

# The Impact Of Atmospheric Pathways On Public Exposure

By

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## Abstract

This dissertation looks at the problem of radon emanating from the slime dams of mines, whether there is a cause for concern with respect to the safety of the public. It has been determined by previous work that the highest radon emanations are from tailings/slimes dams. [Ref 10, 12, 20, 27]

During 1994/1995 the Council for Scientific and Industrial Research (CSIR) published a report known as the GU9301: Final report: Assessment of the radiological impact to the public from surface works on mines: radon and dust exposure pathways. It tried to assess the impact of radiation on the public from the mines in South Africa. It took three mines referred to as mine 1, mine 2, and mine three to represent the West Rand, Western Transvaal and, the Free State gold mining regions respectively. The final data indicates that the doses from the mines were close to the  $250 \mu\text{Sv a}^{-1}$  limit set by the National Nuclear Regulator. The mines conducted independent Public Hazard Assessments and their data shows that the doses from the mines are much smaller than the  $250 \mu\text{Sv a}^{-1}$  limit. This dissertation tries to determine why there is a discrepancy between the GU9301 report published by the (CSIR) and the independent Public Hazard Assessments conducted by the various mines.

This dissertation also tries to find an optimal method for determining radon flux from slimes dams and to characterize the slimes dams to determine the major factors (e.g. age of slimes dam, location and time of measurement etc) affecting the flux.

The major factors affecting radon flux were looked at by studying two slimes dams, namely the inactive No. 2 slime dam at Kloof mine (old) and the active No.1 slime dam at Leeudorn mine (new). The flux measurements were taken around the perimeter and then within the slimes dam itself. Two methods were used to determine the radon flux in this project, namely:

1. The Rad Elec dynamic/active system which requires 24 hours per measurement, and
2. The Rad Elec passive system, which required about 3 hours per measurement.

Studies performed by J. Ellis on his masters' dissertation showed that there is collaboration between the dynamic and passive systems data. [Ref 27]

**NOTE:** the Rad Elec methods are not accepted by the NNR (one of the reasons being that they are not calibrated for South African slimes dams). The values obtained by the Rad Elec systems should not be taken as absolutes. They are only used to compare the readings with each other.



The data obtained by this research indicates that the location of the flux measurements from slimes dams does not affect the readings (the average perimeter and internal readings were approximately the same). The time of measurement is very important. The readings from the dynamic system were higher than readings from the passive system almost by a factor of 5 (in some cases. The age of the dam appears not to play too great a role on radon flux however, the readings from the wet/young slimes dam require more scrutiny as there is a possibility of moisture formation on the electrets and causing premature discharges.

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TABLE OF CONTENTS

TABLE OF CONTENTS ..... iv

LIST OF FIGURES ..... vii

LIST OF TABLES ..... ix

CHAPTER 1 ..... 1

Introduction to the study..... 1

1.1 Introduction ..... 1

1.2 Background information..... 1

1.3 Problem Statement..... 4

1.4 Research Objectives ..... 8

1.5 Justification..... 9

1.6 Study Area ..... 9

CHAPTER 2 ..... 13

Literature review ..... 13

Theoretical calculation ..... 16

CHAPTER 3..... 18

Theoretical background ..... 18

3.1 Radon emanation from the soil..... 18

3.2 Radon transport in the sand ..... 20

3.3 The diffusion equation..... 21

|                                                |           |
|------------------------------------------------|-----------|
| 3.4 The method used by the GU9301 report ..... | 22        |
| 3.5 Measurement techniques .....               | 24        |
| 3.5.1 Accumulator cans .....                   | 24        |
| 3.5.2 Activated charcoal canisters.....        | 25        |
| 3.5.3 PNL flow through radon flux system.....  | 26        |
| 3.5.4 Flow through continuous flux system..... | 27        |
| 3.6 Measurement methods for radon flux.....    | 28        |
| 3.6.1 The Rad Elec dynamic method .....        | 29        |
| 3.6.2 The Rad Elec passive method .....        | 32        |
| 3.7 Deployment strategy.....                   | 35        |
| 3.7.1 Dynamic system deployment .....          | 35        |
| 3.7.2 Passive system deployment.....           | 37        |
| <b>CHAPTER 4.....</b>                          | <b>47</b> |
| <b>Results and Calculations .....</b>          | <b>47</b> |
| 4.1 Sample dynamic system calculation:.....    | 48        |
| 4.2 Sample passive system calculation:.....    | 49        |
| 4.4 Discussion of table 4.....                 | 59        |
| 4.5 Discussion of table 7.....                 | 62        |
| 4.6 Discussion of table 8.....                 | 65        |

|                                                                  |               |
|------------------------------------------------------------------|---------------|
| <b>CHAPTER 5 .....</b>                                           | <b>74</b>     |
| <b>Discussion, Conclusions and Recommendations.....</b>          | <b>74</b>     |
| 5.1 Discussion of the findings .....                             | 74            |
| 5.1.1 The effect of location of measurement on radon flux: ..... | 75            |
| 5.1.2 The effect of time of measurement on radon flux:.....      | 77            |
| 5.1.3 The effect of age of slimes dam on radon flux:.....        | 78            |
| 5.2 Conclusions .....                                            | 80            |
| 5.3 Recommendations .....                                        | 82            |
| 5.4 Possible future work .....                                   | 82            |
| <br><b>References .....</b>                                      | <br><b>84</b> |
| Internet resources:.....                                         | 84            |
| Reference literature: .....                                      | 84            |
| Private communication: .....                                     | 86            |

## LIST OF FIGURES

|                                                                                                                                 |    |
|---------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 1: The decay chain of $^{238}\text{U}$ .....                                                                             | 2  |
| Figure 2: Possible public exposure pathways .....                                                                               | 4  |
| Figure 3: Graph of the GU9301 data and P.H.A. data. ....                                                                        | 6  |
| Figure 4: Map of Kloof slimes dam number 2 .....                                                                                | 11 |
| Figure 5: Map of Leeudorn slimes dam number 1 .....                                                                             | 12 |
| Figure 6: Schematic representation of radon recoil paths in and between mineral grains.<br>.....                                | 19 |
| Figure 7: Schematic presentation of the measurement method used to determine radon<br>generation and transport parameters. .... | 23 |
| Figure 8: Schematic diagram of an S-chamber in the “open” position.....                                                         | 31 |
| Figure 9: The components of the dynamic system. ....                                                                            | 32 |
| Figure 10: Schematic diagram of the deployment of the dynamic system .....                                                      | 36 |
| Figure 11: Schematic diagram of two H-chambers .....                                                                            | 38 |
| Figure 12: Schematic diagram of the deployment of the passive system. ....                                                      | 39 |
| Figure 13: Photo of the two H-chambers. ....                                                                                    | 39 |
| Figure 14: Deployment of the dynamic system .....                                                                               | 40 |
| Figure 15: Deployment of the passive system .....                                                                               | 40 |
| Figure 16: Deployment of the dynamic and passive systems. ....                                                                  | 41 |
| Figure 17: Approximate locations of the dynamic system measurements and calculated<br>flux values. ....                         | 42 |

|                                                                                                             |    |
|-------------------------------------------------------------------------------------------------------------|----|
| Figure 18: Approximate locations of the passive system measurements and calculated<br>flux values. ....     | 43 |
| Figure 19: Approximate locations of the passive system measurements .....                                   | 44 |
| Figure 20: Example of a Kloof mine slimes dam surface.....                                                  | 45 |
| Figure 21: Example of a Leeudorn slimes dam surface.....                                                    | 46 |
| Figure 22: Graph of radon flux Vs site for dynamic measurements taken at Kloof mine                         | 66 |
| Figure 23: Graph of radon flux Vs site for passive measurements taken at Kloof mine..                       | 67 |
| Figure 24: Graph of radon flux Vs site for dynamic measurements taken at Leeudorn<br>mine.....              | 68 |
| Figure 25: Graph of radon flux Vs site for passive measurements taken at Leeudorn mine<br>.....             | 69 |
| Figure 26: Graph of radon flux Vs trial for passive and dynamic measurements taken at<br>Kloof mine.....    | 70 |
| Figure 27: Graph of radon flux Vs trial for passive and dynamic measurements taken at<br>Leeudorn mine..... | 71 |
| Figure 28: Graph of passive radon flux Vs trials taken at Kloof and Leeudorn mines. ...                     | 72 |
| Figure 29: Graph of dynamic radon flux Vs trials taken at Kloof and Leeudorn mines. .                       | 73 |

LIST OF TABLES

Table 1: Physical Data for the dynamic system measurements for slimes dam number 251

Table 2: Data for the passive system measurements for slimes dam number 2 ..... 52

Table 3: Flux calculations for the dynamic system measurements for slimes dam number  
2..... 54

Table 4: Flux calculations for the passive system measurements for Kloof slimes dam  
number 2 ..... 56

Table 5: Data for the dynamic system measurements for Leeudorn slimes dam number 1  
..... 60

Table 6: Data for the passive system measurements for Leeudorn slimes dam number 1.  
..... 61

Table 7: Flux calculations for the dynamic system measurements for Leeudorn slimes  
dam number 1 ..... 62

Table 8: Flux calculations for the passive system measurements for Leeudorn slimes dam  
number 1 ..... 64

Table 9: summary of radon flux and standard deviations..... 75

# CHAPTER 1

## Introduction to the study

### 1.1 Introduction

This chapter introduces the basis of the study. The problem statement, objectives, justification, and study area are discussed.

### 1.2 Background information

Uranium is a radioactive element (half-life of  $4.5 \times 10^9$  years) found everywhere on earth (usually in small quantities). Uranium decays through alpha, beta and gamma decay, eventually to the stable isotopes of lead. Refer to figure 1 for the decay chain for  $^{238}\text{U}$ , which is the most abundant isotope ( $\approx 99.7\%$ ). In some parts of South Africa  $^{238}\text{U}$  is usually found in gold containing ore. One of the daughters of  $^{238}\text{U}$  is  $^{222}\text{Rn}$  (half-life of 3.825 days), which is the only element in the gaseous state in the whole decay chain.

Activities of man (e.g. mining) produce waste, which if not properly taken care of, will result in the public being affected. In the case of radiation, this is referred to as a dose. A public exposure will be caused if: a facility (e.g. mine, tailings dam etc) releases a radioactive discharge (e.g. radon), which could possibly reach the public. The group of people most affected by the discharge is known as the **critical group**. The discharge can reach the critical group in one of two ways referred to as the primary and the secondary pathways. The primary pathways are further subdivided into the atmospheric and the aquatic pathways. (See figure 2). The atmospheric pathway is further subdivided into dust and radon components.

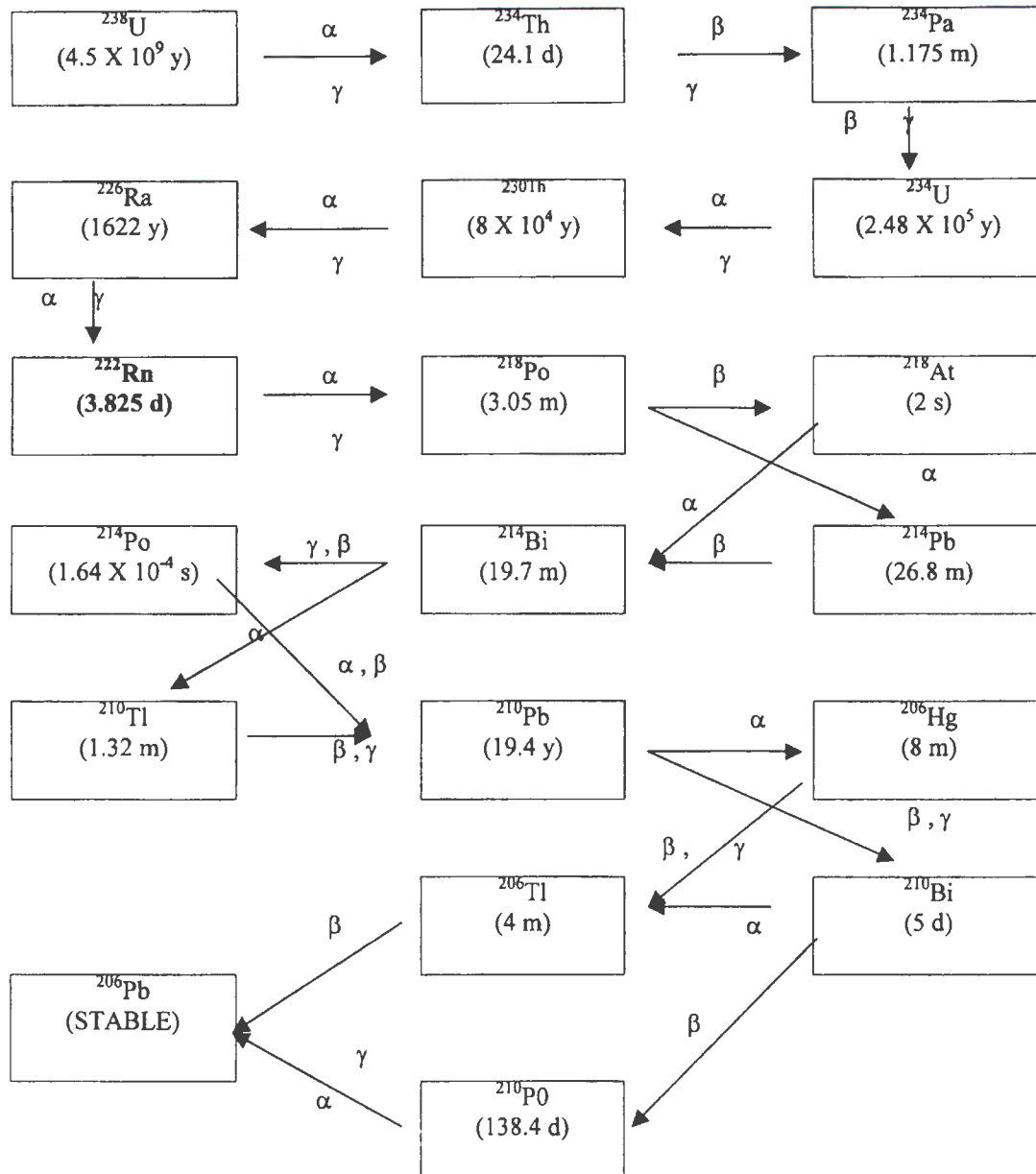


Figure 1: The decay chain of  $^{238}\text{U}$  [Ref 1, 17, 24]

The aquatic pathway is also subdivided into two subdivisions, namely, the surface water and the ground water. The secondary pathways involve the absorption or ingestion of radioactive material by either plants or animals and then the consumption of the irradiated plant/animal by humans. Previous studies have shown that the major contributor to public exposure to radiation is the atmospheric pathway and more specifically, radon exposure. It has also been shown in previous studies that the biggest contributor to public radon exposure from mines is from the slimes dams. [Ref 10, 27]

A hazard assessment consists of the following major components:

1. Determination of the amount of radioactive materials released into the environment by a facility. This can be done at either the facility itself or at the critical group. In most cases it is easier to determine the release at the facility.
2. Using various mathematical models to determine the amount of radioactive substances reaching the critical group via the various pathways.
3. Calculation of the effective radiation dose to the critical group.

The National Nuclear Regulator of South Africa (N.N.R) allows a facility to release radionuclides which will cause a maximum dose of  $250 \mu\text{Sv a}^{-1}$ . If this limit is exceeded, the facility should try to bring its releases down to the allowed level.

Page 4 not in book

The CSIR conducted the trials on three mines referred to as Mine 1, mine 2 and mine 3, which were used to represent the West Rand, Western Transvaal and, the Free State gold mining regions respectively.

After the completion of the assessment, it was found that the releases of one of the three mines caused an annual effective dose just below  $250 \mu\text{Sv}\cdot\text{a}^{-1}$ . The second mine fell below the limit. The third mine was found to exceed the limit set by the NNR. The mines conducted their own independent Public Hazard Assessments (P.H.As) as required by the license. The mines found that their results fell way below the  $250 \mu\text{Sv}\cdot\text{a}^{-1}$  limit set by the NNR. (See figure 3).



This discrepancy between the GU9301 report and the P.H.As is a cause for concern because on the one hand, the GU9301 report says that the public is receiving large exposures as a result of the activities of the mines, and the mine P.H.As on the other hand says that their releases cause doses to the public which are well within the limits set by the NNR. One of the questions arising from this discrepancy is which of the reports are correct? Another question would be why is there such a big discrepancy and what caused it?

