

# **Radon in the Cango Caves**

**By**

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**A thesis submitted in partial fulfillment of the requirements  
for the M.Sc. degree in Physics at the University of the  
Western Cape**



**December 2005**

**Supervisor: Prof. R. Lindsay**

## Declaration

I declare that *Radon in the Cango Caves* is my own work, that it has not been submitted for any degree or examination in any other university, and that all sources I have used or quoted have been indicated and acknowledged by referencing.

Fhulufhelo Nemangwele

December 2005

Signature.....



## Acknowledgements

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

**Prof. Robbie Lindsay**, supervisor, for his guidance, support and patience.

**John Wilcot Speelman**, for helping in all measurements at Cango Caves.

To my parents, **Vha-Nyai vha Mangwele**, for always being on my side whenever I needed them, and for their love and patience.

**iThemba LABS**, for financing my studies.

**National Nuclear Regulator**, for financing my project. In particular, **Mr John Pule** helped with the measurement in 2005.

**UWC Physics Department**, for making me feel at home and all my colleagues for their encouragement.

Cango Cave management and staff for allowing us to access the Cave. In particular, **Mr Hein Gerstner**, **Mr B. Adams**, **Ms Alison Moos** and all guides who were most helpful. **Mr Larry Mottie** helped with the measurements in 2004.

Finally, thanks to almighty God, My creator without him nothing is possible.

# Radon in the Cango Caves

## Keywords

Radon

Radioactive decay

Cango Caves

Exposure

Tour guides

Lung cancer

Electret ion chamber

Radon continuous monitors (RAD7)

Ventilation

Radiation doses



# **Abstract**

## **Radon in the Congo Caves**

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**M.Sc. Thesis, Department of Physics, University of the Western  
Cape.**

Radon is a naturally occurring radioactive element in the  $^{238}\text{U}$  decay series that is found in high concentrations in certain geological formations such as Caves. Exposure to high concentrations of radon has been positively linked to the incidence of lung cancer.

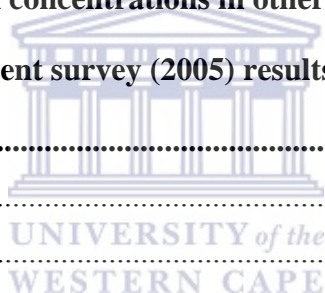
This study used Electret ion chambers and the RAD7 continuous radon monitor to measure radon concentrations in the Congo Caves in the Western Cape Province, South Africa. Measurements were taken during summer i.e. February 2004 and March 2005. The results for the radon activity concentrations range from the minimum of about  $800 \text{ Bq.m}^{-3}$  to a maximum of  $2600 \text{ Bq.m}^{-3}$ . The two techniques give very similar results, though the Electret ion chamber results appear to be consistently higher by a few percent where measurements were taken at the same locations. A mathematical model has been developed to investigate the radon concentrations in the Cave. Diffusion and ventilation have been considered as mechanisms for explaining the distribution of radon concentrations. The ventilation rate in the Cave has been estimated under certain assumptions, and it is found to be about  $7 \times 10^{-6} \text{ s}^{-1}$  for the Van Zyl hall which is the first large chamber in the Cave. The radon concentration increases as one goes deeper into the Cave, but then becomes fairly constant for the deeper parts. The annual effective dose that the guides are exposed to in the Cave as a result of the radon concentrations, depends strongly on the time that they spend in the Cave and in which, halls they spend most of their time in the Cave. The initial results indicate an annual effective dose of 4-10  $\text{mSv}$ , but this needs to be further investigated.

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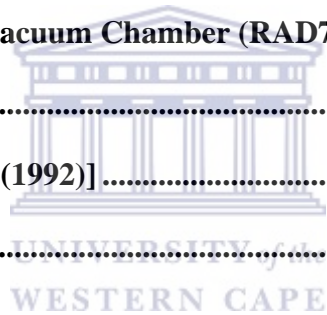
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# Chapter 1

## 1 Introduction to Radon, Research Design and Objectives of the Study

This is a study of the concentration of radon in the Congo Caves in the Western Cape Province. It includes the assessment of ventilation in the Caves as well as estimating the radiation doses that the people who have access to these Caves are exposed to.

For a long time, researches have shown that exposure to certain levels of concentration of radiation from radon is harmful to biological life, including humans [BEIR VI, (1999)]. In some cases, high concentration of radon gas has been identified to be a precursor to lung cancer among persons exposed to high doses of radon. People at risk include miners, workers in Caves, tour guides, and any other persons using the Caves for long periods.

However, while the harmful effect of radon is generally accepted, information on concentration of radon in Caves in South Africa is not readily available. There is therefore a need to study specific Caves with the aim of measuring and documenting the actual level of concentration of radon in particular Caves in order to estimate the actual risk of radon exposure that visitors to these Caves face. Then measures can be taken to reduce the risk if necessary. This study focuses specifically on the Congo Cave with a view of measuring the radon concentration and, therefore, the radiation doses from radon that the workers at the Congo Caves are exposed to.

### 1.1 Background to the study

There has been concern about the effects of radon exposure to people especially miners, in South Africa. Due to lack of information about the concentrations and harmful effects of radon, many people have continued to work in, and visit Caves unaware of the dangers posed to their lives [Clark, (2002)]. There is a lack of information about radon concentrations in specific Caves. There is not only no national database of radon concentration in particular Caves, but also there are very few Caves

that have had measurement of radon concentrations done in South Africa [Strydom et. al., (2002)]

This study is therefore a contribution towards this direction as far as the Cango Caves is concerned. The National Nuclear Regulator (NNR) commissioned this study. Some measurements, which formed part of the current study, were taken in February 2004 but most of the measurements were done in March 2005.

The National Caving Association (NCA) has long recognized radon exposure as one of the potential underground hazards (United Kingdom) [Friend, C., (2002)]. The NCA, with the help of the National Radiation Protection Board (NRPB), produced an advisory booklet, *Radon underground* [Clark, (2002)] and keeps its members updated on the nature and extent of the risks. However even when the data are available, interpreting is not always easy.

## **1.2 Aims of the study**

This study is aimed at assessing the level of radon in the Cango Caves in the Western Cape Province. This was done by measuring radon concentration inside the Caves. We also tried to understand the  $^{222}\text{Rn}$  levels in the Cave by considering the diffusion and ventilation. By doing this, it will be possible to assess radon radiation doses that the workers in the Caves are exposed to.

## **1.3 Objectives**

The objectives of this study are as follows:

1. To measure radon concentration inside the Cango Cave.
2. To model the radon concentration in the Cave
3. To estimate ventilation rates for the Cave.
4. To estimate the radiation doses that workers and guides are exposed to.

## 1.4 Justification and significance of the study

Exposure to radon radiation has been associated with various health risks to humans, such as the predisposition to lung cancer [BEIR VI, (1999)]. This may affect people such as tourists and miners, who come into contact with this radiation while visiting or working in Caves. Given that the risks of exposure to radon are real and well documented, knowledge of how much of the radiation is to be found in the Caves is vital. There exists very little data and records on levels of radon in particular Caves in South Africa [Strydom et. al., (2002)]. Availability of such information will be helpful in understanding the doses that people working in particular Caves are exposed to, and therefore take appropriate measures to reduce exposure. This study is a contribution in this direction by providing such information and data about the Congo Caves.

The Congo Caves are a popular destination for tourists, and therefore an important resource for the Western Cape and South Africa. The ventilation is poor, which is conducive to high radon levels. Some tourists have complained about the quality of air inside the Caves. It is therefore important to understand how much risk these tourists and workers may be exposed to and, therefore, how the risk can be avoided and minimized. This can be done through a study like the current one.

## 1.5 Background on radon

This section discusses the meaning and properties of radon, radon measurements, radon risk, and selected case studies of research both outside and within South Africa.

### 1.5.1 Definition of radon

Radon (chemical symbol, Rn) is a naturally occurring radioactive gaseous element that is emitted by radioactive material in the earth's crust. The most abundant isotope,  $^{222}\text{Rn}$  is produced by the breakdown of uranium in the soil, rocks, and water. Radon is found naturally in certain geological formations such as Cave limestone where  $^{238}\text{U}$  occurs naturally. Radon has numerous different isotopes, but  $^{220}\text{Rn}$ , and  $^{222}\text{Rn}$  are most common.  $^{222}\text{Rn}$  is the decay product of  $^{226}\text{Ra}$ .  $^{222}\text{Rn}$  and its parent,  $^{226}\text{Ra}$ , are part of the

long decay chain of  $^{238}\text{U}$ . Since uranium is found everywhere in the earth's crust,  $^{226}\text{Ra}$  and  $^{222}\text{Rn}$  are present in almost all rocks, soil, and water.  $^{222}\text{Rn}$  is the greatest source (69%) of absorbed dose due to natural radiation [Lario et al., (2005)]. If the gas is inhaled into the lungs, its decay and more importantly the decay of the radon daughters that enter the lung can increase the chance of getting lung cancer [Nazaroff and Nero, (1988)]. The term radon will be used to refer to  $^{222}\text{Rn}$  in this thesis, in accordance with usual practice.

### 1.5.2 Physical and chemical properties of radon

Radon is a colourless, tasteless, radioactive noble gas, which means it is essentially inert. It has a half-life of 3.82 *days* and decays by alpha emission. The alphas have energy of 5.5 *MeV*. Radon has all the properties of other noble gases. Its atomic number is 86. Radon has a high melting point of  $-71^{\circ}\text{C}$  and a boiling point of  $-62.7^{\circ}\text{C}$ . It has first ionization energy of  $1037 \text{ kJ.mol}^{-1}$  and a density of  $9.99 \times 10^{-3} \text{ g.cm}^{-3}$  at  $20^{\circ}\text{C}$  [Durrani, (1997)].

### 1.5.3 Radon measurement instrumentation

There are several radon measurement techniques: Periodic air sampling, Passive radon monitors, Radon etch track detector, Gamma-ray detector, Standard track etch detectors, Alpha sensitive polymer track detectors, Passive integrating detectors, NRPB passive integrating dosimeter, Plastic track detectors, Charcoal Canisters, Sodium iodide detectors, Liquid scintillation counting and Wrenn chamber among others. The detectors used in this study are a radon continues monitor (RAD7) and Electret ion chambers. The choice of these techniques was based on the time over which an instrument can be devoted to measurements at a single location, the kind of the information required, and the desired accuracy with which measurements can be related to an estimate of risk [Bochicchio, Mclaughling and Piermatter, (1995); Paulus, Walker and Thompson, (2003)].

#### 1.5.4 Radon risk and radon studies

As stated earlier, exposure to radon has been seen to pose a risk to the health of humans. One such risk is radon's association with lung cancer. Studies have shown that radon causes lung cancer, and is a threat to health because it tends to collect in places frequented by people such as mines and Caves [Lario et al., (2005)]. It has been identified as the largest source of exposure to naturally occurring radiation.

Since the 1970s, the investigations of exposure of radon radiation in underground Caves systems in many parts of the world have taken place [Przylibski, (1998)]. Research has been conducted in amongst others, Poland, Australia, United States, Venezuela, Switzerland, Northern Spain, Italy, Hungary, Egypt, Ireland, Greece, Slovenia, Norway and many more [Colgan and Gutierrez, (1996)]. The results of the above surveys show that a relatively high ( $>1000 \text{ Bq.m}^{-3}$ ) radon concentration is present in Caves, giving rise to appreciable occupational exposures. This has implications for tour guides and cleaners, because of the increased risk of lung cancer associated with exposure to elevated radon levels [Duffy et al., (1996)].

The United States Environmental Protection Agency (EPA) recommends the following action based on indoor radon level in homes, to reduce the risk of getting lung cancer:

- a.  $< 150 \text{ Bq.m}^{-3}$ , of radon level and recommend that there is no action needed
- b.  $150 - 750 \text{ Bq.m}^{-3}$ , action required within a few years
- c.  $750 - 7500 \text{ Bq.m}^{-3}$ , action required within month
- d.  $> 7500 \text{ Bq.m}^{-3}$ , immediately action required.

Levels greater than  $2000 \text{ Bq.m}^{-3}$  of air radon concentration have been measured in some homes [Guimond, (1988)].

Radon monitoring at highly radioactive locations such as underground mines or Caves is important to assess the radiological hazards to workers and occasional visitors [Ntwaeaborwa et al., (2004)]. The results of conducted studies indicate very high radon

concentrations (of  $kBq.m^{-3}$ ) in most Cave halls. The National Radiological Protection Board (NRPB), in 1990, proposed an action level of  $200 Bq.m^{-3}$  for domestic properties and  $400 Bq.m^{-3}$  in the work place [Sperrin, Denman and Phillips, (1999)]. In certain circumstances, the radon concentration can exceed  $1000 Bq.m^{-3}$ . This requires designation of these as high radon areas. In the United Kingdom they are designated as “radiation controlled areas”. Many of the underground Caves and mines in the “West Country” of the United Kingdom fall into this category.

The Basic Safety standard (BSS) gives a yearly average concentration for radon level in the work place of  $1000 Bq.m^{-3}$  [IAEA, (2004<sup>a</sup>)]. This value is the midpoint of the range of  $500-1500 Bq.m^{-3}$  recommended by the International Commission of Radiological Protection [ICRP, (1993)]. In the workplace employers are required under the ionizing radiation act of 1985 (United Kingdom) to remediate if the levels are above  $1000 Bq.m^{-3}$  [Gillmore et al., (1999)]. Some other organization may wish to use a lower level than that specified in the BSS.

The Department of Minerals and Energy (DME) and the National Nuclear Regulator (NNR) in June 1996 recognized the risk that radon poses to life in South Africa. South Africa uses international basic safety standards for protection against ionizing radiation and for the safety of radiation sources. The National Nuclear Regulator (NNR), data suggested that there were 10000 mineworkers in South Africa exposed to potential annual effective doses exceeding the international recommended limit of  $100 mSv \text{ per } 5 \text{ year}$  period. In a report in 1998, approximately 1000 workers at V2 shaft at Harmony Gold Mine were exposed to the levels of radiation exceeding the dose limit laid down by the NNR [National Union of Mineworkers, (1999)].

The South African National Union of Mine workers recommended a closer working relationship between the CNS and the DME, with a view to ensuring closer monitoring of underground exposures and individual doses received annually by employees. Together, the two enforcing authorities developed a way of informing the workforce of the nature of the hazard, its extent, and how it affects individuals. The NNR in 1999

retained responsibility to protect the workers and members of the public from radiation hazards at the workplace [National Union of Mineworkers, (1999)].

In 1985, the ICRP recommended that a mine worker's Annual Limit on Intake (ALI) of radon decay products (EER) should be  $3.6 \times 10^6 \text{ Bq.h.m}^{-3}$ , which corresponds to an average EER concentration of  $1800 \text{ Bq.m}^{-3}$  for a period of 2000 work hours per year [Åkerblom, (1999)].

The first radon measurements in karst Caves in Slovenia were made using Lucas cells [Kobal et al., (1986)]. Jovanovic et al., (1992), studied radon concentrations in the Postojna Caves. Both studies were performed to identify Caves, which are suitable for the medical treatment, known as speleotherapy [as quoted in Jovanovic, (1996)]. Speleotherapy is a special kind of climatotherapy and has been used for the last 40 years, as additional treatment for curing bronchial and asthmatic diseases of children and adults in several countries. Because the Caves were used for medical treatment, a comprehensive assessment of the Caves was needed. The investigations included the measurement of radon and its daughter concentrations, temperature, humidity, concentrations of ions (positive and negative), ventilation rate, and pressure. Measurements were done during different period of the year including summer and winter. This is because radon concentrations vary in response to parameters such as temperature and hence it varies with seasons.

The Radiological Protection Institute of Ireland in spring 1993 conducted a preliminary investigation to establish the levels of radon and its decay products present in Irish show Caves. The Caves investigations included: Aillwee Cave, Ballyvaughan country Clare, Mitchelstown Cave, Burn court, County Tipperary, Crag Cave, Castle Island, and Country Kerry. These Caves are located in carboniferous limestone in Ireland and attract thousands of visitors each year [Duffy et al., (1996)]. In Aillwee Cave a high value of radon concentration ( $2040 \text{ Bq.m}^{-3}$ ) was found at the central part of the Cave around Mud hall and the Cascadee. In Mitchelstown Cave, the highest level of radon concentration was found namely  $5590 \text{ Bq.m}^{-3}$ . In Crag Cave, the



average radon concentration of three Caves surveyed showed a highest recorded value of about  $7400 \text{ Bq.m}^{-3}$  in Tube, Kitchen and Crystal gallery. This value indicates that the potential for dangerous radon exposure is high.

The Australian National Health and Occupational Council (NHMRC) and the National Occupational Health and Safety Commission (NOHSC) have prepared jointly, recommendations and standards based on the ICRP recommendations, for application in the Australian context. Australia has over 60 tourist or show Caves, under the management of the various state departments, local authorities, or private groups. Preliminary measurements in some of these Caves have shown  $^{222}\text{Rn}$  levels of  $1000 \text{ Bq.m}^{-3}$  [Solomon et al., (1996)].

ICRP 65 has produced guidelines and recommendations dealing with workplace exposure to elevated background radiation. An intervention level for  $^{222}\text{Rn}$  of  $1000 \text{ Bq.m}^{-3}$  is proposed [Solomon et al., (1996)] as the limit, which is associated with the risk of inhalation of radon and radon progeny. These  $^{222}\text{Rn}$  levels show no risk to members of the public viewing the Caves, but may present a potential long-term health risk for the 200 or more full-time staff spending extended periods conducting tours or carrying out maintenance within the Caves. This information is important for comparison purposes with the current study because similar situations and Cave use exist in Congo Caves.

The NRPB demonstrated that several regions in the United Kingdom has elevated radon levels. The granite areas of Cornwall and Devon have been found to have substantially elevated levels of radon. The metamorphic aureole around the granite areas has also been identified as having a significant impact on indoor radon levels. Radon surveys in Caves in such areas face a number of difficult problems. These include the security of radon detectors and the difficulty of designing the placement of detectors necessary to determine, with reliability, the spatially complex pattern of radon concentration.

The radiation dose from the exposure to radon progeny can be derived from measurements of the Potential Alpha Energy Concentration (PAEC) combined with a Dose Conversion Factor (DCF or dose per unit intake) which reflects the radiation dose to the respiratory tract from the deposition of the inhaled progeny [Solomon, (2001)]. The International Commission for Radiological Protection [ICRP, (1993)] in its publication recommends the use of a single factor of  $5 \text{ mSv per WLM}$ , determined from uranium mining epidemiological studies, as the preferred method converting radon progeny exposure to effective dose (radon progeny conversion convention). Working Level Month (WLM) is an exposure to 1 working level for 170 hours (2,000 working hours per year/12 Month per year = approximately 170 hours per Month).

The above discussion shows that radon include in a risk to human life and that a lot of effort has been put into understanding radon and how it affects humans. Measurements of radon have been made all over the world and standards given to show radon danger levels. However it is clear from the literature that such information is not enough or is not readily available in South Africa and therefore there is a need to fill this gap in any way possible. This study, which is aimed at studying radon concentration at the Cango Caves, is one contribution towards this, and tries to reduce this radon information gap in South Africa. The literature also helped in guiding this study towards the most practical methods of assessing radon concentration in Caves. The following section of this chapter will give a summary of the methodology used to achieve the goals of this study. The details of the methods used will be presented in Chapter 4.

