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Dose Assessment for a Life-of-Mine Extension (LoME) of the Rössing Uranium Mine

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2 INTRODUCTION

Rössing Uranium Ltd presently investigates the possibility of a life-of-mine extension (LoME) for the Rössing Uranium mine. During the LoME, some of the dust emission sources on the mine site may change. The tailings impoundment, various waste dumps, other rock dumps as well as the open pit will for instance change in size. The production rate and hence the tons crushed and milled will reach a climax during the life-of-mine extension. Rössing Uranium requested Necsa to perform a dose assessment to compare the current radiological impact of the mine on members of the public with the impact during the life-of-mine extension and also to compare the radiological impacts after mine closure. Details on the re-assessment as well as the results are discussed in this report.

Rev 1 of the document has been extended to incorporate isodose contours of the annual doses from radon and long-lived radioactive dust as per restrictions presented in Section 3 (viii) below.

3 SCOPE OF THE ASSESSMENT

The SOW for the assessment is attached as Appendix A. The following information for the assessment is presently available:

(i) A post-closure radiological impact assessment has been performed during September 2002 and the assessment detail and results are reported in [1]. This includes a detailed context description of the assessment and site description for the Rössing Uranium mine and surrounding environment. Various post-closure mitigation options are also described, including those required in terms of the attached SOW. Such descriptions will also relate to the present assessment but will not be repeated as it can be obtained from [1].

(ii) A subsequent assessment has been performed for a phased mine extension as reported in [2], but it is assumed that the present assessment will replace this.

(iii) A report on atmospheric dispersion modelling results has been received from the Rössing dispersion modelling consultant [3]. This report presents the various fugitive, material-handling and stack emission sources on the Rössing site for the current and proposed LoME phases of the mine. It then models and presents the mean and maximum annual radon doses and long-lived radioactive dust (LLRD) concentrations at the various receptor locations for scenarios defined for the current and proposed LoME operational phases as well as for the post-closure phase of the mine, as related to the current and LoME conditions. In the latter case it also models the effects of the various mitigation strategies presented in the SOW on the post-closure radon doses and LLRD concentrations.

Based on the SOW and the information above, the following scope is foreseen:

(i) The annual radon doses in [3] will be evaluated against exposure conditions as per the scenarios presented in [1] and adjusted where applicable. This will mainly involve an adjustment to indoor and outdoor exposure periods different from those considered in [3].

(ii) The modelled LLRD concentrations, as presented in [3] for the various receptor locations, do not render themselves to an exact dose assessment as only the gross activities of the LLRD concentrations are presented and not the nuclide concentrations. The nuclide concentrations can be derived if the nuclide compositions of the various emission sources are known as well as the contribution of each emission source to the gross activity concentrations at each receptor location. Information in [1] on the nuclide composition of source materials and in [3] on source contributions will be used to obtain approximate nuclide compositions for and doses from the LLRD concentrations at the receptor locations. Additionally some assumptions for current, for LoME and for the related post-closure mitigation strategies will be required.

(iii) Because only mean and maximum values are presented in [3], the stochastic approach in this assessment will not attempt to fit distributions to these values but will only assess mean and conservative doses derived through an uncertainty analysis.

(iv) Both a deterministic and stochastic assessment model is described in [1], the latter defining distributions for the various input parameters and performing a Monte Carlo sampling process to calculate dose distributions for uncertainty analysis. The deterministic model in [1] will be used as basic model for the present dose assessment and will hence not be described again in detail. The referenced report will also be used to obtain radionuclide and other radiological data.

(v) No new information on the impact of the LoME on liquid discharges has been provided. Following discussions with Rössing Uranium, the results of the simple mixing model used for aquatic pathway dose assessments in [1] will again be used for both the current, and LoME phases. This also applies for the related seepage control mitigations options discussed in [1] for the post-closure conditions.

(vi) The following critical groups will be considered:

Scenario 1: Residents of Arandis
Scenario 2: Residents of Arandis Airport
Scenario 3: Farming community at the confluence of Khan River and Dome Gorge

Scenario 4: Farming community at the confluence of Khan River and Panner Gorge
Scenario 5: Residents living and working at the old Khan Mine site
Scenario 6 Factory workers at E-Camp
Scenario 7: Maintenance workers on the Tailings Dam.

The scenario details for scenarios 1 to 5 are similar to those presented in [1]. Scenarios 6 and 7 are new but only consider workers exposed for 2000 hours per annum to radon daughters and dust at the concentrations reported in [3]. For Scenario 6 workers were assumed to be exposed only indoors and for scenario 7 to be exposed only outdoors.

(vii) The following mitigation options during post closure conditions will be considered as per the notation previously used in [1]:

- No mitigation (previously option S1)
- Mitigation of the open pit by releasing tailings effluent into the pit (no previous notation)
- Partial mitigation (a) as per the SOW (previously option S2 (a))
- Partial mitigation (b) as per the SOW (previously option S2 (b))
- Total clean-up (previously option S3)

(viii) This Rev 1 of the document has been extended relative to the initial report of 31 May 2007 to incorporate isodose contours of the annual doses from radon and long-lived radioactive dust (LLRD). The following restrictions apply to these contours, however:

- The doses from radon and LLRD for various receptor locations relate to a separate dose conversion factor for each receptor location as per the scenario detail for that receptor location. Differences considered were for instance variations in the indoor and outdoor exposure periods and the contributions from dust with various nuclide compositions for different receptor locations.
- Because receptor locations relate to specific spatial locations, the doses at these locations cannot be simulated in isodose contours, which cover large spatial areas. These contours will hence relate to a single dose conversion factor for radon and a single dose conversion factor for LLRD presenting a dose related to expected average conditions only.
- The averaging detail and results are presented and discussed in Section 8.

4 ATMOSPHERIC PATHWAY ASSESSMENT DETAIL

The interconnected spreadsheet dose assessment model, described in [1], has been adapted for the assessment. Details of the alterations are discussed below.

4.1 Operational Phase

This covers the current and LoME operational phase assessment, as per the following detail:

4.1.1 Radon Daughter Exposure Assessment

(i) The radon concentrations for each receptor location in the model have been recalculated from the annual doses presented in [3] for the current and LoME mean and maximum scenarios. This was done because the doses were calculated for members of the public at an 80 % indoor and 20 % outdoor occupancy for 8760 $h.a^{-1}$. A 50 % indoor and 50 % outdoor occupancy rather need to be considered for some of the public exposure scenarios as defined in [1], while the E-Camp and Tailings Dam locations will involve workers exposed for 2000 $h.a^{-1}$ at 100 % indoor and 100 % outdoor conditions respectively. The radon doses were subsequently recalculated for different exposure periods and occupancies as per the defined scenarios in [1] also indicated in Section 3 above. The conversion coefficients for this adjustment were 5.56E-06 $mJ.m^{-3}$ per $Bq.m^{-3}$ together with 1.1E+00 mSv per $mJ.h.m^{-3}$ for members of the public and 1.43 mSv per $mJ.h.m^{-3}$ for workers [4].

(ii) It should be noted that the maximum radon doses in [3] relate to uncertainties in the radon source terms used in the dispersion calculations. It should also be noted that results in [3] were based on 2004 weather data, with the variability of the weather data over 10 years also presented. These uncertainties will be discussed in the section on the result uncertainty analysis.

4.1.2 Dust Inhalation Dose Assessment

(i) The dust source terms in [3] are presented only in terms of the long-lived radioactive dust (LLRD) gross activities and not in terms of the activities of each nuclide. The LLRD concentrations at the modelled receptor locations are also only presented in terms of LLRD gross activities. This presented some problems with the dose assessment as the conversion coefficients to dose are nuclide-dependent. To overcome this problem, the relative nuclide composition of various dust source bulk materials, presented in [1] has been used to proportionate the gross activities to nuclide activities. An assumption in this regard has been made that the relative nuclide composition of the airborne dust is similar to that of the analysed bulk material. This data, adjusted slightly from 290 ppm to 350 ppm U in the ore and assuming 20 % of the U and all remaining nuclides remain in the tailings, is presented in Table 4-1 below. The problem is wider, however, because the contribution of each source to the LLRD concentration at each receptor location is also required for each of the different phases and mitigation options to be investigated. The contributions of some of the sources to the modelled LLRD gross activities are presented in Table 7c and Table 8 of [3], but relate to the current and LoME phases respectively. The data from [3] is copied in Table 4-2.

Table 4-1: Analysed or calculated nuclide concentrations [$Bq.g^{-1}$] of solid materials

Sample Description	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
Ore	4.34	4.34	4.34	4.34	4.34	4.34	0.20	0.20	0.20	0.24	0.24	0.24	0.24
Tailings	0.87	0.87	4.34	4.34	4.34	4.34	0.20	0.20	0.20	0.24	0.24	0.24	0.24
Seepage dam sludge	26.7	*26.7*	*0.91*	1.81	1.93	*1.93*	0.08	0.08	0.08	0.27	0.54	0.50	*0.50*
Pool precipitates	2.19	*2.19*	*6.80*	8.1	7.46	*7.46*	0.37	0.37	0.37	0.19	0.22	0.40	*0.40*

Values in italics are interpolated

Table 4-2: Percentage contribution of LLRD sources targeted for mitigation to total the LLRD concentrations at the receptor locations

Arandis	2.1	25.8	4.2	54.8	4.6	3.3	5.2	100	0.733
Arandis airport	1.1	26.1	5.6	53.9	4.8	3.1	5.4	100	0.906
Dome gorge	1.4	16.9	5.9	37.2	1.7	4.6	32.3	100	0.417
Panner gorge	1.4	13.4	4.7	28.8	0.9	24.8	26.0	100	0.031
Khan gorge	2.2	20.0	12.1	46.3	2.6	5.5	11.3	100	0.525
E-camp	2.1	25.8	4.2	54.8	4.6	3.3	5.2	100	2.296
Tailings Dam Center	0.0	33.0	0.0	67.0	0.0	0.0	0.0	100	59.47

(ii) Table 4-2 were used to obtain nuclide-specific LLRD concentrations, but needed to be extended with the following assumptions:

- The contribution from the plant stacks to the LLRD was calculated from LLRD concentrations presented in Table 7c of [3] and added to the data. The LLRD concentrations did not match the percentage contribution presented in Table 7c for the Panner gorge and the former were rather used to re-calculate the percentages.

- For the E-Camp and tailings dam locations, the contributions are not presented in [3]. For E-Camp it is assumed be similar to that at Arandis Town while for the tailings dam the tailings and salt deposits were assumed to contribute respectively 66.7 % and 33.3 % to the airborne dust.

- The contribution of the material handling sources is not presented and is assumed to be the remaining percentage to bring the total up to 100 %.

The percentage contributions in Table 4-2 was assumed to apply to both the current as well as LoME phases and used, together with the LLRD gross-activity concentrations presented in Table 7a of [3], to calculate the nuclide composition of the modelled LLRD concentration at each receptor location.

Table 4-2 is in fact part of one of the spreadsheets indicating the modelled LLRD gross-activity concentrations for the LoME phase in the last column. These gross-activity concentrations were multiplied with the percentage contribution of each source and with the fractional contribution of each nuclide in Table 4-1 to that source to obtain the nuclide concentration at each receptor location.

(iii) It should be noted that the maximum LLRD dust inhalation doses in [3] relate to uncertainties in the LLRD source terms used in the dispersion calculations. It should also be noted that results in [3] were based on 2004 weather data, with the variability of the weather data over 10 years also presented. These uncertainties and variability will be discussed in the section on the uncertainty analysis.

4.2 Post-closure Dose Assessment

This covers the assessment of post-closure conditions following the LoME operational phase. Apart from the adaptations discussed in Section 4.1 for the operational phase, the assessment for the post-closure phase required the following considerations:

4.2.1 Radon Daughter Exposure Assessment

(i) For the post-closure phase, radon doses in [3] are presented for conditions where the material handling sources are removed but where it is assumed that the various dust mitigation measures have no influence on the radon exposures at the various receptor locations.

(ii) Radon mitigation was only assessed in [3] for the open pit as source to determine the influence of a salt deposit remaining after collection and evaporation of tailings dam effluent in the open pit. The radon doses presented in [3], were hence only adapted to the required indoor and outdoor exposure periods as discussed for the operational phase in Section 4.1.1, and corrected with the influence of the salt deposit as an open-pit mitigation strategy.