Page 6 not in book

When a PHA is conducted, there are three major components that are taken into account i.e. the (flux) measurements, the transport codes and the calculations. The transport codes (e.g. Industrial Source Complex Short Term 2) have been verified by experts in the United States of America and the mines and the GU9301 reports used the same codes and so the probability of the discrepancy resulting from the transport code is very small. The calculations are relatively easy and straightforward and with computers performing these calculations, the probability of the discrepancy resulting from the transport code is also very small. Therefore, the only component left where an error could have occurred is the measurement of flux from the mines. Due to these reasons the focus of this project will concentrate on the variables in the measurement of flux.

The measurement of flux has two major components i.e. the methodology and the procedures. The methodology is not considered at this stage since only the Rad Elec dynamic/active and passive methods were used. The emphasis of this project was on the procedures. The procedures involved the characterization of the slimes dam into various parameters. Three major parameters were looked at.

1. **Location** of the measurements. This parameter is concerned with where the measurements took place. It tries to determine whether it matters where the measurements are taken. For this parameter the measurements were taken on the circumference of the dam (perimeter) first and then inside (surface of) the dam itself and the two sets of results were compared.
2. **Time** of the measurements. This parameter is concerned with when the measurements were taken. It looks at the difference between the measurements

taken in the morning and the whole day. Initial trials conducted showed that the passive system can give a reading within three hours, so the electrets were exposed between 8 a.m. ( $\pm 30$  minutes) and 11 a.m. ( $\pm 30$  minutes). Then exposed between 11 a.m. ( $\pm 30$  minutes) and 2 p.m. ( $\pm 30$  minutes) and the final set of readings were taken between 2 p.m. ( $\pm 30$  minutes) and 5 p.m. ( $\pm 30$  minutes).

Initial trials showed that the dynamic/active system on the other hand requires at least 24 hours per reading. The period of measurement was usually from 11 a.m. ( $\pm 5$  minutes) until 11 a.m. ( $\pm 5$  minutes) the following day. The dynamic/active system readings and the passive system readings were compared to determine the effects of the time (not duration) on measurements.

3. **Age of the slimes dam.** This parameter looks at the effect of the age of the slimes dam on the flux measurements. For this parameter two different slimes dams (i.e. Kloof and Leeudorn) were looked at. The slimes dam from Kloof is inactive and therefore considered old and dry. The slimes dam from Leeudorn is active and therefore considered new and wet. If summer is considered to be the wet season and winter the dry season, this could also be used as an indication of the effects of season on flux measurements.

#### **1.4 Research Objectives**

This research project had 3 major objectives.

- 1) To find out the factors that might affect the accurate determination of the radon flux from the slimes dams.
- 2) To get acquainted with the Rad Elec methods of determining flux.

3) To determine the radon flux from the slimes dam using the Rad Elec Dynamic and Passive systems. It should be noted that the values obtained by the Rad Elec methods are not absolute and thus should not be taken at face value. These systems are not calibrated for use in South African conditions. The magnitude of the readings obtained should not be considered but the readings will be used to compare information gathered on the various parameters under consideration, relative to each other.

### **1.5 Justification**

1. The research will help in determining the long-term implications of radon emanation from the slimes dam. (Note: this only applies to public exposure from mines)
2. The research will help improve flux measurement techniques.
3. The research will help determine the factors affecting radon flux from slimes dams.
4. The research will help reassure the public about the role that the mines and the NNR are playing in order to protect them.
5. The research will help this researcher and possibly future researchers become acquainted with the various equipment used.

### **1.6 Study Area**

Two slimes dams were used in the study. The first part of the study was conducted at the Kloof mine (slimes dam number 2), which is an inactive slimes dam. The measurements were taken from the 27<sup>th</sup> of August 2001 until the 25<sup>th</sup> of September 2001. The second part of the study was conducted at the Leeudorn mine (slimes dam number 1). The

measurements were taken from the 17<sup>th</sup> of December 2001 until the 21<sup>st</sup> of December 2001. This dam is currently active. Both slimes dams are located approximately 25 km from Randfontein in the Gauteng province of South Africa. (See to figure 4 and figure 5).

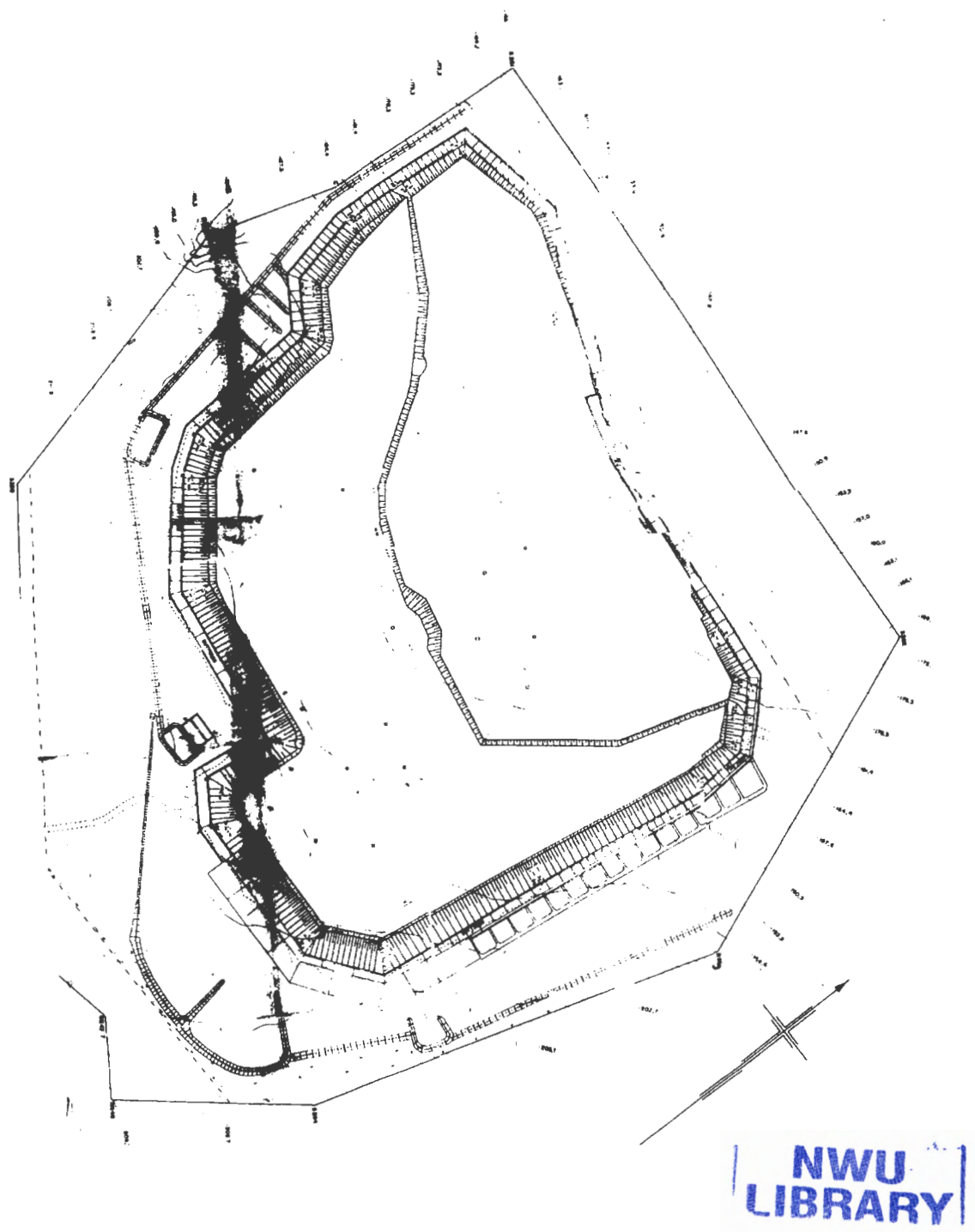


Figure 4: Map of Kloof slimes dam number 2 [Ref 31]

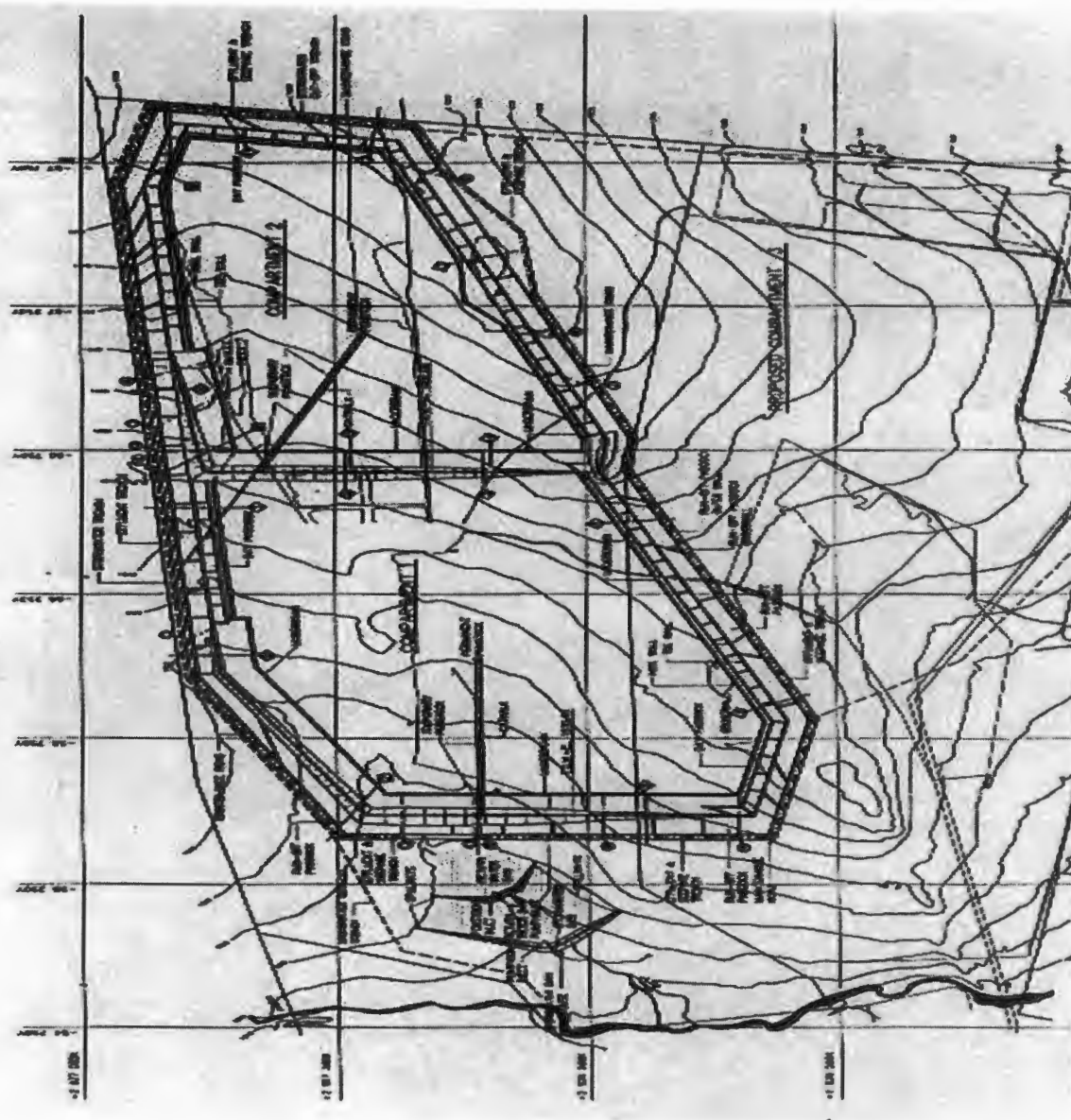


**Figure 5: Map of Leeudorn slimes dam number 1 [Ref 34]**

## CHAPTER 2

### Literature review

This chapter looks at previously conducted studies, such as the Loraine study [Ref 12], theoretical value of flux from slimes dams surfaces, and various issues of concern. The assessment of potential radiation hazards from gold mines in the Free State goldfields to the members of the public by J. F. Ellis [Ref 27], and Measurement of the radon flux from undisturbed soil using E-Perm detectors by J. V. Livingston [Ref 13] among others will be looked at. Some theoretical flux values will also be provided.

J. V. Livingston reported emanation rates (flux) from various soils ranging from  $3 \times 10^{-5}$  to  $0.1 \text{ Bq.m}^{-2}.\text{s}^{-1}$  in the literature review in his masters dissertation [Ref 13]. However, these readings were obtained in the United States of America and as such not really considered as valid readings for South African soils. These measurements used methods such as surface barrier detectors, ion chambers, nuclear track techniques, charcoal canisters and TLDs (Thermo Luminescent Dosimeters) to detect the radon and/or radon daughters. Refer to section 3.5 in the next chapter for details on some of the techniques used in the determination of radon flux/concentration.

By using a closed box method J. F. Ellis found that normal garden soil has an average radon flux of  $0.015 \text{ Bq.m}^{-2}.\text{s}^{-1}$  (with an activity concentration of about  $0.04 \text{ Bq.g}^{-1}$  of  $^{226}\text{Ra}$ ), the tailings had an average radon flux of  $0.050 \pm 0.007 \text{ Bq.m}^{-2}.\text{s}^{-1}$  (with an activity concentration of about  $0.04 \text{ Bq.g}^{-1}$  of  $^{226}\text{Ra}$ ), and the Pyrite dam had a flux of  $0.640$

Bq.m<sup>-2</sup>.s<sup>-1</sup> (with an activity concentration of about 10 Bq.g<sup>-1</sup> of <sup>226</sup>Ra). These readings were obtained from a gold mine in the Free State Goldfields. The diffusion tube method was also used and average flux of 0.183 ± 0.040 Bq.m<sup>-2</sup>.s<sup>-1</sup> was obtained. Trials were also conducted on three slimes dams using the E-perm passive system (refer to sections 3.6.2 and 3.7.2 in the next chapter for a description of this method) and the following results were obtained: for dam 1 the flux was 0.046 ± 0.034 Bq.m<sup>-2</sup>.s<sup>-1</sup>, for dam 2 the flux was 0.021 ± 0.013 Bq.m<sup>-2</sup>.s<sup>-1</sup> and for dam 3 the flux was 0.031 ± 0.009 Bq.m<sup>-2</sup>.s<sup>-1</sup>. By using the dynamic method a flux of 0.03 ± 0.01 Bq.m<sup>-2</sup>.s<sup>-1</sup> was obtained. One of the problems of the closed box method is that it allows a buildup of radon concentration in the box. This can lead to some radon actually diffusing back into the soil (i.e. back diffusion). The range of flux was 0.02 to 0.2 Bq.m<sup>-2</sup>.s<sup>-1</sup>. A conservative flux value of 1 Bq.m<sup>-2</sup>.s<sup>-1</sup> was used in the dispersion model.



In the Loraine study the following procedures were used. [Ref 12] The slimes dams were treated as having a vertical heterogeneity and the piles were treated as multi layers of having homogeneous properties. The flux can then be determined by using the equation (a) below. [Ref 12]

$$F_t = \sum_{i=1}^n R_i \rho_i E_i (\lambda D_{ti})^{0.5} \tanh\{(\lambda/D_{ti})x\} \exp \left\{ -\sum_{j=1}^n (\lambda/D_{tj})^{0.5} x_{tj} \right\} \dots\dots\dots(a)$$

where,

$F_t$  = radon flux from the slimes dam (Bq.m<sup>-2</sup>.s<sup>-1</sup>)

$R$  = radium content of the soil (Bq.g<sup>-1</sup>)

$\rho$  = bulk density (kg.m<sup>-3</sup>)

$E$  = the emanation coefficient (dimensionless)

$\lambda$  = radon decay constant ( $s^{-1}$ )

$D$  = diffusion coefficient ( $m^2.s^{-1}$ )

$x$  = thickness of a layer (m)

The radium content, the bulk density, moisture content of the sample (the diffusion coefficient was calculated using the moisture content and the porosity of the sample), and the thickness of the layer were the measured parameters and the values for  $E$  ( $=0.2$ ),  $\lambda$  ( $=2.01 \times 10^{-6}$ ) and the porosity ( $n = 0.5$ ) were obtained from literature. The radium concentration was determined using gamma spectroscopy.

It was discovered that the emanation coefficient of tailings ranges between 0.02 and 0.85  $Bq.m^{-2}.s^{-1}$ . Three sets of results were gathered namely, the results from the diffusion tube method, from the E-Perm methods and from NNR data. It was found that the NNR and diffusion tube results were of the same magnitude but, the results from the E-Perm system were much lower (in some cases by as much as a factor of 10) and there was no apparent reason for this discrepancy. The data gathered indicated that as far as the radium concentration is concerned, there is not much variation between the sampling points. The average radium concentration of all the sampling points was  $549 \pm 83 Bq.kg^{-1}$ . The average radon flux from the tailing dam was  $0.24 \pm 0.02 Bq.m^{-2}.s^{-1}$ . [Ref 12]

Theoretical calculation

The following assumptions were made in determining the theoretical flux value:

- 1. The radon atoms will only diffuse through a vertical distance of 2m. Any other radon atoms below the 2m will decay before reaching the surface.
- 2. The distance to be traveled by the radon is separated into 2 layers each of 1m thickness.
- 3. The diffusion coefficient is the same for both layers (i.e. the soil is homogeneous).

