Report on a Radiological Public Hazard Assessment for the Proposed Swakop Uranium Husab Project in Namibia

Date: 2010-10-15

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REPORT No.:	NLM-REP-10/080 Version 1.0
DATE:	15 October 2010
TITLE:	REPORT ON A RADIOLOGICAL PUBLIC HAZARD ASSESSMENT FOR THE PROPOSED SWAKOP URANIUM HUSAB PROJECT IN NAMIBIA

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1.0 INTRODUCTION

Metago Environmental Engineers (Pty) Ltd (hereafter referred to as Metago) is presently performing an Environmental Impact Assessment (EIA) for the proposed Swakop Uranium Husab Project (hereafter referred to as the Husab Project) [1]. Necsa has been contracted to perform a Radiological Public Hazard Assessment as a specialist input to the EIA. 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), it is also required to perform a radiological assessment 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. However, a general conclusion on the wider environmental/ecological impact will be made. The assessment will also not consider the occupational exposure of workers (as it forms part of a separate Radiological Worker Hazard Assessment), although construction and exploration workers that stay temporarily on site will be regarded.

Where required, data from the EIA scoping report [1], the specialist study on the Air Quality [3] and decisions on specialist studies [19] 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. A major aim of the prospective assessment is to identify the areas of uncertainty and to make proposals for the acquisition and improvement of such data through an 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.

Although it is possible to perform a study of this nature using generic data, it is preferable to include site specific data and information. Section 4.0 is a summarized site and process description and includes radiological data used to perform the prospective impact assessment for the current status of the Husab Project.

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 covering the various pathways. The approach followed to develop exposure scenarios is discussed in Section 5.0, together with a description of the pathway dependent scenarios considered in the assessment. A large effort in the assessment will be to calculate inhalation doses from radon and dust for adult members of the public on a grid basis as determined through air dispersion modelling. This will cover scenarios for the mine conditions described in [3].

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.

The report is concluded in Sections 7.0 and 8.0 with an evaluation of the public impact assessment results, including some general recommendations for additional information to be acquired through an environmental monitoring program for a more detailed assessment. The assessment results will be evaluated against international radiological criteria based on international radiation protection principles [4] and [5]. In addition, in Section 8.2 is an evaluation of the assessment results against the Environmental Impact Criteria presented in Section 3.5.

Section 9.0 presents the referenced documents.

Three appendices are also attached to the report. Appendix A in Section 10.0 presents a map of the Husab Project site and the surrounding environment. Appendix B in Section 11.0 lists the parameters used in or adapted for the deterministic public dose calculations. Appendix C in Section 12.0 contains an Interaction Matrix identifying possible sources and pathways for the Husab Project, mainly to assist in scenarios development and to serve as reference for future assessments.

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

The 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. The prospective assessment report is concluded with recommendations for additional measurements in a proposed 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 EIA, the radiological specialist investigation also has the following specific objectives and purpose:

- To identify and quantify the radiological pollution sources associated with the various phases of the proposed project (construction, operation, decommissioning and closure phases).
- The radiological study is a cross cutting study that from a pollution dispersion viewpoint must both provide input into the models and make use of the results and conclusions of the modelling studies being conducted by other specialists. Discussions should also take place with the relevant engineers, to correctly understand the pollution emission and release issues associated with the tailings dam, material transport, stockpiles and water circuit.
- From a public health viewpoint, a clear distinction must be made between the mining licence area that is managed in accordance with occupational health and safety legislation, and the area beyond this defined boundary that falls under environmental and public exposure criteria. The study must focus on the environmental and public exposure.
- To describe the relevant legal framework with reference to national and international legislation, conventions and guidelines.

- Assess the cumulative environmental and public radiological impacts for all relevant pathways (external exposure, atmospheric emissions and aquatic releases) and phases (construction, operation, decommissioning and closure), also addressing the assessment criteria.
- To provide input, together with Metago, other specialists and Swakop Uranium (Pty) Ltd, into the 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 do 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) Husab Project 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. The Namibian Atomic Energy Board, also mandated to formulate a national regulatory framework, has only been inaugurated on 18 February 2009, and nuclear regulations in Namibia are still in the development phase [6]. For this reason this document will mainly refer to international standards and recommendations, as contained in IAEA [4], [7], [8] and ICRP [5], [9], [10] 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 $mSv.a^{-1}$ [4] and [5]. 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 0.3 $mSv.a^{-1}$ is for instance recommended as a constraint for the management of waste from uranium mining [8].

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 [9]. 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 [5] 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 *dose constraint* mentioned in the previous paragraph but recommendations will also consider the present international uncertainty.

3.4.2 Assessment Guidance

Broad ICRP guidance on a radiological public hazard assessment is provided in [10]. The IAEA provide broad assessment guidance for mining waste management in [8] and some model guidance in [11]. 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 [7]. 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 only present-day technology, or technologies practised in the past will be considered in the assessment.

While predictive results are presented in [3], these cover only the operational phase of the mine. Mitigation and rehabilitation strategies at mine closure still need to be developed. A complete predictive dose assessment, also considering post-closure conditions hence seems to be impossible at the present stage. 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 Review and Control

If required, the impact from the mine can be reduced by evaluating alternative design options and also evaluating various mitigating control measures during the operational phase but especially at mine closure, e.g. the rehabilitation of the mine tailings dams as well as the open pit. The rehabilitation strategies at mine closure are also still to be developed and this assessment will only evaluate the doses from different dust mitigating strategies during the operational phase of the mine as discussed in the Air Quality Report [3].

3.4.5 Radionuclides Considered in the Assessment

The radionuclides giving rise to the radiological impacts associated with the Husab Project 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 and that should be included in the analysis were selected, where applicable with appropriate half-lives, from [12] 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 x 10^8 years and its daughters 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 for the aquatic pathway, 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 prospective assessment will, however, only cover the atmospheric pathway and will hence not consider in-growth and decay.

As no radionuclide analysis has been performed, nuclide concentrations for the various source materials and the tailings will be deduced from the uranium content in the ore (in parts-per-million (ppm)). For the tailings a leach efficiency of 90.8 % of the milled uranium ore is assumed.

3.4.6 Model Development

Ideally, model development within the assessment should be performed through scenario development considering all exposure pathways and all possible present and future conditions. Where applicable, conceptual models will be developed to define scenarios for relevant exposure pathways. For the first iteration, only scenarios relating to normal non-disruptive conditions are considered.

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

Public dose assessment models 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 [3]. Justification for excluding the aquatic pathway at this early assessment is provided in [19].

Biosphere modelling and the associated radiological assessment will be discussed in Section 6.0.

3.4.7 Critical Groups

Critical groups (redefined in [10] 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. Due to the low population density and the lack of habit data specific to the region, more general data will be used for this assessment.

To calculate the doses to critical groups in general, the assumption will be made that the critical groups consists of adults. While this assumption generally relates to the most conservative dose, doses to other age groups can be deduced from the results.

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 will rather be formulated through the screening of relevant radioactive sources and interacting media, as identified in an interaction matrix, given in Appendix C (see Section 12.0). 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 [3], while a justification for excluding the aquatic pathway is presented in [19].

3.5 EIA Criteria for Impact Evaluation

Metago has also presented general EIA criteria for the evaluation of the environmental impacts in a format involving the ranking of various aspects of the impacts. These are presented in Table 1 and their use will be explained and considered in Section 8.2.

Table 1: Criteria for Impact Evaluation

PART A: DEFINITION AND CRITERIA*		
Definition of SIGNIFICANCE		Significance = consequence x probability
Definition of CONSEQUENCE		Consequence is a function of severity, spatial extent and duration
Criteria for ranking of the SEVERITY of environmental impacts	**H**	Substantial deterioration (death, illness or injury). Recommended level will often be violated. Vigorous community action.
	M	Moderate/ measurable deterioration (discomfort). Recommended level will occasionally be violated. Widespread complaints.
	L	Minor deterioration (nuisance or minor deterioration). Change not measurable/ will remain in the current range. Recommended level will never be violated. Sporadic complaints.
	L+	Minor improvement. Change not measurable/ will remain in the current range. Recommended level will never be violated. Sporadic complaints.
	M+	Moderate improvement. Will be within or better than the recommended level. No observed reaction.
	H+	Substantial improvement. Will be within or better than the recommended level. Favourable publicity.

Criteria for ranking the DURATION of impacts	**L**	Quickly reversible. Less than the project life. Short term
	M	Reversible over time. Life of the project. Medium term.
	H	Permanent. Beyond closure. Long term.
Criteria for ranking the SPATIAL SCALE of impacts	**L**	Localized – Within the site boundary.
	M	Fairly widespread – Beyond the site boundary. Local
	H	Widespread – Far beyond site boundary. Regional/ national.
PROBABILITY (of exposure to impacts)	**H**	Definite/ Continuous
	M	Possible/ frequent
	L	Unlikely/ seldom

PART B: DETERMINING CONSEQUENCE					
SEVERITY = L					
DURATION	Long term	H	Medium	Medium	Medium
	Medium term	M	Low	Low	Medium
	Short term	L	Low	Low	Medium
SEVERITY = M					
DURATION	Long term	H	Medium	High	High
	Medium term	M	Medium	Medium	High
	Short term	L	Low	Medium	Medium
SEVERITY = H					
DURATION	Long term	H	High	High	High
	Medium term	M	Medium	Medium	High
	Short term	L	Medium	Medium	High
			L	**M**	**H**
			Localised Within site boundary Site	Fairly widespread Beyond site boundary Local	Widespread Far beyond site boundary Regional/ national
			SPATIAL SCALE		

PART C: DETERMINING SIGNIFICANCE					
PROBABILITY	Definite /Continuous	H	Medium	Medium	High
	Possible / frequent	M	Low	Medium	High
	Unlikely / seldom	L	Low	Low	Medium
			L	**M**	**H**
			CONSEQUENCE		

PART D: INTERPRETATION OF SIGNIFICANCE	
Significance	**Decision guideline**
High	It would influence the decision regardless of any possible mitigation.
Medium	It should have an influence on the decision unless it is mitigated.
Low	It will not have an influence on the decision.

4.0 SITE AND PROCESS DESCRIPTION

The site infrastructure and process description, together with descriptions of the surrounding environment are presented in the Environmental Scoping Report [1] and elaborated on in the Air Quality Report [3]. As they refer to future site infrastructure they may lack detail. The identification of any additional data requirements and subsequent surveys will be based on the assessment results. Existing descriptions will not be repeated in this report. Only data relevant to the dose assessment are indicated below.

Modelled dose results from sources associated with the mining and processing operations are considered to be additional doses above the background.