(iii) The dust-mitigation strategies were assumed not to influence the radon exposure conditions.

4.2.2 *Dust Inhalation Dose Assessment*

(i) The only source, specifically addressed in [3] for the post-closure conditions, is the salt deposit in the open pit. The results are presented in Table 7b of [3], and are assumed to be the only contributor to post-closure LLRD concentrations at the receptor locations, as related to the complete mitigation option for the dust sources.

(ii) For the other sources, the information on LLRD concentrations in [3] during the post closure conditions is limited to an evaluation of the percentage reduction of the LLRD concentrations at the various receptor locations for mitigation options S2 (a) and S2 (b), as mentioned in Section 3 above. The results are presented in Table 9 and Table 10 of [3]. This does, however, not address the change in the nuclide composition due the mitigation option and the dose impact can hence not be determined accurately.

(iii) In order to assess the various post-closure mitigation options mentioned in Section 3, the following strategy was followed:

- It was assumed that, without the salt deposit, the contribution of the open pit to the post-closure LLRD concentrations at the receptor locations would be insignificant. This has been checked and agreed on with the Rössing dispersion modeller. The percentage contribution of the salt has been calculated for this specific mitigation strategy and added as an additional source to those presented in Table 4-2.
- To assess the dose from the other sources during the various mitigation options, the percentage contributions of the relevant sources were totally eliminated if the source was completely mitigated, but only reduced if partially mitigated as per amounts mentioned in the mitigation option descriptions in [3]. This still did not resolve all the problems because the description in [3] is sometimes only qualitative and not quantitative (e.g. only mentioning the source areas being mitigated but not the associated reduction factor in the source term). Reduction factors were hence estimated by comparing the calculated dose reduction with the LLRD concentration reduction in Table 9 and Table 10 of [3]. The method remained, however, approximate because the dose reduction for various receptor locations differed with various amounts from the LLRD concentration reductions due to the different nuclide compositions of the contributing sources.

5 ATMOSPHERIC PATHWAY ASSESSMENT RESULTS

The assessed results are presented below for the current and LoME operational phase, followed by those for the post-closure phase. The results presented in this section refer to the mean values in [3], as based on the 2004 weather data and are referred to as "reference expected" values. Possible adjustments, based on variations in the weather as well as the source-term data as per the maximum values in [3], are discussed in Section 6 as uncertainties and relate to more conservative values.

5.1 Reference expected radon doses for operational phase

The assessed radon doses for the current and LoME operational conditions are presented in Table 5-1 and Table 5-2 respectively.

Table 5-3 presents the calculated percentage increases of radon doses at the various receptor locations caused by the LoME operations. These re-assessed radon doses for the mean values in [3] are indicated as reference expected values.

Table 5-1 Reference expected radon doses for current operational conditions

Scenario Description	Indoor Rn			Outdoor Rn			Dose
	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[µSv.a^{-1}]
Arandis resident	1.32	0.40	4380	1.32	0.80	4380	43
Arandis Airport resident	1.75	0.40	4380	1.75	0.80	4380	56
Khan river downstream of Dome Gorge	2.10	0.40	4380	2.10	0.80	4380	68
Khan river downstream of Panner Gorge	0.70	0.40	4380	0.70	0.80	4380	23
Khan mine	1.32	0.40	4380	1.32	0.80	4380	43
E-camp	5.09	0.40	2000	5.09	0.80	0	32
Center of Tailings Dam	64.94	0.40	0	64.94	0.80	2000	826

Table 5-2 Reference expected radon doses for LoME operational conditions

Scenario Description	Indoor Rn			Outdoor Rn			Dose
	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[µSv.a^{-1}]
Arandis resident	1.40	0.40	4380	1.40	0.80	4380	45
Arandis Airport resident	1.87	0.40	4380	1.87	0.80	4380	60
Khan river downstream of Dome Gorge	2.14	0.40	4380	2.14	0.80	4380	69
Khan river downstream of Panner Gorge	0.86	0.40	4380	0.86	0.80	4380	28
Khan mine	1.44	0.40	4380	1.44	0.80	4380	46
E-camp	5.56	0.40	2000	5.56	0.80	0	35
Center of Tailings Dam	65.72	0.40	0	65.72	0.80	2000	836

Table 5-3 Percentage radon dose increase due to LoME operations

Scenario Description	% Dose Increase
Arandis resident	5.9
Arandis Airport resident	6.7
Khan river downstream of Dome Gorge	1.9
Khan river downstream of Panner Gorge	22.2
Khan mine	8.8
E-camp	9.2
Center of Tailings Dam	1.2

5.2 Reference expected LLRD inhalation doses for operational phase

The assessed dust inhalation doses for the current and LoME operational conditions are presented in Table 5-4 and

Table 5-5 respectively. Table 5-6 presents the calculated percentage increases of radon doses at the various receptor locations caused by the LoME operations. These re-assessed dust inhalation doses for to the mean values in [3] are indicated as reference expected values.

Table 5-4 Reference expected LLRD inhalation doses for current operational conditions

Scenario description	LLRD [Bq.m^{-3}]	Calculated annual dose [µSv.a^{-1}]					
		1 Year	5 Year	10 Year	15 Year	Adult	Worker
Arandis resident	0.733	40	43	50	57	59	
Arandis Airport resident	0.906	49	53	61	70	72	
Khan river downstream of Dome Gorge	0.417	23	24	28	32	33	
Khan river downstream of Panner Gorge	0.031	2	2	2	2	2	
Khan mine	0.525	28	30	35	40	42	
E-camp	2.296						26
Center of Tailings Dam	59.47						638

Table 5-5 Reference expected LLRD inhalation doses for LoME operational conditions

Scenario description	LLRD [Bq.m^{-3}]	Calculated annual dose [µSv.a^{-1}]					
		1 Year	5 Year	10 Year	15 Year	Adult	Worker
Arandis resident	0.982	53	57	67	76	79	
Arandis Airport resident	1.227	67	71	83	95	98	
Khan river downstream of Dome Gorge	0.600	33	35	40	46	48	
Khan river downstream of Panner Gorge	0.039	2	2	3	3	3	
Khan mine	0.713	39	41	48	55	56	
E-camp	2.577						29
Center of Tailings Dam	83.260						893

Table 5-6 Percentage LLRD inhalation dose increase due to LoME operations

Scenario Description	% Dose Increase
Arandis resident	34.0
Arandis Airport resident	35.4
Khan river downstream of Dome Gorge	43.9
Khan river downstream of Panner Gorge	25.8
Khan mine	35.8
E-camp	12.2
Center of Tailings Dam	40.0

5.3 Reference expected post-closure radon doses

The assessed radon doses for the LoME post-closure conditions with no mitigation (option S1) and with mitigation by creating a layer of salt deposit in the open pit are presented in Table 5-7 and Table 5-8 respectively. Table 5-9 presents the calculated percentage change of radon doses at the various receptor locations due to the salt deposit under LoME post-closure conditions. These re-assessed radon doses for the mean values in [3] are indicated as expected values. Dust mitigation strategies have been assumed not to cause any radon mitigation and were hence not investigated.

Table 5-7 Reference expected radon doses for unmitigated LoME post-closure conditions

Scenario Description	Indoor Rn			Outdoor Rn			Dose
	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[µSv.a^{-1}]
Arandis resident	1.32	0.40	4380	1.32	0.80	4380	39
Arandis Airport resident	1.75	0.40	4380	1.75	0.80	4380	51
Khan river downstream of Dome Gorge	2.10	0.40	4380	2.10	0.80	4380	64
Khan river downstream of Panner Gorge	0.70	0.40	4380	0.70	0.80	4380	23
Khan mine	1.32	0.40	4380	1.32	0.80	4380	39
E-camp	5.09	0.40	2000	5.09	0.80	0	32
Center of Tailings Dam	64.94	0.40	0	64.94	0.80	2000	826

Table 5-8 Reference expected radon doses for LoME post-closure conditions mitigated with a salt deposit in the open pit

Scenario Description	Indoor Rn			Outdoor Rn			Dose
	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[Bq.m^{-3}]	F	Exp.[h.a^{-1}]	[μSv.a^{-1}]
Arandis resident	1.20	0.40	1	0.80	0.80	4380	39
Arandis Airport resident	1.59	0.40	2	0.80	0.80	4380	51
Khan river downstream of Dome Gorge	1.98	0.40	2	0.80	0.80	4380	64
Khan river downstream of Panner Gorge	0.70	0.40	1	0.80	0.80	4380	22
Khan mine	1.20	0.40	1	0.80	0.80	4380	39
E-camp	5.07	0.40	5	0.80	0.80	0	32
Center of Tailings Dam	64.94	0.40	65	0.80	0.80	2000	826

Table 5-9 Percentage radon dose change due to salt deposit

Scenario Description	% Dose Change
Arandis resident	-0.5
Arandis Airport resident	-0.5
Khan river downstream of Dome Gorge	-0.2
Khan river downstream of Panner Gorge	-0.4
Khan mine	-0.6
E-camp	-0.4
Center of Tailings Dam	0.0

5.4 Reference expected post-closure LLRD inhalation doses

As discussed in Section 4.2.2, post-closure LLRD inhalation doses were assessed by eliminating or reducing the sources mitigated. The results on the source contributions for the unmitigated and various mitigation options are presented below, together with the associated LLRD inhalation doses.

5.4.1 LLRD inhalation sources and doses with no mitigation (option S1)

The source contributions assumed for the LoME post-closure conditions with no mitigation (option S1) are presented in Table 5-10, and the assessed LLRD inhalation doses in Table 5-11. These values are used as reference doses to evaluate the dose reductions from the various mitigation options. The column headed with “Total Contribution” indicates the percentage contribution of all sources relative to those during the operational phase due to the elimination or reduction of some sources for the post-closure conditions.

Table 5-10 LLRD source contributions (%) assumed for unmitigated post closure conditions

	Stockpile plumes	Salt deposits	Seepage	Tailings	Tailings plumes	Plant Stack % from mBq/m3	Material Handling	Total Contri-bution
Arandis	2.1	25.8	4.2	54.8	4.6	0.0	0.0	91.5
Arandis airport	1.1	26.1	5.6	53.9	4.8	0.0	0.0	91.5
Dome gorge	1.4	16.9	5.9	37.2	1.7	0.0	0.0	63.1
Panner gorge	1.4	13.4	4.7	28.8	0.9	0.0	0.0	49.2
Khan gorge	2.2	20.0	12.1	46.3	2.6	0.0	0.0	83.2
E-camp	2.1	25.8	4.2	54.8	4.6	0.0	0.0	91.5
Tailings Dam Center	0.0	33.0	0.0	67.0	0.0	0.0	0.0	100

Table 5-11 Reference expected LLRD inhalation doses for unmitigated LoME post-closure conditions

Scenario description	LLRD [Bq.m^{-3}]	Calculated annual dose [µSv.a^{-1}]					
		1 Year	5 Year	10 Year	15 Year	Adult	Worker
Arandis resident	0.982	49	52	61	70	72	
Arandis Airport resident	1.227	61	65	76	88	90	
Khan river downstream of Dome Gorge	0.6	21	22	26	29	30	
Khan river downstream of Panner Gorge	0.039	1	1	1	1	2	
Khan mine	0.713	32	34	40	46	47	
E-camp	2.577						26
Center of Tailings Dam	83.26						893

5.4.2 LLRD inhalation sources and doses with mitigation through a salt deposit in the open pit

While the LLRD concentrations from other post closure sources remain the same, the salt layer in the open pit presents an additional LLRD concentration at the various receptor locations. The percentage contributions from other sources, the percentage increase from the salt layer and the LLRD concentration from only a salt layer in the open pit are presented in Table 5-12. The assessed LLRD dust inhalation doses from this mitigation option are presented in Table 5-13. As indicated in
Table 5-14, the salt deposit actually increases the dust concentrations and the associated doses between 8 % and 16 %. The calculated increase in the LLRD doses seem to be more than the reduction in radon doses presented in Table 5-8 and Table 5-9 and the mitigation option probably needs further investigation before implementation because it seems to increase rather than to decrease the net impact.