The values for emanation coefficient, and radon decay constant were obtained from the technical report series no 333 (measurement and calculation of radon releases from uranium mill tailings) [Ref 29]. The values for the bulk density (an average of the bulk density data available on Kloof slimes dam 2) and diffusion coefficient (an average of the diffusion coefficient data available on Kloof slimes dam 2) were obtained from P.H.A. documents submitted to the NNR.

The following values were used to determine the theoretical flux value.

| Known/measured parameters                                                                     | Unknown parameter |
|-----------------------------------------------------------------------------------------------|-------------------|
| R = radium content = (275, 271, 310, 290) Bq.kg <sup>-1</sup> for sites 9 and 17 respectively | Flux              |
| ρ = bulk density = 1760 kg.m <sup>-3</sup>                                                    |                   |
| E = 0.35                                                                                      |                   |
| D = diffusion coefficient = 2.1 X 10 <sup>-6</sup> m <sup>2</sup> .s <sup>-1</sup>            |                   |
| X = thickness of a layer = 1m                                                                 |                   |

|                                                                              |  |
|------------------------------------------------------------------------------|--|
| $\lambda = \text{radon decay constant} = 2.06 \times 10^{-6} \text{ s}^{-1}$ |  |
|------------------------------------------------------------------------------|--|

Using equation (a) theoretical flux values of 0.099, 0.098, 0.112, and 0.105  $\text{Bq.m}^{-2}.\text{s}^{-1}$  were obtained. These values give an average flux of  $0.103 \pm 0.006 \text{ Bq.m}^{-2}.\text{s}^{-1}$ .

## CHAPTER 3

### Theoretical background

This chapter looks briefly at radon emanation from the soil, radon transport in the sand, the diffusion equation, and the method used to determine the radon concentration in the GU9301 report. It also looks at some of the different methods of determining radon flux, including the two methods used in this study, namely the Rad Elec dynamic and Rad Elec passive methods.



#### 3.1 Radon emanation from the soil

As stated before in chapter 1,  $^{226}\text{Ra}$  decays via alpha decay into radon. When  $^{226}\text{Ra}$  decays in the grain, one of the following three processes can happen:

1. The  $^{226}\text{Ra}$  decays but the energy of the recoil  $^{222}\text{Rn}$  is not sufficient to exit the grain and the decay process continues within the grain. This usually happens when the grain within which the  $^{226}\text{Ra}$  is ingrained is large. (See figure 6). This happens at point A.
2. The  $^{226}\text{Ra}$  decays but the energy of the recoil  $^{222}\text{Rn}$  is such that it exits the grain within which it was formed and penetrates a neighboring grain and continues decaying within that grain. (See figure 6). This happens at points B and D.
3. The  $^{226}\text{Ra}$  decays and the energy of the recoil  $^{222}\text{Rn}$  is sufficient to exit the grain where it was formed and enters a pore space and depending on factors

such as emanation coefficient and depth at which the decay took place it might find its way to the surface. (See figure 6). This happens at point C.

Process three is the only process where the radon will reach the surface. In other two cases the radon will become ingrained in a grain and will not reach the surface. [Ref 14, 15, 28]

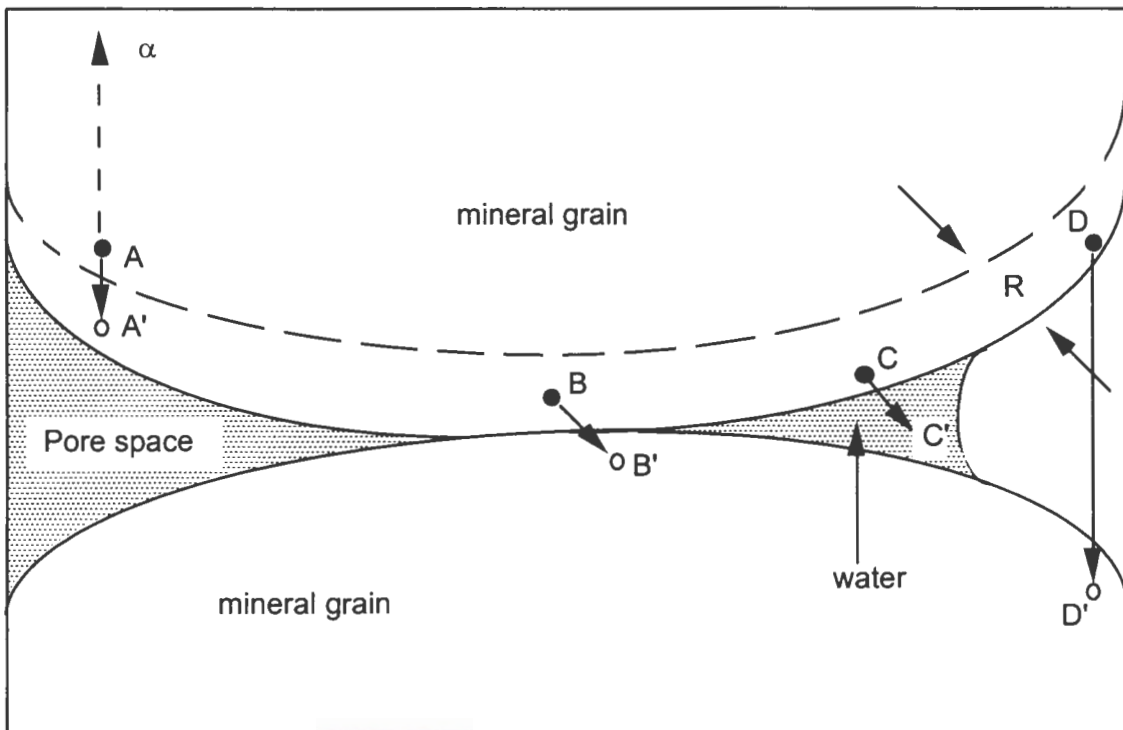


**Figure 6: Schematic representation of radon recoil paths in and between mineral grains. The two grains are in contact at point B. The solid circles represent the radium atoms and the clear circles represent the recoiling radon atoms. [Ref 28]**

### 3.2 Radon transport in the sand

Most of the decay products in the  $^{238}\text{U}$  decay chain are metals and are chemically bound to the rock material, the exception being Rn, which is a gas. The rate at which Rn is produced depends on the activity concentration of  $^{226}\text{Ra}$ . Provided that the decay series is in secular equilibrium, the  $^{226}\text{Ra}$ -activity concentration is equal to the activity concentration of all the other radionuclides present in the decay chain. A decay series is assumed to be in secular equilibrium provided that none of the products escape the material (i.e. in a closed chamber) and after about five times the half-life of the longest lived decay product. In the case of  $^{238}\text{U}$ , secular equilibrium is reached in a few million years.

Radon is a noble gas with a half-life of 3.825 days and possesses a kinetic energy of 86 keV. It is inert and thus will not readily chemically combine with other materials. The radon atoms may also enter a pore space where it will travel a short distance (usually about 2m), before it is stopped. This process where the radon travels through the pore spaces is known as diffusion. Radon may also be carried along by liquid or gas in the pores (advective transport) and may transport the radon over a wide range of distances, depending on the porosity of the soil and velocity of the moving liquid/gas. Radon has an affinity towards water and will move faster through the pores if there is any water present in the pores. Being a noble gas, it will not chemically combine with the water.

In addition to  $^{222}\text{Rn}$ , there are two other isotopes of radon being produced. These are  $^{220}\text{Rn}$  (half-life = 55.6 s), originating from  $^{232}\text{Th}$ , and  $^{219}\text{Rn}$  (half-life of 3.96 s), originating from  $^{235}\text{U}$ . Due to their short half-lives, the distances over which they are transported is also shorter. Thus their concentrations are usually lower than the concentration of  $^{222}\text{Rn}$ . Thus this dissertation is focused on  $^{222}\text{Rn}$  and whenever radon (or Rn) is mentioned, it is referring to  $^{222}\text{Rn}$  [Ref 24].

### 3.3 The diffusion equation

The migration of  $^{222}\text{Rn}$  by diffusion in a homogenous medium can be described by Fick's first law:

$$J = -D\nabla C, \quad (1)$$

Where,  $J$  = flux of particles,

$D$  = diffusion coefficient

$\nabla C$  = change in concentration

The concentration of activity will change according to the equation:

$$\nabla C = D\nabla^2 C - \lambda C + S \quad (2)$$

Where,  $\nabla C$  = change in concentration

$D$  = diffusion coefficient

$\lambda_{\text{Rn}}$  = Decay constant of  $^{222}\text{Rn}$  ( $= 2.10 \times 10^{-6} \text{ s}^{-1}$ ) and

$S$  = generation rate of  $^{222}\text{Rn}$

With the boundary conditions for equation (2) set at  $C = 0$  at  $z = 0$  and  $C = S/\lambda_{\text{Rn}}$  at  $z = -\infty$ , the following solution to the equation is found:

$$C = \{S/\lambda_{\text{Rn}}\} \{1 - \exp [\varepsilon\lambda_{\text{Rn}}/D]\}^{1/2}$$

Where C = activity concentration

$\lambda_{\text{Rn}}$  = Decay constant of  $^{222}\text{Rn}$  ( $= 2.10 \times 10^{-6} \text{ s}^{-1}$ ) and

S = generation rate of  $^{222}\text{Rn}$

D = diffusion coefficient

$\varepsilon$  = Soil porosity

A complete mathematical description of flow is difficult to obtain because of the complexity and diversity of the details of soil structure. [Ref 6, 7, 8, 11, 20, 23]

### 3.4 The method used by the GU9301 report

The method used by the GU9301 report to determine the amount of radon released into the environment is known as the diffusion tube method and it follows the following procedure: A sample from the tailings is sealed to preserve the moisture content. A sub sample is compacted into a short tube, which is attached to a longer tube to provide a well-defined air space above the sample surface. A larger subsample is compacted into a longer tube, which in turn is connected to another tube of the same length. After compaction, the diffusion tubes are sealed for fifteen days (to reach equilibrium). Then the tubes are rapidly opened and a radon gas monitor (RGM) is inserted into the headspace of each tube and the tubes are then sealed for four to five days in order for the monitors to record the radon gas concentration. The moisture content of the sample is obtained by weighing the sample before and after oven drying of the sample. The  $^{226}\text{Ra}$  content of the sub sample is also measured.

The  $^{226}\text{Ra}$  content of the samples was determined by sealing the sample for 30 days (for the radon to achieve equilibrium with  $^{226}\text{Ra}$  in the container), and the  $^{226}\text{Ra}$  concentration can be determined by using gamma spectroscopy of the evolved radon daughters. (See figure 9) [Ref 10, 23].

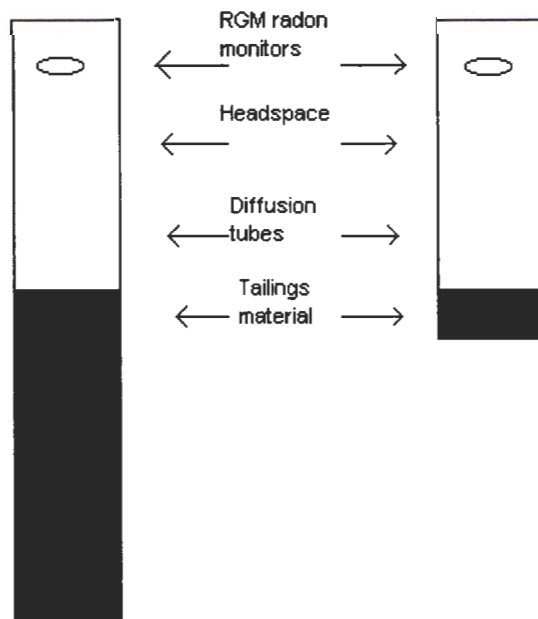


**Figure 7: Schematic presentation of the measurement method used to determine radon generation and transport parameters.**

According to the PHAs submitted to the NNR, most of the mines also used RGMs and similar methods. As stated in chapter 1, three factors are taken into account when a (radon in this case) PHA is conducted. These factors are, radon flux/concentration, transport modeling, and dose calculations. The equations used in the dose calculations are

not very complicated and the possibility of making errors is small [Ref 28]. The models used in the transport modeling has been verified in the United States of America and other places and the mines and the GU9301 report used similar models, so the possibility of the cause for the discrepancy being in the models is also very small. Therefore the discrepancy could be due to errors made in determining radon flux/concentration. Due to these reasons the focus of this project will be aimed at radon flux measurements.

### **3.5 Measurement techniques**

#### **3.5.1 Accumulator cans**

Accumulator cans are based on the linear buildup of Radon with time in a container sealed to the surface of the soil. The radon flux is determined by taking measurements of the radon concentration at prescribed times. It consists of:

1. Accumulator can,
2. Scintillation cell (e.g. Lucas cell) to sample gas in the can,
3. Light tight box with photomultiplier tube and,
4. Scaler for counting radon arriving in the Lucas cell

The edges of the can are sealed to the soil by gently pressing the can into the soil (very carefully so as not to disturb the radon in the soil). The radon concentration will increase as soon as the can is inserted into the soil (linearly at first but the buildup decreases as radon back diffuses into the soil). The optimal time of exposure before sample calculations can be calculated using the formula:

$$T = xV/AD_e \quad (10)$$

Where,  $T$  = sampling time limit (s)

$x$  = soil depth to which can is depressed (cm)

$V$  = volume of can ( $\text{cm}^3$ )

$A$  = surface area of can opening ( $\text{cm}^2$ )

$D_e$  = effective bulk diffusion coefficient of surface soil ( $\text{cm}^2\text{s}^{-1}$ )

**Disadvantages:** The results are only valid for a short period of time (<60 min). Since radon flux varies with time, many measurements are required to obtain a good long-term average radon flux.

**Advantages:** It is simple to use and is relatively accurate.

### 3.5.2 Activated charcoal canisters

This method provides an integrated measurement of radon release from the soil (similar to accumulator cans). It consists of:

1. Canister,
2. Activated charcoal and,
3. Gamma spectroscopy counting apparatus.



The canister is placed in contact with the soil and the radon passes into the activated charcoal contained within the canister. Activated charcoal is a very good radon adsorber and therefore most of the radon will remain in the charcoal and will not pass through the canister into the atmosphere. The amount of radon activity on the activated charcoal is measured via gamma spectroscopy. The air gap between the soil surface and the activated charcoal should be minimized so as to reduce back diffusion. The exposure time of

canisters is a function of temperature (summer < 24h, winter < 4d) and amount of charcoal. Since the half-life of radon is 3.8d, the canisters should not be exposed for more than 4 days.

After the canisters are exposed, the charcoal should be sealed to prevent radon loss. The canisters are then allowed to equilibrate for 4 hours to allow for the ingrowth of radon daughters. A NaI detector and multichannel analyzer can then be used to measure the activity on the charcoal. The number of  $^{214}\text{Bi}$  ( $T_{1/2} = 19.7$  min) and  $^{214}\text{Pb}$  ( $T_{1/2} = 26.8$  min) can be used to quantify the radon. However, the 609 keV  $^{214}\text{Bi}$  peak is preferred because the  $^{214}\text{Bi}$  peak on the spectrum is easier to distinguish.

**Advantages:** easy to use.

### 3.5.3 PNL flow through radon flux system

Components of the PNL are:

1. 76 X 122 X 5 cm aluminum tent,
2. Desiccant to remove excess moisture from sample,
3. Activated Charcoal trap (400g of charcoal in a convoluted steel pipe),
4. Flow meter (to monitor flow), and
5. Air pump (DC powered) to provide air to the system.

As the air flows across the surface being measured, it picks up the radon emanating from the measured area. The air then flows through the radon trap, where more than 98% of

the radon is collected. After sampling, the activated charcoal is sealed and allowed to equilibrate for 4 hours before counting with a NaI or GeLi multichannel analyzer. Once again the 609 keV  $^{214}\text{Bi}$  peak is used.

**Advantages:** This method is able to sample a larger area than the Activated Charcoal Canister method and it uses only twice the activated charcoal, and the sensitivity of the system is improved.

**Disadvantages:** expensive.

More complicated to operate.

#### 3.5.4 Flow through continuous flux system

This is a variation of the PNL system. It consists of:

1. Aluminum collection tent,
2. Flow through Lucas Cell,
3. Photomultiplier tube,
4. High voltage supply,
5. Scaler, and
6. Printer (no radon trap required).

