MEASUREMENT OF THE EQUILIBRIUM FACTOR BETWEEN RADON AND ITS PROGENY IN THE UNDERGROUND MINING ENVIRONMENT

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A DISSERTATION SUBMITTED IN FULFILMENT/PART FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

TO THE DEPARTMENT OF PHYSICS

IN THE

FACULTY OF AGRICULTURE, SCIENCE AND TECHNOLOGY

AT THE

UNIVERSITY OF NORTH-WEST

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MAFIKENG, SOUTH AFRICA
MARCH, 2000

ACKNOWLEDGEMENTS

I am indebted to my supervisors Mr N D Kgwadi and Professor S H Taole who followed all phases of the project giving enthusiastic support and help.

In preparation for my field work, I was guided by the expertise of Mr Alex Tsela (Council for Nuclear Safety). I am grateful for his support.

I appreciate the willingness of Max Lazerson for the loan of his ML98B Radiation Spectrometer for Radon and his regular visits to give lectures on the operation of the instrument. Professor John Waterson (Schonland, University of Witwatersrand) is appreciated for lending me the scintillation cells used in this study. Danny Ramsuchit and his colleagues (Driefontein Gold Mine) are congratulated for the support they gave me when I was conducting experiments at their mine shafts. I appreciate the assistance of K W Sebolai for skilfully editing and refining the language in the text.

Finally I acknowledge the financial support of the National Research Foundation (NRF) and Council for Nuclear Safety (CNS).

ABSTRACT

In an undisturbed area with little air circulation, the short-lived radon daughters will come into equilibrium with the parent radon, that is, the concentration (measured in Bq / m^3) of radon in air will be equal to the concentration of each of the daughters. However, due to removal processes such as ventilation, plateout of radon daughters on surfaces, and attachment of these daughters on the aerosol, it is unlikely for radon and its daughters to be in equilibrium in the air. This implies that the concentration of radon daughters is usually less than that of radon in a given equilibrium mixture. A quantity that describes the state of disequilibrium between the concentration of radon and that of its daughters in air is called the equilibrium factor or the F factor. The radiological dose associated with a certain level of radon is determined by the daughter mixture in equilibrium with radon. Knowledge about the value of the F factor is therefore important for assessment of radon dose delivered to human species due to inhalation of air contaminated with radon gas, especially in unventilated uranium-bearing underground mines where workers are usually exposed to higher levels of radon.

The aim of this study was to calculate the equilibrium factor on different locations in the underground mining environment. This factor was calculated from the measured concentration of radon and that of its short-lived daughters on different locations underground. The measurements of the concentrations were taken using two types of device, namely, scintillation cells and ML98B Radiation Spectrometer for Radon (ML98B RSR). The former were used to measure the concentration of radon and the latter was used to measure the concentrations of the daughters. On every location, the measurements of the scintillation cells and that of the ML98B RSR were taken

simultaneously to ensure that the F factor was the same for both instruments.

The results obtained indicate that the levels of concentration of radon and that of its short-lived daughters were different on different locations. The measured concentrations were later used to calculate the values of the F factor which also were different on different locations.

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CHAPTER 1 : INTRODUCTION

1.1 GENERAL OVERVIEW OF RADON AND ITS DAUGHTERS

1.1.1 PHYSICAL AND CHEMICAL PROPERTIES OF RADON

Radon is a colourless, odourless and tasteless radioactive gas found in group 8 of the periodic table. At a pressure of one atmosphere (1 atm), radon has a density of 9.73 g /l, a boiling point of -62 °C and a melting point of -71°C (Phillips, 1987 : 37; NCRP[1], 1988 : 15). Chemically, radon is a noble gas and has all the properties of other noble gases of its kind such as helium and neon. It does not readily interact chemically with other elements and is relatively difficult, although not impossible, to trap (Bodansky, 1987 : 6; NCRP, 1988 : 1). Radon is relatively soluble in water, and therefore water has been a significant mechanism through which the gas is transported to some underground working environments and some homes where ground water instead of surface water is used.