4.1 RADIOLOGICAL DATA FOR ASSESSMENT

No radiological data were available since no solid materials were collected and analysed. The need for sample collection and analysis over an extended period through an environmental monitoring program will be discussed as outcome of this assessment.

However, input parameters needed for the radiological assessment were either estimated from similar uranium mining operations or taken from the data obtained from Metago [13]. These parameters are tabulated in Table 2. Uranium grades were converted to ppm U from ppm U_3O_8.

Table 2: Input parameters used for the radiological assessment

Parameter Description	Value
U/Th ore grade ratio	4.9
Upgrading factor for activity in PM10 dust	1.64
Mass fraction of processed material coming from Zone 1	0.75
Uranium leach efficiency	90.8 %
Zone 1 uranium ore grade	381 ppm
Zone 2 uranium ore grade	460 ppm
Uranium grade of waste rock from Zone 1 and 2	12 ppm
Uranium grade of Zone 1 roads (cover material)	20 ppm
Uranium grade of Zone 2 roads (cover material)	20 ppm
Uranium grade of outside roads	10 ppm
Ore at crushing and screening	401 ppm
Tailings facilities (only U depleted, other nuclides as per crushing and screening ore values)	37 ppm

4.2 Uranium Ore Grades and Radionuclide Concentrations

The data from Table 2 were used to calculate the radionuclide-specific activity concentrations of outdoor airborne dust for various materials. These calculated radionuclide concentrations are tabulated in Table 3. These concentrations were then subsequently used to convert the gravimetric airborne concentrations given in the Air Quality Report [3] to radionuclide activities needed for the radiation dose assessment.

4.3 Human Behaviour Characteristics

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

- Agricultural activities on farms near the mine,
- Working activities at other nearby mines and the Arandis airport,
- Working and living activities at the Arandis town,
- Impacts to contractors that stay temporarily on site and
- Tourists and tour operators that visit various attractions in the Namib Naukluft Park and West Coast Recreation Area, ranging from 7.5 km to 30 km from the site.

Exposure via the radon and dust pathways from the proposed tailings dam and other sources are assessed as per the modelled radon and dust concentrations presented in the Air Quality Report [3].

5.0 SCENARIO DEVELOPMENT

5.1 SOURCE-PATHWAY-RECEPTOR ANALYSIS.

5.1.1 General

Due to uncertainties already mentioned above a formal systematic source-pathway-receptor analysis process will not be followed for the prospective assessment to develop scenarios. A more generic process will rather be followed as per the human behaviour characteristics identified in Section 4.3 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 cause radon sources. Most important would be the radon exhalation from the tailings dams, with lower emissions possible from the waste rock piles and even lesser amounts from the ore stockpiles. The more important sources will be considered in this assessment, as presented for dust sources in Section 5.1.2.2 below. The radon sources will vary over the different mining operations as per the material amounts handled and their respective Ra-226 concentrations. The details about the source sizes are discussed in [3] while Ra-226 concentrations were taken from Table 3.

Table 3: Calculated radionuclide concentrations for outdoor airborne dust (Bq/g) for various materials.

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
Airborne Zone 1 ore dust	7.74	7.74	7.74	7.74	7.74	7.74	0.36	0.36	0.36	0.52	0.52	0.52	0.52
Airborne Zone 2 ore dust	9.36	9.36	9.36	9.36	9.36	9.36	0.43	0.43	0.43	0.62	0.62	0.62	0.62
Airborne Zone 1& Zone 2 waste dust	0.24	0.24	0.24	0.24	0.24	0.24	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Airborne Zone 1 road dust	0.41	0.41	0.41	0.41	0.41	0.41	0.02	0.02	0.02	0.03	0.03	0.03	0.03
Airborne Zone 2 road dust	0.41	0.41	0.41	0.41	0.41	0.41	0.02	0.02	0.02	0.03	0.03	0.03	0.03
Airborne Zone 1 & 2 outside road dust	0.20	0.20	0.20	0.20	0.20	0.20	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ore crushing and screening material	8.15	8.15	8.15	8.15	8.15	8.15	0.38	0.38	0.38	0.54	0.54	0.54	0.54
Airborne tailings dust at leach efficiency	0.75	0.75	8.15	8.15	8.15	8.15	0.36	0.36	0.36	0.54	0.54	0.54	0.54

5.1.2.2 Dust Sources

Dust sources will vary depending on the mining operations during the typical mining phase. For this assessment two optional mining phases are distinguished, which only differ in as far as mitigation options are introduced for the second option but not for the first. These options are defined below and described in detail in [3]:

- *Unmitigated Mining Operations – Maximum mining rate during the first phase with no dust mitigation procedures in place,*
- *Mitigated Mining Operations – Maximum mining rate during the first phase with dust mitigation procedures in place.*

For each mining phase the mining operations include the following (see [3] for detail):

- *Material handling operations,*
- *Drilling,*
- *Blasting,*
- *Crushing and Screening and*
- *Vehicle activity on unpaved roads.*

The amount of dust from each of these mining operations will, however, vary at the different receptor locations mainly due to different dust generation rates, source-receptor distances and due to a different radionuclide composition of each source. Therefore the dose to each receptor will be calculated separately for the source generated by the applicable mining operation and then summed over all sources applicable to the particular mining phase.

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 natural uranium indicated that a trivial dose[1] of 10 μSv.a^{-1} will not be exceeded at a distance of 0.5 km from the source. This should hence be the limit for permanent public access to the mine sources.

External exposure may also occur from soil contamination due to deposited airborne activity. This will be treated as part of the atmospheric pathway.

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 [3].

Experience at other mines indicated that the atmospheric pathway is important, but only 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 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 (contaminated through drinking contaminated water or eating contaminated plants).

[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 7.1).

Since the aquatic pathway is excluded and plant contamination through airborne deposition is regarded as insignificant, secondary pathway analysis will also be excluded from this assessment.

5.1.4 Receptors

Specific critical groups will be assessed for the atmospheric pathway. These include representatives from the human behaviour characteristics groups identified earlier in Section 4.3 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 12.0. 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

An exposure scenario describes the exposure conditions developed for the human receptors at a particular location. The section below provides detail on the various Exposure Scenarios as per the source-pathway-receptor analysis described in Section 5.1 and the motivations provided for the limited or generic approach during the present prospective assessment.

It should be noted that the exposure scenarios mostly covered only some pathways and that the assessment is mostly performed for each source separately. The assessment of total doses may therefore require the summation of doses. It should be noted that the exposure scenarios only cover the atmospheric pathway in terms of inhalation of dust and radon and that the assessment is performed for the total source from all the mining operations.

5.3.2 Normal Evolution Condition Scenarios

For this assessment, conceptual models for a total of seven exposure scenarios are developed for normal evolution conditions of the atmospheric pathway. The locations of the receptors as described in the Exposure Scenarios are indicated in Figure 1.

5.3.2.1 Exposure Scenario 1: Swakop River Farm

This scenario considers a small farming community living on the banks of the confluence of the Swakop and Khan Rivers (more than 20 km from the mine site) as indicated in Figure 1. There are also other farms on the Swakop River that are more than 40 km southwest of the mine site as well as farms more than 20 km east of the mine site. For the other Swakop River farms the doses are expected to be lower than the chosen farm, while similar doses are expected for farms that are east of the mine site.

The critical group is assumed to consist of adults exposed to radon and long lived radioactive dust as emitted for the various mining operations at the Husab Project site. This scenario is schematically depicted in Figure 2. The uranium concentrations presented in Table 3 will be used for this assessment. To estimate a conservative dose it is further assumed that the people will stay the whole year at this location with 4380 hours indoors and 4380 hours outdoors exposure.

5.3.2.2 Exposure Scenario 2: Inhabitants of Arandis Town

This scenario considers the inhabitants of the Arandis Town, located north of the Husab Project site as indicated in Figure 1. Although all age groups are present in the town, the most conservative doses from the inhalation of radon and long lived radioactive dust are for the adults. The critical group is therefore also assumed to consist of adults. This scenario is similar to Exposure Scenario 1; also with an exposure period of 4380 hours indoors and 4380 hours outdoors. This scenario is also depicted by Figure 2.