The air pump pulls fresh air through the tent and Lucas cell where the radon daughters are counted. The scaler accumulates the counts over a specified time period and prints out the total counts at the end of the sampling period.

**Disadvantages:** 1. Expensive.

2. Lack of portability.
3. Fragile

The radon flux can be calculated using the following equation:

$$J = 10^4 RE\rho\lambda x \quad (11)$$

Where,  $J$  = radon flux ( $\text{pCi.m}^{-2}.\text{s}^{-1}$ )

$10^4$  = conversion factor from  $\text{cm}^2$  to  $\text{m}^2$ .

$R$  =  $^{226}\text{Ra}$  content ( $\text{pCi.g}^{-1}$ )

$E$  = Emanating fraction

$\rho$  = Bulk density ( $\text{g.cm}^{-3}$ )

$\lambda$  = Decay constant for radon ( $= 2.1 \times 10^{-6} \text{ s}^{-1}$ )

$x$  = Depth of tailings (cm)

**Emanation coefficient/fraction** is the fraction of radon atoms generated, which escape the solid phase in which they are formed and are free to diffuse through the bulk medium [Ref 13, 21, 22,23, 26, 28].

### 3.6 Measurement methods for radon flux

This section looks at some of the different methods of determining radon flux, including the two methods used in this study, namely the Rad Elec dynamic and Rad Elec passive methods. There are two components that are common to both the dynamic and passive methods. They are the electrets and the electret reader. The electrets are Teflon coated discs, which are positively charged by a process of ion implantation. They come in two

different thicknesses. The 1.542 mm thick short-term electret and the 0.127 mm thick long-term electret. For the purpose of this study, the short-term electrets were used in both the dynamic and passive methods. The electret reader is used to measure the potential on the electret. The advantage of these systems is that they are very easy to deploy and factors such as diffusion coefficients, soil porosity etc, do not have to be taken into account.

### **3.6.1 The Rad Elec dynamic method**

The apparatus consists of the following components:

1. The electret reader
2. Electrets
3. Two S-chambers
4. Aluminum box (28.7 cm X 36.3 cm X 21 cm) with one end open and two nozzles on opposite ends
5. Air pump with an adjustable airflow
6. 12V rechargeable battery

The initial voltages of two short-term electrets are measured using the electret reader and then the electrets are screwed into the two S-chambers (refer to figure 8 at the end of section 3.7 for a schematic diagram of an S-chamber). The S-chambers are in the “closed” position at this stage. The pump is then connected to the battery and the airflow is set at 1 liter per minute. The pump is then connected to one of the nozzles on the aluminum box. The two S-chambers are attached to hooks placed on roof of the box (inside the box) and the two S-chambers are then opened. For best results, the S-

chambers are placed near the exhaust nozzle (i.e. the opposite end to which the air pump is attached) [Ref 12]. The open end of the box is placed on top of the section on which the flux is to be measured and gently pressed into the ground so as not to unnecessarily disturb the natural radon flux emanating from the surface and thereby creating an artificial environment. The system is left for a period of 1 day then the S-chambers can be removed and placed in the closed position and left alone for 3 hours in order to allow the radon daughters to decay. After 3 hours has elapsed the final voltage of the electret is measured. (See figure 14 and figure 16 at the end of section 3.7 1 for pictures of the dynamic method equipment and deployment of dynamic system).

The theory behind this method is that once the air starts circulating (i.e. air comes in through the inlet nozzle and goes out through the exhaust nozzle) at the top of the aluminum box (i.e. the closed end of the box) it creates a low-pressure cell at the top of the box. The low-pressure cell assists in the movement of radon to the top of the box. Once the radon reaches the top, it enters the S-chambers and ionizes ("knocks" electrons free of atoms present in the S-chamber) the air in the S-chamber. These freed electrons are then attracted to the positively charged electret and upon reaching the electret starts to reduce the potential present on the electret (i.e. causes the electret to discharge). The change in the voltage can then be used to determine the radon flux from the surface using the following equations:

$$\text{Calibration factor} = A + B (V_i + V_f)/2 \quad (3)$$

$$\text{Radon concentration} = \{(V_i - V_f)/(C.F. \times \text{exposure time})\} - B.G. \quad (4)$$

$$\text{Radon flux} = (\text{radon concentration} \times \text{flow rate}) / (60 \times \text{area}) \quad (5)$$

Where, A and B are constants found in the Rad Elec manual

$V_i$  = initial voltage reading of the electret

$V_f$  = final voltage reading of the electret

C.F. = Calibration Factor

B.G. = background gamma reading (electrets are also gamma sensitive) which is also obtained from the manual (= 0.087)

Flow rate = 1 liter.min<sup>-1</sup>

Area = 0.104 m<sup>2</sup>

60 = conversion from minutes into seconds

The units of equation (5) are pCi.l<sup>-1</sup>. The final radon flux can be converted into S.I. units by multiplying equation (5) by 37, and the units will be Bq.m<sup>-2</sup>.s<sup>-1</sup>.

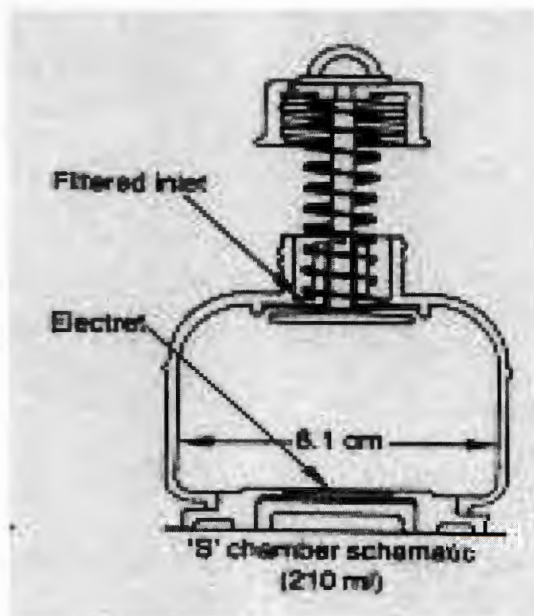


**Figure 8: Schematic diagram of an S-chamber in the “open” position**

Page 32 not in book

radon buildup occurring within the H-chamber. This also reduces the chances of back diffusion of radon. (See figure 11 for a schematic diagram of the H-chambers).

One of the H-chambers' base is covered by a thin aluminum plate (the reason for this will be explained later). The initial reading of two short-term electrets are measured using the reader and screwed onto the two H-chambers. The chambers are then gently pressed into the ground to limit the disturbance of the natural radon flux from the surface. The chambers are then left for 3 hours, after which the electrets are removed and placed in their covers

When the H-chambers with the collars attached are pressed into the soil, the radon trapped within the collar migrates to the surface (when possible) and then enters the H-chamber through the Tyvek window. The radon enters the H-chambers and ionizes the air in the H-chamber. These freed electrons are then attracted to the positively charged electret and upon reaching the electret causes the electret to discharge. One of the H-chambers has an aluminum plate covering the Tyvek window (this H-chamber is referred to as the "blank"). This is because the electrets are gamma sensitive. The aluminum plate prevents any radon entering the H-chamber and thus, the voltage drop on that electret will be entirely due to the gamma radiation present in that area (background). (See figure 12 for a schematic diagram of the deployment of the passive system and to figure 13 for photos of the passive system components). Due to the larger volume of the H-chamber, a reading can be taken in about three hours and because the voltage drop in the passive system is quite rapid, it takes into account the fact that a fresh electret (about 750 V) will

lose its potential more rapidly than a used electret (voltage should be more than 200 V). and a Linearity correction coefficient is introduced to make the potential drop linear. The change in the voltage can then be used to determine the radon flux from the surface using the following equations:

$$\text{Linearity Correction Coefficient} = 0.7727 + \{0.00004568 \times (V_i + V_f)/2\} \quad (6)$$

$$\text{Calibration Factor} = 10.4 \times \text{L.C.C.} \quad (7)$$

$$\text{Discharge rate} = (V_i - V_f)/(\text{exposure time}) \quad (8)$$

$$\text{Flux} = (\text{discharge rate})/(\text{C.F.} \times \text{L.C.C.}) \quad (9)$$

Where,  $V_i$  = initial electret reading

$V_f$  = final electret reading

Exposure time = exposure time of electret in hours

C.F. = calibration factor

L.C.C = linearity correction coefficient

Equations (6) to (9) are used to calculate the flux for both the blank and the radon flux monitor then the flux reading from the blank is subtracted from the flux reading from the radon flux monitor and the result will be the net radon flux. This will be in Flux Units (i.e. 1 F. U. = 1 pCi.l<sup>-1</sup>). To convert flux units to S.I. units (Bq.m<sup>-2</sup>.s<sup>-1</sup>) multiply the flux units by 0.037 [Ref 3, 13, 16, 19, 25, 30, 31, 32].

### 3.7 Deployment strategy

In this section the experimental procedure that was used to determine the radon flux from the surface Kloof and Leeudorn slimes dams is discussed. Identical procedures were used on both slimes dams. Both the dynamic and passive deployments will be discussed in detail.

#### 3.7.1 Dynamic system deployment

The initial voltage reading of the electret was read using the Electret Reader at approximately 7 AM each morning, the serial number of the electret and its initial voltage was noted and placed back in their plastic coverings. Upon arriving at the slimes dam the electret was screwed into the S-chamber (in the closed position) and all the required equipment (the aluminum box, the air pump, battery, S-chamber with electret) was unloaded and the time of the deployment was noted. The S-chamber was opened and placed on one of the hooks in the aluminum box. The box was then inverted (such that the open end was placed face down on the surface of the mine) and gently pressed into the slimes dam surface so as to minimize the disruption to the radon flux/equilibrium. The air pump was connected to the inlet nozzle on the aluminum box and the battery was connected to the air pump. The airflow rate was set at a rate of  $11 \text{ min}^{-1}$ . (See figure 10 for a schematic diagram of the deployment of the dynamic system).



This equipment was then covered with a plastic sheet. This was to keep any rain and dust off the equipment as well as to allow the equipment to blend in with the background (this was to prevent any people walking around the slimes dam coming and disturbing the

equipment). The temperature and the pressure at the time of deployment were noted. The flow rate was checked every 8 hours. 24 hours later the battery and pump were disconnected, the aluminum box was turned over, the S-chamber closed and removed from the box. The final voltage of the electret was read at around 7 PM. This was to ensure that the initial and final readings were read at approximately the same temperature as well as to ensure that at least 3 hours had elapsed after the removal of the S-chamber from the aluminum box (to allow for the radon daughters to decay). This procedure was repeated to get the readings listed in tables 3 and 7.

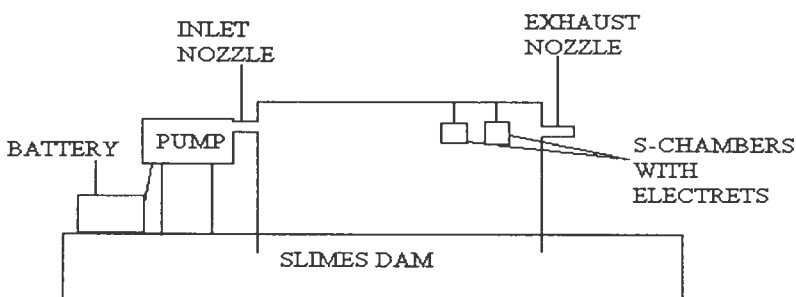


**Figure 10: Schematic diagram of the deployment of the dynamic system**

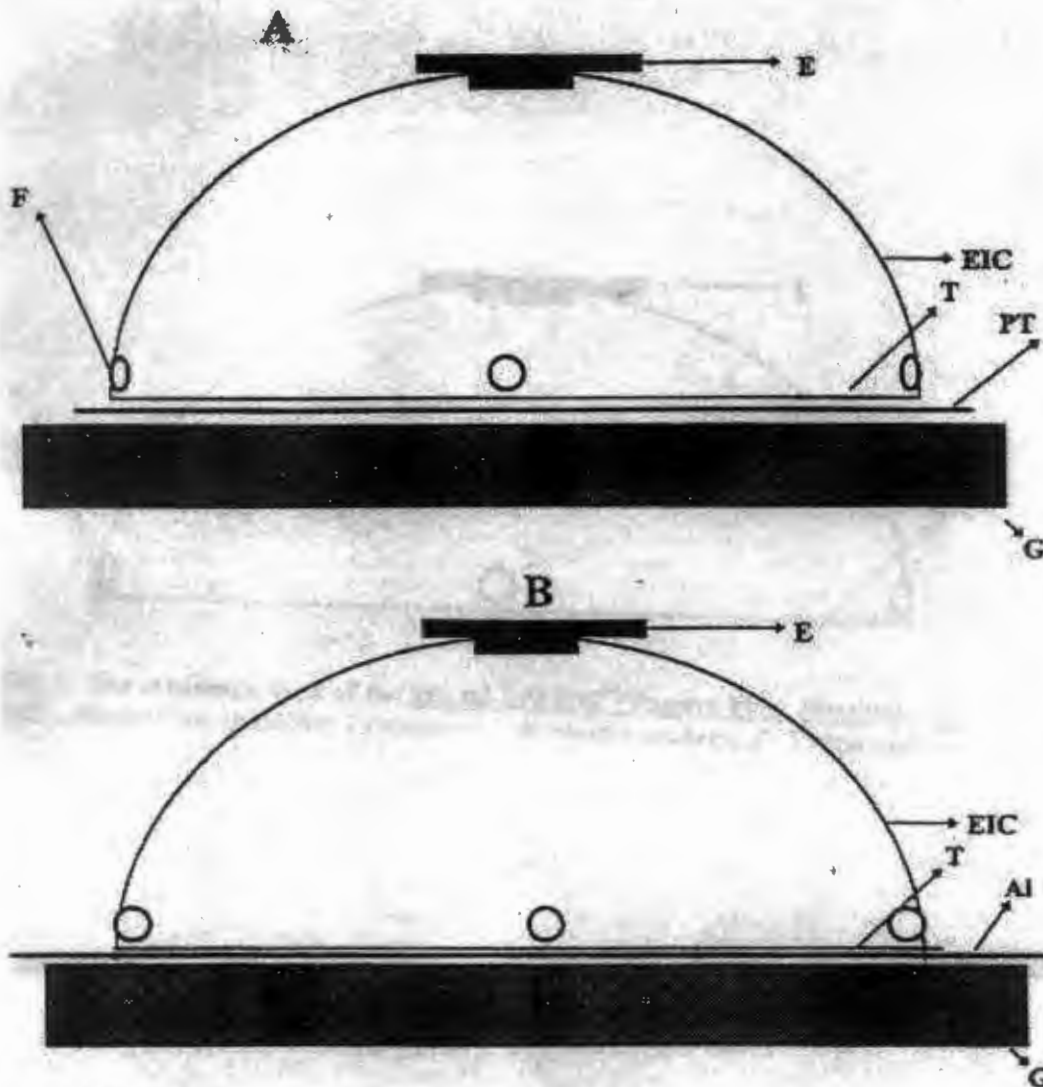
### 3.7.2 Passive system deployment

The “blank” chamber was created by placing one of the H-chambers in an aluminum sandwich tin and screwing the collar to the sandwich tin and to the H-chamber. Any possible openings between the collar and the chamber were sealed using a sealant. As per the dynamic system, the electret serial number and the initial voltage were noted. Upon arriving at the slimes dam, one electret was screwed into the radon flux monitor and another into the blank monitor. Both the chambers were gently pressed into the surface to limit disturbing the radon flux/equilibrium. The chambers were placed approximately one meter apart from each other. Three hours later the electrets were placed back in their covers and placed in a Mylar bag. Time permitting more trials was conducted. The final voltage of the electret was read at around 7 PM. This was to ensure that the initial and final readings were read at approximately the same temperature. This procedure was repeated to get the readings listed in tables 4 and 8. (See figure 12 for a Schematic diagram of the deployment of the passive system).

**NOTE:** Great care should be taken not to touch the electret surface or to get any water on the electret surface as it may cause premature discharge. At the time of writing this dissertation, the effects of temperature and pressure on electrets were being studied by Mr. Thabo Tselane at the University of Western Cape as part of his masters project, hence the effects of temperature and pressure was not taken into consideration [Ref 36].

The first sets of readings were taken from around the circumference of the slimes dam and is referred to as perimeter data from hence forth. The perimeter data refers to the

trials 1 to 8. The second sets of readings were taken from within the slimes dam and is referred to as internal data from hence forth. The internal data refers to the trials 9 to 18.