1.1.2 ISOTOPES OF RADON

Radon has three naturally occurring isotopes. The first one is radon(^{222}Rn), an isotope historically known as emanation and it originates from the decay series of uranium-238. This isotope has a half-life of 3.82 days. The second one known as

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[1]National Council on Radiation Protection and Measurements

thoron(^{220}Rn) comes from the decay series of thorium-232 and has a half-life of 55.6 seconds. The last one is called actinon (^{219}Rn) and it belongs to the uranium-235 (Actinum) decay products. It has a half-life of 3.96 seconds (Monnin, 1992 : 316). The radioactive decay properties of these isotopes are summarized in table 1.1 below.

Series	Isotope	Historical name	Half-life	Radiation energies and intensities	
				Alpha (MeV)	Gamma
Actinum	^{219}Rn	Actinon (An)	3.96 s	6.819 (81 %) 6.553 (12 %)	0.271 (10 %)
Thorium	^{220}Rn	Thoron (Tn)	55.60 s	6.288 (100 %)	-
Uranium	^{222}Rn	Emanation (Em)	3.82 d	5.490 (100 %)	-

Table 1.1 - *Radioactive decay properties of radon isotopes* (NCRP, 1988 : 14)

Due to their very short half-lives, radon-220(thoron) and radon-219 (actinon) are of little interest in terms of application as indicators or inducers of other phenomena. Accordingly, as pointed out by Bodansky (1987 : 6) and Monnin (1992 : 316), the word radon exclusively refers to radon-222. In the same breath, the word radon (unless otherwise specified) will, in this project, be used to denote ^{222}Rn.

1.1.3 THE DECAY SERIES OF RADON

Radon (^{222}Rn) is the direct product of radium (^{226}Ra), which is in turn a product of the decay of uranium (^{238}U) and its isotopes. Subsequently, radon will decay by alpha particle emission to a polonium isotope (^{218}Po) which by further decay through isotopes of lead (^{214}Pb), bismuth (^{214}Bi) and polonium (^{214}Po) ends with a stable

isotope of lead (^{206} Pb). This decay chain of uranium (^{238}U) is shown in Table 1.2 and in Figure 1.1 below.

Isotopic name	Historical name	Half - life	Radiations and energies (MeV)
U-238	Uranium I	4.47 x 10^9 y	α 4.198 (77 %) 4.149 (23 %)
Th-234	Uranium X_1	24.1 d	β 0.198 (72 %)
Pa-234	Uranium X_2	1.17 min	β 2.29 (98 %)
U-234	Uranium II	244 550 y	α 4.773 (72 %) 4.721 (27 %)
Th-230	Ionium	75 000 y	α 4.688 (76 %) 4.621 (23 %)
Ra-226	Radium	1 600 y	α 4.785 (94 %) 4.602 (6 %)
Rn-222	Radon	3.82 d	α 5.490 (100 %)
Po-218	Radium A	3.11 min	α 6.003 (100 %)
Pb-214	Radium B	26.8 min	β 0.65 (50 %)
			γ 0.295 (19 %) 0.352 (37 %)
Bi-214	Radium C	19.8 min	β up to 3.26 MeV
			γ 0.609 (46 %) 1.120 (15 %)
Po-214	Radium C′	1.6 x 10^{-4} s	α 7.687 (100%)
Pb-210	Radium D	22.3 y	β 0.015 (81 %)
Bi-210	Radium E	5.01 d	β 1.161 (100 %)
Po-210	Radium F	138 d	β 5.297 (100 %)
Pb-206	Radium G	stable	none

Table 1.2 - Decay chain from ^{238}U to ^{206}Pb, with minor branches omitted (Robkin, 1987 : 21)

