THE ASSESSMENT OF POTENTIAL RADIATION HAZARDS FROM GOLD MINES IN THE FREE STATE GOLDFIELDS TO MEMBERS OF THE PUBLIC

by

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A dissertation submitted in order to meet the requirements for the degree Master in Medical Sciences (M.Med.Sc.) in the Faculty of Health Sciences (Department of Medical Physics) at the University of the Orange Free State.

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DECLARATION

I declare that the dissertation hereby submitted by me, **Jozua Francois Ellis**, for the degree Master in Medical Sciences (M.Med.Sc.) at the University of the Orange Free State, is my own independent work and that I have not previously submitted the same work for a degree at/in another university/faculty.

I furthermore cede copyright of the dissertation to the University of the Orange Free State.

Signed: Place: ____________________

____________________ Date: ____________________

J F Ellis

I dedicate this study to my father who has been my inspiration in life.

PREFACE

This study is the result of teamwork and commitment by a whole group of people. I sincerely thank the following individuals and companies, without whom this study would not have been possible:

- My supervisors, especially Dr Johan Botha for his guidance, support and patience.
- Anglogold for its financial and technical support.
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- The management and staff of the Anglogold Free State Operations, specifically Jimmy Soden, Tokkie du Toit and Klaas Rooi who did a lot of legwork.
- My family and friends for their support.
- My wife, Benita, who had to bear the brunt of the late nights and short tempers.

I finally thank my Creator without whom nothing is possible.

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CONTENTS

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

The gold mines in the Free State extract and process ore that contains naturally occurring radioactive uranium and its associated decay products. In terms of the nuclear licences[1] issued to the gold mines, it is required by the Council for Nuclear Safety[2] (local regulator) to assess potential radiation exposures to members of the public. In addition to this legal requirement, the mines have a moral obligation towards the public to assess the impact of radioactive effluents from their sites.

The International Commission on Radiological Protection (ICRP) Publication 60[3] states that no practice involving exposures to radiation should be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes. Exposures should be kept as low as reasonably achievable, economic and social factors being taken into account. Any proposed intervention into existing and/or planned activities should do more good than harm, i.e. the reduction in detriment resulting from the reduction in dose should be sufficient to justify the harm and the costs, including social costs, of the intervention.

This assessment endeavoured to cost effectively quantify the potential exposure of members of the public to radiation hazards originating from the major mining and minerals processing facilities in the Free State Goldfields[4].

Due to the vast area of the mining operations in the Free State, an area of some 80 square kilometres, it is a major challenge to conduct a cost-effective, yet representative public hazard assessment within the financial constraints of the

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[1] Nuclear Licence NL-57
[2] Nuclear Energy Act, 1993 (Act No 131 of 1993)
[3] Annals of the ICRP, Publication 60 Recommendations of the International Commission on Radiological Protection, International Commission on Radiological Protection.
[4] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited

gold mining industry. In addition, the significance of the potential radiation exposure is expected to be in the order of natural background levels and an elaborate and expensive assessment is not justified.

The general strategy[5] for assessing potential public exposures was to:

- conduct limited monitoring of potential sources of radioactivity (source terms),
- model the potential exposures to the public from the different source terms,
- conduct environmental monitoring to validate modelling results and background levels, and
- recommend corrective actions and future monitoring programmes, if required.

[5] Council for Nuclear Safety, Licensing guide LG-1032 Revision 0 (April 1997), Guideline on the assessment of radiation hazards to members of the public from mining and minerals processing facilities.

CHAPTER 2

PROCESS DESCRIPTION AND SITE CHARACTERISATION

2.1 PROCESS DESCRIPTION

The mines in the Free State Goldfields are situated in the south-western part of the Witwatersrand Basin[1] and extracts most of their gold bearing ore from the Basal Reef at a depth of between 1000 to 3000 metres below surface. Gold is the primary product with ore reserves of some 25 million tons at an estimated gold value of up to 14.2 grams per ton (g/t). By-products such as uranium and sulphuric acid was produced up to the early 1990's.

A typical gold mining operation consists of the following:

Shafts and underground developments from which gold bearing ore is brought to surface for processing. The underground areas consist of literally thousands of kilometres of passages that provide access to working areas and in which ore and waste rock are returned to main shafts for extraction to the surface. Major ventilation systems provide fresh air to working areas and extract old air consisting of fumes and gasses, including radioactive radon gas, to the upcast discharge shafts on surface.

Metallurgical plants process and extract gold from the ore from underground. A typical gold recovery circuit consists of the following operations[2]:

- Crushing and screening section - ore received from underground mining activities is fed through the crushing and screening section where the ore is crushed under dry conditions
- Milling section - during a wet milling process the particle size is reduced to an optimum level for treatment.
- Thickening - prior to cyanide leaching the percentage of water in the pulp is reduced in thickener or settler units.

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[1] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited

[2] Operating procedures and process flow diagrams, (Personal communications from Plant Management at Anglogold)

- Cyanidation - lime is added for pH control after which cyanide is added to the pulp for leaching of the gold bearing solution.
- Filtration or Carbon In Pulp (CIP) gold extraction - during filtration the gold bearing solution is separated from the solids and the residue is then pumped to the slimes dams for final disposal. In recent times more efficient carbon adsorption and elution have replaced the use of filtration systems.
- Gold is recovered from solution via zinc precipitation and filtration. Again the residue solutions are diluted to the slimes dams.
- Gold melting - precipitated gold is melted into bars of 95% pure gold in the smelt houses situated on site. The final product is then sent to a refinery for final processing and refinement to 99% gold.

Waste rock dumps - waste rock usually consists of rock extracted during shaft sinking and underground developments i.e. the balance of the rock that does not contain gold bearing reef. The waste rock may still contain minimal gold concentrations and may be re-processed if financially feasible.

Tailings or slimes dams - the waste product from the metallurgical plants are stored in massive storage dams. These dams can be up to a few kilometres in circumference and up to 50 metres height. There are more than 30 tailings dams covered in the scope of this assessment, with the total surface area covered by tailings amounting to more than 3000 ha. Most tailings dams are equipped with under-drains to prevent seepage. Each slimes dam has a diversionary system of drains around the perimeter of the dam to store and control storm water and sediment washed off the walls of the dam. Both seepage and run-off is drained back into the return water or process dams for re-use.

Process water dams - provide storage and supply of large volumes of water used in the metallurgical plants and the cooling and mining activities on the shafts.

The following figures provide a summary of a typical gold mining operation:

Process

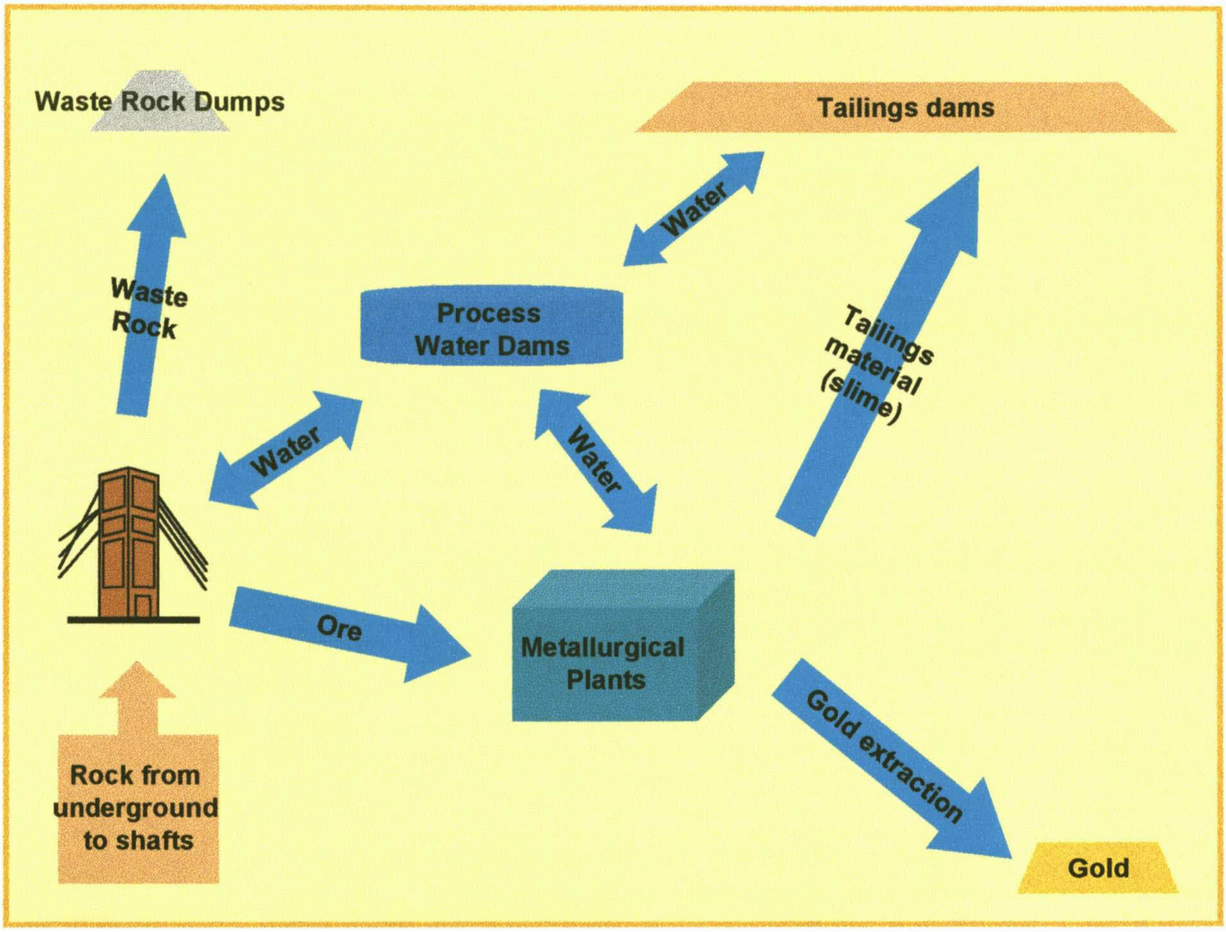

Figure 2-1: A typical gold mining process

Tailings dam

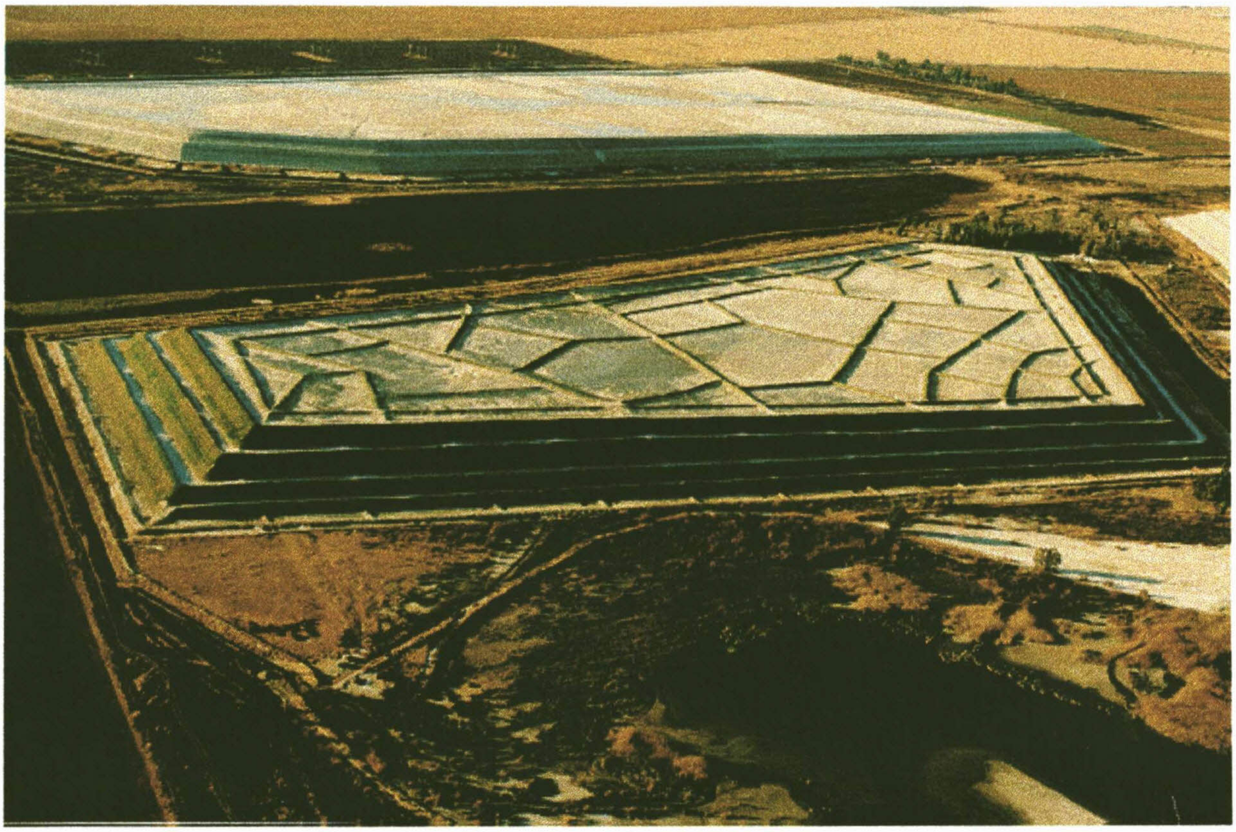

Figure 2-2: The above photograph indicates the magnitude of a typical tailings dam[3] in relation to the environment. The tailings dam in the forefront is a dry, dormant dam that has been rehabilitated and grassed on the side slopes. The dam at the back is wet and still operational.

[3] Photograph compliments of Anglogold, Free State Business Services

2.2 REGIONAL SETTING

The total mining area covers approximately 30 000 ha and includes the majority of mines and/or groups of mines in the Free State Goldfields. The mines are located in and around the towns of Odendaalsrus, Welkom and Virginia in the Free State[4].

The land surrounding the mines is mainly used for agricultural purposes with both grazing and crop farming being practised. The mines are situated in the Sand-Vet River water catchment area, which ultimately drains into the Bloemhof dam and greater Vaal River system. Goudveld Water supplies potable water to the area from mainly the Vaal River system, with a small contribution from a canal on the Sand River system[5].

The majority of the surface mining land is used for cultivation of maize and wheat with small amounts of sunflower making up the balance of crops. The veld type in the area is typical of that on the Highveld.

[4] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited
[5] Water Management Plan Volume 8 (1997), Free State Goldfields and Lower Vet River catchment, Department of Water Affairs and Forestry 2-3, 8-14

2.3 GEOLOGY AND TOPOGRAPHY

The Free State Goldfields are situated in the Highveld region of Southern Africa[6] with a surface elevation ranging between 1300m to 1400m above sea level. The geology comprises mainly of sandstone, siltstone and mudstone of the lower Beaufort and Upper Ecca Groups. The Ecca sediments in the north-west are generally finer and less permeable than the courser Beaufort sediments to the south-east.

The low surface relief gives rise to the formation of many natural pans that collect water during the wet summer months and often dry out during the winter. The topographical characteristic of the area is that of a flat plain with no distinguishing features such as hills or mountains in the area. The Sand River traverses the area from east to west.

The surface area has been divided into approximately ten surface water catchment areas with the Sand River and Mahemspruit being the major focus areas in terms of potential water pollution in general.

2.4 CLIMATE

The regional climate is typical of the Highveld with moderately wet, warm summers and cold dry winters. The area falls within the summer rainfall region and receives an annual precipitation in the order of 530 mm per annum. The annual average temperature is 17 °C with an average maximum of 24 °C and an average minimum of 10 °C. The mean wind direction is from the north north-east with gusts of up to 100 km/h during rainstorms.

[6] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited

The wind rose in Figure 2-3 summarises the predominant wind speeds and directions for the period considered in the assessment. This is based on 5 minute weather data[7] which was also used in the radon gas dispersion modelling discussed in Chapter 5.

WINDROSE[8]

(Period 1 January 1997 to 31 December 1997)

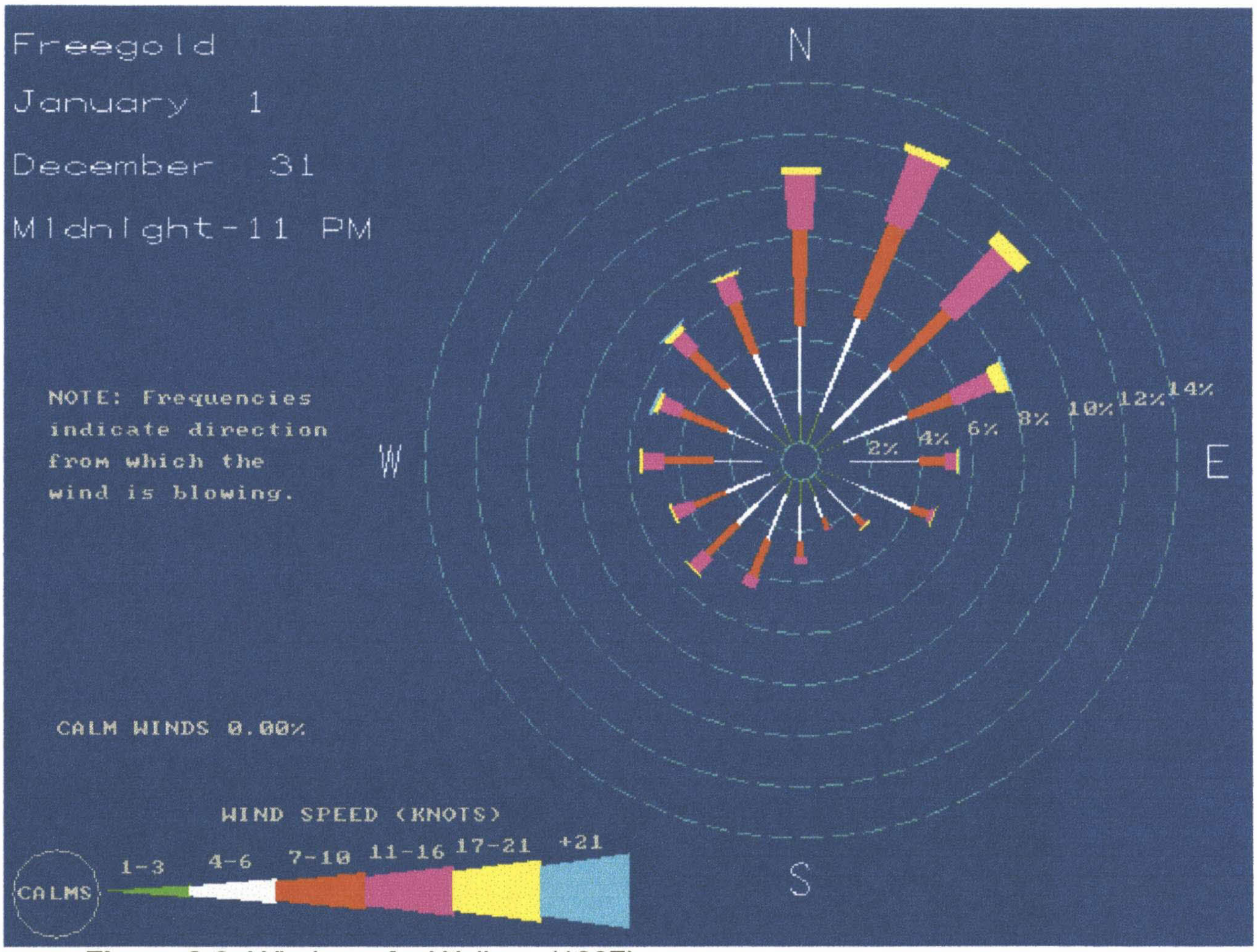

Figure 2-3: Windrose for Welkom (1997)

[7] South African Weather Bureau, Five minute weather data for 1997 (supplied electronically)
[8] Windrose Plot, IAEA Software Programme, SCRAM Bulletin Board

2.5 SOCIO-ECONOMIC STRUCTURES

Gold mines in the area have been in operation for more than forty years and the regional socio-economic structure has developed from a rural, sparsely populated farming community into that of an urban, mining based semi-industrial city.

The support industries for the mining activities constitute the majority of economic activity in the area. The major economic activities[9] can be summarised as follows (Table2-1):

Table 2-1: Socio-economic structure of the Free State Goldfields

Sector	Percentage
Agriculture	4.1%
Mining	67.1 %
Manufacturing	3.7 %
Construction	5.8 %
Commercial	7.3 %
Transport	1.0 %
Services	11.1 %

From the above table it is clear that the gold mining activities has a major socio-economic impact on the area, especially in terms of providing income and financial security to the majority of the population in the Free State Goldfields. It is against these and other benefits that the potential radiological impact, or any other environmental impact, must be measured[10].

[9] Goldfields Population Statistics for 1995.
[10] Annals of the ICRP, Publication 60 Recommendations of the International Commission on Radiological Protection, International Commission on Radiological Protection.

CHAPTER 3

POTENTIAL EXPOSURE PATHWAYS

3.1 URANIUM AND ASSOCIATED NUCLIDES

The main source of radioactivity in the South African gold mining industry is naturally occurring uranium[1] metal contained in the underground ore body at a uranium (U_3O_8) grade[2] of approximately 0.01-0.08%. Uranium-238 is the predominant parent of a long series of radionuclides which finally decays to the stable nuclide Lead-206 (Table 3-1):

Table 3-1: Major isotopes in the Uranium series[3]

Isotope	Half-life	Energy (MeV)	Emission
^{238}U	4.468x10^9 years	4.18 (77%) 4.15 (22%)	α α
^{234}Th	24.1 days	0.19 (65%) 0.10 (35%)	β β
^{234m}Pa	1.175 minutes	2.31	β
^{234}U	2.48x10^5 years	4.77 (72%) 4.72 (28%)	α α
^{230}Th	8.0x10^4 years	4.69 (76%) 4.62 (23%)	α α
^{226}Ra	1622 years	4.78 (94%) 4.60 (6%)	α α
^{222}Rn	3.825 days	***See table 3-2***	
^{218}Po	3.05 minutes	5.99 (+99%)	α
^{214}Pb	26.8 minutes	0.65	β
^{214}Bi	19.7 minutes	1.65	β
^{214}Po	164x10^{-4} seconds	7.69 (100%)	α
^{210}Pb	19.4 years	0.02 (81%) 0.06 (19%)	β β
^{210}Bi	5.0 days	1.16 (99%)	β
^{210}Po	138.4 days	5.29 (100%)	α
^{206}Pb	*Stable*		

[1] Jansen van Vuuren et al (1995), Assessment of the Radiological Impact to the public from surface works on mines: Exposures from aquatic sources, Final Report GU9301, CSIR.
[2] Atomic Energy Corporation of South Africa, Uranium in South Africa (1980-1990)
[3] Cember H (1983), Introduction to Health Physics, Second Edition, Pergamon Press 85 – 85.

3.2 POTENTIAL EXPOSURE PATHWAYS

Uranium and its decay products are found in varying concentrations throughout the gold mining process and are traceable throughout the process stream. This can be seen in the elevated uranium and radium concentrations in ore and the final slimes or tailings material[4].

The initial underground mining process also liberates radon gas from the radium in the surface layers of broken rock. Although not considered the major radon contributor to the public, these underground radon concentrations pose the main radiation exposure risk to the underground workforce[5] and are considered as a potential radiation source to public due to the air emitted from upcast ventilation shafts.

The main potential exposure pathways considered in this assessment[6] were:

Inhalation:

- Inhalation of radon gas ^{222}Rn, and its short-lived progeny from tailings dams, waste rock dumps and upcast shafts from underground[7].
- Inhalation of radioactive dusts containing long-lived alpha emitting nuclides, from mainly the tailings dams[8].

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[4] De Jesus A S M et al (1987), An assessment of the Radium-226 concentration levels in tailings dams and environmental waters in the gold and uranium mining areas of the Witwatersrand, Atomic Energy Corporation

[5] Hazard assessment reports for underground workers, Nuclear Licence NL-57 submissions, Council for Nuclear Safety

[6] Jansen van Vuuren et al (1995), Assessment of the Radiological Impact to the public from surface works on mines: Exposures from aquatic sources, Final Report GU9301, CSIR.

[7] Annals of the ICRP, Publication 65 (September 1993), Protection against Radon-222 at Home and at Work, International Commission on Radiological Protection

[8] Annals of the ICRP, Publication 72 (September 1995), Age dependent doses to members of the public from intake of radionuclides: Part5 Compilation of ingestion and inhalation dose coefficients, International Commission on Radiological Protection

Ingestion[9]:

- Ingestion or consumption of water potentially contaminated with radioactivity.
- Ingestion of foodstuff potentially contaminated with radioactivity.

External exposure:

- External exposure to gamma radiation from tailings and waste rock dumps.

The potential exposure pathways are described by the following interaction matrix[10] and flow diagram (Figures 3-1 and 3-2):

[9] Annals of the ICRP, Publication 72 (September 1995), Age dependent doses to members of the public from intake of radionuclides: Part5 Compilation of ingestion and inhalation dose coefficients, International Commission on Radiological Protection

[10] Licencing guide LG-1032 Revision 0 (April 1997), Guideline on the assessment of radiation hazards to members of the public from mining and minerals processing facilities, Council for Nuclear Safety.

INTERACTION MATRIX:

Source Terms → **Exposure Pathways** → **Human**

Tailings Dams				Erosion	Exhalation	Run-off	Seepage					External radiation
	Waste Rock Dumps			Erosion	Exhalation	Run-off	Seepage					External radiation
		Upcast Shafts			Emission							
			Process Dams			Seepage, discharge	Seepage					
				Dust				Deposition		Deposition		Inhalation
					Radon							Inhalation
						Surface Water	Seepage		Consume		Consume	Consume
							Ground Water					Consume
								Soil		Uptake		
									Aquatic animals			Consume
										Terrestrial Plants	Consume	Consume
											Terrestrial Animals	Consume
												Humans

Figure 3-1: An interaction matrix indicating the major source terms and exposure pathways.

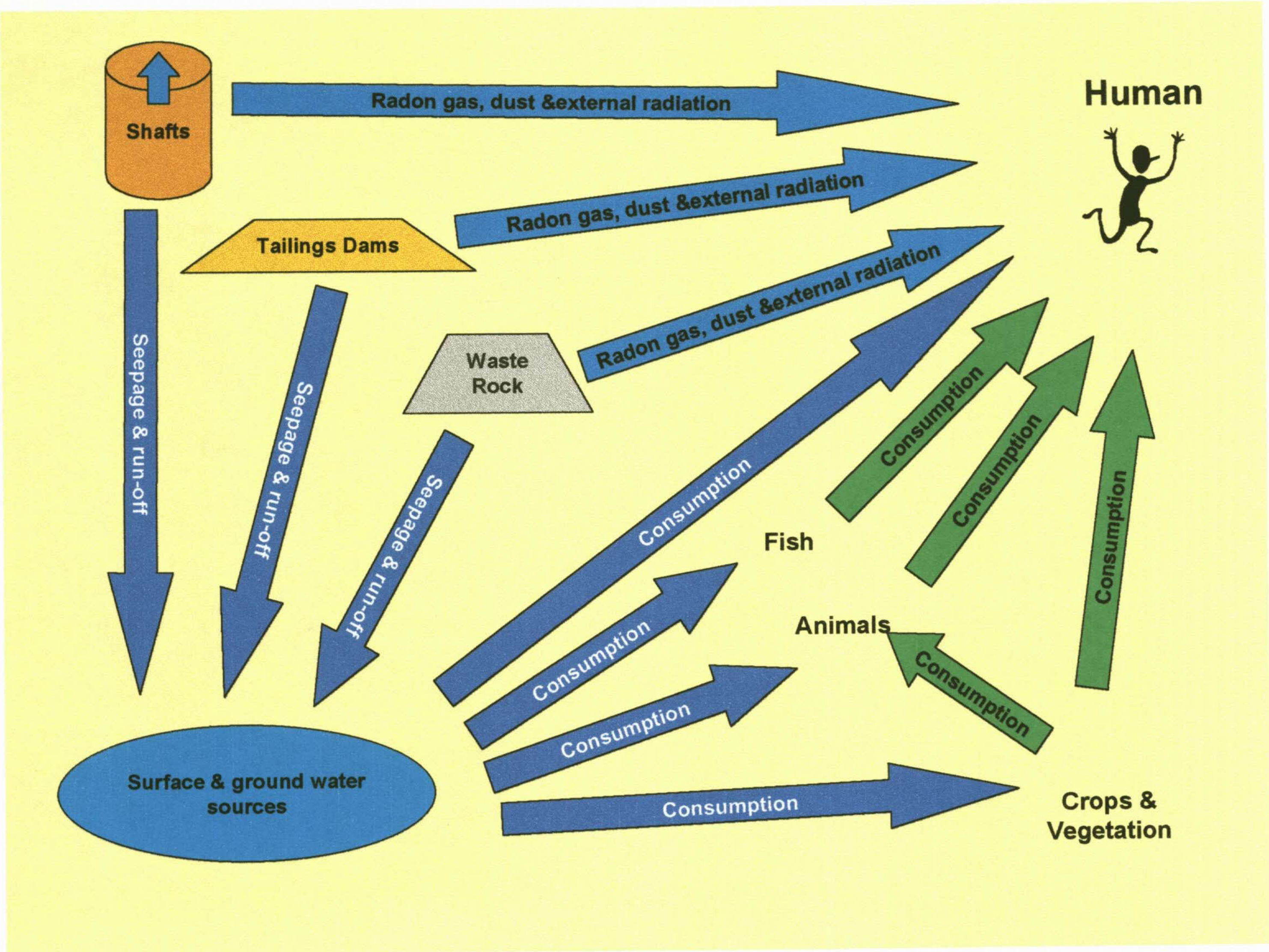

Figure 3-2: Flow diagram indicating major interactions with environment

3.3 RADON GAS AND ITS ASSOCIATED HEALTH RISK

The major contributor to the potential radiation exposures has previously been identified as radon gas emanating from tailing dams, waste rock dumps and upcast shafts from underground[11]. Radon-222 (^{222}Rn) is the immediate decay product of Radium-226 in the uranium series of natural radionuclides. The potential exposure to radon gas is then also the focus of this assessment.

Radon is a noble gas that decays to isotopes of solid elements, the atoms of which attaches themselves to condensation nuclei and dust particles normally present in air. ^{222}Rn, with a half-life of 3.82 days, decays by alpha emission to Polonium-218. Polonium-214 decays to Lead-210 which has a half-life of 23.3 years, and which eventually decays to stable Lead-206.

As radon is chemically inactive, radon gas is freely breathed in and out and being only slightly soluble in water (blood), it is the chemically active decay products such as lead, bismuth and polonium deposited on the tissue of the lungs that poses the risk of radiation induced cancer[12].

The main decay properties of the short lived radon progeny is shown in Table 3-2, indicating energies and yields of the progeny[13]:

[11] Jansen van Vuuren et al (1995), Assessment of the Radiological Impact to the public from surface works on mines: Exposures from aquatic sources, Final Report GU9301, CSIR.
[12] Hopke P H, The measurement of radon decay products in indoor air and their relationship to dose. Dept. of Chemistry, Clarkson University, NY.
[13] Annals of the ICRP, Publication 65 (September 1993), Protection against Radon-222 at Home and at Work, International Commission on Radiological Protection

Table 3-2: Radon decay products

Radio-nuclide	Half-life	Alpha Energy (MeV)	Alpha Yield (%)	Beta Energy (MeV)	Beta Yield (%)	Gamma Energy (MeV)	Gamma Yield (%)
^{222}Rn	3.824 d	5.49	100	-	-	-	-
^{218}Po	3.05 m	6.00	100	-	-	-	-
^{214}Pb	26.8 m	-	-	1.02	6	0.35	37
				0.7	42	0.30	19
				0.65	48	.24	88
^{214}Bi	19.9 m	-	-	3.27	18	.61	46
				1.54	18	1.77	16
				1.51	18	1.12	15
^{214}Po	164 μs	7.69	100	-	-	-	-

d(days), m(minutes), s(seconds)

The potential alpha energy of an atom in the decay chain of radon is the total alpha energy emitted during the decay of this atom to stable ^{210}Pb. The potential alpha energy concentration of any mixture of short-lived radon progeny is the sum of the potential alpha energy of these atoms present per unit volume of air i.e. J m^{-3}. The potential alpha energy concentration of any mixture of radon progeny in air can also be expressed in terms of the so-called equilibrium equivalent concentration of their parent nuclide, radon. The SI unit for the equilibrium equivalent concentration is Bq m^{-3}.

The equilibrium factor, F, is defined as the ratio of the equilibrium equivalent concentration to the activity concentration of the parent nuclide, radon, in air. In other words this equilibrium factor characterises the disequilibrium between the mixture of short-lived progeny and their parent nuclide in air in terms of potential alpha energy. The radiation exposure of an individual to radon gas is the time integral of the potential alpha energy concentration in air, or the corresponding equilibrium equivalent concentration of radon to which the individual is exposed over a given period, normally calculated over one year.

For most purposes it is adequate to use an equilibrium factor of 0.4 and an occupancy of 2000 hours per year at work or 7000 hours indoors (UNSCEAR, 1988)[14]. For outdoor radon the equilibrium factor may be higher (0.6-0.8).

Radon occurs naturally in buildings and the workplace with widely varying concentrations[15]. This makes it extremely difficult to distinguish between radon concentrations that should be treated as "natural background" and radon concentrations due to human practices where the benefits of the practice either offsets the radiation detriment, or not. This fact was also evident in the environment around the gold mines.

The consequences of exposure to ionising radiation are best based on epidemiological studies of human populations. In this context, epidemiology is concerned with the establishment of statistical associations between exposures and health effects. These studies have established beyond any reasonable doubt that high levels of radiation is a causative agent of cancer in many organs in the body, including the lung. A quantitative association between radiation exposures and risk of contracting cancer at low levels is however more difficult.

The main studies include the Life Span Study of the survivors of the atomic bombs at Hiroshima and Nagasaki as well as underground miners exposed to radon at work[16].

[14] UNSCEAR (1988), Sources, Effects and Risks of Ionising Radiation. United Nations Scientific Committee on Effects of Atomic Radiation, 1988 Report to the General assembly, with annexes. United Nations, New York.
[15] Radon concentrations in Klerksdorp homes, Anglogold Vaal River Operations, Nuclear Licence Report
[16] Morrison H et al (1988), Cancer mortality among a group of fluorspar miners exposed to radon progeny. *Am. J. Epideiol.*, 128

The Life Span Study provides estimates of the cancer fatality coefficient for exposure, principally to gamma radiation, that is fairly uniform over the whole lung. The studies on miners provide information on the relationship between the incidence of fatal lung cancer and the concentration of radon progeny in the mining environment.

There has also been many studies aimed at finding a correlation between the incidence of lung cancer and exposure to radon in dwellings. Some of these have shown positive correlation, but many have not. Most of these studies were geographical correlation studies that involved selecting two or more areas, some of high and some of low or average radon concentrations in dwellings. Geographical correlation studies are very difficult to interpret, even qualitatively, because of the presence of several serious confounding factors.

One possible factor is the correlation of radon concentrations with other environmental features. Areas of high radon concentrations are often associated with rocky and hilly regions rather than in the river valleys and alluvial plains where industrial developments are likely to be concentrated. Thus, there could then be an inverse correlation between high radon concentrations and industrialisation. There is a likely correlation between lung cancer and industrialisation, probably associated with smoking. This makes it increasingly difficult to establish a quantitative relation between lung cancer and radon.

Case control studies of radon in dwellings[17] are not inconsistent with the mining studies, but most of them do not provide any quantitative data. At this stage even the ICRP continues to rely heavily on the data from epidemiological studies on miners, because of this lack of statistical power in the studies on dwellings[18].

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[17] Annals of the ICRP, Publication 65 (September 1993), Protection against Radon-222 at Home and at Work, International Commission on Radiological Protection

[18] Schoenberg J B et al (1990), Case control study of residential radon and lung cancer among New Jersey women. *Cancer Res.* 50, 6520-6524

Due to the numerous uncertainties in radon epidemiology, ICRP has concluded that the use of the epidemiology of radon in mines is more direct, and therefor involves less uncertainty and is more appropriate than the indirect use of the Hiroshima and Nagasaki data. The fatality coefficients in ICRP 65 are thus based on the epidemiological studies on miners exposed to radon.

In ICRP 65 the epidemiological evidence for the induction of cancer following inhalation of radon comes from several studies of underground miners, particularly uranium miners. The findings of these reports are summarised and reviewed in reports such as UNSCEAR (1986,1988), NRC (1988), IARC (1988) and ICRP (1991). Many of the studies are consistent with the linear non-threshold relationship between excess risk and cumulative exposure.

If we consider lifetime risk from chronic exposure, the fatality probability coefficient for the general public could be somewhat larger than that for miners because of the inclusion of children in the population. This is however offset by the decreasing excess relative risk with time. For the mortality coefficient for cancer in general, ICRP uses a fatality coefficient of $5x10^{-2}$ per Sv for the public, a factor of 1.25 higher than that of workers[19].