E : Electret  
 G : Ground or tailings  
 PT : Paper Towel to allow radon to pass  
 T : Tyvek Window  
 EIC : Electret Ion Chamber  
 Al : Al sheet to stop radon  
 F : Filtered openings

**NOTE**  
 The Chamber A allows radon  
 The Chamber B stops radon

Figure 11: Schematic diagram of two H-chambers (The one on the bottom is the blank)

Page 39 - 46 not in  
book

## CHAPTER 4

### Results and Calculations

This chapter looks at the results obtained, calculations, tables and graphs. A short discussion will proceed the tables with calculations. The notation used in the tables are of the format xYz, where x is a number used to represent the trial number, Y stands for either A or P where A represents the dynamic/active system readings and P represents the passive system readings, z represents the set of results (only applicable for the passive system). For example: 12A would denote trial 12 with the dynamic/active system readings and 12P3 would denote the third set of results for trial 12 with the passive system.

Tables 1 and 2 are tables of the physical conditions (e.g. temperature, pressure, climatic conditions, coordinates etc) of the sites where the measurements were taken at Kloof mine for the dynamic/active and passive systems respectively. Tables 3 and 4 are the flux calculations from the readings obtained at Kloof mine with the dynamic/active systems and passive systems respectively. Tables 5 and 6 are tables of the physical conditions of the sites where the measurements were taken at Leeudorn mine for the dynamic/active and passive systems respectively. Tables 7 and 8 are the flux calculations from the readings obtained at Leeudorn mine with the dynamic/active systems and passive systems respectively. Table 9 is a summary of the radon flux and the standard deviation.

Equations (3) to (5) have been used to calculate the flux for the dynamic system results and equations (6) to (9) were used to calculate the flux for the passive system results. A sample calculation has been performed for each of the systems. The other flux values were calculated in the same way. All calculations were done using Microsoft Excel™.

4.1 Sample dynamic system calculation:

| Known parameters                       | Unknown parameters  |
|----------------------------------------|---------------------|
| Initial voltage = $V_i = 670\text{ V}$ | Calibration factor  |
| Final voltage = $V_f = 606\text{ V}$   | Radon concentration |
| Exposure time = 1 day                  | Radon flux          |
| Flow rate = $1\text{ l.min}^{-1}$      |                     |
| Area = $0.104\text{ m}^2$              |                     |
| $A = 1.69776$ (from Rad Elec manual)   |                     |
| $B = 0.0005742$ (from Rad Elec manual) |                     |

Calibration factor      =       $A + B \times \{(V_i + V_f)/2\}$   
                                     =       $1.69776 + (0.0005742) \times \{(670 + 606)/2\}$   
                                     =      2.06

Radon concentration   =  $\{(V_i - V_f)\} / \{C.F. \times \text{exposure time}\} - \{\text{gamma background}\}$   
                                     =  $\{(670 - 606)/(2.06 \times 1)\} - \{0.087\}$   
                                     =  $30.92\text{ pCi l}^{-1}$

Radon flux                =  $(\text{radon concentration} \times \text{flow rate}) / (60 \times \text{area})$   
                                     =  $(30.92 \times 1) / (60 \times 0.104)$

$$= 4.95 \text{ pCi.m}^{-2}.\text{s}^{-1}$$
$$= 0.18 \text{ Bq.m}^{-2}.\text{s}^{-1}$$

4.2 Sample passive system calculation:

| Known parameters                                                    | Unknown parameters                      |
|---------------------------------------------------------------------|-----------------------------------------|
| Initial voltage = $V_i$ = 667 V (blank), 624 V (radon flux monitor) | Linearity correction coefficient        |
| Final voltage = $V_f$ = 664 V (blank), 606 V (radon flux monitor)   | Calibration factor                      |
| Exposure time = 3 hours                                             | Discharge rate                          |
| $C = 0.7727$ (from Rad Elec manual)                                 | Flux (blank), Flux (radon flux monitor) |
| $D = 0.0004568$ (from Rad Elec manual)                              | Net flux                                |

For the blank:

Linearity correction coefficient       $= C + D \times \{(V_i + V_f)/2\}$

$$= 0.7727 + (0.0004568) \times (667 + 664)/2$$
$$= 1.077$$

Calibration factor       $= 10.4 \times \text{L.C.C}$

$$= 11.198$$

Discharge rate       $= \{(V_i - V_f)/\text{exposure time}\}$

$$= (667 - 664)/3 \text{ Volts.s}^{-1}$$
$$= 1 \text{ V.s}^{-1}$$

Flux       $= \text{discharge rate}/\text{C.F}$

$$= 1/11.198 \text{ pCi.l}^{-1}.$$

$$= 0.089 \text{ pCi.l}^{-1}$$

For the radon flux monitor:

$$\begin{aligned} \text{Linearity correction coefficient} &= C + D \times \{(V_i + V_f)/2\} \\ &= 0.7727 + (0.0004568) \times (624 + 606)/2 \\ &= 1.054 \end{aligned}$$

$$\begin{aligned} \text{Calibration factor} &= 10.4 \times \text{L.C.C} \\ &= 10.958 \end{aligned}$$

$$\begin{aligned} \text{Discharge rate} &= \{(V_i - V_f)/\text{exposure time}\} \\ &= (624 - 606)/3 \text{ V.s}^{-1} \\ &= 6 \text{ V.s}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Flux} &= \text{discharge rate}/\text{C.F} \\ &= 6/10.958 \text{ pCi.l}^{-1} \\ &= 0.548 \text{ pCi.l}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Net flux} &= \text{radon flux monitor reading} - \text{blank reading} \\ &= 0.548 \text{ pCi.l}^{-1} - 0.089 \text{ pCi.l}^{-1} \\ &= 0.458 \text{ pCi.l}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Net flux} &= 0.458 \text{ pCi.l}^{-1} \times 0.037 \\ &= 1.70 \times 10^{-2} \text{ Bq.m}^{-2}.\text{s}^{-1} \end{aligned}$$

The radium activity concentrations from sites 9 and 17 (2 samples each) were obtained from Mr. Peane Maleka who used gamma spectroscopy to obtain the following results: (Ref 34), **Site 9:**  $(273 \pm 2 \text{ and } 269 \pm 2) \text{ Bq.kg}^{-1}$ , and for **site 17:**  $(308 \pm 2 \text{ and } 288 \pm 2) \text{ Bq.kg}^{-1}$ .

| Date | Trial number | Latitude (S) | Longitude (E) | Alt (m) | Temp (°C) | Pres (mbar) | Ground, Environmental and Climatic conditions                |
|------|--------------|--------------|---------------|---------|-----------|-------------|--------------------------------------------------------------|
| 27/8 | 1A           | 26°40.866'   | 27° 61.396'   | 1696    | 25        | 839         | rocky, hard, some vegetation                                 |
| 28/8 | 2A           | 26° 41.079'  | 27° 61.466'   | 1692    | 22        | 843         | rocky, soft, some vegetation                                 |
| 29/8 | 3A           | 26° 41.339'  | 27° 61.839'   | 1698    | 23        | 834         | dry, rocky, hard, some vegetation                            |
| 30/8 | 4A           | 26° 41.469'  | 27° 62.023'   | 1688    | 22        | 835         | dry, upturned soil, overcast, some vegetation                |
| 3/9  | 5A           | 26° 41.495'  | 27° 62.268'   | 1684    | 22        | 836         | dry, rocky, no vegetation                                    |
| 4/9  | 6A           | 26° 41.292'  | 27° 62.340'   | 1685    | 28        | 835         | dry, hard rocky ground, some vegetation                      |
| 5/9  | 7A           | 26° 40.969'  | 27° 62.388'   | 1687    | 28        | 834         | dry, rocky ground, some vegetation                           |
| 6/9  | 8A           | 26° 40.709'  | 27° 61.961'   | 1689    | 23        | 835         | dry, rocky ground, lot of vegetation                         |
| 10/9 | 9A           | 26° 41.192'  | 27° 61.778'   | 1689    | 27        | 836         | dry, rocky, no vegetation                                    |
| 11/9 | 10A          | 26° 41.105'  | 27° 61.861'   | 1688    | 27        | 832         | dry, rocky, soft, no vegetation, overcast, slight drizzle    |
| 12/9 | 11A          | 26° 41.184'  | 27° 61.933'   | 1686    | 15        | 835         | dry, rocky, soft, some vegetation, sunny, occasional drizzle |
| 13/9 | 12A          | 26° 41.246'  | 27° 62.025'   | 1691    | 10        | 835         | wet, rocky, soft, some vegetation, drizzle                   |
| 17/9 | 13A          | 26° 40.793'  | 27° 62.228'   | 1680    | 24        | 845         | dry, hard, rocky, no vegetation                              |
| 18/9 | 14A          | 26° 40.827'  | 27° 62.212'   | 1679    | 25        | 835         | hard, rocky, some vegetation, sunny                          |
| 19/9 | 15A          | 26° 40.831'  | 27° 62.164'   | 1683    | 20        | 833         | dry, hard, rocky, overcast, some vegetation, slight fog      |
| 20/9 | 16A          | 26° 40.801'  | 27° 61.446'   | 1687    | 15        | 838         | soft, rocky, some vegetation,                                |
| 21/9 | 17A          | 26° 41.045'  | 27° 61.628'   | 1688    | 18        | 835         | hard, rocky, some vegetation                                 |
| 24/9 | 18A          | 26° 41.193'  | 27° 61.620'   | 1688    | 25        | 835         | hard, rocky, some vegetation                                 |
| 25/9 | 19A          | 26° 41.105'  | 27° 61.861'   | 1688    | 30        | 836         | dry, rocky, soft, no vegetation, overcast, slight drizzle    |

**Table 1: Physical Data for the dynamic system measurements for slimes dam**

number 2

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| Date | Trial number | Latitude (S) | Longitude (E) | Alt (m) | Temp (°C) | Pres (mbar) | Ground, Environmental and Climatic conditions                     |
|------|--------------|--------------|---------------|---------|-----------|-------------|-------------------------------------------------------------------|
| 27/8 | 1P1          | 26°40864'    | 27°61398'     | 1696    | 20        | 839         | rocky, dry                                                        |
|      | 1P2          | 26°40820'    | 27°61331'     | 1696    | 23        | 839         | rocky, dry, some grass                                            |
| 28/8 | 2P1          | 26°41079'    | 27°61466'     | 1692    | 25        | 843         | flat, dry, hard, some vegetation, rained previous night, overcast |
|      | 2P2          | 26°40994'    | 27°61458'     | 1692    | 27        | 840         | rocky, soft, some vegetation                                      |
|      | 2P3          | 26°41174'    | 27°61506'     | 1688    | 22        | 839         | rocky, some vegetation                                            |
| 29/8 | 3P1          | 26°41339'    | 27°61839'     | 1698    | 27        | 835         | dry, rocky, hard, some veg                                        |
|      | 3P2          | 26°41326'    | 27°61715'     | 1683    | 28        | 834         | dry, rocky, hard, some veg                                        |
|      | 3P3          | 26°41325'    | 27°61968'     | 1698    | 20        | 833         | dry, rocky, hard, some veg                                        |
| 30/8 | 4P1          | 26°41469'    | 27°62023'     | 1688    | 23        | 836         | dry, upturned soil, overcast, some vegetation                     |
|      | 4P2          | 26°41375'    | 27°62054'     | 1685    | 25        | 837         | dry, upturned soil, overcast, some vegetation                     |
| 3/9  | 5P1          | 26°41495'    | 27°62268'     | 1684    | 20        | 836         | dry, rocky, no vegetation                                         |
|      | 5P2          | 26°41511'    | 27°62058'     | 1684    | 23        | 834         | dry, rocky, no vegetation                                         |
| 4/9  | 6P1          | 26°41292'    | 27°62340'     | 1685    | 22        | 836         | dry, hard rocky ground, some vegetation                           |
|      | 6P2          | 26°41386'    | 27°62332'     | 1682    | 25        | 835         | dry, upturned soil, no veg                                        |
|      | 6P3          | 26°41149'    | 27°62370'     | 1687    | 27        | 834         | dry, hard rocky ground, some vegetation                           |
| 5/9  | 7P1          | 26°40969'    | 27°62388'     | 1687    | 25        | 836         | dry, rocky, some vegetation                                       |
|      | 7P2          | 26°41083'    | 27°62382'     | 1686    | 20        | 835         | rocky, hard, some vegetation                                      |
|      | 7P3          | 26°40875'    | 27°62423'     | 1690    | 28        | 834         | dry, rocky, some vegetation                                       |
| 6/9  | 8P1          | 26°40709'    | 27°61961'     | 1689    | 25        | 836         | dry, rocky, lot of vegetation                                     |
|      | 8P2          | 26°40705'    | 27°62170'     | 1691    | 20        | 835         | dry, rocky, lot of vegetation                                     |
|      | 8P3          | 26°40698'    | 27°62034'     | 1691    | 25        | 836         | dry, hard, flat, lot of vegetation                                |
| 10/9 | 9P1          | 26°41192'    | 27°61778'     | 1689    | 29        | 836         | dry, rocky, no vegetation                                         |
|      | 9P2          | 26°41261'    | 27°61750'     | 1689    | 27        | 835         | dry, rocky, no vegetation                                         |
| 11/9 | 10P1         | 26°41105'    | 27°61861'     | 1688    | 27        | 835         | dry, rocky, soft, no vegetation, overcast, slight drizzle         |
|      | 10P2         | 26°41138'    | 27°61959'     | 1689    | 22        | 834         | dry, rocky, soft, no vegetation, overcast, slight drizzle         |
|      | 10P3         | 26°41110'    | 27°61963'     | 1690    | 27        | 831         | dry, rocky, soft, no vegetation, overcast, slight drizzle         |
| 12/9 | 11P1         | 26°41184'    | 27°61933'     | 1686    | 20        | 834         | dry, rocky, soft, vegetation, sunny, occasional drizzle           |
|      | 11P2         | 26°41184'    | 27°61958'     | 1688    | 15        | 833         | dry, rocky, soft, no vegetation, overcast, occasional drizzle     |
|      | 11P3         | 26°41245'    | 27°61835'     | 1686    | 17        | 832         | flat, hard, wet due to drizzle, some vegetation, rain. Hail       |

**Table 2: Data for the passive system measurements for slimes dam number 2 (page 1 of 2)**

Table 2 (continued)

| Date | Trial number | Latitude (S) | Longitude (E) | Alt (m) | Temp (°C) | Pres (mbar) | Ground, Environmental and Climatic conditions               |
|------|--------------|--------------|---------------|---------|-----------|-------------|-------------------------------------------------------------|
| 14/9 | 12P1         | 26°41246'    | 27°62025'     | 1691    | 14        | 838         | rocky, soft, wet, overcast, some vegetation, overnight rain |
|      | 12P2         | 26°41352'    | 27°62020'     | 1689    | 10        | 840         | rocky, hard, wet, overcast, some vegetation, overnight rain |
| 17/9 | 12P3         | 26°41143'    | 27°62028'     | 1692    | 24        | 836         | soft, rocky, some vegetation                                |
|      | 13P1         | 26°40793'    | 27°62228'     | 1680    | 27        | 837         | hard, rocky, some vegetation                                |
| 18/9 | 13P2         | 26°40978'    | 27°62085'     | 1680    | 18        | 835         | hard, rocky, some vegetation, overcast                      |
|      | 14P1         | 26°40827'    | 27°62212'     | 1679    | 25        | 834         | hard, rocky, some vegetation, sunny                         |
| 19/9 | 14P2         | 26°40940'    | 27°62203'     | 1684    | 14        | 833         | soft, rocky, some vegetation, overcast, slight drizzle      |
|      | 14P3         | 26°40993'    | 27°62152'     | 1682    | 20        | 837         | soft, rocky, some vegetation, sunny, no drizzle             |
| 20/9 | 15P1         | 26°40831'    | 27°62163'     | 1683    | 17        | 836         | dry, hard, rocky, overcast some vegetation, slight fog      |
|      | 15P2         | 26°40898'    | 27°62101'     | 1683    | 15        | 837         | dry, hard, rocky, overcast some vegetation, no fog          |
|      | 15P3         | 26°40787'    | 27°62187'     | 1680    | 18        | 834         | dry, hard, rocky, overcast some vegetation                  |
| 21/9 | 16P1         | 26°40801'    | 27°61448'     | 1687    | 15        | 834         | soft, rocky, some vegetation                                |
|      | 16P2         | 26°40932'    | 27°61518'     | 1689    | 15        | 834         | hard, flat, some veg, sunny                                 |
|      | 16P3         | 26°40925'    | 27°61537'     | 1687    | 19        | 834         | soft, rocky, some vegetation                                |
|      | 17P1         | 26°41045'    | 27°61628'     | 1688    | 17        | 835         | hard, rocky, some vegetation                                |
|      | 17P2         | 26°41085'    | 27°61564'     | 1692    | 19        | 833         | hard ground, some vegetation                                |
|      | 17P3         | 26°41057'    | 27°61698'     | 1690    | 19        | 833         | hard, rocky, lot of vegetation                              |
| 22/9 | 18P2         | 26°4143'     | 27°61648'     | 1689    | 19        | 835         | hard, rocky, wet, some veg                                  |
|      | 18P3         | 26°41104'    | 27°61776'     | 1690    | 19        | 835         | soft, rocky, wet, some veg                                  |
| 24/9 | 18P1         | 26°41193'    | 27°61620'     | 1688    | 19        | 835         | hard, rocky, wet, some                                      |
|      | 19P2         | 26°41105'    | 27°61861'     | 1688    | 25        | 835         | dry, rocky, hard, no vegetation,                            |
| 25/9 | 19P1         | 26°41138'    | 27°61959'     | 1689    | 25        | 837         | dry, rocky, soft, no vegetation,                            |
|      | 19P3         | 26°41110'    | 27°61963'     | 1690    | 20        | 837         | dry, rocky, soft, no vegetation,                            |
| 26/9 | 20P1         | 26°41184'    | 27°61933'     | 1686    | 20        | 836         | dry, rocky, hard, some veg                                  |
|      | 20P2         | 26°41184'    | 27°61933'     | 1686    | 22        | 836         | dry, rocky, hard, no vegetation                             |