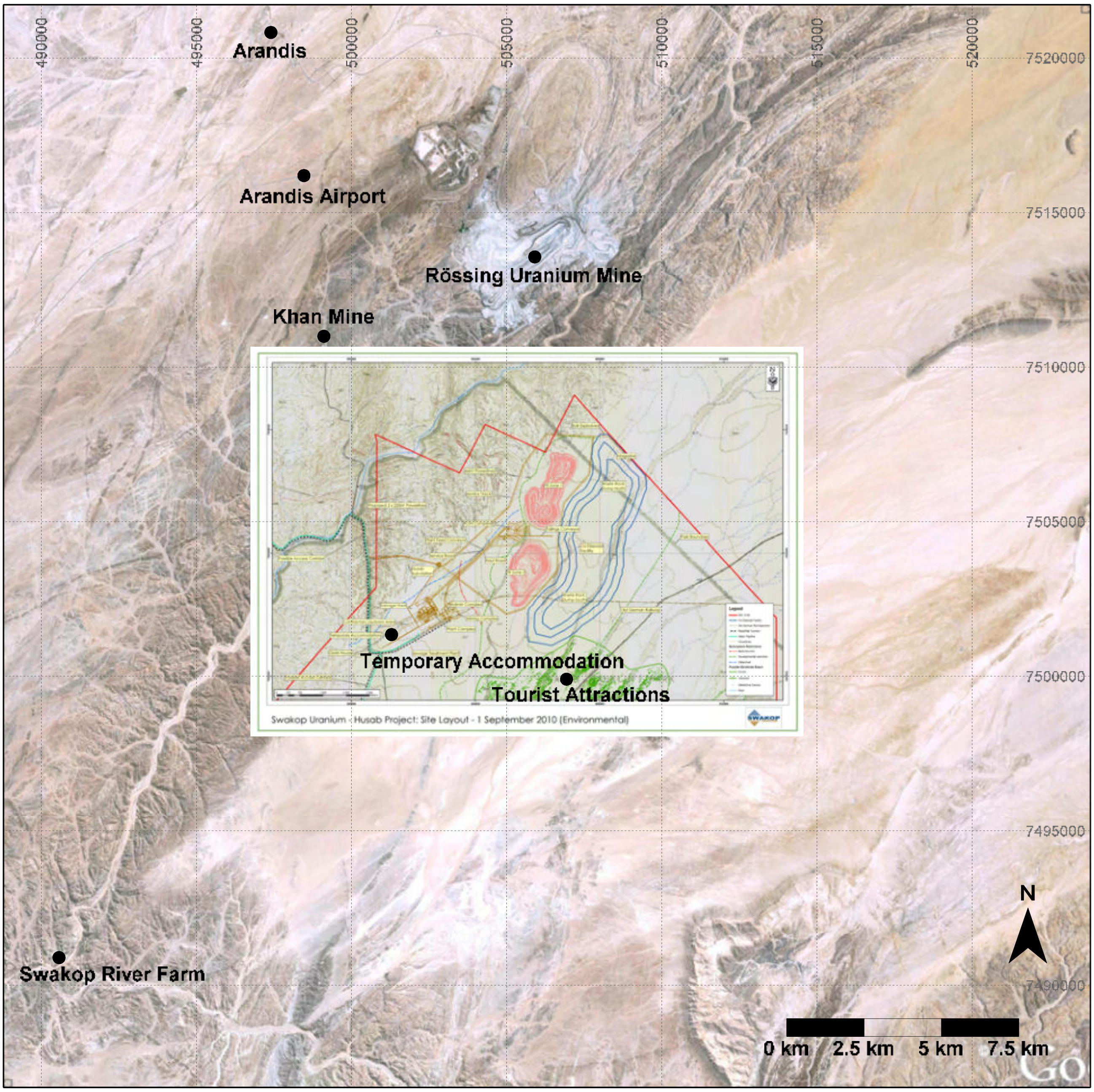

Figure 1: Location of sensitive receptors as described in the Exposure Scenarios

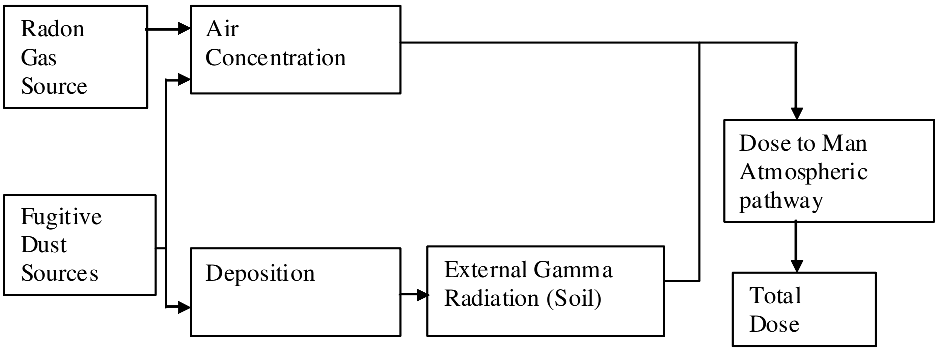

Figure 2: Schematic presentation of Exposure Scenario 1

5.3.2.3 Exposure Scenario 3: Workers at Arandis Airport

This scenario considers workers at the Arandis Airport (indicated in Figure 1). It is assumed that the critical group consists of adults working for a period of 2000 hours per year outdoors. They are exposed to radon and airborne long lived radioactive dust as emitted for the various mining operations at the Husab Project site. This scenario is also presented by Figure 2.

5.3.2.4 Exposure Scenario 4: Workers at Rössing Mine

This scenario is similar to Exposure Scenario 3. The adults considered are working at the Rössing Mine (indicated in Figure 1) also for a period of 2000 hours per year assumed to be outdoors. This scenario is also presented by Figure 2.

5.3.2.5 Exposure Scenario 5: Future workers at Khan Mine

This scenario considers possible future workers at the Khan Mine located close to the Husab Project site (indicated in Figure 1). The scenario is also similar to Exposure Scenario 3 with an exposure period of 2000 hours per year outdoors for adults. This scenario is also presented by Figure 2.

5.3.2.6 Exposure Scenario 6: Temporary Accommodation at Husab Project site

In this scenario it is assumed that workers will stay at the temporary accommodation area within the Husab Project site (see layout given in Section 10.0). This scenario is similar to Exposure Scenario 5, the only difference being the exposure time. All contractors will be adults and are staying in the camp for 6 days a week and off site for 1 day a week. Although contractors will stay on site for different periods, for this exposure scenario it is conservatively assumed that a person will stay for 12 months. Furthermore, as they are also regarded as radiation workers only the exposure time during off times will be used i.e. 12 hours per day indoors or 3744 hours per annum. This scenario is also presented by Figure 2.

5.3.2.7 Exposure Scenario 7: Tourist Attractions

In this scenario it is assumed that the public visit tourist attractions that are located in the Namib Naukluft Park, part of which are included in the Husab Project site (see Figure 1). This scenario is similar to Exposure Scenario 1, the only difference being the exposure time. It is assumed that all visitors are adults and they are staying in the area for a maximum of one week (168 hours outdoors). This scenario is also presented by Figure 2.

5.3.3 Disruptive Scenarios

Consideration of scenarios for disruptive events falls outside the scope of this prospective assessment. These can better be considered in future iterations or in a post-closure assessment together with assessments related to institutional control failures.

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

Radon exhalation source terms can be measured experimentally, but such data are presently unavailable for the Husab Project. For this prospective assessment, radon exhalation source terms will hence be calculated from the estimated Ra-226 concentrations assuming published values for the emanation and diffusion coefficients for uranium mine tailings.

The radon flux at the surface of a flat surface of tailings material with a uniform density and Ra-226 content is expressed by [14]:

$$F_t = R \,.\, \rho \,.\, E \,.\, \sqrt{\lambda \,.\, D_t} \qquad \text{Eq. 1}$$

where

F_t	=	Radon flux at the surface of the tailings dam	[Bq.m^{-2}.s^{-1}]
R	=	Ra-226 concentration in the tailings	[Bq.kg^{-1}]
ρ	=	Bulk density of tailings (assumed to be 1500 kg.m^{-3})	[kg.m^{-3}]
E	=	Emanation coefficient of tailings (assumed to be 0.2)	[-]
λ	=	Decay constant of Rn-222 (2.06E-06 s^{-1})	[s^{-1}]
D_t	=	Diffusion coefficient of tailings (assumed to be 1.0E-06 m^2.s^{-1})	[m^2.s^{-1}]

The total source strength is obtained by multiplying the flux by the total surface area of the emanating surface of the tailings dam or other sources.

6.2.2 Dust Source Terms

Gravimetric dust source terms are assessed in [3] and will be converted to activity source terms using the calculated radioanalytical results in Table 3.

6.3 Assessment of Atmospheric Transfers

Atmospheric transfer of radon and dust emissions is usually modelled by dispersion models, covering the region between the sources and receptor locations.

The radon dispersion modelling, as reported in [3] is performed assuming a unit radon flux from the various sources considered. The radon concentrations reported will hence be adjusted linearly to the flux calculated for each source as per the calculated Ra-226 concentration in the source material, using Equation 1.

Gravimetric dust concentrations are assessed in [3] and will be converted to radionuclide concentrations using the calculated radioanalytical results in Table 3.

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 [9]. 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

$$D_{Radon} = 1.0\times10^{3}.\left(Conc_i\ .\ F_i\ .\ T_i + Conc_o\ .\ F_o\ .\ T_o\right).\ CC_{Rn}\ .\ DC_{Rn} \qquad \text{Eq. 2}$$

where

D_{Radon}	= Dose from radon exposure	[µSv.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 times 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 $m^3 h^{-1}$ [15] was assumed when the scenario refers to non-occupational exposure. This implied 8 hours of sleeping as indicated in Table 10.

(c) For the adult members of the critical groups from each exposure scenario a breathing rate of 1.2 $m^3 h^{-1}$ [15] was assumed when the scenario refers to occupational exposure.

The dose coefficients (in units of $Sv.Bq^{-1}$) for inhalation were taken from [4] and [15]. The mathematical model to calculate the dust inhalation dose from each radionuclide is expressed by:

$$D_{inh,Dust} = 1.0 \times 10^{6} . Conc_{Dust} . DC_{inh} . (T_o + SF . T_i) . BR \qquad \text{Eq. 3}$$

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	[$m^3.h^{-1}$]

6.4.3 Dust Deposition Pathway

Through the process of deposition and re-suspension, airborne activity can be redistributed. Modelled results for dust deposition rates are provided by the dispersion modelling in [3]. While the dust may be re-suspended, a suitable re-suspension factor could not be found for a desert environment. A re-suspension factor of 0.1 y^{-1} was assumed. For this reason a deposition period of 100 years for environmental outdoor conditions is assumed for the deposited dust where-after the source is assumed to have reached an equilibrium state. External doses are determined from the deposition sources above, assumed to be an infinitely large surface source as per the methodology in Section 6.4.4 below.

6.4.4 External Exposure Pathway

External exposure occurs when soil is contaminated either through the deposition of airborne radioactivity or through the irrigation of soil with contaminated water. In the case of deposited material, the activity is present as a thin cover layer. The external dose is in this case calculated from the surface activity concentration of the soil by using published dose coefficients. Dose coefficients are factors (sometimes also referred to as dose conversion factors), presenting the dose per unit activity or dose rate per unit activity concentration. For external radiation it presents the dose rate in $\mu Sv.h^{-1}$ at a distance of 1 metre above an infinite plane source of unit surface activity concentration in $Bq.m^{-2}$. In the case of irrigated soil the activity is more likely to penetrate the soil to generate a thick slab of radioactive soil. The external dose is in this case calculated from the volume activity concentration of the soil by using published dose coefficients, presenting the dose rate in $\mu Sv.h^{-1}$ at a distance of 1 metre above an infinite slab source of unit mass activity concentration in $Bq.g^{-1}$.

The mathematical model for external gamma radiation is given by

$$D_{ext,soil} = 1.0\times10^{6}.Conc_{Soil}\,.\,DC_{ext}\,.\,(EP_o + SF\,.\,EP_i) \qquad \text{Eq. 4}$$

where

$D_{ext,\ soil}$	=	External dose from the contaminated soil	[$\mu Sv.a^{-1}$]
$Conc_{soil}$	=	Soil surface or soil mass activity concentration	[$Bq.m^{-2}$]or [$Bq.g^{-1}$]
DC_{ext}	=	Dose coefficient for external exposure	[$Sv.h^{-1}$ per $Bq.m^{-2}$] or [$Sv.h^{-1}$ per $Bq.g^{-1}$]
EP_O	=	Annual outdoor exposure period	[$h.a^{-1}$]
EP_I	=	Annual indoor exposure period	[$h.a^{-1}$]
SF	=	Indoor shielding factor	(taken as 1)

Dose coefficients are taken from [17] and are presented in Table 12 and Table 13: in Appendix B.