Based on comprehensive data on world-wide indoor radon concentrations, UNSCEAR (1988)[20] adopted an arithmetic mean of 40 Bq m^{-3} with a geometric mean of 25 Bq m^{-3} and standard deviation of 2.5 Bq m^{-3}. However elevated regional values ranging up to several times these values occur fairly widely and values of up to thousands of Bq m^{-3} have been found in houses in Finland[21] and Sweden.

[19] Annals of the ICRP, Publication 65 (September 1993), Protection against Radon-222 at Home and at Work, International Commission on Radiological Protection 12-13
[20] UNSCEAR (1988), Sources, Effects and Risks of Ionising Radiation. United Nations Scientific Committee on Effects of Atomic Radiation, 1988 Report to the General assembly, with annexes. United Nations, New York.
[21] Castren O (1987), Dealing with radon in dwellings: the Finnish experience, Proceedings of the second International Speciality Conference on Indoor Radon, Air Pollution Control Association 45-56

UNSCEAR (1988) assumes occupancy factors of 0.80 indoors and 0.20 outdoors for world-wide calculations. These occupancy factors have been challenged by some European studies such as the UK[22] and Sweden where indoor occupancy goes up to 90%. However, the rounded factor of 0.80 corresponds to 7000 hours per annum indoors and serves as a fairly representative occupancy factor.

ICRP defines a radon-prone area as being an area where the radon concentration in buildings is likely to be higher than the typical radon concentration of the country as a whole. Such definition of a radon prone area should however be related to a number of dwellings per area, and not as individual radon prone dwellings. This is important as high radon concentrations could be recorded in a few buildings or houses without it being part of a so-called radon-prone area, and visa versa.

From the proposed remedial and preventative measures for reducing high radon concentrations indoors, the removal of solid material such as contaminated soil is only considered in extreme cases and the focus is rather placed on engineering controls in the construction of the dwellings in the radon-prone area[23]. This is an important consideration in the gold mining areas where the perceived high source of radon gas is the tailings dams and upcast shafts and not necessarily the underlying soil.

Remedial action is almost always justified if the continued annual effective dose exceeds 10 mSv. For simple remedial measures the action levels could be reduced, however considering the fact that a reduction of a factor of 5 to 10 would reduce the action level to a value well below the dose from natural background sources. In ICRP 65 the range of action levels is usually in the order of 3-10 mSv/a, which relates to a radon concentration of between 200 to 600 Bq m^{-3} (occupancy of 7000 hours and equilibrium of 0.4).

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[22] Brown L (1983), National radiation survey in the UK: Indoor occupancy factors. Radiat. Prot. Dosimetry 5(4), 203-208
[23] Annals of the ICRP, Publication 65 (September 1993), Protection against Radon-222 at Home and at Work, International Commission on Radiological Protection 14-15

Differences in action levels for existing dwellings and future proposed development do not differ very much. Here the emphasis should be on areas with higher radium-bearing wastes, such as tailings material, calcine spills and redundant plant foundations.

Any proposed remedial action, either voluntary or enforced by a regulator should be weighed against the perceived socio-economic benefits as well as the priority of all the prevailing health risks in the area considered. From a public health perspective, radon-induced lung cancer risk could be a relatively minor importance when compared to smoking, as was indicated in recent Canadian studies[24].

Investigations are ongoing about the effect of low level radiation on the human body and several studies[25] yield results that seem to be contrary to the linear non-threshold theory. A number of international experts[26] are convinced that exposures to low level radiation, specifically radon gas, could actually be beneficial to the human body.

In an American study, Jagger (1998)[27] reported that the age-adjusted overall cancer death rate is 1.26 times higher in the Gulf Coast of the USA than in the Rocky Mountain states, although the natural background radiation levels are 3.2 times higher in the last mentioned. The average radon gas concentrations in the living areas of homes in the Gulf Coast are 18.5 Bq m^{-3}, compared to the 96 Bq m^{-3} in the Rocky Mountain states.

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[24] Ayotte Pierre (1998), Indoor exposure to ^{222}Rn: A public health perspective, Health Physics 75(3): 297-302
[25] Jawarowski Z (1995) Beneficial Radiation. *Nukleonika* 40, 3-12.
[26] Cohen B L (1997), Test of the linear no-threshold theory of radiation cacinogenesis for inhaled radon decay products, Health Physics 68 (157-174)
[27] Jagger John (1998), Natural background radiation and cancer death in Rocky Mountain states and Gulf Coast, Health Physics 75(4): 428-430

It is possible that factors such as smoking, poverty, or environmental pollution could contribute to the differences in cancer mortality, but the large factor of disproportion (4.0-7.5) strains credulity that such factors could reverse this negative correlation.

Present scientific evidence on the effects of low doses is inconclusive with contradicting views and it may be that the natural background radiation levels (20-100 Bq m^{-3}) are too low to be a significant cause of cancer mortality, or that there is a non-linearity of the dose-effect curve, or even hormesis[28].

[28] Pollycove M (1988), the rise and fall of the linear no-threshold (LNT) theory, Annual Congress of the South African Radiation Protection Association. University of California, San Francisco.

CHAPTER 4

SOURCE TERM DETERMINATION

4.1 RADON FLUX MEASUREMENTS

The main sources of radon gas have previously been identified as tailings dams, waste rock dumps and upcast air from underground workings.

The radon concentration in upcast air was measured simply by placing radon gas monitors in the upcast draft. A maximum measured concentration of 3000 Bq m^{-3} for the upcast shafts was used to calculate a conservative discharge rate for the dispersion modelling.

Due to their size and the varying radium (^{226}Ra) concentrations in the tailings dams[1] and waste rock dumps, it was extremely difficult to accurately determine the radon emanation rate from the dams. There are a number of factors that influence the emanation rate or flux from a tailings dam. If we consider a tailings dam with n layers of material, then the radon flux at the surface of the dam can be described as follows[2]:

$$F_t = \sum_{i=1}^{n} R_i \rho_i E_i \sqrt{\lambda D_{ti}} \, \mathbf{tanh}\left(\sqrt{\frac{\lambda}{D_{ti}}} x\right) \mathbf{exp}\left(-\sum_{j=i+1}^{n} \sqrt{\frac{\lambda}{D_{tj}}} x_{tj}\right) \qquad 4\text{-}1$$

Where:

F_t	-	Radon flux at the surface of the dam (Bq m^{-2} s^{-1})
R	-	Radium content of the tailings material (Bq kg^{-1})
ρ	-	Bulk density (kg m^{-3})
E	-	Emanation coefficient
D	-	Diffusion coefficient (m^2 s^{-1})

[1] Slimes dam survey results (1996), Nuclear Licence NL-57, Appendix III
[2] IAEA Technical Reports Series No 333, Measurement and calculation of radon releases from uranium mill tailings, VIENNA, 1992

X - Thickness of a layer (m)

λ - Radon decay constant (s^{-1})

The influence of some of the major parameters on the radon flux[3] are described in Figures 4-1, 4-2 and 4-3:

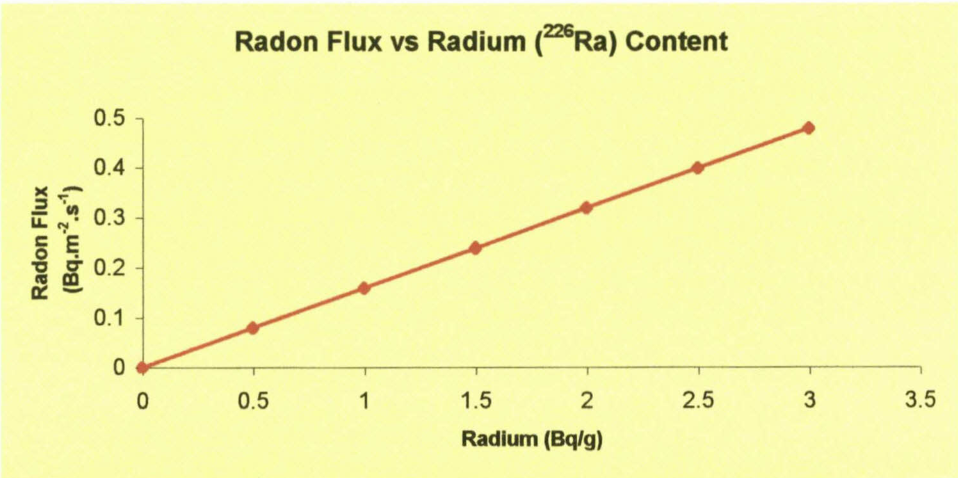

Figure 4-1: Radon flux vs ^{226}Ra

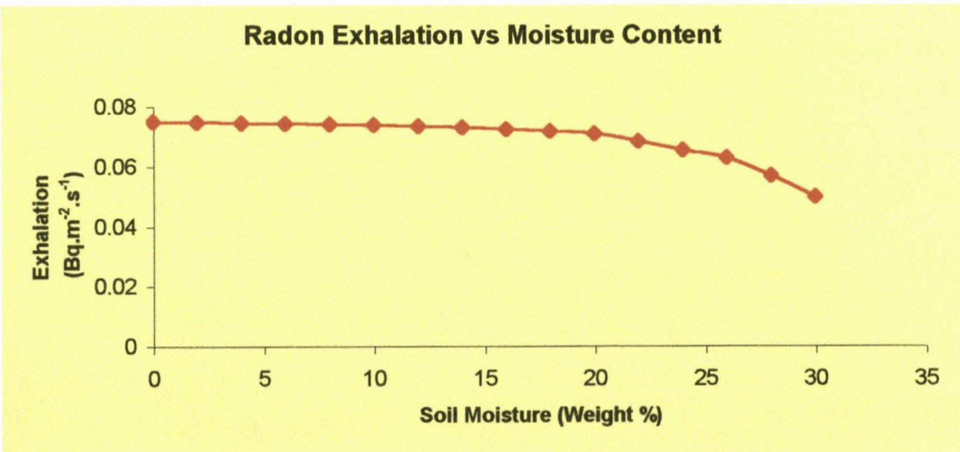

Figure 4-2: Radon flux vs moisture content

[3] Intercomparison of radon exhalation measurements (March 1998), Council for Nuclear Safety Report, (48CB0180)

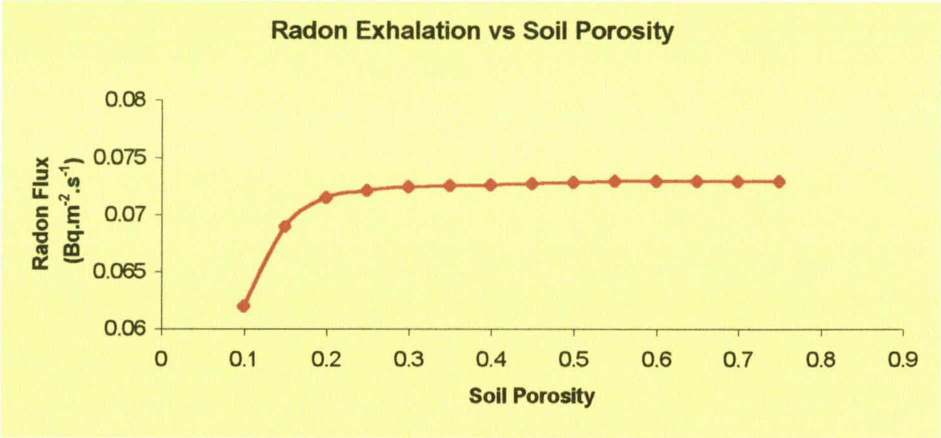

Figure 4-3: Radon flux vs porosity

One of the major parameters is the emanation coefficient (E) in Equation 4-1 that also shows a linear relationship with the flux from the surface of the dam:

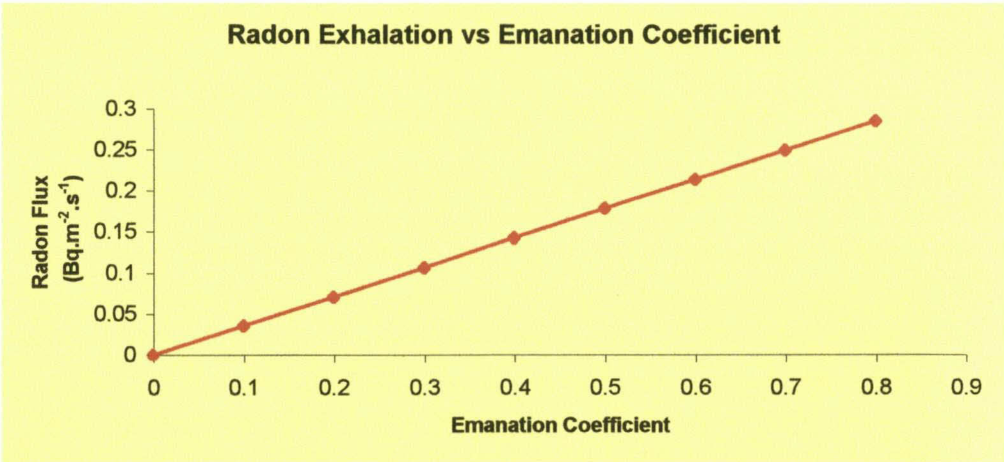

Figure 4-4: Radon flux vs Emanation Coefficient

Due to the potential influence of all the parameters in Equation 4-1, especially the emanation coefficient, it was essential to determine the flux from the tailings dam by in situ radon flux monitoring techniques.

The influence of the flux measurement itself on the radon flux from the tailings dam is a major consideration when embarking on any such experiments[4,5]. Due to the uncertainty regarding the accuracy of flux measurements, it was decided to explore as many techniques as possible to ensure that at least the appropriate range of flux values were used in the dispersion modelling exercise.

There are mainly three approaches to radon flux measurement:

- By using equations describing flux from a surface e.g. Equation 4-1, and measuring just the ^{226}Ra content of the material and assuming theoretical values for the other parameters, the radon flux may be calculated.

- A second similar approach is to take a physical sample of the material and then determine the flux, using the ^{226}Ra content and laboratory measured values for as many of the remaining parameters as possible.

- The third basic technique is the in situ measurement of flux by means of some kind of "vessel" i.e. monitor, ionisation chamber, etc. placed on the surface of the tailings material and the radon flux deducted from the radon concentration inside the vessel.

The different flux measurement techniques employed during the assessment are discussed in more detail in the next sections.

Prior to embarking on the study a contamination survey was conducted of 27 tailings dams in the area to determine the relative radioactivity concentrations of the different dams[6].

---

4 Samuelsson C (1987), A critical assessment of Radon-222 exhalation measurements using the closed-can method, Lund University, Sweden.
5 Jonassen N (1983), the determination of radon exhalation rates, Health Physics 45 (2), 369-376
6 Slimes dam survey results (1996), Nuclear Licence NL-57, Appendix III

The highest contamination areas on the dams were identified using a hand-held beta/gamma contamination monitor[7] to survey the surface area of the dam by trisecting the dam in different directions.

Samples of the tailings material were taken at these "hot-spots" and analysed for ^{226}Ra, the parent nuclide of radon gas in the tailings dams[8]. The distribution of these maximum ^{226}Ra activity concentrations is as follows:

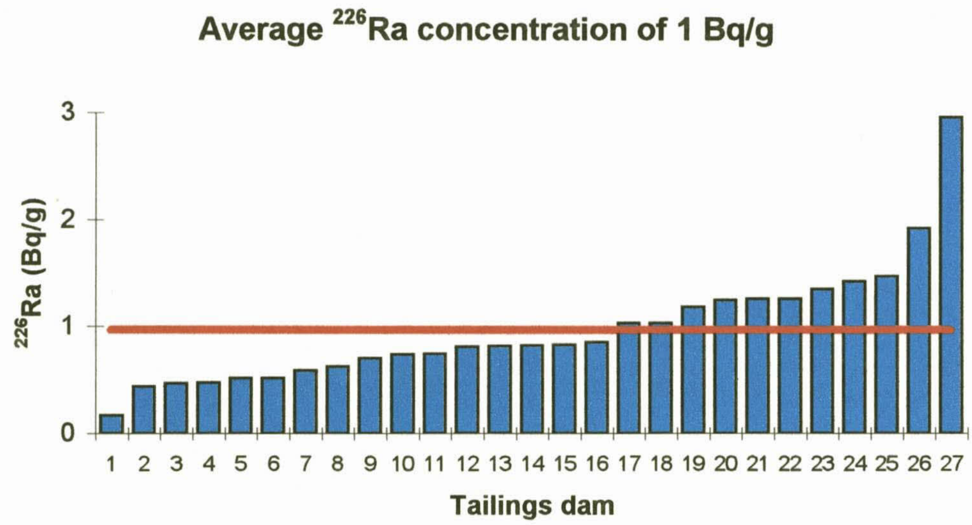

Figure 4-5: Highest ^{226}Ra concentrations in tailings dams

Based on the above distribution the flux measurements were done on tailings dams with a ^{226}Ra activity concentration of about 1 Bq/g. Only dry, dormant dams were considered as this represents a worst case scenario in terms of potential radon flux[9]. It was further assumed that most of the tailings dams would be dormant and dry within the next 30 to 50 years[10].

---

[7] Training Manual prepared and issued by the Technical Services of the Chamber of Mines of South Africa (1992), 134.
[8] Isotopes were analysed by γ,α-spectroscopy, Atomic Energy Corporation.
[9] IAEA Technical Reports Series No 333, Measurement and calculation of radon releases from uranium mill tailings, VIENNA, 1992
[10] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited

Three different tailings dams were considered. For inter comparison purposes radon flux measurements were also conducted on a pyrite dam, with much higher ^{226}Ra concentrations, as well as limited measurements on normal garden soil.

4.1.1 CLOSED BOX METHOD

The radon concentration inside a vessel placed on a surface emanating radon gas[11] is described in Figure 4-6:

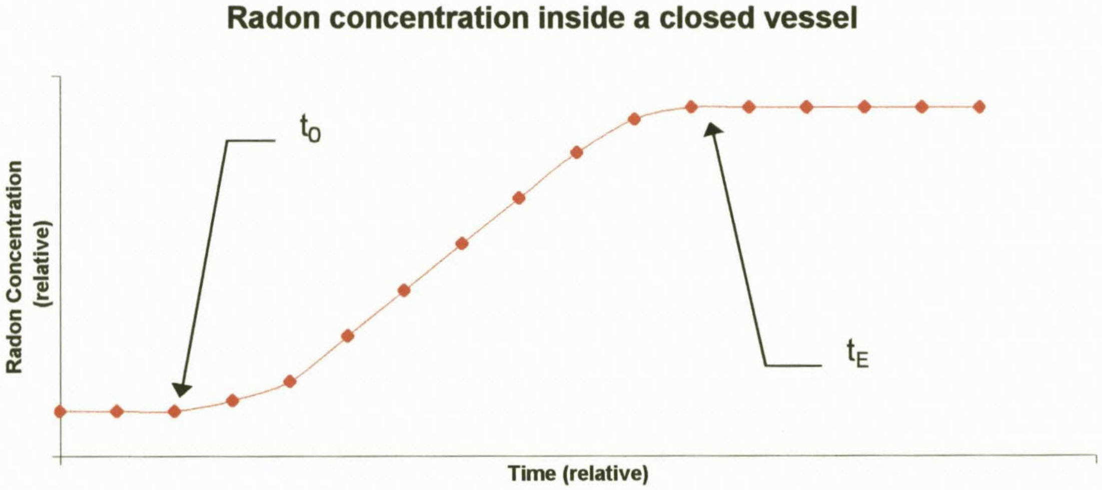

Figure 4-6: ^{222}Rn inside a closed vessel placed on a tailings surface

In Figure 4-6 a closed or semi-closed vessel is placed on the surface of a tailings dam at time t_O., with equilibrium being established at t_E. This state of equilibrium is also described as the concentration at which the diffusion rate into the vessel is equal to the rate of "back diffusion". This "back diffusion" is the effective result of the radon concentration gradient between the vessel and its surroundings, possible leakage from the vessel and radon decay inside the vessel.

[11] Aldenkamp RJ et al (1990), An assessment of a method for in situ radon exhalation measurements, Kernfysich Versneller Instituut, Croningen, 4 (17-28)

The radon concentration inside the vessel may be described by Equation 4-3, following from Fick's first law (Equation 4-2):

$$\vec{F}(t)=\xi D\vec{\nabla}C(t)\Big|_{surface} \qquad 4-2$$

$$\frac{\partial C_{can}}{\partial t}=\frac{F(t)A}{V}-\lambda_{Rn}C_{can}-\lambda_{leak}C_{can} \qquad 4-3$$

Where:

F(t)	-	flux through the surface (Bq m^{-2} s^{-1})
A	-	surface area of the material covered by the vessel (m^2)
V	-	volume of the vessel (m^3)
C_{can}	-	radon concentration in the can (Bq m^{-3})

and where the diffuse leakage of radon from the vessel is proportional to the radon concentration with the rate constant λ_{leak}.

Consider the radon concentration in the vessel at time t_0, as described by Figure 4-6. The radon concentration inside the vessel at t_0 would be the same as that outside the vessel. Thus at time $t = t_0$ or $t \approx t_0$ the radon concentration inside the vessel would be $C_{can}(t_o)$.

If we consider the initial rate of change (slope) of the radon concentration inside the vessel, the flux F(t) would be directly proportional to this initial rate of change and the flux can be determined by:

$$\frac{\partial C_{can}}{\partial t}=\frac{F(t\approx t_0)A}{V}-C_{can}(t_0) \qquad 4-4$$

$$F(t\approx t_0)=\frac{V}{A}\times\left(\frac{\partial C_{can}}{\partial t}\right)-C_{can}(t_0) \qquad 4-5$$

By continuous measurement of the radon concentration inside the vessel with known dimensions, the net flux can be determined by calculating the initial slope of the graph in Figure 4-6.

In the assessment, this method was used by placing a closed and sealed glass box (300x300x450mm) tightly on the surface of a tailings dam and measuring the radon concentration inside the box at 10-minute intervals with an Alphaguard[12] Radon Gas Monitor. The experimental set-up is described in Figure 4-7.

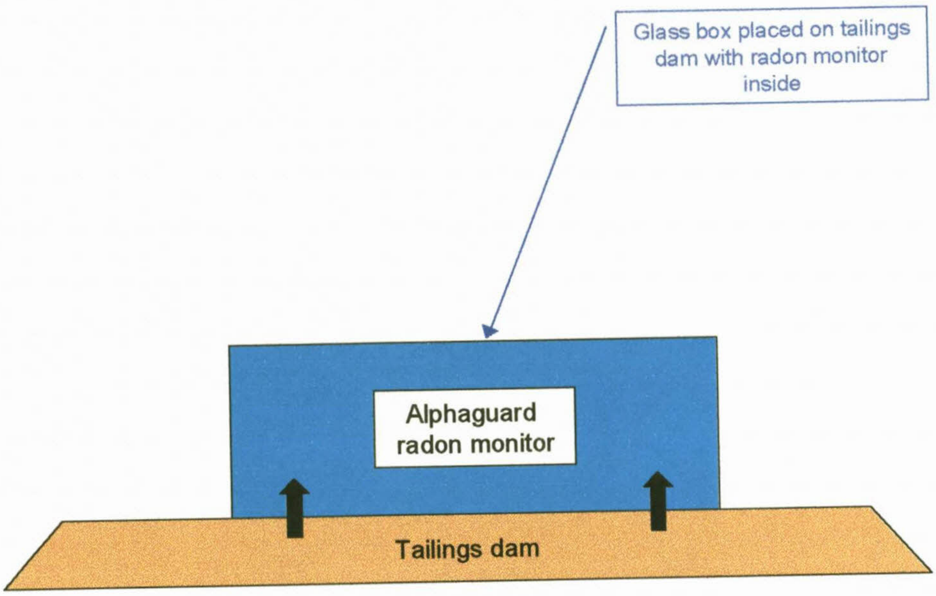

Figure 4-7: Experimental set-up for closed box experiment

By plotting the radon concentration at 10-minute intervals, flux calculations were then based on the initial rate of change of the radon concentration inside the box, according to Equation 4-5.

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[12] AlphaGUARD Professional Radon Monitor (1997), Operating Manual. Genitron Instruments, Frankfurt, Germany

RESULTS

The following results were obtained with the closed box method:

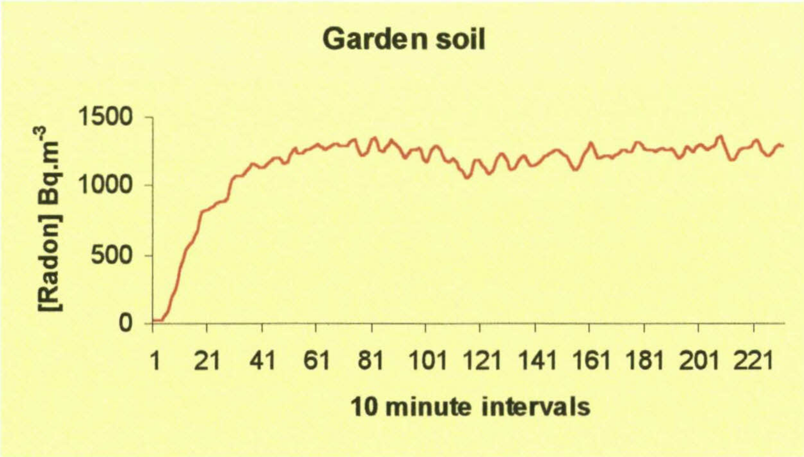

Figure 4-8: Radon concentration inside a closed box placed on normal garden soil for a period of approximately 36 hours.

If we only consider the initial part of the graph, i.e. shortly after the box is placed on the surface of the soil, the radon concentration is represented as follows:

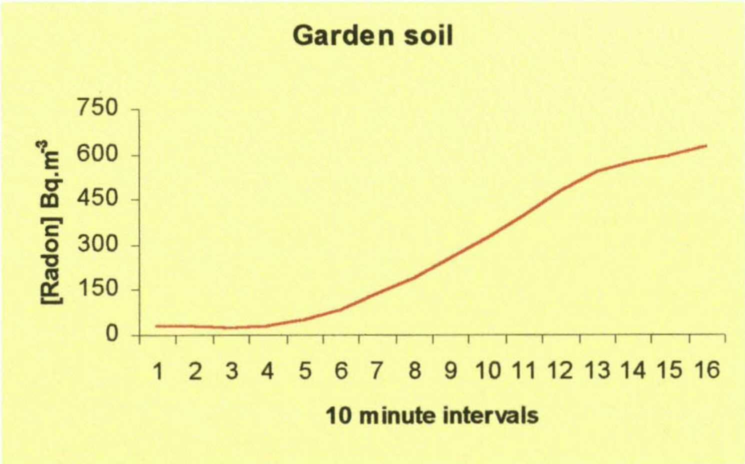

Figure 4-9: Initial 2½ hours period.

The slope or rate of change in radon concentration of the initial part of the graph is directly proportional to the radon flux from the tailings dam, in accordance with Equation 4-2:

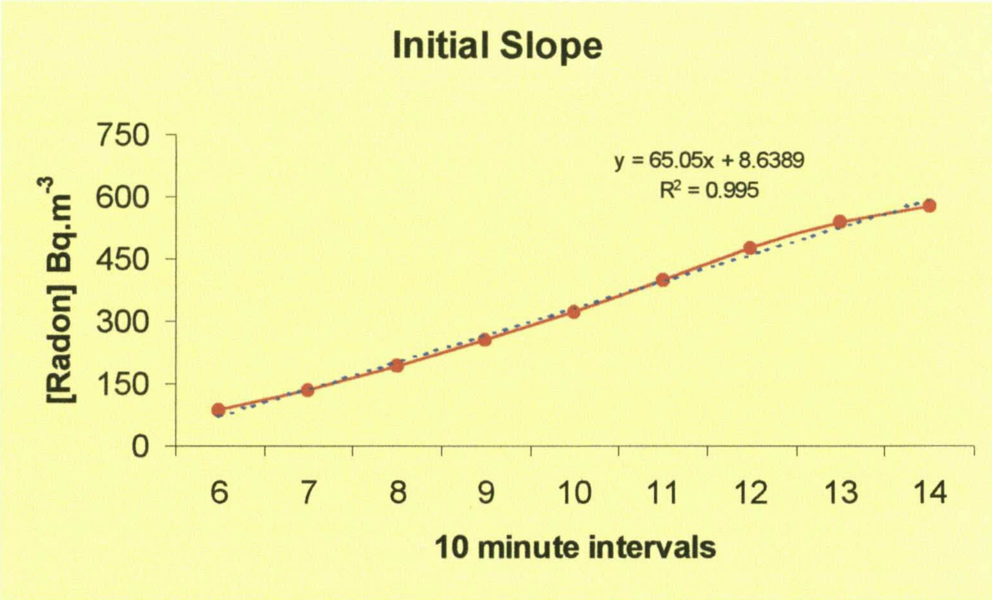

Figure 4-10: First few 10 minute intervals

The results obtained from the different tailings dams and soil are as follows:

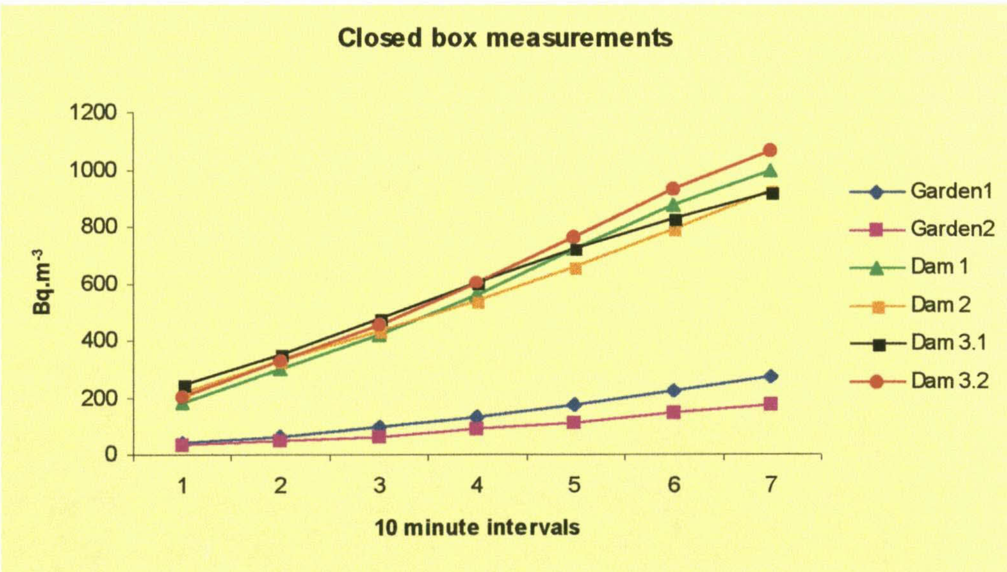

Figure 4-11: Initial slopes for different tailings dams and normal soil

Table 4-1: Closed box flux measurement results

Material	Location	Radon Flux (Bq m^{-2} s^{-1})
Soil	Garden soil 1	0.012
at ±0.04 Bq/g ^{226}Ra	Garden soil 2	0.017
Tailings	Dam 1	0.050
at ±1.0 Bq/g ^{226}Ra	Dam 2	0.044
	Dam 3.1	0.060
	Dam 3.2	0.047
	Average	0.050
	STD	0.007
Pyrite at ±10.0 Bq/g ^{226}Ra	Pyrite dam	0.640

Based on the flux measurements and the ^{226}Ra concentrations for soil, tailings material and pyrite, the following graph indicates to some extent a linear relationship between the radon flux from a surface and the radium (^{226}Ra) concentration of the material as theoretically expected[13]:

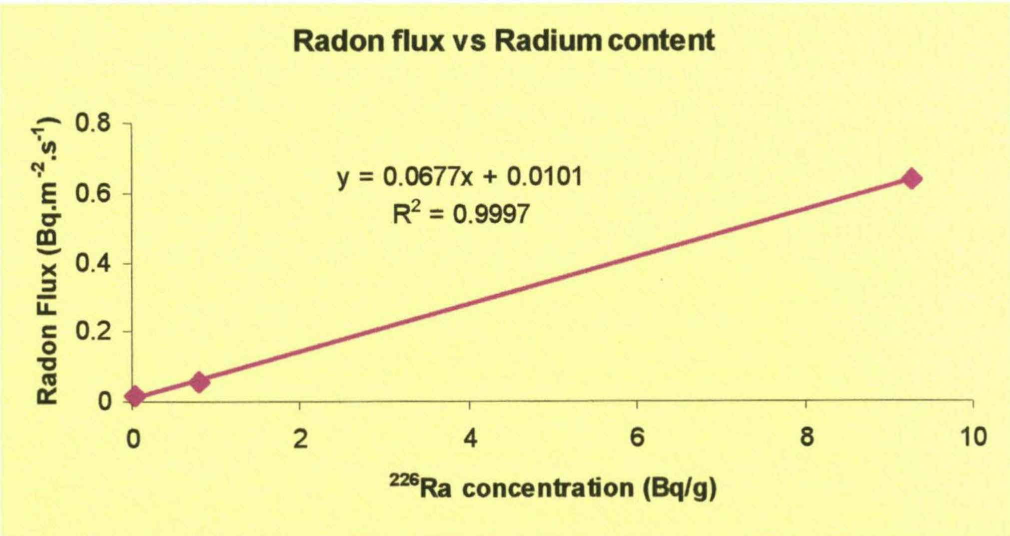

Figure 4-12: ^{222}Rn flux vs ^{226}Ra content

Based on the above graph one could deduct a relationship of 0,07 Bq m^{-2} s^{-1} per unit activity concentration (1 Bq/g) of radium, all other parameters being equal.

[13] IAEA Technical Reports Series No 333, Measurement and calculation of radon releases from uranium mill tailings, VIENNA, 1992

4.1.2 DIFFUSION TUBE METHOD

In the so-called diffusion tube method[14,15] used by the consultants PARC Scientific[16], a sample of the tailings material is obtained and sealed to preserve the moisture content. A sub-sample of the material is then compacted into a short diffusion tube, which is attached to a longer tube to provide a well-defined air space above the sample surface.

Another similar but larger sub-sample is then compacted into a longer tube and connected to a diffusion tube with the same dimensions as the first. The two sub-samples thus have the same geometry of air space above the compacted material as illustrated in Figure 4-13:

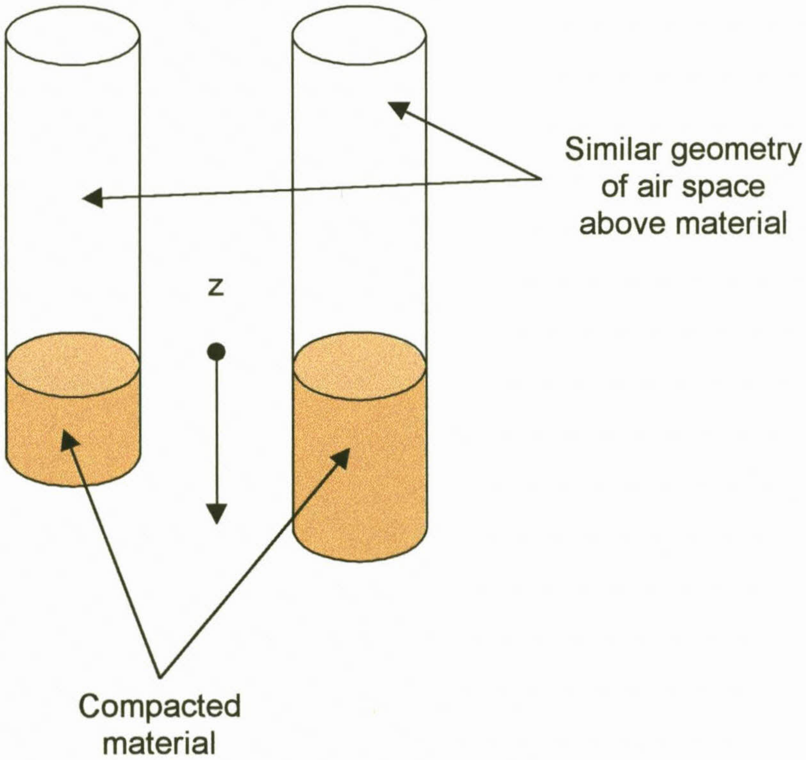

Figure 4-13: Experimental set-up for the diffusion tube method

[14] IAEA Technical Reports Series No 333, Measurement and calculation of radon releases from uranium mill tailings, VIENNA, 1992
[15] Rogers V C et al (1980), Characterisation of uranium tailings cover materials for radon flux reduction, NUREG/CR-1081
[16] Strydom R, PARC Scientific Technical Documents, PARC-002/95;PARC-004/95;PARC-EXMOD-001/95; PARC-EXPAR-001/94

The material was then compacted to between 1300 and 1600 kg m^{-3}, the bulk density for tailings material as determined from literature[17]. After compaction the tubes were sealed for up to fifteen days for the radon exhalation to establish equilibrium. The tubes are then rapidly opened and radon gas etched track monitors (RGM's) inserted into the air space of each, after which the tubes are again sealed for a period of 4-5 days. These radon monitors record the radon gas concentration as an integrated concentration over the exposure period.

The geometry of the diffusion tubes is such that the exhalation of radon from the two sample surfaces can be modelled by one-dimensional diffusion theory.