## **1.6 Methodology**

This section will give a general introduction to the measurement methods that were used in this study. These include data collection tools and techniques, data analysis, and data presentation. The details of all these are discussed in Chapter 4.

### 1.6.1 Data collection

This study uses the Electret ion chambers and the RAD7 methods to measure radon concentration in the Cango Caves. Both measurements were taken during summer i.e February 2004 and March 2005. The radiation dose from the exposure to radon progeny can be derived from measurements of the Potential Alpha Energy Concentration factors, which reflect the radiation dose to the respiratory tract from the deposition of the inhaled progeny. The International Commission for Radiological Protection (ICRP) in its publication recommends the use of a single factor of  $5 \text{ mSv per WLM}$ , determined from uranium mining epidemiological studies, as the preferred method converting radon progeny exposure to effective dose (radon progeny conversion convention) [ICRP, (1993)].

Both techniques RAD7 and Electret ion chambers were deployed overnight and during the day at strategic places inside the Cave. The data collected from these measurements of radon concentration were used to estimate ventilation and dose rate (see Chapter 4).

### 1.6.2 Data analysis and data presentation

The data collected in this study were analyzed using an Excel spreadsheet. Excel is used to calculate radon background, radon concentration, and to estimate the dose rates of both tour guides and Cave cleaners. The results of this study are presented in Chapter 5 using tables and graphs.

## 1.7 Outline of this thesis

Chapter 2 includes a description of Cango Cave. The subsections are: Cango Cave, geological formation of the Cave and radon background.

The origin of radon and the study of radon, the health effects of radon exposure, principal decay properties of radon, and radiation quantities and its units are discussed in Chapter 3.

Chapter 4 deals with the methodology used in this study. This includes the technical description of data collection methods and instruments used as well as the mathematical modeling of radon transport.

In Chapter 5, the experimental and modeling results are given and discussed.

A conclusion and recommendations are presented in Chapter 6.



## **Chapter 2**

### **2 Description of Cango Cave**

This Chapter explains the Cango Cave formation with the aim of tracing the origin of radon in this Cave. To understand this, the environment of the Cave is described, including its geology and meteorology. Human influence resulting from commercial activities such as tourism and modification of the Cave, are also discussed. These are analyzed in the context of how they affect the level of radon in the Caves.

#### **2.1 Caves and the Cave environment**

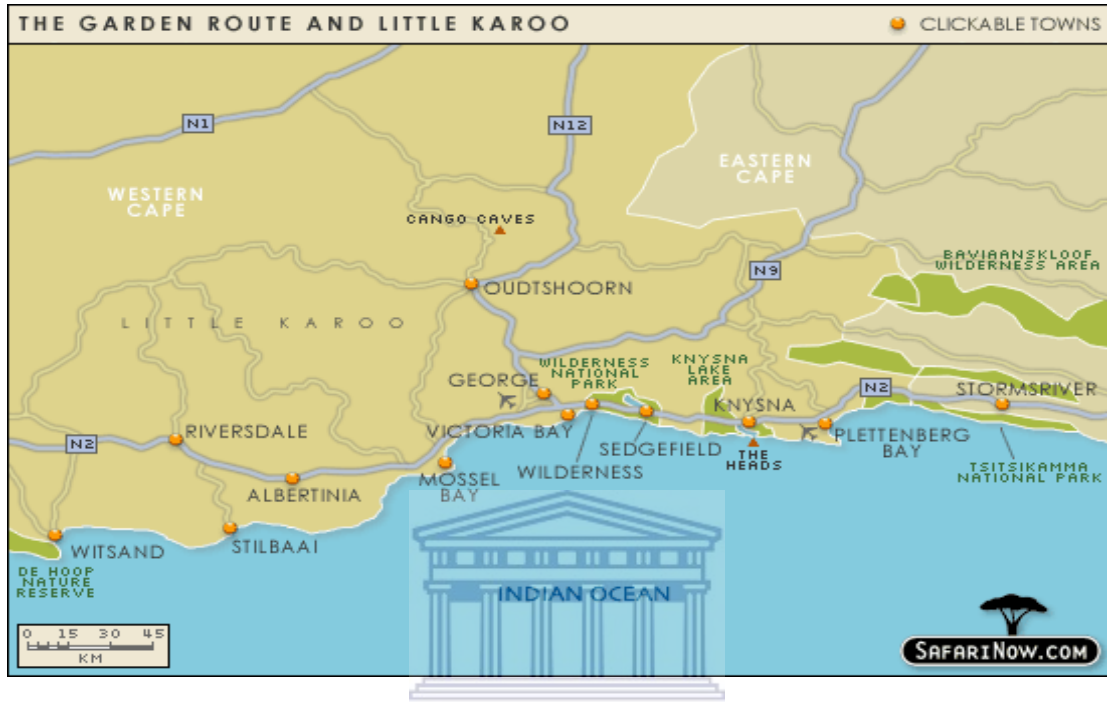
A Cave is usually considered to be any naturally formed underground cavity big enough for a human being to enter. The term Cave is usually used for horizontal passages and the term “pothole” for vertical passages. A “Cavern” is another term for a Cave, but it is usually reserved for large chambers [Pate, (2005)].

Caves are commonly considered as having a static environment where there is complete darkness. Parameters such as temperature and humidity are usually relatively stable [Durrani, (1997)]. However other parameters may vary significantly due to a lot of exchange between the Cave air and the water in the Cave. Air radon concentration is one of these parameters, which continuously changes in response to changes of other factors in the environment.

#### **2.2 Cango Caves and its environment**

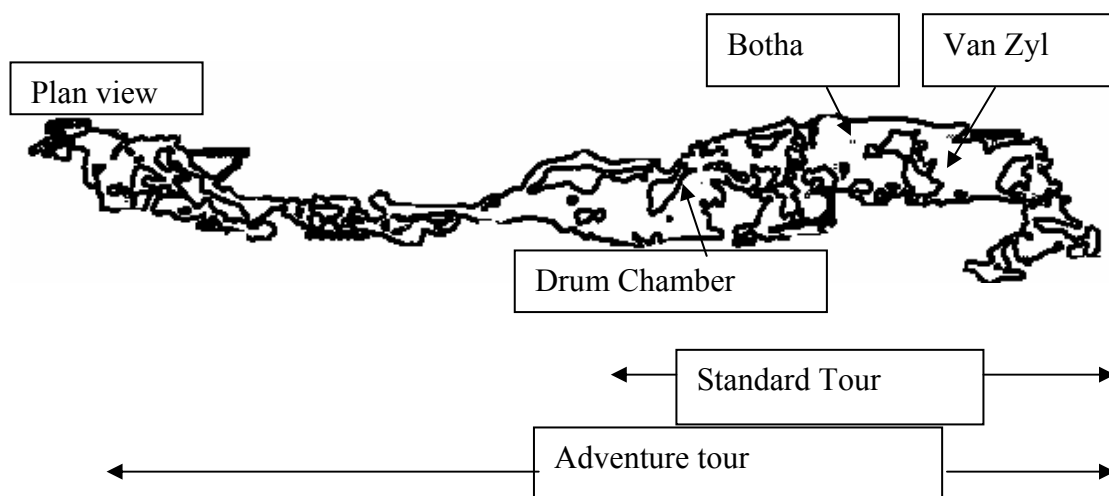
The Cango Caves are found in the Swartberg Mountain range about 30 *km* North of Oudtshoorn in the Western Cape Province, South Africa (see Fig 2.1). They have been visited for their natural beauty since soon after Westerners located them in 1795 [Cango Cave website]. Before then, indigenous people used the entrance as a shelter for thousands of years.

The Cango Caves are run by the Oudtshoorn Municipality as a commercial concern - as one of the major tourist attractions of the area. The Cave is visited by about 300 000 visitors per year [Cango Cave website].



**Fig 2.1: Position of Cango Caves** [www.SafariNow.com]

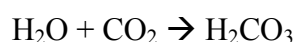
The Caves consist of three sections, Cango I, Cango II and Cango III. Cango I is the developed show-Cave that is visited by tourists (see Fig. 2.2 and Appendix E), the other two sections are still in their original state, especially Cango III, which can only be reached via an underground river. Cango I is the subject of this research. The total length of the whole Cango Cave is about 5 km , while Cango I is about 1.3 km long [Cango Cave website].



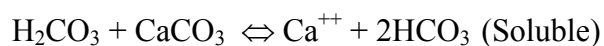
**Figure 2.2: Profile of Cango I. The entrance is to the right [Craven 1992].**

### 2.2.1 Geological formation of Cango Caves

The Cango Caves lie in the Swartberg Mountain range (an International Heritage Site) in a limestone belt measuring 1.5 km in width and almost 16 km in length [Cango Cave website]. The Caves are typical limestone Caves with formations of calcium carbonate (CaCO<sub>3</sub>), which were derived from the chemical equation: Rainwater + Carbon dioxide (from air) → Carbonic acid that reacts with rocks.



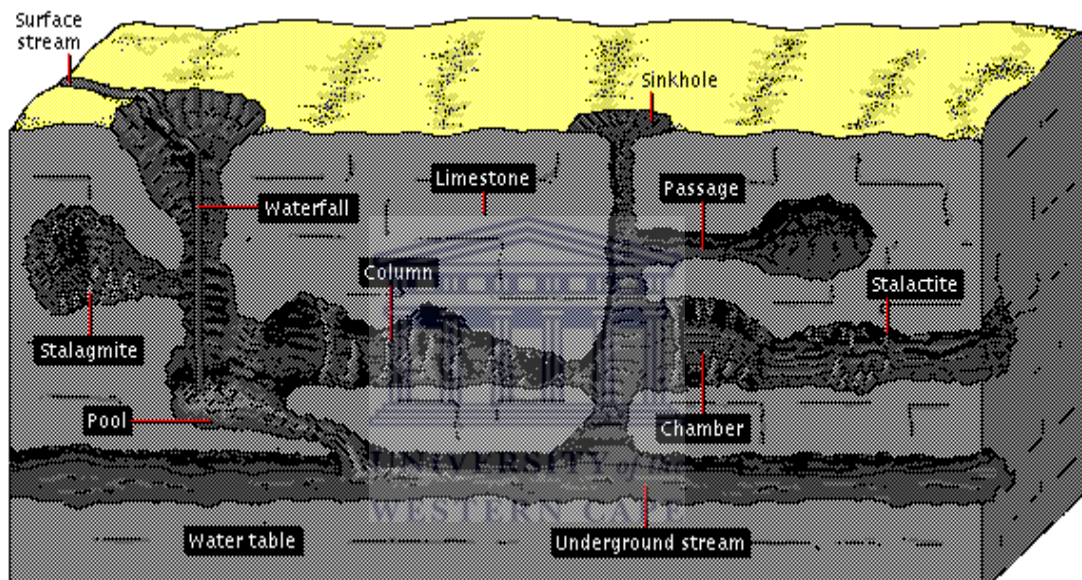
The carbonic acid dissolves certain rocks and minerals, e.g. limestone.



Rain picks up atmospheric CO<sub>2</sub> as it falls and more of it from plant roots while passing through the soil. Decaying vegetable matter dissolves into water along with complex organic acid.

Limestone rocks that are contained in the Cave have few pore spaces, and therefore ground water penetration through the rock joints is restricted. The water that cannot

penetrate into the rock fills up the rock spaces causing pressure, which results in three-dimensional formations or large dome-shaped chambers. The surface between the plane where the pore spaces in rock are filled with water and the plane where the pore spaces are filled with air is called the water table. A lot of Cave development occurs just below the water table (see Fig 2.3). Limestone Caves occur just below the water table. As mentioned above, the Congo Caves are located in a limestone area. As far as this is concerned, one of the aims of this study is to investigate the limestone rock in the Congo Caves in order to find out whether this rock is the source of radon or not.



**Fig 2.3:** *Cave formations* [www.dwb.unl.edu]

### **2.2.2 Radon in Caves**

Normally, air currents disperse radon to give relatively low concentrations of radon in air but in confined spaces such as a Cave or a mine, concentration builds up. Radon and its decay products, which themselves are radioactive when present in the air, can be breathed into the lungs where radioactive decay may occur.

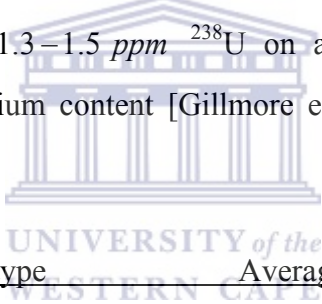
Radon can migrate under the surface with water and gases over large distances and can cause higher concentrations in Cave chambers. The type of topography that is formed



over limestone by the solution of the rocks and is characterized by closed depressions or sink holes, Caves and underground drainage is known as karst areas. The extent of radon migration in karst systems depends on the velocity of the transporting medium (water, soil) and also on the geometric sizes of fissures and cavities.

The concentration of radon is a complex function of geology, Cave design, and meteorology. Extensive studies have been carried out in some countries to identify the area of enhanced risk. In Venezuela, for example, it is known that radon emission depends on geological factors, and the conditions of the local micrometeorology [Sajo-Bohus et al., (1997)]. Caves with a geological environment favourable for the transport of radon from the earth's interior to the surface may have high radon concentration.

The sources of radon in Caves are the bedrock and deposits. Primarily the uranium content of the rock influences radon levels in Caves. Limestone and other sedimentary rocks are found to contain 1.3–1.5 ppm  $^{238}\text{U}$  on average [Hakl et al., (1997)]. Worldwide averages for uranium content [Gillmore et al., (1999)] are presented in Table 2.1.



	Rock type	Average Uranium content (ppm)
Igneous rocks	Granites	4.8
	Basalts	0.6
Sedimentary rocks	Organic-rich black shales	8.2
	Common shales	3.5
	Limestones	2.0

**Table 2.1:** *World wide average uranium content. A  $^{238}\text{U}$  content of 1ppm corresponds to 12 Bq.kg<sup>-1</sup>.*

Bonnotto and Andrews in 1997 determined the uranium content of carboniferous limestone in the Mendip hills Cave (UK) and found that it ranges between 0.48 and 1.22 Bq.kg<sup>-1</sup> [as quoted Gillmore et al., (1999)]. Gunderson in 1992 and Brill in 1994 suggest that although most carbonates are low in uranium, the soil and residuum

derived from them (which form Cave deposits) may often be very high in uranium and radium. McAulay and Marsh in 1992 indicate that in Ireland, limestone areas with high soil radium concentration should be investigated, as some limestone types are very permeable to radon gas [as quoted Duffy et al., (1996)]. The soil in the Cango Caves and rocks are not rich in uranium but the man-made concrete steps and paths shows a high level of uranium content (see Chapter 5).

The high amount of CO<sub>2</sub> in the atmosphere changes the important natural formations inside the Caves (for example, stalagmites and stalactites). The number of people, such as tourists, who are entering the Cave, determines the amount of CO<sub>2</sub> in the air. The Cango Caves have their own special natural morphology, which maintains the temperature inside and keeps it constant. Craven in 1992 measured the temperature in the Cango Caves and found it to be 18.3<sup>o</sup>C [as quoted in Craven, (1992)]. The temperature at Oudtshoorn varies seasonally but that inside the Cave is constant at about 18<sup>o</sup>C (see temperature below).

The time that the guides spend inside the Cave is not the same every day. This is determined by the groups of tourists booked for the day and how many trips the guides will take. The Cango Caves receive tourists on a daily basis for 364 *days per year*. There are generally fewer tourist groups during weekdays than over holidays and weekends.

### **2.3 Cave atmosphere**

The Cango Cave is a low energy Cave which means that there is no natural air flow which could dissipate the heat, water vapour, and carbon dioxide introduced into the Cave by the visitors, and the heat caused by electric lighting. The absence of good natural ventilation means that the energy introduced by the visitors and electric lighting will tend to increase the temperature, relative humidity, and CO<sub>2</sub>. Carbon dioxide in the Cave can affect the speleotherms, such that if the CO<sub>2</sub> rises, its solubility in any water on the speleotherms will rise tending to dissolve the speleotherms. The important point is that, the CO<sub>2</sub> exhaled by the tourists may be expected to have a

major influence on the Cave atmosphere. James [as quoted in Craven, (1992)] says that one person in  $1000\text{ m}^3$  will raise the percentage of  $\text{CO}_2$  by 0.3% in 24 hours and the dimensions of Van Zyl hall in the Congo Caves are  $99\text{ m} \times 50\text{ m} \times 16\text{ m}$  high, giving a volume of approximately  $80000\text{ m}^3$ . A rough calculation indicates that if 200 people were to stay in Van Zyl hall for 12 hours, and if the Van Zyl hall was considered to be sealed, the  $\text{CO}_2$  would increase by  $\frac{200 \times 0.3 \times 12\text{ hours}}{80 \times 24\text{ hours}} \approx 0.38\%$ . The Van Zyl hall is

big and it is not sealed meaning that some of the  $\text{CO}_2$  will escape, both to the outside and elsewhere in the Cave. It appears that  $\text{CO}_2$  may not be an environmental problem in a large chamber in the Congo Cave.

### **2.3.1 Temperature**

Air temperature is an important variable in a single entrance, low energy Cave because it contributes to natural air interchanges within the Cave itself, and between the Cave and the exterior. Two factors can be expected to raise the temperature in the Congo Cave; heat from the electric lighting and from the tourists. Heat from the electric lighting is reduced by switching off when the light is not required. The only way to reduce the heat from the tourists is to limit the number of tourists.

## **2.4 Human impact in Congo Caves**

As indicated above, one of the factors that influence the level of creation of  $\text{CO}_2$  is human influence. In these Caves, the major human activity is tourism and related developments. The number and presence of tourists in the Caves at any one particular time affects elements such as temperature and level of  $\text{CO}_2$  production.

### **2.4.1 Tourist activity in Cango Cave**

As already noted, the Cango Caves are a major tourist attraction. Visitors to the Cave have a choice of two tour routes:

- i. The standard tour is approximately 600 *m* long and starts from the Cathedral-like Van Zyl hall and goes until what is called the African Drum chamber [Cango Cave website]. These tours concentrate on the historical information on the formation of the Caves. This tour takes about one hour.
- ii. The Adventure Tour, which takes visitors to all chambers of Cango I. This involves further exploration into narrow tunnels. The trip only accommodates 45 people per group. The tour lasts for at least one and half-hours, longer if the tour group is larger.

The facilities inside the Cave require more careful planning than those outside, because the environment inside the Cave is fragile. The enlargement of the passages and the creation of a parallel passage affected the natural ventilation inside the Cave. The enlargement increased the area available to accommodate a larger number of visitors in the Cave within a given period of time. This affects the temperature and CO<sub>2</sub> variation inside the Cave.

### **2.5 Conclusion of this Chapter**

The Cango Caves are a typical limestone Cave with a fragile environment. Human activity such as electric lighting, and heat produced by their bodies affects elements such as temperature and levels of CO<sub>2</sub> in small chambers. The time that guides spend inside the Caves on a daily basis is of particular interest in this study since these data are needed to make dose estimates.