6.5 ASSESSMENT

The mathematical models, as detailed in 6.4, were developed as interconnecting worksheets on a Microsoft Excel spreadsheet file. By using best estimates of published parameter values (see Appendix B in Section 11.0), deterministic doses were assessed for the atmospheric and aquatic pathways applicable to the critical group of each normal evolution scenario developed in Section 5.3.2. Assessment detail and the results are presented in Section 6.6.

6.6 RESULTS

Dose assessment results for the atmospheric pathway are presented below.

6.6.1 Dust Source Contributions

Due to the mitigation options that are in effect, different dust sources are applicable. Each mining operation was divided into different sources. The contribution of each source was calculated through dispersion modelling [3]. Various materials that are of importance to the radiological assessment were identified (see Table 3) and linked to the different mining operation sources. Refer to Table 5 for these correlations.

6.6.2 Radon Inhalation Pathway

The radon dispersion results for each of the mining operation sources obtained from [3] was calculated using a radon source with a radon flux of 1 $Bq.m^{-2}.s^{-1}$. To reflect the situation as indicated by the radioanalytical results (see Table 3), a radon flux correction was done. This correction factor was calculated by using Equation 1 and the Ra-226 value of the material that linked to the mining operation (see Table 5 for these correlations). The resulting correction factors were multiplied with the applicable radon dispersion results and converted to a dose for an adult member of the public (although radon doses are age-independent) by using Equation 2 and a one year exposure time (that is 4380 hours indoors and 4380 hours outdoors). No indoor modelling was performed as it was assumed that the indoor and outdoor concentrations are equal but equilibrium factors of 0.4 and 0.8 respectively as suggested in [9] are used. The doses for all the mining operation sources were added to obtain the total radon inhalation dose. The total radon inhalation dose results, indicated as contour plots, are depicted in Figure 3.

From the above-mentioned results, the doses for the different identified public and worker critical groups as per Exposure Scenarios in Section 5.3.2 were also derived firstly by obtaining the yearly dose at the locations applicable to each group and secondly correcting it for the applicable exposure periods by applying Equation 2. The respective total radon inhalation doses to each identified group are summarised in Table 4. As mitigation is not expected to affect radon exhalation, only one set of data is presented.

Table 4: Doses ($\mu Sv.a^{-1}$) from Radon Inhalation for the different Exposure Scenarios.

Exposure Scenario	Unmitigated Mining Operations
1: Swakop River Farm	4.1×10^{-5}
2: Arandis Town	2.5×10^{-5}
3: Arandis Airport	1.1×10^{-5}
4: Rössing Mine	1.2×10^{-5}
5: Khan Mine	2.3×10^{-5}
6: Temporary Accommodation	1.1×10^{-4}
7: Tourist Attractions	7.7×10^{-6}

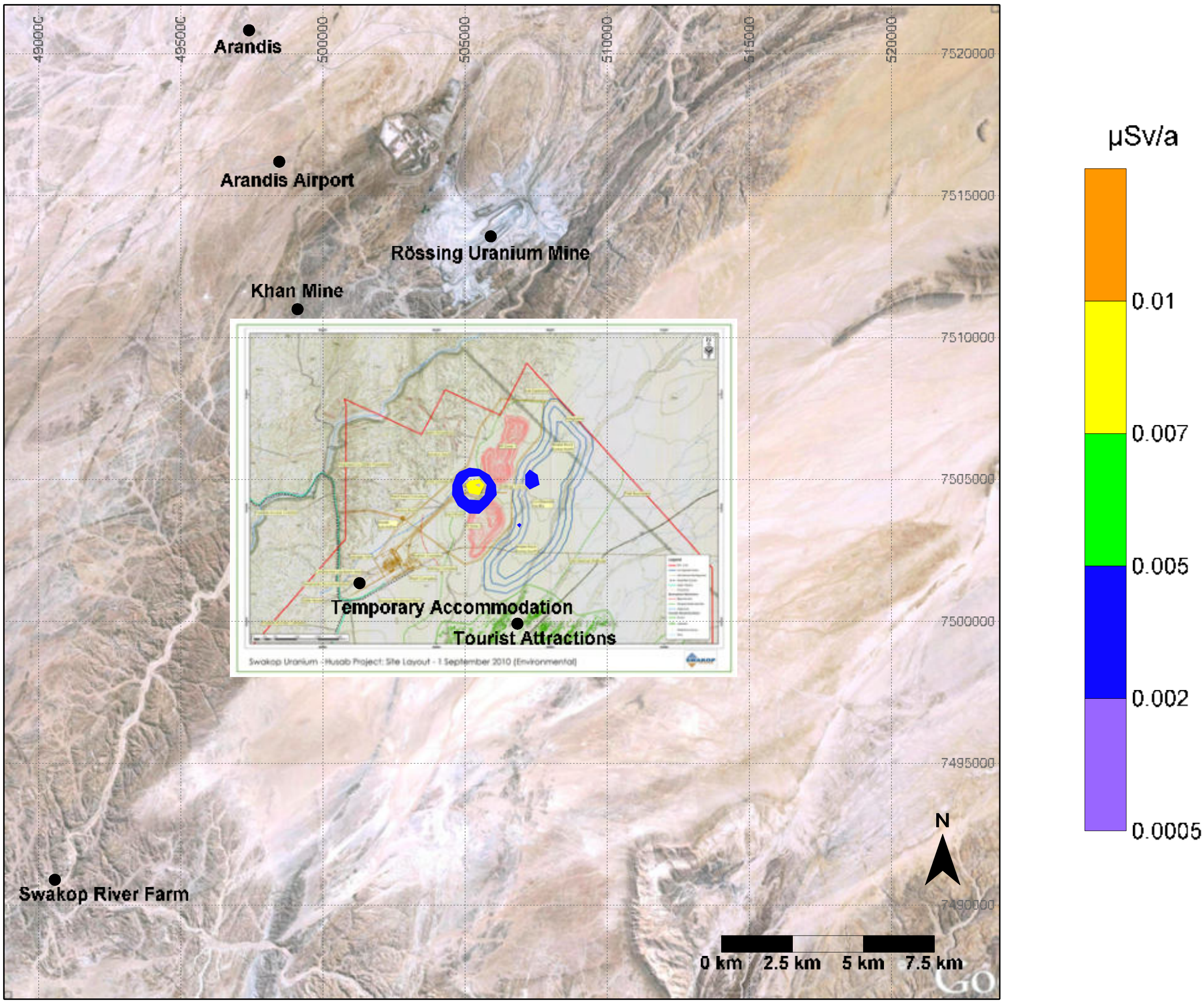

Figure 3: Calculated doses (µSv.a^{-1}) for Radon Inhalation from the mining operations for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors)

Table 5: The various materials, for which radionuclide concentrations are available, linked to the mining operation sources.

Description of Material	Mining Operation Source
Airborne Zone 1 ore dust	BL_Z1, DR_Z1, MH_Z1
Airborne Zone 2 ore dust	BL_Z2, DR_Z2, MH_Z2
Airborne Zone 1& Zone 2 waste dust	WE_WD, MH_WST_01, MH_WST_02, MH_WST_03, MH_WST_04
Airborne Zone 1 road dust	UPR_Z1
Airborne Zone 2 road dust	UPR_Z2
Airborne Zone 1 & 2 outside road dust	UPR_Z1_01, UPR_Z1_02, UPR_Z1_03, UPR_Z1_04, UPR_Z1_05, UPR_Z1_06, UPR_Z1_07, UPR_Z1_08, UPR_Z1_09, UPR_Z1_10, UPR_Z1_11, UPR_Z2_12, UPR_Z2_13, UPR_Z2_14, UPR_Z2_15, UPR_Z2_16
Ore crushing and screening material	MH_ORE_01, MH_ORE_02, CRU_ROMC
Airborne tailings dust at leach efficiency	WE_WD, MH_WST_01, MH_WST_02, MH_WST_03, MH_WST_04

6.6.3 Dust Inhalation Pathway

The PM10 dust dispersion results were used to determine the dose due to dust inhalation. These results, obtained from [3], for each of the mining operation sources were changed to radionuclide concentrations by multiplying with the total radionuclide concentrations (see Table 3) of the samples that are linked to the mining operation source (see Table 5). No indoor modelling was performed as it was assumed that the indoor and outdoor concentrations are equal. The resulting concentrations were converted to a dose for an adult member of the public by using Equation 3 with a breathing rate of 0.93 $m^3.h^{-1}$ and a one year exposure period (that is 4380 hours indoors and 4380 hours outdoors). The doses for all the mining operation sources were added to obtain the total dust inhalation dose for an adult member of the public. This was done for mitigated and unmitigated mining operations (per Section 5.1.2.2). The total PM10 dust inhalation dose results, indicated as contour plots, are depicted in Figure 4 and Figure 5.

From the above-mentioned results, the doses for the different critical groups as per the Exposure Scenarios in Section 5.3.2 were derived firstly by obtaining the yearly dose at the locations and secondly correcting it for the applicable exposure periods and inhalation rates by applying Equation 3. The respective total dust inhalation doses to each identified group for mitigated and unmitigated mining operations are summarised in Table 6.

Public doses for other age groups relate to the adult doses through conversion to other inhalation rates and dose coefficients (see Appendix B in Section 11.0). Performing such a correction indicates lower doses than for adults for all age groups.

Table 6: Doses ($\mu Sv.a^{-1}$) from Dust Inhalation for the different Exposure Scenarios.