The generation and transport properties of the sample material determine the rate at which radon will be exhaled from the surface of the material. This diffusion though the surface of the material can be described by the following one-dimensional diffusion equation (Equation 4-6):

$$D\frac{\partial^2 C}{\partial z^2} - \lambda C + \frac{R\rho\lambda\varepsilon}{P} = 0 \qquad 4-6$$

Where:

D	-	effective diffusion constant ($m^2\ s^{-1}$)
C	-	interstitial radon concentration (atoms m^{-3})
λ	-	radon decay constant ($2.097 \times 10^{-6}\ s^{-1}$)
R	-	Radium content (Bq kg^{-1})
z	-	co-ordinate perpendicular from the surface into the material

[17] Macphail G, (1995) Metago Environmental Engineers, Personal Communications.

The solution of Equation 4-6 is given by:

$$C(z) = C_\infty (1 - \frac{\tanh^{-1}(z/L)}{k \tanh^{-1}(L/z)}) \qquad 4-7$$

Where C_∞ = radon concentration at infinite depth of the material

$C(z)$ = radon concentration at depth z into the material

L = diffusion length

= $(D/\lambda)^{1/2}$

The radon flux at the surface is then given by:

$$F = -D \frac{dC(z)}{dz}\bigg|_{z=Z} \qquad 4-8$$

Where Z is the z co-ordinate at the surface of the material.

Equations 4-7 and 4-8 then form the basis for modelling the radon flux from the surface of the material[18].

[18] Strydom R, PARC Scientific Technical Documents, PARC-004/95: Modelling of radon exhalation rate and resulting source term from tailings impoundments and sand dumps.

RESULTS

The following results were obtained by PARC Scientific on one of the tailings dams considered in the assessment, using the diffusion tube method:

Table 4-2: Diffusion tube flux measurement results

Sample Location	Diffusion coefficient ($m^2 s^{-1}$)	Flux ($Bq m^{-2} s^{-1}$)
1	3.9x10-7	0.211
2	9.2x10-7	0.191
3	3.4x10-7	0.150
4	2.1x10-7	0.237
5	5.2x10-7`	0.126
	Average	**0.183**
	Standard Dev	0.040

4.1.3 PASSIVE E-PERM FLUX MEASUREMENTS

Passive E-PERM flux monitors[19] were used to measure the radon flux from the surface of a tailings dam without interfering with the physical nature of the slimes material[20]. The electret ion chamber is a passive integrating ionisation monitor consisting of a very stable electret mounted inside a small chamber made of electrically conducting plastic. The electret is a charged Teflon disk, which serves both as a source of electrostatic field and as a sensor. Radon gas passively diffuses into the chamber and the alpha particles emitted by the decay process ionise air molecules inside the chamber. The ions produced inside the chamber collect on the electret and cause a reduction of its surface charge or potential. The reduction in charge or change in voltage is a function of the total ionisation, or if calibrated accordingly, the integrated radon concentration over the exposure period.

The E-PERM flux monitor consists of an H electret ion chamber that has been modified with an electrically conducting diffusion window made of Tyvek. The chamber is vented by four outlets that ensure that the radon does not accumulate in the chamber. Thus, when the flux monitor is placed on the surface of the tailings dam the radon enters through the Tyvek barrier and exits through the vents. The semi-equilibrium radon concentration established inside the chamber is representative of the flux from the surface. Because of the equilibrium between the radon from the ground and the radon in the outside air through the vents, the flux from the tailings surface is not disturbed. The semi-equilibrium radon concentration is representative of dynamic flux from the surface. The discharge rate of the electret is a measure of the radon flux.

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[19] E-PERM® System Manual, Radon & Radiation Measurements, Rad Elec Inc.

[20] Stieff R and Kotrappa P (1996), Passive E-PERM radon flux monitors for measuring undisturbed radon flux from the ground, International Radon Symposium, II - 1.1.

The E-PERM flux monitors have been calibrated on well characterised radon flux beds at CANMET[21] (Canada), which are known to produce *a* radon flux of 7.7 $\pm$1.1 pCi m^{-2} s^{-1} (0.285 $\pm$ 0.04 Bq m^{-2} s^{-1}).

As the electret chambers are prone to gamma induced ionisation, corrections were made for the gamma background by placing duplicate flux monitors on the tailings dam which had been sealed with steel plate to prevent radon from the surface to enter through the Tyvek window. The experimental arrangement[22] is described in Figure 4-14:

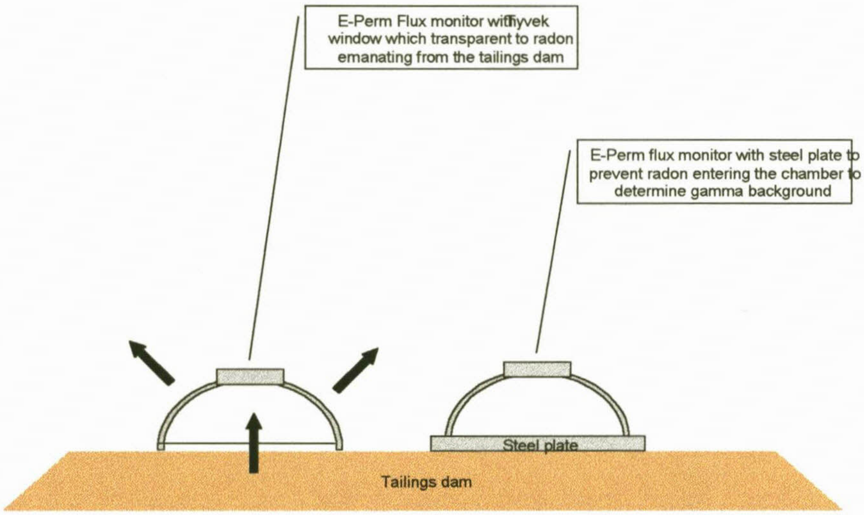

Figure 4-14: Experimental set-up for E-PERM flux monitors

The net voltage drop after gamma background correction provided a measure of the radon flux from the tailings dam surface.

[21] Bigu J, CANMET Elliot Lake Laboratory (National Reference Standard), Ontario, Canada.
[22] E E-PERM® System Manual (1994), Radon & Radiation Measurements, Rad Elec Inc. Part II 10 Measurement of undisturbed flux from the ground.

It is important to note that the discharge rate of the electret in electret ion chambers is not the same for unit flux for all operating voltages of the electret. The result must thus be multiplied by a linearity correction coefficient[23] given by:

$$LLC = 0.7727 + 0.0004568 \times \{(I + F)/2\} \quad 4\text{-}9$$

Where I and F are the initial and final voltage readings of the electret.

RESULTS

The following results were obtained with the E-PERM flux monitors:

Table 4-3: E-PERM flux measurement results (1)

Location	Sample	Exposure period (hours)	Flux ($Bq\ m^{-2}\ s^{-1}$)
Dam 1	1	6.5	0.099
	2	6.5	0.0006
	3	6.5	0.056
	4	6.5	0.031
		Average	0.046
		Standard Dev	0.034

Following the first set of results, the flux monitors were slightly modified by placing a flat steel ring-plate around the base of the monitor and sealing it tightly with silicon-gel to prevent any radon from escaping between the ring-plate and the monitor. This modification was necessary to ensure that the monitor could be tightly placed on the uneven tailings dam surface without damage to the monitor or leakage between the monitor and the tailings dam surface.

[23] E E-PERM® System Manual (1994), Radon & Radiation Measurements, Rad Elec Inc. Part II 10 B Page 2.

Better correlation were obtained amongst the individual flux monitors, following this modification:

Table 4-4: E-PERM flux measurement results (2)

Location	Sample	Exposure period (hours)	Flux ($Bq\ m^{-2}\ s^{-1}$)
Dam 2	1	6	0.009
	2	6	0.008
	3	6	0.041
	4	6	0.014
	5	6	0.023
	6	6	0.008
	7	6	0.028
	8	6	0.037
		Average	0.021
		Standard Dev	0.013

Table 4-5: E-PERM flux measurement results (3)

Location	Sample	Exposure period (hours)	Flux ($Bq\ m^{-2}\ s^{-1}$)
Dam 3.1	1	8	0.021
	2	8	0.035
	3	8	0.025
	4	8	0.016
	5	8	0.025
	6	8	0.075
	7	8	0.016
	8	8	0.022
	9	8	0.022
		Average	0.029
		Standard Dev	0.018

Due to the large error as indicated by the standard deviation the experiment was repeated on the last tailings dam, but the exposure period was extended to 27 hours to ensure that a true equilibrium of the radon concentration is reached. This proved to be a critical aspect of the monitoring technique as the E-PERM Flux Monitor acts as a vented closed-box requiring a relatively long time for equilibrium to be established. As expected, better correlation was established amongst the different sets of monitors deployed on the tailings dam:

Table 4-6: E-PERM flux measurement results (4)

Location	Sample	Exposure period (hours)	Flux ($Bq\ m^{-2}\ s^{-1}$)
Dam 3.2	1	27	0.043
	2	27	0.029
	3	27	0.025
	4	27	0.026
	5	27	0.046
	6	27	0.024
	7	27	0.022
	8	27	0.041
	9	27	0.025
		Average	0.031
		Standard Dev	0.009

4.1.4 DYNAMIC FLOW-THROUGH METHOD

The dynamic flow-through method for measuring undisturbed radon flux from tailings dams was based on the dynamic method described in the Electret Operating Manual (1994)[24] and Livingstone & Jester (1990)[25]. In this assessment, the E-PERM radon gas monitors were just substituted with and Alphaguard radon monitor. This was done to more accurately determine the conditions inside the vessel at shorter intervals. A graph of the radon gas concentration inside the vessel clearly indicates when steady state equilibrium is achieved inside the vessel. This value represents the average radon gas concentration required to calculate the flux from the tailings dam.

The radon flux from the tailings dam (J) was calculated based on the measurement of the radon concentration (R) inside the box with known area (A) and air flow rate (F). This is determined assuming that (R) is the steady state radon concentration inside the box, that the flow rate (F) is constant and that the detector measures a representative radon concentration inside the box. This condition is described by the following equation:

$$J = \frac{R \times F}{60 \times A} \qquad 4\text{-}10$$

Where:

J	-	Radon flux (Bq m^{-2} s^{-1})
R	-	Average radon concentration inside the box (Bq m^{-3})
F	-	Flow rate (m^3 min^{-1})
A	-	area of the tailings dam surface covered by the box (m^2)
60	-	conversion factor (sec min^{-1})

[24] E-PERM® System Manual, Radon & Radiation Measurements, Rad Elec Inc.
[25] Livingstone J V et al (1990) Annual Meeting of American Nuclear Society, Volume 61 Pages 1-39

In Equation 4-10 the radon balance is established i.e.

radon in (JxA) = **radon out** (RxF).

In the experiment, this method was used by placing a closed and sealed glass box (300x300x450mm) tightly on the surface of a tailings dam. A pre-calibrated air pump was attached to an outlet in the box, with an inlet to the outside air on the other side of the box. The radon concentration inside the box was then measured at 10-minute intervals with an Alphaguard[26] Radon Gas Monitor.

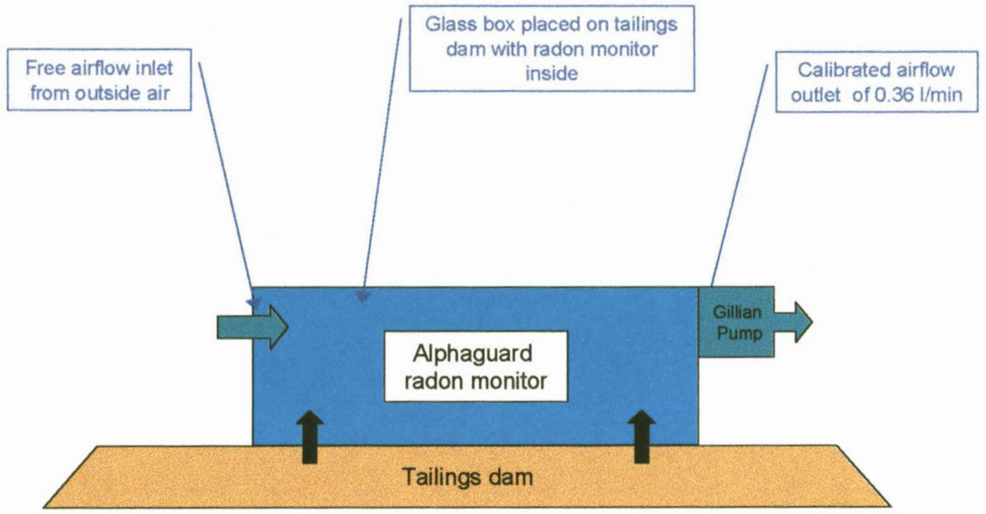

Figure 4-15: Experimental set-up for dynamic flow-through method

The surface area of the box was 0.126 m^2 and the flow rate calibrated at 0.36 l min^{-1}.

[26] AlphaGUARD Professional Radon Monitor (1997), Operating Manual. Genitron Instruments, Frankfurt, Germany

The radon concentration inside the box is described by Figure 4-16.

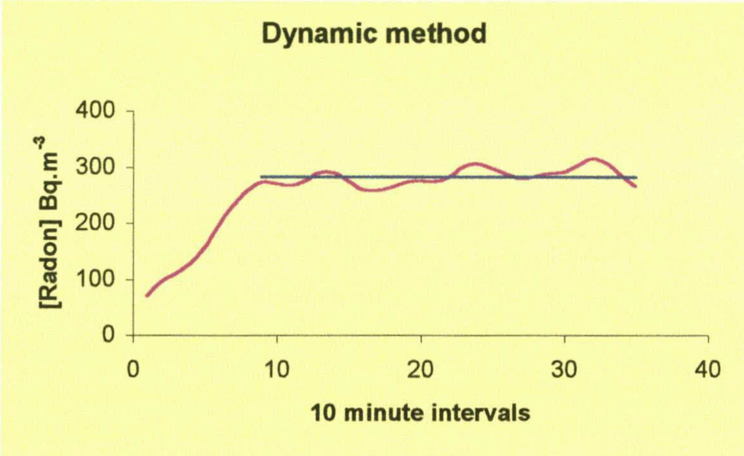

Figure 4-16: Radon concentration inside the box in the dynamic flow through method

The average radon concentration when steady state equilibrium is achieved was calculated from the graph and the radon flux calculated as 0.014 Bq m^{-2} s^{-1}.

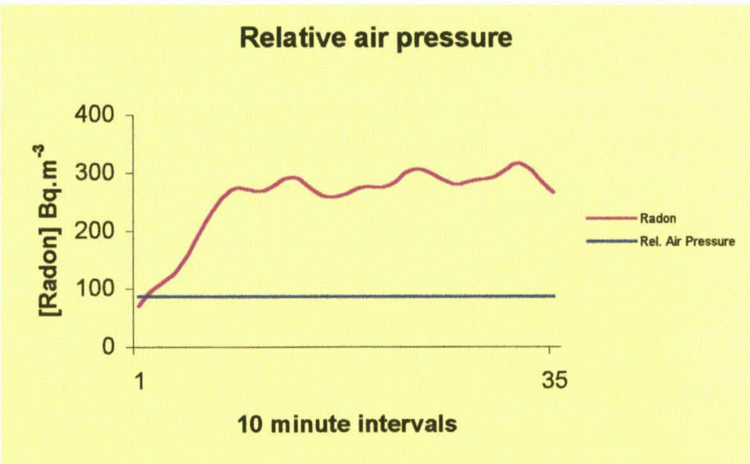

Figure 4-17: Radon concentration inside the box vs the relative air pressure inside the box

The constant air pressure inside the box (Figure 4-17) confirms that no additional leakage of air into or out of the box occurred during the experiment.

Due to a heavy downpour of rain the days before the above results were obtained, the experiment was repeated to prevent any potential reduction in the radon flux due to the high humidity of the tailings material. Both the closed box method and the dynamic method was used, consecutively at the same sampling location. The whole experiment was repeated again the next day.

The following results were obtained:

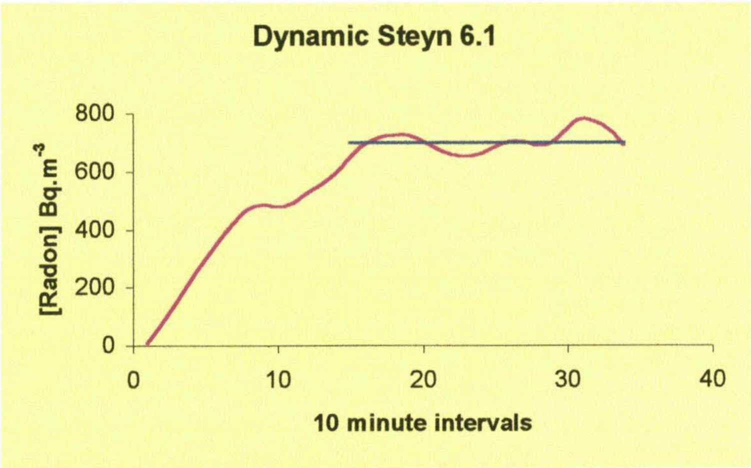

Figure 4-18: Dynamic method on dam Steyn 6.1

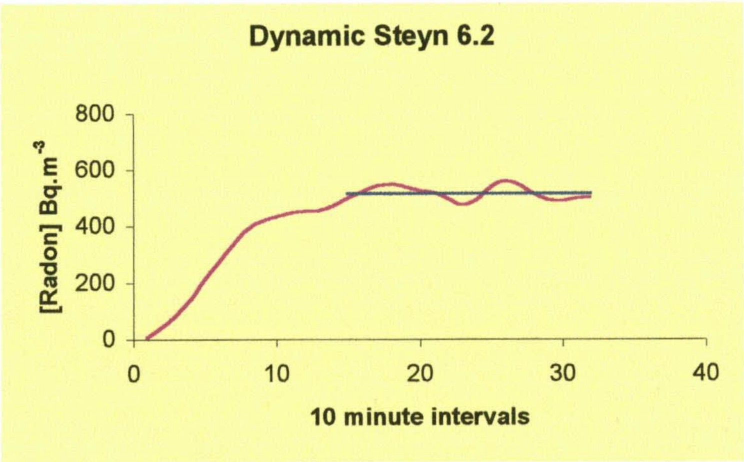

Figure 4-19: Dynamic method dam Steyn 6.2

Table 4-7: Dynamic method vs Closed Box method

Parameters	Steyn 6.1	Steyn 6.2
Volume (m^3)	0.0311	0.0311
Area (m^2)	0.1258	0.1258
Closed box method		
Rate of change / slope (Bq m^{-3} per 10min)	92	82.7
Flux (Bq m^{-2} s^{-1})	0.037	0.034
Dynamic method		
Average radon concentration inside box (Bq m^{-3})	700	516
Pump flow rate (l/min)	0.36	0.36
Flux (Bq m^{-2} s^{-1})	0.033	0.025

By inter-comparing the different radon flux measurement techniques, the following was found[27]:

Table 4-8: Inter-comparison of flux measurement techniques

Technique	Average flux measurement (Bq m^{-2} s^{-1})
E-PERM Flux Monitors	0.046
Closed Box Method	0.03 - 0.05
Dynamic Method	0.025 - 0.035
Diffusion Tube Method	0.211
*Theoretical Calculation	0.245

*The ^{226}Ra was analysed and the flux calculated according to Equation 4-1, assuming typical values for the other parameters.

It is to be expected that the diffusion tube method would give approximately the same answer as the theory predicts as it follows from an assumption that all the parameters are as per the theory. In practice however, the sedimentation of the

[27] Intercomparison of radon exhalation measurements (March 1998), Council for Nuclear Safety Report, (48CB0180)

wet slime causes different values of compaction, some surfaces being rock hard whereas others may be sandy. The E-perm and closed box methods must be the considered as the preferred methods as no assumptions on the physical properties of the slime material are made. These methods merely measure the radon entering the collectors from the tailings.

It is however clear from the results obtained that radon flux from tailings dams is very difficult to accurately determine.

All the methods employed during the assessment has some associated degree of uncertainty, either due to assumptions made or due to the influence of the measurement technique on the radon flux parameters.

Because of these uncertainties and the fact that the maximum radium concentrations of the tailings dams in the Free State were as high as 3.0 Bq/g, a value of **1 Bq m^{-2} s^{-1}** was used as a conservative radon flux value in the dispersion modelling exercise.

CHAPTER 5

MODELLING

5. MODELLING

5.1 RADON DISPERSION MODELLING

This section provides a summary of the computer programmes, input parameters such as source term data, receptor data and meteorological data, as well as a short validation for the modelling programs used in modelling the dispersion of radon gas emanating from the tailings dams, waste rock dumps and upcast shafts to the environment.

5.1.1 BRIEF HISTORY OF THE INDUSTRIAL SOURCE COMPLEX (ISC) MODELS

The ISC Short Term area source model[1] is based on a numerical integration over the area in the upwind and crosswind directions of the Gaussian point source plume formula.

Individual area sources may be represented as rectangles with aspect ratios (length/width) of up to 10 to 1. In addition, the rectangles may be rotated relative to a north-south and east-west orientation. Note that for the size and shape of the individual area sources, the only requirement is that each area source must be a rectangle. Dividing an area source into multiple rectangular areas simulates an irregular shaped area. Because of the flexibility in specifying elongated area sources with the Short Term model, up to an aspect ratio of about 10 to 1, the ISCST area source algorithm may also be useful for modelling certain types of line sources.

To shorten the processing time due to a large number of sources, an irregular shaped source was modelled by a rectangular source totally enclosing the original source.

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[1] U S Environmental Protection Agency (September 1995), User's guide for the Industrial Source Complex (ISC3) Dispersion Models, Volume II – Description of Model Algorithms, Office for Air Quality Planning and Standards, Emmisions, Monitoring, and Analysis Division (EPA), North Carolina.

This artificial enlargement of the source leads to an over estimation of the potential radon dose. This conservative approach is preferred to complex groups of small sources approximating the irregular source.

The ground-level concentration at a receptor located downwind of all or a portion of the source area is given by a double integral in the upwind (x) and crosswind (y) directions. The user assigns the effective emission height, being the physical release height. This was set equal to the physical height of the source of emissions, above local terrain height. For example, the emission height of a tailings dam is the physical height of the tailings dam.

5.1.2 THE GAUSSIAN EQUATION

The ISC short term model uses a steady-state Gaussian plume equation[2] to model emissions from sources. For a steady-state Gaussian plume, the hourly concentration at downwind distance x (metres) and crosswind distance y (metres) is given by Equation 5-1:

$$\chi = \frac{QKVD}{2\pi u_s \sigma_y \sigma_z} \mathbf{exp}\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] \qquad 5-1$$

Where:

Q	-	pollutant emission rate (mass per unit time)
K	-	scaling coefficient to convert calculated concentrations
V	-	vertical term
D	-	decay term
σ_y, σ_z	-	standard deviation of the lateral and vertical concentration distribution (m)
u_s	-	mean wind speed ($m\ s^{-1}$) at release height

[2] Petersen W B at al (1987), Users guide for PAL 2.0 – A Gaussian-Plume Algoritnm for Point, Area, and Line Sources, EPA/600/8-87/009, U S Environmental Protection Agency, Carolina, USA.

The vertical term includes the effects of source elevation, receptor elevation, plume rise and limited mixing in the vertical. The x-axis is positive in the downwind direction, the y-axis is crosswind (normal) to the x-axis and the z-axis extends vertically. Fixed receptor locations are converted to each source's co-ordinate system for each hourly concentration. The hourly concentrations calculated are summed to obtain the total concentration produced at each receptor by the combined source emissions.

5.1.3 SHORT-TERM AREA SOURCE MODEL

Individual area sources may be represented as rectangles with aspect ratios (length/width) of up to 10 to 1. The rectangles may be rotated relative to a north-south and east-west orientation.

The ground-level concentration at the receptor located downwind of all or a portion of the source area is given by the double integral[3] in the upwind (x) and crosswind (y) directions as:

$$\chi = \frac{Q_A K}{2\pi u_s} \int_x \frac{VD}{\sigma_y \sigma_z} \left(\int_y \mathbf{exp}\left[-0.5\left(\frac{y}{\sigma_y} \right)^2 \right] dy \right) dx \qquad 5-2$$

With the effective emission height being the physical release height. This should be set equal to the physical height of the source of emission above the terrain height. In this instance the release height of the tailings dam is the physical height of the tailings dam. The integral is not defined for receptors inside the source.

[3] Environmental Protection Agency (1992), Sensitivity analysis of a revised area source algorithm for the Industrial Source Complex Short Term Model, EPA-454/R-92-015, U S Environmental Protection Agency, Carolina, USA

5.1.4 DISPERSION MODELLING OVERVIEW

The ISCST3 computer-modelling programme[4] was used to model the dispersion of radon from radium sources. This suite of programmes is based upon the U.S. Environmental Protection Agency (EPA) ISCST3 and ISCLT3 models and is nothing more than a user friendly software tool to manipulate input data. The modelling itself is still done according to EPA ISCST3.

The ISCST3 and ISCLT3 models are designed to estimate pollutant concentrations or deposition from an industrial source complex. Both models predict pollutant concentrations from continuous point, area, volume, and open pit sources. These versatile models enable one to estimate concentrations from virtually any type of source emitting a non-reactive pollutant.

There are two versions of ISC3, a short-term model (ISCST3) and a long-term model (ISCLT3). The models differ in the averaging times available for calculation, available terrain and deposition options, and the format of input meteorological data.

5.1.5 ISC SHORT-TERM MODEL

The Industrial Source Complex (ISC) Short Term model provides options to model emissions from a wide range of sources that might be present at a typical industrial source complex. The basis of the model is the straight-line, steady-state Gaussian plume equation, which is used with some modifications to model emissions from stacks, storage piles, etc.

Emission sources are categorised into four basic types of sources, i.e., point sources, volume sources, area sources and open pit sources.

[4] Computer Software Package, Shareware on Internet, EPA ISCST3

The algorithms used to model each of these source types are modified to account for both simple (flat) terrain and complex terrain (significant elevations in sources and receptor points).

The ISC short term model accepts hourly meteorological date records to define the conditions for plume rise, transport, diffusion, and deposition. The model estimates the concentration of deposition value for each source and receptor combination for each hour of input, and calculates user-selected short-term averages. The user also has the option of selecting averages for the entire period of input meteorology.

5.1.6 ISC3 PARAMETER LIMITS

ISCST3[5] has a set limit of one thousand (1,000) sources, five hundred (500) source groups, twelve (12) pollutants, ten thousand (10,000) receptors, five (5) gridded receptor networks, and seven (7) short-term averages (ISCST3).

5.1.7 REGULATORY APPLICABILITY

The U.S. Environmental Protection Agency (EPA) maintains the Guideline on Air Quality Models (Revised)[6] (hereafter referred to as the "Guideline") which provides the agency's guidance on regulatory applicability of air quality dispersion models in the review and preparation of new source permits and State Implementation Plan (SIP) revisions. When using the ISCST3 model the regulatory default option as described below was used. This ensures compliance with most of the Council for Nuclear Safety's requirements on dispersion modelling.

[5] U S Environmental Protection Agency (September 1995), User's guide for the Industrial Source Complex (ISC3) Dispersion Models, Volume I – User Instructions. Office for Air Quality Planning and Standards, Emissions, Monitoring, and Analysis Division (EPA), North Carolina.
[6] Environmental Protection Agency (1987b), Guideline on air quality models (Revised) and Supplement A, EPA-450/2-78-027R, U S Environmental Protection Agency, Carolina, USA

5.1.8 REGULATORY DEFAULT OPTION

The regulatory default option is controlled from the MODELOPT keyword on the CO pathway. As its name implies, this keyword controls the selection of modelling options. It is a mandatory, non-repeatable keyword, and it is an especially important keyword for understanding and controlling the operation of the ISC models. The regulatory default options, as specified in the Guideline on Air Quality Models, are truly the default options for the ISC models. That is to say that, unless specified otherwise through the available keyword options, the ISC models implement the following regulatory options:

- Use stack-tip downwash (except for Schulman-Scire downwash);
- Use buoyancy-induced dispersion (except for Schulman-Scire downwash);
- Do not use gradual plume rise (except for building downwash);
- Use the calms processing routines;
- Use upper-bound concentration estimates for sources influenced by building downwash from super-squat buildings;
- Use default wind profile exponents; and
- Use default vertical potential temperature gradients.

5.1.9 METEOROLOGICAL DATA

Five-minute weather data for a full year (1997) was manipulated to calculate the variation in wind speed and direction and an hourly average was then used. The 1997 data for Welkom was obtained from the National Weather Bureau[7].

The standard deviation Φ_2 of the wind direction was calculated for hourly averaged data according to the method of Campbell Scientific[8]. The stability classes were calculated using the method of Turner[9].

[7] Five minute weather data for 1997 supplied electronically by the South African Weather Bureau
[8] Cambell Scientific, Inc. (1995) CR10X Measurement and control system, *Operators Manual.*
[9] Turner B D (1970). Workbook of Atmospheric Dispersion Estimate.

The Weather Bureau could not provide mixing height data as they only fly meteorological weather balloons at midday. To overcome this problem a set of mixing height data obtained from Mr J Slabbert of PSI Consultants was used to determine conservative mixing heights not area bound to be used for the dispersion modelling. For winter days and winter nights mixing heights of 200 and 60 metres were used. For summer days and nights mixing heights of 1000 and 100 metres were used.

This assumption may be shown to be conservative as the following simulation of a single tailings dam using the true mixing heights and the conservative mixing heights shows:

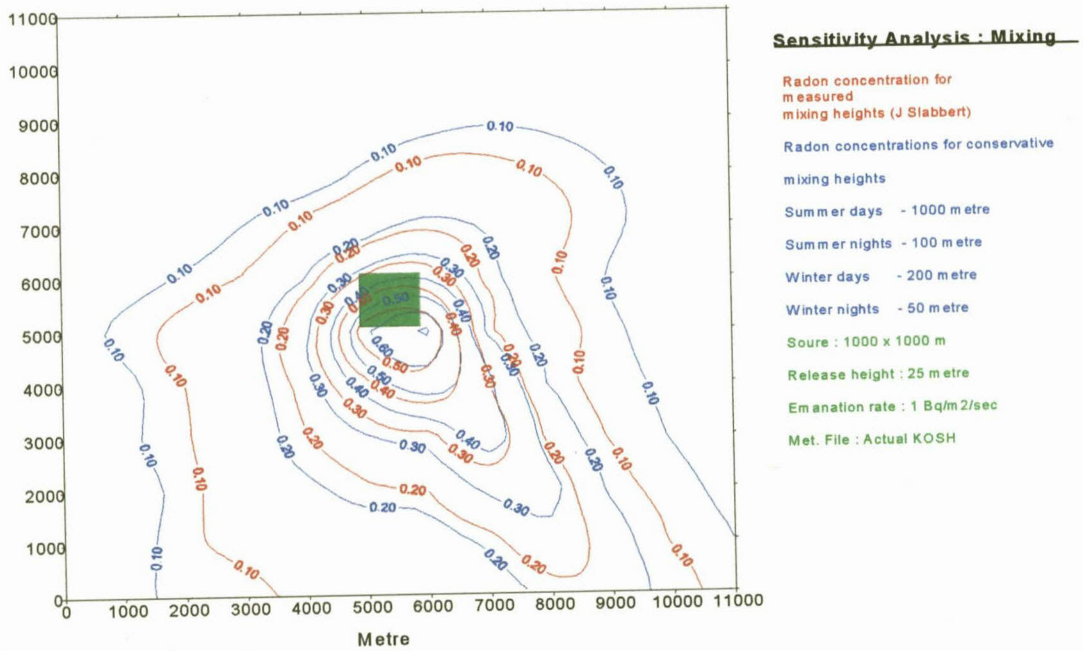

Figure 5.1: Simulation of different Mixing Heights.

5.1.10 VALIDATION OF THE ISCST3 MODEL.

The Chamber of Mines commissioned Industry and Environment Consultants CC to model and to validate the ISCST3 model against the Impact model[10]. A number of tailings dams at Anglogold's Vaal River Operations[11] were modelled using ISCST3. This report has been submitted to the Council for Nuclear Safety under separate cover Anglogold, Vaal River Operations. The weather and geographical information was then submitted to the consultants who then modelled the same slimes dams using Impact. The following table compares the calculated radon concentrations in a line across the site and in the predominant wind direction. The correlation is acceptable considering the large number of variables.

Distance	Impact ($Bq\ m^{-3}$)	ISC3 ($Bq\ m^{-3}$)
2.2km	2.8	1.4
4.0km	1.8	1.2
6.0km	1.2	1.1
10km	0.8	0.8

Table 5-1: Comparison of radon concentrations calculated using ISCST3 and Impact models.

[10] Beak Consultants Limited (1996), Integrated Model for the Probabilistic Assessment of Contaminant Transport (IMPACT), Arrow Road, Ontario, Canada.
[11] Similar gold mining operations in the Klerksdorp area, located in the North-West Province

5.1.11 MODELLING RESULTS AND DOSE CONVERSION

The weather data is available on site in electronic format.

The ISCST3 input and output files used for the calculations are attached as **APPENDIX 1**.

The calculated radon concentrations were interpolated using the Surfer Grid Based Contouring programme[12] and a Kriging algorithm[13] (geostatistical interpolation method that produces contour and surface plots from irregularly spaced data).

The radon concentrations were converted using a dose conversion factor of 14.6 Bq m^{-3} radon gas per 250 μSv effective dose per annum as per the Basic Safety Series, IAEA Safety Series No.116, Page 99[14].

The final potential radon dose contours in μSv/a are indicated in **Figure 5-2**. The **area sources** (tailings dams and waste rock dumps) are indicated by yellow squares and the **point sources** (upcast shafts) are indicated by red dots. The whole surface area considered is indicated on a grid of about 32 000 metres by 40 000 metres, with north being in the positive y direction.

The maximum potential radon gas contribution to the potential dose from the sources considered, is 106 μSv/a:

1ST HIGHEST VALUE IS 6.19 Bq m^{-3} AT (13000, 4500)

2ND HIGHEST VALUE IS 6.17 Bq m^{-3} AT (16000, 4500)

[12] Surfer for Windows, Version 6
[13] Cressie N A C, (1990) The origins of Kriging. Mathematical Geology Vol 22 p 239-252
[14] IAEA, International basic safety standards for protection against ionising radiation and the safety of radiation sources, Vienna, IAEA Safety Series No 116, Page 99.

Although the highest potential radon concentrations are predicted on top of the tailings dams, this is as a result of interpolation and is not calculated values, the reason being that the integral in Equation 5-2 is not mathematically defined inside a source.

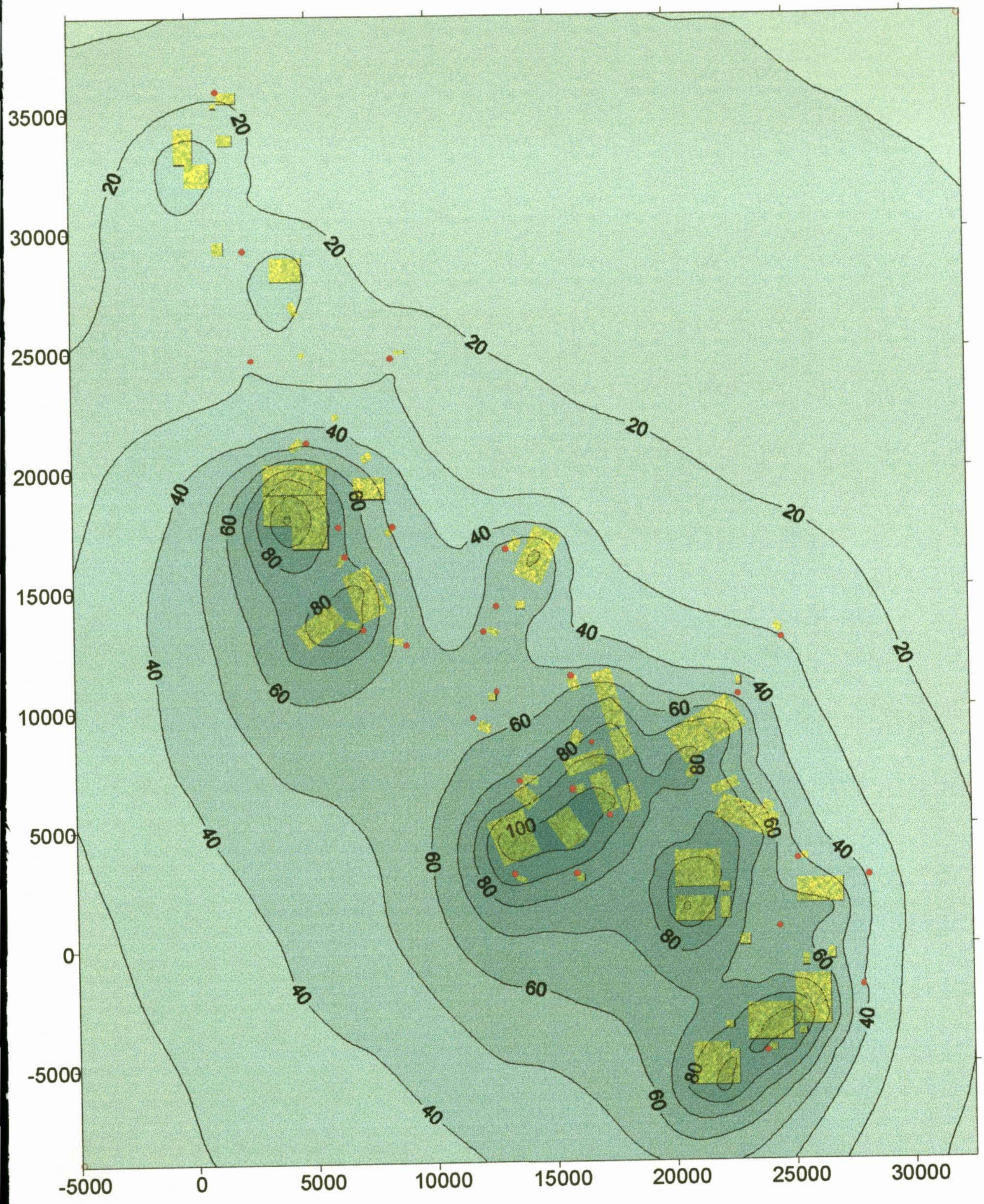

Figure 5-2: Potential radon dose contours for the Welkom area (μSv/a)

5.2 WATER DOSE MODELLING

The potential exposure to radioactively contaminated water sources was modelled using a simple Microsoft Excel spreadsheet for calculating transfers of activity from the water source via the different pathways e.g. soil, plants, animals etc., to final consumption by humans. The structure of the model is indicated in **APPENDIX 2**. The activity concentration values and isotope ratios in the appendix are typical of that in the water sources around the mines[15]. This is summarised in Table 5-2:

Table 5-2: Typical concentrations in water

Uranium-238 Series

Nuclide	Bq/l
U-238	**0.06**
Th-234	**0.06**
Pa-234	**0.06**
U-234	**0.06**
Th-230	**0.06**
Ra-226	**0.02**
Pb-214	**0.02**
Bi-214	**0.02**
Pb-210	**0.02**
Bi-210	**0.02**
Po-210	**0.008**

The transfer factors and dose conversion factors were based on ICRP 72[16], Licensing Guide LG-1032[17], as well as IAEA Basic Safety Standards[18]. Only the ^{238}U-series was considered, as it is the predominant decay series.