## Chapter 3

### 3 An Introduction to Radon and Ionizing Radiation

Ionizing radiation is any of the various forms of radiant energy that causes ionization when they interact with matter. The most common types are alpha radiation, beta radiation and gamma and X-rays, the latter consisting of high-energy photons. Radon is an alpha emitter found in the decay chain of uranium and radium. Radon and its progeny may cause harmful health effects after being inhaled, as will be discussed below.

#### 3.1 The history and the origin of radon

Radon was discovered in 1900 by Friedrich Ernst Dorn, who called it Radium emanation [O’Riordan et al., (1982)]. The element was isolated in 1908 by Ramsay and Gray, who named it Nitron. Since 1923 Dorn named it radon [Miles, (2000)]. There are probably 27 isotopes of the radioactive element radon. They range in mass number from 200 to 226. Three occur in nature,  $^{219}\text{Rn}$ ,  $^{220}\text{Rn}$ , and  $^{222}\text{Rn}$ .  $^{222}\text{Rn}$  is the most important in radiological protection because of its relatively long half-life of 3.82 *days*.

The radon gas is created as the first disintegration product of  $^{226}\text{Ra}$  (see Fig 3.1). As mentioned earlier, radium is a disintegration product of  $^{238}\text{U}$  existing in soil and rocks. This means that the most usual sources of radon are soil and rocks. Radium is not uniformly distributed in soil or rocks, but its concentration varies greatly, often over a distance of a few *metres*. The migration of radon gas takes place in the form of diffusion and advection. The migration of radon gas through the ground surface or rocks may vary locally inside the Cave. It is possible to divide the areas inside the Cave into different sections, according to the radioactivity in the rocks and soil.

The proposed radon classes are: negligible, normal, high and very high. The radon classes are defined according to the radium content of soil and/or the radon content in the pores of soil [Slunga, (1988)].

The radon class of an area may be considered **negligible** if the Cave is composed of soil or rock types with radium content of less than  $35 \text{ Bq.kg}^{-1}$ :

- i) Generally areas inside the Cave with a bedrock of diorite, diabas or other rock type like sandstone, clay stone and rock types transformed from these.
- ii) Limestone, under which no radioactive formation exists.

The radon class of an area may be considered **normal** (or moderate) if the area includes to a great extent:

- i) Soil and rock types with a normal radium content of about  $35 - 100 \text{ Bq.kg}^{-1}$
- ii) Sand and silt formation with radon content in the pores of soil of about  $10 - 50 \text{ kBq.m}^{-3}$
- iii) Cracks and crushed zone in rock covered by soil layers thicker than two metres.



The radon class of an area may be considered to be **high**, if the area includes to a great extent:

- i) Soil and rock types with a high radium content of about  $100 - 500 \text{ Bq.kg}^{-1}$ .
- ii) Soil type with a high radon content in the pores of about  $50 - 250 \text{ kBq.m}^{-3}$  and with a high permeability.
- iii) Generally areas with bedrock of granite and pegmatite with higher uranium content.

The radon class of an area is considered to be very **high (or extremely high)** if the area includes to a great extent:

- i) Soil and rock types with very high radium content  $> 500 \text{ Bq.kg}^{-1}$ .
- ii) Soil type with a very high radon content in the pores  $> 250 \text{ kBq.m}^{-3}$  and with a very high permeability.
- iii) Cracks and crushed zone in rock with high content of uranium.

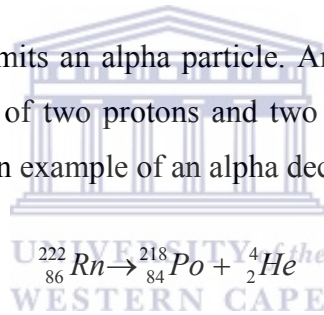
## 3.2 Radon decay

In 1895, Wilhelm Roentgen discovered X-rays. Henri Becquerel in 1896 was using natural fluorescent mineral to study the properties of X-rays, which led to the discovery of radioactivity [Ralph and Howard, (1972)]. The term radioactivity was coined by Marie Curie and her husband, Pierre, when investigating the phenomena relating to the discovery of radioactive decay.

Decay rates depend on the type of interaction and on the amount of energy released. There are three common types of radioactive decay, alpha, beta, and gamma. The difference between them is the particles emitted by the nucleus during the decay process. All three types occur in the  $^{222}\text{Rn}$  series.

### 3.2.1 Alpha decay

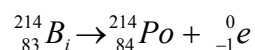
In alpha decay, the nucleus emits an alpha particle. An alpha particle is essentially a helium nucleus; it is a group of two protons and two neutrons. A helium nucleus is very stable [Krane, (1988)]. An example of an alpha decay involves  $^{222}\text{Rn}$ :



The process of transforming one element to another is known as transmutation. Alpha particles do not travel far in air before being absorbed (see principal decay properties below).

### 3.2.2 Beta decay

A beta particle is an electron, or a positron. If an electron is involved, the number of neutrons in the nucleus decreases by one and the number of protons increases by one. An example of such a process in the  $^{222}\text{Rn}$  decay chain is:



In terms of safety, beta particles are much more penetrating than alpha particles, but much less than gamma particles (see principal decay properties below).

### 3.2.3 Gamma decay

The third class of radioactive decay is gamma decay, in which the nucleus changes from a higher-level energy state to a lower level.

### 3.3 Radon decay constant and half life

The decay processes occurring inside the Cave are important in this study. It is impossible to predict when a specific atom would disintegrate to form another. The radioactive decay law is derived from two simple assumptions. The number of decays  $\Delta N$  in a time  $\Delta t$ , and  $N$ , the number of radioactive nuclei present:

$$\frac{\Delta N}{\Delta t} = -\lambda N \quad (3.1)$$

where  $\lambda$  ( $s^{-1}$ ) is called the decay constant of a specific radioactive nucleus.

$$\lambda = -\frac{\left(\frac{\Delta N}{\Delta t}\right)}{N} \quad (3.2)$$

The above decay explains the nature of  $\lambda$ , which is the probability per unit time for the decay of an atom. The value of  $\lambda$  differs for each nuclide. The solution of equation (3.2) is called the exponential decay law of radioactivity. It is given by

$$N(t) = N_0 e^{-\lambda t} \quad (3.3)$$

where  $N_0$  is the original number of nuclei present at time  $t = 0$ . There is a statistical time  $T_{1/2}$  after which half of the number of nuclei will have decayed.

To get  $T_{1/2}$ ,  $\frac{N(t)}{N_0}$  is set equal to  $\frac{1}{2}$ . Taking logarithms, it follows that  $\log_e 2 = \lambda t$ ,

so that the half-life is given by

$$T_{1/2} = \frac{\ln 2}{\lambda} \quad (3.4)$$



### 3.4 Principal decay properties of $^{222}\text{Rn}$ and its progeny

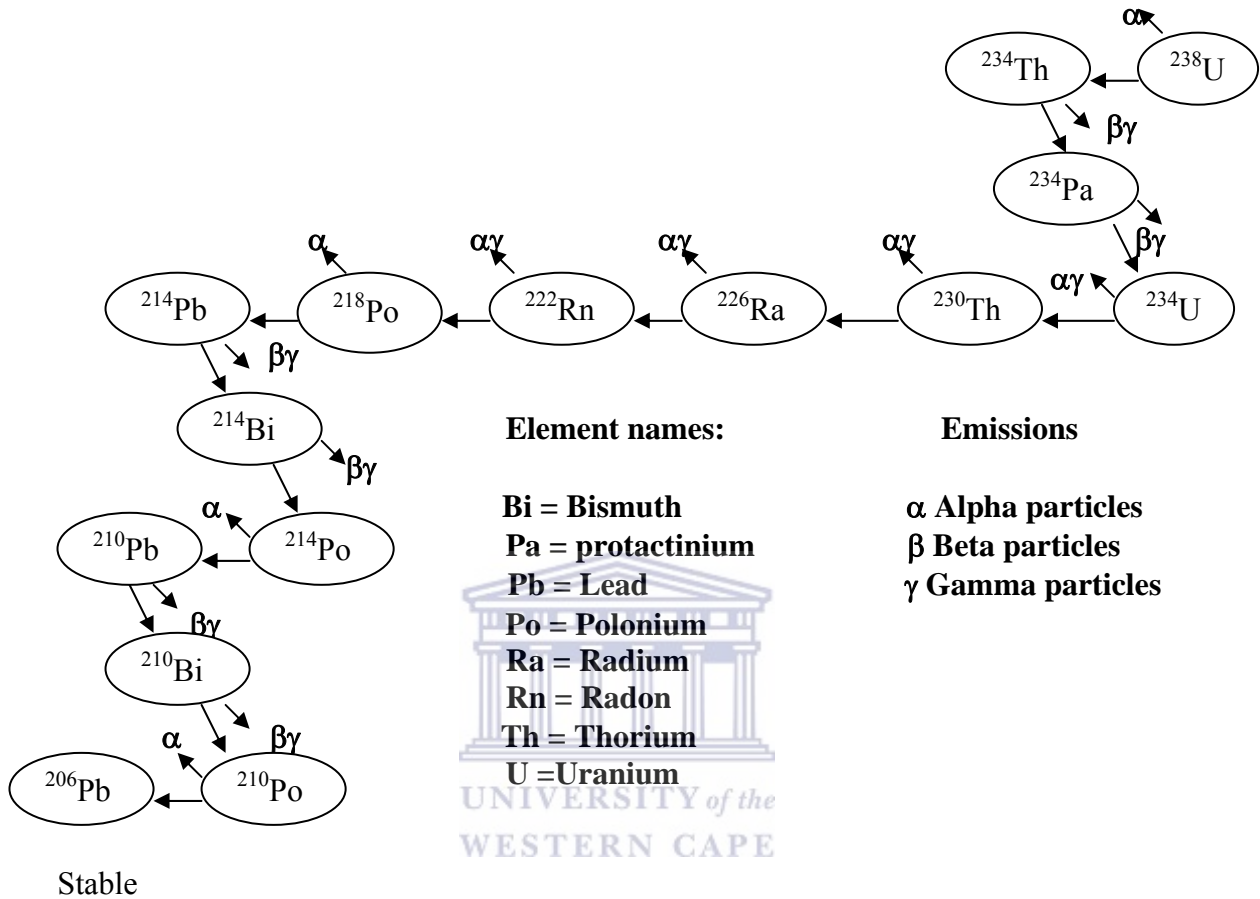
Radon has more radiological significance than other members of the uranium decay chain due to the fact that it is a noble gas. A radon atom is relatively free to move, provided that radon first reaches the material's pore space. Once in pore space, macroscopic transport of radon is possible, either by molecular diffusion or by flow of the gas. Radon can reach air or water, to which humans have access, provided that the transport is sufficiently rapid to be completed before radon decays [Nazaroff and Nero, (1988)].

Radon is formed in the  $^{238}\text{U}$  decay chain as shown in Fig 3.1.  $^{222}\text{Rn}$  is the most important radon isotope, because it has the longest half-life (3.8 *days*). Radon decays to radionuclides that are chemically active, and relatively short-lived. The four radionuclides following decay of  $^{222}\text{Rn}$  have half-lives of less than 30 *min*.



**Atomic Number**

82      83      84      85      86      87      88      89      90      91      92



**Fig 3.1: Uranium-238 decay chain**

Half-lives differ widely from one radioactive material to another and range from a fraction of a second, to millions of years. The decay constant,  $\lambda$ , for  $^{222}\text{Rn}$  is  $2.1 \times 10^{-6} \text{ s}^{-1}$ .

The radon principal decay products and that of its immediate descendants are given in Table 3.1. The polonium isotopes are alpha emitters while the lead and bismuth isotopes are both beta and gamma emitters.

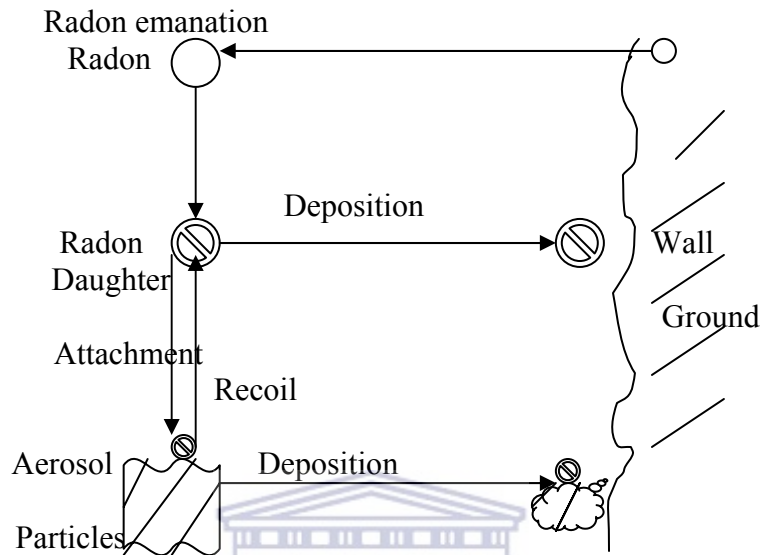
Main radiation energies and intensities							
Nuclide	Half-life	$\alpha$		$\beta$		$\gamma$	
		Energy (MeV)	Yield (%)	Max-Energy (MeV)	Yield (%)	Energy (MeV)	Yield (%)
$^{222}\text{Rn}$	3.82d	5.49	100	-	-	-	-
$^{218}\text{Po}$	3.05 min	6.00	100	-	-	-	-
$^{214}\text{Pb}$	26.8 min	-	-	0.67	48	0.30	19
				0.73	42	0.35	37
$^{214}\text{Bi}$	19.7 min	-	-	<1.5	32	0.61	46
				1.5-2.5	49	1.12	15
				3.27	18	1.76	16
$^{214}\text{Po}$	163.7 $\mu\text{s}$	7.69	100	-	-	-	-

**Table 3.1:** *Principal decay properties of  $^{222}\text{Rn}$  and its immediate descendants [O’Riordan et al., (1982)]*

### 3.5 Behavior of radon decay products

Assume that  $^{222}\text{Rn}$  and its decay products are removed only by radioactive decay, then radon and its decay products would be in a state of secular equilibrium, having the same (radioactive) activity. However, radon and its decay products are removed from air, not only by radioactive decay, but also by ventilation, which is driven by pressure differences caused by airflow [Przylibski, (1999); Pflitsch and Plasecki, (2003)]. A further difference between  $^{222}\text{Rn}$  itself and the radon decay products is their chemical activity. The radon decay products can attach to airborne particles, and when inhaled, attach itself to the human respiratory tract. Radon decay products after being inhaled can be deposited either directly in the lungs, or while attached to particles, stick to the lung.

Radon progeny are formed throughout the volume of the compartment by the radioactive decay of radon gas. Like radon, the progeny can leave by ex-filtration and by decay. Unlike radon, the progeny can attach themselves to aerosol particles or the walls (see Fig 3.2).



**Fig. 3.2: Processes influencing the activity balance of radon ( $^{222}\text{Rn}$ ) decay products**

The free progeny and the ones attached to particles need to be treated differently. The terms “unattached” and “attached” radon progeny are commonly used to distinguish between these two states of radon progeny. Fig. 3.2 shows the physical processes, which occur inside the Cave: radon decay, radon attachment, deposition and recoil.

### 3.5.1 Behavior of unattached radon progeny

After an atom of  $^{222}\text{Rn}$  has decayed in the atmosphere, the first daughter product of  $^{222}\text{Rn}$ ,  $^{218}\text{Po}$  becomes a positively charged ion. There will initially be excess electrons remaining, but these are stripped away by recoil, and one or more orbital electrons are lost as well.

Short-lived radon daughters are initially born in an atomic state but subjected to attachment to the aerosol particles and/or wall surface. Fractions of unattached radon

daughter are considered to be an important parameter in estimating the dose to human respiratory organs through inhalation of radon daughters [Kojima and Abe, (1988)].

In the Cave atmosphere, the ratio of the respective activity concentrations of short lived radon progeny to radon, changes rapidly with the age of the ventilating air as it flows through the Cave [IAEA, (2004<sup>b</sup>)]. In relatively fresh air, the ratio is low, but it approaches unity in old (stagnant) air. Most radon progeny, in the form of small positive ions or neutral atoms clustered on water or other molecules in the air, become attached to atmospheric aerosol particles of about 0.3  $\mu\text{m}$  diameter and therefore, like the unattached progeny, are respirable

### **3.5.2 Behavior of attached radon daughters**

Air normally contains copious numbers of small solid or liquid particles called aerosol particles or aerosols. These particles range in size from almost atomic dimensions up to several micrometers in diameter [Nazaroff and Nero, (1988)]. Aerosol plays an important role in the behavior of radon progeny in underground places such as Caves.

Radon progeny whether attached or unattached tends to deposit on and stick to the surface exposed to the air. Since material removed from the air is no longer available to be breathed, surface deposition supplements ventilation as a means of reducing human exposure to radon progeny.

### **3.6 Health effects of radon exposure**

Radon gas presents a serious internal alpha radiation hazard to the lungs. It can decay to its daughters while in the lungs or its daughters can be inhaled after radon decays in the air. The daughters are solid particles and when they are inhaled they release radiation (alpha, beta) into the lungs, which can potentially cause cancerous cell growth (in the lungs) [BEIR VI, (1999)].

Radon is identified as the second leading cause of lung cancer, while tobacco smoke is the primary cause. It is calculated that in the United States of America, 5000 to 21000

deaths per year are caused by radon induced lung cancer [Guimond, (1998)]. The problem in isolating the effect of  $^{222}\text{Rn}$  is that, the majority of the documented results were miners. Most of them are smokers and inside the mine they all inhaled dust containing radon and other pollutants. Because radon and cigarette smoke both cause lung cancer, it is complicated to separate the effects of the two kinds of exposure.

The combination of smoking and radon exposure can greatly increase the risk of developing lung cancer. There exists evidence that, if a person smokes or lives with someone who smokes where radon levels exceed the acceptable levels, the risk of lung cancer is 1.2% higher than for those who have never smoked [ICRP, (1993)]. The Biological Effect of Ionizing Radiation committee [BEIR VI, (1999)] further reported that, apart from the results of very limited in vitro and animal experiments, the only source of evidence on the combined effects of the two carcinogens (cigarette smoke and radon) was the data from 6 of the miner studies. Analysis of that data indicates a synergistic effect of the two exposures acting together, which was characterized as sub multiplicative, i.e. less than the anticipated effect if the joint effect were the product of the risks from the two agents individually, but more than if the joint effect were the sum of the individual risk. The BEIR VI committee studies this multiplication although the committee could not precisely characterize the joint effect of smoking and radon exposure. The committee preferred the sub-multiplication relation because it was found to be more consistent with the available data.

The major conclusion by BEIR VI was that “radon is the second leading cause of lung cancer after smoking”. BEIR VI further realizes a statistical analysis of results from the latest epidemiologic follow-up of 11 cohorts of underground miners in the United States, which, in all, included about 2700 lung cancers among 68000 miners, representing nearly 1.2 million person years of observations.

### **3.7 Ionizing radiation**

Ionizing radiation can overcome the binding energy of electrons in an atom. Electromagnetic waves (gamma rays) are released from the nuclei of radioactive atoms undergoing decay. The energy possessed by these particles and rays are capable of

damaging living tissues at the molecular level (for example DNA) by breaking chemical bonds [DME, (2005)].