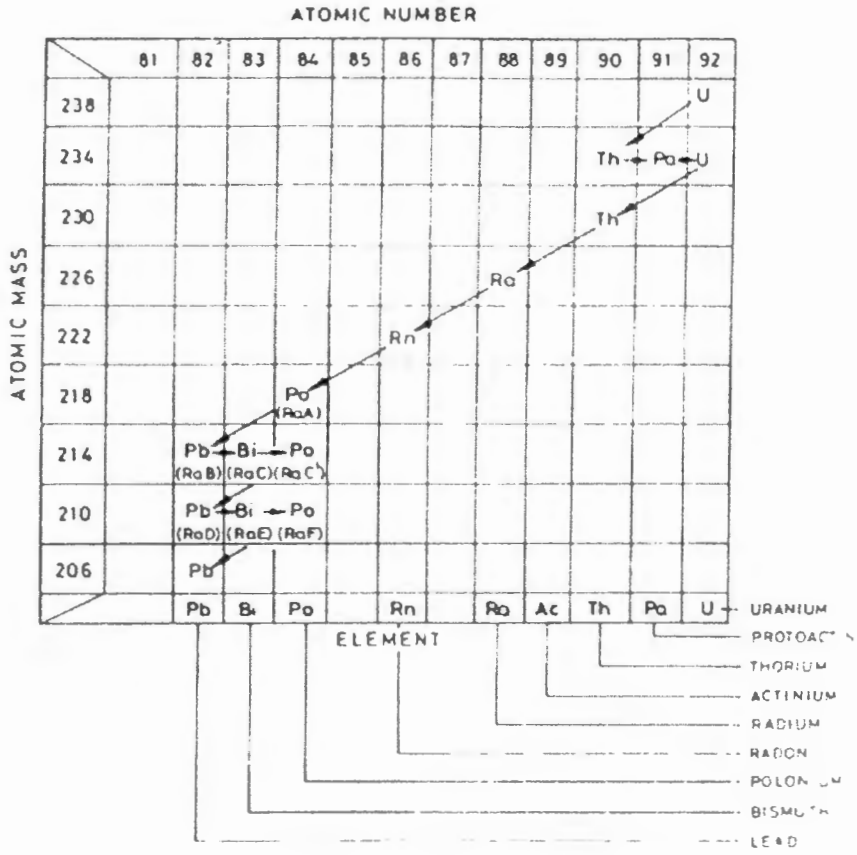

Figure 1.1 : Uranium decay series (Rose,1981 : 742)

1.1.4 RADON DAUGHTERS / PROGENY

1.1.4.1 INTRODUCTION

The term "radon daughters" or "radon progeny " is used to designate the four short-lived nuclei immediately following radon (^{222}Rn) in the decay chain of uranium-238. These are Polonium-218(RaA), Lead-214(RaB), Bismuth-214(RaC) and Polonium-214(RaC'). It should be noted (from Table 1.2 above) that the fifth nucleus after ^{222}Rn , which is ^{210}Pb, has a relatively long half-life of 22 years, and is therefore in a different category together with those radionuclides which come after it (Bodansky, 1987 : 7).

1.1.4.2 PHYSICAL PROPERTIES OF RADON DAUGHTERS

1.1.4.2.1 POLONIUM-218

Polonium-218 is a member of eleven occurring isotopes of Polonium. The most stable isotope of Polonium is Po-209 and it is found in group 6 of the periodic table of elements. Polonium-218 is a metallic radioactive element with a half-life of 3 minutes (Weast, 1975 : 25). It decays by emitting alpha particles. It has a melting point of 254 °C and a boiling point of 962 °C. It is therefore solid at room temperature. Unlike its parent radon, Po-218 can react chemically with other elements.

1.1.4.2.2 LEAD - 214 (Pb-214)

There are several isotopes of lead (Pb) of which Pb-214 is a member. Lead has three stable isotopes, namely Pb-207, Pb-207 and Pb-208. Pb-207 is found in group 4 of the periodic table of elements. Pb-214 is a metallic radioactive element with a half-life of 27 minutes. It decays through emission of alpha particles. Its atomic number is 82 and it has an atomic mass of 214. It has a melting point of 328 °C and a boiling point of 1740 °C (Weast, 1975 : 19). It is solid at room temperature and can react chemically with other elements.