[15] Analysis by the Atomic Energy Corporation
[16] Annals of the ICRP, Publication 72 (September 1995), Age dependent doses to members of the public from intake of radionuclides: Part5 Compilation of ingestion and inhalation dose coefficients, International Commission on Radiological Protection
[17] Licencing guide LG-1032 Revision 0 (April 1997), Guideline on the assessment of radiation hazards to members of the public from mining and minerals processing facilities, Council for Nuclear Safety.
[18] IAEA, International basic safety standards for protection against ionising radiation and the safety of radiation sources, Vienna, IAEA Safety Series No 115

The mines are establishing extensive water management systems to monitor mainly non-radioactive pollutants from the mining processes. These parameters such as acidity, salt loading and chemical toxins[19] are the predominant environmental hazards and it is a safe assumption that controlling water systems according to these parameters, would also be adequate in terms of uranium and its associated decay products. Radioactivity levels must however still be considered in these monitoring and management systems[20].

Seeing that drinking water is mainly supplied to the area from sources that are not located in the mining area[21], the immediate exposure potential is negligible. The one scenario, that of secondary exposure such as consuming crops and animals living on potentially contaminated water, is also fairly insignificant if one considers the effective transfer of ^{238}U series (Table 5-3).

Table 5-3: Typical exposure scenario for consumption of contaminated water

Dose to the Public

	Adult μSv/a	**15 year** μSv/a	**10 year** μSv/a	**5 year** μSv/a	**1 year** μSv/a
FOODSTUFF					
Meat	3.11	4.43	3.36	2.82	1.69
Poultry	0.35	0.42	0.36	0.26	0.16
Eggs	0.12	0.14	0.13	0.10	0.05
Fish Products	0.66	0.51	0.62	0.45	0.17
Grain Products	0.00	0.00	0.00	0.00	0.00
Roots & Fruits	0.00	0.00	0.00	0.00	0.00
Leafy Vegetables	0.00	0.00	0.00	0.00	0.00
LIQUIDS					
Milk Products	0.96	2.34	2.45	3.40	6.25
Water & Beverages	35.69	63.96	35.73	37.71	54.69
EFFECTIVE ANNUAL DOSE μSv/a	**40.88**	**71.81**	**42.65**	**44.73**	**63.01**

19 Water Management Plan Volume 8 (1997), Free State Goldfields and Lower Vet River catchment, Department of Water Affairs and Forestry 2-3
20 Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited
21 Vaal River system

The major potential exposure pathways in this regard is the drinking water scenario, and to a much lesser extent the consumption of meat (Table 5-4). From the last table the following ratios are determined:

Table 5-4: Relative contribution (%) of different pathways to the total potential dose (100%) from water sources.

	Adult %	15 year %	10 year %	5 year %	1 year %
FOODSTUFF					
Meat	7.61	6.17	7.88	6.30	2.68
Poultry	0.86	0.58	0.84	0.58	0.25
Eggs	0.29	0.19	0.30	0.22	0.08
Fish Products	1.61	0.71	1.45	1.01	0.27
Grain Products	0.00	0.00	0.00	0.00	0.00
Roots & Fruits	0.00	0.00	0.00	0.00	0.00
Leafy Vegetables	0.00	0.00	0.00	0.00	0.00
LIQUIDS					
Milk Products	2.35	3.26	5.74	7.60	9.92
Water & Beverages	87.30	89.07	83.77	84.31	86.80
EFFECTIVE DOSE (%)	**100**	**100**	**100**	**100**	**100**

From the last table it is clear that the tolerable activity concentrations in water can be much higher if water is not used for drinking purposes, which contributes for more than 80% of the potential water dose. This is significant in terms of the typical agricultural activities around the mines.

Process water dams are not considered as a direct source term as the quality of the water is generally so bad in terms of acidity and taste, that it is not regarded as a potable source[22].

The long term water quality and management is one of the aspects that must still be addressed by most of the mines and will form part of an overall monitoring and modelling programme that falls outside the scope of this assessment.

[22] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited

Previous studies[23] on the movement of Uranium and its decay series in soils and water systems around the mining areas show that no significant enhancement of radium concentrations could be detected in and around the Witwatersrand mining area. In spite of the vast quantities of total radium contained in the tailings dams[24], its relatively low concentration together with the verification of its extremely low mobility[25] indicate that its spread in the environment, at least in the short to medium term, is unlikely to reach concerning proportions.

In addition, the Department of Water Affairs and Forestry (DWAF) performed extensive water analysis during 1996 (Kempster)[26]. The radioactivity concentrations in the Sand River were well below the target water quality values set by DWAF. The only area of concern was indicated as being the Mahem Spruit that has subsequently being monitored extensively for all pollutants. This area is also one of the focus areas of the Anglogold Hydrological Contamination Master Plan (HCMP) for the whole lease area.

The water analyses results for the Welkom, Harmony, Virginia and Odendaalsrus areas summarised in the following tables:

[23] De Jesus et al (1987) An assessment of the radium-226 concentration levels in tailings dams and environmental waters in the gold / uranium mining areas of the Witwatersrand, Atomic Energy Corporation of South Africa, 11-14
[24] Slimes dam survey results (1996), Nuclear Licence NL-57, Appendix III
[25] Rahn P H (1978) Seepage from uranium tailing ponds and its impact on ground water m Albuquerque, New Mexico
[26] Kempster P L et al (1996) Overview of radioactivity in water sources: Uranium, Radium and Thorium. Appendix 1 Table 6.

Table 5-5: ^{226}Ra Water Analysis Results (Bq m^{-3}) around Harmony and Virginia (1995)[27]

POSITION NUMBER	SAMPLING POSITION	APR	MAY	JUN	JUL	AUG	SEPT
1	Linabo bridge	< 30	< 30	< 30	< 30	< 30	< 30
31	River above Mosterd canal	87	NR	69	38	<30	<30
33	River at new bridge	<30	<30	<30	75	<30	<30
POSITION NUMBER	**BOREHOLE NUMBER**	**JAN**	**JUN**	**JUL**	**AUG**	**OCT**	**NOV**
1	HB1	<25	<25	<25	<25	<25	<25
2	HB4	31	<25	<25	<25	<27	<25
3	HW2	<25	<25	<25	<25	<25	<25
4	HW88	<25	75	<25	<25	<25	<25
5	V1	<25	<25	<25	<25	<25	<25
6	VNS2	<25	<25	<25	<25	<25	<25
7	18 ASH	<25	<25	<25	<25	<25	<25
8	BB215	<25	<25	<25	<25	<25	<25
9	SW1	<25	53	<25	<25	<25	<25
10	14 IMB	<25	70	<25	<25	<25	<25
11	6 LIM	<25	<25	27	<25	<25	<25
12	BB221	N/S	<25	<25	<25	<25	<25
13	MS4	N/S	<25	<25	<25	40	<25
14	MS13	N/S	<25	<25	<25	<25	<25

*N/S – not sampled

[27] Harmony Gold Mine Water Analysis Results

Table 5-6: Water analyses results in and around the Welkom area[28]

No	Location	Date	226Ra (Bq m^{-3})
49	Doringpan	24/07/96	62
50	Doringpan	18/03/97	<25
51	Doringpan	08/10/96	40
52	Doringpan	08/10/96	58
53	Doringpan	23/02/96	39
54	Doringpan	08/10/96	<30
55	Doringpan	12/12/97	78
56	Doringpan	08/10/96	58
57	Doringpan	08/10/96	62
58	Doringpan	17/09/97	66
111	Hester's Pan - Municipality side	17/09/97	25
112	Hester's Pan - Municipality side	09/01/97	115
113	Hester's Pan - Municipality side	12/12/97	82
114	Hester's Pan - Municipality side	18/03/97	97
121	Mahem spruit	8/9/98	682
122	Mahem spruit	1/98	143
123	Mahem spruit	17/09/97	120
127	Mostert Canal	1/98	23
128	Mostert Canal	17/09/97	25
129	Mostert Canal	8/9/98	<25
130	Mostert Canal	04/10/95	<30
131	Mostert Canal	18/03/97	<25
144	V-Notch Sandriver	18/03/97	49
145	V-Notch Sandriver	21/06/96	<25
146	V-Notch Sandriver	08/10/96	<30
147	V-Notch Sandriver	1/98	152
148	V-Notch Sandriver	09/01/97	<25
149	V-Notch Sandriver	24/07/96	<25
150	Welkom to Bultfontein road "Mahem spruit culvert"	24/07/96	<25
157	Witpan	09/01/97	<25
158	Witpan	18/03/97	<25
159	Witpan	8/9/98	<25
160	Witpan	1/98	52

[28] Nuclear Licence NL-57 Effluent Reports

Table 5-7: Water analyses results in and around the Odendaalsrus and Allanridge areas[29] (July and October 1997, respectively)

Location	Uranium (μg/L)	^{226}Ra (Bq m^{-3})	Uranium (μg/L)	^{226}Ra (Bq m^{-3})
Borehole DC-316 Swartpan	10	<25	15	<25
Farm Graspan – Taljaard	6	<25	10	<25
Farm Graspan – Haasbroek	23	<25	<3.25	<25
Farm Klein Bloemfontein	10	<25	10	<25
Farm Rosedale - Du Randt	<3.25	<25	11	<25
Farm Spes Bona - Naude	17	<25	4	292
Borehole DC-316 Swartpan	119	<25	<3.25	<25
Farm Graspan - Taljaard	6	<25	22	<25
Farm Graspan - Haasbroek	23	<25	<3.25	<25
Farm Klein Bloemfontein	<3.25	<25	15	<25
Farm Rosedale - Du Randt	24	<25	17	<25
Farm Spes Bona - Naude	20	<25	<3.25	<25

The only major potential contribution to the public dose is that of drinking water from the limited intake from the Sand River. From table 5-5 it seems that no significant increase in the radioactivity concentrations occurs between the upstream and downstream sampling locations. The potential doses calculated for the Free State area in the industry study[30] is also in the order of 20-70 μSv/a.

As stated earlier in the report, the lack of appropriate background radioactivity concentrations in natural water sources makes it very difficult to determine incremental contributions from the mines. This is one of the important aspects that will have to be addressed in future monitoring and modelling programmes.

[29] Loraine Gold Mines: Report LGMLREP001 Rev0
[30] Jansen van Vuuren et al (1995), Assessment of the Radiological Impact to the public from surface works on mines: Exposures from aquatic sources, Final Report GU9301, CSIR.

5.3 DUST MODELLING

Inhalation

From a previous industry study[31] conducted on a few typical gold mines in South Africa, one of which is in the Free State Goldfields, the contribution to the potential public dose by inhalation of radioactive dust from the slimes dams and waste rock dumps is very small. This, and the fact that the current thinking is to grass all tailings dams in the future[32], thus drastically reducing the potential for windblown dust, makes any elaborate study of this exposure pathway unjustifiable. It was decided to use the extensive dust measurements results obtained over a few years at Ergo located near Brakpan.

The industry study quotes a potential dose from dust sources as being not higher than 50 μSv/a.

Radiation hazard assessments conducted on tailings dam workers[33] wearing personal air samplers indicated potential dust exposures less than the detection limits of the instrumentation[34]. In addition, an interesting observation is that the respirable fraction of the dust was very small compared to the total volume of dust collected. The dust from tailings dams could thus pose more of a nuisance value than a radiation exposure risk.

The methods to determine the dust source terms are fraught with difficulties. The principle of the method is sound but the actual measurement component degrades the result considerably[35] Equipment is also frequently stolen from the veld.

[31] Jansen van Vuuren et al (1995), Assessment of the Radiological Impact to the public from surface works on mines: Exposures from aquatic sources, Final Report GU9301, CSIR. Chapter 2.2

[32] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited

[33] Slimes dam survey results (1996), Nuclear Licence NL-57

[34] ML Instrumentation, ML-114B spectrometer, LLD = 0.0052 $Bq.m^{-3}$

[35] GU9301;Assessment of radiological impact from to the public from surface works on mines; Radon and dust exposure pathways, Strydom et al.

For this reason and the high cost of measuring the airborne dust concentrations, it was decided to use the extensive dust measurements results obtained over a few years at Ergo located near Brakpan[36].

To calculate the contribution of the dust to the public dose, the results of the dust model of Anglogold's ERGO operations by Environmental management Services CC (Dr. Lucien Burger) in *Report No. ERGO/95/a* was used. The USA Environmental Agency's Industrial Source Complex ISCST2 and Fugitive Dust FDM models were used. The highest dust concentration calculated at the 16 km square Withok dam is 400 $\mu g\ m^{-3}$. The average concentration of uranium in slimes dam dust at the Free State mines is 2.35 Bq/g for Uranium and about 1 Bq/g for Radium. If the assumption is made that the material contains only Uranium in secular equilibrium with its progeny and that the concentration is 2.35 Bq/g, the dose due to a dust concentration of $0{,}4 mg/m^3$ may be calculated. According to the IAEA Basic Safety Standards. the annual limit of intake of uranium ore dust is 3000Bq/a for workers working 2000hrs per year. For a member of the public the time is 8760hrs. The dust concentration of $0{,}4\ mg\ m^{-3}$ will give a dose of about $70\mu Sv/a$ to a member of the public.

In a study of inhalation dust at the Stilfontein Mine[37] the highest average, worst case dose due to airborne radioactive dust is 161 $\mu Sv/a$. The industry study GU 9301[54] done for Hartebeesfontein with the dust actually measured, indicated a dose due to inhalation of 47 $\mu Sv/a$.

Similar to the Free State, dust sampling was performed on slimes dam workers in the Klerksdorp area as part of the hazard assessment for slimes dam workers[38].

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[36] Report AER97.039 Q erg, Annergan Environmental Research (PTY) LTD
[37] Assessment of public radiological exposure via the air pathway from sources and releases at Stilfontein Gold Mining Co, R Strydom, September 1998
[38] MNMVR/REP008 Vaal Reefs Slimes Dams Hazard Assessment Report

These measurements over a period of two months showed no radiation dose to workers due to the inhalation of dust. Similar results were also obtained for all the mines in area. This indicates that the dust concentration derived from the theoretical model done for Ergo is extremely conservative. Further, comparing the theoretical values of the dust deposited to the actual dust deposited shows that the models used over predicts the dust fall out 17 times. It may therefor be concluded that the dose due to inhaled dust is exaggerated.

Ingestion

If it is difficult to measure the inhalation of radioactive dust then it is even more difficult to measure the amount of dust ingested by the public. This study did not attempt to quantify the ingestion of dust .

The study done by Bain et al[39] analysed vegetables grown on the Marievale Farm in the Brakpan area, and the Vlakfontein and Luipaardsvlei Farms in the Randfontein Area. The study attempted to quantify the effect of radioactively contaminated water on the uptake of radioactivity in the plants. As the plants were harvested from the farms the effect of radioactive dust on the plants cannot be excluded and the doses calculated by the authors in the study must therefor be seen to be due to the water used for irrigation and dust settling on the plants. Furthermore the plants are grown in soil which is covered by mine dust which is ploughed into the soil every time the soil is tilled.

Table 5-8: Annual Effective Dose and committed Effective dose from various ingestion pathways (Bain et al) in μSv.

Nuclide	Drinking water		Vegetables				*Oats		Fish		Soil Ingested		Soil External	
			Leafy		Root									
	D	D_{50}	D	D_{50}	D	D_{50}	D	D_{50}	D	D_{50}	D	D_{50}	D	D_{50}
^{238}U	1,7	2.3	0,04	0,06	0,12	0,17	2,3	3,1	-	0,02	-	-	0,001	-
^{226}Ra	0,88	7,8	0,22	1,9	0,65	6,0	20	180	1,8	16	1,3	10	0,002	-

*The oats was cultivated on a slimes dam and is therefor not applicable to the argument.

The results show that the highest dose due to the ingestion of vegetables is 2μSv.

[39] Bain et al, Investigations into the concentration ratios of selected Radionuclides in aquatic ecosystems affected by mine drainage effluents with reference to the Study of Potential Pathways to Man, WRC Report No. 313/1/94

CHAPTER 6

ENVIRONMENTAL MEASUREMENTS AND ANALYSES

6 ENVIRONMENTAL MEASUREMENTS

6.1 ENVIRONMENTAL RADON MEASUREMENTS

Environmental radon gas measurements were taken in and around the Free State Goldfields area to identify excessively high radon concentrations (> 200 Bq m^{-3})[1] and to establish some correlation with the predicted results of the modelling exercise. The following techniques were used to measure radon concentration in the outdoor air, as well as limited measurements indoors:

- Alpha track etch devices, in this case RGM's[2], were exposed for a period of approximately 2 to 3 months during 1996 as part of an assessment of radiation doses to tailings dam workers[3]. The workers on the tailings dams wore some of the RGM's and a few were placed in buildings on the site. These results are listed in Table 6-1.
- Radon gas concentrations were also measured around the Welkom area over 24-hour periods using an Alphaguard Radon Gas Monitor[4] that measures the radon gas concentration continuously and records the values at ten-minute intervals. These results are listed in Table 6-2.
- A number of E-PERM Electret gas monitors were placed outdoors in the areas surrounding the mines, as well as a few non-mining areas. These are listed in Table 6-3 and 6-4.

The measurements taken in the areas well outside the gold mining area serves as criteria for "background" radon concentrations.

The results of these environmental radon gas measurements are summarised in the following tables and diagrams.

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[1] Annals of the ICRP, Publication 65 (September 1993), Protection against Radon-222 at Home and at Work, International Commission on Radiological Protection
[2] Strydom R, PARC Scientific
[3] Slimes dam survey results (1996), Nuclear Licence NL-57
[4] AlphaGUARD Professional Radon Monitor (1997), Operating Manual. Genitron Instruments, Frankfurt, Germany

Table 6-1: RGM results of tailings dam workers and on-site dwellings

Measurement Location	Exposure Period	RGM No.	Radon concentration (Bq m^{-3})
(Tailings dam)			
Worker 1	23/9/96 -02/12/96	1959	47
Worker 2	23/9/96 -02/12/96	1963	45
Worker 3	23/9/96 -02/12/96	1965	49
Worker 4	23/9/96 -02/12/96	1964	43
Worker 5	23/9/96 -28/11/96	1950	40
Worker 6	23/9/96 -20/11/96	1958	68
Worker 7	23/9/96 -28/11/96	1975	49
Worker 8	23/9/96 -28/11/96	1976	60
Worker 9	23/9/96 -20/11/96	1957	57
Worker 10	23/9/96 -25/11/96	1949	35
Worker 11	23/9/96 -28/11/96	1973	57
Worker 12	23/9/96 -28/11/96	1974	49
Worker 13	23/9/96 -02/12/96	1962	40
Worker 14	23/9/96 -20/11/96	1954	46
Worker 15	23/9/96 -23/11/96	1977	35
Worker 16	23/9/96 -23/11/96	1978	53
Worker 17	23/9/96 -23/11/96	1980	37
Worker 18	23/9/96 -20/11/96	1956	57
Worker 19	23/9/96 -02/12/96	1967	36
Worker 20	23/9/96 -02/12/96	1968	87
Worker 21	23/9/96 -20/11/96	1952	50
Worker 22	23/9/96 -20/11/96	1953	58
Worker 23	23/9/96 -20/11/96	1955	60
	Average		**50**
	Standard Dev.		**12.1**

Measurement Location	Exposure Period	RGM No.	Radon concentration (Bq m^{-3})
(Indoors on site)			
Building 1	23/9/96 -20/11/96	1983	52
Building 2	25/9/96 -20/11/96	1969	39
Building 3	25/9/96 -25/11/96	1970	53
Building 4	25/9/96 -20/11/96	1971	35
Building 5	25/9/96 -20/11/96	1972	51
Building 6	23/9/96 -23/11/96	1979	40
Building 7	23/9/96 -20/11/96	1951	61
Building 8	23/9/96 -23/11/96	1981	38
Building 9	23/9/96 -23/11/96	1982	50
	Average		**46.6**
	Standard Dev.		**8.8**

Table 6-2: AlphaGUARD results on environmental measurements

Measurement Location	*Average radon concentration (Bq m^{-3})	Standard Deviation (Bq m^{-3})
Homes (indoors)		
Welkom 1	35.6	10.7
Welkom 2	33.4	6.5
Welkom 3	29.8	7.9

Measurement Location	*Average radon concentration (Bq m^{-3})	Standard Deviation (Bq m^{-3})
Environment (outdoors)		
Welkom 1	22.6	13.5
Welkom 2	20.6	6.0
Welkom 3	24.1	7.2
Roodepoort 1	24.8	7.0
Roodepoort 2	25.6	12.5
Bethlehem	28.7	9.8
	*(Exposure period of at least 24 hours)	

No excessively high radon gas concentrations were detected in the buildings on the mines or even on top of the tailings dams. This corresponds well with the predictions of the dispersion modelling.

The day night variation in the environmental radon gas concentration as a result of the temperature and inversion layer changes can be clearly seen in Figures 6-1, 6-2 and 6-3. The highest radon concentrations were measured early in the morning. This corresponds well with studies elsewhere in the world such as Gessel (1983)[5].

[5] Gessel T F (1983) Background atmospheric 222Rn concentrations outdoors and indoors: A Review, Health Physics, Vol. 45 No 2 (289-302)

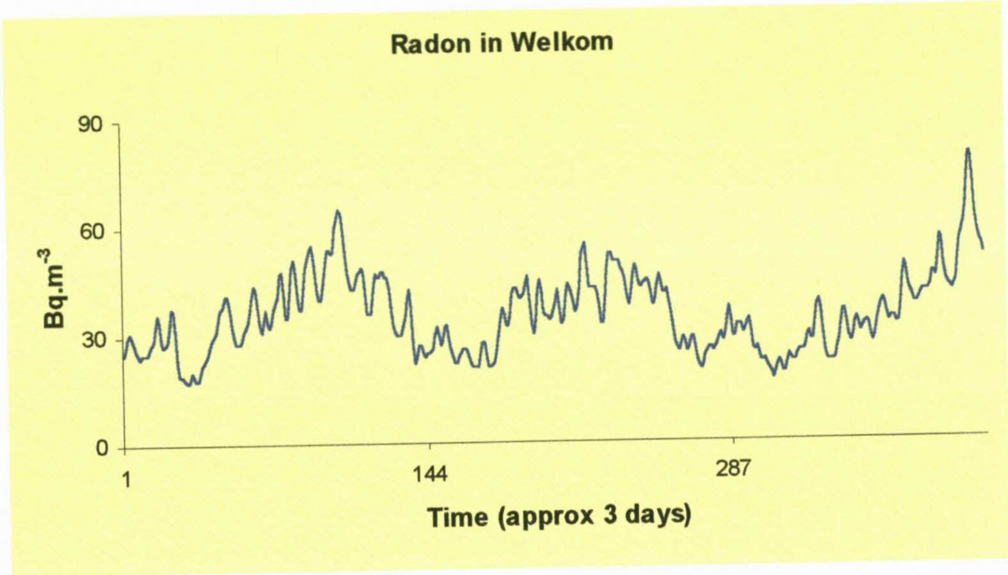

Figure 6-1: Daily variation in radon concentration in the Welkom area

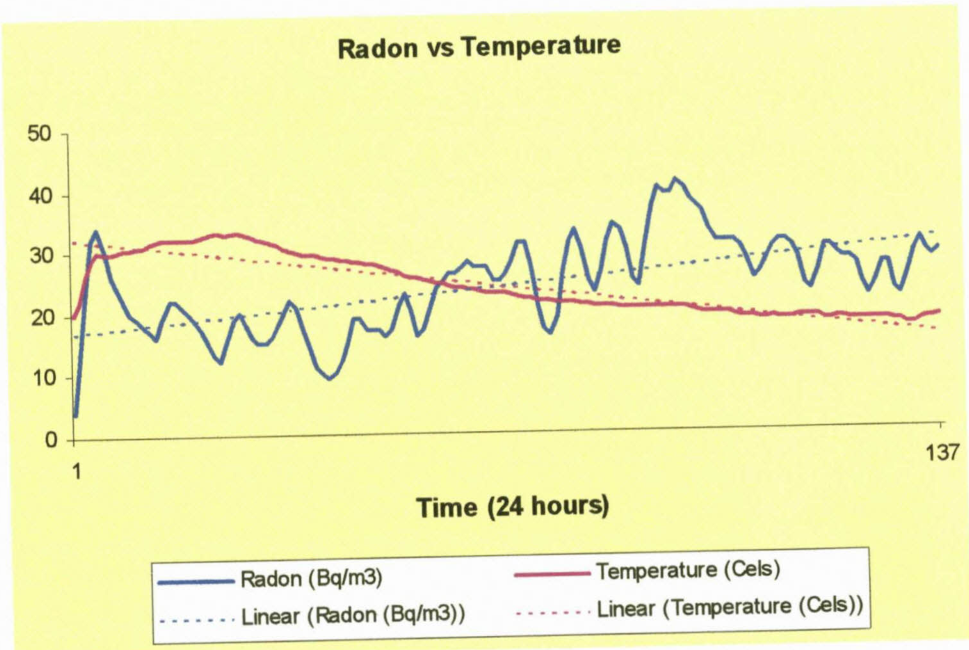

Figure 6-2: Radon concentration as a function of temperature

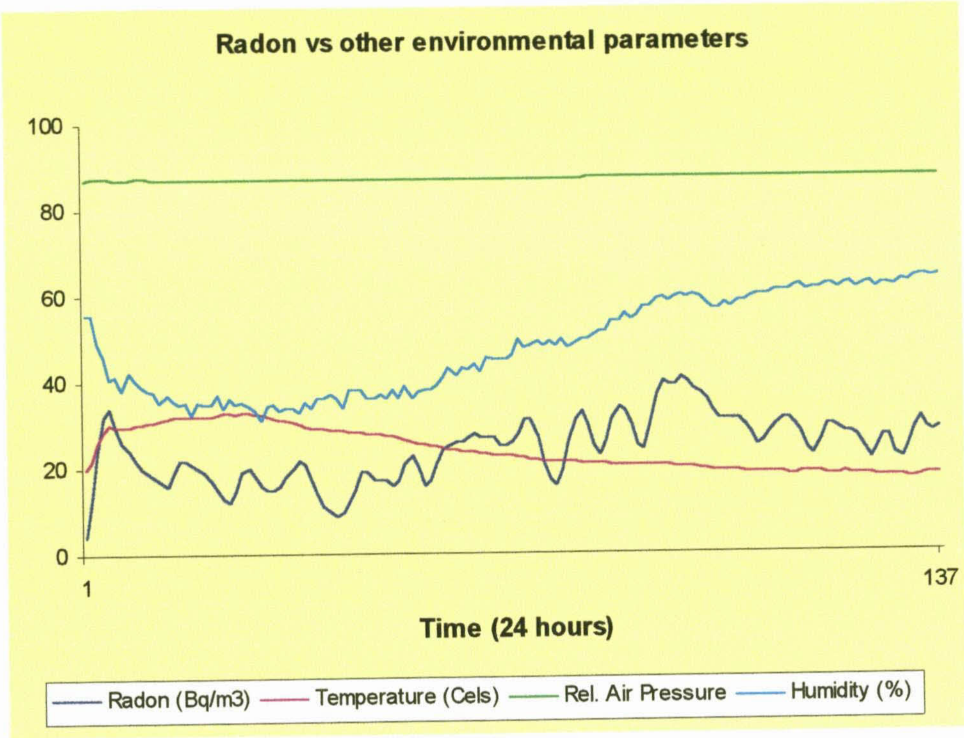

Figure 6-3: Radon gas concentrations as a function of other environmental parameters

Radon gas measurements were also taken in areas outside the Free State Goldfields to establish some kind of a reference background. This can be seen in Figure 6-4:

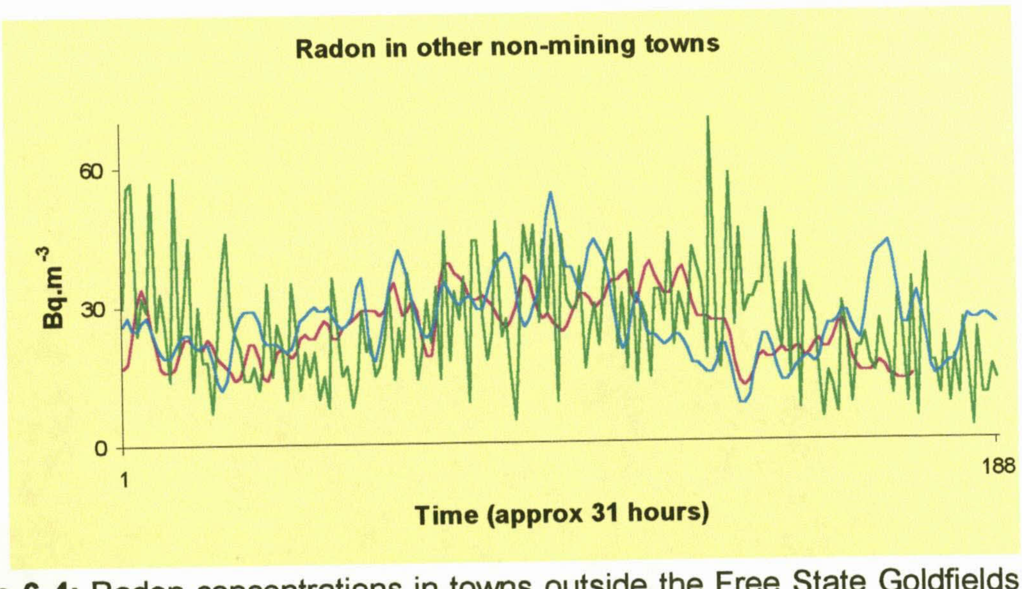

Figure 6-4: Radon concentrations in towns outside the Free State Goldfields *(See Table 6-2 for detail)*

From the outdoor and indoor radon concentrations measured in this assessment, it is clear that the radon concentrations in and around the Free State Goldfields are not significantly higher than in any other non-mining area. In addition, according to the RGM and Alphaguard surveys inside houses the average indoor radon concentration is in the order of 30 Bq m^{-3} to 45 Bq m^{-3}, compared to a South African national average of 50 Bq m^{-3} as determined by Leuschner (1991)[6].

The Alphaguard measurements estimated an average outdoor radon gas concentration for the Goldfields in the order of 20 Bq m^{-3} to 25 Bq m^{-3}, compared to a similar range of concentrations for towns outside the gold mining area.

[6] Leuschner et al (Nov 1991). National seasonally averaged radon concentrations, Atomic Energy Corporation & Department of Health AEC, Pretoria

As part of the assessment RGM's were deployed around a single tailings dam to determine the correlation between the dispersion modelling results and environmental radon concentrations. However, as is evident from Table 6-3, the potential contribution from the tailings dam fails to be statistically significant considering the natural radon background levels. The contribution from the tailings dam is in the order of 1-4 Bq m^{-3} and disappears in the natural radon background of 25-35 Bq m^{-3}.

As the daily variation in outdoor radon concentrations is already in the order of tens of Bq m^{-3} only very long term integrated radon measurements may indicate some statistically meaningful inter-comparison with the modelling exercise. It is however safe to say that the order of magnitude of the radon contributions from the mines are correct in that no significantly high radon levels were observed in the area.

Table 6-3: E-PERM Electret monitor (LST) results for the Goldfields area

Location	Exposure Time (days)	Gamma Correction ($\mu Sv\ h^{-1}$)	RnC ($Bq\ m^{-3}$)
Coghlan St	49.8	0.1	31.5
Cordelia St	49.8	0.1	54.6
Bronville	49.8	0.1	27.5
Hospital	50.1	0.1	33.9
Campbell St	50.7	0.1	40.1
Toronto St	50.7	0.1	33.0
Agulhas St	50.7	0.1	57.9
FG Club	50.1	0.1	16.0
Odendaalsrus	49.8	0.1	57.8
Holdings G/Plant	51.0	0.1	64.8
Stores	50.8	0.1	32.5
Golf Club	49.9	0.1	45.6
Virginia	50.7	0.1	64.4
	50.7	0.1	52.7
Tsepong	49.1	0.1	43.6
	49.1	0.1	24.9
Hospital Odendaalsrus	50.1	0.1	50.5
	50.1	0.1	64.1
Thabong	50.7	0.1	59.4
FEMTS	49.9	0.1	37.5
	49.9	0.1	39.4

Location	Exposure Time (days)	Gamma Correction ($\mu Sv\ h^{-1}$)	RnC ($Bq\ m^{-3}$)
Dagbreek North	49.9	0.1	64.8
	49.9	0.1	50.8
Pump Station Witpan	50.1	0.1	56.3
Pump Station D Dam.	50.1	0.1	50.8
	50.1	0.1	37.9
Bronville	49.8	0.1	66.6
	49.8	0.1	62.3
	50.1	0.1	66.2
S. G Tappin & Son	50.1	0.1	39.6
	50.1	0.1	26.0
	49.1	0.1	40.9
Hospital	50.1	0.1	56.6
	50.1	0.1	50.2
Mine Mess	50.1	0.1	23.9
	50.1	0.1	25.8
Airport	50.1	0.1	34.2
	50.1	0.1	46.7
Doring Pan Game Farm	50.1	0.1	40.5
	50.1	0.1	33.6
Poultry Farms	50.1	0.1	36.7
	50.1	0.1	44.5
		Average	**44.9**
		Standard Dev.	**13.7**

Table 6-4: E-PERM Electret monitor (LST) results for non-mining areas

Location	Exposure Time (days)	Gamma Correction ($\mu Sv\ h^{-1}$)	RnC ($Bq\ m^{-3}$)
Koppies Farms	49.8	0.1	77.2
Pretoria	47.8	0.1	58.8
	47.8	0.1	69. 2
Bultfontein	58.4	0.1	29.5
	58.4	0.1	41.1
		Average	55.2

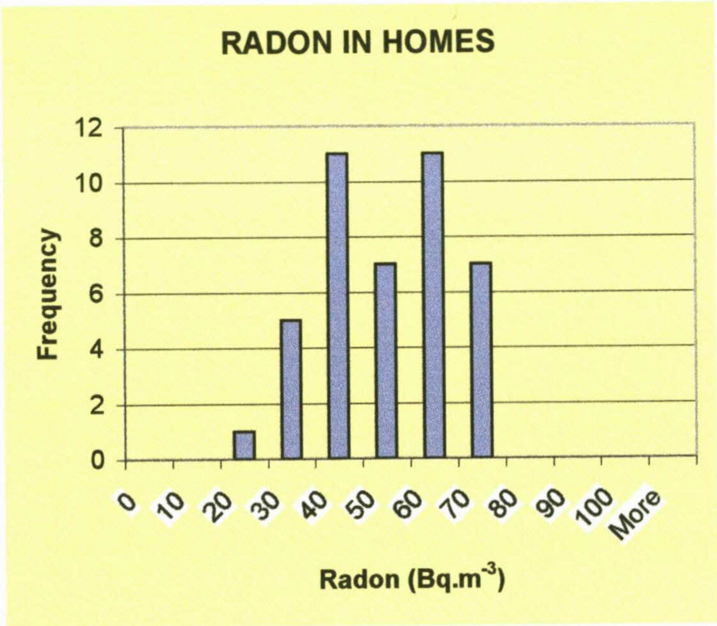

Figure 6-5: Frequency distribution of radon concentrations (Table 6-3)

The E-PERM measurements were consistently higher than the Alphaguard measurements and did not seem to be consistent where duplicate sets of monitors were deployed. This is attributed to the large influence that external radiation has on the Electret ion chambers[7]. In Table 6-3 and Table 6-4 a generic correction for the gamma background was used and this is one of the possible explanations for the inconsistency. However, the order of magnitude of the radon concentrations in the Free State Goldfields seem to be the same as that measured in towns outside the gold mining area.