Exposure Scenario	Unmitigated Mining Operations	Mitigated Mining Operations
1: Swakop River Farm	6.25	1.55
2: Arandis Town	4.05	0.93
3: Arandis Airport	1.84	0.41
4: Rössing Mine	2.06	0.44
5: Khan Mine	3.68	0.85
6: Temporary Accommodation	18.38	5.56
7: Tourist Attractions	0.96	0.27

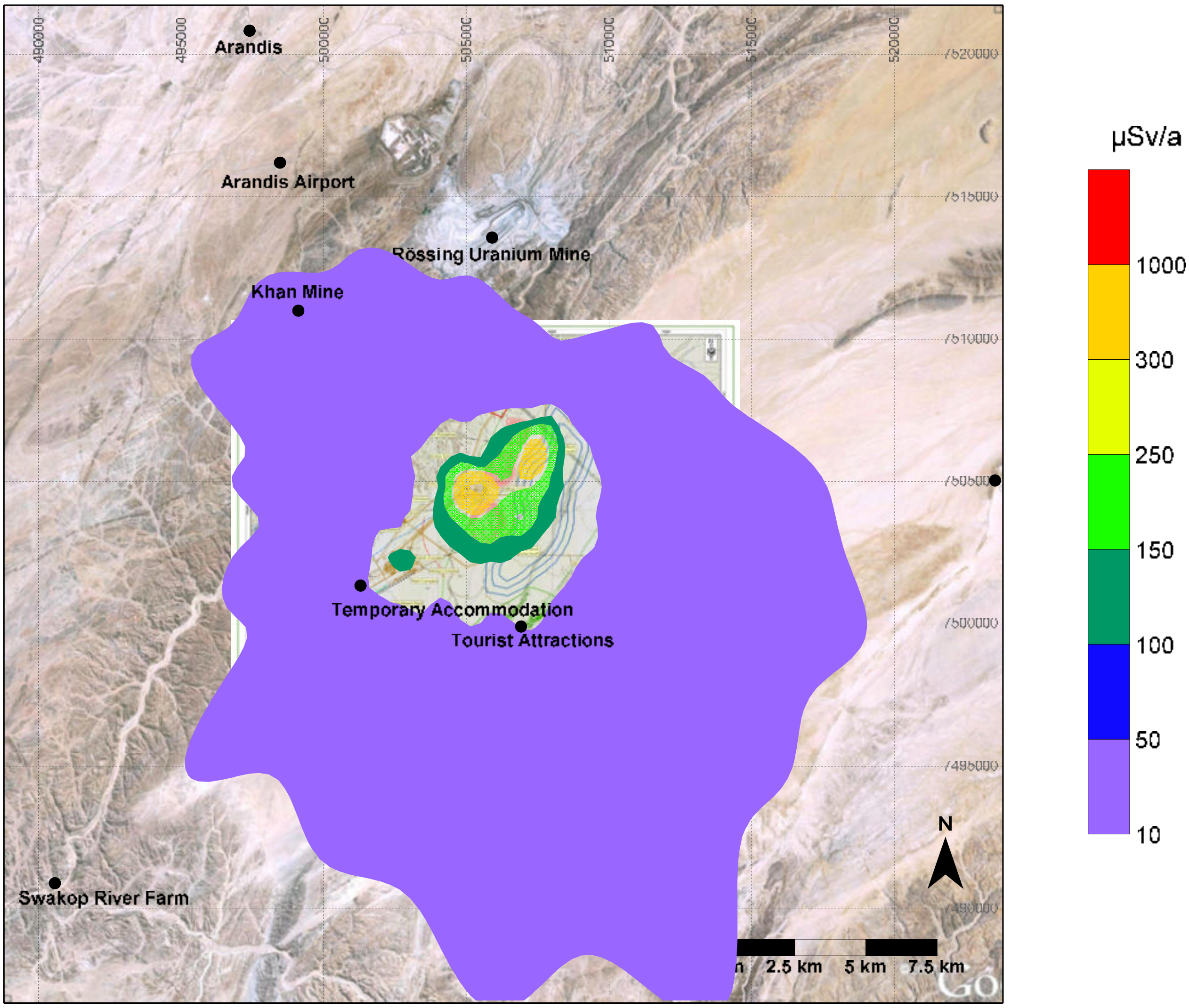

Figure 4: Calculated doses ($\mu Sv.a^{-1}$) for Dust Inhalation from the Unmitigated mining operations for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors).

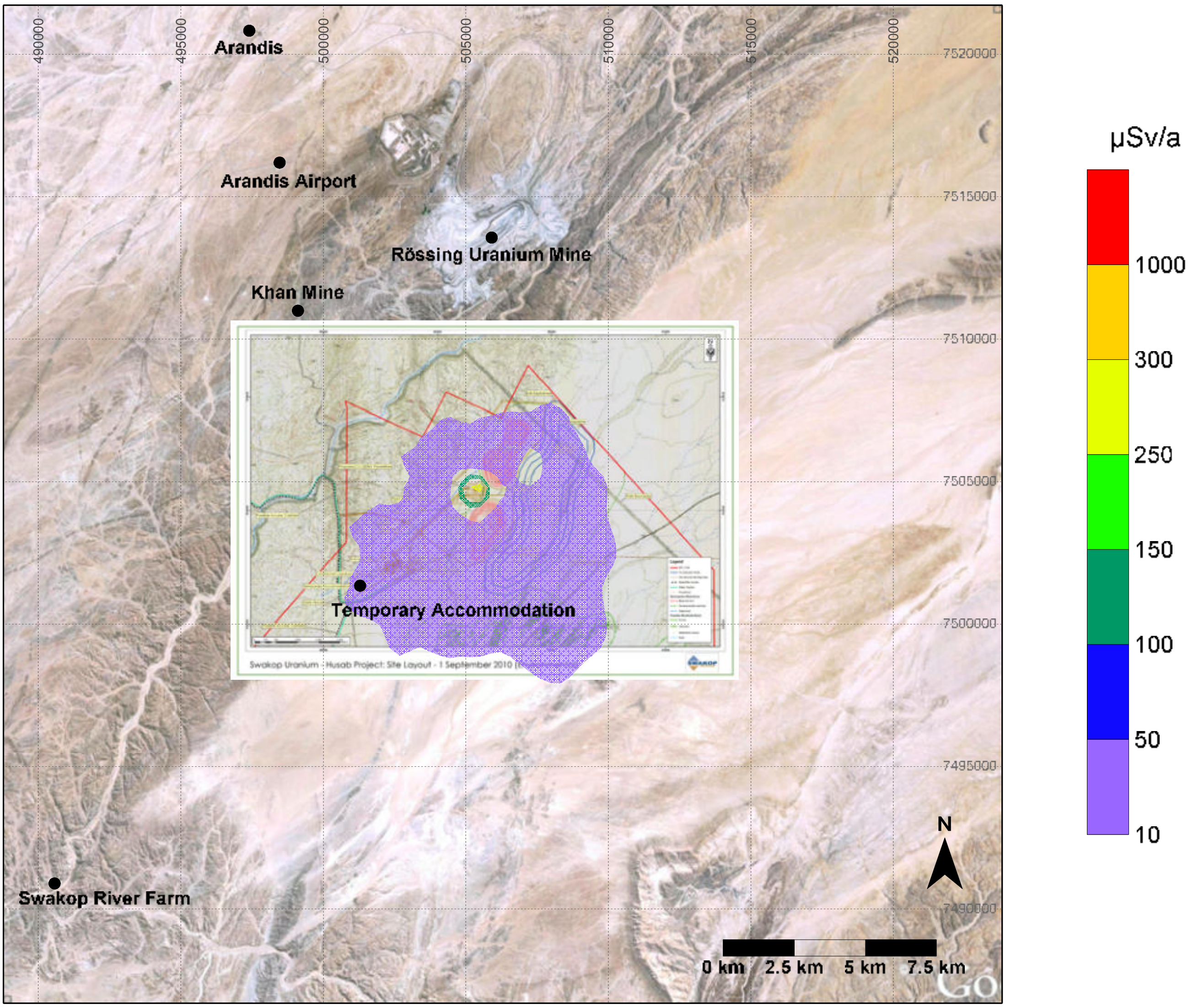

Figure 5: Calculated doses ($\mu Sv.a^{-1}$) for Dust Inhalation from the Mitigated mining operations for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors).

6.6.4 External Exposure to Deposited Dust

The TSP dust dispersion results were used to determine the dose due to dust deposition. These results, obtained from [3], for each of the mining operation sources were changed to radionuclide concentrations by multiplying with the total radionuclide concentrations (see Table 3) of the samples that are linked to the mining operation source (see Table 5). No indoor modelling was performed and it was assumed that the indoor and outdoor concentrations are equal. The resulting concentrations were converted to a dose for an adult by using Equation 4 with a one year exposure time (that is 4380 hours indoors and 4380 hours outdoors). The doses for all the mining operation sources were added to obtain the total dust deposition dose for an adult member of the public. This was done for both mitigated and unmitigated mining operations (per Section 5.1.2.2). The total TSP dust deposition dose results, indicated as contour plots, are depicted in Figure 6 and Figure 7.

From the above-mentioned results, the doses for the different Exposure Scenarios (per Section 5.3.2) were derived firstly by obtaining the yearly dose at the locations and secondly correcting it for the applicable exposure times by applying Equation 4. The respective total dust deposition doses are summarised in Table 7. External doses from deposited dust are age-independent and apply to both adults and children.

Table 7: Doses (μSv.a^{-1}) from Dust Deposition for the different Exposure Scenarios.

Exposure Scenario	Unmitigated Mining Operations	Mitigated Mining Operations
1: Swakop River Farm	0.024	0.011
2: Arandis Town	0.010	0.0037
3: Arandis Airport	0.0046	0.0018
4: Rössing Mine	0.0082	0.0043
5: Khan Mine	0.016	0.0068
6: Temporary Accommodation	0.13	0.064
7: Tourist Attractions	0.021	0.015