1.1.4.2.3 BISMUTH - 214 (Bi-214)

Bi-214 is a member of several isotopes of Bismuth. The stable isotope of Bismuth is Bi-209 and it is found in group 5 of the periodic table of elements. Bi-214 is a metallic radioactive element with a half-life of 20 minutes. It decays by emitting beta particles. Its atomic number is 83 and it has an atomic mass of 214. It has a melting point of 282 °C and a boiling point of 1610 °C. (Weast, 1975 : 25). It is solid at room temperature and can react chemically with other elements.

1.1.4.3 HEALTH IMPACT OF RADON DAUGHTERS

The short - lived daughter products of radon play a central role in the exposure of human beings to radiation doses. Unlike the parent radon, the daughter products can readily attach themselves to atmospheric aerosol. During inhalation process, these daughters are delivered to the lungs and are eventually deposited on the bronchial tissues of the lungs. During the decay process, the deposited radon daughters will irradiate the epithelial tissues and this may culminate in radiogenic lung cancer in due course (NCRP, 1988 : 16). However, only two of these radon products, ^{218}Po and ^{214}Po, are potential emitters of alpha particles, which are highly effective in damaging the lung tissue (Robkin, 1987 : 20; EPA[2], 1998 : 20). Essentially, it is these alpha emitting radionuclides which are directly associated with radiation-induced lung cancer problem in human beings.

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[2]Environmental Protection Agency

1.2 SOURCES OF RADON

1.2.1 INTRODUCTION

Uranium (^{238}U) is one of the most widely spread of all the elements. It is present in almost all rocks and in the soil in the earth's crust and therefore, in most of the raw materials from which finished products are processed (Robkin*, 1987 : 51). As a result, its daughter, radium (^{226}Ra), is widely spread, particularly in various materials such as soil, water, building materials and other products which are made from mineral products. The immediate source of radon and its short-lived daughters in the atmosphere is therefore radium-226 in the uranium-238 decay series.

The concentration of radon and its short-lived daughters, in the atmosphere, substantially varies with time and space. Comparatively, levels of radon are usually higher in the mines than in both indoor (e.g. houses) and outdoor atmospheres. However, indoor levels of radon may be a factor of 10 or more higher than those in outdoor space, particularly if radon can accumulate in poorly ventilated spaces (NCRP, 1984 : 15 ; Fry, 1976 : 13). Due to these variations, sources of radon gas in indoor, outdoor and mining environment will be separately considered in this project.

1.2.2 RADON IN INDOOR SPACE

An indoor space may be a house, an apartment or any other building with or without ventilation. In indoor space, radon emanates from walls, doors and ceilings which are

constructed of building materials which have traces of uranium, rocks or soil, and is released from materials brought into a room, such as radon-rich water (Robkin*, 1987 : 51).

1.2.2.1 SOIL

Under normal circumstances, the dominant contributor to indoor radon concentration is soil (Robkin*, 1987 : 55; UNSCEAR, 1982 : 156). This may be specially true if there are cracks in the base structure. The emanation of radon from the soil allows it to diffuse directly into buildings from the ground on which a building is based. Unless the building is carefully sealed, radon can find portals of entry through cracks in the foundation, along pipe penetrations or from floor drains (Robkin*, 1987 : 55).

1.2.2.2 GROUND WATER

The contribution to high levels of ^{222}Rn in indoor air by domestic water wells may be a source of interest to indoor airborne ^{222}Rn concentration (Lawrence, 1992 : 171). Radon and radium are soluble in water. When ground water moves through radium-bearing soil and rocks, both radium and radon are dissolved and transported from one place to another with water (Robkin, 1987 : 53). When radon-containing water is used for domestic purposes, the gas can be released into the living space. Although ground water used for domestic purposes may be a significant source of high levels of radon gas in indoor air, Lawrence (1992 : 171) reports that, there are indications that direct ingestion of the gas may be less hazardous to human health than inhalation.