[7] Cole C M (June 1998) Appropriate methods for implementing ambient background subtraction regarding radon monitoring results obtained with Electret ion chamber (EIC's) in field monitoring applications, Project Team Meeting, Council for Nuclear Safety Information Bulletin No 7

6.2 WATER ANALYSES

The process water dams on site are not considered as sources of drinking water due to the taste and quality (pH & salt concentration) of the water and the fact that drinking water is supplied from a source outside the mining area. The process water dams could however have a long-term impact on ground water systems and will be considered as part of the overall water management programme of the mines.

Groundwater management and monitoring systems are being established[8] and radioactivity will be one of the potential pollutants considered in the overall water management programmes of the mines in the Free State. This is a long-term project and adequate data must first be collected from the bore hole monitoring before any final judgement can be made on the longer term impacts of radioactivity from the mines on the underground water systems.

From the previous studies (de Jesus et al)[9] and monitoring results in other areas (Vaal River Operations)[10] it would seem that no significant quantities of the ^{238}U series finds their way to the groundwater systems.

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[8] Environmental Management Programme Report (1997) Version 4, Free State Consolidated Gold Mines (Operations) Limited

[9] De Jesus A S M et al (1987), An assessment of the Radium-226 concentration levels in tailings dams and environmental waters in the gold and uranium mining areas of the Witwatersrand, Atomic Energy Corporation

[10] Anglogold Vaal River Operations groundwater analysis results

In addition to water analysis, fresh fish caught in one of the pans in the area were analysed for radioactivity. The specific pan received large volumes of water discharged from one of the shafts in the area and was considered to be a potential worst case in terms of potential contamination. The public uses the pan for recreational purposes and fishing in the area is fairly common.

Table 6-5: Radio-analysis[11] of fish samples from pan

Sample	^{238}U (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{226}Ra (Bq kg^{-1})
Carp			
Edible parts	2.37	<0.012	3.33
Intestines	7.4	0.206	2.95
Bones	5.85	0.032	4.39
Barbel			
Edible parts	0.64	<0.009	<0.6
Intestines	16.1	0.119	4.67
Bones	12.8	<0.049	3.50

Assuming equilibrium with the other nuclides in the ^{238}U series, an annual consumption of 25 kg of fish[12] equates to an effective radiation dose of 200 μSv/a for an adult living solely of the barbel in the pan. This is a very conservative calculation as equilibrium is assumed between ^{238}U and ^{226}Ra and their decay products, as well as the fact that no background correction was made for natural radioactivity levels in fish. More detailed analysis is required to determine the equilibrium ratios of all the nuclides as well as analysis of fish originating from areas outside the Goldfields for background corrections.

A possible concern in terms of surface water sources is that of informal settlements around the process water dams which contain fairly high concentrations of uranium and radium, up to a few hundred Bq m^{-3}. If for

[11] Atomic Energy Corporation of South Africa, Report No RA 1171-1

example a human should consume its full quota of water and related foodstuff from a process dam with ^{238}U and ^{226}Ra concentrations of 2000 Bq m^{-3} and 700 Bq m^{-3} respectively, the potential radiation exposure would be in the order of 3 t0 4 mSv/a.

There will have to be close co-operation between local authorities and the mines to prevent access to and use of these potentially contaminated water sources for drinking water. Education of the public on the potential health hazards associated with mining activities in general is of utmost importance.

[12] IAEA, International basic safety standards for protection against ionising radiation and the safety of radiation sources, Vienna, IAEA Safety Series No 115

6-3 EXTERNAL RADIATION

SABS TLD badges[13] were issued to workers on the tailings dams for a period of two months. None of the workers registered a gamma dose that corresponds to a dose equivalent of more than 0.15 mSv for the wearing period. In addition, when the closest distance of any member of the public from a tailings dam or waste rock dump is considered, this exposure pathway becomes insignificant in terms of the inverse square relationship between gamma dose rate and distance. Locations of the TLD's are listed in Table 6-6.

Table 6-6: TLD's issued to tailings dam workers and stationary locations all yielded zero results (i.e. less than 0.15 mSv)

Location	Exposure Period	TLD No.	Dose (mSv)
North Dams (Roving)	23/9/96 -25/11/96	12191	< 0.15
Welkom. (Roving)	23/9/96 -02/12/96	32392	< 0.15
Welkom. (Roving)	23/9/96 -02/12/96	65937	< 0.15
Welkom. (Roving)	23/9/96 -02/12/96	30465	< 0.15
St. Helena. (Roving)	23/9/96 -02/12/96	6617	< 0.15
South Dams (Roving)	23/9/96 -28/11/96	56354	< 0.15
PS. 1,2 &4. (Roving)	23/9/96 -20/11/96	30529	< 0.15
PS 5 Vegetation. (Roving)	23/9/96 -28/11/96	20005	< 0.15
PS 5 Vegetation. (Roving)	23/9/96 -28/11/96	73939	< 0.15
PB. A+D, PBW. (Roving)	23/9/96 -20/11/96	29722	< 0.15
Ind. Landscaping (Roving)	23/9/96 -28/11/96	21993	< 0.15
Ind. Landscaping (Roving)	23/9/96 -28/11/96	4753	< 0.15
Holdings Roving)	23/9/96 -02/12/96	50657	< 0.15
FSS 6 (Roving)	23/9/96 -20/11/96	36427	< 0.15
FSS 4 (Roving)	23/9/96 -23/11/96	56018	< 0.15
FSS 4 (Roving)	23/9/96 -23/11/96	32563	< 0.15
FSS 4 (Roving)	23/9/96 -23/11/96	61028	< 0.15
FSS 1,3,5b,6. (Roving)	23/9/96 -20/11/96	61505	< 0.15
FSG. Gold. (Roving)	23/9/96 -02/12/96	40297	< 0.15
FSG. Float. (Roving)	23/9/96 -02/12/96	31734	< 0.15
ECMP South Dams (Roving)	23/9/96 -20/11/96	6929	< 0.15
ECMP South Dams (Roving)	23/9/96 -20/11/96	46249	< 0.15
ECMP South Dams (Roving)	23/9/96 -20/11/96	14454	< 0.15
Watermeyer St. Welkom.(Stat)	23/9/96 -20/11/96	64488	< 0.15
PS. 4# Sample Prep. (Stat.)	25/9/96 –20/11/96	8375	< 0.15
PS. 4# Sample Prep. (Stat.)	25/9/96 –25/11/96	51067	< 0.15
PS. 4# Sample Prep. (Stat.)	25/9/96 –20/11/96	52123	< 0.15

[13] South African Bureau of Standards.

Location	Exposure Period	TLD No.	Dose (mSv)
PS. 4# Sample Prep. (Stat.)	25/9/96 -20/11/96	62843	< 0.15
FSS 4 (Stat)	23/9/96 -23/11/96	54811	< 0.15
ECMP Offices (Stat. BG.)	23/9/96 -20/11/96	66959	< 0.15
Coghlan St. Welkom.(Stat.)	23/9/96 -23/11/96	14113	< 0.15
Anglo St. Bronville. (Stat.)	23/9/96 -23/11/96	17350	< 0.15

Similarly to public access control to potentially contaminated water sources, some form of institutional controls will have to be set up to prevent the building of houses or informal settlements on tailings dams. Although the gamma dose rate diminishes with distance from the tailings dams, living directly on top of a tailings dam could cause significant gamma radiation exposures when measured against public dose limits.

CHAPTER 7

CONCLUSIONS

7 CONCLUSIONS

It is clear from the **radon flux** measurements that the result of a flux measurement depends on the type of measurement conducted. All the techniques employed during the assessment proved to be sensitive in terms of disturbing the medium from which the radon flux is measured or the influence it has on the radon flux from the medium itself. However, the range of radon fluxes between 0.05 Bq m^{-2} s^{-1} and 0.2 Bq m^{-2} s^{-1} gives a good indication of the true radon flux from the tailings dams.

The value of 1 Bq m^{-2} s^{-1} used in the modelling exercise may well prove to be conservative once more work is done in this regard.

The **environmental radon levels** measured indoors and outdoors seem to confirm that the natural radon levels in the Free State Goldfields do not differ much from other non-mining areas. No excessively high indoor radon concentrations (>200Bq m^{-3}) could be detected and no intervention is required at this stage.

Radon from the tailings dams, waste rock dumps and upcast shafts is considered to be main contributor to the potential radiation exposures to the public. The maximum potential radon contribution from all these sources was in the order of 6 Bq m^{-3}, or an equivalent dose of 106 μSv/a. This was calculated for a conservative radon flux of 1 Bq m^{-2} s^{-1}.

Dust from tailings dams is not considered to be a long term radiation exposure problem as most of the mines' Environmental Management Programmes (EMPR's) indicate that the tailings dams will all be rehabilitated and grassed within the next 30 odd years. From limited studies conducted around gold mines in South Africa, dust seems to have more of a nuisance value than a radiation exposure risk.

External gamma radiation from the tailings dams and waste rock dumps has a negligible contribution to the public dose, especially when compared to natural background levels and also considering the distance of potentially exposed members of the public from the waste rock dumps and tailings dams. Some institutional controls will however have to be established to prevent uncontrolled housing settlement on top of tailings dams.

Potential radiation exposure due to consumption and use of contaminated **surface process water** sources on the mines might have an impact on the public if access to process water dams are not properly controlled. If for example a human should consume its full quota of water and related foodstuff from some of the worst contaminated process dams, the potential radiation exposure would be in the order of a few mSv/a.

Drinking water, which constitutes about 80% of the potential exposure to water sources, is provided mainly from sources outside the Free State Goldfields and is not considered as an immediate problem area. The water quality and taste of the process water dams are generally very poor and even inadvertent use of these sources for drinking water is highly unlikely.

One potential radiological impact from surface water sources as well as tailings dams and waste rock dumps is possible seepage and contamination into **groundwater** systems. Much more detailed monitoring and modelling exercises are required determine the long-term impact on the groundwater systems. From the impermeable geology of the area and the slow migration properties of ^{238}U and its decay products in groundwater systems, it is not expected that groundwater systems will be adversely affected by radioactivity from the mines. However, radioactivity must be addressed as another pollutant in the current water management programmes being established by the mines.

Groundwater monitoring programmes are extremely costly and usually take several years to provide adequate data for modelling of water movement and possible contamination plumes. Predictions on long-term groundwater impacts can only be made once these detailed results are available.

One of the difficulties during the assessment was the lack of information on natural background radiation levels, especially in terms of water, dust (soil) and associated products. It is relatively easy to determine the characteristics of radiation sources for modelling exercises, but the model results must be verified with environmental measurements. In other words it is essential to determine the incremental contributions from the mining activities to background radiation levels. More data is thus required on what is considered as background radiation levels.

The total potential radiation dose to the public from the mining activities is estimated as being in the order of 130 μSv/a to 250 μSv/a:

Table 7-1: Potential radiation exposures to members of the public

Source	Potential dose range (μSv/a)
Radon gas	30 – 110
Water sources and associated produce	50 – 70
Dust (Inhalation & Ingestion)	50 – 70
External radiation (off tailings dams)	N/A
Total	**130 – 250**

When compared to other day to day hazards the potential radiation dose from the mines seems fairly insignificant. Table 7-2 summarises some common causes of death in the UK[1] as an example.

Table 7-2: Average annual risk of death from some common causes

Cause	Risk of death per year		
Smoking 10 cigarettes a day	1	in	200
Natural causes (40 years old)	1	in	700
Road accidents	1	in	10 000
Accidents at home	1	in	10 000
Accidents at work	1	in	50 000
Nuclear effluent exposure (300μSv)	1	in	70 000

*United Kingdom Data

The gold mines in the Free State have been operational for the last fifty to hundred years. Only in the early 1990's did the Council for Nuclear Safety intervene in terms of radiological protection of the workers in mainly the acid and uranium plants and the underground areas where potential exposures of up to 20 mSv/a were experienced. The mines were issued with Nuclear Licences in terms of the Nuclear Energy Act[2], which stipulated a public dose limit of 250 μSv/a to members of the public.

The situation in the early 1990's could have been regarded as one of intervention by the Council for Nuclear Safety, i.e. most of the tailings dams, waste rock dumps and upcast shafts were in operation or already redundant by the time the first licences were issued. This makes the interpretation and justification of the public dose limit in the nuclear licences very difficult. ICRP 60 (1990)[3] regards the dose limit of 1 mSv/a only applicable to practices and not to intervention situations where the sources, pathways and exposed individuals are already in place when the decisions about control measures are considered.

[1] National Radiological Protection Board (1989) Living with radiation, Fourth Edition p 24
[2] Nuclear Energy Act, 1993 (Act No 131 of 1993)
[3] Annals of the ICRP, Publication 60 Recommendations of the International Commission on Radiological Protection, International Commission on Radiological Protection

In most cases intervention cannot be applied at source. Intervention must always do more good than harm.

This assessment considered most of the mines in the Free State Goldfields and the potential radiation exposures estimated in the assessment can be considered as the combined impact of nearly all of these facilities. It would seem that the more appropriate dose limit to be considered, is the 1000 μSv/a quoted in ICRP 60 (1990). Measured against this limit the mines seem to be within, or at least in the order of what could be considered as an international public dose limit.

Although not fully quantified in this assessment, the radiological benefits of possible intervention measures such as relocation or capping of tailings dams or waste rock dumps seems unlikely to exceed the detrimental effects it would have on the existing operations that provides financial security and infrastructure to a whole city of people.

Add to this the scepticism and uncertainly of the assumed biological detriment of low level radiation and one could state that the potential exposures to the public from the mines in the Free State Goldfields are well within the principles of ALARA, i.e. doses are As Low as Reasonably Achievable, considering all social and economic factors.

APPENDIX 1

ISC3 MODELLING FILES (.LST)

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1            ISCST3 - (DATED 96113)

        IBM-PC VERSION (3.06)  ISCST3R
   (C) COPYRIGHT 1992-1997, TRINITY CONSULTANTS, INC.

Run Began on 12/10/1998 at 12:53:05

** BREEZE AIR ISCST3 - C:\BREEZE\FSO\FSO.INP
** Trinity Consultants Incorporated, Dallas, TX

CO STARTING
CO TITLEONE  ANGLOGOLD - FREE STATE OPERATIONS
CO TITLETWO  ENVIRONMENTAL RADON MODELLING
CO MODELOPT  CONC  RURAL
CO AVERTIME  ANNUAL
CO POLLUTID  RADON
CO HALFLIFE  330394
CO TERRHGTS  FLAT
CO FLAGPOLE  1.5
CO RUNORNOT  RUN
CO FINISHED

SO STARTING
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SO LOCATION  FSOS2B  AREA  3000.0  19060.0  0
SO LOCATION  FSOS2C  AREA  4330.0  20330.0  0
SO LOCATION  FSOS2D  AREA  4330.0  19060.0  0
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SO SRCGROUP NL57 FSOWI FSOWJ FSOWK FSOWL FSOWM FSOWN FSOWO FSOWR FSOWS
SO FINISHED

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RE GRIDCART CART1 XYINC -5000 26 1500 -9000 33 1500
RE GRIDCART CART1 END
RE FINISHED

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ME SURFDATA 12345 1997
ME UAIRDATA 12345 1997
ME STARTEND 97 01 01 1 97 12 31 24
ME WDROTATE 180.0
ME WINDCATS 1.54 3.09 5.14 8.23 10.80
ME FINISHED

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OU PLOTFILE ANNUAL LOR C:\BREEZE\FSO\LOR.DAT
OU PLOTFILE ANNUAL KAD C:\BREEZE\FSO\KAD.DAT
OU PLOTFILE ANNUAL FREE C:\BREEZE\FSO\FREE.DAT
OU PLOTFILE ANNUAL NL57 C:\BREEZE\FSO\NL57.DAT
OU FINISHED

*** Message Summary For ISC3 Model Setup ***
```

--------- Summary of Total Messages --------

A Total of 0 Fatal Error Message(s)
A Total of 0 Warning Message(s)
A Total of 0 Informational Message(s)

******** FATAL ERROR MESSAGES ********
*** NONE ***

******** WARNING MESSAGES ********
*** NONE ***

****
*** SETUP Finishes Successfully ***
****

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** MODEL SETUP OPTIONS SUMMARY ***

- -

**Intermediate Terrain Processing is Selected

**Model Is Setup For Calculation of Average CONCentration Values.

-- SCAVENGING/DEPOSITION LOGIC --
**Model Uses NO DRY DEPLETION. DDPLETE = F
**Model Uses NO WET DEPLETION. WDPLETE = F
**NO WET SCAVENGING Data Provided.
**Model Does NOT Use GRIDDED TERRAIN Data for Depletion Calculations

**Model Uses RURAL Dispersion.

**Model Uses User-Specified Options:
1. Final Plume Rise.
2. Stack-tip Downwash.
3. Buoyancy-induced Dispersion.
4. Calms Processing Routine.
5. Not Use Missing Data Processing Routine.
6. Default Wind Profile Exponents.
7. Default Vertical Potential Temperature Gradients.

**Model Assumes Receptors on FLAT Terrain.

**Model Accepts FLAGPOLE Receptor Heights.

**Model Calculates ANNUAL Averages Only

**This Run Includes: 104 Source(s); 7 Source Group(s); and 858 Receptor(s)

**The Model Assumes A Pollutant Type of: RADON

**Model Set To Continue RUNning After the Setup Testing.

**Output Options Selected:
Model Outputs Tables of ANNUAL Averages by Receptor
Model Outputs External File(s) of High Values for Plotting (PLOTFILE Keyword)

**NOTE: The Following Flags May Appear Following CONC Values: c for Calm Hours
m for Missing Hours
b for Both Calm and Missing Hours

**Misc. Inputs: Anem. Hgt. (m) = 10.00 ; Decay Coef. = .2097E-05 ; Rot. Angle = 180.0
Emission Units = BQ/M2/SEC ; Emission Rate Unit Factor = 1.0000
Output Units = BQ/M3

**Input Runstream File: C:\BREEZE\FSO\FSO.INP ; **Output Print File: C:\BREEZE\FSO\FSO.LST

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** POINT SOURCE DATA ***

SOURCE ID	NUMBER PART. CATS.	EMISSION RATE (USER UNITS)	X (METERS)	Y (METERS)	BASE ELEV. (METERS)	STACK HEIGHT (METERS)	STACK TEMP. (DEG.K)	STACK EXIT VEL. (M/SEC)	STACK DIAMETER (METERS)	BUILDING EXISTS	EMISSION RATE SCALAR VARY BY
FSOUB1E	0	.25000E+07	17420.0	5450.0	.0	13.44	300.00	28.60	6.00	NO	
FSOUB1W	0	.11000E+07	15870.0	6570.0	.0	13.00	300.00	10.00	6.70	NO	
FSOUTSE	0	.27000E+07	8450.0	24750.0	.0	12.20	300.00	14.30	6.90	NO	
FSOUMAN	0	.19000E+07	4870.0	21240.0	.0	15.00	300.00	15.30	7.20	NO	
FSOUMAE	0	.19000E+07	8450.0	17690.0	.0	15.00	300.00	9.10	9.50	NO	
FSOUMAS	0	.17000E+07	6420.0	16450.0	.0	10.00	300.00	14.30	7.10	NO	
FSOUMAK	0	.30000E+06	6180.0	17700.0	.0	10.00	300.00	5.10	4.90	NO	
ARMUAM1	0	.30000E+06	13180.0	16690.0	.0	7.00	300.00	3.00	6.00	NO	
ARMUAM2	0	.90000E+06	12780.0	14300.0	.0	14.00	300.00	18.20	4.70	NO	
ARMUAM3	0	.40000E+06	12210.0	13240.0	.0	12.50	300.00	4.20	6.00	NO	
ARMUAM6	0	.10000E+07	8960.0	12720.0	.0	14.00	300.00	10.90	6.40	NO	
ARMUAM7	0	.80000E+06	7180.0	13360.0	.0	14.00	300.00	8.60	6.40	NO	
KADUST1	0	.80000E+06	15870.0	11330.0	.0	13.00	300.00	6.10	7.40	NO	
KADUST2	0	.80000E+06	16720.0	8510.0	.0	12.00	300.00	6.60	7.40	NO	
KADUFR7	0	.60000E+06	2600.0	24700.0	.0	13.00	300.00	9.90	5.10	NO	
KADULO3	0	.16000E+07	2270.0	29300.0	.0	10.00	300.00	17.50	6.10	NO	

HARUHA1	0	.22000E+07	24500.0	690.0	.0	12.00	300.00	22.90	4.50	NO
HARUHV3	0	.12000E+07	28000.0	-1810.0	.0	16.00	300.00	31.90	4.00	NO
HARUH4A	0	.84000E+06	25300.0	3540.0	.0	16.00	300.00	22.80	4.00	NO
HARUHUN	0	.75000E+06	16000.0	3000.0	.0	1.00	300.00	26.00	3.50	NO
HARUHM2	0	.16000E+07	23900.0	-4540.0	.0	8.20	300.00	21.30	4.00	NO
HARUH5A	0	.21000E+06	28300.0	2810.0	.0	10.00	300.00	7.00	1.10	NO
HARUFS5	0	.21000E+07	24720.0	12870.0	.0	13.00	300.00	16.70	8.90	NO
HARUFS4	0	.22000E+07	22870.0	10480.0	.0	13.00	300.00	17.10	8.90	NO
HARUHM5	0	.22000E+07	13390.0	3000.0	.0	13.00	300.00	17.50	8.90	NO
HARUHM6	0	.16000E+07	13660.0	6930.0	.0	13.00	300.00	15.30	6.60	NO
HARUHM7	0	.90000E+06	12750.0	10690.0	.0	13.00	300.00	19.00	4.40	NO
HARUHM8	0	.90000E+06	11720.0	9600.0	.0	13.00	300.00	19.00	4.40	NO
LORU2	0	.10000E+07	1210.0	36000.0	.0	14.40	300.00	8.79	7.10	NO

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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** AREA SOURCE DATA ***

SOURCE ID	NUMBER PART. CATS.	EMISSION RATE (USER UNITS /METER**2)	COORD (SW CORNER) X (METERS)	Y (METERS)	BASE ELEV. (METERS)	RELEASE HEIGHT (METERS)	X-DIM OF AREA (METERS)	Y-DIM OF AREA (METERS)	ORIENT. OF AREA (DEG.)	INIT. SZ (METERS)	EMISSION RATE SCALAR VARY BY
FSOS2A	0	.10000E+01	3000.0	20330.0	.0	30.00	1260.00	1350.00	90.00	.00	
FSOS2B	0	.10000E+01	3000.0	19060.0	.0	30.00	1260.00	1350.00	90.00	.00	
FSOS2C	0	.10000E+01	4330.0	20330.0	.0	30.00	1260.00	1350.00	90.00	.00	
FSOS2D	0	.10000E+01	4330.0	19060.0	.0	30.00	1260.00	1350.00	90.00	.00	
FSOS3	0	.10000E+01	4240.0	17780.0	.0	30.00	990.00	1470.00	90.00	.00	
FSOS4	0	.10000E+01	6810.0	19780.0	.0	30.00	900.00	1320.00	90.00	.00	
FSOS5A	0	.10000E+01	6300.0	15600.0	.0	30.00	1065.00	1200.00	67.00	.00	
FSOS5B	0	.10000E+01	6690.0	14630.0	.0	30.00	1065.00	1200.00	67.00	.00	
FSOS6	0	.10000E+01	4300.0	13360.0	.0	30.00	990.00	1890.00	52.00	.00	
FSOS8A	0	.10000E+01	16720.0	11420.0	.0	30.00	1230.00	810.00	74.00	.00	
FSOS8B	0	.10000E+01	17060.0	10210.0	.0	30.00	1230.00	810.00	74.00	.00	
FSOS8C	0	.10000E+01	17420.0	8930.0	.0	30.00	1230.00	810.00	74.00	.00	
FSOS9	0	.10000E+01	15480.0	7720.0	.0	30.00	690.00	1740.00	71.00	.00	
FSOS10	0	.10000E+01	12210.0	5150.0	.0	30.00	1980.00	1650.00	68.00	.00	
FSOS11	0	.10000E+01	14750.0	5210.0	.0	30.00	1560.00	1110.00	55.00	.00	
FSOS12	0	.10000E+01	16540.0	7060.0	.0	30.00	1710.00	810.00	70.00	.00	
FSOS13	0	.10000E+01	17690.0	6540.0	.0	30.00	1140.00	720.00	70.00	.00	
FSOS17	0	.10000E+01	13330.0	6360.0	.0	30.00	960.00	690.00	45.00	.00	
FSOWC	0	.10000E+01	8600.0	25090.0	.0	30.00	165.00	420.00	90.00	.00	
FSOWD	0	.10000E+01	5930.0	22360.0	.0	30.00	255.00	270.00	62.00	.00	
FSOWE	0	.10000E+01	4090.0	21060.0	.0	30.00	330.00	600.00	48.00	.00	
FSOWF	0	.10000E+01	7120.0	20600.0	.0	30.00	300.00	450.00	56.00	.00	
FSOWG	0	.10000E+01	6060.0	16090.0	.0	30.00	240.00	480.00	24.00	.00	
FSOWH	0	.10000E+01	8090.0	17420.0	.0	30.00	240.00	390.00	39.00	.00	
FSOWI	0	.10000E+01	6420.0	13540.0	.0	30.00	630.00	270.00	16.00	.00	
FSOWJ	0	.10000E+01	7810.0	15300.0	.0	30.00	960.00	210.00	66.00	.00	
FSOWK	0	.10000E+01	8240.0	12780.0	.0	30.00	570.00	300.00	7.00	.00	
FSOWL	0	.10000E+01	13240.0	16720.0	.0	30.00	420.00	600.00	29.00	.00	
FSOWM	0	.10000E+01	12330.0	13240.0	.0	30.00	510.00	270.00	25.00	.00	
FSOWN	0	.10000E+01	13600.0	14480.0	.0	30.00	330.00	420.00	90.00	.00	
FSOWO	0	.10000E+01	11900.0	9150.0	.0	30.00	540.00	390.00	26.00	.00	
FSOWR	0	.10000E+01	13750.0	6840.0	.0	30.00	660.00	360.00	8.00	.00	
FSOWS	0	.10000E+01	15930.0	6660.0	.0	30.00	360.00	390.00	70.00	.00	
ARMS7A	0	.10000E+01	13510.0	15630.0	.0	30.00	1230.00	1125.00	24.00	.00	
ARMS7B	0	.10000E+01	13960.0	16660.0	.0	30.00	1230.00	1125.00	24.00	.00	
KADS1	0	.10000E+01	3420.0	29000.0	.0	30.00	1000.00	1290.00	90.00	.00	
KADWA	0	.10000E+01	4090.0	27060.0	.0	30.00	600.00	300.00	65.00	.00	
KADWB	0	.10000E+01	4600.0	25000.0	.0	30.00	180.00	240.00	85.00	.00	
KADWP	0	.10000E+01	15660.0	11210.0	.0	30.00	600.00	420.00	69.00	.00	
KADWQ	0	.10000E+01	15720.0	8570.0	.0	30.00	450.00	600.00	28.00	.00	

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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** AREA SOURCE DATA ***

SOURCE ID	NUMBER PART. CATS.	EMISSION RATE (USER UNITS /METER**2)	COORD (SW CORNER) X (METERS)	Y (METERS)	BASE ELEV. (METERS)	RELEASE HEIGHT (METERS)	X-DIM OF AREA (METERS)	Y-DIM OF AREA (METERS)	ORIENT. OF AREA (DEG.)	INIT. SZ (METERS)	EMISSION RATE SCALAR VARY BY
KADWL3	0	.10000E+01	1000.0	29120.0	.0	30.00	450.00	540.00	.00	.00	
HARS1	0	.10000E+01	20120.0	2360.0	.0	30.00	1920.00	1560.00	.00	.00	
HARS2	0	.10000E+01	20120.0	900.0	.0	30.00	1620.00	1050.00	.00	.00	
HARS3	0	.10000E+01	25240.0	1660.0	.0	30.00	1950.00	1020.00	.00	.00	
HARS4A	0	.10000E+01	25090.0	-3480.0	.0	30.00	1500.00	1050.00	.00	.00	
HARS4B	0	.10000E+01	25090.0	-2450.0	.0	30.00	1500.00	1100.00	.00	.00	
HARS5	0	.10000E+01	23090.0	-4120.0	.0	30.00	1890.00	1560.00	.00	.00	
HARS6	0	.10000E+01	20780.0	-6000.0	.0	30.00	1500.00	1800.00	.00	.00	
HARS7	0	.10000E+01	22240.0	-6000.0	.0	30.00	450.00	1470.00	.00	.00	
HARS14A	0	.10000E+01	19840.0	8840.0	.0	30.00	1530.00	1500.00	57.00	.00	
HARS14B	0	.10000E+01	21150.0	9660.0	.0	30.00	1530.00	1500.00	57.00	.00	
HARS15	0	.10000E+01	21660.0	6600.0	.0	30.00	450.00	1170.00	67.00	.00	
HARS16A	0	.10000E+01	21810.0	5300.0	.0	30.00	1275.00	1050.00	21.00	.00	
HARS16B	0	.10000E+01	23000.0	4840.0	.0	30.00	1275.00	1050.00	21.00	.00	
HARW1	0	.10000E+01	22000.0	2150.0	.0	30.00	420.00	390.00	.00	.00	
HARW2	0	.10000E+01	22000.0	1000.0	.0	30.00	420.00	900.00	.00	.00	
HARW3	0	.10000E+01	22780.0	-120.0	.0	30.00	450.00	450.00	.00	.00	
HARW4	0	.10000E+01	25450.0	-1000.0	.0	30.00	300.00	450.00	.00	.00	
HARW5	0	.10000E+01	26510.0	-720.0	.0	30.00	300.00	450.00	.00	.00	
HARW6	0	.10000E+01	22150.0	-3630.0	.0	30.00	300.00	300.00	.00	.00	

HARW7	0	.10000E+01	24000.0	-4300.0	.0	30.00	300.00	300.00	90.00	.00
HARW8	0	.10000E+01	25240.0	-3930.0	.0	30.00	300.00	300.00	.00	.00
HARW9	0	.10000E+01	25450.0	3450.0	.0	30.00	300.00	300.00	.00	.00
HARW10	0	.10000E+01	12390.0	10300.0	.0	30.00	300.00	300.00	.00	.00
HARWU	0	.10000E+01	16000.0	2660.0	.0	30.00	300.00	300.00	.00	.00
HARWT	0	.10000E+01	13430.0	2720.0	.0	30.00	450.00	240.00	16.00	.00
HARWFU	0	.10000E+01	20600.0	7060.0	.0	30.00	360.00	570.00	28.00	.00
HARWV	0	.10000E+01	23810.0	5690.0	.0	30.00	450.00	330.00	21.00	.00
HARWW	0	.10000E+01	22810.0	11240.0	.0	30.00	390.00	180.00	90.00	.00
HARWX	0	.10000E+01	24360.0	13360.0	.0	30.00	390.00	270.00	51.00	.00
LORS1	0	.10000E+01	-570.0	33000.0	.0	30.00	780.00	1500.00	.00	.00
LORS2	0	.10000E+01	-90.0	32000.0	.0	30.00	990.00	1000.00	.00	.00
LORS3	0	.10000E+01	1000.0	35320.0	.0	30.00	240.00	210.00	.00	.00
LORW1	0	.10000E+01	1270.0	35510.0	.0	30.00	780.00	480.00	.00	.00
LORW2	0	.10000E+01	1270.0	33750.0	.0	30.00	600.00	480.00	.00	.00

*** SOURCE IDs DEFINING SOURCE GROUPS ***

GROUP ID SOURCE IDs

ARM ARMS7A , ARMS7B , ARMUAM1 , ARMUAM2 , ARMUAM3 , ARMUAM6 , ARMUAM7 ,

FSO FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A , FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C ,
FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC , FSOWD , FSOWE , FSOWF , FSOWG , FSOWH ,
FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , FSOWO , FSOWR , FSOWS , FSOUB1E , FSOUB1W , FSOUTSE ,
FSOUMAN , FSOUMAE , FSOUMAS , FSOUMAK ,

HARMONY HARS1 , HARS2 , HARS3 , HARS4A , HARS4B , HARS5 , HARS6 , HARS7 , HARS14A , HARS14B , HARS15 , HARS16A ,
HARS16B , HARW1 , HARW2 , HARW3 , HARW4 , HARW5 , HARW6 , HARW7 , HARW8 , HARW9 , HARW10 , HARWU ,
HARWT , HARWFU , HARWV , HARWW , HARWX , HARUHA1 , HARUHV3 , HARUH4A , HARUHUN , HARUHM2 , HARUH5A , HARUFS5 ,
HARUFS4 , HARUHM5 , HARUHM6 , HARUHM7 , HARUHM8 ,

LOR LORS1 , LORS2 , LORS3 , LORW1 , LORW2 , LORU2 ,

KAD KADS1 , KADWA , KADWB , KADWP , KADWQ , KADWL3 , KADUST1 , KADUST2 , KADUFR7 , KADULO3 ,

FREE FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A , FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C ,
FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC , FSOWD , FSOWE , FSOWF , FSOWG , FSOWH ,
FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , FSOWO , FSOWR , FSOWS , FSOUB1E , FSOUB1W , FSOUTSE ,
FSOUMAN , FSOUMAE , FSOUMAS , FSOUMAK , ARMS7A , ARMS7B , ARMUAM1 , ARMUAM2 , ARMUAM3 , ARMUAM6 , ARMUAM7 , KADS1 ,
KADWA , KADWB , KADWP , KADWQ , KADWL3 , KADUST1 , KADUST2 , KADUFR7 , KADULO3 , HARS1 , HARS2 , HARS3 ,
HARS4A , HARS4B , HARS5 , HARS6 , HARS7 , HARS14A , HARS14B , HARS15 , HARS16A , HARS16B , HARW1 , HARW2 ,
HARW3 , HARW4 , HARW5 , HARW6 , HARW7 , HARW8 , HARW9 , HARW10 , HARWU , HARWT , HARWFU , HARWV ,
HARWW , HARWX , HARUHA1 , HARUHV3 , HARUH4A , HARUHUN , HARUHM2 , HARUH5A , HARUFS5 , HARUFS4 , HARUHM5 , HARUHM6 ,
HARUHM7 , HARUHM8 , LORS1 , LORS2 , LORS3 , LORW1 , LORW2 , LORU2 ,

*** SOURCE IDs DEFINING SOURCE GROUPS ***

GROUP ID SOURCE IDs

NL57 FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A , FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C ,
FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC , FSOWD , FSOWE , FSOWF , FSOWG , FSOWH ,
FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , FSOWO , FSOWR , FSOWS , FSOUB1E , FSOUB1W , FSOUTSE ,
FSOUMAN , FSOUMAE , FSOUMAS , FSOUMAK , ARMS7A , ARMS7B , ARMUAM1 , ARMUAM2 , ARMUAM3 , ARMUAM6 , ARMUAM7 ,

*** GRIDDED RECEPTOR NETWORK SUMMARY ***

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

*** X-COORDINATES OF GRID ***
(METERS)

-5000.0, -3500.0, -2000.0, -500.0, 1000.0, 2500.0, 4000.0, 5500.0, 7000.0, 8500.0,
10000.0, 11500.0, 13000.0, 14500.0, 16000.0, 17500.0, 19000.0, 20500.0, 22000.0, 23500.0,
25000.0, 26500.0, 28000.0, 29500.0, 31000.0, 32500.0,

*** Y-COORDINATES OF GRID ***
(METERS)

-9000.0, -7500.0, -6000.0, -4500.0, -3000.0, -1500.0, .0, 1500.0, 3000.0, 4500.0,
6000.0, 7500.0, 9000.0, 10500.0, 12000.0, 13500.0, 15000.0, 16500.0, 18000.0, 19500.0,
21000.0, 22500.0, 24000.0, 25500.0, 27000.0, 28500.0, 30000.0, 31500.0, 33000.0, 34500.0,
36000.0, 37500.0, 39000.0,

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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

* RECEPTOR FLAGPOLE HEIGHTS IN METERS *

Y-COORD (METERS)	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
37500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
36000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
34500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
33000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
31500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
30000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
28500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
27000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
25500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
24000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
22500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
21000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
19500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
18000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
16500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
15000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
13500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
12000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
10500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
9000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
7500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
6000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
4500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
3000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
1500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-1500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-3000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-4500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-6000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-7500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-9000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

* RECEPTOR FLAGPOLE HEIGHTS IN METERS *

Y-COORD (METERS)	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
37500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
36000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
34500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
33000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
31500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
30000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
28500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
27000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
25500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
24000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
22500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
21000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
19500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
18000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
16500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
15000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
13500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
12000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
10500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
9000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
7500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
6000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
4500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
3000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50

1500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-1500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-3000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-4500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-6000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-7500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-9000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
PAGE 10
**MODELOPTs: CONC RURAL FLAT FLGPOL

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

* RECEPTOR FLAGPOLE HEIGHTS IN METERS *

Y-COORD (METERS)	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
37500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
36000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
34500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
33000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
31500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
30000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
28500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
27000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
25500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
24000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
22500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
21000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
19500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
18000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
16500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
15000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
13500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
12000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
10500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
9000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
7500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
6000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
4500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
3000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
1500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-1500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-3000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-4500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-6000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-7500.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
-9000.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
PAGE 11
**MODELOPTs: CONC RURAL FLAT FLGPOL

* SOURCE-RECEPTOR COMBINATIONS FOR WHICH CALCULATIONS MAY NOT BE PERFORMED *
LESS THAN 1.0 METER OR 3*ZLB IN DISTANCE, OR WITHIN OPEN PIT SOURCE

SOURCE ID	- - RECEPTOR LOCATION - - XR (METERS)	YR (METERS)	DISTANCE (METERS)
HARUHUN	16000.0	3000.0	.00

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
PAGE 12
**MODELOPTs: CONC RURAL FLAT FLGPOL

*** METEOROLOGICAL DAYS SELECTED FOR PROCESSING ***
(1=YES; 0=NO)