Table 5-12 LLRD source contributions (%) assumed for post closure conditions mitigated with a salt deposit in the open pit

	Stockpile plumes	Salt deposits	Seepage	Tailings	Tailings plumes	Plant Stacks	Salt in Open Pit (LLRD % Increase)	Salt LLRD Conc. (mBq/m3)
Arandis	2.1	25.8	4.2	54.8	4.6	0.0	8.0	0.0790
Arandis airport	1.1	26.1	5.6	53.9	4.8	0.0	7.7	0.0950
Dome gorge	1.4	16.9	5.9	37.2	1.7	0.0	9.8	0.0590
Panner gorge	1.4	13.4	4.7	28.8	0.9	0.0	4.1	0.0016
Khan gorge	2.2	20.0	12.1	46.3	2.6	0.0	13.7	0.0980
E-camp	2.1	25.8	4.2	54.8	4.6	0.0	0.3	0.0074
Tailings Dam Center	0.0	33.0	0.0	67.0	0.0	0.0	0.0	0.0000

Table 5-13 Reference expected LLRD inhalation doses for LoME post-closure conditions mitigated with a salt deposit in the open pit

Scenario description	LLRD [Bq.m^{-3}]	Calculated annual dose [μSv.a^{-1}]					
		1 Year	5 Year	10 Year	15 Year	Adult	Worker
Arandis resident	0.982	53	57	67	76	78	
Arandis Airport resident	1.227	66	71	83	95	98	
Khan river downstream of Dome Gorge	0.600	24	25	30	34	35	
Khan river downstream of Panner Gorge	0.039	1	1	1	2	2	
Khan mine	0.713	38	40	47	53	55	
E-camp	2.577						26
Center of Tailings Dam	83.260						893

Table 5-14 Percentage LLRD inhalation dose change due to salt deposit in open pit

Scenario Description	% Dose Change
Arandis resident	8.7
Arandis Airport resident	8.4
Khan river downstream of Dome Gorge	15.5
Khan river downstream of Panner Gorge	8.3
Khan mine	16.5
E-camp	0.3
Center of Tailings Dam	0.0

5.4.3 LLRD inhalation sources and doses with partial mitigation option S2 (a)

Because the salt deposit in the open pit seems not to be a dose-reduction option, the dose reductions for partial mitigation option S2 (a) has been evaluated against the post closure conditions without a salt deposit in the open pit (option S1).

The source contributions assumed for the LoME post-closure conditions with mitigation option S2 (a) involves the removal of the salt deposits on the tailings dam, the seepage precipitates and a 50 % reduction of the stockpile plumes. The source contributions are presented in Table 5-15, and the assessed doses in Table 5-16. The percentage reductions of mitigation option S2 (a) from the unmitigated LLRD doses (option S1) are presented in Table 5-17.

Table 5-15 LLRD source contributions (%) assumed for post closure conditions mitigated with option S2 (a)

	Stockpile plumes	Salt deposits	Seepage	Tailings	Tailings plumes	Plant Stacks	Salt in Open Pit	Total Contri-bution
Arandis	1.1	0.0	0.0	54.8	0.0	0.0	0.0	56
Arandis airport	0.6	0.0	0.0	53.9	0.0	0.0	0.0	54
Dome gorge	0.7	0.0	0.0	37.2	0.0	0.0	0.0	38
Panner gorge	0.7	0.0	0.0	28.8	0.0	0.0	0.0	30
Khan gorge	1.1	0.0	0.0	46.3	0.0	0.0	0.0	47
E-camp	1.1	0.0	0.0	54.8	0.0	0.0	0.0	56
Tailings Dam Center	0.0	0.0	0.0	67.0	0.0	0.0	0.0	67

Table 5-16 Reference expected LLRD inhalation doses for LoME post-closure conditions mitigated with option S2 (a)

Scenario description	LLRD [Bq.m^{-3}]	Calculated annual dose [µSv.a^{-1}]					
		1 Year	5 Year	10 Year	15 Year	Adult	Worker
Arandis resident	0.982	30	32	38	44	45	
Arandis Airport resident	1.227	37	39	46	53	55	
Khan river downstream of Dome Gorge	0.600	12	13	16	18	19	
Khan river downstream of Panner Gorge	0.039	1	1	1	1	1	
Khan mine	0.713	19	20	23	27	28	
E-camp	2.577						16
Center of Tailings Dam	83.260						602

Table 5-17 Percentage LLRD inhalation dose change due to mitigation option S2 (a)

Scenario Description	% Dose Change
Arandis resident	-38.5
Arandis Airport resident	-40.0
Khan river downstream of Dome Gorge	-39.4
Khan river downstream of Panner Gorge	-39.5
Khan mine	-42.5
E-camp	-39.6
Center of Tailings Dam	-32.6

5.4.4 LLRD inhalation sources and doses with partial mitigation option S2 (b)

Because the salt deposit in the open pit seems not to be a dose-reduction option, the dose reductions for partial mitigation option S2 (b) has been evaluated against the post closure conditions without a salt deposit in the open pit (option S1).

The source contributions assumed for the LoME post-closure conditions with mitigation option S2 (b) involves the removal of the salt deposits on the tailings dam, the seepage precipitates and a 50 % reduction of the stockpile plumes similar as for option S2 (a) above. It additionally, however, involves the covering of the outer slopes of the tailings dam with a water erosion protection cover and the construction of wind breaks to reduce wind speed on the upper surface of the tailings dam. As indicated in Section 4.2.2, the remaining source contribution from the tailings dam is not presented in [3], and was estimated from the percentage reduction in the LLRD concentrations, presented in Table 10 of [3]. The source contributions are presented in Table 5-18, and the assessed doses in Table 5-19. The percentage reductions of mitigation option S2 (b) relative to the unmitigated (option S1) LLRD doses are presented in Table 5-20.

Table 5-18 LLRD source contributions (%) assumed for post closure conditions mitigated with option S2 (b)

	Stockpile plumes	Salt deposits	Seepage	Tailings	Tailings plumes	Plant Stacks	Salt in Open Pit	Total Contri-bution
Arandis	1.1	0.0	0.0	16.0	0.0	0.0	0.0	17
Arandis airport	0.6	0.0	0.0	15.0	0.0	0.0	0.0	16
Dome gorge	0.7	0.0	0.0	27.0	0.0	0.0	0.0	28
Panner gorge	0.7	0.0	0.0	27.0	0.0	0.0	0.0	28
Khan gorge	1.1	0.0	0.0	19.0	0.0	0.0	0.0	20
E-camp	1.1	0.0	0.0	23.0	0.0	0.0	0.0	24
Tailings Dam Center	0.0	0.0	0.0	27.0	0.0	0.0	0.0	27

Table 5-19 Reference expected LLRD inhalation doses for LoME post-closure conditions mitigated with option S2 (b)

Scenario description	LLRD [Bq.m^{-3}]	Calculated annual dose [µSv.a^{-1}]					
		1 Year	5 Year	10 Year	15 Year	Adult	Worker
Arandis resident	0.982	9	10	12	13	14	
Arandis Airport resident	1.227	10	11	13	15	16	
Khan river downstream of Dome Gorge	0.600	9	10	11	13	14	
Khan river downstream of Panner Gorge	0.039	1	1	1	1	1	
Khan mine	0.713	8	8	10	11	12	
E-camp	2.577						7
Center of Tailings Dam	83.260						243

Table 5-20 Percentage LLRD inhalation dose change due to mitigation option S2 (b)

Scenario Description	% Dose Change
Arandis resident	-81.2
Arandis Airport resident	-82.9
Khan river downstream of Dome Gorge	-55.7
Khan river downstream of Panner Gorge	-43.2
Khan mine	-75.6
E-camp	-73.9
Center of Tailings Dam	-72.8

6 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 the post-closure assessment in 2002 [1] will be presented below as an indication of possible doses from aquatic sources under post-closure conditions for both the current and LoME conditions. These results are extracted from Table 13 and Table 14 of [1], and are presented in
Table 6-1.

Table 6-1 Public doses assessed for the aquatic pathways in [1]

Scenario No.	1	2	3	4	5	9	11
Total doses from primary aquatic pathways							
1 year	0	0	202	202	0	405	131
5 year	0	0	151	151	0	301	105
10 year	0	0	137	137	0	279	97
15 year	0	0	193	193	0	417	127
Adult/Worker	0	0	126	126	0	244	85
Total doses from secondary ingestion pathways							
1 year	0	0	77	77	0	151	64
5 year	0	0	56	56	0	109	47
10 year	0	0	58	58	0	124	49
15 year	0	0	81	81	0	198	67
Adult/Worker	0	0	27	27	0	53	23
Total doses from all aquatic pathways							
1 year	0	0	279	279	0	556	195
5 year	0	0	207	207	0	410	152
10 year	0	0	195	195	0	402	146
15 year	0	0	275	275	0	614	194
Adult/Worker	0	0	153	153	0	296	108

The doses were assessed from analysed nuclide concentrations in seepage water from the tailings dam after being mixed through a simple mixing model into the Khan River. Hypothetical farming communities at the Dome and Panner gorge confluences with the Khan River (scenarios 3 and 4) were the only critical groups considered to consume this water and to use it for agricultural purposes. The background doses from analysed samples of the Khan River upstream of the Rössing mine were subtracted from the doses calculated for the mixed

water below the mine. The background doses are themselves presented as doses for scenario 9 in
Table 6-1, while doses indicated for scenario 10 were calculated for water containing radionuclides at the minimum detectable concentration during analysis.

7 SENSITIVITY AND UNCERTAINTY ANALYSIS

Sensitivities were only addressed in a limited way in [3] as part of the uncertainty analysis by varying the parameters within their uncertainty ranges and recording the modelling results. High sensitivities in the source-term and dispersion parameters were hence reflected in higher uncertainties. As ICRP dose conversion factors are regarded as internationally accepted fixed values, only the dispersion uncertainties will be projected into dose uncertainties in the analysis and discussion below. Additional uncertainties in the isodose curves are discussed in Section 8 below.

The uncertainties of the atmospheric pathway results will be analysed against the variations presented in [3] and by comparing them with results in [1]. Doses from exposure to radon daughters are age-independent. Due to this and because adults always receive the highest doses from the inhalation of LLRD, only adult doses will be considered in the uncertainty analysis for the atmospheric pathway presented below. Uncertainties in the aquatic results are discussed in [1].

7.1 Atmospheric Pathway

The following two uncertainties are mentioned in [3]:

7.1.1 Source term assessment

Uncertainties in the source terms are addressed in [3] through separate assessments of the maximum radon doses and maximum LLRD concentrations. The maximum radon and LLRD doses will be considered as representing the upper 95 % confidence level of the dose distributions, assumed to be normal distributions, and hence relate to an interval of 1.96 standard deviations.

7.1.2 Annual variation in weather data

While the dispersion assessment in [3] was performed with 2004 weather data, the annual variation of the doses for 10 years of weather data is presented in Table 5a and Table 5b of [3] for the first 5 receptor locations. For the first four scenarios the 2004 weather data seems to under-predict the doses, while for the fifth scenario there seems to be some over-prediction. As part of the uncertainty evaluation the expected doses were first corrected to the 10-year average weather conditions. These doses will be referred to as the 10 year corrected doses. Secondly the standard deviations of the 10 year corrected doses were calculated for the limited weather data set.

7.1.3 Total uncertainty

An estimate of the total standard deviation σ_T was obtained for each assessed dose from the standard deviation σ_S of the doses arising from the source term variations and the standard deviation σ_W of the doses arising from variations in the weather data, as per equation below.

$$\sigma_T = \sqrt{\sigma_S^2 + \sigma_W^2}$$

A 95 % upper confidence level was next assumed to be represented by 1.96 time this total standards deviation. Using the assumptions above an expected and upper 95 % confidence level has been calculated for the radon and LLRD annual doses in a spreadsheet copied as

Table 7-1. The current, LoME and post-closure (PC) conditions are covered. The LLRD doses for major dust mitigation options were also covered but not the radon doses as mitigation is assumed not to affect the PC radon doses. The ratio of the 95 % confidence levels and the expected reference as well as the expected 10 year average values are presented in the last two column of the table, while doses above a dose constraint of 300 μSv.a^{-1} are highlighted in yellow.