1.2.2.3 BUILDING MATERIALS

All building materials contain radioactivity which is inherent in the natural raw materials of which they are composed (Coolè, 1980 : 12). Materials made from stone, sand, ore byproducts and the like contain uranium and radium and consequently generate radon. Many of these materials such as bricks, wall board or concrete are sufficiently porous to allow the radon gas to escape into indoor air. Table 1.3 summarizes the radium concentration found in various building materials in studies carried out in the United Kingdom, Russia, West Germany, Spain and the United States of America.

Material	United Kingdom	USSR	West Germany	Spain	USA	USA*
Gypsum	22.2		18.5	2.96	-	0.34
Sand, Gravel	-	22.2 - 37	22.2	14.06 - 22.94	-	
Bricks	7.4 - 51.8	18.5 - 55.5	62.9	34.04	7.4 -129.5	0.8 - 1.2
Concrete	-	25.9	18.5	75.48	-	-
Tile	-	-	-	70.3	62.9 -70.3	-
Granite	88.8	111	103.6	77.33	-	

Table 1.3 : Concentrations of Ra-226 in selected building materials from several countries(Bq / kg) (Robkin, 1987 : 52)

** Quoted concentrations are for uranium-238 (not radium-226)*

It can be seen that, except for granite which is relatively homogeneous and whose radium-226 content is high, the materials outlined in table 1.3 above differ in their radium-226 content.

1.2.2.4 NATURAL GAS

Since it is produced from the underground reservoir, natural gas contains radon as well. Radon enters the natural gas in the earth by diffusion from radium deposits (UNSCEAR, 1982 :158). Used in unrented appliances such as kitchen ranges and space heaters, natural gas may be a source of radon in buildings (Coolè, 1980 : 9).

Heavy hydrocarbons such as propane for example, are removed during removal of impurities from natural gas, recovered and distributed under pressure as liquefied petroleum gas (LPG). This process may remove up to 50 % of the radon in natural gas, but a substantial fraction of radon will remain in the LPG which is sold by retailers for use in buildings (Coolè, 1980 : 9). The radon-containing LPG may therefore also serve as a significant source of radon in indoor environments.

1.2.3 SOURCES OF RADON IN OUTDOOR ATMOSPHERE

1.2.3.1 INTRODUCTION

The sources of radon and its short-lived daughters in outdoor environments are soil, ground water, oceans, phosphate residues, uranium mill tailings, coal residues, natural gas, coal combustion, volcanic eruption and geothermal power stations. In outdoor environments, radon is diluted to low concentration in the air and therefore significantly poses less risk than it does indoors.

1.2.3.2 SOIL

The first contributor to the rise levels of outdoor radon concentration is emanation from the soil in top layers of the ground. The overall global average of radon emitted from this soil into the atmosphere is approximately 80 %(Nevissi, 1987 : 42). It is estimated that the average world wide concentration of radon in soil is 25 Bq / kg (UNSCEAR, 1982 : 148). This emanation of radon from the soil is associated with the presence of radium in the ground and its ultimate precursor, uranium.

1.2.3.3 GROUND WATER

The second source of interest is ground water. When in contact with the crustal rock, this water penetrates the pores and voids present in rocks and soil and dissolves radon which emanates from these spaces following the decay of radium-226 (Nevissi, 1987 : 43). Nevissi (1987 : 43) added that, in the air above the ground, radon partial pressures are infinitesimal compared to one atmosphere (1 atm), but sufficiently high radon partial pressures exist in underground rock pores to permit very high concentrations of radon in the water. Subsequently, when this water reaches the earth surface, most of radon is released into the outdoor air.

1.2.3.4 OCEANS

The third important source is the ocean where the concentration of radon and radium is less in the water than it is in soil and rocks. Typical values are about 9 pCi / l (or 0.3

Bq/m^3) [3] (Nevissi, 1987 : 44). Due to this low concentration and solubility of the radon gas in water, a low level concentration of radon is released from the ocean surface water into the atmosphere. Thus, unlike ground water, the contribution to radon concentration of ocean waters to the outdoor environments is minimal.