```
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1  1 1 1 1 1 1
```

METEOROLOGICAL DATA PROCESSED BETWEEN START DATE: 97 1 1 1
AND END DATE: 97 12 31 24

NOTE: METEOROLOGICAL DATA ACTUALLY PROCESSED WILL ALSO DEPEND ON WHAT IS INCLUDED IN THE DATA FILE.

*** UPPER BOUND OF FIRST THROUGH FIFTH WIND SPEED CATEGORIES ***
(METERS/SEC)

1.54, 3.09, 5.14, 8.23, 10.80,

*** WIND PROFILE EXPONENTS ***

STABILITY CATEGORY	WIND SPEED CATEGORY 1	2	3	4	5	6
A	.70000E-01	.70000E-01	.70000E-01	.70000E-01	.70000E-01	.70000E-01
B	.70000E-01	.70000E-01	.70000E-01	.70000E-01	.70000E-01	.70000E-01
C	.10000E+00	.10000E+00	.10000E+00	.10000E+00	.10000E+00	.10000E+00
D	.15000E+00	.15000E+00	.15000E+00	.15000E+00	.15000E+00	.15000E+00
E	.35000E+00	.35000E+00	.35000E+00	.35000E+00	.35000E+00	.35000E+00
F	.55000E+00	.55000E+00	.55000E+00	.55000E+00	.55000E+00	.55000E+00

*** VERTICAL POTENTIAL TEMPERATURE GRADIENTS ***
(DEGREES KELVIN PER METER)

STABILITY CATEGORY	WIND SPEED CATEGORY 1	2	3	4	5	6
A	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
B	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
C	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
D	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00	.00000E+00
E	.20000E-01	.20000E-01	.20000E-01	.20000E-01	.20000E-01	.20000E-01
F	.35000E-01	.35000E-01	.35000E-01	.35000E-01	.35000E-01	.35000E-01

*** THE FIRST 24 HOURS OF METEOROLOGICAL DATA ***

FILE: C:\BREEZE\FSO\FSOMET.ASC   FORMAT: FREE
SURFACE STATION NO.: 12345   UPPER AIR STATION NO.: 12345
NAME: UNKNOWN   NAME: UNKNOWN
YEAR: 1997   YEAR: 1997

YEAR	MONTH	DAY	HOUR	FLOW VECTOR	SPEED (M/S)	TEMP (K)	STAB CLASS	MIXING HEIGHT (M) RURAL	URBAN	USTAR (M/S)	M-O LENGTH (M)	Z-0 (M)	IPCODE	PRATE (mm/HR)
97	1	1	1	111.0	1.50	291.0	5	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	2	149.0	2.10	290.0	4	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	3	105.0	1.90	289.0	5	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	4	345.0	1.70	288.0	3	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	5	339.0	3.10	290.0	6	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	6	324.0	2.30	293.0	5	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	7	288.0	1.20	296.0	1	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	8	15.0	1.30	299.0	1	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	9	11.0	1.90	300.0	1	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	10	277.0	3.10	302.0	1	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	11	263.0	4.20	302.0	2	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	12	251.0	4.80	303.0	3	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	13	258.0	5.40	304.0	3	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	14	257.0	5.60	304.0	2	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	15	257.0	4.90	304.0	2	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	16	229.0	4.30	303.0	3	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	17	223.0	5.20	301.0	5	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	18	214.0	3.90	299.0	6	1000.0	1000.0	.0000	.0	.0000	0	.00
97	1	1	19	251.0	4.20	297.0	1	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	20	158.0	3.60	294.0	2	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	21	81.0	3.00	292.0	5	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	22	94.0	2.30	293.0	6	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	23	103.0	2.00	293.0	6	100.0	100.0	.0000	.0	.0000	0	.00
97	1	1	24	103.0	2.00	293.0	6	100.0	100.0	.0000	.0	.0000	0	.00

*** NOTES: STABILITY CLASS 1=A, 2=B, 3=C, 4=D, 5=E AND 6=F.
FLOW VECTOR IS DIRECTION TOWARD WHICH WIND IS BLOWING.

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ARM ***
INCLUDING SOURCE(S): ARMS7A , ARMS7B , ARMUAM1 , ARMUAM2 , ARMUAM3 , ARMUAM6 , ARMUAM7 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD (METERS)	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00	.02784	.02845	.03046	.03110	.03178	.02926	.02721	.02994	.03263
37500.00	.02988	.02985	.03135	.03297	.03394	.03372	.02982	.03108	.03406
36000.00	.03030	.03209	.03253	.03428	.03614	.03730	.03429	.03265	.03572
34500.00	.03126	.03293	.03463	.03581	.03824	.03962	.03972	.03626	.03761
33000.00	.03447	.03412	.03606	.03814	.03972	.04215	.04462	.04239	.04000
31500.00	.03792	.03843	.03745	.03954	.04204	.04506	.04806	.04918	.04483
30000.00	.04180	.04253	.04299	.04175	.04450	.04806	.05130	.05519	.05305
28500.00	.04803	.04692	.04842	.04839	.04656	.05039	.05433	.05891	.06219
27000.00	.05851	.05618	.05410	.05555	.05591	.05362	.05848	.06522	.07027
25500.00	.06980	.07018	.06764	.06477	.06445	.06452	.06421	.07010	.07728
24000.00	.08037	.08348	.08553	.08420	.08107	.07979	.07827	.07787	.08482
22500.00	.08406	.08880	.09617	.10286	.10546	.10575	.10121	.10020	.10003
21000.00	.09758	.10088	.10429	.10953	.12034	.13079	.14001	.14313	.14099
19500.00	.10815	.11601	.12211	.13011	.13797	.14732	.16114	.18266	.20352
18000.00	.11206	.12185	.12870	.13822	.15048	.16616	.18879	.20888	.24390

16500.00 |	.10440	.11393	.12845	.14595	.15520	.16677	.18566	.21376	.25710
15000.00 |	.10121	.11309	.12665	.14164	.15918	.18689	.21051	.23129	.27914
13500.00 |	.10315	.11386	.12657	.14206	.16092	.18261	.21309	.25740	.29660
12000.00 |	.10419	.11373	.12402	.13842	.16012	.19218	.24526	.32386	.45837
10500.00 |	.10314	.11540	.13042	.15446	.18417	.21802	.28506	.34693	.44497
9000.00 |	.11121	.12644	.14495	.16634	.19731	.23606	.27223	.34335	.40150
7500.00 |	.12029	.13418	.15242	.17272	.19948	.22933	.27342	.30990	.33703
6000.00 |	.12258	.13615	.15449	.17049	.19756	.22841	.25432	.26610	.28925
4500.00 |	.12185	.13955	.14932	.17246	.19713	.20742	.22404	.23929	.26419
3000.00 |	.12532	.13363	.15323	.17251	.17809	.18987	.19408	.21858	.24144
1500.00 |	.12117	.13834	.15224	.15365	.16239	.17118	.18640	.20646	.22483
.00 |	.12628	.13544	.13634	.14468	.14748	.15746	.17507	.19218	.20884
-1500.00 |	.12148	.12241	.12828	.12825	.14017	.14948	.16666	.18148	.19041
-3000.00 |	.11071	.11505	.11694	.12315	.13164	.14588	.15320	.17138	.17086
-4500.00 |	.10500	.10629	.10795	.11900	.12656	.13979	.14654	.15934	.15602
-6000.00 |	.09648	.09866	.10641	.11153	.12463	.12921	.14146	.14544	.14407
-7500.00 |	.09103	.09469	.10227	.11068	.11852	.12323	.13392	.13311	.13400
-9000.00 |	.08655	.09325	.09721	.10916	.11130	.11983	.12486	.12349	.12579

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ARM ***
INCLUDING SOURCE(S): ARMS7A , ARMS7B , ARMUAM1 , ARMUAM2 , ARMUAM3 , ARMUAM6 , ARMUAM7 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00 |	.03670	.03788	.03982	.04345	.04590	.04592	.04288	.04820	.04785
37500.00 |	.03850	.04060	.04260	.04685	.04911	.04903	.04699	.05234	.05090
36000.00 |	.04010	.04395	.04584	.05054	.05294	.05251	.05239	.05663	.05422
34500.00 |	.04190	.04772	.04967	.05457	.05743	.05656	.05871	.06175	.05797
33000.00 |	.04404	.05135	.05429	.05923	.06253	.06191	.06548	.06696	.06270
31500.00 |	.04681	.05476	.05994	.06507	.06829	.06904	.07341	.07238	.06730
30000.00 |	.05090	.05864	.06657	.07252	.07571	.07798	.08275	.07888	.07353
28500.00 |	.05873	.06337	.07367	.08122	.08650	.08936	.09497	.08645	.08253
27000.00 |	.07085	.06981	.08148	.09078	.10090	.10279	.10740	.09769	.09327
25500.00 |	.08501	.08458	.09128	.10433	.11919	.12157	.12127	.11308	.10357
24000.00 |	.09765	.10478	.10562	.12391	.14601	.15061	.14229	.12910	.12129
22500.00 |	.11053	.12797	.13355	.14868	.18672	.19248	.17159	.15646	.13651
21000.00 |	.14125	.15365	.17685	.19009	.24404	.24977	.22021	.18297	.14355
19500.00 |	.22445	.22833	.24285	.28135	.35445	.36227	.27724	.19637	.14617
18000.00 |	.30552	.38302	.43686	.52056	.72391	.55444	.30929	.20481	.14857
16500.00 |	.32669	.44010	.64190	1.47968	2.03167	.77999	.35365	.22984	.16948
15000.00 |	.37084	.48774	.72414	1.36608	1.72411	.64719	.34223	.23197	.17585
13500.00 |	.43372	.57248	.77060	1.11273	.88695	.48995	.30694	.21553	.16599
12000.00 |	.55586	.62339	.72200	.77989	.60128	.37945	.27711	.20301	.15546
10500.00 |	.49860	.48716	.58345	.55830	.44045	.29988	.23643	.18783	.14867
9000.00 |	.41027	.42824	.47510	.43318	.34599	.25319	.20273	.17089	.13698
7500.00 |	.35088	.37591	.38849	.35608	.28700	.21140	.17933	.15364	.13186
6000.00 |	.31528	.31949	.33018	.30293	.24324	.18430	.16349	.13474	.12402
4500.00 |	.28774	.27834	.28669	.26144	.21231	.16103	.14893	.12648	.11056
3000.00 |	.25662	.24180	.25090	.22881	.18662	.14535	.13335	.11937	.10477
1500.00 |	.22454	.21300	.22013	.20256	.16577	.13345	.12024	.10996	.09809
.00 |	.19940	.19205	.19639	.18189	.14817	.12225	.11204	.10218	.09195
-1500.00 |	.17951	.17535	.17785	.16546	.13420	.11106	.10445	.09604	.08567
-3000.00 |	.16321	.16085	.16239	.15070	.12244	.10135	.09732	.09130	.08143
-4500.00 |	.15090	.14832	.14897	.13781	.11357	.09382	.08942	.08619	.07888
-6000.00 |	.14054	.13746	.13733	.12685	.10585	.08729	.08238	.08100	.07616
-7500.00 |	.13088	.12799	.12721	.11747	.09904	.08235	.07650	.07572	.07266
-9000.00 |	.12199	.11969	.11825	.10908	.09283	.07813	.07124	.07085	.06873

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: ARM ***
INCLUDING SOURCE(S): ARMS7A , ARMS7B , ARMUAM1 , ARMUAM2 , ARMUAM3 , ARMUAM6 , ARMUAM7 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00 |	.04595	.04362	.04211	.04191	.03991	.03846	.03817	.03724
37500.00 |	.04885	.04589	.04535	.04424	.04154	.04147	.04044	.03913
36000.00 |	.05171	.04904	.04885	.04583	.04509	.04418	.04261	.04148
34500.00 |	.05474	.05359	.05152	.04911	.04862	.04673	.04518	.04471
33000.00 |	.05876	.05810	.05429	.05389	.05168	.04960	.04886	.04416
31500.00 |	.06517	.06179	.06008	.05770	.05501	.05375	.04836	.04241
30000.00 |	.07157	.06750	.06522	.06180	.05968	.05343	.04678	.04397
28500.00 |	.07776	.07472	.07053	.06708	.05966	.05213	.04855	.04552
27000.00 |	.08687	.08217	.07668	.06743	.05881	.05434	.05106	.04769
25500.00 |	.09823	.08984	.07752	.06739	.06212	.05740	.05186	.04583
24000.00 |	.10850	.09123	.07920	.07189	.06384	.05541	.04768	.04203
22500.00 |	.11105	.09596	.08281	.06991	.05899	.05164	.04653	.04240
21000.00 |	.11673	.09454	.07788	.06612	.05746	.05223	.04879	.04612
19500.00 |	.11280	.09139	.07887	.07010	.06361	.05803	.05289	.04848
18000.00 |	.11580	.09753	.08451	.07450	.06687	.06102	.05612	.05171
16500.00 |	.13636	.11317	.09701	.08457	.07416	.06563	.05882	.05334
15000.00 |	.13968	.11620	.09935	.08632	.07628	.06857	.06246	.05738
13500.00 |	.13538	.11375	.09741	.08536	.07637	.06909	.06288	.05746

12000.00 |	.12895	.11230	.09743	.08412	.07386	.06627	.06070	.05618
10500.00 |	.12024	.10166	.09056	.08209	.07430	.06706	.06074	.05527
9000.00 |	.11530	.09656	.08381	.07653	.07045	.06513	.06019	.05533
7500.00 |	.10939	.09375	.08119	.07067	.06394	.06027	.05644	.05316
6000.00 |	.10635	.08992	.07972	.07070	.06184	.05576	.05225	.04963
4500.00 |	.10185	.08862	.07679	.06820	.06242	.05565	.05011	.04656
3000.00 |	.09487	.08578	.07516	.06722	.06023	.05522	.05006	.04566
1500.00 |	.08978	.08258	.07364	.06518	.05937	.05419	.04983	.04544
.00 |	.08476	.07899	.07273	.06424	.05759	.05304	.04899	.04556
-1500.00 |	.07960	.07429	.07030	.06473	.05704	.05158	.04794	.04456
-3000.00 |	.07487	.07054	.06627	.06311	.05791	.05141	.04671	.04372
-4500.00 |	.07045	.06671	.06343	.05983	.05704	.05211	.04683	.04271
-6000.00 |	.06748	.06325	.06023	.05735	.05454	.05173	.04729	.04301
-7500.00 |	.06593	.06029	.05718	.05501	.05214	.05003	.04700	.04328
-9000.00 |	.06421	.05818	.05486	.05245	.05041	.04796	.04602	.04287

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: FSO ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00 |	.20535	.20596	.21458	.22348	.22918	.23894	.25257	.26535	.27053
37500.00 |	.22489	.22062	.22681	.23761	.24901	.25620	.26948	.28365	.28908
36000.00 |	.24975	.23692	.24486	.25408	.26623	.27695	.29201	.30515	.31144
34500.00 |	.27522	.26491	.25798	.27686	.28635	.30090	.31977	.32746	.33904
33000.00 |	.30094	.29803	.28463	.29512	.31183	.32863	.35210	.35890	.37250
31500.00 |	.32928	.33572	.32405	.31875	.33940	.36574	.38665	.40219	.41353
30000.00 |	.35738	.37702	.37511	.36137	.37642	.40000	.43557	.45579	.46760
28500.00 |	.37782	.40336	.42881	.42877	.42819	.45265	.48914	.52232	.53742
27000.00 |	.41284	.44369	.47271	.48980	.48863	.53638	.57803	.61355	.62875
25500.00 |	.48500	.49343	.52708	.56285	.57883	.60822	.69442	.75741	.77360
24000.00 |	.59962	.61104	.62845	.66949	.70793	.74776	.84919	.95982	1.05248
22500.00 |	.73508	.78397	.83096	.87146	.94080	1.01703	1.18553	1.38275	1.33900
21000.00 |	.84943	.94587	1.07389	1.21586	1.38145	1.60561	2.09182	2.20074	1.76691
19500.00 |	.91322	1.04166	1.21885	1.48548	1.93277	2.79680	4.22766	3.60520	2.64951
18000.00 |	.96507	1.10485	1.30318	1.61695	2.25761	3.58075	5.12445	4.19386	2.83164
16500.00 |	1.00856	1.16558	1.39828	1.77214	2.31884	3.28781	4.27780	3.76016	2.95709
15000.00 |	1.04945	1.23566	1.48697	1.81796	2.27298	2.95105	3.45723	3.55286	3.91679
13500.00 |	1.09366	1.27194	1.49574	1.75596	2.14880	2.66327	3.32781	4.21653	3.78914
12000.00 |	1.12479	1.28949	1.44570	1.68164	2.01320	2.47358	3.05984	3.13439	2.67842
10500.00 |	1.10326	1.21946	1.39306	1.63232	1.91062	2.21854	2.48851	2.42311	2.15280
9000.00 |	1.07618	1.18173	1.35101	1.55843	1.76032	1.95880	2.13266	2.05490	1.90102
7500.00 |	1.03005	1.15334	1.29810	1.45210	1.58233	1.76993	1.88797	1.83593	1.77829
6000.00 |	.98530	1.09521	1.22047	1.31413	1.44123	1.59073	1.68849	1.66547	1.67130
4500.00 |	.94894	1.03688	1.11880	1.21673	1.33608	1.44600	1.51541	1.51385	1.54373
3000.00 |	.91159	.98683	1.06366	1.15383	1.25554	1.34715	1.40808	1.43036	1.46840
1500.00 |	.87713	.93896	1.01318	1.09633	1.17333	1.25543	1.31207	1.34677	1.40892
.00 |	.83077	.89362	.95831	1.03187	1.10206	1.18556	1.26112	1.30616	1.36247
-1500.00 |	.79526	.86159	.92886	1.00008	1.06318	1.13998	1.19753	1.24900	1.27318
-3000.00 |	.78822	.84392	.90355	.95855	1.01723	1.08148	1.14721	1.17095	1.15967
-4500.00 |	.77244	.81694	.86977	.91019	.96980	1.04115	1.07600	1.08286	1.04438
-6000.00 |	.74735	.78839	.83286	.87412	.93421	.98065	1.00366	.98043	.96391
-7500.00 |	.72001	.75896	.80168	.84301	.88896	.91893	.91464	.91074	.89545
-9000.00 |	.69482	.73948	.77066	.80617	.83679	.84229	.85181	.85183	.84496

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: FSO ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00 |	.28551	.28950	.29599	.29381	.29302	.28423	.27696	.27621	.26529
37500.00 |	.30752	.30985	.31835	.31374	.31161	.30316	.29654	.29368	.28386
36000.00 |	.33220	.33316	.34158	.33755	.33296	.32330	.31815	.31565	.30029
34500.00 |	.35950	.36024	.36719	.36216	.35794	.34816	.34507	.33294	.31139
33000.00 |	.39053	.39413	.40183	.39456	.38846	.38019	.36554	.34695	.32974
31500.00 |	.42783	.44076	.44087	.42960	.42553	.40339	.38397	.36908	.34885
30000.00 |	.47346	.48960	.49654	.47885	.45263	.43004	.41261	.38852	.36599
28500.00 |	.53663	.55498	.55474	.51436	.49183	.45847	.43496	.41753	.38615
27000.00 |	.62854	.65811	.60597	.56409	.52803	.49614	.47406	.44039	.40723
25500.00 |	.80379	.77624	.69311	.62788	.57080	.53144	.49022	.45075	.42197
24000.00 |	1.18928	.91171	.76940	.69055	.62556	.56700	.52352	.47534	.45031
22500.00 |	1.24562	1.00471	.82428	.72680	.64687	.58386	.54572	.50051	.47737
21000.00 |	1.47072	1.10052	.90532	.77256	.69827	.62674	.59116	.54220	.50528
19500.00 |	1.86663	1.26092	1.01992	.84593	.77052	.69957	.64486	.59213	.54848
18000.00 |	1.92930	1.42923	1.11314	.96108	.85675	.75766	.70037	.64811	.59854
16500.00 |	2.17706	1.50063	1.18568	1.15010	.95224	.83373	.77221	.71734	.64803
15000.00 |	2.42070	1.52813	1.26075	1.15394	1.01079	.89490	.85453	.79446	.71529

13500.00	2.31702	1.56678	1.35351	1.30757	1.09593	1.00240	1.00772	.92991	.80836
12000.00	2.01635	1.56268	1.41355	1.36756	1.25666	1.23983	1.34858	1.13268	.90957
10500.00	1.78946	1.57484	1.46507	1.46819	1.51777	1.77768	2.35470	1.42384	1.02377
9000.00	1.69830	1.62102	1.70625	1.76552	1.86719	2.28172	2.90192	1.71429	1.10077
7500.00	1.68644	1.71216	1.89807	2.09567	2.54152	3.31429	3.26917	1.85150	1.13760
6000.00	1.70863	1.86446	2.17255	2.91243	3.42027	3.80412	3.56183	1.93681	1.15335
4500.00	1.63695	1.92967	2.65898	4.24382	3.88960	3.90923	2.67974	1.62148	1.09738
3000.00	1.58939	1.90110	2.56841	3.58214	3.12462	2.65545	1.95260	1.32182	.99435
1500.00	1.56178	1.80166	2.16781	2.48470	2.25362	1.99553	1.55073	1.10865	.89748
.00	1.45762	1.57825	1.80774	1.91292	1.75597	1.59210	1.29727	.98084	.81981
-1500.00	1.30592	1.40072	1.51741	1.57365	1.45166	1.32031	1.11702	.87809	.75140
-3000.00	1.17429	1.24416	1.32551	1.33581	1.22983	1.13378	.97258	.79078	.69904
-4500.00	1.06821	1.11508	1.17655	1.16656	1.06798	.99763	.85636	.71866	.65273
-6000.00	.98612	1.01229	1.04546	1.03182	.94806	.89155	.76646	.65278	.61022
-7500.00	.91053	.92953	.94101	.92085	.85385	.80459	.69660	.59778	.56129
-9000.00	.84339	.84916	.85605	.83272	.77830	.73183	.64018	.55059	.51713

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: FSO ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD (METERS)	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00	.26409	.26409	.25196	.23921	.22682	.21715	.20730	.19798
37500.00	.28011	.27075	.26179	.24718	.23508	.22371	.21200	.20324
36000.00	.28885	.28395	.27218	.25590	.24326	.22809	.21697	.20910
34500.00	.30475	.29805	.28288	.26463	.24673	.23337	.22460	.21570
33000.00	.32184	.31280	.28977	.26951	.25330	.24297	.23320	.22220
31500.00	.33881	.32139	.29750	.27861	.26538	.25064	.23708	.22611
30000.00	.35556	.33455	.30734	.28792	.27063	.25833	.24522	.23201
28500.00	.37142	.34500	.31975	.29777	.27927	.26209	.24820	.23411
27000.00	.38440	.35048	.32300	.30094	.28283	.26778	.25158	.23852
25500.00	.39792	.36314	.33690	.31442	.29620	.27959	.26492	.25344
24000.00	.41442	.37980	.35301	.33124	.31145	.29142	.27721	.26581
22500.00	.44276	.40134	.37052	.34705	.32626	.30979	.29489	.27624
21000.00	.46011	.42340	.39500	.36996	.34516	.32528	.30347	.28285
19500.00	.49500	.45281	.41821	.38908	.36802	.34400	.32006	.29728
18000.00	.53891	.49503	.45927	.42600	.39172	.35996	.32998	.30514
16500.00	.58547	.53563	.49096	.44820	.40807	.36983	.34025	.31692
15000.00	.63626	.57496	.51575	.46329	.41565	.37995	.34914	.32062
13500.00	.70513	.60910	.53337	.46978	.42284	.38239	.34696	.31521
12000.00	.75309	.64244	.54341	.47261	.42098	.37609	.33708	.30936
10500.00	.80490	.64903	.55456	.47670	.41470	.37205	.34167	.31501
9000.00	.81965	.66163	.54784	.48026	.42755	.38280	.34991	.32422
7500.00	.81938	.66229	.56253	.49328	.44007	.39633	.35869	.32736
6000.00	.84135	.67775	.57223	.49930	.44412	.40158	.36643	.33617
4500.00	.83963	.67893	.57760	.50568	.45221	.40903	.37428	.34543
3000.00	.79419	.65322	.55894	.48802	.43485	.39710	.36690	.34046
1500.00	.74260	.62330	.53242	.46910	.42170	.38095	.34922	.32406
.00	.69224	.60096	.51917	.45336	.40790	.37000	.33962	.31484
-1500.00	.64786	.56787	.50420	.44707	.39740	.36221	.33322	.30657
-3000.00	.60974	.53938	.48276	.43405	.39221	.35369	.32514	.30280
-4500.00	.57487	.51850	.46434	.42149	.38134	.34963	.31934	.29455
-6000.00	.54767	.49326	.45073	.40742	.37419	.34069	.31533	.29194
-7500.00	.52121	.46909	.43379	.39834	.36407	.33586	.30840	.28732
-9000.00	.49279	.45088	.41735	.38679	.35567	.32967	.30441	.28196

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: HARMONY ***
INCLUDING SOURCE(S): HARS1 , HARS2 , HARS3 , HARS4A , HARS4B , HARS5 , HARS6 ,
HARS7 , HARS14A , HARS14B , HARS15 , HARS16A , HARS16B , HARW1 , HARW2 , HARW3 , HARW4 , HARW5 , HARW6 ,
HARW7 , HARW8 , HARW9 , HARW10 , HARWU , HARWT , HARWFU , HARWV , HARWW , HARWX , HARUHA1 , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD (METERS)	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00	.13876	.14076	.14119	.14317	.14136	.13727	.13490	.13016	.12721
37500.00	.14241	.14592	.14712	.14822	.14924	.14620	.14341	.13991	.13481
36000.00	.14584	.15058	.15312	.15421	.15599	.15497	.15244	.15021	.14438
34500.00	.14704	.15467	.15940	.16048	.16274	.16351	.16162	.16055	.15612
33000.00	.15044	.15591	.16462	.16831	.16875	.17234	.17125	.16999	.16919
31500.00	.15752	.15994	.16591	.17568	.17736	.17887	.18202	.18030	.18033
30000.00	.16482	.16836	.17048	.17757	.18698	.18746	.19057	.19322	.19041
28500.00	.17239	.17662	.18088	.18242	.19124	.19851	.19954	.20370	.20481
27000.00	.18426	.18525	.19004	.19502	.19685	.20585	.21152	.21369	.21981
25500.00	.19566	.19994	.20057	.20561	.21055	.21468	.22160	.22652	.23198
24000.00	.21173	.21262	.21802	.21911	.22449	.22838	.23422	.24037	.24518
22500.00	.23190	.23176	.23230	.23798	.24075	.24707	.25190	.25485	.26188
21000.00	.25593	.25725	.25644	.25694	.26155	.26554	.27172	.28089	.28040
19500.00	.28034	.28384	.28817	.28769	.28854	.29137	.29603	.30210	.31033
18000.00	.30896	.31051	.31350	.32291	.32453	.32784	.33152	.33557	.34425
16500.00	.33968	.34447	.34795	.35079	.36009	.36630	.37371	.38149	.38766

15000.00 |	.37231	.37894	.38755	.39498	.39953	.41101	.41557	.42729	.43821
13500.00 |	.40180	.41450	.42670	.43666	.44930	.46193	.47542	.48797	.50155
12000.00 |	.42235	.43878	.45544	.47364	.49202	.50827	.52889	.55823	.57815
10500.00 |	.44220	.46174	.48282	.50412	.52494	.54976	.57721	.60740	.64215
9000.00 |	.45401	.47726	.50324	.53129	.56155	.59338	.62569	.66550	.71181
7500.00 |	.47158	.49740	.52559	.55667	.59183	.63241	.68092	.73573	.79809
6000.00 |	.48524	.51717	.55090	.58873	.63144	.68042	.73438	.79892	.88294
4500.00 |	.48693	.52035	.55892	.60086	.64626	.69553	.75673	.83875	.91292
3000.00 |	.49153	.52387	.55968	.59802	.64473	.69972	.78168	.85261	.93161
1500.00 |	.49217	.51974	.55701	.60496	.66018	.73331	.79568	.87065	.97261
.00 |	.49722	.53713	.57916	.63060	.68317	.73623	.79533	.89110	.99620
-1500.00 |	.51151	.54705	.59324	.63546	.68584	.74224	.82876	.90890	1.00453
-3000.00 |	.50523	.54456	.58042	.62454	.67739	.74247	.80690	.88538	1.01306
-4500.00 |	.50298	.53424	.57278	.62042	.66998	.72101	.79950	.89702	.98833
-6000.00 |	.49962	.53539	.57784	.61875	.66536	.74046	.81345	.89645	.97050
-7500.00 |	.51106	.54954	.58242	.62811	.69591	.75960	.81976	.88259	.94974
-9000.00 |	.52042	.54802	.59275	.64926	.69932	.73906	.78880	.83893	.91098

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
PAGE 21
**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: HARMONY ***
INCLUDING SOURCE(S): HARS1 , HARS2 , HARS3 , HARS4A , HARS4B , HARS5 , HARS6 ,
HARS7 , HARS14A , HARS14B , HARS15 , HARS16A , HARS16B , HARW1 , HARW2 , HARW3 , HARW4 , HARW5 , HARW6 ,
HARW7 , HARW8 , HARW9 , HARW10 , HARWU , HARWT , HARWFU , HARWV , HARWW , HARWX , HARUHA1 , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00 |	.13100	.14207	.14982	.15792	.16505	.16708	.17464	.18350	.19135
37500.00 |	.13553	.14513	.15471	.16317	.17134	.17502	.18197	.19194	.19997
36000.00 |	.14261	.14837	.16002	.16857	.17806	.18355	.19006	.20111	.20960
34500.00 |	.15145	.15405	.16436	.17493	.18507	.19215	.19949	.21081	.22036
33000.00 |	.16255	.16253	.16908	.18174	.19260	.20120	.21059	.22098	.23222
31500.00 |	.17685	.17295	.17671	.18787	.20145	.21069	.22273	.23227	.24509
30000.00 |	.19150	.18688	.18756	.19485	.21036	.22099	.23532	.24583	.25905
28500.00 |	.20388	.20403	.20183	.20442	.21964	.23360	.24849	.26204	.27473
27000.00 |	.21890	.22021	.21987	.21840	.23051	.24611	.26255	.27953	.29274
25500.00 |	.23595	.23679	.23835	.23842	.24415	.26106	.28028	.29892	.31449
24000.00 |	.25151	.25552	.25991	.25947	.26537	.27681	.29836	.32122	.34008
22500.00 |	.27050	.27539	.28261	.28604	.29183	.29725	.32084	.34840	.36842
21000.00 |	.29152	.30091	.30619	.31704	.32497	.32330	.34879	.37691	.40361
19500.00 |	.31101	.32789	.33663	.34813	.36564	.36609	.38185	.41204	.44571
18000.00 |	.34705	.34986	.37524	.38711	.41044	.42125	.42841	.45216	.49700
16500.00 |	.39912	.40162	.40821	.43733	.45300	.49318	.49891	.51405	.55438
15000.00 |	.45205	.46759	.48026	.50741	.52618	.55852	.57551	.60007	.64631
13500.00 |	.51511	.53843	.56626	.60916	.64064	.65215	.68284	.70584	.76126
12000.00 |	.60523	.62868	.66497	.75127	.80416	.81334	.84866	.89425	.98090
10500.00 |	.67625	.73478	.83058	1.03400	.98887	1.06429	1.13750	1.30508	1.53493
9000.00 |	.78241	.86365	1.03786	1.04718	1.10942	1.24092	1.44273	1.84447	2.98078
7500.00 |	.87777	.99414	1.13692	1.14327	1.26146	1.39430	1.70794	2.34527	3.54021
6000.00 |	.96599	1.06295	1.20756	1.30712	1.45483	1.60442	1.94380	2.44262	3.17506
4500.00 |	1.00931	1.14654	1.29888	1.44852	1.60605	1.84686	2.13443	2.53207	3.20541
3000.00 |	1.04652	1.18812	1.34726	1.52172	1.78943	1.93645	2.32557	2.99650	4.51190
1500.00 |	1.08867	1.22009	1.42640	1.67403	1.82918	2.09060	2.42403	3.23853	4.76314
.00 |	1.12102	1.29784	1.47629	1.67339	1.78239	2.08915	2.45283	3.06228	3.83059
-1500.00 |	1.14481	1.28944	1.46952	1.63682	1.81122	2.09744	2.37730	2.87566	3.27507
-3000.00 |	1.11602	1.25770	1.40073	1.58924	1.78629	2.05028	2.33783	2.72014	3.15069
-4500.00 |	1.08908	1.20765	1.36533	1.55774	1.70061	1.93983	2.28152	2.79256	3.51176
-6000.00 |	1.06416	1.18816	1.31960	1.46255	1.57884	1.82545	2.15373	2.68789	3.92383
-7500.00 |	1.03931	1.14085	1.26222	1.37852	1.53613	1.77581	2.07029	2.52906	3.15679
-9000.00 |	.99980	1.09754	1.21422	1.35557	1.49912	1.68866	1.92237	2.19118	2.45963

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: HARMONY ***
INCLUDING SOURCE(S): HARS1 , HARS2 , HARS3 , HARS4A , HARS4B , HARS5 , HARS6 ,
HARS7 , HARS14A , HARS14B , HARS15 , HARS16A , HARS16B , HARW1 , HARW2 , HARW3 , HARW4 , HARW5 , HARW6 ,
HARW7 , HARW8 , HARW9 , HARW10 , HARWU , HARWT , HARWFU , HARWV , HARWW , HARWX , HARUHA1 , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00 |	.20068	.20145	.19422	.19594	.20014	.20404	.20427	.20399
37500.00 |	.21014	.21019	.20357	.20644	.21165	.21425	.21379	.21313
36000.00 |	.22024	.22005	.21384	.21839	.22381	.22539	.22372	.22320
34500.00 |	.23096	.23158	.22508	.23163	.23727	.23717	.23431	.23412
33000.00 |	.24278	.24449	.23780	.24594	.25235	.24946	.24618	.24575
31500.00 |	.25683	.25853	.25195	.26296	.26760	.26285	.25965	.25904
30000.00 |	.27333	.27380	.26801	.28219	.28369	.27719	.27558	.27324
28500.00 |	.29199	.29009	.28858	.30258	.30144	.29373	.29372	.28524
27000.00 |	.31209	.30910	.31244	.32519	.32155	.31398	.30858	.30099
25500.00 |	.33342	.33250	.33912	.35199	.34382	.33236	.32936	.31713
24000.00 |	.36014	.36047	.37070	.38037	.36383	.35698	.35130	.33703
22500.00 |	.39045	.39324	.40816	.40600	.39258	.38589	.37277	.35879
21000.00 |	.42673	.43411	.44467	.44294	.42786	.41477	.40359	.38512