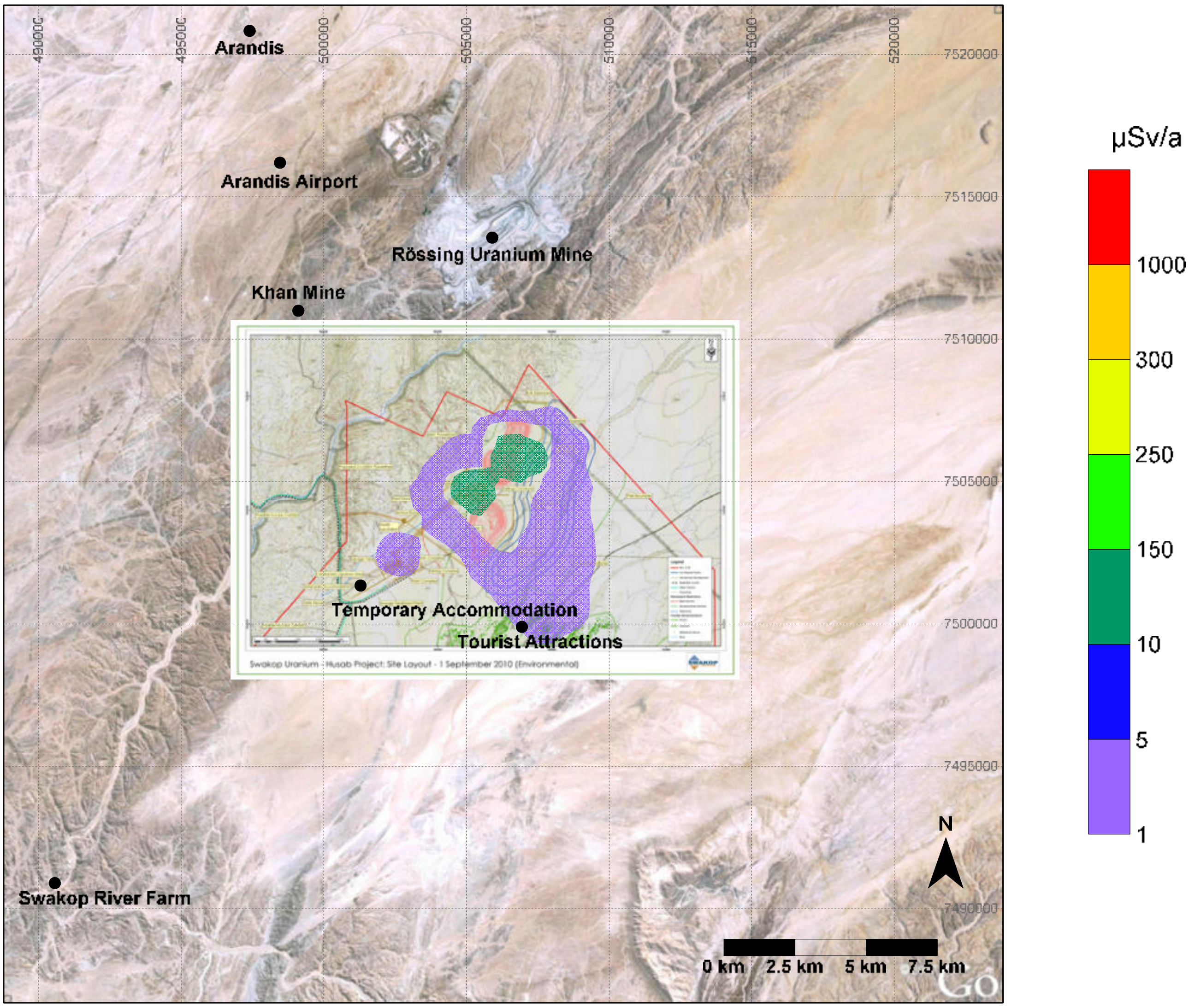

Figure 6: Calculated doses (µSv.a^{-1}) for Dust Deposition from the Unmitigated mining operations for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors).

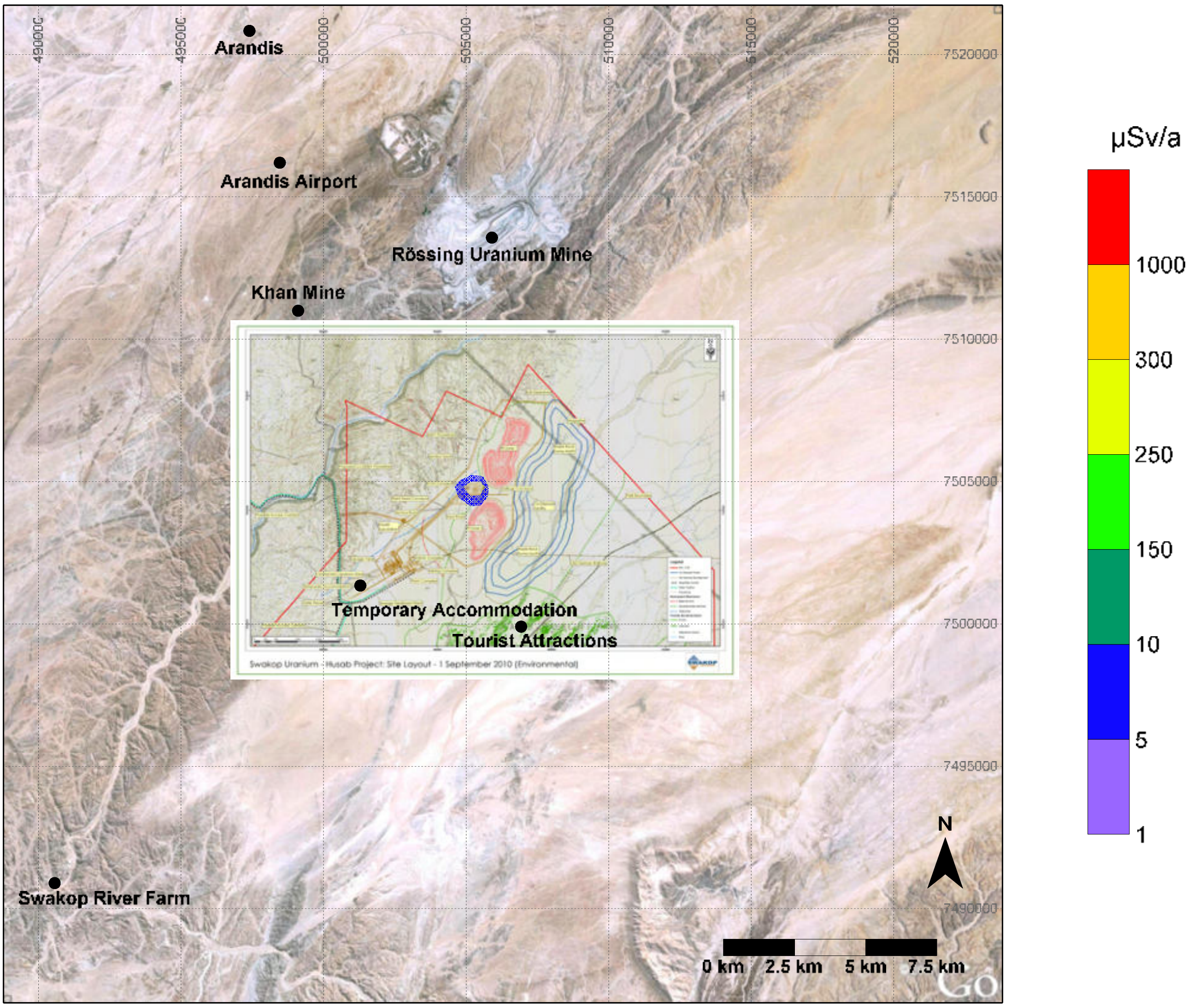

Figure 7: Calculated doses ($\mu Sv.a^{-1}$) for Dust Deposition from the Mitigated mining operations for an adult exposed for 8760 hours (4380 hours indoors and 4380 hours outdoors).

6.6.5 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 8.

Table 8: Total Doses (μSv.a^{-1}) from the Atmospheric Pathways for the different Exposure Scenarios.

Exposure Scenario	Unmitigated Mining Operations	Mitigated Mining Operations
1: Swakop River Farm	6.27	1.56
2: Arandis Town	4.06	0.93
3: Arandis Airport	1.85	0.41
4: Rössing Mine	2.07	0.45
5: Khan Mine	3.70	0.86
6: Temporary Accommodation	18.51	5.62
7: Tourist Attractions	0.98	0.29

7.0 DISCUSSION OF RESULTS AND RECOMMENDATIONS

7.1 EVALUATION AGAINST RADIOLOGICAL CRITERIA

The following radiological criteria are considered in the discussion below:

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

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

c) Doses between 300 µSv.a^{-1} and 1000 µSv.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).

d) Doses above 1000 µSv.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.

7.1.1 Radon Inhalation

The doses due to radon inhalation are summarised in Table 4. The assessed doses from radon inhalation for all the Exposure Scenarios for mitigated and unmitigated mining operations are trivial (smaller than 10 μSv.a^{-1}). The dose is age independent and also applies to children. No measures are hence recommended to safeguard the community at the Swakop River farm, the residents of Arandis Town, the workers at the Arandis Airport, the workers at Rössing Mine, the possible workers at Khan Mine, the workers that will stay at the temporary accommodation on the Husab Project site and the public at the tourist attractions, from radon inhalation.

7.1.2 Dust Inhalation

The doses due to dust inhalation are summarised in Table 6. The assessed doses from dust inhalation are all trivial (smaller than 10 μSv.a^{-1}) for all the Exposure Scenarios with mitigated mining operations. Therefore no measures are recommended for safeguarding the public from dust inhalation when the mitigation measures are in place.

In the case of unmitigated mining operations the assessed doses from dust inhalation are trivial (smaller than 10 μSv.a^{-1}) for all the Exposure Scenarios except for the workers that will stay at the temporary accommodation (Exposure Scenario 6). No measures are hence recommended to safeguard the community at the Swakop River farm, the residents of Arandis Town, the workers at the Arandis Airport, the workers at Rössing Mine, the possible workers at Khan Mine and the public at the tourist attractions from dust inhalation when no mitigation measures are used.

For the workers that will stay at the temporary accommodation the dose from dust inhalation is low, not exceeding 19 μSv.a^{-1}. Therefore no measures are recommended for safeguarding these workers from dust inhalation when no mitigation measures are used.

7.1.3 Dust Deposition

The doses due to dust deposition are summarised in Table 7. The assessed doses from dust deposition for all the Exposure Scenarios are trivial (smaller than 10 μSv.a^{-1}). No measures are hence recommended to safeguard the community at the Swakop River farm, the residents of Arandis Town, the workers at the Arandis Airport, the workers at Rössing Mine, the possible workers at Khan Mine , the workers that will stay at the temporary accommodation on the Husab Project site and the public at the tourist attractions, from dust deposition.

7.1.4 Total Dose for Atmospheric Pathways

The total doses for the atmospheric pathway are more or less the same as those of dust inhalation. The conclusions are therefore similar to those mentioned above for the dust inhalation pathway.

7.1.5 Radiation Management Program

Draft regulations of the National Radiation Protection Authority of Namibia [6] 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 has 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 the Husab Project site on the surrounding public and other interests and covers some mitigation options, 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. The Husab Project may therefore need to compile a radioactive waste management program addressing the long-term (e.g. post-closure) and other management requirements as the segregation and categorization of radioactive waste.

7.2 BACKGROUND RADIOLOGICAL CONDITIONS

A baseline (pre-mining) survey for the Swakop Uranium Husab project site is in progress. This involves on-site surveys to measure gamma radiation levels, in-situ Ra-226 and Ra-228 as well as radon gas concentrations. Samples are also collected for analyses to determine nuclide concentrations in water, sediments, surface soils and obtainable biota. The baseline survey will be separately reported on when completed. An interim report has been completed [16]. Some preliminary results from [16] as well as results that became available since then are discussed below. It should, however, be stressed that these may not cover a sufficient time span to represent annual averages as specified for the baseline study.

The baseline doses are intended to define pre-mining conditions, which are not controllable and should be regarded as background conditions against which additional doses should be evaluated following the commencement of mining operations.