Table 7-1 Expected and upper 95 % confidence levels estimated for the 10 year corrected radon and LLRD doses

Scenario	Uncorrected Radon Dose [μSv.a-1]			Corrected Radon Dose [μSv.a-1]			Ratio (95 %/ 10 Year Expected)	Ratio (95 %/ 2004 Expected)
	Current Mean	Current Max	St. Dev	**Current Expected**	St. Dev	**Current 95 %**		
Arandis	43	176	68	**48**	77	**199**	4.2	4.7
Arandis Airport	56	230	89	**103**	165	**425**	4.1	7.6
Dome Gorge	68	283	110	**70**	115	**296**	4.2	4.4
Panner Gorge	23	101	40	**23**	42	**106**	4.5	4.7
Khan Gorge	43	176	68	**34**	55	**141**	4.2	3.3
Scenario	**Uncorrected LLRD Dose [μSv.a-1]**			**Corrected LLRD Dose [μSv.a-1]**			**Ratio (95 %/ 10 Year Expected)**	**Ratio (95 %/ 2004 Expected)**
	Current Mean	Current Max	St. Dev	**Current Expected**	St. Dev	**Current 95 %**		
Arandis	59	86	14	**62**	17	**96**	1.6	1.6
Arandis Airport	72	105	17	**133**	46	**222**	1.7	3.1
Dome Gorge	33	55	11	**33**	13	**59**	1.8	1.8
Panner Gorge	2	3	0	**3**	1	**4**	1.5	1.8
Khan Gorge	42	63	11	**32**	11	**54**	1.7	1.3
Scenario	**Uncorrected Radon Dose [μSv.a-1]**			**Corrected Radon Dose [μSv.a-1]**			**Ratio (95 %/ 10 Year Expected)**	**Ratio (95 %/ 2004 Expected)**
	LoME Mean	LoME Max	St. Dev	**LoME Expected**	St. Dev	**LoME 95 %**		
Arandis	45	186	72	**51**	81	**210**	4.2	4.7
Arandis Airport	60	244	94	**110**	174	**451**	4.1	7.5
Dome Gorge	69	286	111	**72**	117	**300**	4.2	4.4
Panner Gorge	28	108	41	**29**	43	**113**	3.9	4.1
Khan Gorge	46	183	70	**37**	56	**146**	4.0	3.2

Scenario	Uncorrected LLRD Dose [µSv.a-1]			Corrected LLRD Dose [µSv.a-1]			Ratio (95 %/ 10 Year Expected)	Ratio (95 %/ 2004 Expected)
	LoME Mean	LoME Max	St. Dev	**LoME Expected**	St. Dev	**LoME 95 %**		
Arandis	79	115	19	**83**	23	**129**	1.6	1.6
Arandis Airport	98	142	23	**180**	62	**301**	1.7	3.1
Dome Gorge	48	82	18	**48**	20	**87**	1.8	1.8
Panner Gorge	3	4	0	**4**	1	**5**	1.4	1.7
Khan Gorge	56	85	15	**44**	15	**73**	1.7	1.3
Scenario	**Uncorrected Radon Dose [µSv.a-1]**			**Corrected Radon Dose [µSv.a-1]**			**Ratio (95 %/ 10 Year Expected)**	**Ratio (95 %/ 2004 Expected)**
	PC S1, S2 (a) & S2 (b) Mean	PC S1, S2 (a) & S2 (b) Max	St. Dev	**PC S1, S2 (a) & S2 (b) Expected**	St. Dev	**PC S1, S2 (a) & S2 (b) 95 %**		
Arandis	39	186	75	**44**	85	**210**	4.8	5.4
Arandis Airport	51	244	98	**94**	181	**449**	4.8	8.8
Dome Gorge	64	286	114	**67**	119	**300**	4.5	4.7
Panner Gorge	23	108	43	**23**	45	**112**	4.8	5.0
Khan Gorge	39	183	73	**31**	59	**145**	4.7	3.8
Scenario	**Uncorrected LLRD Dose [µSv.a-1]**			**Corrected LLRD Dose [µSv.a-1]**			**Ratio (95 %/ 10 Year Expected)**	**Ratio (95 %/ 2004 Expected)**
	PC S1 Mean	PC S1 Max	St. Dev	**PC S1 Expected**	St. Dev	**PC S1 95 %**		
Arandis	72	106	17	**76**	22	**119**	1.6	1.6
Arandis Airport	90	131	21	**165**	57	**277**	1.7	3.1
Dome Gorge	30	52	11	**31**	13	**55**	1.8	1.8
Panner Gorge	2	2	0	**2**	0	**3**	1.4	1.7
Khan Gorge	47	71	12	**37**	13	**61**	1.7	1.3
Scenario	**Uncorrected LLRD Dose [µSv.a-1]**			**Corrected LLRD Dose [µSv.a-1]**			**Ratio (95 %/ 10 Year Expected)**	**Ratio (95 %/ 2004 Expected)**
	PC S2 (a) Mean	PC S2 (a) Max	St. Dev	**PC S2 (a) Expected**	St. Dev	**PC S2 (a) 95 %**		
Arandis	45	66	11	**47**	13	**74**	1.6	1.6
Arandis Airport	55	79	13	**100**	34	**167**	1.7	3.1
Dome Gorge	19	32	7	**19**	8	**34**	1.8	1.8
Panner Gorge	1	1	0	**1**	0	**2**	1.4	1.7
Khan Gorge	28	42	7	**22**	7	**36**	1.7	1.3
Scenario	**Uncorrected LLRD Dose [µSv.a-1]**			**Corrected LLRD Dose [µSv.a-1]**			**Ratio (95 %/ 10 Year Expected)**	**Ratio (95 %/ 2004 Expected)**
	PC S2 (b) Mean	PC S2 (b) Max	St. Dev	**PC S2 (b) Expected**	St. Dev	**PC S2 (b) 95 %**		
Arandis	14	20	3	**14**	4	**22**	1.6	1.6
Arandis Airport	16	23	4	**29**	10	**48**	1.7	3.1
Dome Gorge	14	23	5	**14**	6	**25**	1.8	1.8
Panner Gorge	1	1	0	**1**	0	**1**	1.4	1.7
Khan Gorge	12	18	3	**9**	3	**15**	1.7	1.3

7.2 Aquatic Pathway

Uncertainties in aquatic pathway doses are discussed in [1], but 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, mixed into the Khan River water and neglect major effects in the transport behaviour of the radionuclides in the water and soil. While this will force the results to the conservative side it may overestimate the aquatic doses by considerably. No attempt will hence be made to assess uncertainties for the aquatic pathway results, and the values in Table 6-1 will merely be used in a qualitative way.

8 ISODOSE CONTOURS

8.1 Radon Isodose Contours

As indicated in Section 3 (viii), a single suitable dose conversion factor for radon is to be used for presenting isodose curves for radon. Such curves were in fact presented in [3] but based in a ratio of 80 % indoors exposure and 20 % outdoors exposure. As for Rössing the public scenarios are more related to a 50 % indoors and 50 % outdoors exposure, the data presented in [3] were corrected for these conditions. This caused an increase for the public exposure to radon daughters with a factor of 1.25. The radon dose contours were hence obtained from the data in [3], by multiplication with a factor of 1.25. The results are indicated in **Figure 1** to **Figure 6** for the current, LoME and post-closure scenarios. It should be noted that the contour maps only apply to the public exposure scenarios and not the worker exposure scenarios e.g. the Fish Factory scenario. In fact the dose values for the centre of the tailings dam are much higher than those reported in the tables because they relate to an annual exposure period of 8760 h and not 2000 h as applicable to workers.