19500.00 |	.47382	.47497	.49400	.48601	.46358	.45592	.43588	.40109
18000.00 |	.52275	.53379	.54965	.53408	.51106	.49839	.45972	.42172

16500.00 |	.59222	.61076	.61278	.60189	.57415	.53542	.48857	.45070
15000.00 |	.69219	.71101	.71891	.69426	.63427	.57270	.52972	.48511
13500.00 |	.85047	.90063	.92143	.80197	.70585	.62812	.56310	.50740
12000.00 |	1.12571	1.20122	1.09786	.89614	.77256	.68828	.61452	.54812
10500.00 |	1.86628	1.69309	1.22207	.99953	.86099	.75675	.66241	.59153
9000.00 |	3.57995	2.05165	1.41963	1.15146	.97169	.83578	.72535	.64133
7500.00 |	3.05067	2.10186	1.59128	1.27941	1.07236	.90628	.78750	.67633
6000.00 |	3.53234	2.70296	1.86906	1.43173	1.18482	.99897	.82937	.71949
4500.00 |	3.84311	3.50780	2.13520	1.66034	1.35527	1.10061	.89488	.74645
3000.00 |	4.26395	3.04433	2.48739	2.21434	1.74270	1.20350	.95418	.78470
1500.00 |	4.08377	2.87726	3.02424	3.03979	1.92433	1.30185	1.00845	.81819
.00 |	3.43856	3.06469	2.97421	2.56615	1.84752	1.29641	.98400	.78746
-1500.00 |	3.26179	3.24388	3.45012	3.05369	1.77406	1.27231	.95581	.77776
-3000.00 |	3.51284	4.41236	4.88643	3.44382	1.79665	1.25910	.97723	.79824
-4500.00 |	4.44785	4.61649	4.08231	2.51033	1.64435	1.19645	.95116	.77964
-6000.00 |	4.70409	3.65604	2.84026	1.97656	1.44773	1.10676	.91117	.75750
-7500.00 |	3.11204	2.74726	2.14267	1.61766	1.26030	1.01601	.84702	.72482
-9000.00 |	2.39120	2.17948	1.76541	1.36396	1.12780	.93573	.78986	.68883

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: LOR ***
INCLUDING SOURCE(S): LORS1 , LORS2 , LORS3 , LORW1 , LORW2 , LORU2 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00 |	.12107	.12462	.12034	.14929	.17375	.18674	.16822	.13396	.10940
37500.00 |	.14967	.17644	.19071	.21226	.25080	.28245	.21043	.15123	.11490
36000.00 |	.21994	.24216	.29393	.38325	.51422	.49343	.25805	.16664	.12291
34500.00 |	.29735	.39795	.53729	.84395	.95593	.53403	.26588	.16952	.12651
33000.00 |	.31393	.44952	.78142	1.58115	1.23453	.49955	.27397	.17807	.13467
31500.00 |	.31521	.46811	.71759	1.25937	.91714	.40613	.25329	.17408	.13176
30000.00 |	.32690	.42378	.59311	.77013	.53691	.32524	.21207	.15865	.12169
28500.00 |	.29579	.36007	.45472	.51427	.37567	.25036	.18841	.14591	.11155
27000.00 |	.25381	.30034	.36364	.37782	.27967	.19766	.17226	.13040	.10992
25500.00 |	.22105	.26795	.28970	.29660	.22147	.16976	.14571	.12136	.10185
24000.00 |	.19947	.23066	.23841	.24327	.18303	.14735	.12331	.11103	.09351
22500.00 |	.18610	.19845	.20344	.20529	.15590	.12640	.10853	.09855	.08893
21000.00 |	.16766	.17039	.17719	.17676	.13576	.10959	.09842	.08896	.08050
19500.00 |	.14966	.15021	.15625	.15459	.12023	.09691	.09071	.08176	.07333
18000.00 |	.13207	.13508	.13957	.13693	.10794	.08689	.08275	.07447	.06748
16500.00 |	.11838	.12239	.12630	.12261	.09802	.07883	.07492	.06897	.06401
15000.00 |	.10820	.11137	.11549	.11074	.08980	.07227	.06824	.06506	.06039
13500.00 |	.10046	.10203	.10634	.10075	.08285	.06682	.06275	.06127	.05645
12000.00 |	.09359	.09421	.09841	.09227	.07689	.06219	.05801	.05706	.05309
10500.00 |	.08700	.08763	.09139	.08498	.07171	.05817	.05378	.05288	.05048
9000.00 |	.08085	.08203	.08510	.07865	.06715	.05464	.05002	.04924	.04822
7500.00 |	.07535	.07721	.07945	.07311	.06309	.05152	.04674	.04622	.04585
6000.00 |	.07056	.07300	.07435	.06823	.05947	.04875	.04391	.04363	.04327
4500.00 |	.06641	.06925	.06975	.06390	.05621	.04629	.04145	.04128	.04070
3000.00 |	.06283	.06585	.06561	.06005	.05328	.04410	.03931	.03908	.03838
1500.00 |	.05973	.06271	.06188	.05662	.05063	.04214	.03740	.03703	.03640
.00 |	.05702	.05977	.05851	.05352	.04821	.04037	.03569	.03513	.03470
-1500.00 |	.05464	.05701	.05542	.05072	.04600	.03875	.03412	.03340	.03318
-3000.00 |	.05250	.05441	.05260	.04817	.04396	.03727	.03269	.03183	.03178
-4500.00 |	.05055	.05196	.05002	.04584	.04208	.03590	.03138	.03041	.03044
-6000.00 |	.04875	.04968	.04766	.04371	.04034	.03464	.03017	.02913	.02916
-7500.00 |	.04704	.04755	.04547	.04176	.03874	.03347	.02907	.02797	.02796
-9000.00 |	.04540	.04556	.04347	.03997	.03725	.03238	.02805	.02690	.02684

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: LOR ***
INCLUDING SOURCE(S): LORS1 , LORS2 , LORS3 , LORW1 , LORW2 , LORU2 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00 |	.08483	.07265	.06099	.05227	.04662	.04166	.03698	.03346	.03072
37500.00 |	.09235	.07470	.06101	.05150	.04559	.04123	.03734	.03448	.03235
36000.00 |	.09442	.07879	.06692	.05713	.05044	.04532	.04084	.03698	.03376
34500.00 |	.10175	.08435	.07149	.06207	.05483	.04903	.04426	.04029	.03697
33000.00 |	.10700	.08737	.07472	.06585	.05876	.05255	.04699	.04229	.03852
31500.00 |	.10370	.08724	.07547	.06579	.05710	.05078	.04618	.04271	.03986
30000.00 |	.09858	.08021	.07014	.06138	.05456	.04948	.04463	.04079	.03768
28500.00 |	.09308	.08052	.06711	.05850	.05249	.04704	.04291	.03993	.03685
27000.00 |	.08598	.07397	.06590	.05781	.05148	.04658	.04248	.03838	.03510
25500.00 |	.08632	.07028	.06114	.05534	.04993	.04489	.04174	.03869	.03578
24000.00 |	.08226	.07016	.05956	.05213	.04751	.04387	.03964	.03702	.03495
22500.00 |	.07737	.06855	.05891	.05174	.04552	.04167	.03895	.03566	.03318
21000.00 |	.07353	.06536	.05786	.05078	.04568	.04054	.03712	.03502	.03232
19500.00 |	.06855	.06287	.05649	.04975	.04466	.04083	.03670	.03347	.03180
18000.00 |	.06297	.06015	.05443	.04938	.04365	.03986	.03683	.03359	.03054
16500.00 |	.05847	.05506	.05313	.04809	.04332	.03887	.03595	.03349	.03096
15000.00 |	.05418	.05158	.05010	.04685	.04309	.03839	.03503	.03268	.03065
13500.00 |	.05173	.04863	.04585	.04571	.04194	.03874	.03447	.03190	.02993

12000.00 |	.04970	.04537	.04359	.04244	.04109	.03803	.03485	.03126	.02930
10500.00 |	.04740	.04334	.04152	.03925	.03962	.03718	.03469	.03154	.02859
9000.00 |	.04510	.04189	.03906	.03766	.03663	.03640	.03404	.03169	.02879
7500.00 |	.04301	.04034	.03733	.03612	.03430	.03461	.03334	.03141	.02899
6000.00 |	.04118	.03874	.03616	.03426	.03310	.03218	.03240	.03075	.02902
4500.00 |	.03956	.03728	.03503	.03284	.03189	.03046	.03059	.03012	.02859
3000.00 |	.03800	.03594	.03380	.03183	.03047	.02951	.02869	.02895	.02802
1500.00 |	.03636	.03470	.03264	.03094	.02932	.02851	.02738	.02735	.02728
.00 |	.03465	.03352	.03163	.02999	.02845	.02738	.02659	.02588	.02603
-1500.00 |	.03295	.03238	.03072	.02901	.02770	.02645	.02574	.02486	.02472
-3000.00 |	.03137	.03121	.02985	.02812	.02695	.02572	.02482	.02418	.02357
-4500.00 |	.02997	.03000	.02900	.02737	.02614	.02508	.02406	.02344	.02275
-6000.00 |	.02875	.02877	.02816	.02671	.02535	.02445	.02345	.02267	.02216
-7500.00 |	.02766	.02756	.02729	.02609	.02466	.02380	.02291	.02203	.02151
-9000.00 |	.02666	.02644	.02638	.02548	.02407	.02312	.02238	.02153	.02084

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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: LOR ***
INCLUDING SOURCE(S): LORS1 , LORS2 , LORS3 , LORW1 , LORW2 , LORU2 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00 |	.02834	.02644	.02496	.02368	.02247	.02130	.02018	.01913
37500.00 |	.03044	.02854	.02669	.02497	.02342	.02205	.02083	.01974
36000.00 |	.03110	.02888	.02697	.02532	.02387	.02260	.02147	.02047
34500.00 |	.03415	.03174	.02964	.02779	.02616	.02469	.02338	.02219
33000.00 |	.03553	.03307	.03096	.02910	.02742	.02588	.02449	.02321
31500.00 |	.03727	.03475	.03229	.03000	.02796	.02620	.02469	.02340
30000.00 |	.03506	.03285	.03105	.02955	.02821	.02692	.02564	.02437
28500.00 |	.03384	.03142	.02943	.02770	.02617	.02484	.02372	.02279
27000.00 |	.03284	.03098	.02902	.02726	.02575	.02442	.02320	.02206
25500.00 |	.03274	.03015	.02815	.02659	.02510	.02370	.02255	.02159
24000.00 |	.03301	.03088	.02855	.02652	.02484	.02351	.02229	.02107
22500.00 |	.03151	.02998	.02865	.02707	.02528	.02367	.02228	.02114
21000.00 |	.03016	.02868	.02736	.02620	.02521	.02401	.02265	.02136
19500.00 |	.02954	.02761	.02630	.02522	.02415	.02326	.02246	.02151
18000.00 |	.02904	.02724	.02546	.02423	.02337	.02246	.02160	.02089
16500.00 |	.02816	.02667	.02527	.02368	.02245	.02168	.02100	.02022
15000.00 |	.02869	.02620	.02467	.02352	.02216	.02097	.02018	.01964
13500.00 |	.02822	.02670	.02452	.02300	.02195	.02082	.01972	.01889
12000.00 |	.02758	.02613	.02495	.02306	.02158	.02058	.01958	.01864
10500.00 |	.02708	.02556	.02431	.02338	.02176	.02036	.01939	.01847
9000.00 |	.02635	.02516	.02381	.02272	.02196	.02059	.01928	.01836
7500.00 |	.02646	.02445	.02347	.02227	.02131	.02069	.01953	.01833
6000.00 |	.02665	.02446	.02282	.02197	.02091	.02006	.01954	.01857
4500.00 |	.02679	.02466	.02272	.02140	.02064	.01971	.01896	.01850
3000.00 |	.02669	.02476	.02294	.02121	.02015	.01945	.01864	.01796
1500.00 |	.02617	.02491	.02298	.02143	.01991	.01903	.01838	.01767
.00 |	.02565	.02459	.02320	.02147	.02008	.01876	.01801	.01742
-1500.00 |	.02475	.02412	.02316	.02161	.02015	.01887	.01775	.01709
-3000.00 |	.02361	.02353	.02275	.02179	.02020	.01899	.01779	.01685
-4500.00 |	.02255	.02256	.02232	.02153	.02045	.01898	.01793	.01683
-6000.00 |	.02163	.02158	.02160	.02115	.02041	.01918	.01792	.01697
-7500.00 |	.02097	.02073	.02067	.02067	.02009	.01932	.01803	.01698
-9000.00 |	.02044	.01998	.01986	.01987	.01973	.01912	.01825	.01701

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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: KAD ***
INCLUDING SOURCE(S): KADS1 , KADWA , KADWB , KADWP , KADWQ , KADWL3 , KADUST1 ,
KADUST2 , KADUFR7 , KADULO3 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00 |	.04705	.04948	.04857	.04677	.05440	.05982	.06822	.06906	.07351
37500.00 |	.05257	.05486	.05702	.05338	.06011	.06884	.08116	.08332	.08595
36000.00 |	.05662	.06193	.06473	.06913	.06752	.08277	.09803	.10131	.09876
34500.00 |	.06910	.07045	.07549	.08259	.08428	.10173	.11929	.12840	.11907
33000.00 |	.10472	.09395	.09265	.09771	.11268	.12619	.15935	.16616	.13633
31500.00 |	.12812	.15618	.15150	.14076	.15520	.18249	.23326	.21325	.16692
30000.00 |	.14672	.17582	.21499	.27390	.32744	.33765	.39094	.32727	.19736
28500.00 |	.14876	.17590	.21879	.32134	.58902	.72001	1.23522	.47686	.23824
27000.00 |	.16094	.20888	.26541	.36332	.51048	.71465	.91894	.41633	.22331
25500.00 |	.17026	.21319	.28381	.35127	.46896	.55940	.59369	.33492	.20801
24000.00 |	.17676	.22187	.26042	.32561	.40987	.56505	.43360	.27214	.19405
22500.00 |	.18648	.21166	.25645	.30206	.36475	.40162	.32095	.21563	.16690
21000.00 |	.18561	.20463	.23329	.26674	.32099	.31307	.24562	.17913	.15086
19500.00 |	.17585	.20094	.21860	.24405	.27090	.26011	.20846	.15728	.13425
18000.00 |	.16775	.17853	.20532	.22918	.24038	.22643	.18163	.14060	.12836
16500.00 |	.15599	.17294	.18916	.20687	.21698	.20743	.16737	.13670	.12404
15000.00 |	.14218	.16356	.17662	.18668	.20018	.18845	.15544	.13593	.12889
13500.00 |	.14005	.15242	.16461	.16916	.18170	.17582	.15151	.13541	.12940
12000.00 |	.13518	.14275	.15204	.15846	.16729	.15972	.13535	.12448	.13100
10500.00 |	.12422	.13226	.13563	.14534	.15251	.14675	.12703	.12013	.12661

9000.00 |	.11934	.12579	.12846	.13833	.14417	.13891	.12093	.11535	.12279
7500.00 |	.11355	.11741	.12130	.12987	.13551	.13065	.11413	.11320	.12420
6000.00 |	.10967	.11280	.11825	.12489	.13094	.12884	.11728	.11561	.12068
4500.00 |	.10382	.10673	.11481	.12276	.12815	.12407	.11122	.11503	.12353
3000.00 |	.10175	.10524	.11104	.11707	.12151	.12126	.11356	.11624	.12188
1500.00 |	.09631	.10185	.10786	.11484	.12013	.11653	.11259	.11160	.11383
.00 |	.09385	.09937	.10570	.11168	.11294	.11610	.10675	.10619	.11115
-1500.00 |	.09161	.09713	.10059	.10669	.11350	.10759	.10407	.10186	.10105
-3000.00 |	.08892	.09158	.09892	.10695	.10408	.10663	.09787	.09399	.09229
-4500.00 |	.08533	.09184	.09726	.09926	.10414	.09852	.09137	.08592	.08854
-6000.00 |	.08615	.08846	.09196	.09971	.09551	.09227	.08527	.08288	.08216
-7500.00 |	.08214	.08517	.09205	.09167	.08976	.08680	.08067	.07894	.08071
-9000.00 |	.08003	.08453	.08493	.08674	.08476	.08135	.07896	.07413	.07769

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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: KAD ***
INCLUDING SOURCE(S): KADS1 , KADWA , KADWB , KADWP , KADWQ , KADWL3 , KADUST1 , KADUST2 , KADUFR7 , KADULO3 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00 |	.07078	.06727	.06625	.05930	.05636	.05123	.04947	.04465	.04173
37500.00 |	.08051	.07755	.06739	.06428	.05883	.05416	.05014	.04456	.04176
36000.00 |	.09411	.08022	.07530	.06707	.06211	.05317	.05015	.04455	.04282
34500.00 |	.10038	.09364	.07929	.06837	.06149	.05466	.05118	.04523	.04403
33000.00 |	.11911	.09528	.08203	.07092	.06148	.05609	.05467	.04830	.04618
31500.00 |	.12973	.10327	.08557	.07456	.06570	.05744	.05403	.04868	.04761
30000.00 |	.13374	.10571	.08810	.07532	.06691	.05966	.05702	.05272	.05204
28500.00 |	.16075	.12266	.10118	.08625	.07728	.06813	.06353	.05914	.05762
27000.00 |	.15153	.11729	.10191	.08958	.08125	.07217	.06673	.06302	.06071
25500.00 |	.13958	.11418	.09704	.08171	.07509	.07033	.06732	.06609	.06281
24000.00 |	.14260	.10793	.09365	.08463	.07881	.07224	.06593	.06496	.06168
22500.00 |	.13471	.10726	.08891	.08056	.07665	.07293	.06947	.06940	.06417
21000.00 |	.12631	.10557	.09034	.07968	.07155	.07196	.07164	.07113	.06746
19500.00 |	.12219	.10471	.08922	.08058	.07597	.07325	.07332	.07426	.07159
18000.00 |	.11215	.10592	.09235	.08162	.07853	.08142	.08178	.07880	.07548
16500.00 |	.10801	.10241	.09683	.08756	.08308	.08830	.09248	.09028	.08405
15000.00 |	.11586	.10442	.10047	.09582	.09032	.10000	.10811	.10692	.09325
13500.00 |	.12251	.12467	.11848	.10997	.10849	.12576	.14487	.12016	.09979
12000.00 |	.13494	.13319	.13799	.15347	.15650	.22668	.19037	.14389	.10901
10500.00 |	.13119	.13813	.16381	.18939	.28289	.57804	.24550	.16126	.11581
9000.00 |	.12946	.14553	.17668	.24430	.34188	.43662	.30540	.16406	.11176
7500.00 |	.13746	.15224	.18831	.22353	.35590	.46347	.27895	.15792	.11306
6000.00 |	.13488	.16425	.18188	.22613	.28497	.30667	.20142	.14527	.10201
4500.00 |	.14414	.15046	.17138	.20459	.22930	.22836	.15477	.12503	.10044
3000.00 |	.13150	.14819	.15690	.17162	.19386	.18839	.12781	.10659	.09466
1500.00 |	.12827	.13460	.14367	.15105	.16191	.15925	.10909	.09875	.08610
.00 |	.11402	.11978	.13261	.13870	.14257	.13709	.09528	.09228	.07608
-1500.00 |	.10508	.11491	.11907	.12359	.12681	.12033	.08495	.08242	.07140
-3000.00 |	.09660	.10874	.11084	.10995	.11445	.10710	.07717	.07327	.06849
-4500.00 |	.09332	.09893	.10291	.10108	.10462	.09652	.07113	.06628	.06574
-6000.00 |	.08966	.09220	.09462	.09415	.09690	.08799	.06616	.06110	.06204
-7500.00 |	.08280	.08534	.08647	.08799	.09040	.08097	.06206	.05702	.05706
-9000.00 |	.07913	.07957	.08051	.08280	.08458	.07516	.05864	.05357	.05245

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
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**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: KAD ***
INCLUDING SOURCE(S): KADS1 , KADWA , KADWB , KADWP , KADWQ , KADWL3 , KADUST1 , KADUST2 , KADUFR7 , KADULO3 ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00 |	.04026	.03789	.03423	.03252	.03123	.03002	.02909	.02778
37500.00 |	.04003	.03804	.03582	.03368	.03159	.03005	.02920	.02781
36000.00 |	.04206	.03859	.03563	.03362	.03228	.03159	.03081	.03025
34500.00 |	.04317	.03983	.03729	.03585	.03491	.03430	.03289	.03143
33000.00 |	.04453	.04176	.03925	.03769	.03615	.03402	.03253	.03068
31500.00 |	.04485	.04163	.03889	.03739	.03639	.03533	.03390	.03294
30000.00 |	.04876	.04577	.04426	.04286	.04081	.03921	.03728	.03581
28500.00 |	.05324	.04880	.04681	.04449	.04278	.04023	.03857	.03752
27000.00 |	.05667	.05323	.05092	.04848	.04599	.04381	.04246	.04036
25500.00 |	.05754	.05513	.05176	.04988	.04722	.04612	.04394	.04095
24000.00 |	.05761	.05603	.05461	.05178	.05027	.04701	.04330	.04114
22500.00 |	.06037	.05699	.05483	.05315	.04988	.04682	.04491	.04043
21000.00 |	.06474	.06218	.05826	.05310	.04911	.04655	.04113	.03914
19500.00 |	.06833	.06612	.06063	.05627	.05237	.04533	.04155	.03722
18000.00 |	.07429	.06682	.06141	.05718	.05054	.04503	.04076	.03773
16500.00 |	.07519	.06900	.06423	.05331	.04732	.04408	.04174	.03750
15000.00 |	.08041	.06909	.05762	.05366	.04872	.04304	.03963	.03753
13500.00 |	.08477	.06829	.06081	.05289	.04628	.04307	.04040	.03665
12000.00 |	.08544	.06855	.05704	.05161	.04658	.04373	.04192	.03981
10500.00 |	.08766	.07488	.06727	.05788	.04976	.04423	.04021	.03697
9000.00 |	.08699	.07282	.06489	.05850	.05169	.04564	.04137	.03850

7500.00 |	.08926	.07450	.06494	.05712	.05162	.04657	.04215	.03877
6000.00 |	.08437	.06845	.06018	.05442	.05030	.04651	.04133	.03690
4500.00 |	.07851	.06770	.05757	.05231	.04726	.04281	.04027	.03778
3000.00 |	.07684	.06563	.05619	.05050	.04519	.04233	.03939	.03630
1500.00 |	.07549	.06317	.05659	.04879	.04447	.04068	.03766	.03553
.00 |	.07376	.06265	.05418	.04967	.04370	.03999	.03676	.03452
-1500.00 |	.06669	.06249	.05326	.04761	.04421	.03981	.03642	.03371
-3000.00 |	.06020	.06006	.05392	.04647	.04253	.03985	.03660	.03357
-4500.00 |	.05743	.05491	.05347	.04697	.04133	.03847	.03629	.03387
-6000.00 |	.05491	.05029	.05067	.04758	.04150	.03736	.03517	.03333
-7500.00 |	.05286	.04833	.04688	.04634	.04250	.03737	.03419	.03242
-9000.00 |	.05106	.04650	.04344	.04388	.04246	.03808	.03406	.03156

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: FREE ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00 |	.54006	.54926	.55513	.59380	.63044	.65201	.65111	.62845	.61326
37500.00 |	.59941	.62769	.65300	.68444	.74310	.78740	.73428	.68918	.65879
36000.00 |	.70244	.72367	.78916	.89495	1.04009	1.04541	.83480	.75596	.71320
34500.00 |	.81997	.92091	1.06477	1.39966	1.52750	1.13976	.90626	.82218	.77833
33000.00 |	.90448	1.03151	1.35934	2.18038	1.86748	1.16883	1.00127	.91549	.85269
31500.00 |	.96804	1.15836	1.39648	1.93407	1.63110	1.17825	1.10326	1.01898	.93735
30000.00 |	1.03761	1.18747	1.39664	1.62468	1.47220	1.29836	1.28042	1.19009	1.03008
28500.00 |	1.04277	1.16284	1.33159	1.49514	1.63064	1.67188	2.16659	1.40767	1.15417
27000.00 |	1.07033	1.19431	1.34587	1.48147	1.53150	1.70813	1.93918	1.43916	1.25203
25500.00 |	1.14173	1.24466	1.36876	1.48105	1.54423	1.61655	1.71960	1.51028	1.39269
24000.00 |	1.26791	1.35964	1.43080	1.54163	1.60636	1.76829	1.71853	1.66119	1.67000
22500.00 |	1.42358	1.51459	1.61927	1.71960	1.80761	1.89783	1.96808	2.05193	1.95670
21000.00 |	1.55616	1.67898	1.84504	2.02578	2.22002	2.42452	2.84752	2.89278	2.41957
19500.00 |	1.62718	1.79261	2.00391	2.30183	2.75030	3.59241	4.98378	4.32885	3.37086
18000.00 |	1.68586	1.85077	2.09019	2.44409	3.08085	4.38788	5.90893	4.95321	3.61554
16500.00 |	1.72694	1.91927	2.19006	2.59824	3.14903	4.10699	5.07925	4.56090	3.78979
15000.00 |	1.77330	2.00255	2.29319	2.65191	3.12158	3.80953	4.30680	4.41224	4.82322
13500.00 |	1.83908	2.05466	2.31988	2.60449	3.02346	3.55032	4.23041	5.15838	4.77294
12000.00 |	1.88004	2.07889	2.27550	2.54431	2.90937	3.39582	4.02718	4.19786	3.89887
10500.00 |	1.85976	2.01640	2.23322	2.52109	2.84380	3.19113	3.53145	3.55035	3.41688
9000.00 |	1.84154	1.99316	2.21265	2.47291	2.73036	2.98165	3.20139	3.22819	3.18518
7500.00 |	1.81075	1.97946	2.17677	2.38435	2.57213	2.81369	3.00303	3.04083	3.08330
6000.00 |	1.77330	1.93424	2.11835	2.26635	2.46047	2.67700	2.83824	2.88956	3.00728
4500.00 |	1.72788	1.87269	2.01152	2.17661	2.36370	2.51917	2.64870	2.74803	2.88490
3000.00 |	1.69294	1.81536	1.95314	2.10136	2.25303	2.40195	2.53656	2.65672	2.80155
1500.00 |	1.64643	1.76152	1.89209	2.02629	2.16653	2.31846	2.44398	2.57234	2.75641
.00 |	1.60507	1.72527	1.83793	1.97225	2.09375	2.23559	2.37382	2.53059	2.71317
-1500.00 |	1.57442	1.68510	1.80630	1.92109	2.04859	2.17790	2.33097	2.47447	2.60217
-3000.00 |	1.54549	1.64945	1.75234	1.86129	1.97420	2.11360	2.23770	2.35336	2.46750
-4500.00 |	1.51622	1.60121	1.69771	1.79462	1.91246	2.03625	2.14463	2.25541	2.30755
-6000.00 |	1.47827	1.56050	1.65663	1.74772	1.85998	1.97712	2.07387	2.13418	2.18964
-7500.00 |	1.45118	1.53582	1.62380	1.71515	1.83180	1.92191	1.97794	2.03321	2.08768
-9000.00 |	1.42714	1.51075	1.58893	1.69120	1.76933	1.81481	1.87241	1.91517	1.98613

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: FREE ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00 |	.60880	.60934	.61286	.60674	.60694	.59009	.58092	.58600	.57692
37500.00 |	.65440	.64782	.64403	.63953	.63646	.62258	.61296	.61698	.60883
36000.00 |	.70343	.68449	.68963	.68084	.67649	.65785	.65157	.65491	.64067
34500.00 |	.75496	.73999	.73197	.72209	.71676	.70055	.69868	.69099	.67071
33000.00 |	.82321	.79064	.78193	.77226	.76382	.75192	.74326	.72545	.70933
31500.00 |	.88490	.85897	.83855	.82287	.81805	.79132	.78029	.76509	.74870
30000.00 |	.94815	.92103	.90890	.88290	.86015	.83813	.83232	.80671	.78828
28500.00 |	1.05304	1.02553	.99851	.94472	.92771	.89658	.88484	.86506	.83786
27000.00 |	1.15576	1.13937	1.07509	1.02065	.99214	.96376	.95321	.91898	.88903
25500.00 |	1.35062	1.28203	1.18089	1.10765	1.05913	1.02925	1.00080	.96752	.93861
24000.00 |	1.76326	1.45006	1.28810	1.21064	1.16323	1.11050	1.06971	1.02762	1.00828
22500.00 |	1.83869	1.58385	1.38820	1.29378	1.24755	1.18815	1.14653	1.11039	1.07962
21000.00 |	2.10328	1.72597	1.53652	1.41011	1.38447	1.31226	1.26887	1.20820	1.15219
19500.00 |	2.59275	1.98468	1.74507	1.60569	1.61119	1.54195	1.41392	1.30821	1.24369
18000.00 |	2.75688	2.32811	2.07195	1.99968	2.11320	1.85457	1.55662	1.41740	1.35008
16500.00 |	3.06927	2.49972	2.38564	3.20265	3.56315	2.23397	1.75315	1.58495	1.48685
15000.00 |	3.41353	2.63937	2.61561	3.16995	3.39433	2.23889	1.91533	1.76605	1.66129
13500.00 |	3.43999	2.85087	2.85459	3.18498	2.77383	2.30888	2.17673	2.00327	1.86526
12000.00 |	3.36194	2.99318	2.98196	3.09449	2.85958	2.69722	2.69946	2.40498	2.18412
10500.00 |	3.14275	2.97812	3.08429	3.28899	3.26947	3.75690	4.00865	3.10941	2.85163

9000.00	3.06541	3.10019	3.43479	3.52767	3.70094	4.24862	4.88658	3.92519	4.35879
7500.00	3.09541	3.27465	3.64894	3.85452	4.47989	5.41774	5.46844	4.53943	4.95137
6000.00	3.16580	3.44975	3.92816	4.78254	5.43610	5.93134	5.90255	4.68986	4.58315
4500.00	3.11753	3.54214	4.45072	6.19091	5.96882	6.17561	5.14814	4.43493	4.54211
3000.00	3.06187	3.51504	4.35700	5.53579	5.32468	4.95485	4.56768	4.57290	5.73332
1500.00	3.03946	3.40385	3.99043	4.54296	4.43947	4.40704	4.23122	4.58294	5.87170
.00	2.92656	3.22125	3.64446	3.93664	3.85731	3.96772	3.98378	4.26317	4.84414
-1500.00	2.76811	3.01261	3.31436	3.52833	3.55141	3.67538	3.70928	3.95684	4.20795
-3000.00	2.58131	2.80248	3.02913	3.21359	3.27975	3.41804	3.50955	3.69951	4.02293
-4500.00	2.43132	2.59982	2.82259	2.99039	3.01272	3.15266	3.32231	3.68699	4.33161
-6000.00	2.30908	2.45871	2.62496	2.74189	2.75481	2.91654	3.09200	3.50528	4.69408
-7500.00	2.19101	2.31108	2.44400	2.53074	2.60389	2.76735	2.92817	3.28145	3.86910
-9000.00	2.07085	2.17225	2.29526	2.40548	2.47872	2.59673	2.71463	2.88754	3.11860

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: FREE ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD (METERS)	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00	.57932	.57348	.54746	.53325	.52056	.51095	.49900	.48611
37500.00	.60954	.59339	.57321	.55650	.54327	.53151	.51625	.50303
36000.00	.63395	.62049	.59746	.57903	.56830	.55183	.53557	.52449
34500.00	.66776	.65477	.62640	.60900	.59367	.57624	.56033	.54813
33000.00	.70342	.69020	.65205	.63610	.62086	.60191	.58523	.56598
31500.00	.74292	.71807	.68068	.66665	.65232	.62875	.60366	.58388
30000.00	.78427	.75445	.71586	.70429	.68301	.65507	.63048	.60937
28500.00	.82823	.79002	.75507	.73960	.70930	.67300	.65275	.62515
27000.00	.87284	.82594	.79205	.76927	.73490	.70431	.67684	.64959
25500.00	.91983	.87073	.83342	.81025	.77444	.73915	.71262	.67891
24000.00	.97364	.91838	.88605	.86178	.81421	.77431	.74175	.70706
22500.00	1.03610	.97748	.94494	.90315	.85297	.81778	.78135	.73897
21000.00	1.09842	1.04288	1.00313	.95830	.90478	.86281	.81962	.77457
19500.00	1.17943	1.11285	1.07797	1.02664	.97170	.92652	.87281	.80556
18000.00	1.28075	1.22036	1.18023	1.11594	1.04350	.98682	.90814	.83715
16500.00	1.41734	1.35516	1.29019	1.21159	1.12611	1.03659	.95036	.87866
15000.00	1.57719	1.49739	1.41624	1.32097	1.19702	1.08518	1.00108	.92025
13500.00	1.80391	1.71839	1.63747	1.43292	1.27323	1.14342	1.03303	.93556
12000.00	2.12065	2.05055	1.82062	1.52748	1.33549	1.19489	1.07376	.97205
10500.00	2.90602	2.54405	1.95867	1.63951	1.42142	1.26038	1.12437	1.01720
9000.00	4.62795	2.90768	2.13985	1.78940	1.54326	1.34987	1.19603	1.07769
7500.00	4.09493	2.95667	2.32327	1.92268	1.64922	1.43004	1.26424	1.11390
6000.00	4.59074	3.56338	2.60383	2.07800	1.76193	1.52281	1.30884	1.16069
4500.00	4.88957	4.36744	2.86972	2.30778	1.93770	1.62774	1.37843	1.19465
3000.00	5.25617	3.87352	3.20046	2.84114	2.30297	1.71752	1.42909	1.22500
1500.00	5.01746	3.67108	3.70968	3.64411	2.46963	1.79661	1.46347	1.24081
.00	4.31471	3.83169	3.64333	3.15473	2.37661	1.77813	1.42731	1.19973
-1500.00	4.08045	3.97244	4.10078	3.63455	2.29273	1.74472	1.39106	1.17963
-3000.00	4.28094	5.10550	5.51177	4.00900	2.30936	1.72296	1.40341	1.19510
-4500.00	5.17282	5.27885	4.68553	3.05999	2.14438	1.65557	1.37147	1.16753
-6000.00	5.39542	4.28413	3.42333	2.50990	1.93828	1.55565	1.32679	1.14268
-7500.00	3.77284	3.34551	2.70103	2.13789	1.73903	1.45851	1.25458	1.10477
-9000.00	3.01953	2.75488	2.30077	1.86688	1.59599	1.37047	1.19253	1.06219

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: NL57 ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD (METERS)	X-COORD (METERS) -5000.00	-3500.00	-2000.00	-500.00	1000.00	2500.00	4000.00	5500.00	7000.00
39000.00	.23319	.23441	.24504	.25458	.26095	.26819	.27978	.29529	.30315
37500.00	.25476	.25048	.25816	.27058	.28295	.28992	.29929	.31473	.32314
36000.00	.28005	.26901	.27739	.28836	.30237	.31424	.32630	.33780	.34716
34500.00	.30648	.29785	.29261	.31267	.32459	.34052	.35948	.36372	.37665
33000.00	.33541	.33215	.32068	.33326	.35155	.37078	.39672	.40130	.41250
31500.00	.36721	.37415	.36150	.35829	.38144	.41080	.43471	.45136	.45836
30000.00	.39919	.41955	.41810	.40312	.42092	.44805	.48687	.51098	.52065
28500.00	.42585	.45028	.47723	.47716	.47475	.50304	.54347	.58123	.59961
27000.00	.47135	.49987	.52682	.54535	.54454	.59000	.63652	.67878	.69902
25500.00	.55479	.56361	.59472	.62762	.64328	.67274	.75863	.82751	.85088
24000.00	.67999	.69452	.71398	.75369	.78901	.82755	.92745	1.03769	1.13729
22500.00	.81914	.87277	.92713	.97432	1.04625	1.12278	1.28674	1.48295	1.43903