$^{238}\text{U}$  and its progeny in the soil are an important source of background radiation. Due to the high concentration of  $^{222}\text{Rn}$  and low ventilation levels in underground mines and Caves, it is necessary to measure radiation dose in order to monitor the effects of nuclear radiation on biological tissue. In this thesis we are mostly interested in alpha radiation because  $^{222}\text{Rn}$  and two of its daughters are alpha emitters. The main concern is the inhalation of radon and these daughters by tour guides, since the high energy alphas can damage cells.

Alpha radiation from polonium isotopes produce radiologically significant dose. Alpha particles deposit their energy within body tissue. The concentration of radon decay product in air is ordinarily not given in terms of individual decay product concentration, but it is given by a combined collection that is normalized to the amount of alpha decay energy. Finally the result from the mixture of radon decay product that is present is called Equilibrium-Equivalent Decay Product Concentration (EEDC). EEDC is the amount of each decay product necessary collectively or have the same Potential Alpha Energy Concentration (PAEC) that is actually present.

### **3.7.1 Radiation quantity and units**

This section discusses the properties, which are considered when ionizing radiation is measured. Ionizing radiation is measured in terms of the:

- i) Strength or radioactivity of the radiation source.
- ii) Energy of the radiation.
- iii) Level of radiation in the environment.
- iv) Radiation dose or the amount of radiation energy absorbed by the human body.

From the point of view of the occupational exposure, the radiation dose is the most important measure. The risk of radiation-induced diseases depends on the total

radiation dose that a person receives over a period of time. Radioactivity or the strength of a radioactive source is measured in units of Becquerel ( $Bq$ ).

### 3.7.1.1 Radon Concentration

Historically, the Potential Alpha Energy Concentration (PAEC) of  $^{222}\text{Rn}$  radioactivity was expressed in the unit Working Level ( $WL$ ).  $WL$  is the common unit for expressing radon exposure rate.  $WL$  is a combination of short-lived  $^{222}\text{Rn}$  daughters in one litre of air that will result in an ultimate release of  $1.3 \times 10^5 \text{ MeV}$  of potential alpha energy [Mustafa and Vanisht, (1987); Kotrappa et al., (1983); ICRP, (1993)]. A PAEC of 1  $WL$  is approximately the PAEC of the  $^{222}\text{Rn}$  progeny in radioactive equilibrium with  $^{222}\text{Rn}$  concentration of approximately  $3700 \text{ Bq.m}^{-3}$ . Thus, a  $370 \text{ Bq.m}^{-3}$  equilibrium mixture represents 0.1  $WL$ .

The amount of radioactive material can be specified in principle, by either mass or activity. The activity is the actual rate at which atoms decay and the standard international (SI) unit for activity is the Becquerel ( $Bq$ ) equal to a decay rate of one per second ( $s^{-1}$ ). The collective quantity for the decay product used in the EEDC is based on the alpha decay energies and half lives of the  $^{222}\text{Rn}$  decay series. Then EEDC is given in terms of individual decay product concentrations,  $I$ , as:

$$\text{EEDC } (^{222}\text{Rn}) = 0.106 \times I (^{218}\text{Po}) + 0.1513 \times I (^{214}\text{Pb}) + 0.381 \times I (^{214}\text{Bi})$$

The concentrations of each decay product (and of the EEDC) are given in  $\text{Bq.m}^{-3}$  [Nazaroff and Nero, (1988)].

Assume that, if  $C_i$  is the activity concentration of a decay product nuclide,  $i$ , the

PAEC of the progeny mixture is  $C_p = \sum_i C_i \left( \frac{\epsilon_{p,i}}{\lambda_{r,i}} \right)$ . The  $C_p$  quantity is expressed in

the SI units ( $1 \text{ J.m}^{-3} = 6.242 \times 10^{12} \text{ MeV.m}^{-3}$ ) [ICRP, 1993] and  $\lambda_r$  radioactive decay constant. The PAEC of any mixture of radon progeny in air can be also expressed in



terms of the so called Equilibrium Equivalent concentration (EEC) ( $C_{eq}$ ) of their parent nuclide, radon. The EEC ( $C_{eq}$ ) corresponds to a non-equilibrium mixture of radon progeny in air. EEC ( $C_{eq}$ ) is the activity concentration of radon in radioactive equilibrium with its short-lived progeny that has the same PAEC ( $C_p$ ) as the actual non-equilibrium mixture. The SI unit of the EEC is  $Bq.m^{-3}$ . Then F is defined as the ratio of the EEC to the activity concentration of the parent nuclide, radon, in air. The equilibrium factor (F) characterizes the disequilibrium between the mixture of the short lived progeny and their parent nuclides in air in terms of potential alpha energy.

### 3.7.1.2 Radon Exposure

When ionizing radiation interacts with the human body, it gives its energy to the body tissue. The amount of energy absorbed per unit mass of the organ or tissue is called absorbed dose. It is expressed in units of gray (Gy). One gray is equivalent to one-joule radiation energy absorbed per kilogram of organ or tissue.

Equal doses of all types of ionizing radiation are not equally harmful, alpha particles produce greater harm than beta particles, gamma ray and X-rays for a given absorbed dose. To account for this difference, radiation dose is expressed as equivalent dose in units of Sievert (Sv) [Allisy-Roberts, (2005)]. The dose equivalent in (Sv) is equal to absorbed dose multiplied by a radiation-weighting factor (see Table 3.2) i.e. Dose in Sv = Absorbed Dose in Gy  $\times$  radiation weighting factor (WR).

Type and Energy range	Radiation weighting factor, WR
Gamma rays and X-rays	1
Beta particles	1
Neutrons, energy	
<10 keV	5
>10 keV to 100 keV	10
>100 keV to 2 MeV	20
>2 MeV to 20 MeV	10

>20 MeV	5
Alpha Particles	20

**Table 3.2: Radiation weighting factors WR [ICRP, (1990)]**

### 3.7.1.2.1 Inhalation exposure of individual

The quantity “exposure”,  $P$ , of an individual to radon progeny is defined as the time integral of the PAEC in air,  $C_p$ , or the corresponding equilibrium concentration,  $C_{eq}$ , of radon to which the individual is exposed over a given period  $T$ .

i.e. potential alpha energy exposure  $P_p(T) = \int_0^T C_p(t) dt$  and

Equilibrium equivalent exposure  $P_{eq}(T) = \int_0^T C_{eq}(t) dt$

The unit of the exposure  $P_p$  is  $J.h.m^{-3}$ . For exposure quantity  $P_{eq}$ , the unit is  $Bq.h.m^{-3}$ . The potential alpha energy exposure,  $P_p$  of workers (tour guides) is often expressed in historical units of working level Month (WLM). 1 WL was originally defined as the concentration of potential alpha energy associated with the radon progeny in equilibrium with  $100 pCi.L^{-1}$  ( $3700 Bq.m^{-3}$ ). This concentration corresponds to about  $1.3 \times 10^5 MeV.L^{-1}$ , but the precise value depends on the estimates of alpha energy per disintegration. The working level is now defined as a concentration of potential alpha energy of  $1.3 \times 10^8 MeV.m^{-3}$  [ICRP, (1993)]. The WL quantity was introduced for specifying occupational exposure, 1 Month was taken to be 170 hours, and  $1 MeV = 1.602 \times 10^{-13} J$ . The relationship between the historical and the SI units is as follows:

$$1 WLM = 3.54 mJ.h.m^{-3}$$

$$1 mJ.h.m^{-3} = 0.282 WLM$$

As mentioned earlier, the F factor is defined as the ratio of the EEC to the activity concentrations of the parent nuclide, radon, in air. To calculate the effective dose affecting tour guides and cleaners, equilibrium factors of 0.4 is used [Mustafa and Vanish, (1987)].

Radiation doses due to radon decay products for tour guides in the Cave were calculated according to the ICRP 65 methodology [ICRP, (1993)]. The basic input data are radon concentrations and equilibrium factors in the Cave and the total time spent by the tour guides per day in the Cave.

According to the ICRP 65 dose conversion convection, the effective dose per unit of exposure at work is *5 mSv per WLM* [ICRP, (1993)]. To calculate the effective dose for tour guides in the Cave, the conversion factor (dose factor) is needed and expressed as:

$$cf = \frac{5 \text{ mSv}}{\text{WLM}}$$

The occupancy in the Cave is taken to be *1584 hours per year* for workers, assuming a *6 hours day, 7 days per week and 12 months per year*. The annual effective doses due to exposure to radon decay products [Papachristodoulou et al., (2004); Veiga et al., (2004); Vaupotic et al., (2001)] were calculated as:

$$E = C_{Rn} \times F \times t \times cf \times u \quad (3.5)$$

where E= effective dose (*mSv per year*),  $C_{Rn}$  = air radon concentration ( $Bq.m^{-3}$ ), F= equilibrium factor between radon and its decay product, t= time spent annually inside the Cave (*hour per year*), cf=conversion factor (*mSv per mJ.h.m<sup>-3</sup>*), u=unit dose conversion factor (*mJ.m<sup>-3</sup> per Bq.m<sup>-3</sup>*).

The effective dose given by a type of ionizing radiation depends on the amount of energy imparted (deposited by the matter). Some types of particle produces more significant effects than others for the same amount of energy imported. Equal exposure to different types of radiation does not, however necessarily produce equal biological effects.

Exposure unit	SI unit	Conversion for traditional unit	Traditional unit
Activity,	$Bq$	$1 Ci = 3.7 \times 10^{10} Bq$ ( $1 pCi = 0.037 Bq$ )	<i>Curie</i>
Absorbed dose,	$Gy$	$1 Gy = 1 J.kg^{-1}$	<i>rad</i>
Dose equivalent,	$Sv$	$1 Sv = 100 rem$	<i>rem</i>
Concentration,	$Bq.m^{-3}$	$1 pCi/L = 37 Bq.m^{-3}$	
PAEC, $J.m^{-3}$		$1 WL = 1.3 \times 10^5 MeV.L^{-1} = 2.08 \times 10^{-5} J.m^{-3}$	
EEDC ( $^{222}Rn$ ), $Bq.m^{-3}$		$1 WL (PAEC) = 3740 Bq.m^{-3}$	

**Table 3.3: SI units and equivalents for traditional units**

Table 3.3 shows the summary of the radiation quantities and its units, and conversion from the traditional units to Standard International units (SI).

### 3.8 Conclusion of this Chapter

This Chapter describes  $^{222}Rn$  and its decay products found in Caves including Cango Caves. Radon is an alpha emitter and can decay to its daughter after or before inhalation. After being inhaled  $^{222}Rn$  decays to its four radionuclide daughters having half lives of less than 30 min, which causes ill health effects in the body. The unattached radon decay product before being inhaled is removed from air not only by radioactive decay but also by ventilation, which is driven by airflow caused by pressure differences. There will be an increase in lung cancer in people who breathe in air with large concentrations of radon for a long period of time. The injury caused by the type of ionizing radiation depends on the amount of energy imparted (deposited by the matter). The fractions of unattached radon daughters are considered to be an important parameter used to estimate the dose rate to human respiratory organs through inhalation of radon daughters.

## Chapter 4

### 4 Instrumentation, Radon Transportation and Modeling

This Chapter discusses the methods used in this study. The process of radon transportation from the rocks and soil to the atmosphere is described, as a background to the mathematical model used in analyzing data in this study. This includes an explanation of how airflow influences radon transportation. Finally, the mathematical modeling of the production, estimation of the ventilation rate, and the speed of air, which is getting into the Cave through the entrance is presented.

#### 4.1 Instruments used in this study

The measurements of radon concentration inside the Cave were made using a radon continuous monitor (RAD7) and Electret ion chambers. Measurements using a sodium iodide (NaI) detector were also done. The measurements using the RAD7 and Electret ion chambers were taken during the day and overnight. The map of the Cave was used as a guideline to decide where the instruments were to be placed (see Appendix C).

The measuring tools and settings during the measurement were as follows:

- RAD7: This was used only in the important or great halls, which were easily accessible.
- Electret ion chambers: These were placed at different locations inside the Cave.
- NaI detector: This was connected to a laptop computer and was used to try to locate radon sources inside the Cave.

Descriptions of these instruments are given in the following sections. Measurements in a Cave can be problematic due to the high humidity. The humidity in the Cave ranges between 80-100%.

### 4.1.1 Short-term Electret ion chamber (SST)

The Electret ion chamber is a passive integrating ionization monitor, consisting of a stable Electret mounted (fixed) inside a small chamber made of electrically conductive plastic (see Fig 4.1). The Electret is a charged Teflon disk that serves as both a source of the electrostatic field and as a sensor. Radon gas diffuses into the chamber through filtered inlets, and the alpha particles emitted by the decay process (see Fig 3.1) ionize air molecules. The ions produced inside the chamber are collected onto the Electret, causing a reduction of its surface charge (Voltage). The Surface Potential Electret Reader (SPER-1) was used to read the voltage from Electret surface potential. This voltage drop was used to calculate the calibration factors and radon concentrations (see Appendix A).



**Fig 4.1:** *Electret ion chambers and Electret reader (SPER-1)*

During the visit in March 2005 short-term Electrets were deployed in so called ‘S’ chambers for periods of less than 24 *hours*. The chambers were deployed on top of cardboard cylinders 22 *cm* high above the floor and at least 10 *cm* from the walls. The measurements were taken in different halls, overnight and during the day (see Chapter

5). Two Electret ion chambers were placed at the same location to improve precision and act as a check.

#### **4.1.2 Continuous radon monitor (RAD7)**

This is a high-resolution Electronic Radon Detector with a real-time spectral analysis capability (see Fig 4.2). It is an instrument that is used to measure radon in air and water [RAD7, (2000)]. RAD7 work on the principle of particle detection as there is several radionuclides in the  $^{238}\text{U}$  decay series that decay via alpha radiation and can be easily detected using an alpha detector. As mentioned earlier in section 1.5.3 there are several radon measurement techniques used to measure radon. The RAD7 falls in the first category since the detector consist of a semiconductor material. The RAD7 possess a periodic-fill cell. The cell is filled with air by means of a small pump that draws air into the cell, once during each pre-selected time interval. In this defined cell, the radon or the  $^{218}\text{Po}$  may decay, and the decays are counted and the cycle repeated [Speelman, (2004)].

RAD7 was used in measurements in February 2004 and March 2005. The RAD7 requires about 2 *hours* to perform a complete measurement of radon in air (RAD7 cycle). This means that we can get several results in the same place. The RAD7 was used in most of the important (bigger) halls in the Cave for a period of a few hours during the day and overnight.

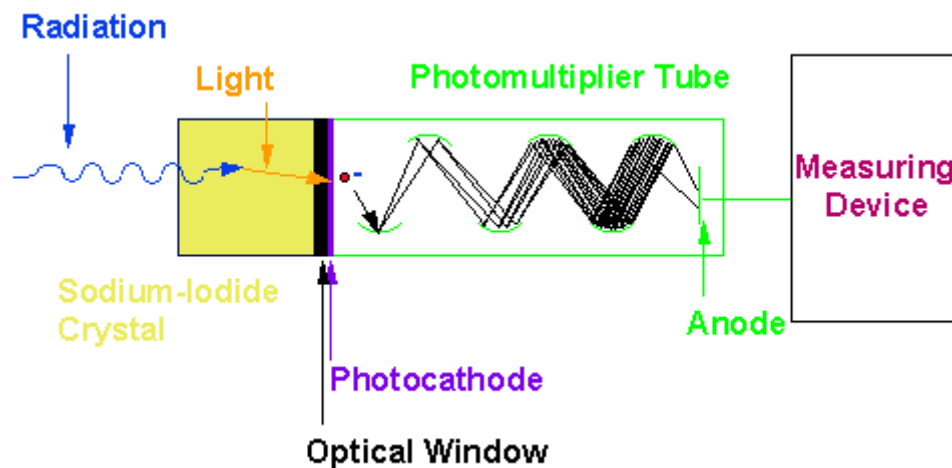


**Fig 4.2:** *Radon continues monitor (RAD7)*

### **4.1.3 Gamma measurements**

Gamma-ray spectra were collected with a portable NaI detector in order to try to understand the origin of the radon in the Caves. NaI is the second most common type of radiation detector usually called the scintillation detector [Cassella and Dewberry, (2001)]. The basic principle behind the scintillation detector instrument is the use of a special material, which glows or “scintillates” when radiation interacts with it. The light produced from the scintillation process is reflected through a clear window where it interacts with a photomultiplier tube (see Fig 4.3).





**Fig 4.3: Radiation detection on surveying using sodium iodide (NaI) detector**

The first part of the photomultiplier tube is made of special material called a photocathode. The photocathode has the characteristic of producing electrons when light strikes its surface by means of the photoelectric effect. These electrons are then pulled towards a series of plates called dynodes through the application of a positive high voltage. When electrons from the photocathode hit the first dynode, several electrons are produced for each initial electron hitting its surface. This “bunch” of electrons is then pulled towards the next dynode, where more electron “multiplication” occurs. The sequence continues until the last dynode is reached, where the electron pulse is now millions of times larger than it was at the beginning of the tube. At this point, an anode at the end of the tube forming an electronic pulse collects the electrons. The electronic pulse is then detected. Scintillation detectors especially NaI detectors are very sensitive radiation instruments and are used for special environmental surveys.

## 4.2 Radon transport

Like all gases, radon gas moves through rocks and the soil because of pressure differences and differences in gas concentration [Stranded et al., (1985)]. Radon will move from regions of higher concentration (from soil and rock where it is formed) to where the concentration is lower. The higher the radon levels in underlying rocks and soil, generally the higher the possibility of it being greater in the Cave. Radon moves

quickly through rocks and soils that are permeable. Radon entering poorly ventilated underground areas such as Caves and mines may reach potentially dangerous concentrations.

Radon inside the Cave moves by two basic means, diffusion and airflow.

#### **4.2.1 Diffusion**

Diffusion is the movement of particles from a region of high concentration to a region of low concentration. There are different types of diffusion such as vapour diffusion and thermal driven diffusion. The unit of diffusion flow is substance per area per second ( $m^{-2}.s^{-1}$ ).

#### **4.2.2 Air flow**

It is a common assumption in Cave climatology that radon air movements in a Cave are the results of exogenic and endogenic factors. The selection of endogenous and exogenous factors as a cause of radon air circulation is made due to thermodynamic differences. For the exogenous factor, the mass transfer is contemporaneous with the transfer of energy between the Cave gas phase and the outside atmosphere [Pflitsch and Plasecki, (2003)].

##### **4.2.2.1 Exogenic factor**

The following processes generate radon air movements:

- i.) Differences between radon air pressure inside the Cave and the outer atmosphere, which in turn are the result of the continuously changing pressure system.
- ii.) Pressure differences generated by the different orientation of openings compared to the actual wind direction. e.g. the top portion shows higher values of radon air pressure than the down portion.

- iii.) Temperature difference resulting from pressure differences between the Cave and outer air. The difference between the pressures is governed by temperature differences between the radon air inside and outside the Cave.
- iv.) During the day or in summer, air entering the Cave cools down, gains weight, descends, and flows outside through a lower opening. The amount of air affected is mostly very small and depends on the relationship between the Cave volume and the diameter of the openings.

This shows the complicated relationship between the changes in pressure and different radon air density (air outside and inside the Cave), air temperature outside, and the velocity of currents within the Cave.