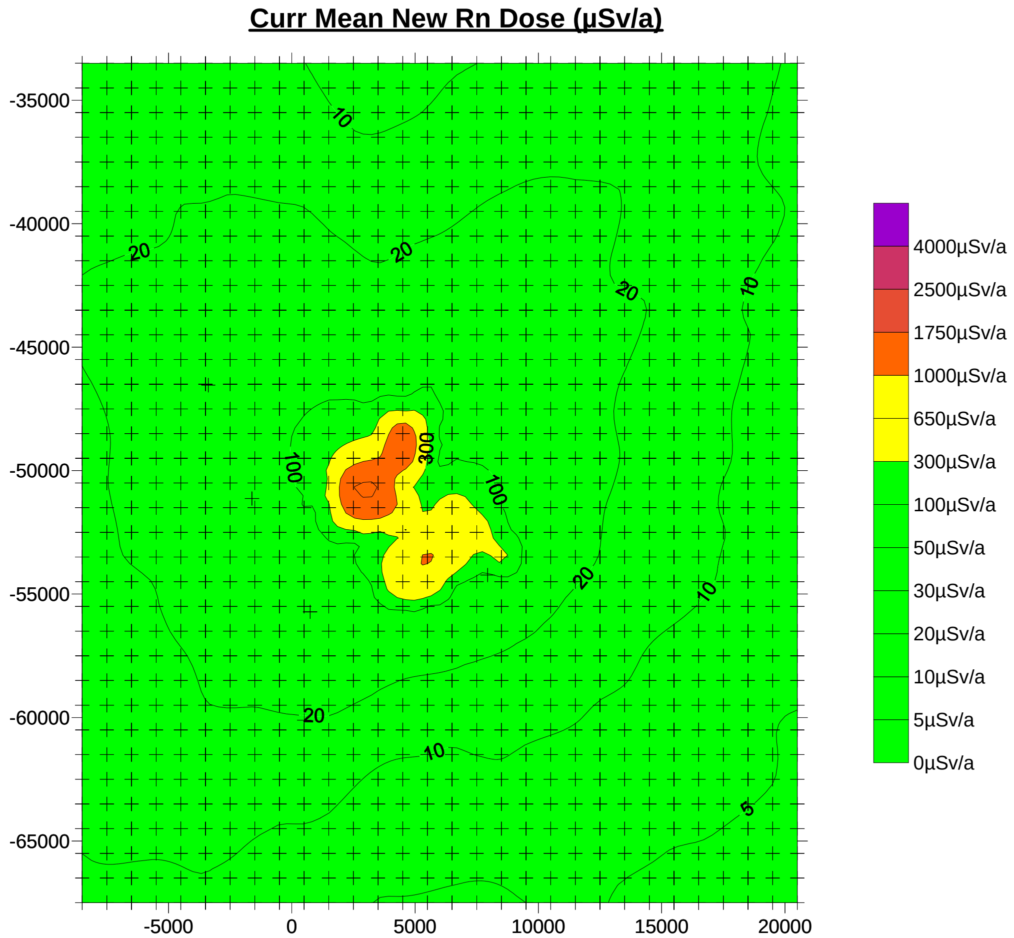

Figure 1: Mean radon daughter isodose contours for current scenario

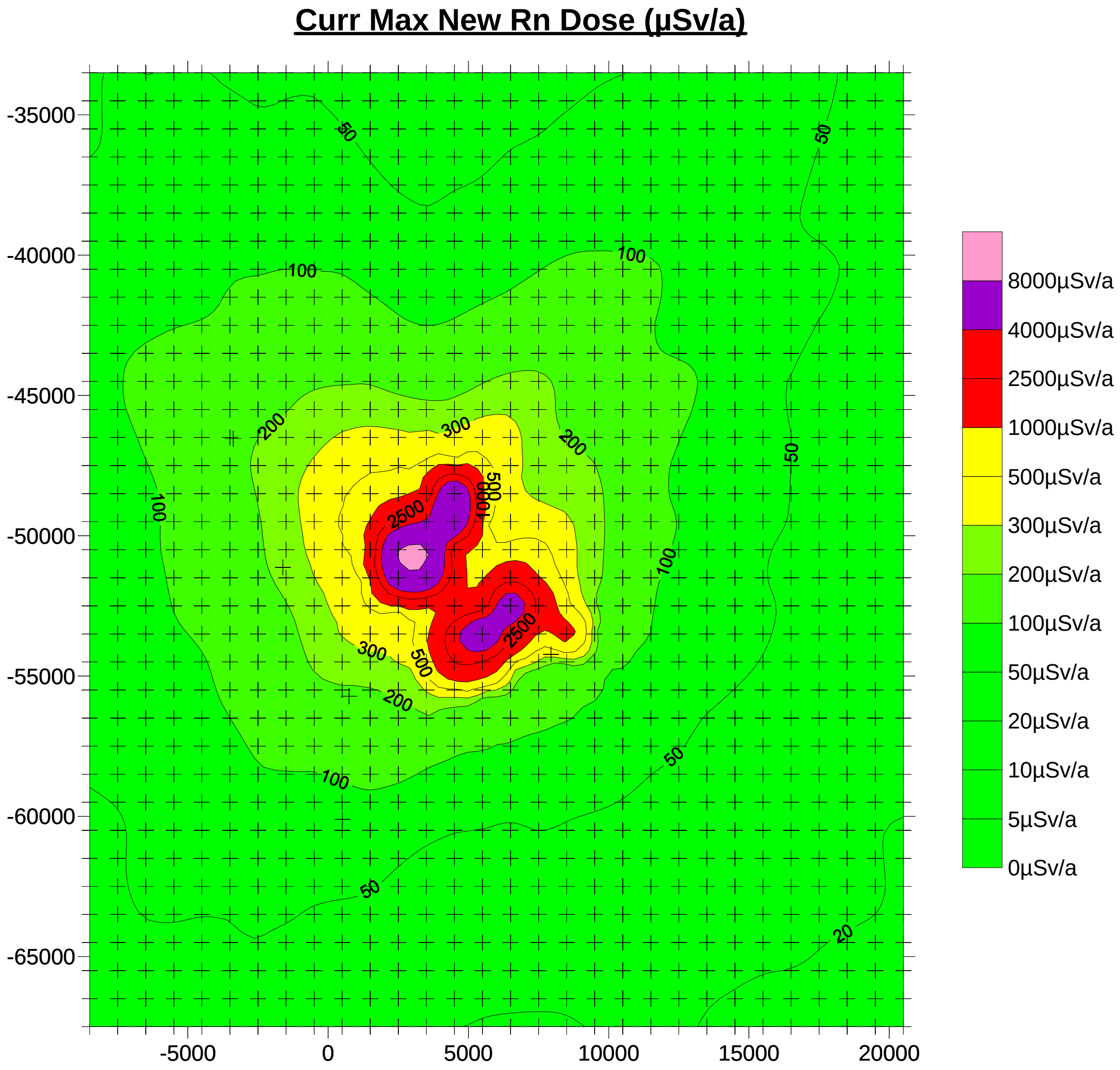

Figure 2: Maximum radon daughter isodose contours for current scenario

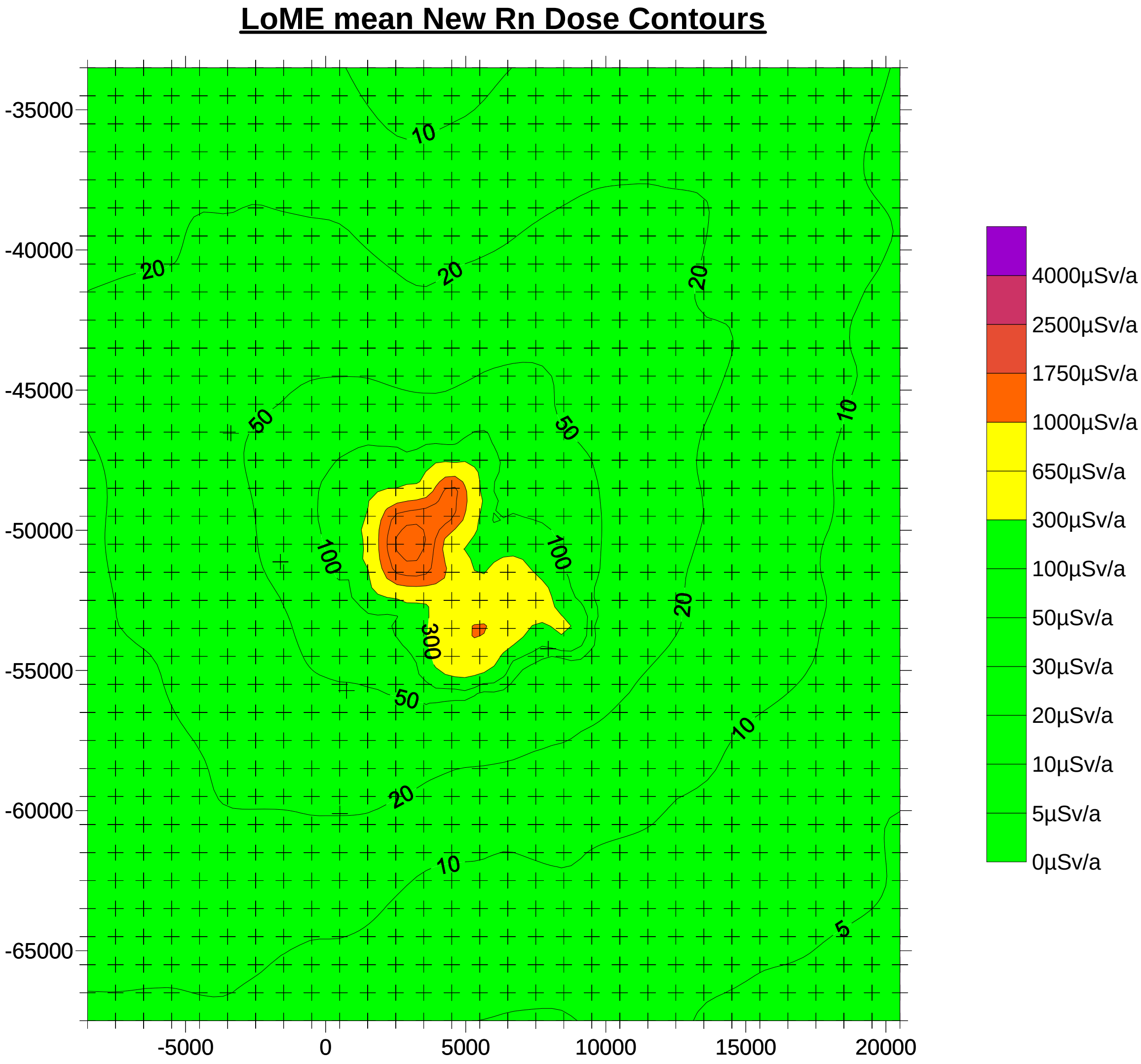

Figure 3: Mean Radon daughter isodose contours for LoME scenario

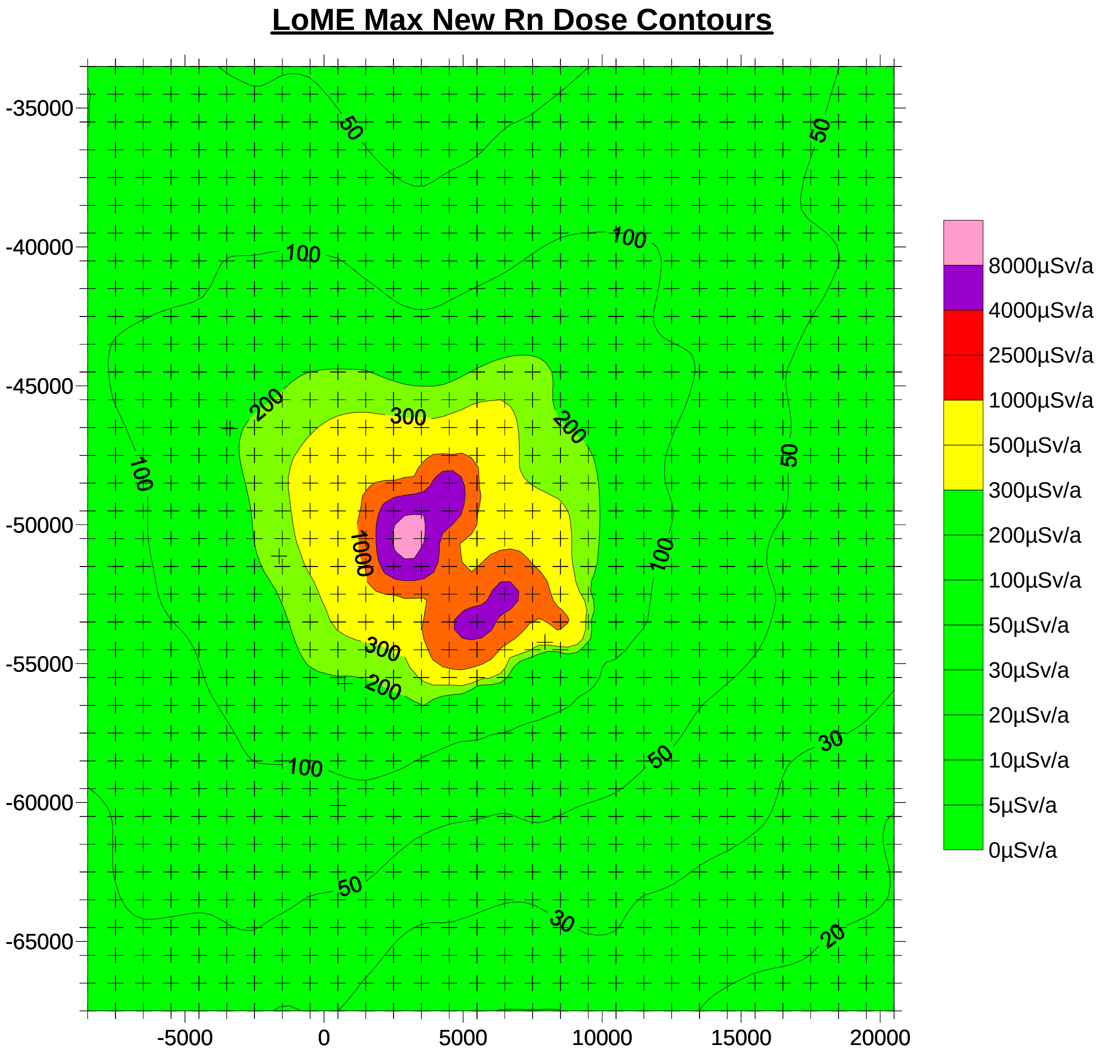

Figure 4: Maximum Radon daughter isodose contours for LoME scenario

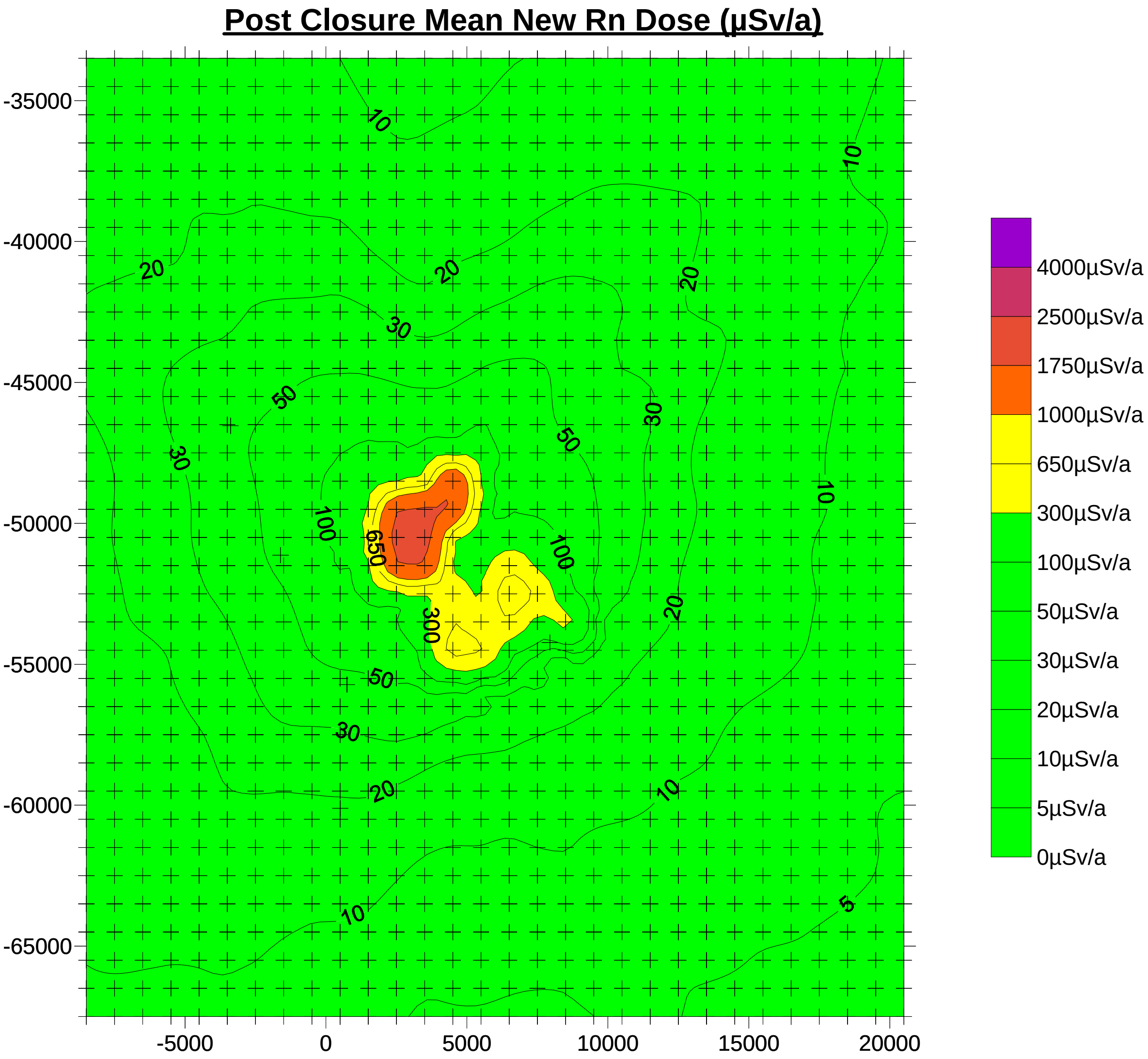

Figure 5: Mean Radon daughter isodose contours for post-closure scenario

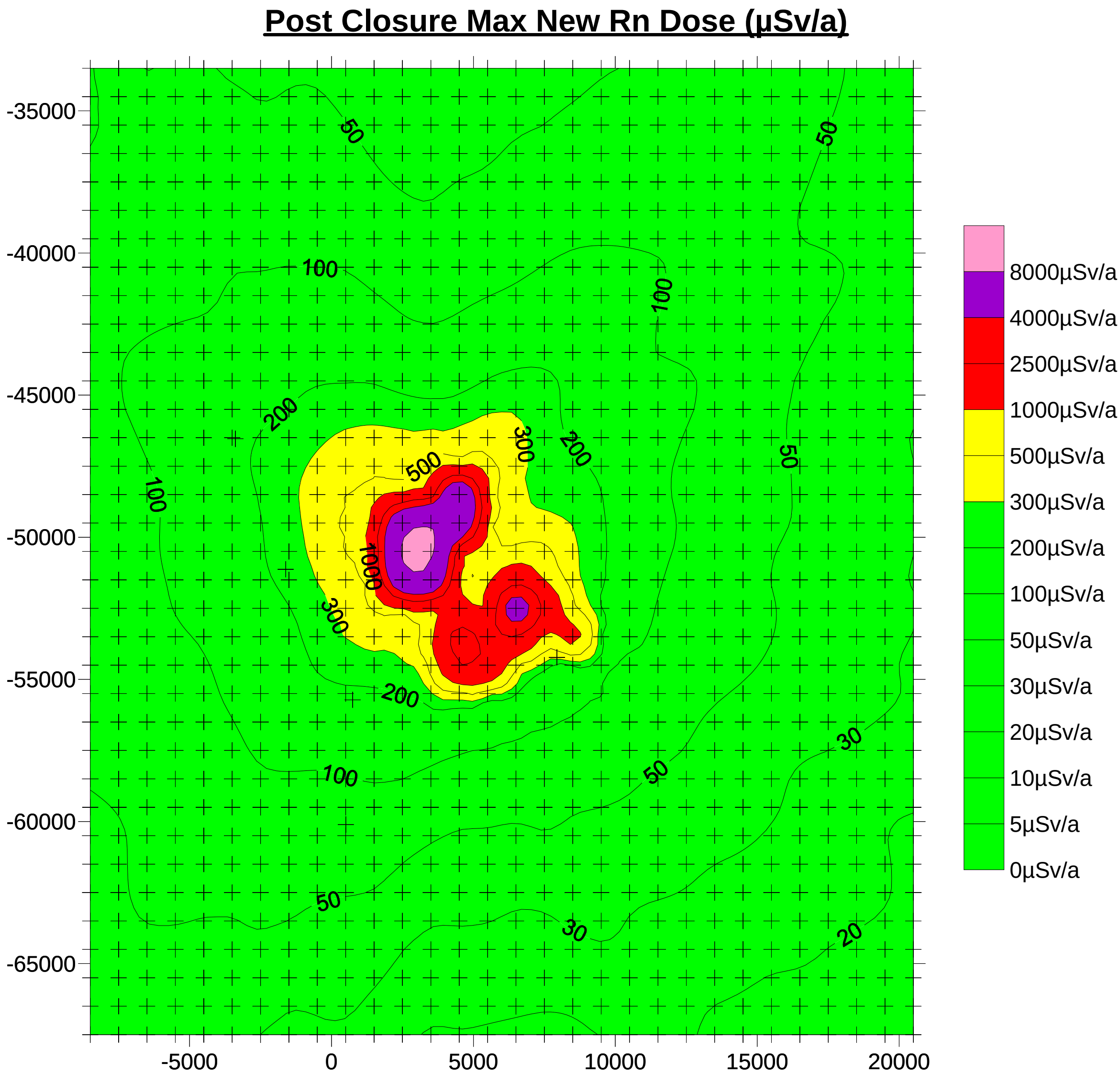

Figure 6: Maximum Radon daughter isodose contours for post-closure scenario

8.2 LLRD Isodose Contours

As indicated in Section 3 (viii), a single suitable dose conversion factor for the LLRD concentrations in [3] is to be used for presenting isodose curves for dust inhalation. Isodose curves were only presented in [3] for the airborne alpha activity concentrations in mBq.m^{-3} of the LLRD. These are converted to annual doses through multiplication with the dose conversion factors, the annual exposure period and the breathing rate, which are scenario dependent and also depend on the nuclide composition of the various sources contributing to the airborne dust. To obtain scenario-independent annual doses, some effort was made to obtain a suitable single dose conversion factor. This was done by first calculating single age-dependent effective inhalation dose coefficients for the different source materials at Rössing Uranium. These are indicated in the top section of

Table 9-2. As the tailings material is the major contributor to public doses from dust emitted by these sources, the error introduced when using only the dose coefficient for the tailings was calculated. The age-dependent errors are indicated in the centre section of

Table 9-2 and are conservative as they were calculated by simple averaging and do not consider the major contribution from the tailings. Finally the errors introduced by using only the adult dose coefficient, together with a correction for the age-dependent breathing rates were calculated and are presented in the bottom section of