Table 2: Data for the passive system measurements for slimes dam number 2 (page

| Trial number                   | Exposure time (d) | Flow rate l.min <sup>-1</sup> | Area m <sup>2</sup> | V <sub>i</sub> (V) | V <sub>f</sub> (V) | Calibration factor | Radon conc (pCi l <sup>-1</sup> ) | Flux (Bqm <sup>-2</sup> s <sup>-1</sup> ) |
|--------------------------------|-------------------|-------------------------------|---------------------|--------------------|--------------------|--------------------|-----------------------------------|-------------------------------------------|
| 1A                             | 05                | 1                             | 0.104               | 680                | 670                | 2.09               | 9.50                              | 0.06                                      |
| 2A                             | 1                 | 1                             |                     | 670                | 606                | 2.06               | 30.92                             | 0.18                                      |
| 3A                             | 1                 | 1                             |                     | 637                | 589                | 2.05               | 23.33                             | 0.14                                      |
| 4A                             | 1                 | 1                             |                     | 649                | 581                | 2.02               | 33.07                             | 0.20                                      |
| 5A                             | 1                 | 1                             |                     | 575                | 531                | 2.08               | 21.75                             | 0.13                                      |
| 6A                             | 1                 | 1                             |                     | 688                | 632                | 1.98               | 26.88                             | 0.16                                      |
| 7A                             | 1                 | 1                             |                     | 506                | 478                | 2.02               | 14.05                             | 0.08                                      |
| 8A                             | 1                 | 1                             |                     | 575                | 562                | 2.02               | 6.34                              | 0.04                                      |
| 9A                             | 1                 | 1                             |                     | 576                | 535                | 1.95               | 20.24                             | 0.12                                      |
| 10A                            | 1                 | 1                             |                     | 456                | 429                | 1.92               | 13.75                             | 0.08                                      |
| 11A                            | 1                 | 1                             |                     | 425                | 366                | 1.92               | 30.56                             | 0.18                                      |
| 12A                            | 1                 | 1                             |                     | 504                | 472                | 1.98               | 16.09                             | 0.10                                      |
| 13A                            | 1                 | 1                             |                     | 432                | 386                | 1.93               | 23.72                             | 0.14                                      |
| 14A                            | 1                 | 1                             |                     | 705                | 638                | 2.08               | 32.07                             | 0.19                                      |
| 15A                            | 1                 | 1                             |                     | 425                | 380                | 1.93               | 23.24                             | 0.14                                      |
| 16A                            | 1                 | 1                             |                     | 633                | 605                | 2.05               | 13.55                             | 0.08                                      |
| 17A                            | 1                 | 1                             |                     | 254                | 226                | 1.84               | 15.17                             | 0.09                                      |
| 18A                            | 1                 | 1                             |                     | 300                | 246                | 1.85               | 29.06                             | 0.17                                      |
| 19A                            | 1                 | 1                             |                     | 262                | 233                | 1.84               | 15.72                             | 0.09                                      |
| Mean flux (perimeter)          |                   |                               |                     |                    |                    |                    |                                   | 0.124                                     |
| Standard deviation (perimeter) |                   |                               |                     |                    |                    |                    |                                   | 0.058                                     |
| Mean flux (internal)           |                   |                               |                     |                    |                    |                    |                                   | 0.124                                     |
| Standard deviation (internal)  |                   |                               |                     |                    |                    |                    |                                   | 0.038                                     |
| Mean flux (overall)            |                   |                               |                     |                    |                    |                    |                                   | 0.124                                     |
| Standard deviation (overall)   |                   |                               |                     |                    |                    |                    |                                   | 0.046                                     |

**Table 3: Flux calculations for the dynamic system measurements for slimes dam number 2**

### 4.3 Discussion of table 3

Trials 1A to 8A were conducted on the outer region of the slimes dam (perimeter data) and trials 9A to 18A were conducted within the slimes dam (internal data) and trial 19A was conducted on the same location as trial 10A. The average flux from the perimeter and internal are the same with a standard deviation of 0.058 and 0.038 respectively. The

data suggests that the location of the place of measurement the flux does not affect the values of flux obtained. It seems advisable to conduct the trials on the perimeter as the entire range of the internal flux  $(0.124 \pm 0.038) \text{ Bq.m}^{-2}.\text{s}^{-1}$  falls within the range for the perimeter flux range of  $(0.124 \pm 0.058) \text{ Bq.m}^{-2}.\text{s}^{-1}$ .

| Trial no | V <sub>i</sub> (V) | V <sub>f</sub> (V) | Exposure Time (h) | LCC   | C. F:  | DISCHARGE RATE: Vh <sup>-1</sup> | FLUX: (F. U.) | NET FLUX: (F.U) | NET FLUX: (Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
|----------|--------------------|--------------------|-------------------|-------|--------|----------------------------------|---------------|-----------------|--------------------------------------------------|
| 1P2      | 667                | 664                | 3                 | 1.077 | 11.198 | 1.000                            | 0.089         | 0.458           | 1.70E-02                                         |
|          | 624                | 606                | 3                 | 1.054 | 10.958 | 6.000                            | 0.548         |                 |                                                  |
| 1P1      | 664                | 659                | 2.5               | 1.075 | 11.179 | 2.000                            | 0.179         | 1.002           | 3.71E-02                                         |
|          | 606                | 574                | 2.5               | 1.042 | 10.839 | 12.800                           | 1.181         |                 |                                                  |
| 2P2      | 659                | 656                | 3                 | 1.073 | 11.160 | 1.000                            | 0.090         | 1.799           | 6.65E-02                                         |
|          | 568                | 508                | 3                 | 1.018 | 10.592 | 20.000                           | 1.888         |                 |                                                  |
| 2P1      | 656                | 653                | 3                 | 1.072 | 11.145 | 1.000                            | 0.090         | 1.785           | 6.61E-02                                         |
|          | 508                | 450                | 3                 | 0.992 | 10.312 | 19.333                           | 1.875         |                 |                                                  |
| 2P3      | 648                | 641                | 2.5               | 1.067 | 11.098 | 2.800                            | 0.252         | 2.181           | 8.07E-02                                         |
|          | 450                | 389                | 2.5               | 0.964 | 10.029 | 24.400                           | 2.433         |                 |                                                  |
| 3P2      | 641                | 637                | 3                 | 1.065 | 11.072 | 1.333                            | 0.120         | 0.900           | 3.33E-02                                         |
|          | 386                | 356                | 3                 | 0.942 | 9.799  | 10.000                           | 1.021         |                 |                                                  |
| 3P1      | 658                | 649                | 3                 | 1.071 | 11.141 | 3.000                            | 0.269         | 1.149           | 4.25E-02                                         |
|          | 657                | 610                | 3                 | 1.062 | 11.046 | 15.667                           | 1.418         |                 |                                                  |
| 3P3      | 693                | 689                | 3                 | 1.088 | 11.319 | 1.333                            | 0.118         | 0.595           | 2.20E-02                                         |
|          | 684                | 660                | 3                 | 1.080 | 11.229 | 8.000                            | 0.712         |                 |                                                  |
| 4P2      | 689                | 685                | 3                 | 1.087 | 11.300 | 1.333                            | 0.118         | 1.361           | 5.03E-02                                         |
|          | 610                | 562                | 3                 | 1.040 | 10.820 | 16.000                           | 1.479         |                 |                                                  |
| 4P1      | 356                | 351                | 3                 | 0.934 | 9.715  | 1.667                            | 0.172         | 2.125           | 7.86E-02                                         |
|          | 606                | 532                | 3                 | 1.033 | 10.739 | 24.667                           | 2.297         |                 |                                                  |
| 5P2      | 658                | 652                | 3                 | 1.072 | 11.148 | 2.000                            | 0.179         | 1.674           | 6.20E-02                                         |
|          | 686                | 624                | 3                 | 1.072 | 11.148 | 20.667                           | 1.854         |                 |                                                  |
| 5P1      | 530                | 524                | 2.5               | 1.013 | 10.540 | 2.400                            | 0.228         | 1.774           | 6.57E-02                                         |
|          | 351                | 303                | 2.5               | 0.922 | 9.590  | 19.200                           | 2.002         |                 |                                                  |
| 6P2      | 624                | 620                | 3                 | 1.057 | 10.991 | 1.333                            | 0.121         | 1.049           | 3.88E-02                                         |
|          | 304                | 271                | 3                 | 0.904 | 9.402  | 11.000                           | 1.170         |                 |                                                  |
| 6P1      | 511                | 505                | 3                 | 1.005 | 10.449 | 2.000                            | 0.191         | 0.985           | 3.64E-02                                         |
|          | 654                | 615                | 3                 | 1.063 | 11.050 | 13.000                           | 1.176         |                 |                                                  |
| 6P3      | 590                | 580                | 3                 | 1.040 | 10.815 | 3.333                            | 0.308         | 1.137           | 4.21E-02                                         |
|          | 564                | 518                | 3                 | 1.020 | 10.606 | 15.333                           | 1.446         |                 |                                                  |
| 7P2      | 271                | 266                | 3                 | 0.895 | 9.312  | 1.667                            | 0.179         | 1.049           | 3.88E-02                                         |
|          | 614                | 574                | 3                 | 1.044 | 10.858 | 13.333                           | 1.228         |                 |                                                  |
| 7P1      | 586                | 581                | 3                 | 1.039 | 10.808 | 1.667                            | 0.154         | 1.151           | 4.26E-02                                         |
|          | 533                | 492                | 3                 | 1.007 | 10.471 | 13.667                           | 1.305         |                 |                                                  |
| 7P3      | 520                | 515                | 3                 | 1.009 | 10.495 | 1.667                            | 0.159         | 1.003           | 3.71E-02                                         |
|          | 623                | 585                | 3                 | 1.049 | 10.906 | 12.667                           | 1.161         |                 |                                                  |

**Table 4: Flux calculations for the passive system measurements for Kloof slimes**

dam number 2 (page 1 of 4)

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Table 4 continued...

| Trial no | V <sub>i</sub> (V) | V <sub>f</sub> (V) | Exposure Time (h) | LCC   | C. F:  | DISCHARGE RATE: Vh <sup>-1</sup> | FLUX: (F. U.) | NET FLUX: (F.U) | NET FLUX: (Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
|----------|--------------------|--------------------|-------------------|-------|--------|----------------------------------|---------------|-----------------|--------------------------------------------------|
| 8P2      | 268                | 264                | 3                 | 0.894 | 9.300  | 1.333                            | 0.143         | 0.494           | 1.83E-02                                         |
|          | 630                | 609                | 3                 | 1.056 | 10.979 | 7.000                            | 0.638         |                 |                                                  |
| 8P1      | 581                | 578                | 3                 | 1.037 | 10.789 | 1.000                            | 0.093         | 0.226           | 8.37E-03                                         |
|          | 514                | 504                | 3                 | 1.005 | 10.454 | 3.333                            | 0.319         |                 |                                                  |
| 8P3      | 574                | 571                | 3                 | 1.034 | 10.756 | 1.000                            | 0.093         | 0.944           | 3.49E-02                                         |
|          | 490                | 458                | 3                 | 0.989 | 10.288 | 10.667                           | 1.037         |                 |                                                  |
| 9P2      | 570                | 566                | 3                 | 1.032 | 10.734 | 1.333                            | 0.124         | 0.850           | 3.14E-02                                         |
|          | 557                | 526                | 3                 | 1.020 | 10.609 | 10.333                           | 0.974         |                 |                                                  |
| 9P1      | 267                | 262                | 3                 | 0.894 | 9.293  | 1.667                            | 0.179         | 1.174           | 4.35E-02                                         |
|          | 611                | 567                | 3                 | 1.042 | 10.834 | 14.667                           | 1.354         |                 |                                                  |
| 10P2     | 264                | 260                | 3                 | 0.892 | 9.281  | 1.333                            | 0.144         | 1.525           | 5.64E-02                                         |
|          | 563                | 510                | 3                 | 1.018 | 10.585 | 17.667                           | 1.669         |                 |                                                  |
| 10P1     | 524                | 520                | 3                 | 1.011 | 10.516 | 1.333                            | 0.127         | 1.524           | 5.64E-02                                         |
|          | 502                | 451                | 3                 | 0.990 | 10.300 | 17.000                           | 1.651         |                 |                                                  |
| 10P3     | 565                | 561                | 3                 | 1.030 | 10.711 | 1.333                            | 0.124         | 1.478           | 5.47E-02                                         |
|          | 478                | 429                | 3                 | 0.980 | 10.191 | 16.333                           | 1.603         |                 |                                                  |
| 11P2     | 534                | 527                | 3                 | 1.015 | 10.556 | 2.333                            | 0.221         | 1.673           | 6.19E-02                                         |
|          | 561                | 501                | 3                 | 1.015 | 10.559 | 20.000                           | 1.894         |                 |                                                  |
| 11P1     | 260                | 257                | 3                 | 0.891 | 9.264  | 1.000                            | 0.108         | 1.985           | 7.34E-02                                         |
|          | 520                | 455                | 3                 | 0.995 | 10.352 | 21.667                           | 2.093         |                 |                                                  |
| 11P3     | 499                | 485                | 3                 | 0.997 | 10.373 | 4.667                            | 0.450         | 3.734           | 1.38E-01                                         |
|          | 450                | 326                | 3                 | 0.950 | 9.879  | 41.333                           | 4.184         |                 |                                                  |
| 12P2     | 326                | 322                | 3                 | 0.921 | 9.575  | 1.333                            | 0.139         | 1.174           | 4.34E-02                                         |
|          | 681                | 637                | 3                 | 1.074 | 11.167 | 14.667                           | 1.313         |                 |                                                  |
| 12P1     | 529                | 520                | 3                 | 1.012 | 10.528 | 3.000                            | 0.285         | 0.602           | 2.23E-02                                         |
|          | 457                | 430                | 3                 | 0.975 | 10.143 | 9.000                            | 0.887         |                 |                                                  |
| 12P3     | 322                | 319                | 3.5               | 0.919 | 9.559  | 0.857                            | 0.090         | 2.926           | 1.08E-01                                         |
|          | 639                | 525                | 3.5               | 1.039 | 10.801 | 32.571                           | 3.016         |                 |                                                  |
| 13P1     | 400                | 397                | 3                 | 0.955 | 9.929  | 1.000                            | 0.101         | 1.730           | 6.40E-02                                         |
|          | 483                | 427                | 3                 | 0.981 | 10.198 | 18.667                           | 1.830         |                 |                                                  |
| 13P2     | 319                | 316                | 3.3               | 0.918 | 9.544  | 0.909                            | 0.095         | 0.753           | 2.79E-02                                         |
|          | 427                | 399                | 3.3               | 0.961 | 9.998  | 8.485                            | 0.849         |                 |                                                  |
| 14P1     | 690                | 686                | 2.5               | 1.087 | 11.305 | 1.600                            | 0.142         | 1.396           | 5.16E-02                                         |
|          | 519                | 479                | 2.5               | 1.001 | 10.407 | 16.000                           | 1.537         |                 |                                                  |
| 14P2     | 316                | 313                | 3                 | 0.916 | 9.530  | 1.000                            | 0.105         | 0.839           | 3.11E-02                                         |
|          | 478                | 449                | 3                 | 0.984 | 10.238 | 9.667                            | 0.944         |                 |                                                  |

Table 4: Flux calculations for the passive system measurements for Kloof slimes

dam number 2 (page 2 of 4)