#### **4.2.2.2 Endogenic factors**

For the endogenous factors, no change in mass takes place. The transfer of energy occurs in a closed thermodynamic system. The following processes generate air movement:

- i.) Pressure difference inside the Cave is caused by difference in air density, which in turn results in temperature difference, humidity, and CO<sub>2</sub> content. It becomes fairly obvious that air temperature is one of the key factors for the generation of air currents. This process is clearly influenced by the tourists visiting the Cave.
- ii.) Temperature differences within the Cave and between the Cave and outer atmosphere can lead to balancing air currents, with weak air currents that are due to endogenic factors and high velocity currents in the range of  $m.s^{-1}$ , due to exogenic factors [Pflitsch and Plasecki, (2003)].
- iii.) The temperature inside is mainly governed by the rock temperature, which in turn reflects the long-term mean annual air temperature of the outside atmosphere.
- iv.) Cave temperature can be estimated based on the respective latitude and elevation above the sea level at which the Cave is located. However, there are even more factors that have an influence on the temperature such as Cave structure, and the minor effect of Cave geothermal heat flux.

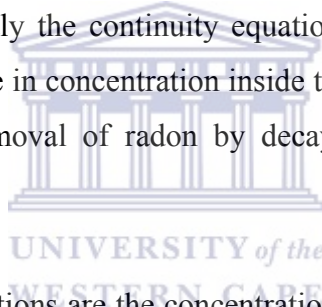
- v.) The shape of a Cave with respect to the slopes inside influences the Cave temperature.

In general, only very low wind speed of the order of  $cm/s$  can be observed due to endogenic factor, which rarely exceed  $1 m/s$ .

### 4.3 Modeling of radon in the Cave

The atmospheric system in the Cave is complicated and there are so many unknowns that it is difficult to get an accurate model of the radon in the different halls in the Cave. However, it is possible to make various assumptions and to consider the implication on the radon levels. In this way, certain indications of the behavior of radon in the Caves can be found.

Most of the models used in this thesis depend on the mass balance of radon in a specific volume or equivalently the continuity equation which relates the flow from and into a region to the change in concentration inside the region, the creation of radon (from the rocks) and the removal of radon by decay. The flow could happen by diffusion or ventilation.



The different terms and definitions are the concentration,  $C = \frac{N}{V}$  of  $^{222}\text{Rn}$  in the Cave

or the activity concentration by  $C' = \frac{\lambda_{Rn}N}{V}$  where  $\lambda_{Rn}$  is the decay constant, and  $N$  is the average number of  $^{222}\text{Rn}$  atoms in a volume,  $V$ .

The rock and formations form the source term and is represented by  $S$ , the activity concentration of  $^{222}\text{Rn}$  entering a hall through the walls per second and is given in  $Bq.s^{-1}$ . This is related to the exhalation flux,  $\Phi$ ,  $S = \Phi \times A$  where  $A$  is the area of the rocks where the  $^{222}\text{Rn}$  enters.

The radon activity, or decay per second is given by  $\lambda_{Rn}N$  or  $\lambda_{Rn}C$  if we want to describe in terms of the radon activity concentration.

## 4.4 Derivation of diffusion equation

In this section, a mathematical formulation that describes the radon activity concentration in the Cango Caves will be considered. The equation that will be developed in this section will describe the transport of radon by the process of diffusion only. The equation takes into account the production of new radon as well as the removal thereof due to the decay of radon during the diffusion process.

Radon diffusion results when radon atoms migrate due to concentration gradients. The diffusion is largely described by Fick's law, which connects the concentration gradient to the flux. This section will describe some of the influencing factors surrounding the radon diffusion coefficient as well as the modeling of the radon concentration by considering the time-independent radon diffusion equation.

### 4.4.1 Radon diffusion coefficient

The concentration gradient and the flux of the radon atoms can be linked by a diffusion coefficient ( $D$ ) as described by Fick's law [Kovler et al., (2004)].

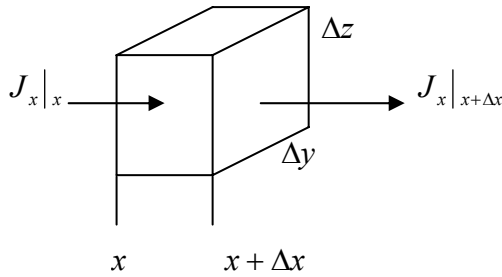
$$J_x = -D \frac{\partial C}{\partial x} \quad (4.1)$$

where  $J$  is the activity flux density, measured in  $Bq.m^{-2}.s^{-1}$ , and  $x$  is the one-dimensional direction into the direction of concentration change. The negative sign in front of the diffusion coefficient arises from the fact that the diffusion occurs in the opposite direction of the increasing concentration. The total diffusion through an area  $A$  is given by

$$Q = J \times A. \quad (4.2)$$

#### 4.4.2 Time dependent radon transport equation including only diffusion

Consider the concentration that varies over position and time, and current flow,  $J$ . Consider a small volume ( $\Delta V = \Delta x \Delta y \Delta z$ ) in the Cave, where there is a flux in the  $x$ -direction only. We have



**Fig 4.2: Flux in  $x$  direction**

where  $J_x|_x$  indicates the mass flux density in the  $x$ -direction at the point  $x$ . Assume that inside the Cave there is no production of radon or loss within the control volume and that the incoming  $J_x|_x$  is equal to the outgoing  $J_x|_{x+\Delta x}$  (see Fig 4.4). Expressed mathematically:

$$(J_x|_x - J_x|_{x+\Delta x})\Delta y\Delta z = 0 \quad (4.3)$$

Consider next the concentration in the hall which changes with time within the control volume i.e. there is no steady state, then the continuity equation gives

$$\Delta J_x \Delta x \Delta y = \frac{\partial N}{\partial t} = \frac{\partial C}{\partial t} \Delta V \quad (4.4)$$

The net change of concentration over the Cave at the distance  $x$  and  $x + \Delta x$  within the control volume is equal to:

$$(J_x|_x - J_x|_{x+\Delta x})\Delta y\Delta z = \frac{\partial C}{\partial t} \Delta x \Delta y \Delta z \quad (4.5)$$

That is flux into the entrance wall, times the area, minus the flux at the exit wall, times its area equals the change in concentration in the volume according to the continuity equation in an interval of time  $\Delta t$ . This diffusion occurs in response to the

concentration gradient  $\frac{\partial C}{\partial x}$ . Applying Fick's law from equation (4.1) and substituting into equation (4.5), we get:

$$\left( -D \frac{\partial C}{\partial x} \Big|_x + D \frac{\partial C}{\partial x} \Big|_{x+\Delta x} \right) \Delta y \Delta z = \frac{\partial C}{\partial t} \Delta x \Delta y \Delta z \quad (4.6)$$

Dividing both sides by  $\Delta x \Delta y \Delta z$  will give

$$\left[ \frac{-D \frac{\partial C}{\partial x} \Big|_x + D \frac{\partial C}{\partial x} \Big|_{x+\Delta x}}{\Delta x} \right] = \frac{\partial C}{\partial t} \quad (4.7)$$

Taking the  $\lim_{\Delta x \rightarrow 0}$ , and shrinking  $\Delta x$  to a differential size (and assume that D is constant in the atmosphere) we have:

$$D \frac{\partial \left( \frac{\partial C}{\partial x} \right)}{\partial x} = \frac{\partial C}{\partial t} \quad \text{or} \quad D \frac{\partial^2 C}{\partial x^2} = \frac{\partial C}{\partial t} \quad (4.8)$$

One possible interpretation of the Congo data is that we can determine the change of radon concentration in a steady state with respect to time. We can observe the increase in the concentration of radon gas within the volume element bound by the two closed parallel planes of area  $\Delta y \Delta z$ . This follows from equation (4.8) when applied to the x-direction. In the case of radon transport, decay and source terms still have to be included (see section 4.6)

At steady state there is no change of concentration with respect to time and a simple model can be derived if we ignore other processes which will only be considered in the following section. From equation (4.8) we have:

$$\frac{\partial C}{\partial t} = 0 \quad \text{thus} \quad D \frac{\partial^2 C}{\partial x^2} = 0$$

This implies that both equations are equal to a constant

$$\frac{\partial C}{\partial x} = \text{const} = C_1 \quad (4.9)$$

The solution of the above equation is

$$C(x) = C_0 + C_1 x \quad (4.10)$$

Where  $C$  is the radon concentration function,  $C_1$  is a concentration gradient;  $C_0$  is the measured radon concentration at  $x = 0$ .

## 4.5 Modeling of the ventilation

In this section we assume that the diffusion is small and consider only ventilation. The basic mechanism for heat dissipation from a system to the atmosphere is by natural ventilation that results in heat transfer. The key role of ventilation to the atmosphere is then to cool the Cave.

Natural ventilation is caused by pressure and the resultant density gradient. The density of air depends on temperature and humidity. Ventilation comes from the natural air movement and the air movement caused by visitors.

The ventilation is given by the volume of the air leaving or entering a hall. Consider the Van Zyl hall where the ventilation is probably the highest. Consider firstly the air exchange with the outside. The change in concentration caused by ventilation can be modeled by [Perrier et al., (2005)]

$$-\lambda_v(C - C_0) \quad (4.11)$$

where  $\lambda_v$  the ventilation is constant,  $C$  is the concentration and inside,  $C_0$  is the concentration outside.

This equation has the same form as the decay term. Thus the ventilation removes  $^{222}\text{Rn}$  just as the decay does. The air with higher  $^{222}\text{Rn}$  concentration may enter Botha hall from the Van Zyl hall can similarly be found from

$$-\lambda_v(C_{Van\ Zyl} - C_{Botha}) \quad (4.12)$$

$\lambda_v$  can be related to the volume of air leaving or entering a hall (see in section 4.8.3).

Radon levels are usually controlled by natural ventilation inside the Cave. Poor natural ventilation can result in high concentrations of radon. Low oxygen concentration in the Caves generally indicates high radon, but normal oxygen can accompany high or low radon [Przylibski, (1998)].



## 4.6 Summary of mathematical model

The Cango Cave is composed of a number of halls, but the greatest air exchange from the outside atmosphere to inside probably occurs at the first hall (Van Zyl hall). If we ignore the air exchange to the Botha hall, the change in radon concentration due to creation, decay and ventilation is given by:

$$\frac{\partial C}{\partial t} = \frac{S}{V} - \lambda_{Rn} C - \lambda_v (C - C_0) \quad (4.13)$$

where S is the radon source and  $\lambda_v$  is the ventilation rate with the outside atmosphere [Perrier et al., (2004)]. We see that the ventilation is a mechanism for losing  $^{222}\text{Rn}$  and acts similarly to the  $^{222}\text{Rn}$  decay term.

We wish to summarize the discussion in section 4.4 to section 4.6 to describe the radon concentration in one specific hall, say the Van Zyl hall which probably has the most ventilation to the outside.

The diffusion term can be simplified to

$$D \frac{\partial^2 C}{\partial x^2} = D \frac{\partial}{\partial x} \left( \frac{\partial C}{\partial x} \right) = \frac{\partial}{\partial x} J = \frac{\partial}{\partial x} \left( \frac{Q}{A} \right) \approx \frac{Q}{V} \quad (4.14)$$

if we assume that the hall can be taken as a whole and the diffusion only takes place at the entrance. This leads to the following equation for the Van Zyl hall where we are neglecting the effect of the next hall.

$$\frac{\partial C}{\partial t} = \frac{S}{V} - \lambda_{Rn} C - \lambda_v (C - C_0) - \frac{Q}{V} \quad (4.15)$$

The terms on the right hand side describe the source, decay, ventilation and diffusion respectively. To study the  $^{222}\text{Rn}$  concentration in the Cave, different assumptions need to be made to study the various contributions.

## 4.7 Different models for radon transport

### 4.7.1 Assumption A - No ventilation or diffusion

Deep inside the Cave, it may be reasonable to assume that the diffusion and the ventilation are small and that we have a steady state, i.e. a constant radon concentration. If these assumptions are applied to (4.15), we have

$$\frac{S}{V} = \lambda_{Rn} C \quad (4.16)$$

### 4.7.2 Assumption B - Diffusion dominates

In the case where the ventilation is very small, the diffusion will dominate and the major reason why the Van Zyl hall has a lower concentration will be due to diffusion to the outside. This would lead to

$$Q = S \quad (4.17)$$

if the diffusion even dominates the decay term.

### 4.7.3 Assumption C - Ventilation dominates

The number of atoms leaving the hall per second due to ventilation,  $\lambda_v N$ , must be proportional to the volume of air leaving the hall per second:

$$\begin{aligned} \lambda_v N &= \frac{\Delta V}{\Delta t} * C = \frac{\Delta V}{\Delta t} * \frac{N}{V} \\ \lambda_v &= \frac{1}{V} * \frac{\Delta V}{\Delta t} = \frac{\Delta V}{V} * \frac{1}{\Delta t} \end{aligned} \quad (4.18)$$

from (4.15)

$$\frac{\partial C}{\partial t} = \frac{S}{V} - \lambda_{Rn} C - \lambda_v C - \frac{Q}{V}$$

In the steady state case, there is no change of radon atoms with respect to time and if we can ignore diffusion,

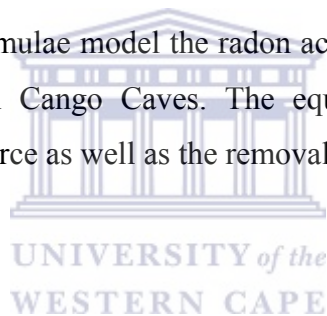
$$\frac{S}{V} - \lambda_{Rn} C - \lambda_v C = 0 \quad (4.19)$$

therefore 
$$\frac{S}{V} = \lambda_{Rn} C + \lambda_v C = 0 \quad (4.20)$$

## 4.8 Conclusion of this Chapter

The RAD7 and Electret ion chambers were used to measure radon concentrations in the Cango Caves during March 2005. The measurements were taken using both techniques simultaneously. A NaI detector was used to survey the Cave. The transport of radon in the Cave is due to for example, the pressure difference between that in the rock and soil, and the Cave atmosphere. In the atmosphere, radon concentration moves as a result of exogenic and endogenic factors. An exogenic radon air movement is generated by the difference between air pressure in the Cave and at the outside atmosphere, Cave openings, and temperature. Endogenic radon air movement occurs in a closed thermodynamic system. Radon air movement is due to pressure difference and air density inside the Cave, which is influenced by rock temperature difference, humidity, and CO<sub>2</sub> content.

The derived mathematical formulae model the radon activity concentration of soil and rock as the radon source in Cango Caves. The equation takes into account the production of a new radon source as well as the removal thereof.



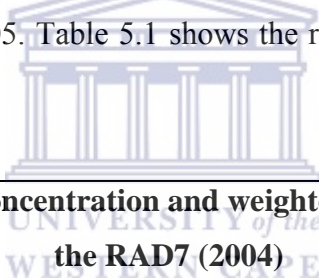
## Chapter 5

### 5 Results and Discussion

In this Chapter, results from measurement in the Cave using different techniques are presented. These include results from Electret ion chambers (2005), RAD7 (2004 and 2005) and Gamma ray survey results. We further present the outcomes of the mathematical modeling derived in Chapter 4. The calculation of the annual effective dose rate of the tour guides in the Cango Caves is also given in this Chapter. This dose depends on the time spent by the tour guides in each Cave hall.

#### 5.1 RAD7 results from 2004

The measurements were done at several measurement points in the Cango Caves in February 2004 and March 2005. Table 5.1 shows the results that were obtained using the RAD7 in February 2004.

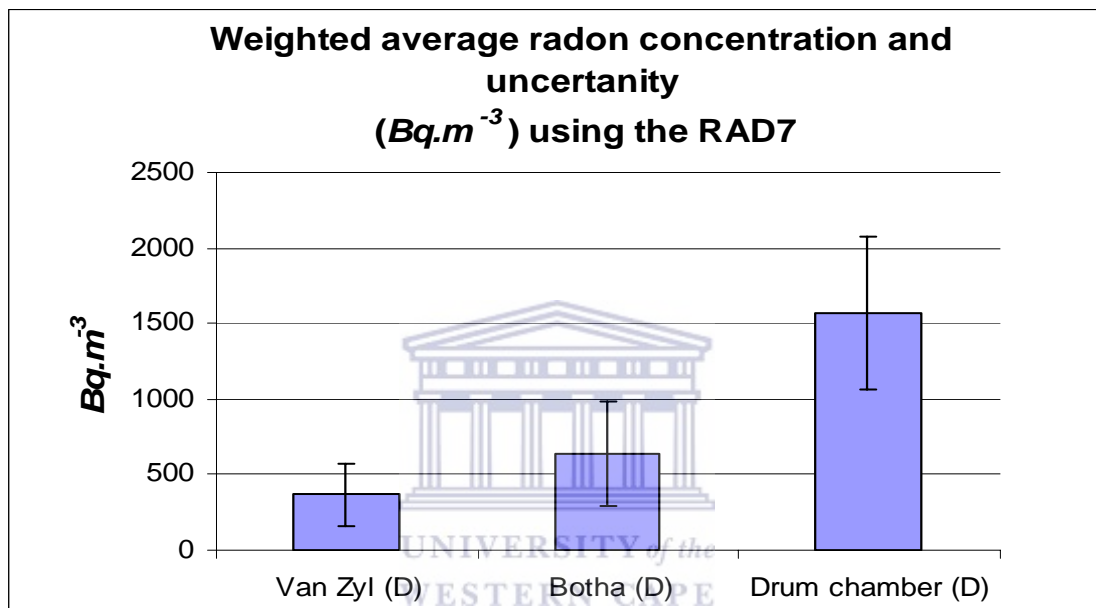


<b>Weighted average radon concentration and weighted uncertainty (<math>Bq.m^{-3}</math>) using the RAD7 (2004)</b>	
<b>Names of halls</b>	<b>Weighted average radon concentration and uncertainty (<math>Bq.m^{-3}</math>)</b>
Van Zyl (D)	$366 \pm 204$
Botha (D)	$638 \pm 351$
Drum chamber (D)	$1572 \pm 506$

**Table 5.1:** *RAD7 results for February 2004 (D stand for day measurements). The uncertainty is given as one sigma.*

The February 2004 RAD7 results were taken as an initial survey and to find out the range of radon concentrations in the different parts of the Cave. The results indicate where we can expect high levels of radon concentrations. As mentioned earlier, the purpose of the measurements was to find the level of radon concentration in the Cave.

These measurements were taken for two days only, 1 *hour* in the Van Zyl hall and 2 *hours* each in the Botha hall and Drum chamber. The values found in this survey range between  $366 \pm 204 \text{ Bq.m}^{-3}$  and  $1572 \pm 506 \text{ Bq.m}^{-3}$ . The measurements show high uncertainty due to the short measuring times. However, the measurements give us a rough approximation of radon concentration in the Cango Caves. The values of radon concentration increased from Van Zyl hall as we go deeper in to the Drum chamber (see Fig 5.1).