Table 9-2. Again these errors are conservative as they do not consider the major contribution from the tailings. The results indicate that doses would mostly be overestimated when using either a single set of age-dependent dose coefficients. Only for the seepage dam sludge some underestimation may be possible but this should be unimportant due to the relative low impact of this material. Even a smaller underestimation would result if only the breathing-rate-corrected dose coefficient for adults is used, as indicated in the bottom section of
Table 9-2.

Table 9-2: Errors introduced when using only single inhalation dose coefficients

Weighted Dose Coefficient (Sv/αBq)					
Sample Description	1 year	5 year	10 year	15 year	Adult
Ore	2.1E-05	1.3E-05	8.7E-06	7.6E-06	7.1E-06
Tailings	1.2E-05	1.2E-05	8.2E-06	7.2E-06	6.7E-06
Seepage dam sludge	1.1E-05	1.7E-05	1.1E-05	9.0E-06	8.4E-06
Jarosite sludge	6.2E-06	1.1E-05	7.3E-06	6.2E-06	5.7E-06
Pool precipitates	6.3E-06	1.2E-05	7.8E-06	6.8E-06	6.3E-06
Breathing Rate (m3/h)	0.22	0.36	0.64	0.84	0.93
Deviation from Age-specific Dose Coefficient of Tailings (%)					
Ore	-39	-7	-6	-5	-5
Tailings	0	0	0	0	0
Seepage dam sludge	18	-25	-22	-20	-20
Jarosite sludge	101	12	13	16	17
Pool precipitates	97	5	5	6	6
Deviation from Adult Dose Coefficient of Tailings (%)					
Ore	40	27	11	-3	-5
Tailings	131	37	18	3	0
Seepage dam sludge	171	2	-8	-18	-20
Jarosite sludge	364	53	33	19	17
Pool precipitates	355	44	24	8	6

Based on this finding the LLRD concentrations in [3] were hence converted to annual dose rates by using the effective adult dose coefficient *DC* for the tailings material together with the adult breathing rate. This presents a conversion factor *DCF* of

$$DCF = 1E + 03 \cdot 8760 \cdot 0.93 \cdot DC = 5.46E + 01\ \mu Sv.a^{-1}\ \ per\ mBq.m^{-3}$$

to convert the LLRD concentrations in [3] from $mBq.m^{-3}$ to $\mu Sv.a^{-1}$. The graphs are presented for the various options in **Figure 7** to **Figure 10**