7.2.1 Direct Exposure to Radiation

In the context of the natural environment, radiation can occur from natural sources such as cosmic and terrestrial radiation. Preliminary baseline external dose rates on the preoperational mine site indicate an average dose of 0.5 $mSv.a^{-1}$ with an upper 95 percentile value of 0.8 $mSv.a^{-1}$ in a scenario where people are situated on-site and without any shielding from the measured terrestrial radiation for approximately 8 hours a day over an extended period (e.g. 1 year).

In the context of the mine, radiation typically originates from mineralised substances (ore, mineralised waste, uranium product) and radioactive non-mineralised waste in the form of alpha radiation, beta radiation and/or gamma radiation. As discussed in Section 5.1.3.1, typically, radiation doses exceeding a trivial level of 10 $\mu Sv.a^{-1}$ are unlikely at distances of more than 500 m from these mineralised sources. This dose is regarded as trivial and requires no further consideration in terms of the radiation that third parties are exposed to [4].

7.2.2 Groundwater

Preliminary analytical results on various water samples collected inside and outside the Swakop Uranium Husab project area are also available, but may not represent annual-averaged concentrations. Full nuclide analyses have been performed on samples collected at the Hildenhof Farm and from Borehole SW2 in the Swakop River. Additional uranium analyses have been performed in 2010 as part of chemical analyses on borehole samples collected at various locations indicated on the map in Figure 8.

The analytical results have been used as part of the pre-mining baseline conditions to calculate effective radiological doses if people regularly consume the water in a given year. Doses were also calculated for when the water is used for agricultural purposes e.g. for stock watering and for crop production. Background doses ranged from approximately 0.3 $mSv.a^{-1}$ to over 1 $mSv.a^{-1}$ for Swakop River water and from 0.6 $mSv.a^{-1}$ up to 3 $mSv.a^{-1}$ for water collected within the mining area (borehole RS1). These doses are regarded as uncontrollable and related to background conditions. It should also be noted that salt concentrations in all the water samples were at levels that would cause the water to be non-potable.

7.2.3 Soil and Food

Soil and food contamination are mainly related to the transfer of activity from the soil to plants used as food, directly or via forage or pasture. Soil contamination again mainly associates with water contamination through irrigation. Ingestion doses have been calculated through such pathways using transfer parameters in [18]. When such food present 100 % of people's diet, meat, milk and egg consumption could present doses at 10 % to 20 % of those related to water consumption while crop ingestion relates to doses less than 1 % of those from water consumption. Exceptional high doses of just above 1 $mSv.a^{-1}$ were calculated when analysed grass, found at the boundary of the Husab Project site, was assumed to be consumed by stock. If these animals form a significant contribution to the food chain of the people in the area, it may require further investigation as it will form part of an uncontrollable background dose that the people may receive.

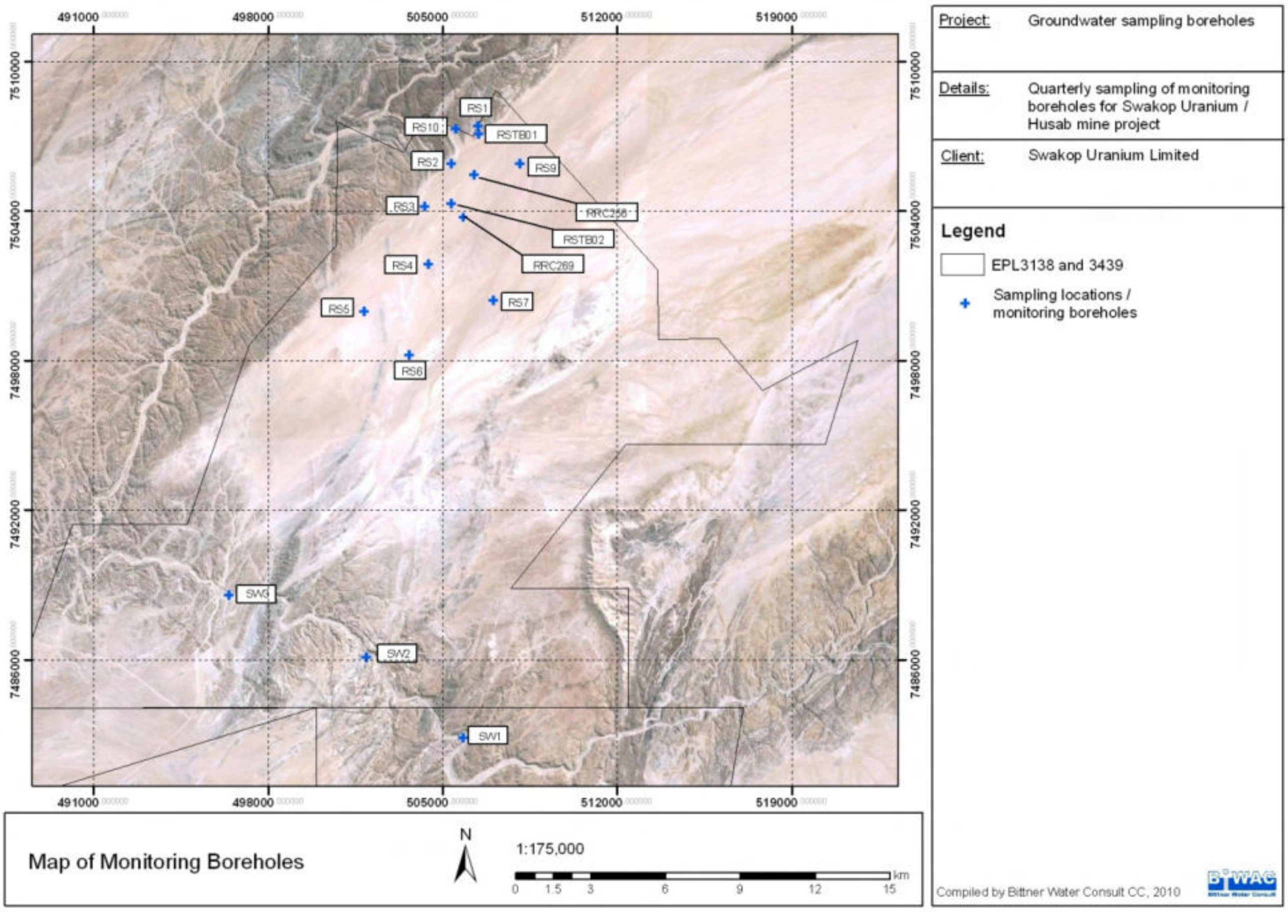

Figure 8: Map of monitoring boreholes.

7.2.4 Radon Gas

Natural baseline (pre-mining) radon gas monitoring are still in progress but the initial results indicate low potential on-site doses (if the same people are exposed on a daily basis in any given year) averaging 0.4 mSv/a with a 95 percentile at 0.7 $mSv.a^{-1}$ in the scenario where exposure is 50 % indoors and 50 % outdoors. It must be noted that the data is incomplete and should therefore only be used indicatively.

When considering third party exposure, there is some international debate about the relevant dose limits for radon gas. For uncontrollable sources actions are recommended as to optimise radon doses below 10 mSv/a [5]. Actions for controllable sources are still unclear as per draft recommendations of the ICRP in 2010 but the annual recommended dose limit of 1 $mSv.a^{-1}$ (from all sources excluding medical and natural sources) is considered relevant for new practices in the context of this EIA.

7.2.5 Inhalable Dust and Dust Fallout

No comment can be given on the background doses for inhalable dust and dust fallout since no analysis data is presently available. However, it will be addressed in the baseline survey when finalised.

8.0 EVALUATION AGAINST EIA CRITERIA

8.1 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 present the following table as a detriment-adjusted nominal risk coefficient (10^{-2} Sv^{-1}) for stochastic effects after exposure to radiation at low dose rate.

Exposed population	Cancer (Fatal and Non-fatal)	Heritable effects	Total
Whole population	5.5	0.2	5.7
Adult Worker	4.1	0.1	4.2

On the basis of these calculations the ICRP proposes nominal probability coefficients for detriment-adjusted cancer risk as 5.5 x 10^{-2} Sv^{-1} for whole population and 4.1 x $10^{-1}Sv^{-1}$ for adult workers. These values relate to the probability of contracting cancer when a dose of 1 Sv is received. Following the doses calculated in this assessment, it means that the possibility is very low.

8.2 EIA RISKS

The Criteria for ranking the SEVERITY of impacts and PROBABILITY (of exposure to impacts) are based on the ICRP proposed data. Should a person contract cancer the SEVERITY 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 the Husab Project all the doses except one are regarded as very low (below the trivial level of 10 $\mu Sv.a^{-1}$) and low (close to the trivial level). For this reason the SEVERITY and PROBABILITY is taken as L-. The DURATION is taken as H as it is long-term and could remain post-closure. The SPATIAL SCALE is taken as M because the impact could reach the site boundary but not regions far beyond the site boundary.

Using the above mentioned indicators, the significance of the risk for Exposure Scenario 6: Temporary Accommodation is determined as **Low** and all the other Exposure Scenarios are determined as **Low -**.

In Table 9 the Exposure Scenarios are linked to the criteria for the environmental impact assessment.

Table 9: Radiological criteria linked to environmental impact assessment criteria.

	Criteria for ranking of the SEVERITY of environmental impacts	Criteria for ranking the DURATION of impacts	Criteria for ranking the SPATIAL SCALE of impacts	PROBABILITY (of exposure to impacts
Exposure Scenario 1:Swakop River Farm				
Unmitigated Mining Operations	L-	H	M	L-
Mitigated Mining Operations	L-	H	M	L-
Exposure Scenario 2: Arandis Town				
Unmitigated Mining Operations	L-	H	M	L-
Mitigated Mining Operations	L-	H	M	L-

	Criteria for ranking of the SEVERITY of environmental impacts	Criteria for ranking the DURATION of impacts	Criteria for ranking the SPATIAL SCALE of impacts	PROBABILITY (of exposure to impacts
Exposure Scenario 3: Arandis Airport				
Unmitigated Mining Operations	L-	H	M	L-
Year Mitigated Mining Operations	L-	H	M	L-
Exposure Scenario 4: Rössing Mine				
Unmitigated Mining Operations	L-	H	M	L-
Mitigated Mining Operations	L-	H	M	L-
Exposure Scenario 5: Khan Mine				
Unmitigated Mining Operations	L-	H	M	L-
Mitigated Mining Operations	L-	H	M	L-
Exposure Scenario 6: Temporary Accommodation				
Unmitigated Mining Operations	L	H	M	L
Mitigated Mining Operations	L	H	M	L

8.3 Final Conclusion and Recommendations

The outcome of the assessment indicated that, for the identified critical groups as per the defined exposure scenarios, the exposures from the relevant sources of exposure during the proposed mining operations are trivial to very low and within the specified criteria levels.