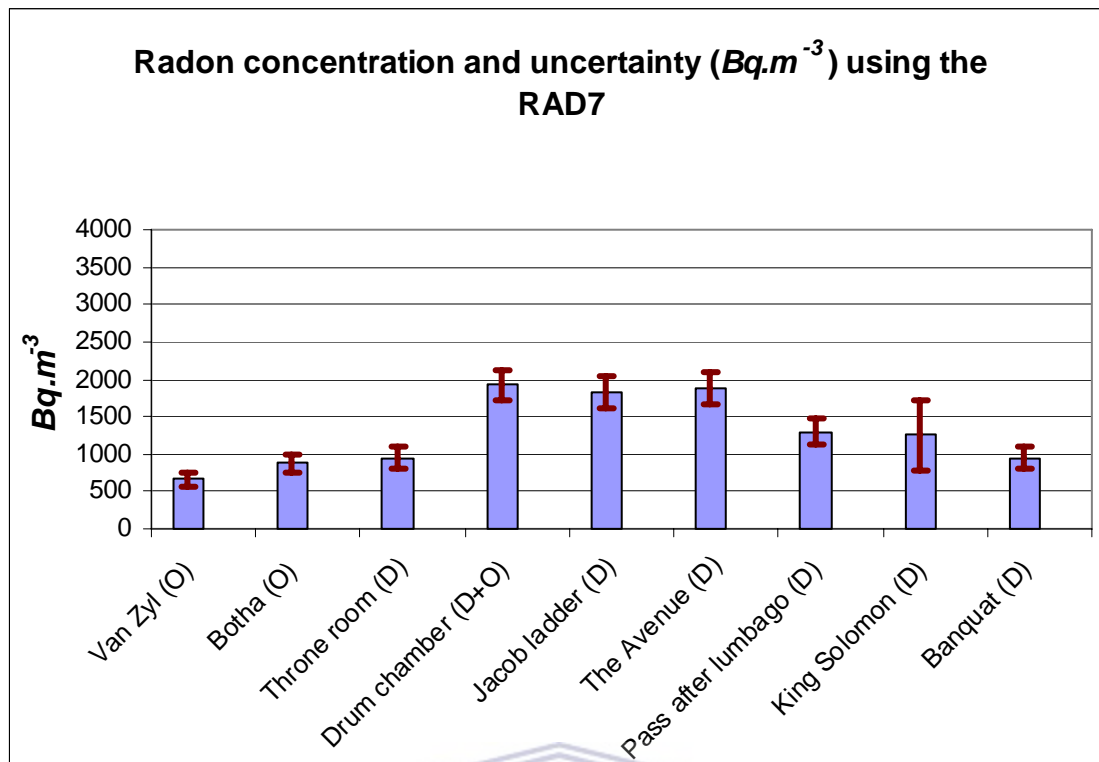
**Fig 5.1:** Average radon concentration measured in 2004 (where D stands for Day measurements)

More extensive sets of measurements were taken with the RAD7 over a four day period in March 2005 (see Table 5.2). Measurements were taken overnight in the Van Zyl hall and Botha hall as well as the Drum chamber. The measurements were taken for durations of between 2 and 4 *hours* in the other Cave halls. The RAD7 was used in modes where the reading was printed out after intermediate periods of 30 *minutes* and 1 *hour*.

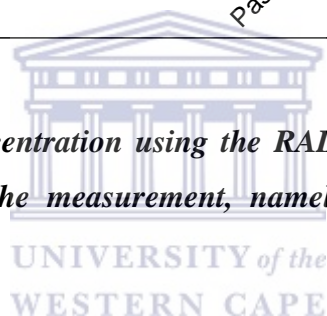
<b>Names of halls</b>	<b>Average radon concentration and uncertainty (<math>Bq.m^{-3}</math>) using the RAD7</b>
Van Zyl (O)	$668 \pm 97$
Botha (O)	$873 \pm 108$
Throne room (D)	$1134 \pm 409$
Drum chamber (D+O)	$1925 \pm 201$
Jacob ladder (D)	$1825 \pm 210$
The Avenue (D)	$1870 \pm 213$
Pass after lumbago (D)	$1298 \pm 179$
King Solomon mine (D)	$1254 \pm 468$
Banquet (D)	$952 \pm 137$

**Table 5.2:** *Measurements during March 2005. The indications D, O and D+O indicate the time of the measurement, namely day, overnight and day + overnight respectively.*





**Fig 5.2:** Average radon concentration using the RAD7. The indications *D*, *O* and *D+O* indicate the time of the measurement, namely day, overnight and day + overnight respectively.



The values taken in similar places correspond fairly well with the earlier results of 2004 though the 2005 results are higher. The radon concentration values range from  $668 \pm 97 \text{ Bq.m}^{-3}$  to  $1925 \pm 201 \text{ Bq.m}^{-3}$  (see Fig 5.2). These values agree with the 2004 RAD7 results as the values were increasing from Van Zyl hall to the African Drum chamber. In the 2005 measurements, the uncertainties were general very low compared to 2004 results. The 2005 measurements were taken overnight and long period during the daytime while the 2004 measurements were taken for 1 and 2 *hours* during the day only. All the RAD7 measurements were taken during summer, so that any seasonal variation in the radon concentrations has not been measured.

## 5.2 Electret ion chamber results taken in 2005

In this section the formulas for calculating calibration factor and radon concentration are given. Also presented are the full procedures and the steps taken in the calculation for the calibration factor and radon concentration (see Appendix A). The results of the radon measurements are given in a graph (see Fig 5.4). The spreadsheet of the given radon measurement results is also presented (see Appendix B (B.2)).

The procedure used to measure radon concentration in the Cango Caves using short term Electrets in a so called “S” Electret ion chamber (SST) (see Fig 5.3) was as follows:



**Fig 5.3: E-perm S-chambers**

We measured the initial voltage reading ( $V_i$ ) (see Chapter 4), and deployed the Electrets for one or two days. The final voltage ( $V_F$ ) was then measured, taking note of the time at the beginning and at the end of deployment. Both times were recorded. To calculate the radon concentration, we first calculated the calibration factor, CF, using the formula:

$$CF = 0.045885 + 0.000016 \times \left( \frac{V_i + V_F}{2} \right) \quad (5.1)$$

which will only apply for the SST arrangement. We then calculated the radon concentration using the formula:



$$C_{Rn} (Bq.m^{-3}) = \left[ \left( \frac{V_i - V_f}{C.F. \times T_A} \right) - Bg \right] \quad (5.2)$$

where Bg is the gamma background correction for which we used the default value of 32, which is only applicable to the SST arrangement.  $T_A$  is in units of days.  $C_{Rn}$  is the radon concentration in units of  $Bq.m^{-3}$ . The gamma background value is based on the default value of 10  $\mu R/h$  [Rad elec, (1994)]. Using the calculated calibration factor, different times, voltage difference and gamma background, the different radon concentrations were calculated (see Appendix B).

The Electret ion chambers results are presented in Fig 5.4. The readings are ordered from left to right according to the depth into the Cave, except for the place called the SAN, which is the entrance to the Cave. The measurements were taken during day time, overnight and daytime plus overnight. Note that the values increase from the entrance as expected but only as far as the Avenue. After the Avenue, the concentrations, as we go deeper into the Cave are lower (decreases).

The 2005 measurements for both techniques (RAD7 and Electret ion chamber) can be compared to the values of other measurements in the Caves around the world. For example, Duffy et al. 1996 measured the radon concentration in Ireland Caves and found it to range from 488  $Bq.m^{-3}$  to 11285  $Bq.m^{-3}$ . At the Cave entrance, the measured value was 200  $Bq.m^{-3}$ . These values show that as expected, the radon concentration increases from the entrance and as we go deeper inside the Cave. The Cango Cave consists of a sequence of halls where one hall is joined to the other with a small opening to Cango II. This opening could be the factor affecting the build up of the radon concentration towards the back of Cango I. Further investigation is needed to confirm this.

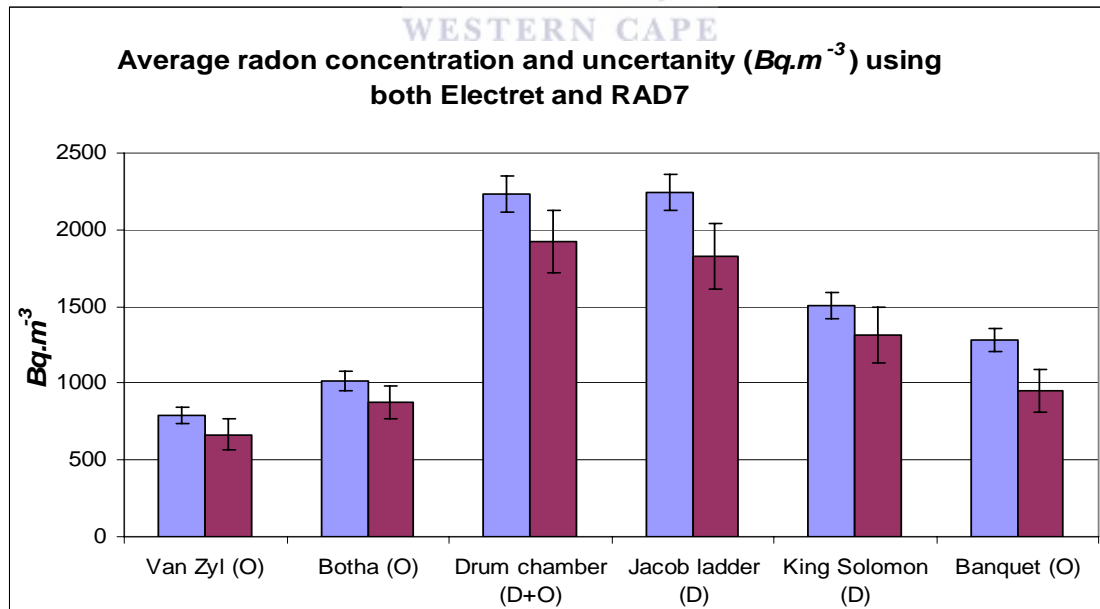


- 1) After the measurement at Congo Caves, the Electret measurements require a background correction. The Electret is sensitive to gamma rays as well. This leads to a voltage drop equivalent to the voltage drop caused by  $3.2 \text{ Bq.m}^{-3}$  of radon for each  $\mu\text{R/h}$ . It is possible that this background correction is underestimated.
  
- 2) When Electrets are deployed in a high radon environment for a few *hours*, the final reading should be delayed by *3 hours* while the Electret ion chambers are left in a low  $^{222}\text{Rn}$  area. This was not practical in the Cave, so we read the Electret voltages immediately. An experiment was carried out to correct for this. The correction experiment for the Congo Caves measurements was performed at the UWC nuclear laboratory in April 2005 (see Appendix A.2 for experimental procedures). The experiment was performed using a source with  $^{226}\text{Ra}$  dissolved in water [Colle, Kotrappa and Hutchinson, (1995)]. 6 Electret ion chambers were deployed inside a vacuum chamber with the source attached inside the chamber. The experiment took *3.72 days*. We read 3 Electret immediately and 3 after *3 hours* and compared the results. The difference was only 3%. The 3% difference was added to all the original results measured in the Congo Caves (see Appendix B (B.1)).
  
- 3) The calibration factor of the RAD7 or the SPER-1 reader used to read the Electret may be slightly off. This was investigated by including a connection to the RAD7 in the experiment described in 2 above. The results are presented in Appendix D.

<b>Electret/RAD7 Comparison</b>		
<b>Name of halls</b>	<b>Electret ion chamber</b>	<b>RAD7</b>
	Average concentration and weighted uncertainty ( $Bq.m^{-3}$ )	Average concentration and weighted uncertainty ( $Bq.m^{-3}$ )
Van Zyl (O)	$787 \pm 51$	$668 \pm 97$
Botha (O)	$1016 \pm 61$	$873 \pm 108$
Drum chamber (D+O)	$2230 \pm 117$	$1925 \pm 201$
Jacob ladder (D)	$2243 \pm 119$	$1825 \pm 210$
King Solomon mine (D)	$1505 \pm 83$	$1315 \pm 180$
Banquet (D)	$1284 \pm 72$	$952 \pm 137$

**Table 5.3: Comparison of Electret and the RAD7 results (D, O, D+O stands for Day-time, Overnight and Day-time plus Overnight respectively)**

After the correction, the Electret ion chamber results are still higher than the RAD7 results (see Fig 5.5).



**Fig 5.5: Comparison of Electret and RAD7 results**

## 5.4 Comparison to radon concentrations in other Caves

The distribution of radon concentration inside the Cave is shown in Fig 5.5. The minimum and maximum concentrations recorded through the study were  $792 \pm 51 \text{ Bq.m}^{-3}$  to  $2230 \pm 117 \text{ Bq.m}^{-3}$  for the Electret ion chambers and  $668 \pm 97 \text{ Bq.m}^{-3}$  to  $1925 \pm 201 \text{ Bq.m}^{-3}$  for the RAD7 respectively (see Table 5.3). These values can be compared with data from other selected Caves in the world (see Table 5.4).

<b>Radon data report for Caves in international literature</b>					
<b>Radon concentrations (<math>\text{Bq.m}^{-3}</math>)</b>					
<b>Country</b>	<b>Number-type of Caves</b>	<b>Min</b>	<b>Max</b>	<b>Mean</b>	<b>References</b>
Australia	57-show Caves			6330 (ann); 500 (win); 795 (spr)	Solomon et al., (1996)
Greece	Perama Cave			1311 (win); 925 (sum)	Papachristodoulou et al., (2004)
Ireland	3-show Caves	488	11285	2040; 5590; 7400	Duffy et al., (1996)
Poland	2-Caves	100 (win)	3600 (sum)		Przylibski, (1998)
Slovenia	10- Caves			2350 (sum) to 27000 (win)	Jovanovic, (1996)
UK	3-recreational Caves	32	12552		Sperrin et al., (2000)
UK	Lime stone	27	7800		Gillmore et al., (1999)

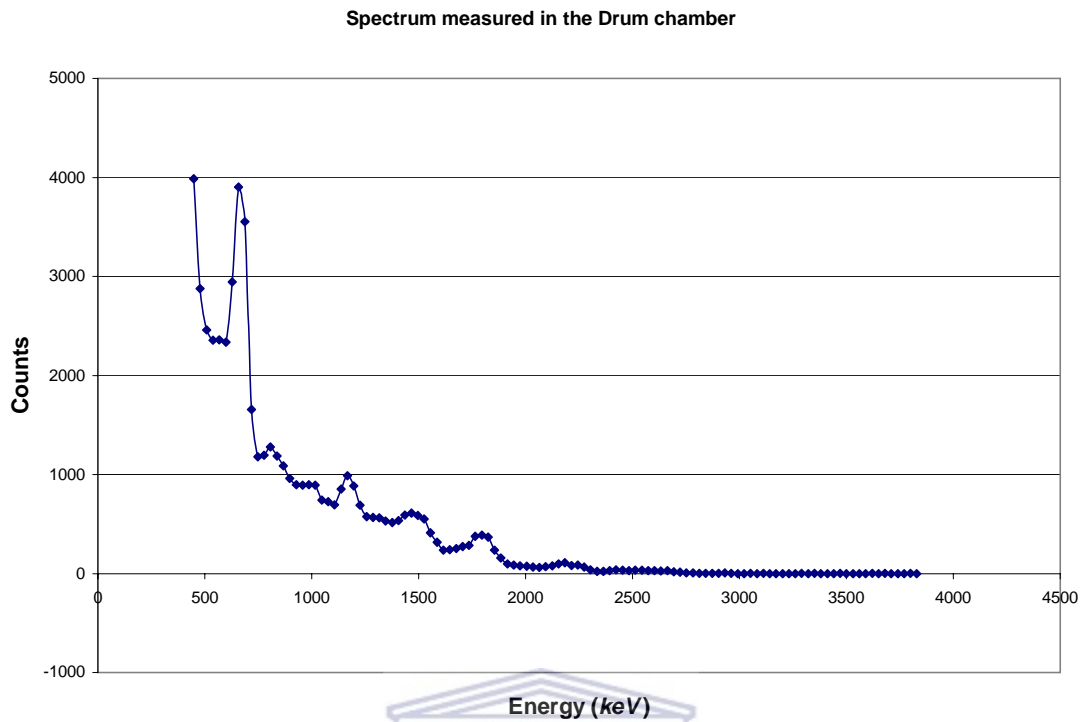
North-Spain	Ultamira Cave	186	7120	5562 (sum)	Lario et al., (2005)
Venezuela	Show Caves	100	80000		Sajo-Bohus et al., (1997)

**Table 5.4: Radon concentration from Caves worldwide (Min, Max, win, spr, sum and ann stand for Minimum, Maximum, Winter, Spring, Summer and Annual reading respectively)**

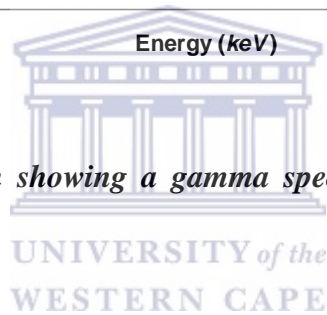
Radon concentration values measured in the Cango Caves are not extremely high and showed quite moderate spatial fluctuations. The concentration near the entrance shows a lower value as a result of air circulation. The change in radon concentration observed (see Fig 5.5) in the present study, probably results from the flow of air in the Cave. The air circulation in the Cave dominates at the entrance. Air ventilation probably occurs mainly through the two entrances of the Cave. These entrances are situated at the opposite side along the Cave axis (see Chapter 4). The entrances are at the bottom and top of Van Zyl hall. The two entrances are opened during the day to allow groups of visitors to enter and exit the Cave. The bottom entrance is solid, whereas the top entrance is a metal gate consisting only of metal bars.

## **5.5 Gamma measurement survey (2005) results**

As mentioned earlier in Chapter 4, gamma ray measurements using a NaI detector were performed in order to try to understand the origin of radon in the Cave. Spectra were collected in several places in the Cave using a portable NaI detector connected to a laptop computer. The purpose of these measurements was to give an indication of the radon potential in different places. A mostly qualitative comparison of the radon daughters that emit gamma rays was done. The geometry in the Caves disallowed a full quantitative analysis. A typical spectrum is shown in Fig. 5.6



**Fig 5.6:** *A typical spectrum showing a gamma spectrum measured in the drum chamber in this case*



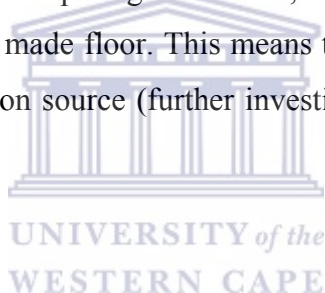
The relative strength of the gamma rays from  $^{40}\text{K}$  and the  $^{232}\text{Th}$  and  $^{238}\text{U}$  decay series for different locations are given in Table 5.5.