21000.00	.94701	1.04673	1.17817	1.32539	1.50178	1.73640	2.23183	2.34386	1.90789
19500.00	1.02136	1.15766	1.34095	1.61559	2.07073	2.94411	4.38878	3.78785	2.85302
18000.00	1.07712	1.22670	1.43187	1.75516	2.40808	3.74690	5.31322	4.40272	3.07552
16500.00	1.11295	1.27951	1.52672	1.91808	2.47402	3.45457	4.46345	3.97390	3.21417
15000.00	1.15065	1.34874	1.61362	1.95959	2.43215	3.13792	3.66773	3.78412	4.19590
13500.00	1.19680	1.38579	1.62231	1.89802	2.30970	2.84586	3.54089	4.47390	4.08571
12000.00	1.22897	1.40321	1.56972	1.82005	2.17330	2.66574	3.30509	3.45824	3.13676

10500.00 |	1.20640	1.33485	1.52348	1.78678	2.09476	2.43655	2.77355	2.77003	2.59773
9000.00 |	1.18738	1.30816	1.49594	1.72477	1.95762	2.19484	2.40486	2.39822	2.30248
7500.00 |	1.15033	1.28751	1.45051	1.62481	1.78180	1.99923	2.16137	2.14579	2.11529
6000.00 |	1.10788	1.23134	1.37496	1.48462	1.63877	1.81913	1.94279	1.93155	1.96053
4500.00 |	1.07077	1.17642	1.26811	1.38918	1.53319	1.65341	1.73942	1.75313	1.80790
3000.00 |	1.03689	1.12045	1.21688	1.32633	1.43362	1.53701	1.60216	1.64893	1.70983
1500.00 |	.99830	1.07729	1.16540	1.24997	1.33571	1.42660	1.49846	1.55321	1.63373
.00 |	.95705	1.02905	1.09463	1.17653	1.24953	1.34301	1.43619	1.49833	1.57131
-1500.00 |	.91673	.98399	1.05712	1.12831	1.20333	1.28944	1.36417	1.43047	1.46357
-3000.00 |	.89892	.95897	1.02047	1.08169	1.14885	1.22735	1.30039	1.34231	1.33052
-4500.00 |	.87743	.92323	.97771	1.02917	1.09635	1.18092	1.22253	1.24219	1.20038
-6000.00 |	.84383	.88704	.93927	.98564	1.05882	1.10985	1.14510	1.12585	1.10796
-7500.00 |	.81103	.85364	.90394	.95368	1.00747	1.04214	1.04854	1.04383	1.02943
-9000.00 |	.78136	.83273	.86787	.91532	.94808	.96210	.97666	.97531	.97074

**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: NL57 ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,

*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***

** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 8500.00	10000.00	11500.00	13000.00	14500.00	16000.00	17500.00	19000.00	20500.00
39000.00 |	.32220	.32737	.33581	.33726	.33892	.33015	.31984	.32440	.31313
37500.00 |	.34602	.35045	.36094	.36059	.36072	.35218	.34352	.34602	.33476
36000.00 |	.37230	.37711	.38741	.38809	.38590	.37582	.37054	.37228	.35451
34500.00 |	.40140	.40796	.41686	.41673	.41538	.40471	.40377	.39469	.36937
33000.00 |	.43457	.44547	.45612	.45378	.45099	.44210	.43102	.41390	.39243
31500.00 |	.47464	.49552	.50081	.49466	.49382	.47243	.45737	.44146	.41615
30000.00 |	.52436	.54824	.56311	.55137	.52834	.50802	.49536	.46740	.43952
28500.00 |	.59536	.61835	.62841	.59558	.57833	.54783	.52992	.50398	.46868
27000.00 |	.69938	.72791	.68744	.65487	.62892	.59892	.58145	.53808	.50050
25500.00 |	.88880	.86081	.78440	.73221	.68999	.65301	.61149	.56382	.52554
24000.00 |	1.28693	1.01649	.87502	.81445	.77157	.71761	.66581	.60444	.57159
22500.00 |	1.35614	1.13268	.95782	.87548	.83359	.77635	.71731	.65696	.61387
21000.00 |	1.61196	1.25416	1.08216	.96265	.94231	.87650	.81136	.72517	.64883
19500.00 |	2.09108	1.48925	1.26277	1.12726	1.12496	1.06183	.92210	.78849	.69464
18000.00 |	2.23480	1.81224	1.54999	1.48163	1.58064	1.31208	1.00964	.85292	.74711
16500.00 |	2.50374	1.94072	1.82757	2.62974	2.98385	1.61369	1.12584	.94717	.81751
15000.00 |	2.79152	2.01585	1.98487	2.51996	2.73483	1.54207	1.19674	1.02642	.89113
13500.00 |	2.75073	2.13923	2.12408	2.42026	1.98287	1.49234	1.31465	1.14543	.97434
12000.00 |	2.57216	2.18602	2.13551	2.14742	1.85793	1.61927	1.62569	1.33568	1.06502
10500.00 |	2.28801	2.06198	2.04849	2.02647	1.95820	2.07753	2.59111	1.61167	1.17242
9000.00 |	2.10854	2.04922	2.18131	2.19866	2.21312	2.53490	3.10464	1.88516	1.23773
7500.00 |	2.03730	2.08803	2.28650	2.45171	2.82850	3.52567	3.44849	2.00511	1.26945
6000.00 |	2.02389	2.18391	2.50270	3.21533	3.66349	3.98839	3.72529	2.07153	1.27736
4500.00 |	1.92467	2.20798	2.94565	4.50521	4.10186	4.07022	2.82865	1.74796	1.20793
3000.00 |	1.84600	2.14287	2.81929	3.81093	3.31122	2.80079	2.08593	1.44117	1.09911
1500.00 |	1.78631	2.01463	2.38792	2.68723	2.41938	2.12895	1.67097	1.21860	.99556
.00 |	1.65701	1.77028	2.00411	2.09479	1.90413	1.71434	1.40930	1.08301	.91176
-1500.00 |	1.48542	1.57606	1.69525	1.73909	1.58585	1.43136	1.22145	.97412	.83707
-3000.00 |	1.33748	1.40499	1.48789	1.48649	1.35225	1.23512	1.06988	.88207	.78047
-4500.00 |	1.21910	1.26339	1.32551	1.30436	1.18154	1.09143	.94577	.80485	.73161
-6000.00 |	1.12664	1.14975	1.18278	1.15865	1.05390	.97883	.84884	.73377	.68638
-7500.00 |	1.04140	1.05749	1.06821	1.03831	.95289	.88693	.77309	.67349	.63394
-9000.00 |	.96538	.96885	.97429	.94180	.87113	.80996	.71142	.62144	.58586

**MODELOPTs: CONC RURAL FLAT FLGPOL
*** THE ANNUAL (8736 HRS) AVERAGE CONCENTRATION VALUES FOR SOURCE GROUP: NL57 ***
INCLUDING SOURCE(S): FSOS2A , FSOS2B , FSOS2C , FSOS2D , FSOS3 , FSOS4 , FSOS5A ,
FSOS5B , FSOS6 , FSOS8A , FSOS8B , FSOS8C , FSOS9 , FSOS10 , FSOS11 , FSOS12 , FSOS13 , FSOS17 , FSOWC ,
FSOWD , FSOWE , FSOWF , FSOWG , FSOWH , FSOWI , FSOWJ , FSOWK , FSOWL , FSOWM , FSOWN , . . . ,
*** NETWORK ID: CART1 ; NETWORK TYPE: GRIDCART ***
** CONC OF RADON IN BQ/M3 **

Y-COORD | (METERS) |	X-COORD (METERS) 22000.00	23500.00	25000.00	26500.00	28000.00	29500.00	31000.00	32500.00
39000.00 |	.31004	.30771	.29406	.28113	.26673	.25561	.24546	.23522
37500.00 |	.32896	.31664	.30714	.29142	.27661	.26518	.25244	.24236
36000.00 |	.34056	.33299	.32103	.30172	.28835	.27227	.25958	.25058
34500.00 |	.35949	.35163	.33440	.31374	.29535	.28010	.26978	.26041
33000.00 |	.38060	.37091	.34406	.32340	.30497	.29257	.28205	.26636
31500.00 |	.40398	.38318	.35757	.33631	.32039	.30439	.28544	.26852
30000.00 |	.42713	.40204	.37256	.34971	.33030	.31176	.29200	.27597
28500.00 |	.44917	.41972	.39028	.36485	.33893	.31422	.29675	.27963
27000.00 |	.47127	.43265	.39968	.36836	.34164	.32212	.30263	.28621
25500.00 |	.49615	.45298	.41442	.38181	.35832	.33699	.31678	.29927
24000.00 |	.52291	.47102	.43221	.40312	.37529	.34682	.32488	.30784
22500.00 |	.55380	.49729	.45332	.41696	.38525	.36143	.34142	.31864
21000.00 |	.57683	.51794	.47287	.43608	.40262	.37750	.35227	.32897
19500.00 |	.60779	.54420	.49708	.45918	.43163	.40204	.37294	.34576
18000.00 |	.65470	.59256	.54377	.50050	.45858	.42098	.38610	.35684
16500.00 |	.72182	.64878	.58796	.53277	.48223	.43546	.39908	.37026
15000.00 |	.77594	.69115	.61509	.54960	.49192	.44852	.41160	.37800
13500.00 |	.84051	.72284	.63077	.55513	.49920	.45148	.40985	.37267
12000.00 |	.88204	.75474	.64083	.55673	.49484	.44236	.39778	.36553
10500.00 |	.92514	.75068	.64512	.55879	.48900	.43911	.40241	.37028
9000.00 |	.93495	.75818	.63165	.55678	.49799	.44793	.41010	.37955
7500.00 |	.92876	.75604	.64371	.56394	.50401	.45660	.41513	.38052

6000.00 |	.94769	.76766	.65194	.56999	.50595	.45734	.41868	.38580
4500.00 |	.94147	.76754	.65438	.57387	.51463	.46468	.42439	.39199
3000.00 |	.88906	.73899	.63409	.55524	.49507	.45231	.41696	.38612
1500.00 |	.83238	.70587	.60605	.53427	.48107	.43514	.39905	.36950
.00 |	.77699	.67995	.59189	.51759	.46548	.42304	.38861	.36040
-1500.00 |	.72745	.64216	.57450	.51180	.45444	.41379	.38116	.35113
-3000.00 |	.68461	.60991	.54903	.49716	.45012	.40510	.37185	.34652
-4500.00 |	.64532	.58521	.52776	.48131	.43838	.40174	.36617	.33726
-6000.00 |	.61514	.55651	.51096	.46476	.42872	.39242	.36262	.33494
-7500.00 |	.58713	.52937	.49097	.45335	.41621	.38588	.35540	.33060
-9000.00 |	.55699	.50906	.47221	.43923	.40607	.37763	.35043	.32483

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
PAGE 35
**MODELOPTs: CONC RURAL FLAT FLGPOL

*** THE SUMMARY OF MAXIMUM PERIOD (8736 HRS) RESULTS ***

** CONC OF RADON IN BQ/M3 **

GROUP ID		AVERAGE CONC	RECEPTOR (XR, YR, ZELEV, ZFLAG)	NETWORK OF TYPE	GRID-ID
ARM	1ST HIGHEST VALUE IS	2.03167	AT (14500.00, 16500.00, .00, 1.50)	GC	CART1
	2ND HIGHEST VALUE IS	1.72411	AT (14500.00, 15000.00, .00, 1.50)	GC	CART1
FSO	1ST HIGHEST VALUE IS	5.12445	AT (4000.00, 18000.00, .00, 1.50)	GC	CART1
	2ND HIGHEST VALUE IS	4.27780	AT (4000.00, 16500.00, .00, 1.50)	GC	CART1
HARMONY	1ST HIGHEST VALUE IS	4.88643	AT (25000.00, -3000.00, .00, 1.50)	GC	CART1
	2ND HIGHEST VALUE IS	4.76314	AT (20500.00, 1500.00, .00, 1.50)	GC	CART1
LOR	1ST HIGHEST VALUE IS	1.58115	AT (-500.00, 33000.00, .00, 1.50)	GC	CART1
	2ND HIGHEST VALUE IS	1.25937	AT (-500.00, 31500.00, .00, 1.50)	GC	CART1
KAD	1ST HIGHEST VALUE IS	1.23522	AT (4000.00, 28500.00, .00, 1.50)	GC	CART1
	2ND HIGHEST VALUE IS	.91894	AT (4000.00, 27000.00, .00, 1.50)	GC	CART1
FREE	**1ST HIGHEST VALUE IS**	**6.19091**	**AT (13000.00, 4500.00, .00, 1.50)**	**GC**	**CART1**
	2ND HIGHEST VALUE IS	**6.17561**	**AT (16000.00, 4500.00, .00, 1.50)**	**GC**	**CART1**
NL57	1ST HIGHEST VALUE IS	5.31322	AT (4000.00, 18000.00, .00, 1.50)	GC	CART1
	2ND HIGHEST VALUE IS	4.50521	AT (13000.00, 4500.00, .00, 1.50)	GC	CART1

*** RECEPTOR TYPES: GC = GRIDCART
GP = GRIDPOLR
DC = DISCCART
DP = DISCPOLR
BD = BOUNDARY

*** ISCST3 - VERSION 96113 *** *** ANGLOGOLD - FREE STATE OPERATIONS *** 12/10/98
*** ENVIRONMENTAL RADON MODELLING *** 12:53:08
PAGE 36
**MODELOPTs: CONC RURAL FLAT FLGPOL

*** Message Summary : ISCST3 Model Execution ***
--------- Summary of Total Messages --------
A Total of 0 Fatal Error Message(s)
A Total of 0 Warning Message(s)
A Total of 0 Informational Message(s)

******** FATAL ERROR MESSAGES ********
*** NONE ***

******** WARNING MESSAGES ********
*** NONE ***

****
*** ISCST3 Finishes Successfully ***
****

EXCEL WATER MODEL

The following provides an example of the water model used to determine the exposures from ground and surface water sources:

EXPOSURE DUE TO CONSUMPTION OF FOODSTUFFS AND LIQUIDS FOR ACTUAL AND HYPOTHETICAL CRITICAL GROUPS (USING MEASURED VALUES FROM AEC)

Water Intake	Annual Consumptions, kg/a				
	Adults	15 year	10 year	5 year	1 year
Water & Beverages	730	600	350	300	260
Milk Products	250	300	300	300	300
Meat Products	100	100	75	50	20
Poultry	75	75	60	35	15
Eggs	30	30	25	15	6
Grain Products	150	128	90	75	60
Leafy Vegatables	130	111	78	65	52
Roots & Fruits	170	145	102	85	68
Fish Products	25	10	10	5	1

MODEL OF ALL PATHWAYS TO HUMAN EXPOSURE FROM GROUNDWATER
(Roots, Fruits and Leavy vegatables)

This model contains all the possible pathways to humans from the use of groundwater.
Consumption intake and concentration factors used in this model are all from LG 1032.
All values in green are LG 1032 references
All values in blue are assumptions.
All values in red are ICRP72 references
All values in grey are export concentrations to Model

GROUNDWATER		SOIL	ROOT VEGETABLES				FRUIT				Roots : Fruits	LEAFY VEGETABLES				GRAINS	
(Measured)				WET	DRY			WET	DRY				WET	DRY			
Nuclide	Bq/l	Bq/g	Fv2	Bq/g	Bq/g 20% Bq/g	Bq/g	Fv2	Bq/g	Bq/g 10% Bq/g	Bq/g	Bq/g	Fv2	Bq/g	Bq/g 15% Bq/g	Bq/g	Fv2	Bq/g
U-238	3.0E+00	3.00E-03	1.51E-02	4.53E-05	9.06E-06	5.44E-05	4.00E-04	1.20E-06	1.20E-07	1.32E-06	3.84E-05	5.06E-03	1.52E-05	2.28E-06	1.75E-05	7.50E-04	2.25E-06
U-234	3.0E+00	3.00E-03	1.51E-02	4.53E-05	9.06E-06	5.44E-05	4.00E-04	1.20E-06	1.20E-07	1.32E-06	3.84E-05	5.06E-03	1.52E-05	2.28E-06	1.75E-05	7.50E-04	2.25E-06
Th-230	3.0E+00	3.00E-03	4.01E-04	1.20E-06	2.40E-07	1.44E-06	4.00E-04	1.20E-06	1.20E-07	1.32E-06	1.41E-06	5.00E-03	1.50E-05	2.25E-06	1.73E-05	7.50E-04	2.25E-06
Ra-226	1.5E-01	1.48E-04	2.00E-02	2.96E-06	5.93E-07	3.56E-06	2.02E-02	2.99E-06	2.99E-07	3.29E-06	3.48E-06	2.01E-02	2.97E-06	4.45E-07	3.41E-06	5.12E-03	7.58E-07
Pb-210	2.9E-02	2.90E-05	1.00E-02	2.90E-07	5.81E-08	3.49E-07	1.00E-02	2.90E-07	2.90E-08	3.19E-07	3.40E-07	1.50E-02	4.36E-07	6.54E-08	5.02E-07	2.52E-02	7.32E-07
Po-210	2.9E-02	2.90E-05	1.10E-03	3.19E-08	6.38E-09	3.83E-08	1.00E-03	2.90E-08	2.90E-09	3.19E-08	3.64E-08	1.15E-03	3.34E-08	5.00E-09	3.84E-08	1.50E-03	4.35E-08
U-235	2.1E-02	2.10E-05	3.00E-02	6.30E-07	1.26E-07	7.56E-07	4.00E-04	8.40E-09	8.40E-10	9.24E-09	5.32E-07	1.00E-02	2.10E-07	3.15E-08	2.42E-07	1.30E-03	2.73E-08
Pa-231	2.1E-02	2.10E-05	1.00E-02	2.10E-07	4.20E-08	2.52E-07	5.00E-03	1.05E-07	1.05E-08	1.16E-07	2.11E-07	8.00E-03	1.68E-07	2.52E-08	1.93E-07	2.00E-02	4.20E-07
Ac-227	2.1E-02	2.10E-05	2.00E-03	4.20E-08	8.40E-09	5.04E-08	1.00E-03	2.10E-08	2.10E-09	2.31E-08	4.22E-08	1.50E-03	3.15E-08	4.73E-09	3.62E-08	3.00E-04	6.30E-09
Th-227	2.1E-02	2.10E-05	8.00E-04	1.68E-08	3.36E-09	2.02E-08	4.00E-04	8.40E-09	8.40E-10	9.24E-09	1.69E-08	1.00E-02	2.10E-07	3.15E-08	2.42E-07	1.00E-03	2.10E-08
Ra-223	2.1E-02	2.10E-05	4.00E-02	8.40E-07	1.68E-07	1.01E-06	4.00E-02	8.40E-07	8.40E-08	9.24E-07	9.83E-07	4.00E-02	8.40E-07	1.26E-07	9.66E-07	1.00E-02	2.10E-07
Th-232	2.6E-03	2.60E-06	8.00E-04	2.08E-09	4.16E-10	2.50E-09	4.00E-04	1.04E-09	1.04E-10	1.14E-09	2.09E-09	1.00E-02	2.60E-08	3.90E-09	2.99E-08	1.00E-03	2.60E-09
Th-228	2.6E-03	2.60E-06	8.00E-04	2.08E-09	4.16E-10	2.50E-09	4.00E-04	1.04E-09	1.04E-10	1.14E-09	2.09E-09	1.00E-02	2.60E-08	3.90E-09	2.99E-08	1.00E-03	2.60E-09
Ra-228	2.6E-03	2.60E-06	4.00E-02	1.04E-07	2.08E-08	1.25E-07	4.00E-02	1.04E-07	1.04E-08	1.14E-07	1.22E-07	4.00E-02	1.04E-07	1.56E-08	1.20E-07	1.00E-02	2.60E-08
Ra-224	2.6E-03	2.60E-06	4.00E-02	1.04E-07	2.08E-08	1.25E-07	4.00E-02	1.04E-07	1.04E-08	1.14E-07	1.22E-07	4.00E-02	1.04E-07	1.56E-08	1.20E-07	1.00E-02	2.60E-08

MODEL OF ALL PATHWAYS TO HUMAN EXPOSURE FROM GROUNDWATER
(Milk Products)

Sheep, goats, pigs

GROUNDWATER		**SOIL**	**PLANTS**		**Intake**	**Intake**		**Activity in Milk**		**Activity in Milk**		**Activity in Milk**	
(Measured)			**Pasture, grass, browse**		Soil	**Dry Feed**	**Water**	Dry solid food intake		Water intake		Total Sheep	Cow (90%)
Nuclide	Bq/l	Bq/g	Fv1	Bq/g	20% Bq/g	kg/d 4 Bq/d	l/d 15 Bq/d	Units/d/l Fm	Bq/l	Fm Units/d/l	Bq/l	Bq/l	Sheep (10%) Comb Bq/l
U-238	3.000	3.00E-03	1.00E-01	3.00E-04	3.60E-04	1.44E+00	4.50E+01	3.42E-04	4.92E-04	3.42E-04	1.54E-02	1.59E-02	7.32E-02
U-234	3.000	3.00E-03	1.00E-01	3.00E-04	3.60E-04	1.44E+00	4.50E+01	3.42E-04	4.92E-04	3.42E-04	1.54E-02	1.59E-02	7.32E-02
Th-230	3.000	3.00E-03	5.00E-02	1.50E-04	1.80E-04	7.20E-01	4.50E+01	3.75E-06	2.70E-06	3.75E-06	1.69E-04	1.71E-04	7.90E-04
Ra-226	0.148	1.48E-04	2.01E-01	2.97E-05	3.56E-05	1.42E-01	2.22E+00	6.54E-04	9.31E-05	6.54E-04	1.45E-03	1.54E-03	7.14E-03
Pb-210	0.029	2.90E-05	2.50E-01	7.25E-06	8.70E-06	3.48E-02	4.35E-01	1.65E-04	5.74E-06	1.65E-04	7.18E-05	7.75E-05	3.59E-04
Po-210	0.029	2.90E-05	5.03E-02	1.46E-06	1.75E-06	6.99E-03	4.35E-01	1.55E-03	1.08E-05	1.55E-03	6.74E-04	6.85E-04	3.16E-03
U-235	0.021	2.10E-05	2.00E-01	4.20E-06	5.04E-06	2.02E-02	3.15E-01	6.00E-04	1.21E-05	6.00E-04	1.89E-04	2.01E-04	9.30E-04
Pa-231	0.021	2.10E-05	1.00E-01	2.10E-06	2.52E-06	1.01E-02	3.15E-01	5.00E-06	5.04E-08	5.00E-06	1.58E-06	1.63E-06	7.50E-06
Ac-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.52E-06	1.01E-02	3.15E-01	2.00E-04	2.02E-06	2.00E-04	6.30E-05	6.50E-05	3.00E-04
Th-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.52E-06	1.01E-02	3.15E-01	5.00E-06	5.04E-08	5.00E-06	1.58E-06	1.63E-06	7.50E-06
Ra-223	0.021	2.10E-05	4.00E-01	8.40E-06	1.01E-05	4.03E-02	3.15E-01	1.30E-03	5.24E-05	1.30E-03	4.10E-04	4.62E-04	2.15E-03
Th-232	0.003	2.60E-06	1.00E-01	2.60E-07	3.12E-07	1.25E-03	3.90E-02	5.00E-06	6.24E-09	5.00E-06	1.95E-07	2.01E-07	9.28E-07
Th-228	0.003	2.60E-06	1.00E-01	2.60E-07	3.12E-07	1.25E-03	3.90E-02	5.00E-06	6.24E-09	5.00E-06	1.95E-07	2.01E-07	9.28E-07
Ra-228	0.003	2.60E-06	4.00E-01	1.04E-06	1.25E-06	4.99E-03	3.90E-02	1.30E-03	6.49E-06	1.30E-03	5.07E-05	5.72E-05	2.66E-04
Ra-224	0.003	2.60E-06	4.00E-01	1.04E-06	1.25E-06	4.99E-03	3.90E-02	1.30E-03	6.49E-06	1.30E-03	5.07E-05	5.72E-05	2.66E-04

Cattle

GROUNDWATER		SOIL	PLANTS		Intake	Intake		Activity in Milk		Activity in Milk		Activity in Milk	
(Measured)			Pasture, grass, browse		Soil	Dry Feed	Water	Dry solid food intake		Water intake		Total Cattle	Cow (90%)
Nuclide	Bq/l	Bq/g	Fv1	Bq/g	5% Bq/g	kg/d 25 Bq/d	l/d 75 Bq/d	Units/d/l Fm	Bq/l	Fm Units/d/l	Bq/l	Bq/l	Sheep (10%) Comb Bq/l
U-238	3.000	3.00E-03	1.00E-01	3.00E-04	3.15E-04	7.88E+00	2.25E+02	3.42E-04	2.69E-03	3.42E-04	7.68E-02	7.95E-02	7.32E-02
U-234	3.000	3.00E-03	1.00E-01	3.00E-04	3.15E-04	7.88E+00	2.25E+02	3.42E-04	2.69E-03	3.42E-04	7.68E-02	7.95E-02	7.32E-02
Th-230	3.000	3.00E-03	5.00E-02	1.50E-04	1.58E-04	3.94E+00	2.25E+02	3.75E-06	1.48E-05	3.75E-06	8.44E-04	8.59E-04	7.90E-04
Ra-226	0.148	1.48E-04	2.01E-01	2.97E-05	3.12E-05	7.79E-01	1.11E+01	6.54E-04	5.09E-04	6.54E-04	7.25E-03	7.76E-03	7.14E-03
Pb-210	0.029	2.90E-05	2.50E-01	7.25E-06	7.62E-06	1.90E-01	2.18E+00	1.65E-04	3.14E-05	1.65E-04	3.59E-04	3.90E-04	3.59E-04
Po-210	0.029	2.90E-05	5.03E-02	1.46E-06	1.53E-06	3.83E-02	2.18E+00	1.55E-03	5.93E-05	1.55E-03	3.37E-03	3.43E-03	3.16E-03
U-235	0.021	2.10E-05	2.00E-01	4.20E-06	4.41E-06	1.10E-01	1.58E+00	6.00E-04	6.62E-05	6.00E-04	9.45E-04	1.01E-03	9.30E-04
Pa-231	0.021	2.10E-05	1.00E-01	2.10E-06	2.21E-06	5.51E-02	1.58E+00	5.00E-06	2.76E-07	5.00E-06	7.88E-06	8.15E-06	7.50E-06
Ac-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.21E-06	5.51E-02	1.58E+00	2.00E-04	1.10E-05	2.00E-04	3.15E-04	3.26E-04	3.00E-04
Th-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.21E-06	5.51E-02	1.58E+00	5.00E-06	2.76E-07	5.00E-06	7.88E-06	8.15E-06	7.50E-06
Ra-223	0.021	2.10E-05	4.00E-01	8.40E-06	8.82E-06	2.21E-01	1.58E+00	1.30E-03	2.87E-04	1.30E-03	2.05E-03	2.33E-03	2.15E-03
Th-232	0.003	2.60E-06	1.00E-01	2.60E-07	2.73E-07	6.83E-03	1.95E-01	5.00E-06	3.41E-08	5.00E-06	9.75E-07	1.01E-06	9.28E-07
Th-228	0.003	2.60E-06	1.00E-01	2.60E-07	2.73E-07	6.83E-03	1.95E-01	5.00E-06	3.41E-08	5.00E-06	9.75E-07	1.01E-06	9.28E-07
Ra-228	0.003	2.60E-06	4.00E-01	1.04E-06	1.09E-06	2.73E-02	1.95E-01	1.30E-03	3.55E-05	1.30E-03	2.54E-04	2.89E-04	2.66E-04
Ra-224	0.003	2.60E-06	4.00E-01	1.04E-06	1.09E-06	2.73E-02	1.95E-01	1.30E-03	3.55E-05	1.30E-03	2.54E-04	2.89E-04	2.66E-04

MODEL OF ALL PATHWAYS TO HUMAN EXPOSURE FROM GROUNDWATER
(Meat Products)

Sheep, goats, pigs

GROUNDWATER		SOIL	PLANTS		Intake	Intake		ACTIVITY IN SHEEP,GOAT,PIG FLESH			
(Measured)			Pasture, grass, browse		Soil	Dry Feed	Water	Daily Int	Ff	Activity	Cattle:Sheep
Nuclide	Bq/l	Bq/g	Fv1	Bq/g	20% Bq/g	kg/d 4 Bq/d	l/d 15 Bq/d	Bq/d	d/kg	Bq/kg	50:50 Bq/kg total
U-238	3.000	3.00E-03	1.00E-01	3.00E-04	3.60E-04	1.44E+00	4.50E+01	4.64E+01	1.50E-02	6.97E-01	2.09E+00
U-234	3.000	3.00E-03	1.00E-01	3.00E-04	3.60E-04	1.44E+00	4.50E+01	4.64E+01	1.50E-02	6.97E-01	2.09E+00
Th-230	3.000	3.00E-03	5.00E-02	1.50E-04	1.80E-04	7.20E-01	4.50E+01	4.57E+01	2.50E-03	1.14E-01	3.43E-01
Ra-226	0.148	1.48E-04	2.01E-01	2.97E-05	3.56E-05	1.42E-01	2.22E+00	2.36E+00	2.55E-03	6.02E-03	1.82E-02
Pb-210	0.029	2.90E-05	2.50E-01	7.25E-06	8.70E-06	3.48E-02	4.35E-01	4.70E-01	5.05E-04	2.37E-04	7.16E-04
Po-210	0.029	2.90E-05	5.03E-02	1.46E-06	1.75E-06	6.99E-03	4.35E-01	4.42E-01	2.80E-03	1.24E-03	3.72E-03
U-235	0.021	2.10E-05	2.00E-01	4.20E-06	5.04E-06	2.02E-02	3.15E-01	3.35E-01	3.00E-02	1.01E-02	3.03E-02
Pa-231	0.021	2.10E-05	1.00E-01	2.10E-06	2.52E-06	1.01E-02	3.15E-01	3.25E-01	5.00E-03	1.63E-03	4.89E-03
Ac-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.52E-06	1.01E-02	3.15E-01	3.25E-01	4.00E-04	1.30E-04	3.91E-04
Th-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.52E-06	1.01E-02	3.15E-01	3.25E-01	5.00E-03	1.63E-03	4.89E-03
Ra-223	0.021	2.10E-05	4.00E-01	8.40E-06	1.01E-05	4.03E-02	3.15E-01	3.55E-01	5.00E-03	1.78E-03	5.38E-03
Th-232	0.003	2.60E-06	1.00E-01	2.60E-07	3.12E-07	1.25E-03	3.90E-02	4.02E-02	5.00E-03	2.01E-04	6.05E-04
Th-228	0.003	2.60E-06	1.00E-01	2.60E-07	3.12E-07	1.25E-03	3.90E-02	4.02E-02	5.00E-03	2.01E-04	6.05E-04
Ra-228	0.003	2.60E-06	4.00E-01	1.04E-06	1.25E-06	4.99E-03	3.90E-02	4.40E-02	5.00E-03	2.20E-04	6.66E-04
Ra-224	0.003	2.60E-06	4.00E-01	1.04E-06	1.25E-06	4.99E-03	3.90E-02	4.40E-02	5.00E-03	2.20E-04	5.56E-04

Cattle

GROUNDWATER		SOIL	PLANTS		Intake	Intake		ACTIVITY IN CATTLE FLESH			
(Measured)			Pasture, grass, browse		Soil	Dry Feed	Water	Daily Int	Ff	Activity	Cattle:Sheep
Nuclide	Bq/l	Bq/g	Fv1	Bq/g	20% Bq/g	kg/d 4 Bq/d	l/d 15 Bq/d	Bq/d	d/kg	Bq/kg	50:50 Bq/kg total
U-238	3.000	3.00E-03	1.00E-01	3.00E-04	3.60E-04	1.44E+00	4.50E+01	2.33E+02	1.50E-02	3.49E+00	2.09E+00
U-234	3.000	3.00E-03	1.00E-01	3.00E-04	3.15E-04	7.88E+00	2.25E+02	2.33E+02	1.50E-02	3.49E+00	2.09E+00
Th-230	3.000	3.00E-03	5.00E-02	1.50E-04	1.58E-04	3.94E+00	2.25E+02	2.29E+02	2.50E-03	5.73E-01	3.43E-01
Ra-226	0.148	1.48E-04	2.01E-01	2.97E-05	3.12E-05	7.79E-01	1.11E+01	1.19E+01	2.55E-03	3.03E-02	1.82E-02
Pb-210	0.029	2.90E-05	2.50E-01	7.25E-06	7.62E-06	1.90E-01	2.18E+00	2.37E+00	5.05E-04	1.19E-03	7.16E-04
Po-210	0.029	2.90E-05	5.03E-02	1.46E-06	1.53E-06	3.83E-02	2.18E+00	2.21E+00	2.80E-03	6.20E-03	3.72E-03
U-235	0.021	2.10E-05	2.00E-01	4.20E-06	4.41E-06	1.10E-01	1.58E+00	1.69E+00	3.00E-02	5.06E-02	3.03E-02
Pa-231	0.021	2.10E-05	1.00E-01	2.10E-06	2.21E-06	5.51E-02	1.58E+00	1.63E+00	5.00E-03	8.15E-03	4.89E-03
Ac-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.21E-06	5.51E-02	1.58E+00	1.63E+00	4.00E-04	6.52E-04	3.91E-04
Th-227	0.021	2.10E-05	1.00E-01	2.10E-06	2.21E-06	5.51E-02	1.58E+00	1.63E+00	5.00E-03	8.15E-03	4.89E-03
Ra-223	0.021	2.10E-05	4.00E-01	8.40E-06	8.82E-06	2.21E-01	1.58E+00	1.80E+00	5.00E-03	8.98E-03	5.38E-03
Th-232	0.003	2.60E-06	1.00E-01	2.60E-07	2.73E-07	6.83E-03	1.95E-01	2.02E-01	5.00E-03	1.01E-03	6.05E-04
Th-228	0.003	2.60E-06	1.00E-01	2.60E-07	2.73E-07	6.83E-03	1.95E-01	2.02E-01	5.00E-03	1.01E-03	6.05E-04
Ra-228	0.003	2.60E-06	4.00E-01	1.04E-06	1.09E-06	2.73E-02	1.95E-01	2.22E-01	5.00E-03	1.11E-03	6.66E-04
Ra-224	0.003	2.60E-06	4.00E-01	1.04E-06	1.09E-06	2.73E-02	1.95E-01	2.22E-01	5.00E-03	1.11E-03	5.56E-04

MODEL OF ALL PATHWAYS TO HUMAN EXPOSURE FROM GROUNDWATER
(Poulrty and eggs)

GROUNDWATER		SOIL	Plants		DAILY INTAKE		Ratio	Activity in Meat		Activity in Eggs	
(Measured)			Pasture, grass, browse		Plants	Water	Liquid:feed	Ff - Poultry		Ff - eggs	
Nuclide	Bq/l	Bq/g	Fv1	Bq/g	kg/d 0.15 Bq/d	l/d 0.3 Bq/d	2:1 Bq/d	Unit/d/kg	Bq/kg	Unit/d/kg	Bq/kg
U-238	3.000	3.00E-03	1.00E-01	3.00E-04	4.50E-02	0.9	0.61500075	1.20E+00	7.38E-01	1.00E+00	6.15E-01
U-234	3.000	3.00E-03	1.00E-01	3.00E-04	4.50E-02	0.9	0.61500075	1.20E+00	7.38E-01	1.00E+00	6.15E-01
Th-230	3.000	3.00E-03	5.00E-02	1.50E-04	2.25E-02	0.9	0.60750375	4.00E-03	2.43E-03	2.01E-03	1.22E-03
Ra-226	0.148	1.48E-04	2.01E-01	2.97E-05	4.45E-03	0.0444	0.0310837	9.90E-04	3.08E-05	2.00E-05	6.22E-07
Pb-210	0.029	2.90E-05	2.50E-01	7.25E-06	1.09E-03	0.0087	0.00616265	2.00E-03	1.23E-05	2.00E-03	1.23E-05
Po-210	0.029	2.90E-05	5.03E-02	1.46E-06	2.19E-04	0.0087	0.00587286	4.00E-03	2.35E-05	1.80E-02	1.06E-04
U-235	0.021	2.10E-05	2.00E-01	4.20E-06	6.30E-04	0.0063	0.00441	1.00E+00	4.41E-03	1.00E+00	4.41E-03
Pa-231	0.021	2.10E-05	1.00E-01	2.10E-06	3.15E-04	0.0063	0.004305	1.00E+00	4.31E-03	1.00E+00	4.31E-03
Ac-227	0.021	2.10E-05	1.00E-01	2.10E-06	3.15E-04	0.0063	0.004305	1.00E+00	4.31E-03	1.00E+00	4.31E-03
Th-227	0.021	2.10E-05	1.00E-01	2.10E-06	3.15E-04	0.0063	0.004305	1.00E+00	4.31E-03	1.00E+00	4.31E-03
Ra-223	0.021	2.10E-05	4.00E-01	8.40E-06	1.26E-03	0.0063	0.00462	1.00E+00	4.62E-03	1.00E+00	4.62E-03
Th-232	0.003	2.60E-06	1.00E-01	2.60E-07	3.90E-05	0.0008	0.000533	1.00E+00	5.33E-04	1.00E+00	5.33E-04
Th-228	0.003	2.60E-06	1.00E-01	2.60E-07	3.90E-05	0.0008	0.000533	1.00E+00	5.33E-04	1.00E+00	5.33E-04
Ra-228	0.003	2.60E-06	4.00E-01	1.04E-06	1.56E-04	0.0008	0.000572	1.00E+00	5.72E-04	1.00E+00	5.72E-04
Ra-224	0.003	2.60E-06	4.00E-01	1.04E-06	1.56E-04	0.0008	0.000572	1.00E+00	5.72E-04	1.00E+00	5.72E-04

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It even compares well with the local dose limit set by the Council for Nuclear Safety of 250 µSv/a per individual mine, considering that this assessment included the majority of the mines in the area.

The only long-term source of concern is the potential impact that the mines might have on water sources. Characteristics of the geology and the fact that uranium and its decay products do not migrate very effectively, predicts that major concern in this regard could be unwarranted. However, the potential impact on the water sources should be assessed as part of the overall water management programmes on the mines, with radioactivity as one of the potential pollutants.

Institutional controls will probably have to be established to prevent inadvertent public access to and settlement on tailings dams and surface process water dams.

In conclusion, it seems that the potential exposures to the public from the mines in the Free State Goldfields are well within the principles of ALARA, i.e. doses are As Low as Reasonably Achievable, considering social and economic factors.

SUMMARY:

The gold mines in the Free State Goldfields extract and process ore from underground, which contains naturally radioactive uranium and its associated decay products. This assessment aimed to cost effectively determine the major potential radiation hazards to the public from the gold mines in the area.

The potential exposure sources from the mines are radon gas, radioactive dust, contaminated water and external gamma radiation. The assessment focussed mainly on the public's potential exposure to radon gas emanating from tailings dams, waste rock dumps and upcast shafts from underground workings.

The rate of radon emanation from the dams was measured using several different techniques, and the potential dispersion of the radon was modelled using internationally accepted modelling codes and local weather data for the Free State Goldfields. A **maximum** potential contribution to the natural background radon levels of 6 Bq m^{-3} was calculated. This is a small increment to the background levels in the order of 25 to 35 Bq m^{-3}.

Environmental measurements of outdoor radon concentrations confirmed the modelling results to the extent that no significantly high radon concentration could be detected in the environment. Background radon levels in towns outside the Free State Goldfields are in the same order as those measured around the mines. Similar environmental measurements of airborne dust and water sources around the mines indicated relatively low levels of radiation.

A conservative estimate of the total potential exposure of the public in the Free State Goldfields is in the order of 130 to 250 μSv/a. This can be interpreted as well within the internationally accepted public dose limit of 1000 μSv/a.