	1.6	2.7	66.5	1.2	2.0	218	3	2.7
^{228}Ra	223	47	140	114	36	110	173	30	87	114	26	74	160	51	160
^{228}Th	213	28	86	127	30	96	158	18	52	77.8	15.6	51	166	33	110
^{40}K	815	132	370	846	126	340	1240	110	240	930	119	300	954	195	580
Gross alpha	54900	3000	2700	41600	2700	2500	20000	1900	2100	26700	2100	2100	113000	4000	2900
Gross beta	20200	300	390	16000	300	350	5530	190	260	5620	190	290	26100	400	540

Field code	12A Tailings Percipitate			12B Tailings Percipitate			13 Seepage Dredged Material			FineCrushing Plant			Tarmac Main Road		
Lab code	RJ2010-0016X011			RJ2010-0016X012			RJ2010-0016X013			RJ2010-0016X014			RJ2010-0016X015		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA
^{238}U	4740	50	1.4	607	7	1.4	2530	30	1.4	7000	70	1.4	2860	30	1.4
^{234}U	4780	50	1.4	613	8	1.4	2550	30	1.4	7060	70	1.4	2890	30	1.4
^{226}Ra	7170	150	160	4270	110	130	857	34	56	6670	120	110	2160	380	70
^{210}Pb	7210	530	1300	4520	220	510	1780	80	210	Not analysed			Not analysed		
^{235}U	218	2	0.063	28.0	0.3	0.064	117	1	0.063	322	3	0.063	132	1	0.063
^{232}Th	824	12	3.8	193	3	2.0	76.3	1.2	2.8	293	4	3.5	151	2	2.6
^{228}Ra	335	71	210	160	59	190	64	28	89	299	54	170	85	29	90
^{228}Th	609	53	140	196	34	100	103	15	45	177	43	130	134	19	56
^{40}K	500	210	660	490	160	490	611	106	280	1040	160	470	893	122	310
Gross alpha	49000	2900	2500	25400	2100	2100	29300	2200	2300	69200	3400	3200	32000	2300	2300
Gross beta	15100	300	370	5570	190	280	9610	240	300	38000	500	430	10600	300	310

Field code	Dustaside Road			Roadwya without Dustaside			Tailings road			Coarse ore Stockpile Conveyor Road		
Lab code	RJ2010-0016X016			RJ2010-0016X017			RJ2010-0016X018			RJ2010-0016X019		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA	Value	Unc.	MDA
^{238}U	1700	20	1.3	3940	40	1.3	420	6	1.3	1130	10	1.4
^{234}U	1720	20	1.4	3970	40	1.4	423	6	1.4	1140	10	1.4
^{226}Ra	1190	40	51	3870	80	78	878	31	49	2080	50	56
^{235}U	78.5	0.8	0.062	181	2	0.062	19.3	0.3	0.062	52.2	0.5	0.064
^{232}Th	84.8	1.6	2.5	157	2	2.5	49.5	0.8	1.7	62.9	1.2	2.1
^{228}Ra	70.3	22.1	68	135	34	100	54	20	63	69	26	84
^{228}Th	68.6	14.0	42	117	23	73	49	15	50	81.1	21.4	68
^{40}K	838	102	250	814	127	360	1020	110	230	853	107	270
Gross alpha	12900	1500	2000	44300	2700	2400	12700	1500	2000	33500	2400	2200
Gross beta	3440	150	220	12400	300	350	3470	150	220	9160	240	320

17.0 APPENDIX F: RADON CONCENTRATIONS (Bq.m^{3}) AND CALCULATED DOSES (µSv.a^{-1}) FOR THE GRID POINTS USED IN THIS ASSESSMENT.

This appendix is only included in the report that is used for internal purposes, but it is available on request.

18.0 APPENDIX G: DUST CONCENTRATIONS (Bq.m^{-3}) AND CALCULATED DOSES (µSv.a^{-1}) FOR THE GRID POINTS USED IN THIS ASSESSMENT.

This appendix is only included in the report that is used for internal purposes, but it is available on request.