Location	Relative U values from 1765 keV line in $^{214}\text{Bi}$	Relative $^{232}\text{Th}$ values from 2614 keV $^{218}\text{Tl}$ line	$^{40}\text{K}$ 1461 keV line
Drum – floor	2.06	0.03	2.71
Drum – rock	2.03	0.07	2.43
Drum – formations	1.28	0.2	3.03
Jacob – rocks	2	0.9	6.07
Jacob – cement	2.12	1.32	6.7
The Avenue – clay	0.92	0.78	6.67

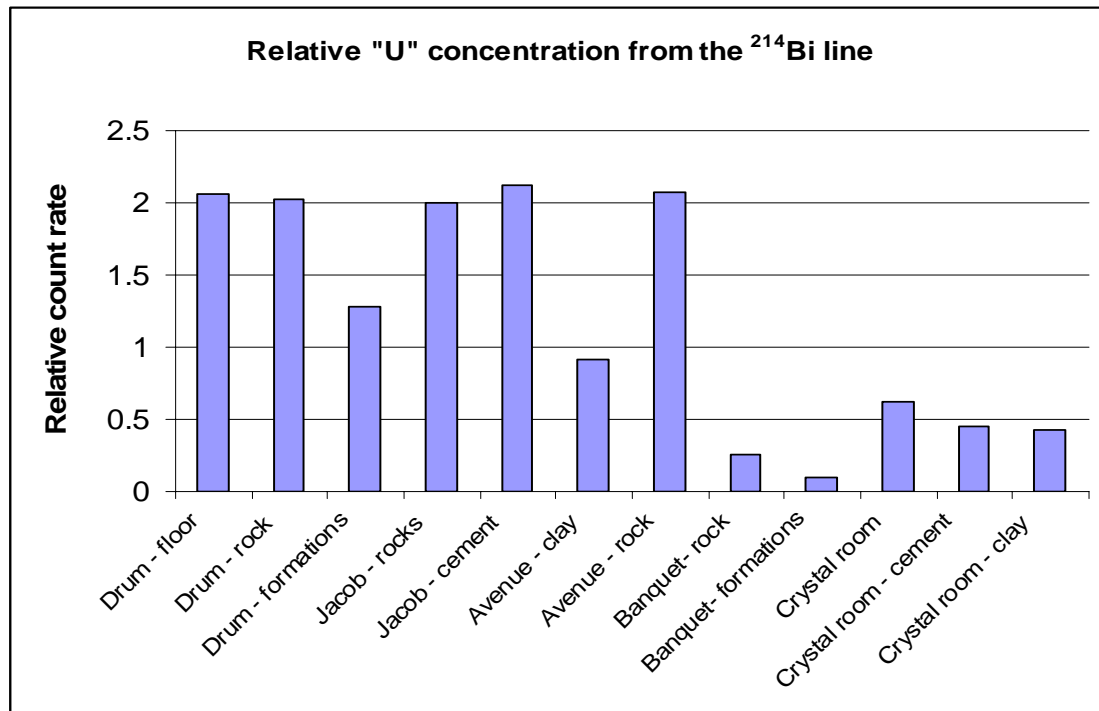
The Avenue – rock	2.07	0.12	2.79
Banquet hall – rock	0.26	0.05	0.35
Banquet hall – formations	0.1	0.03	0.32
Crystal room	0.62	0	1
Crystal room –cement	0.45	0.39	4.7
Crystal room – clay	0.43	0.18	2.45

**Table 5.5: Relative strengths of the natural radionuclides**

The values presented in Table 5.5 were arrived at by taking the count rate from the given peaks in the spectra for the specified lines. The count rate as detected from the spectra shows the uranium content. The results (see Table 5.4) indicate the relative source of radon in the Cave. Comparing the results, the rocks show lower values of uranium content than the man made floor. This means that, the man made floor in the Cave acts as an important radon source (further investigation are needed to elaborate this).







**Fig 5.7: Relative uranium value**

Fig. 5.7 shows the relative Uranium values in different parts of the Cave. The values in the graph (see Fig 5.7) are approximate. When measuring, it is impossible to shield the detector from gamma rays coming from different sides other than the source. But the results do indicate that the CaCO<sub>3</sub> formations are very inactive, whereas the rock and clay areas are more active.

## 5.6 Modeling results

This section present the results of the mathematical modeling derived in Chapter 4. This includes the radon concentration, diffusion from the rock and soil to the atmosphere, estimation of the ventilation rate and the speed of air, which enters the Cave through the entrance as well as scaling methods.

### 5.6.1 Scaling methods

In the steady state there is no change of concentration with respect to time. We can assume that deep inside the Cave the ventilation and diffusion to the outside is small. If these two terms are neglected and we assume a steady state so that  $\frac{\partial C}{\partial t} = 0$ , equation (4.15) gives

$$\frac{S}{V} - \lambda_{Rn} C = 0 \quad (5.3)$$

$$S = \lambda_{Rn} C \times V \quad (5.4)$$

This gives a very approximate idea of the source term deep inside the Cave. If we consider the Avenue, the  $^{222}\text{Rn}$  concentration is about  $2600 \text{ Bq.m}^{-3}$ . This implies a source of

$$S = 2 \times 10^{-6} \text{ s}^{-1} \times 2600 \text{ Bq.m}^{-3} \times 6600 \text{ m}^3 \approx 34 \text{ Bq.s}^{-1} \quad (5.5)$$

This implies a radon flux from the rocks of

$$\phi = \frac{S}{\text{Area of hall}} = \frac{34 \text{ Bq.s}^{-1}}{550 \text{ m}^2 \times 4} = 5.5 \times 10^{-3} \text{ Bq.m}^{-2}.\text{s}^{-1}. \quad (5.6)$$

This is very similar to a measurement of the flux found in a limestone Cave in Australia [Solomon et al., 1992]. The Avenue is a long thin passage so the area has been approximated to four times the floor area.

Equation (5.3) and (5.6) imply that  $C \approx \frac{\phi \times A}{\lambda_{Rn} V}$ . This would indicate that the radon concentration should be larger in small halls, since the area to volume ratio is larger for small volumes.

This appears to be the case for some halls (see Fig 5.5), which shows that the Botha and Van Zyl hall have lower radon concentration. However, these halls are also close to the entrance where ventilation leads to lower radon levels. The area of the hall is quite complicated to calculate as a result of the intricate formations present, which may affect the scaling (see Appendix E). The area was calculated naively using the formula  $L \times B$  (see Table 5.7) following James method [Craven, (1992)].

Since the halls in the Cave are very complicated structures due to the stalactites and stalagmites, the area to volume ratio may not be as simple as expected. There seems to be little indication that such a scaling behavior describes the radon in the Cave.

### 5.6.2 Diffusion

If we assume that diffusion dominates as discussed in section 4.8.3, the diffusion out of the Van Zyl hall can be described by

$$Q = JA = -DA \frac{\Delta C}{\Delta x} \quad (5.6)$$

where  $D$  is the diffusion coefficient for radon in air (which =  $1 \times 10^{-6} \text{ m}^2 \cdot \text{s}$ ),  $A$  the area of the entrance,  $\Delta C$  is the change in concentration from the inside to the outside and  $\Delta x$  is the length of the entrance passage.

Using very approximate values for the entrance passage (length =  $5 \text{ m}$  and area  $4 \text{ m}^2$ ) implies a diffusion rate of the order of  $10^{-3} \text{ Bq} \cdot \text{s}^{-1}$ . This is much lower than the estimated creation rate of the radon (see section 5.6.1), which appears to imply that diffusion is not the main contributor for radon movement in the first few halls in the Cave.

### 5.6.3 Ventilation

As mentioned, one of the aims of this study was to find out about the ventilation in the Cave. This was done by considering Van Zyl hall at night when one of the entrances is closed. Again we further assume that the volumes from Van Zyl hall to the Avenue are the same (see Chapter 4 assumption A). Using the assumption C in section 4.8.3, the following numerical example is given:

If we assume that the concentration ( $C_0$ ) in Van Zyl hall would equal to the concentration in the Avenue if the ventilation and diffusion was small,  $\frac{S}{V} \approx 2600$ , the equation 4.20 in Chapter 4 gives

$$2600 = \lambda_{Rn} C + \lambda_v C \quad (5.7)$$

Where C is the real concentration in Van Zyl hall, therefore

$$2600 = 800 + \frac{\lambda_v}{\lambda_{Rn}} (800)$$

and

$$\lambda_v = \frac{2600}{800} \lambda_{Rn} = 3.25 \lambda_{Rn} \approx 7 * 10^{-6} s^{-1} \quad (5.8)$$

which is the ventilation constant that we are looking for. From equation (4.18)

$$\lambda_v = \frac{\Delta V}{V} * \frac{1}{\Delta t} = \frac{\Delta V}{\Delta t} * \frac{1}{V} \quad (5.9)$$

therefore

$$\frac{\Delta V}{\Delta t} = V * 3.25 \lambda_{Rn} = 80000 m^3 * 3.25 * 2.1 * 10^{-6} s^{-1} = 0.520 \frac{m^3}{s} \quad (5.10)$$

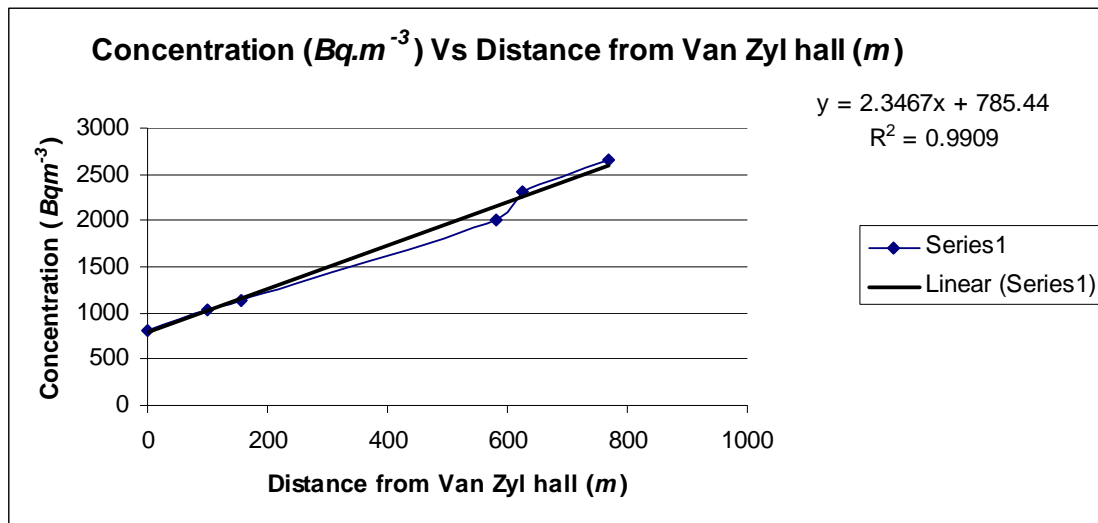
This is the volume of air that leaves Van Zyl hall per second. To get the velocity, we must divide equation (5.7) by the area. Then

$$Velocity = \frac{\Delta V}{A \Delta t} \approx \frac{0.520 m^3 / s}{12 m^2} \approx 4 * 10^{-2} m / s = 4. cm / s \quad (5.11)$$

This value shows that the speed of air getting into Van Zyl hall through the entrance is very low. This is a very approximate value, but indicates that the air speed is of the order of a few *cm/s*.

#### 5.6.4 Linear model

This section discusses the results of time dependent <sup>222</sup>Rn transport equation including only diffusion. By considering the concentration that varies over position and time, the diffusion equation is derived (see section 4.5.2). As mentioned earlier in the steady state there is no change of concentration with respect to time. Applying steady state to the diffusion equation (4.8), the diffusion solution equation (4.10) is obtained. This section will present the results of the diffusion solution, Cave volumes and Cave floor area.



**Fig 5.8: Concentration Vs Distance from Van Zyl hall**

To estimate the concentration function in the Cave, the value of the radon concentration measured at Van Zyl hall was used. As mentioned earlier, the concentration in the Cave increases from Van Zyl hall as we go deeper until the Avenue. The linear equation (4.10) derived in Chapter 4 was used to plot the graph (see Fig 5.8). The linear line was fitted to the graph to get the gradient, which is  $2.4 \text{ Bq.m}^{-2}$ . Using the  $C_0$  values measured in Van Zyl hall and the calculated gradient, we substituted both (gradient and  $C_0$ ) into equation (4.10), to get Concentration function (C). The calculated values are given in Table 5.7 and they range from  $813 \text{ Bq.m}^{-3}$  to  $2661 \text{ Bq.m}^{-3}$ .

The Cango Caves halls are arranged in sequence, where one follows another. The halls in the Caves have different volumes. The volumes of the major halls range from  $6600 \text{ m}^3$  to  $79200 \text{ m}^3$ . For example, the volume of Van Zyl hall is  $79200 \text{ m}^3$  indicating that it is the largest of the halls in the Cango Caves (see Table 5.7 for the volumes of other halls).

<b>Diffusion Model Results Using Electret Values</b>				
<b>Name of the halls</b>	Distance from Van Zyl hall (m)	C ( $Bq.m^{-3}$ )	Volume ( $m^3$ )	Floor Area ( $m^2$ )
<b>Van Zyl</b>	0	813	79200	4950
<b>Botha</b>	100	1051	43000	2870
<b>Passage after Botha</b>	160	1191	41000	3470
<b>Drum chamber</b>	580	2208	5590	220
<b>Grand</b>	620	2311	13400	560
<b>The Avenue</b>	770	2661	6600	550

**Table 5.7: Diffusion model using Electret values. The measured values are given in appendix B.2**

The discussion in 5.6.2 concluded that the diffusion is probably low, but the change due to ventilation will lead to a very similar linear approximation for the radon distribution. The discussion is very approximate since it ignores the decay and the production in the different halls

## **5.7 Dose calculation**

One of the objectives of this study is to calculate the annual effective dose of tour guides in Cango Caves. In order to determine the annual effective dose in  $mSv$ , we used the Dose Conversion Factor (DCF) of  $5 mSv \text{ per } WLM$  recommended by ICRP 65. A useful approach is to first calculate the maximum time that a tour guide will spend in the Cave. In this study, daily time spent within the Cave by a tour guide is taken to be  $6 \text{ hours}$ ,  $7 \text{ days a week}$ , for about 4 weeks with an off period of  $6 \text{ days}$ . The time spent in the Cave by one guide is therefore approximately  $132 \text{ hours per } 28 \text{ days}$

period, which gives an annual exposure time of about 1584 *hours per year*, when annual vacations are taken into account.

In order to calculate the effective dose we need the dose conversion factor. It is helpful to provide a unit dose conversion factor from radon exposure to effective dose [ICRP, (1993)]. The unit dose conversion factor (udcf) is calculated as follows:

$$udcf = \frac{2.082 \times 10^{-8} J}{3700 Bq.m^{-3}} = 5.62 \times 10^{-12} J \text{ per } Bq.m^{-3} = 5.62 \times 10^{-6} mJ.m^{-3} \text{ per } Bq.m^{-3}$$

As explained earlier in Chapter 3, the unit of potential alpha energy exposure is  $J.h.m^{-3}$ . The potential alpha energy exposure of workers (tour guides) is often expressed in the historical unit WLM. Then, we have:

$$1 WLM \approx 3.54 mJ.h.m^{-3}$$

According to the ICRP 65 dose conversion convention, the effective dose per unit of exposure at work is  $5 mSv \text{ per } WLM$ . To calculate the effective dose for tour guides in the Cave, the conversion factor (dose factor) is needed and is given as:

$$cf = \frac{5 mSv}{WLM}$$

$$\text{Then, } cf = \frac{5 mSv}{3.54 mJ.h.m^{-3}} = 1.41 mSv.mJ.h.^{-3}$$

The occupancy in the Cave is taken to be 1584 *hours per year* for workers (tour guides). The annual effective doses due to exposure to radon decay product can then be calculated as:

$$E = C_{Rn} \times F \times t \times cf \times u \quad (5.12)$$

Where E= effective dose ( $mSv \text{ per year}$ ),  $C_{Rn}$  = air radon concentration ( $Bq.m^{-3}$ ), F= equilibrium factor between radon and its decay products which was taken to be 0.4, t= time spent annually inside the Cave (*hours per year*), cf=conversion factor ( $1.4 mSv \text{ per } mJ.h.m^{-3}$ ), u= unit conversion factor ( $mJ.m^{-3} \text{ per } Bq.m^{-3}$ ).

The results obtained from equation (5.12) are given in Table 5.11 based on the Electret values. Table 5.11 shows the annual effective dose results for the tour guides at Cango Caves. The unit dose conversion factor is calculated using the method proposed by ICRP 65 (as shown above) and it is  $1.41 mSv \text{ per } mJ.h.m^{-3}$ . The calculated annual

effective dose rate ranges from 3.9 *mSv* (in the Van Zyl) to 12.8 *mSv* (the Avenue). At the Cave entrance, the calculated annual effective dose is 1.4 *mSv*. The effective dose rate calculated seems reasonable compared to the worldwide doses found in underground Caves (see Table 5.10).

<b>World Wide Effective Doses (<i>mSv</i>)</b>			
<b>Country</b>	<b>Type of Cave</b>	<b>Effective dose (<i>mSv</i>)</b>	<b>References.</b>
UK	Medips recreational Cave	120	Sperrin et al., (2000)
Venezuela	Karstic zone	6-100	Sajo'-Bohus et al., (1997)
Slovenia	Karst Cave	10-50	Jovanovic, (1996)
Ireland	Show Cave	2-7.5	Duffy et al., (1996)

**Table 5.10: World wide annual effective doses.**

It is difficult to compare the effective doses as many sources use different DCF, equilibrium factor and the time the guides spend inside the Cave. For guides if they spent all their time inside the Cave in a specific hall. In practice guides divide their time fairly equally between the Van Zyl hall, Botha hall and Drum chamber hall on the standard tour. This would indicate an annual effective dose of around 6 *mSv*. The value on the adventure tour will not differ much from this, as the <sup>222</sup>Rn values further inside the Cave are not much higher.

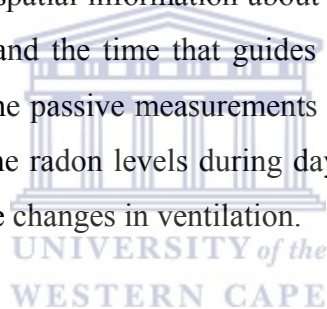


<b>Electret Effective Dose Rate Results</b>		
<b>Name of the halls</b>	<b>Weighted average concentration (<math>Bq.m^{-3}</math>)</b>	<b>Effective dose (<math>mSv.y^{-1}</math>)</b>
Van Zyl (O)	792	<b>4</b>
Van Zyl (D)	790	<b>4</b>
Botha (O)	984	<b>5</b>
Botha (D)	1016	<b>5</b>
Passage after Botha (D)	1105	<b>6</b>
Drum chamber (D + O)	2230	<b>11</b>
Drum chamber (O)	1834	<b>9</b>
Drum chamber (D)	1806	<b>9</b>
Jacob ladder (D+O)	2243	<b>11</b>
The Avenue (D)	2577	<b>13</b>
Lumbago walk (D+O)	1538	<b>8</b>
King Solomon (D+O)	1505	<b>8</b>
Devil workshop (D+O)	1028	<b>5</b>
Banquet (D)	1284	<b>6</b>
Letter box (D+O)	1275	<b>6</b>
Devil chimney (D+O)	1103	<b>6</b>
SAN (D+O)	201	<b>1</b>

**Table 5.11:** *Electret annual effective dose rate (D, O and D+O stand for Day, Overnight and Day + Overnight respectively). The data in this table have been compiled from the data in Appendix B.2 and measurement in the same place consolidated.*

The maximum effective dose rate at Cango Cave is lower than the international recommendation for radiation workers for 20 *mSv per year* but much higher than the values for members of the public. The 13.0 *mSv* is the maximum annual effective dose found at Cango Caves. This value is similar to the annual effective doses found in international Caves. The values found in Karst Cave (Slovenia) range between 10-50 *mSv per year*. The 10-50 *mSv per year* values found in Karst Cave disagree with the present annual effective dose found in Cango Caves as Karst Cave values lie below and above the international recommended value of 20 *mSv per year*. In the UK (Medips recreational Cave) the annual effective dose is 6 times the radiation worker recommended value of 20 *mSv per year* (see Table 5.10).