1.2.3.5 URANIUM MILL TAILINGS

The fourth contributor to the concentration of radon outdoors is the residue (called mill tailings) that remains after uranium has been extracted from uranium ore(Coolè, 1980 : 9). Mill tailings virtually contain almost all the mass of the ore and much of radioactivity. In most cases, the tailings have been brought into more contact with the outside than it was before the ore was mined. A suggestion made by Nevissi (1987 : 47) is that, a substantial long-term health impact from the tailings comes from the escape of radon to the atmosphere and from the leaching of radium into surface water.

1.2.3.6 PHOSPHATE RESIDUES

Fifthly, phosphate mining presents a problem somewhat analogous to uranium tailings. Phosphate ores have relatively high concentrations of uranium and radium, and consequently, high levels of radon concentration are therefore encountered in regions of phosphate mining (Nevissi, 1987 : 46). Typically, ^{226} Ra concentration in a phosphate ore is about 1480 Bq / kg. The use of phosphate products and byproducts

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[3]The units, curie (Ci) and becquerel (Bq) are defined in section 1.3

contribute largely to levels of radon (and its progeny) in outdoor environments. For example, the use of phosphate-based fertilizers results in the redistribution of naturally-occurring radionuclides, principally members of ^{238}U series, in the atmosphere (Coolè, 1980 : 11).

1.2.4 OTHER SOURCES OF OUTDOOR RADON

Other sources of little impact on levels of radon in outdoor environments are volcanic activity and geothermal power stations. On the one hand, volcanic activity as a source of radon in outdoor air has been investigated in countries such a Hawaii and the United States of America. In Hawaii, levels of radon concentration of the order of 50 Bq / m^3 have been reported, whereas the radon release from the eruption of Mount St.Helens (USA) has been estimated to be about 10^{17} Bq of radon in the plume, which corresponds to about 10 % of the total atmospheric inventory (UNSCEAR, 1982 : 148). On the other hand, from a global perspective, geothermal power stations are also a minor source of radon. Concentration of radon in geothermal steam at Wairakei and Broadland in New Zealand is 100 - 400 Bq / kg steam and this results in an annual radon release of 10^{11} to 10^{12} Bq (UNSCEAR, 1982 : 148).

1.2.5 RADON IN MINING ENVIRONMENT

1.2.5.1 INTRODUCTION

As mentioned earlier, the underground mining atmosphere undisputably has higher concentration of radon than indoor and outdoor environments. In mines and other underground buildings, sources of radon are rocks, soil and underground water. In general, mines with higher grades of uranium have corresponding higher levels of radon concentration (UNSCEAR, 1992 : 158). Furthermore, crushed rocks in abandoned parts of a mine are also a significant source of radon in non-uranium mines. Although radon can, due to traces of uranium present in almost all rocks, be produced from any underground mining environment, only four cases of mining environments namely coal mining, uranium mining , phosphate mining and gold mining will be examined in this project.

1.2.5.2 COAL MINING

Coal contains varying concentrations of uranium and its radioactive progeny (Coolè, 1980 : 8). Radon is released into the atmosphere during the exposure of coal seams as well as the breaking up of the coal being mined. In the United States of America, for example, the coal which is mined in the western states contains significantly higher amounts of uranium (0.01 - 0.1 %) than the one mined in central and eastern regions (< 0.01 %) (Coolè, 1980 : 8). In addition, except for the radon gas, which is released into the atmosphere, all other radionuclides from coal

combustion are associated with the discharge of fly ash. This fly ash, as Coolè (1980 : 9) points out, may contain radon progenitors, such as uranium or radium which ultimately decay to become radon.

1.2.5.3 URANIUM MINING

Uranium is extracted from both underground and open cast mines. In the case of the former, radon formed is largely discharged to the atmosphere from ventilation shafts. In the case of the latter, radon disperses in much the same way as it does in the soil. Most of the radon gas produced underground is subject to emanation or diffusion to the atmosphere especially when the rate of ventilation is relatively high (NCRP, 1984 : 17). Therefore, the underground mining releases of radon are not significant as global sources when compared to the tailing piles where many years of production residue is exposed.