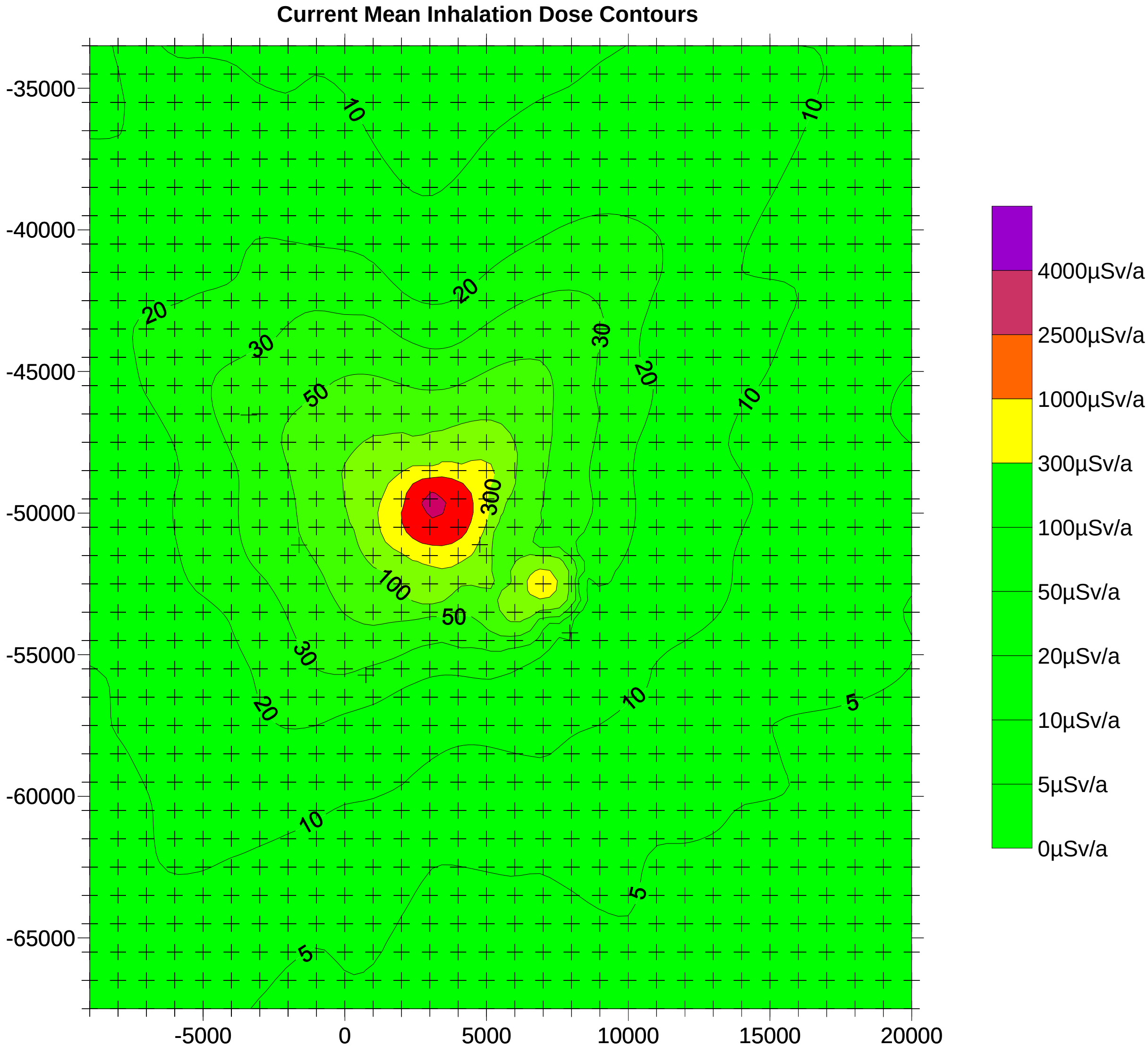

Figure 7: Mean dust inhalation isodose curves for current scenario

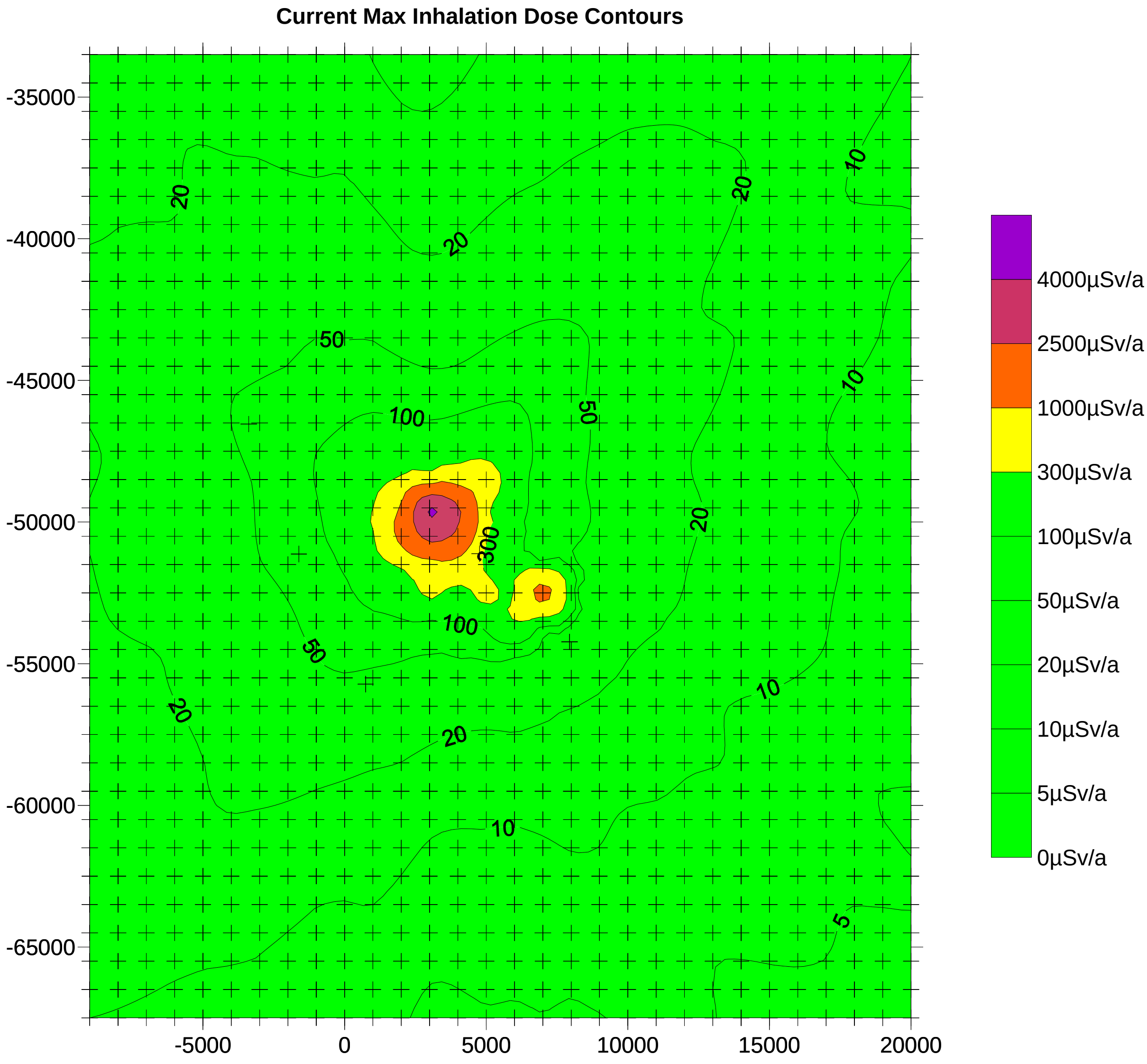

Figure 8: Maximum dust inhalation isodose curves for current scenario

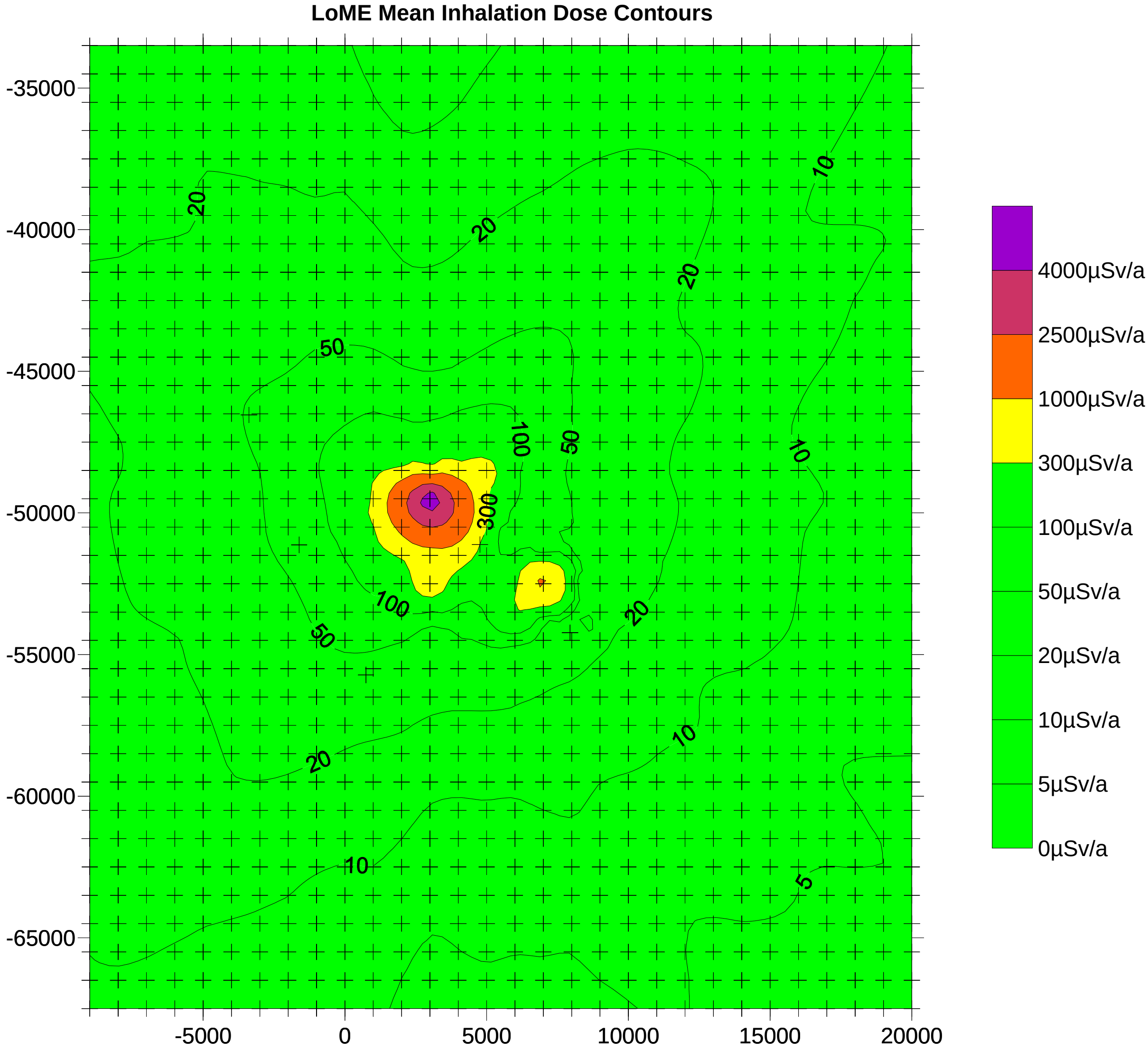

Figure 9: Mean dust inhalation isodose curves for LoME scenario

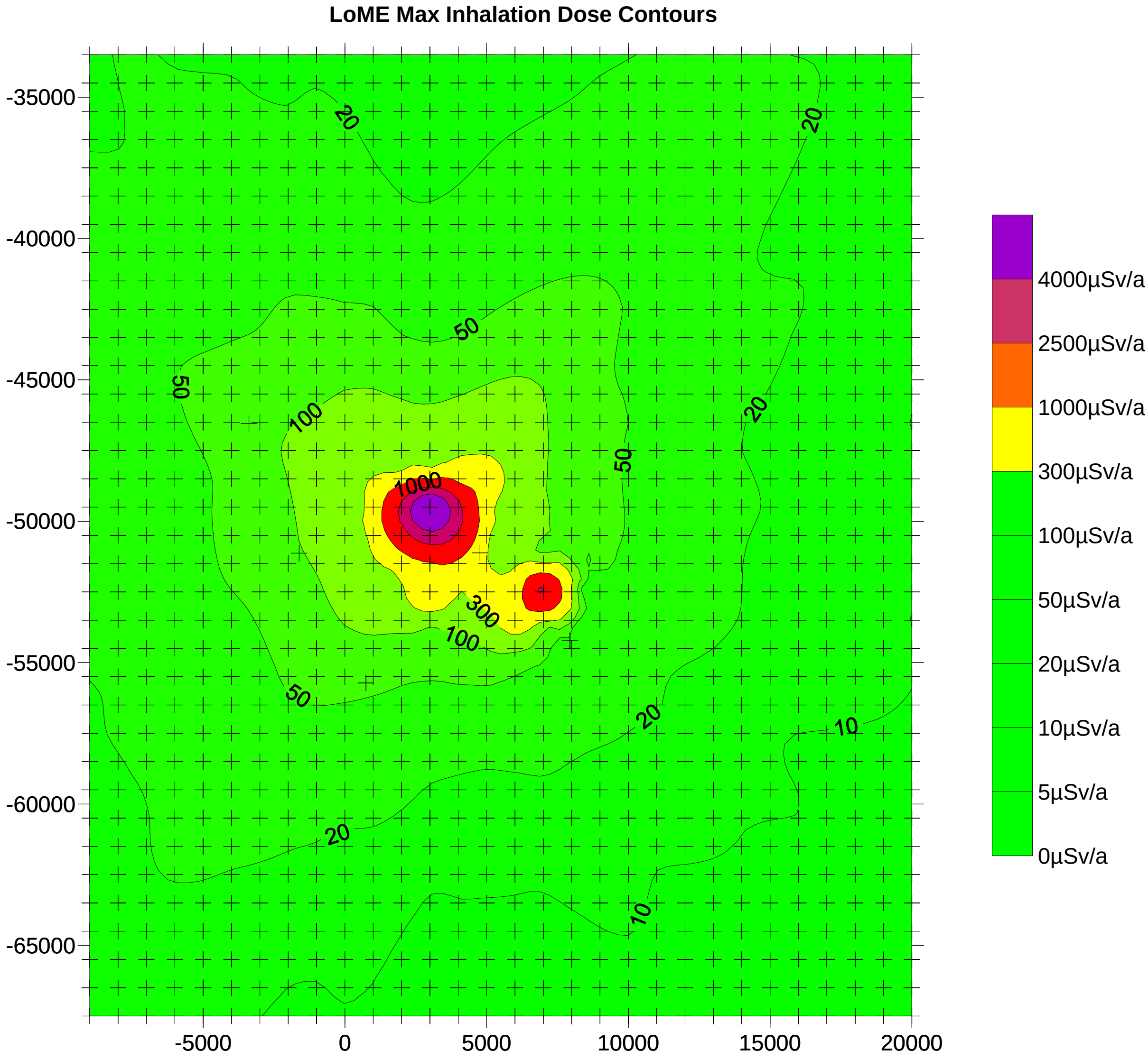

Figure 10: Maximum dust inhalation isodose curves for LoME scenario

9 DISCUSSION OF RESULTS

9.1 Criteria for Discussion of Assessed Doses

For LLRD inhalation doses and ingestion doses, the public dose limit of 1 mSv.a^{-1} will be used as a criterion. The same criterion will apply for a worker to be registered and treated as a radiation worker. Additionally a dose constraint of 300 µSv.a^{-1} will be considered as a level above which specific actions will be considered to reduce exposure from specific sources.