Full analysis of the radon effective doses to permanent guides in Cango Caves would require detailed seasonal and spatial information about the equilibrium factor between radon and its decay product and the time that guides spend in the different halls. It should further be noted that the passive measurements performed in the present study might not accurately reflect the radon levels during daytime. The increases of human activities are expected to cause changes in ventilation.



The primary estimates of radiation dose from this study suggest that all tour guides at Cango Caves receive annual effective doses of less than the occupational limit of 20 *mSv* for radiation workers.

## **5.8 Conclusion of this Chapter**

Radon concentration measurements in the Cango Caves were taken in February 2004 and March 2005 at several points in the Cave. The measurements were taken using Electret ion chambers and the RAD7. The measured values range between 813  $Bq.m^{-3}$  and 2651  $Bq.m^{-3}$ .

A survey of radon sources at Cango Caves was done using a NaI detector. The results of this survey indicate that floors and rocks in the Cave are the main radon sources.

The annual effective dose was calculated using the radon concentration found in the Cave. The occupancy in the Cave was estimated to be about 1584 *hour per year* for Cango Caves tour guides. Using the equilibrium factor of 0.4 and the unit dose conversion factor of  $5.6 \times 10^{-6} \text{ mJ.m}^{-3} \text{ per Bq.m}^{-3}$  substituting these into the equation (5.12):

$$E = C_{Rn} \times F \times t \times cf \times u$$

including the conversion factor of  $1.4 \text{ mSv per mJ.h.m}^{-3}$ , the annual effective dose were calculated at each measurement (electret) point. Doses range from  $4 \text{ mSv to } 13 \text{ mSv}$  inside the Cave.



## Chapter 6

### Conclusion and Recommendations

This Chapter summarizes the findings of the research based on the expectations of the research objectives. The achievement of the research aims is discussed.

The main objectives of this study were to measure radon concentration in the Congo Caves, modeling it, finding out about ventilation, and estimating the dose rates of the tour guides.

The radon concentrations at Congo Caves were measured using the continuous radon monitor (RAD7) and Electret ion chambers. The results of these two measurement techniques in the Cave range from a minimum of  $668 \text{ Bq.m}^{-3}$  to a maximum of  $1925 \text{ Bq.m}^{-3}$  for RAD7 and  $778 \text{ Bq.m}^{-3}$  to  $2636 \text{ Bq.m}^{-3}$  for the Electret ion chambers. The radon concentrations measured here show good agreement with the values available in the literature (see Chapter 1).

The radon source value estimated in the Congo Cave far away from the entrance is  $34 \text{ Bq.s}^{-1}$ . The radon source term is not very high, but in a closed space like Cave a high radon concentration will occur. The level of radon production in Congo Caves is mainly caused by the material deposits and the bedrocks, but also by the man-made floor.

The ventilation rate estimated in Chapter 5 is  $7 \times 10^{-6} \text{ s}^{-1}$  which is very low. Higher concentrations of radon are observed in the Cave halls far away from the entrance (for example Drum and the Avenue) where there is poor ventilation. Thus, the ventilation process in the Cave is probably the main factor controlling the changes of radon concentration in the Cave air. The risk of tour guides can be reduced by improving ventilation inside the Cave. The problem is that, it is impossible to improve ventilation in the show Cave (Congo Caves) since it affects the delicate balance of  $\text{CO}_2$ , partial

pressure, temperature and humidity. This includes the risk of damaging the Caves formations such as the stalactite and stalagmite.

The annual effective doses calculated in the Cango Caves ranges from a minimum of 4 *mSv* (Van Zyl) to a maximum of 13 *mSv* (The Avenue) using the radon concentrations measured with the Electret ion chambers.

In order to improve the radiation doses estimated for the tour guides, future studies should cover seasonal radon concentration, equilibrium factor and aerosol condition in Cango Caves, as well as an investigation into the time spent by the guides in the Cave.



## Appendices

### Appendix A

#### Calibration Equation and Correction for Electret Background Gamma Radiation

##### A.1. Calculation of radon concentration

During March 2005 Electret ion chambers were deployed in the Cave to measure the radon concentration. Before measurements, we measure the initial voltage from the Electret surface potential using the SPER-1 reader. Then we deploy the Teflon disk into Electret chambers and open the top of the chamber to allow the air radon to get inside [Rad elec, 1994]. When the radon in the air gets inside the chamber, it decreases the Electret surface potential voltage as a result of the ionization caused by radon and the progeny decay [Vuza, (2002)]. We measured the initial voltage reading ( $V_i$ ) and deployed the chambers for one or two days in the Cave. The final voltage ( $V_f$ ) was then measured, taking note of the time at the beginning and at the end of deployment.

To calculate the radon concentration we follow the procedure below

1. We first calculate the calibration factor (C.F) using the formula

$$C.F = 0.045885 + 0.0000155 \times \left( \frac{V_i - V_f}{2} \right) \quad (A.1)$$

We apply the above equation only for the SST measurements.

2. We calculate radon concentration using the formula

$$C_{Rn} (Bq.m^{-3}) = \left[ \left( \frac{V_i}{C.F \times T_A} \right) - Bg \right] \quad (A.2)$$

where Bg is the gamma background correction for which we used the default value of 32 , which is only applicable to SST arrangement. Time ( $T_A$ ) is in units of *days*;  $C_{Rn}$  is the radon concentration in units of  $Bqm^{-3}$ . The gamma background value is based on the default value of  $10 \mu R/h$ .

## Method of estimating uncertainty

There are three sources of error in Electret ion chamber radon monitor measurements

$$E_T = \sqrt{E_1^2 + E_2^2 + E_3^2} \quad (\text{A.3})$$

1. The error related to the system components ( $E_1$ ), which include uncertainty in chamber volume, Electret thickness, and other components parameter. This is experimentally measured to be 5%
2. Error in Electret voltage reading ( $E_2$ ). There can be uncertainty of 1 volt of both the initial and final voltage reading, so the error of two different readings is 1.4, which is the square root of two. The percentage error then is:

$$\frac{100 \times 1.4}{V_i - V_f}$$

3. Error due to uncertainty in the gamma background ( $E_3$ ).

### A.2. Experimental procedure to test the correction to the Electret in S-chamber if read immediately.

The experiment to obtain the correction caused by radon daughter decay was performed during April 2005 at the UWC Nuclear Physics laboratory. The purpose of the experiment is to find the percentage difference of the Electrets when read immediately, and when read after 3 hours. The experiment will help to correct the Cave measurements. The procedure of the experiment was as follows: Connect RAD7 to 12L vacuum chamber, via in and outputs in the chamber. Put 6 Electrets and a NIST radon source [Colle, Kotrappa and Hutchinson, (1995)] in the Vacuum chamber, close the chamber tightly run, until the RAD7 indicates a concentration of over  $1000 \text{ Bq.m}^{-3}$ . Stop and open, read 3 of the chambers immediately and leave 3 Electrets for 3 hours in low radon area for radon daughters to decay. Compare two sets of readings.

## Appendix B

### Electret Ion Chamber Results

#### B.1. Radon daughter concentration (Electret) results

Radon daughter correction (Electret) results							
Electret reading time	$V_i$	Date stated	Time started	$V_f$	Date ended	Time ended	Radon concentration ( $Bq.m^{-3}$ )
Immediately	308	3/18/2005	17:10	190	3/22/2005	15:05	574
Immediately	515	3/18/2005	17:10	386	3/22/2005	15:05	591
Immediately	233	3/18/2005	17:10	115	3/22/2005	15:05	588
after 3 hours	328	3/18/2005	17:10	204	3/22/2005	15:05	601
after 3 hours	281	3/18/2005	17:10	165	3/22/2005	15:05	569
after 3 hours	264	3/18/2005	17:10	136	3/22/2005	15:05	635

#### B.2. Electret ion chamber results

Radon concentrations in the Cave							
Electret results							
Name of the halls	Voltage Initial ( $V_i$ )	Date started	Time started	Voltage final ( $V_f$ )	Date ended	Time ended	Radon concentration and uncertainty ( $Bq.m^{-3}$ )
Van Zyl (O)	214	3/11/2005	16:32	186	3/12/2005	8:55	828±68
Van Zyl (O)	202	3/11/2005	16:32	175	3/12/2005	8:55	800±67
Van Zyl (O)	203	3/12/2005	17:32	176	3/13/2005	9:55	825±60



<b>Van Zyl (D+O)</b>	175	3/12/2005	9:00	136	3/13/2005	8:55	800±60
<b>Botha (O)</b>	242	3/11/2005	16:36	205	3/12/2005	9:35	1057±74
<b>Botha (O)</b>	334	3/11/2005	16:36	299	3/12/2005	9:35	968±70
<b>Botha (D+O)</b>	205	3/12/2005	9:43	155	3/13/2005	8:54	1060±69
<b>Botha (D+O)</b>	299	3/12/2005	9:43	249	3/13/2005	8:54	1030±68
<b>Passage after Botha (D+O)</b>	291	3/12/2005	11:05	242	3/13/2005	8:54	1075±70
<b>Passage after Botha (D+O)</b>	267	3/12/2005	11:05	213	3/13/2005	8:54	1198±75
<b>Drum chamber (O)</b>	278	3/11/2005	17:04	198	3/12/2005	10:00	2320±127
<b>Drum chamber (O)</b>	305	3/11/2005	17:04	226	3/12/2005	10:00	2270±125
<b>Drum chamber (D+O)</b>	198	3/12/2005	10:00	113	3/13/2005	9:12	1840±102
<b>Drum chamber (D+O)</b>	226	3/12/2005	10:00	136	3/13/2005	9:12	1933±107
<b>Drum chamber (D)</b>	241	3/13/2005	9:16	212	3/13/2005	16:50	1882±135
<b>Drum chamber (D)</b>	210	3/13/2005	9:16	186	3/13/2005	16:50	1834±134
<b>Jacob ladder (D+O)</b>	231	3/12/2005	11:15	130	3/13/2005	09:30	2268±122

<b>Jacob ladder (D+O)</b>	281	3/12/2005	11:15	175	3/13/2005	09:30	2346±125
<b>The Avenue (D)</b>	266	3/13/2005	10:20	232	3/13/2005	16:35	2666±176
<b>The Avenue (D)</b>	206	3/13/2005	10:20	173	3/13/2005	16:35	2636±176
<b>Lumbago walk (D+O)</b>	340	3/12/2005	11:25	261	3/13/2005	10:27	1642±93
<b>Lumbago walk (D+O)</b>	319	3/12/2005	11:25	246	3/13/2005	10:27	1523±88
<b>King Solomon (D+O)</b>	231	3/12/2005	11:35	156	3/13/2005	11:26	1555±89
<b>King Solomon (D+O)</b>	255	3/12/2005	11:35	180	3/13/2005	11:26	1543±89
<b>Devil workshop (D+O)</b>	203	3/13/2005	15:10	165	3/14/2005	10:40	954±68
<b>Devil workshop (D+O)</b>	210	3/13/2005	15:10	164	3/14/2005	10:40	1160±76
<b>Banquet (D+O)</b>	283	3/12/2005	11:50	211	3/13/2005	15:00	1283±76
<b>Banquet (D+O)</b>	279	3/12/2005	11:50	203	3/13/2005	15:00	1358±80
<b>Letter box (D+O)</b>	218	3/13/2005	15:30	164	3/14/2005	10:55	1372±84
<b>Letter box (D+O)</b>	257	3/13/2005	15:30	207	3/14/2005	10:55	1372±84
<b>Devil chimney (D+O)</b>	215	3/13/2005	15:50	171	3/14/2005	10:52	1251±79

<b>SAN (D+O)</b>	218	3/12/2005	10:46	210	3/13/2005	12:42	122±40
<b>SAN (D+O)</b>	264	3/12/2005	10:46	247	3/13/2005	12:42	292±44

**Where D, O and D+O stands for Day, Overnight and Day + Overnight respectively.**

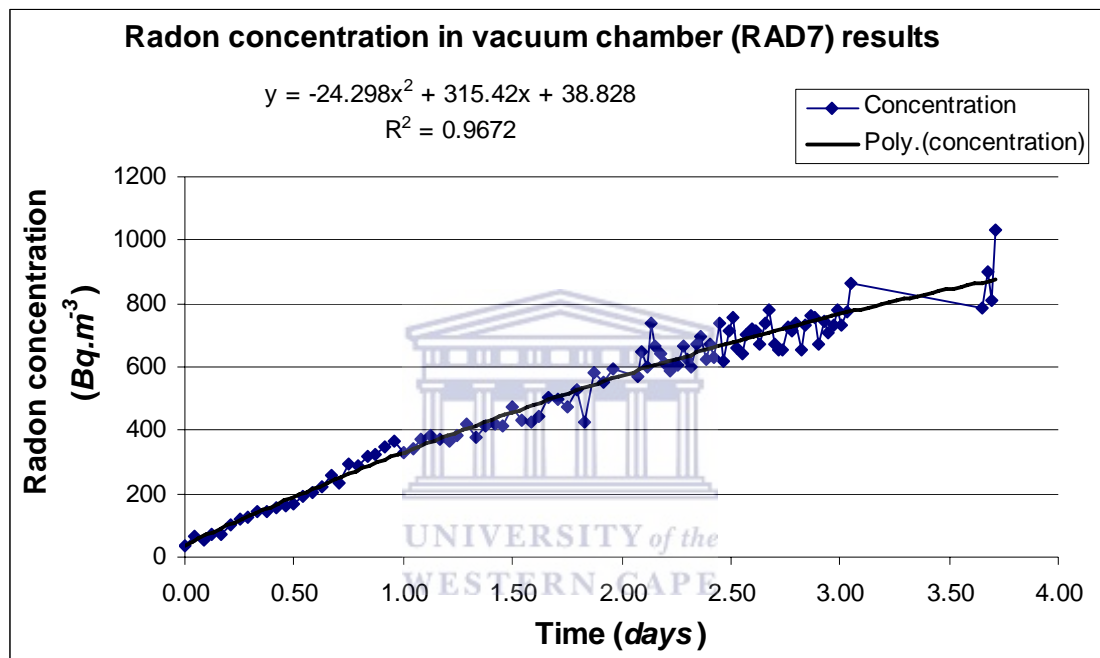




## Appendix D

### Radon Concentration in a Vacuum Chamber (RAD7) Results

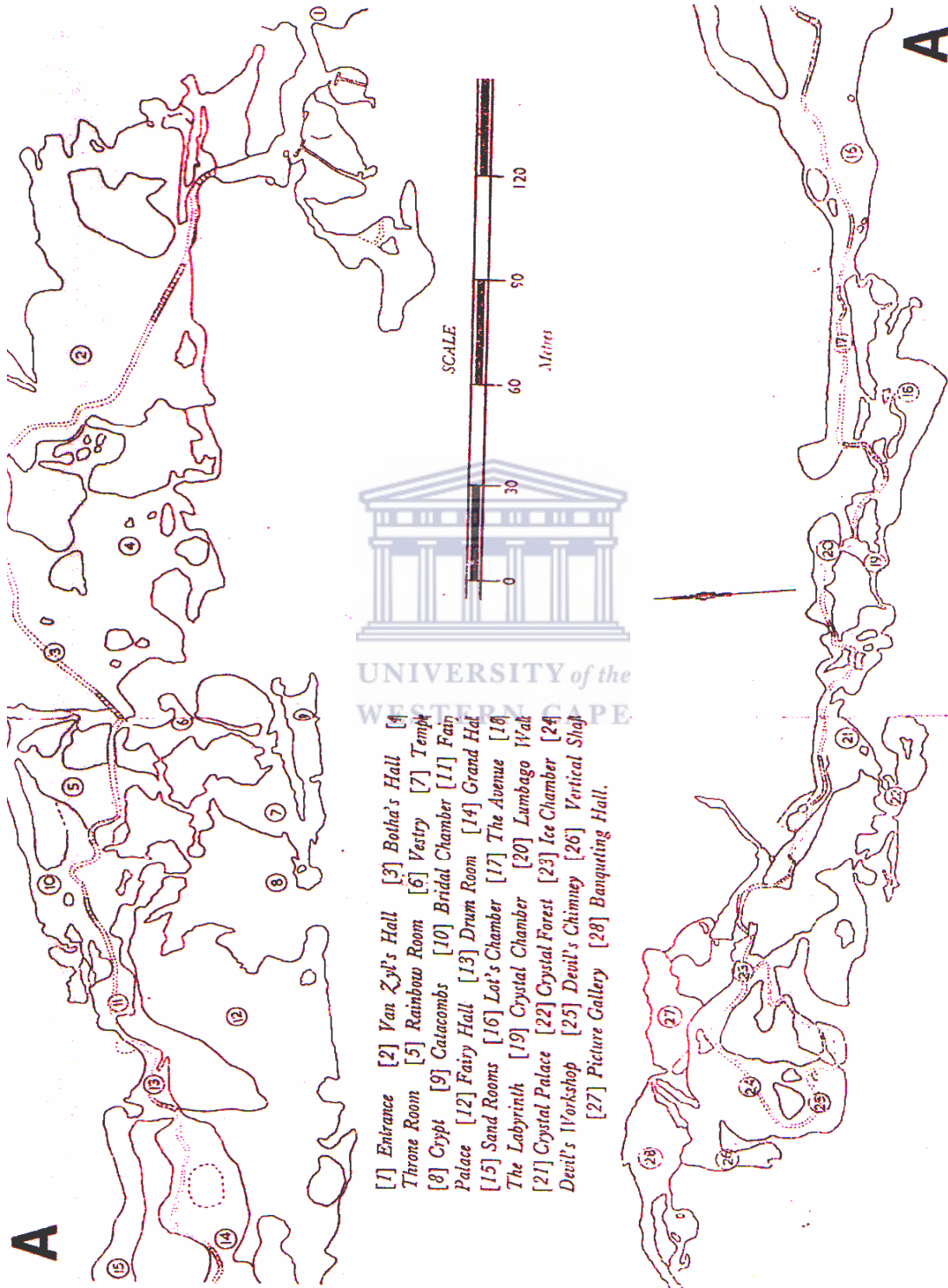
While doing the experiment to look at the effect of not waiting for 3 *hours* of radon daughter to decay, the air inside the vacuum chamber was circulated through the RAD7.



To compare the Electret ion chamber to the RAD7 values. The RAD7 values (see Fig above) were fitted by a polynomial. The fitted polynomial equation was integrated to give an average value of  $513 \text{ Bq.m}^{-3}$  for a period of 3.72 days. The Electret gives an average radon concentration of  $602 \pm 50 \text{ Bq.m}^{-3}$  for a period of 3.72 day. Comparing the Electret to the RAD7, the Electret is higher than the RAD7, indicating a possible calibration error in one of the systems.

# Appendix E

## Cango Caves Map [Craven, (1992)]



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