Table 4 continued...

| Trial no | V <sub>i</sub> (V) | V <sub>f</sub> (V) | Exposure Time (h) | LCC   | C. F:  | DISCHARGE RATE: Vh <sup>-1</sup> | FLUX: (F. U.) | NET FLUX: (F.U) | NET FLUX: (Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
|----------|--------------------|--------------------|-------------------|-------|--------|----------------------------------|---------------|-----------------|--------------------------------------------------|
| 14P3     | 399                | 393                | 3                 | 0.954 | 9.917  | 2.000                            | 0.202         | 1.440           | 5.33E-02                                         |
|          | 686                | 631                | 3                 | 1.074 | 11.164 | 18.333                           | 1.642         |                 |                                                  |
| 15P3     | 258                | 254                | 3                 | 0.890 | 9.252  | 1.333                            | 0.144         | 1.411           | 5.22E-02                                         |
|          | 727                | 674                | 3                 | 1.093 | 11.364 | 17.667                           | 1.555         |                 |                                                  |
| 15P1     | 672                | 669                | 3                 | 1.079 | 11.221 | 1.000                            | 0.089         | 1.915           | 7.09E-02                                         |
|          | 368                | 310                | 3                 | 0.928 | 9.647  | 19.333                           | 2.004         |                 |                                                  |
| 15P2     | 392                | 390                | 3                 | 0.951 | 9.894  | 0.667                            | 0.067         | 1.778           | 6.58E-02                                         |
|          | 312                | 260                | 3                 | 0.903 | 9.395  | 17.333                           | 1.845         |                 |                                                  |
| 16P2     | 479                | 475                | 3                 | 0.991 | 10.302 | 1.333                            | 0.129         | 1.363           | 5.04E-02                                         |
|          | 446                | 401                | 3                 | 0.966 | 10.048 | 15.000                           | 1.493         |                 |                                                  |
| 16P1     | 310                | 308                | 3                 | 0.914 | 9.504  | 0.667                            | 0.070         | 1.950           | 7.22E-02                                         |
|          | 669                | 602                | 3                 | 1.063 | 11.055 | 22.333                           | 2.020         |                 |                                                  |
| 16P3     | 342                | 338                | 3                 | 0.928 | 9.651  | 1.333                            | 0.138         | 1.189           | 4.40E-02                                         |
|          | 390                | 351                | 3                 | 0.942 | 9.796  | 13.000                           | 1.327         |                 |                                                  |
| 17P2     | 261                | 258                | 3                 | 0.891 | 9.269  | 1.000                            | 0.108         | 2.367           | 8.76E-02                                         |
|          | 674                | 592                | 3                 | 1.062 | 11.043 | 27.333                           | 2.475         |                 |                                                  |
| 17P1     | 475                | 469                | 3                 | 0.988 | 10.278 | 2.000                            | 0.195         | 1.916           | 7.09E-02                                         |
|          | 401                | 339                | 3                 | 0.942 | 9.794  | 20.667                           | 2.110         |                 |                                                  |
| 17P3     | 308                | 305                | 3                 | 0.913 | 9.492  | 1.000                            | 0.105         | 0.867           | 3.21E-02                                         |
|          | 634                | 602                | 3                 | 1.055 | 10.972 | 10.667                           | 0.972         |                 |                                                  |
| 18P2     | 258                | 256                | 3                 | 0.890 | 9.257  | 0.667                            | 0.072         | 1.597           | 5.91E-02                                         |
|          | 350                | 302                | 3                 | 0.922 | 9.585  | 16.000                           | 1.669         |                 |                                                  |
| 18P3     | 305                | 301                | 3                 | 0.911 | 9.476  | 1.333                            | 0.141         | 1.568           | 5.80E-02                                         |
|          | 470                | 418                | 3                 | 0.976 | 10.145 | 17.333                           | 1.708         |                 |                                                  |
| 18P1     | 256                | 253                | 3                 | 0.889 | 9.245  | 1.000                            | 0.108         | 1.246           | 4.61E-02                                         |
|          | 348                | 309                | 3                 | 0.923 | 9.597  | 13.000                           | 1.355         |                 |                                                  |
| 19P2     | 227                | 224                | 3                 | 0.876 | 9.107  | 1.000                            | 0.110         | 1.347           | 4.99E-02                                         |
|          | 303                | 262                | 3                 | 0.902 | 9.378  | 13.667                           | 1.457         |                 |                                                  |
| 19P1     | 604                | 600                | 3                 | 1.048 | 10.896 | 1.333                            | 0.122         | 1.392           | 5.15E-02                                         |
|          | 603                | 554                | 3                 | 1.037 | 10.784 | 16.333                           | 1.515         |                 |                                                  |
| 19P3     | 340                | 337                | 3                 | 0.927 | 9.644  | 1.000                            | 0.104         | 0.882           | 3.26E-02                                         |
|          | 603                | 571                | 3                 | 1.041 | 10.825 | 10.667                           | 0.985         |                 |                                                  |
| 20P2     | 246                | 243                | 3                 | 0.884 | 9.198  | 1.000                            | 0.109         | 1.162           | 4.30E-02                                         |
|          | 592                | 551                | 3                 | 1.034 | 10.751 | 13.667                           | 1.271         |                 |                                                  |
| 20P1     | 554                | 550                | 3                 | 1.025 | 10.658 | 1.333                            | 0.125         | 1.061           | 3.93E-02                                         |
|          | 337                | 303                | 3                 | 0.919 | 9.556  | 11.333                           | 1.186         |                 |                                                  |

Table 4: Flux calculations for the passive system measurements for Kloof slimes

dam number 2 (page 3 of 4)

Table 4 continued...

|                                | Flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
|--------------------------------|------------------------------------------------|
| Mean flux (perimeter)          | 0.050                                          |
| Standard deviation (perimeter) | 0.022                                          |
| Mean flux (internal)           | 0.071                                          |
| Standard deviation (internal)  | 0.028                                          |
| Mean flux (overall)            | 0.062                                          |
| Standard deviation (overall)   | 0.027                                          |

**Table 4: Flux calculations for the passive system measurements for Kloof slimes dam number 2 (page 4 of 4)**

**4.4 Discussion of table 4**

Trials 1P1 to 8P3 were conducted on the perimeter of the slimes dam and trials 9P1 to 18P3 were conducted within the slimes dam. Trials 19P1 to 20P2 were repeat trials on sites 10 and 11 respectively. The average flux from the perimeter is 0.050 with a standard deviation of 0.022 and the internal flux is 0.071 with a standard deviation of 0.028. The average of flux (overall) is 0.062 with a standard deviation of 0.027. There is approximately 41% overlap between the ranges. This data also suggests that the location of the place of measurement does not affect values of the flux obtained. When the dynamic and passive system flux (for the perimeter) is compared, the dynamic system readings are higher by a factor of almost 2.5 (i.e.  $0.124 \pm 0.058$  versus  $0.050 \pm 0.022$  Bq.m<sup>-2</sup>.s<sup>-1</sup>). When the dynamic and passive system flux (internal) are compared, the

dynamic system readings are higher by a factor more than 1.7 (i.e.  $0.124 \pm 0.038$  versus  $0.071 \pm 0.028 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ). If the overall flux is considered, the dynamic system readings are higher by a factor of 2 than the readings from the passive system (i.e.  $0.124 \pm 0.046$  versus  $0.062 \pm 0.027 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ).

These consistently higher flux readings from the dynamic system imply that the time of measurement of the flux is very important. This conclusion can be reached because the passive system was only deployed during the day (from around 8 AM to 6 PM) for periods of 2.5 to 3 hours each, whereas the dynamic system was deployed for an entire 24 hours which would allow it to register the variation of flux with time to a greater degree of accuracy than the passive system.

| Date  | Site | Coordinates     |                  |              |                    |            | Comments                                                            |
|-------|------|-----------------|------------------|--------------|--------------------|------------|---------------------------------------------------------------------|
|       |      | Latitude<br>(S) | Longitude<br>(E) | Temp<br>(°C) | Pressure<br>(mbar) | alt<br>(m) | Ground and climatic conditions                                      |
| 17/12 | 21A  | 26°46.325'      | 27°56.143'       | 28<br>28     | 848<br>848         | 1555       | Soft, wet ground with cracks.<br>Moisture formed on s-chamber & box |
| 18/12 | 22A  | 26°46.250'      | 27°56.164'       | 27<br>27     | 849<br>849         | 1549       | Wet, flat, hard ground<br>Moisture formed on s-chamber & box        |
| 19/12 | 23A  | 26°46.269'      | 27°56.063'       | 28           | 848                | 1551       | Wet, flat, hard ground<br>Moisture formed on s-chamber & box        |
| 20/12 | 24A  | 26°46.154'      | 27°56.121'       | 28           | 847                | 1556       | Hard, flat, wet ground<br>Moisture formed on s-chamber & box        |
| 21/12 | 25A  | 26°46.199'      | 27°56.276'       | 28           | 847                | 1560       | Soft, wet ground<br>Moisture formed on s-chamber & box              |

Table 5: Data for the dynamic system measurements for Leudorn slimes dam

number 1

| Date  | Trial no | Coordinates  |               | Comments  |                 |              |                                                            |
|-------|----------|--------------|---------------|-----------|-----------------|--------------|------------------------------------------------------------|
|       |          | Latitude (S) | Longitude (E) | Temp (°C) | Pressure (mbar) | Altitude (m) | Ground and climatic conditions                             |
| 17/12 | 21P1     | 26°46.320'   | 27°56.139'    | 28        | 847             | 1556         | Soft, wet ground with cracks. Drizzled for about 5 minutes |
|       | 21P2     | 26°46.328'   | 27°56.148'    | 30        | 847             | 1555         | Soft, wet ground with cracks. Drizzled for about 5 minutes |
|       | 21P3     | 26°46.324'   | 27°56.158'    | 30        | 848             | 1556         | Soft, wet ground with cracks.                              |
|       | 21P4     | 26°46.283'   | 27°56.137'    | 27        | 848             | 1555         | Soft, wet ground with cracks.                              |
| 18/12 | 22P1     | 26°46.235'   | 27°56.171'    | 27        | 849             | 1547         | Wet, hard ground with cracks                               |
|       | 22P2     | 26°46.248'   | 27°56.165'    | 27        | 849             | 1549         | Wet, hard ground with cracks                               |
|       | 22P3     | 26°46.260    | 27°56.208'    | 28        | 849             | 1558         | Very wet, hard ground with cracks                          |
|       | 22P4     | 26°46.226'   | 27°56.190'    | 28        | 849             | 1551         | Very wet, hard ground with cracks                          |
| 19/12 | 23P1     | 26°46.334'   | 27°56.071     | 27        | 847             | 1554         | Very wet, hard ground with cracks                          |
|       | 23P2     | 26°46.291'   | 27°56.060'    | 27        | 847             | 1555         | Very wet, hard ground with cracks                          |
|       | 23P3     | 26°46.374'   | 27°55.975'    | 28        | 846             | 1558         | Very wet, hard ground with cracks                          |
|       | 23P4     | 26°46.263'   | 27°56.080'    | 28        | 846             | 1559         | Very wet, hard ground with cracks                          |
| 20/12 | 24P1     | 26°46.217'   | 27°56.113'    | 26        | 847             | 1559         | Hard, flat wet ground                                      |
|       | 24P2     | 26°46.174'   | 27°56.128'    | 26        | 847             | 1559         | Hard, flat wet ground                                      |
|       | 24P3     | 26°46.181'   | 27°56.153'    | 28        | 848             | 1551         | Hard, flat wet ground                                      |
|       | 24P4     | 26°46.186'   | 27°56.167'    | 28        | 848             | 1554         | Hard, flat wet ground                                      |
| 21/12 | 25P1     | 26°46.161'   | 27°56.316'    | 26        | 848             | 1550         | Soft, wet ground with cracks.                              |
|       | 25P2     | 26°46.196'   | 27°56.267'    | 26        | 848             | 1561         | Soft, wet ground with cracks.                              |
|       | 25P3     | 26°46.166'   | 27°56.253'    | 28        | 847             | 1563         | Hard, dry ground                                           |
|       | 25P4     | 26°46.140'   | 27°56.312'    | 28        | 847             | 1565         | Hard, dry ground                                           |

**Table 6: Data for the passive system measurements for Leudorn slimes dam**

**number 1. Note: the area in which these readings were taken was very windy.**

| Site | Exposure<br>time<br>(days) | Flow<br>rate<br>(l.min <sup>-1</sup> ) | V <sub>i</sub><br>(V) | V <sub>f</sub><br>(V) | Calibration<br>Factor | Area<br>(m <sup>2</sup> ) | Radon<br>conc.<br>(pCi.l <sup>-1</sup> ) | Flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
|------|----------------------------|----------------------------------------|-----------------------|-----------------------|-----------------------|---------------------------|------------------------------------------|------------------------------------------------|
| 21A  | 1                          | 1                                      | 296                   | 290                   | 1.87                  | 0.104                     | 3.13                                     | 0.02                                           |
|      | 1                          | 1                                      | 542                   | 529                   | 2.01                  |                           | 6.40                                     | 0.04                                           |
| 22A  | 1                          | 1                                      | 333                   | 301                   | 1.88                  |                           | 16.94                                    | 0.10                                           |
|      | 1                          | 1                                      | 393                   | 369                   | 1.92                  |                           | 12.44                                    | 0.07                                           |
| 23A  | 1                          | 1                                      | 290                   | 275                   | 1.86                  |                           | 7.98                                     | 0.05                                           |
|      | 1                          | 1                                      | 529                   | 456                   | 1.98                  |                           | 36.77                                    | 0.22                                           |
| 24A  | 1                          | 1                                      | 301                   | 286                   | 1.87                  |                           | 7.95                                     | 0.05                                           |
|      | 1                          | 1                                      | 369                   | 354                   | 1.91                  |                           | 7.79                                     | 0.05                                           |
| 25A  | 1                          | 1                                      | 275                   | 268                   | 1.85                  |                           | 3.69                                     | 0.02                                           |
|      | 1                          | 1                                      | 456                   | 443                   | 1.96                  |                           | 6.56                                     | 0.04                                           |
|      |                            |                                        |                       |                       |                       | Mean flux (overall)       | 0.090                                    |                                                |
|      |                            |                                        |                       |                       |                       | Standard deviation        | 0.077                                    |                                                |

**Table 7: Flux calculations for the dynamic system measurements for Leeudorn  
slimes dam number 1**

**4.5 Discussion of table 7**

Using the data from previous trials (1A to 19A) it was determined that the location of the measurements is not really an issue so, for the readings taken from Leeudorn slimes dam number 1 were not separated into perimeter and internal readings. The average (overall) flux obtained from the dynamic system readings from the “old” Kloof slimes dam number 2 (i.e.  $0.124 \pm 0.046 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ) falls within the range for the mean flux (overall) obtained from the active Leeudorn slimes dam number 1 (i.e.  $0.090 \pm 0.077 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ). This seems to suggest that the age of the slimes dam is also not an issue. However, it should be noted that in each of the trials conducted at Leeudorn mine, some condensation was seen to have been formed on the aluminum box as well as on the S-chamber itself.