For exposure to NORM, radon daughter exposures are evaluated against action levels of annual doses between 3 and 6 mSv.a^{-1} as presented in [4]. While the extension of these criteria to uranium mining is uncertain, such an evaluation will be presented non-the-less. Additionally radon doses will be evaluated together with the LLRD inhalation doses and estimates of the aquatic doses against the public dose limit of 1 mSv.a^{-1} and a source-related constraint of 300 µSv.a^{-1}. Referencing two ICRP documents this source constraint is recommended by the IAEA as appropriate for post-closure waste management in the mining and milling of ores [5].

In all cases ALARA requirements expect doses to be reduced to an optimum levels based on costs and risk reduction, but this is not discussed as a specific criterion.

9.2 Evaluation of the Reference Expected Doses against Criteria

Expected doses, based on the 2004 reference weather data, were corrected with variations in the weather data over 10 years. While the 10-year expected doses increased the reference expected values by a factor of 1.9 for Arandis Airport, it decreased the doses at Khan Gorge by a factor of 0.8. In the discussion below the ranges presented are for the expected 10-years weather data, except for the E-Camp and Tailings Dam receptor locations, where results in [3] are only presented for the 2004 weather data.

9.2.1 Aquatic Pathway Doses

Aquatic pathway doses apply only to the hypothetical groups at the Dome and Panner Gorges, where the assessed expected dose for the most sensitive age-group was assessed [1] within the range 200 to 300 µSv.a^{-1}. Because of the large uncertainty in these doses and because they are not expected to be influenced by the LoME operations, they will only be considered qualitatively in the evaluation below. The retardation associated with the transport behaviour of the groundwater will likely cause the public impact to relate only to post-closure conditions and it will hence not be considered for the operational phase.

9.2.2 Radon Doses

Expected radon doses for the current and LoME operational phase are low (in the range 23 to 103 µSv.a^{-1}) for all the critical groups considered except for the workers on the tailings dam. In the latter case a dose of 826 µSv.a^{-1} was assessed. The LoME extensions will increase the radon doses above to the range 29 to 110 µSv.a^{-1} and the worker dose to 836 µSv.a^{-1}.

For the post-closure phase the expected public radon doses are reduced due to the elimination of the material handling sources to the range of 23 to 94 µSv.a^{-1} without any mitigation.

Expected public radon doses will hence remain well below the dose constraint of 300 µSv.a^{-1} and worker doses below 1 mSv.a^{-1} for all current, and LoME operational phases, as well as the LoME post-closure phase.

All radon doses are well below the radon action level of between 3 and 6 mSv.a^{-1} and will hence not require any action as per [4].

9.2.3 LLRD Inhalation Doses

Expected LLRD inhalation doses for the current and LoME operational phase are low (in the range 3 to 133 $\mu Sv.a^{-1}$) for all the critical groups considered except for the workers on the tailings dam. In the latter case a dose of 638 $\mu Sv.a^{-1}$ was assessed. The LoME extensions will increase the radon doses above to the range 4 to 180 $\mu Sv.a^{-1}$ and the worker dose to 893 $\mu Sv.a^{-1}$.

For the post-closure phase the expected public LLRD inhalation doses are reduced due to the elimination of the material handling sources to the range of 2 to 165 $\mu Sv.a^{-1}$ without any mitigation.

Expected public LLRD inhalation doses will hence remain well below the dose constraint of 300 $\mu Sv.a^{-1}$ and worker doses below 1 $mSv.a^{-1}$ for all current, and LoME operational phases, as well as the LoME post-closure phase.

9.2.4 Total Doses

Assessed total expected public doses from radon and dust for the operational phase are well below the public dose limit and also below the source constraint of 300 $\mu Sv.a^{-1}$ for both the current and LoME operational conditions. Because of a slight reduction, this also applies to the post-closure conditions without mitigation. For the post-closure phase the contribution from the aquatic pathway may need a better evaluation as a simple modelling exercise indicate that this contribution may cause the total dose to exceed the dose constraint above.

The combined impact of radon and LLRD inhalation for workers on the tailings dam will also unlikely be affected significantly by the LoME operations but may for both the current and LoME operations exceed 1 $mSv.a^{-1}$ for a 2000 $h.a^{-1}$ exposure period and hence require some time restriction or persons need to be registered radiation worker.

9.3 Uncertainty Analysis

The uncertainty analysis involved both the correction to convert the doses, from the 2004 weather data, to doses based on the average of 10 years weather data. The correction factor varied for various receptor locations from an increase by a factor of 1.9 to a decrease by a factor of 0.4. The uncertainties related to variations in the weather data was also assessed and relate to correction factors to be applied to ensure conservative results.

An analysis on these uncertainties indicated that conservative values, related to a 95 % confidence level, may exceed the expected value by the following factors:

(i) Within the range 1.5 to 1.8 for the 10 year LLRD doses and 1.3 to 3.1 for the 2004 reference LLRD doses

(ii) Within the range 3.9 to 4.8 for the 10 year radon doses and 3.2 to 8.8 for the 2004 reference radon doses.

The large increase factor associated with the radon conservatism is mainly due to the uncertainty in the radon source term assessment in [3]. These uncertainties will increase the conservative doses to the following ranges applicable only to scenarios 1 to 6:

- 95 % radon doses for the current and LoME operational phase to the range 106 to 451 $\mu Sv.a^{-1}$.
- 95 % LLRD inhalation doses for the current and LoME operational phase to the range 4 to 301 $\mu Sv.a^{-1}$.

The increase from the current to the LoME conditions is still small (maximum for radon from 425 to 451 $\mu Sv.a^{-1}$ and for LLRD from 222 to 301 $\mu Sv.a^{-1}$ for Arandis Airport), and may still not require additional restrictions. The overall uncertainty in the assessment and specifically in the radon source assessment may, however, cause the conservative doses to require some mitigation in order to meet the dose constraint of 300 $\mu Sv.a^{-1}$, even when the dose from the aquatic pathway is not considered.

9.4 Dust Mitigation Options

A salt layer in the open pit does not seem to reduce the public radon doses significantly but increase the dose from LLRD inhalation and may need further investigation.

While the dust mitigation options are not regarded to decrease the radon doses substantially, the assessed LLRD dose reductions are as follows:

- Partial mitigation option S2 (a): Reduce expected doses to doses to below 100 $\mu Sv.a^{-1}$ and 95 % doses to 167 $\mu Sv.a^{-1}$, well below the dose constraint of 300 $\mu Sv.a^{-1}$. The contribution of the mitigation actions on the dust inhalation pathway may, however, still be important to determine whether the total dose is below the constraint.
- Partial mitigation option S2 (b): Reduce expected LLRD doses as well as the 95 % LLRD doses to a trivial level of around 50 $\mu Sv.a^{-1}$. The contribution of the dust inhalation pathway may hence become insignificant in determining whether the total dose is below the constraint.

9.5 Isodose Contours

Isodose contours were plotted for radon and LLRD inhalation doses for those scenarios for which data from [3] were available for such plots. A single conversion coefficient was however, used for all spatial grid points to ensure smooth curves. The doses reflected in the contours may hence deviate somewhat from the doses calculated for specific critical groups in the space covered but mainly to the conservative side. Especially they relate to public exposure and are hence much higher than the doses reported in the tables for the worker dose scenarios.

10 CONCLUSIONS

Following a public dose assessment for the proposed life-of-mine extension (LoME) for the Rössing Uranium mine, the following are concluded:

(i) The expected public doses from atmospheric emission of radon and dust for both the current and LoME operational conditions will likely remain below a dose constraint of 300 µSv.a^{-1}. Due to the elimination of the material handling sources the expected public doses will also below the constraint during the post-closure phase, even without mitigation.

(ii) The contribution of doses from the aquatic pathway may, however, require a better evaluation for the post-closure phase to determine whether the total dose will still be below the constraint.

(iii) Two partial dust mitigation options were also investigated. Option S2 (a) reduced the dust doses substantially to around 50 % of the constraint and option S2 (b) to a trivial level of around 20 % of the constraint.

(iv) Uncertainties in especially the radon source term assessment cause conservative doses for radon and dust (at an estimated 95 % confidence level) to exceed the constraint above and may require investigation into the radon source term assessment methodology.

11 REFERENCES

[1] G P de Beer, A Ramlakan and R Schneeweiss, An Assessment of the Post-Closure Radiological Impact of Rössing Uranium Mine. NECSA Report GEA-1582, September 2002.

[2] G P de Beer, Post Closure Public Dose Assessment for the Phase III Expansion of the Rössing Uranium Mine, Report GEA-1617, August 2003.

[3] R Strydom, Atmospheric dispersion modelling of radon and long-lived radioactive dust for current, life-of-mine extension and post closure mine operating scenarios. PARC Scientific Report 96/12589/07. October 2006.

[4] ICRP, Protection Against Radon-222 at Home and at Work, ICRP Publication 65, Annals of the ICRP, Vol. 23, No. 2, 1993.

[5] IAEA, Management of Radioactive Waste from the Mining and Milling of Ores Safety Guide No. WS-G-1.2, Vienna, 2002.

APPENDIX A: SCOPE OF WORK

The Public Dose Assessment of the mining area of Rössing Uranium Mine and its neighboring areas is required. The final report should have:

- Mean, best and worst case scenarios
- Public dose at receptor locations, considering all possible pathways.
- Public dose (considering all possible pathways) as indicated by isopleths (lines joining places with the same dose) on a map for the Rössing mining and surrounding areas.
- The Public Dose should be modeled for (i) current, (ii) during life of mine extension and (iii) after closure of mine.
- The public dose should also be modeled for a number of dust mitigation options during post closure namely (i) Do nothing (ii) Partial Mitigation (a) (iii) Partial mitigation (b) and (iv) Total clean-up
- The effect of error accumulation from data variability and model assumptions should be taken into consideration.
- A sensitivity analysis should be done on the model predictions to determine the impact of cumulative data variability and model assumptions.
- Indicate the constraint dose limit used and the origin thereof.

Assistance Provided by Rössing

- A report on atmospheric dispersion modeling that will highlight the (i) current (ii) during life of mine extension and at (iii) closure scenarios of the radioactive fugitive dust as well as the radon emissions from sources at Rössing Uranium Mine. The radioactive fugitive dust and radon concentrations at the different receptor locations will be indicated in this report.
- A map of the Rössing Uranium mining site enclosing all the receptor points with their exact location. The map will also include lines joining places with the same dust and radon concentrations.
- To assist in the obtaining of other data that may be necessary to compile the report.

Other important Considerations

- During the life of mine extension source terms may change. For example the tailings impoundment, various waste dumps, other rock dumps as well as the open pit will change in size. The production rate, the tons milled/crushed will reach a climax during the life of mine extension. All these changes will need to be considered in the public dose assessment.
- Model assumptions and verification approaches need to be checked to confirm that these are relevant for the scenarios being investigated. For example when dose levels at nearby receptor points are modeled for the full mine operations proper validation should be given for modeling the post closure dose levels.
- In compiling the public dose report consideration should be taken of the fact that Rössing will have to determine what the liability, reputational and long term management

implications of exceeding the constraint limits are. For example, does it require long term land use restrictions and/or access control to be established in the affected area? If this is the case then alternative tailings deposition and/or closure requirements may need to be considered for the LoME project.

Receptor Locations.

The receptor locations are as follows (AutoCAD coordinates):

Name	X	Y
Arandis	+2560	+46193
Arandis Airport	+1628	+51101
Dome Gorge	-8151	+54138
Panner Gorge	-3315	+58337
Khan Mine Gorge	+744	+55720
E-camp (Fish Factory)	-5772	+47018

Time Frame

The report should be completed by 31 May 2007.