A report highlighting, amongst others, the cumulative doses from all mining activities to public living in the Erongo Region [20] indicated that the total dose is lower than 1 $mSv.a^{-1}$. Even with the addition of the doses of the Husab Project this will still be the case.

Mitigation options proved to be successful as doses from mitigated mining operations were significantly lower than the unmitigated mining operations.

The results for the modelled radon doses are insignificant. This is however not consistent with radiological assessments done for other Namibian mines. It is recommended that radon measurements are done, as set out below, in order to investigate this anomaly.

A Public Radiation Protection Program or routine environmental monitoring and surveillance program must be compiled for authorized actions and the data from the Public Hazard Assessment must be used as a guideline. This needs to be site-specific because it is influenced by factors such as site location, climate and the off-site environmental and population distribution.

The environmental monitoring program must consider the source characteristics and the expected discharge rate, radionuclide composition, significance of exposure pathways, doses to individuals, radioactive effluents and the emission of radioactive dust and radon, collective doses to populations and the potential for accident releases. The program should include a structured environmental database.

The following recommendations follow in terms of such a monitoring program:

- Radon gas monitoring should be done around the major exposure sources such as the tailings dam, open pits and waste rock stockpiles. Sampling should focus around taking radon gas measurements at specific locations upwind and downwind from the major sources. It is proposed that radon gas monitoring be performed at the same respective positions where the dust fall-out samplers are deployed (see third bullet below). The wind directions and speed should also be captured during the monitoring to enable correlation between monitoring data and meteorological conditions.

- Radon exhalation measurements should be performed for the respective exposure sources at the Husab Project. For the current Necsa assessment generic data was used. The results should however, be confirmed once real site data becomes available.

- Dust fall-out as well as airborne dust monitoring should be performed with specific reference to the major exposure sources. Specific locations upwind and downwind with the accompanying meteorological data, as for radon above, should have preference. The sampling can be performed at the locations as recommended by the air dispersion specialists.

- Sampling of solid samples from the different sources must be performed on a three monthly basis for a period of one year. The purpose of the sampling exercises will be to verify the calculated nuclide specific analysis results in Table 3 as well as to collect data that will inform the future post-closure planning of the Husab Project. These samples should be split and analysed (full nuclide specific) for the course and fine fraction as to determine a nuclide upgrading factor for the airborne dust. Each sample could be a composite sample but should be collected as per approved methodologies.

The Necsa assessment was performed taking cognisance of specific critical groups. The scenarios may, however change with time. The management of the Husab Project 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 ongoing basis, the validity of the identified critical group(s) and re-define these if changes are noticed.

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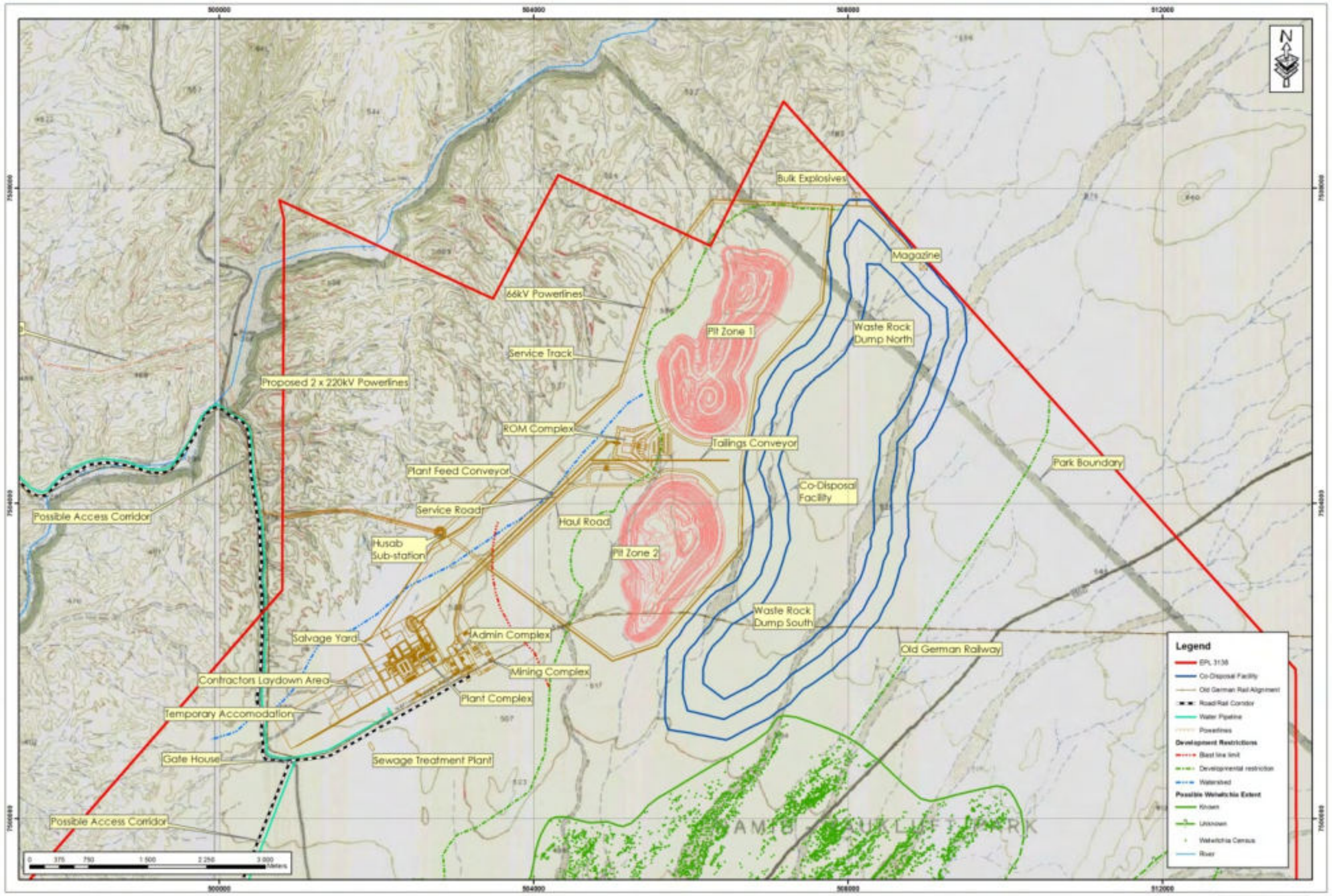
10.0 APPENDIX A: MAP OF THE SITE LAYOUT OF THE HUSAB PROJECT



Swakop Uranium - Husab Project: Site Layout - 1 September 2010 (Environmental)

11.0 APPENDIX B: DOSE ASSESSMENT PARAMETERS

Table 10: 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 11: Dose coefficients (Sv.Bq^{-1}) to calculate inhalation doses for the public impact assessment.

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

Table 12: Dose coefficients (Sv.h^{-1} per Bq.m^{-2}) to calculate the dose from external surface.

Age Group	U-238+	U-234	Th-230	Ra-226+	Pb-210+	Po-210	U-235+	Pa-231	Ac-227+	Th-232	Ra-228+	Th-228	Ra-224+
0 – 2	4.5E-13	3.0E-15	3.0E-15	6.3E-12	1.4E-13	3.0E-17	6.1E-13	1.5E-13	1.8E-12	2.2E-15	3.5E-12	8.8E-15	5.4E-12
2 – 7	4.5E-13	3.0E-15	3.0E-15	6.3E-12	1.4E-13	3.0E-17	6.1E-13	1.5E-13	1.8E-12	2.2E-15	3.5E-12	8.8E-15	5.4E-12
7 – 12	4.5E-13	3.0E-15	3.0E-15	6.3E-12	1.4E-13	3.0E-17	6.1E-13	1.5E-13	1.8E-12	2.2E-15	3.5E-12	8.8E-15	5.4E-12
12 – 17	4.5E-13	3.0E-15	3.0E-15	6.3E-12	1.4E-13	3.0E-17	6.1E-13	1.5E-13	1.8E-12	2.2E-15	3.5E-12	8.8E-15	5.4E-12
Adults	4.5E-13	3.0E-15	3.0E-15	6.3E-12	1.4E-13	3.0E-17	6.1E-13	1.5E-13	1.8E-12	2.2E-15	3.5E-12	8.8E-15	5.4E-12
Workers	4.5E-13	3.0E-15	3.0E-15	6.3E-12	1.4E-13	3.0E-17	6.1E-13	1.5E-13	1.8E-12	2.2E-15	3.5E-12	8.8E-15	5.4E-12

A + after the nuclide symbol indicates the inclusion of radiation from the short-lived daughters up to the next listed nuclide

Table 13: Dose coefficients ($Sv.h^{-1}$ per $Bq.g^{-1}$) to calculate the dose from external volume.

Age Group	U-238+	U-234	Th-230	Ra-226+	Pb-210+	Po-210	U-235+	Pa-231	Ac-227+	Th-232	Ra-228+	Th-228	Ra-224+
0 – 2	5.2E-09	1.3E-11	3.8E-11	3.5E-07	1.9E-10	1.6E-12	2.3E-08	5.9E-09	6.3E-08	1.6E-11	1.9E-07	2.5E-10	3.2E-07
2 – 7	5.2E-09	1.3E-11	3.8E-11	3.5E-07	1.9E-10	1.6E-12	2.3E-08	5.9E-09	6.3E-08	1.6E-11	1.9E-07	2.5E-10	3.2E-07
7 – 12	5.2E-09	1.3E-11	3.8E-11	3.5E-07	1.9E-10	1.6E-12	2.3E-08	5.9E-09	6.3E-08	1.6E-11	1.9E-07	2.5E-10	3.2E-07
12 – 17	5.2E-09	1.3E-11	3.8E-11	3.5E-07	1.9E-10	1.6E-12	2.3E-08	5.9E-09	6.3E-08	1.6E-11	1.9E-07	2.5E-10	3.2E-07
Adults	5.2E-09	1.3E-11	3.8E-11	3.5E-07	1.9E-10	1.6E-12	2.3E-08	5.9E-09	6.3E-08	1.6E-11	1.9E-07	2.5E-10	3.2E-07
Workers	5.2E-09	1.3E-11	3.8E-11	3.5E-07	1.9E-10	1.6E-12	2.3E-08	5.9E-09	6.3E-08	1.6E-11	1.9E-07	2.5E-10	3.2E-07

A + after the nuclide symbol indicates the inclusion of radiation from the short-lived daughters up to the next listed nuclide

12.0 APPENDIX C: 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