Thus the probability of condensation forming on the electret is also quite high. The validity of the set of readings for Leeudorn mine is debatable.

| Trial No | V <sub>i</sub> (V) | V <sub>f</sub> (V) | Exposure Time (h) | LCC   | C. F.  | DISCHARGE RATE: (VPH) | FLUX: (F. U.) | NET FLUX: (F.U) | NET FLUX: (Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
|----------|--------------------|--------------------|-------------------|-------|--------|-----------------------|---------------|-----------------|--------------------------------------------------|
| 21P1     | 220                | 217                | 3                 | 0.873 | 9.074  | 1.000                 | 0.110         | 0.096           | 3.54E-03                                         |
|          | 356                | 350                | 3                 | 0.934 | 9.713  | 2.000                 | 0.206         |                 |                                                  |
| 21P2     | 242                | 239                | 3                 | 0.883 | 9.179  | 1.000                 | 0.109         | 0.109           | 4.03E-03                                         |
|          | 565                | 558                | 3                 | 1.029 | 10.704 | 2.333                 | 0.218         |                 |                                                  |
| 21P3     | 232                | 227                | 3                 | 0.878 | 9.126  | 1.667                 | 0.183         | 0.094           | 3.49E-03                                         |
|          | 594                | 585                | 3                 | 1.042 | 10.837 | 3.000                 | 0.277         |                 |                                                  |
| 21P4     | 301                | 297                | 3                 | 0.909 | 9.457  | 1.333                 | 0.141         | 0.205           | 7.57E-03                                         |
|          | 547                | 536                | 3                 | 1.020 | 10.609 | 3.667                 | 0.346         |                 |                                                  |
| 22P1     | 238                | 235                | 3                 | 0.881 | 9.160  | 1.000                 | 0.109         | 0.297           | 1.10E-02                                         |
|          | 558                | 545                | 3                 | 1.025 | 10.656 | 4.333                 | 0.407         |                 |                                                  |
| 22P2     | 217                | 214                | 3                 | 0.871 | 9.060  | 1.000                 | 0.110         | 0.131           | 4.84E-03                                         |
|          | 349                | 342                | 3                 | 0.931 | 9.677  | 2.333                 | 0.241         |                 |                                                  |
| 22P3     | 223                | 218                | 3                 | 0.873 | 9.084  | 1.667                 | 0.183         | 0.029           | 1.06E-03                                         |
|          | 296                | 290                | 3                 | 0.907 | 9.428  | 2.000                 | 0.212         |                 |                                                  |
| 22P4     | 586                | 582                | 3                 | 1.039 | 10.811 | 1.333                 | 0.123         | 0.988           | 3.66E-02                                         |
|          | 536                | 501                | 3                 | 1.010 | 10.499 | 11.667                | 1.111         |                 |                                                  |
| 23P1     | 218                | 212                | 3                 | 0.871 | 9.057  | 2.000                 | 0.221         | 0.027           | 1.02E-03                                         |
|          | 290                | 283                | 3                 | 0.904 | 9.397  | 2.333                 | 0.248         |                 |                                                  |
| 23P2     | 235                | 230                | 3                 | 0.879 | 9.141  | 1.667                 | 0.182         | 0.220           | 8.14E-03                                         |
|          | 582                | 569                | 3                 | 1.036 | 10.770 | 4.333                 | 0.402         |                 |                                                  |
| 23P3     | 214                | 210                | 3                 | 0.870 | 9.043  | 1.333                 | 0.147         | 0.268           | 9.91E-03                                         |
|          | 342                | 330                | 3                 | 0.926 | 9.632  | 4.000                 | 0.415         |                 |                                                  |
| 23P4     | 501                | 494                | 3                 | 1.000 | 10.400 | 2.333                 | 0.224         | 0.279           | 1.03E-02                                         |
|          | 545                | 529                | 3                 | 1.018 | 10.587 | 5.333                 | 0.504         |                 |                                                  |
| 24P1     | 212                | 210                | 3                 | 0.869 | 9.038  | 0.667                 | 0.074         | 0.204           | 7.56E-03                                         |
|          | 330                | 322                | 3                 | 0.922 | 9.585  | 2.667                 | 0.278         |                 |                                                  |
| 24P2     | 210                | 205                | 3                 | 0.867 | 9.022  | 1.667                 | 0.185         | 0.251           | 9.29E-03                                         |
|          | 569                | 555                | 3                 | 1.029 | 10.706 | 4.667                 | 0.436         |                 |                                                  |

**Table 8: Flux calculations for the passive system measurements for Leeudorn slimes**

**dam number 1 (page 1 of 2)**

| Trial No | V <sub>i</sub> (V) | V <sub>f</sub> (V) | Exposure Time (h) | LCC   | C. F.  | DISCHARGE RATE: (VPH)        | FLUX: (F. U.) | NET FLUX: (F.U) | NET FLUX: (Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
|----------|--------------------|--------------------|-------------------|-------|--------|------------------------------|---------------|-----------------|--------------------------------------------------|
| 24P3     | 230                | 227                | 3                 | 0.877 | 9.122  | 1.000                        | 0.110         | 0.180           | 6.66E-03                                         |
|          | 494                | 485                | 3                 | 0.996 | 10.362 | 3.000                        | 0.290         |                 |                                                  |
| 24P4     | 529                | 524                | 3                 | 1.013 | 10.537 | 1.667                        | 0.158         | 0.091           | 3.37E-03                                         |
|          | 283                | 276                | 3                 | 0.900 | 9.364  | 2.333                        | 0.249         |                 |                                                  |
| 25P1     | 227                | 223                | 3                 | 0.875 | 9.105  | 1.333                        | 0.146         | 0.499           | 1.84E-02                                         |
|          | 494                | 474                | 3                 | 0.994 | 10.335 | 6.667                        | 0.645         |                 |                                                  |
| 25P2     | 210                | 206                | 3                 | 0.868 | 9.024  | 1.333                        | 0.148         | 0.297           | 1.10E-02                                         |
|          | 524                | 510                | 3                 | 1.009 | 10.492 | 4.667                        | 0.445         |                 |                                                  |
| 25P3     | 210                | 202                | 3                 | 0.867 | 9.015  | 2.667                        | 0.296         | 1.432           | 5.30E-02                                         |
|          | 569                | 514                | 3                 | 1.020 | 10.609 | 18.333                       | 1.728         |                 |                                                  |
| 25P4     | 276                | 271                | 3                 | 0.898 | 9.335  | 1.667                        | 0.179         | 0.241           | 8.91E-03                                         |
|          | 322                | 310                | 3                 | 0.917 | 9.537  | 4.000                        | 0.419         |                 |                                                  |
|          |                    |                    |                   |       |        | Mean flux (overall)          |               |                 | 0.023                                            |
|          |                    |                    |                   |       |        | Standard deviation (overall) |               |                 | 0.020                                            |

**Table 8: Flux calculations for the passive system measurements for Leeudorn slimes dam number 1 (page 2 of 2)**

#### 4.6 Discussion of table 8

The lower limit of the average (overall) flux obtained from the passive system readings from the “old” Kloof slimes dam number 2 (i.e.  $0.062 \pm 0.027 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ) barely falls within the upper limit for the mean flux (overall) obtained from the active Leeudorn slimes dam number 1 (i.e.  $0.023 \pm 0.020 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ). This seems to suggest that the age of the slimes dam could be an issue but since the passive system does not take an entire days flux into consideration and the high standard deviation the validity of the data is once again debatable.

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# **CHAPTER 5**

## **Discussion, Conclusions and Recommendations**

This chapter looks at the findings from the study; conclusions that can be arrived at from the data; recommendations and possible future work in this field.

### **5.1 Discussion of the findings**

The purposes of this study were to:

1. Find out the factors that might affect the accurate determination of the radon flux from the slimes dams.
2. Get acquainted with the Rad Elec methods of determining radon flux
3. Determine radon flux from slimes dams using the dynamic/active and passive systems.

Parts 2 and 3 have been performed and now part 1 (the factors affecting radon flux) will be discussed in more detail.

Page 67 - 74 not in  
book

| Slimes<br>dam                                                                | Dynamic/Active system                                               |                                                                    |                                                                | Passive system                                                      |                                                                    |                                                                |
|------------------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------------------|----------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------------------|----------------------------------------------------------------|
|                                                                              | Mean<br>perimeter<br>flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) | Mean<br>internal<br>flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) | Mean<br>overall flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) | Mean<br>perimeter<br>flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) | Mean<br>internal<br>flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) | Mean overall<br>flux<br>(Bq.m <sup>-2</sup> .s <sup>-1</sup> ) |
| Kloof                                                                        | 0.124 ±<br>0.058                                                    | 0.124 ±<br>0.038                                                   | 0.124 ±<br>0.046                                               | 0.050 ±<br>0.022                                                    | 0.071 ±<br>0.028                                                   | 0.062 ± 0.027                                                  |
| Leeudorn                                                                     | N/A                                                                 | N/A                                                                | 0.090 ±<br>0.077                                               | N/A                                                                 | N/A                                                                | 0.023 ± 0.020                                                  |
| Theoretical flux value = 0.103 ± 0.006 Bq.m <sup>-2</sup> .s <sup>-1</sup> . |                                                                     |                                                                    |                                                                |                                                                     |                                                                    |                                                                |

**Table 9: summary of radon flux and standard deviations**

**5.1.1 The effect of location of measurement on radon flux:**

This subsection discusses the effects of location of the measurement of radon flux. The dynamic system and passive systems will be treated separately and then the data will be looked at as a whole.

**5.1.1.1 Dynamic system results**

From table 3 and 9, it can be seen that the entire range of the internal measurements (0.124 ± 0.038) Bq.m<sup>-2</sup>.s<sup>-1</sup> falls within the range for the perimeter measurements (0.124 ± 0.058) Bq.m<sup>-2</sup>.s<sup>-1</sup>. The overall average range (0.124 ± 0.046) Bq.m<sup>-2</sup>.s<sup>-1</sup> also falls entirely

within the perimeter data measurements. There is about 65% overlap between the mean perimeter and mean internal data range. This indicates that the location where the measurements were taken (whether on the perimeter or internally) does not play a major role on the average radon flux.

#### **5.1.1.2 Passive system results**

From tables 4 and 9 it can be seen that the perimeter data range is  $(0.050 \pm 0.022) \text{ Bq.m}^{-2}.\text{s}^{-1}$  and the internal data range is  $(0.071 \pm 0.028) \text{ Bq.m}^{-2}.\text{s}^{-1}$ . There is about 37% overlap between the mean perimeter and mean internal data range. This is also an indication that the location of the measurement is not a major aspect of radon flux measurements.

#### **5.1.1.3 Combined system results**

The passive and dynamic/active systems were positioned in approximately the same locations so, not much information can be gathered by comparing the two sets of data. Due to the dynamic system showing that the location of measurement is not a major factor the Leeudorn measurements were not separated into perimeter and internal measurements. Thus the Leeudorn data is not considered for this section. The dynamic system data is clearly much higher than the passive system data and the reason for this will be explained in the section dealing with the effect of time on measurement of radon flux.

### **5.1.2 The effect of time of measurement on radon flux:**

This subsection discusses the effects of the time of the measurement of radon flux. The dynamic system and passive systems will be treated separately and then the data will be looked at as a whole.

#### **5.1.2.1 Dynamic system results**

The dynamic system trials were run for a whole day. This system is a more accurate indicator of the radon flux from slimes dam surfaces as it takes into account the flux variations over the entire 24 hours. From tables 3, 7, and 9 it can be seen that the dynamic system readings are consistently higher than the readings from the passive system.

#### **5.1.2.2 Passive system results**

The passive systems were only run for a maximum of 3 hours. This was sufficient to give an average drop of approximately 40 Volts, which is sufficient to determine the flux. This system was only run during the morning. A comparison between the passive system readings and the dynamic system is a good indicator of the flux variations with time. From tables 4, 8, and 9 it can be seen that the passive system readings are consistently lower than the readings from the dynamic system.

### 5.1.2.3 Combined system results

From tables 3, 4, 7, 8 and 9 it is clearly seen that the dynamic system gives a much higher average value of flux data ( $0.124 \pm 0.046 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ) when compared with the passive system average value ( $0.062 \pm 0.027 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ). The data obtained in this research project shows that there is a clear difference in flux measurements taken during the day (8 AM to 6 PM) and flux measurements taken during over a period of 24 hours. And since previous studies have shown that there is collaboration between the dynamic and passive systems [Ref 27], this could be as a result of the varying flux at different times of the day.

### 5.1.3 The effect of age of slimes dam on radon flux:

This subsection discusses the effects of the age of the slimes dam on the measurement of radon flux. The dynamic system and passive systems will be treated separately and then the data will be looked at as a whole. The data from both Kloof and Leeudorn mines will be looked at in this section

#### 5.1.3.1 Dynamic system results

From tables 3, 7 and 9 it can be seen that the dynamic system average flux values for Kloof and Leeudorn are ( $0.124 \pm 0.046$ )  $\text{Bq.m}^{-2}.\text{s}^{-1}$  and ( $0.090 \pm 0.077$ )  $\text{Bq.m}^{-2}.\text{s}^{-1}$  respectively. There is only about 8% overlap of this data. The dynamic system results for

Leeudorn mine might be unreliable because there is a high probability that some moisture may have formed on the electret resulting in incorrect readings being obtained.

#### **5.1.3.2 Passive system results**

From tables 4, 8 and 9 it can be seen that the passive system average flux values for Kloof and Leeudorn are  $(0.062 \pm 0.027) \text{ Bq.m}^{-2}.\text{s}^{-1}$  and  $(0.023 \pm 0.020) \text{ Bq.m}^{-2}.\text{s}^{-1}$  respectively. Even though the lower limit of the Kloof data and the upper limit of the Leeudorn data overlap there is only about 1% overlap of the overall data. Once again, due to the moisture present on the surface of the Leeudorn slimes dam, the validity of the data obtained from Leeudorn is debatable.

#### **5.1.2.3 Combined system results**

A conclusive comparison between the data from the inactive (old) Kloof slimes dam and the active (new) Leeudorn slimes dam cannot be performed because of the questionable reliability of the data from Leeudorn mine (this is evident by the high standard deviations from Leeudorn data). The accuracy of the E-Perm system is questionable when measurements are taken in areas with high moisture content.

## 5.2 Conclusions

The Rad Elec passive and dynamic systems provide a quick and easy way of determining flux. However, the readings obtained are easily corrupted by factors such as moisture and/or dust forming on the surface of the electret. The theoretical flux value of  $0.103 \pm 0.006 \text{ Bq.m}^{-2}.\text{s}^{-1}$  and the measured flux values  $0.124 \pm 0.046$  of  $\text{Bq.m}^{-2}.\text{s}^{-1}$  and  $0.090 \pm 0.077 \text{ Bq.m}^{-2}.\text{s}^{-1}$  are in agreement with each other within experimental error. The data from measurements taken at Kloof slimes dam 2 shows that the place of measurement is not really relevant. (Compare the results from sites 1P1 to 8P3, which were from the perimeter of the slimes dam, with results from sites 9P1 to 18P3, which were taken from the inside surface of the dam). The results for sites 19P1 to 20P2 are repeat measurements. The average perimeter flux was  $(0.12 \pm 0.058) \text{ Bq.m}^{-2}.\text{s}^{-1}$  and the average internal flux was also  $(0.12 \pm 0.038) \text{ Bq.m}^{-2}.\text{s}^{-1}$  for the dynamic system, and the average perimeter flux was  $(0.050 \pm 0.020) \text{ Bq.m}^{-2}.\text{s}^{-1}$  and the average internal flux was  $(0.071 \pm 0.028) \text{ Bq.m}^{-2}.\text{s}^{-1}$  for the passive system. (Note: there is collaboration between the dynamic and passive systems [Ref 27]).

The data from Kloof mine further show that the time when the measurements are taken is very important. This is clearly evident when the average flux from the passive system ( $0.05 \pm 0.020 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ) is compared with the average flux from the dynamic system ( $0.12 \pm 0.046 \text{ Bq.m}^{-2}.\text{s}^{-1}$ ). One of the causes for this is the fact that radon flux is not constant at all times. The passive system was used to take readings only in the mornings (for a period of three hours) whereas the dynamic system takes an entire day to give a

reading. From the data it appears that the flux is much higher in the evening/early morning. Another possible reason for the higher reading on the dynamic system could be due to some condensation/dust forming on the electret and causing the electret to discharge.

When comparing the data from Kloof and Leeudorn mines (graph 7), the dynamic system shows that there is a big difference in the readings between the Kloof mine (old, dry and inactive slimes dam) and the slimes dam from Leeudorn (new, wet and active). It should however be noted that in the case of Leeudorn mine, condensation formed on the inside of the aluminum box and on the S-chambers placed inside in every single trial. Therefore, the possibility of condensation also having formed on the electret is also quite high. This could not be verified, as three hours had to elapse (for the radon daughters to decay) before opening the S-chamber, which is enough time for some/all of the moisture to evaporate. It could also imply that the age of the dam is also quite important in flux measurements but more research needs to be done to verify these possibilities.

In order to determine which of the flux/concentration readings (from the GU9301 report or the mine PHA) is valid, an intercomparison of the Rad Elec and the other methods used in the GU9301 report and the P.H.As would have to be performed.

### 5.3 Recommendations

1. The preliminary data shows that radon could be a problem in the mines.
2. Any future flux measurements should be performed so as to take both night and day into account.
3. Determine the effects of season on flux.
4. Determine the effects of vegetation on flux.
5. Perform an intercomparison between the various methods used in flux determination.
6. Determine the effects of age of slimes dam on radon flux using moisture independent system.
7. More data is required with a National Nuclear Regulator approved system to verify these findings.

### 5.4 Possible future work

1. Try to determine if there is indeed collaboration between the Rad Elec systems as reference (12) says there is. (Possibly by putting a H-chamber in with the S-chambers in the aluminum box. Since the volume of the H-chamber is approximately 5 times larger than the S-chamber, the H-chamber's reading should be approximately 5 times larger).
2. Perform the experiments at different times of day, on the same spot to determine the effects of time on flux.

3. Perform the experiments in different seasons, on the same spot to determine the seasonal effects on flux.
4. Perform the experiments on locations with vegetation to determine the effects of vegetation on flux.
5. Carry out intercomparison of the different methods used in flux measurement.

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