1.2.5.4 PHOSPHATE MINING

Phosphate mining and manufacturing industry as sources of radon are somewhat similar to the uranium mining. Phosphate rocks contain naturally occurring quantities of uranium and radium which are redistributed among various products, byproducts and wastes of this industry (Coolè, 1980 :10). Thus, as Coolè (1980:10) reports, the enhancement of natural radon levels occurs during the mining and milling operations, from the use of various phosphate products and by products, and above all, from the use of reclaimed phosphate lands for residential and commercial development.

1.2.5.5 GOLD MINING

Like some of the minerals discussed above, gold-bearing ores may contain varying grades of uranium and its radioactive daughter products. On the one hand, there are gold mines where uranium is produced as a by-product and on the other, gold can be produced as a by-product in uranium mines. It is therefore likely that, in many gold mines, uranium will be produced as a by-product and hence radon as decay product of uranium. The first and the second systematic surveys of radiation levels from radon in the South African gold / uranium mines were conducted during the period 1958 to 1961 and 1968 to 1970 respectively (Haasbroek, 1973 : 49). The surveys revealed that , in general, the gold mines producing uranium as a by-product had higher radiation levels. In general, a positive relationship emerged between radon-daughter concentration and uranium grades. Table 1.4 summarises the average radon-daughter concentrations as determined in mines of different classes of resources.

Class of resource	Uranium grades (%)	Radon-daughter concentrations (Bq/kg)
Gold/Uranium mine	0.02	0.86
Uranium/Gold mine	0.03	3.34
Copper/Uranium mines (open cast)	0.004	-

Table 1.4 : Average radon-daughter concentrations of different South African mines (Haasbroke, 1973 : 50)

In South Africa, most of underground mines are gold mines which contain uranium as a by-product. There is therefore a growing need to assess levels of radiation in South

African gold mines due to the presence of uranium in their ore. The intent of this study was to measure the concentrations of radon and that of its daughters in an underground mine producing uranium as a by product. The measured concentrations were later used to calculate the equilibrium factor between radon and its daughter products.

1.3 TERMINOLOGY FOR SPECIAL QUANTITIES AND UNITS

1.3.1 INTRODUCTION

This section presents special quantities and units that are used to characterise the concentration of radon and its short-lived progeny in air. Among other things, special attention will be given to fundamental units such as becquerels, working levels (WL), gray, rad and sievert in which radiation dose is expressed, whereas quantities of interest are potential alpha energy concentration (PAEC) , equivalent equilibrium concentration (EEC), equilibrium factor, F, or F factor, and attached and unattached fractions of radon daughters.

1.3.2 BECQUEREL

The rate of disintegration of a radioactive isotope is called its activity and is designated the letter A. Radioactive isotopes decay in accordance with the relation

$$A = A_0 e^{-\lambda t} \qquad (1.1)$$

Where A = Activity of the radioactive source at time t

A_0 = Initial activity of the radioactive source

λ = Constant characteristic of the particular radioactive species, and is called the decay constant

The activity of a radioactive source is expressed in becquerel (abbreviated Bq). One becquerel is equal to one disintegration per second (dps). An older unit of activity, which is still in use, is the curie, and is abbreviated as Ci. One curie was originally defined as the number of disintegration per second of one gram of radium.

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Therefore 1mCi = 3.7×10^7 Bq or 37 MBq

1.3.3 RADIATION DOSE

Radiation can interact with matter and the damage caused is correlated with the amount per gram of the energy deposited on the material through which radiation passes. This energy deposition constitutes the physical dose or simply the dose (Robkin, 1987 : 19; Leuschner, 1992 : 45). In the traditional centimeter-gram-seconds (cgs) system, the unit used to measure dose is rad, but in the SI unit system it is measured in gray (Gy). Gray is defined as the deposition of one Joule of energy in one kilogram, while one rad is the deposition of 100 ergs of energy in one gram of material (Robkin, 1987:19). One gray equals one hundred rad.

Apart from the absorbed dose, the biological damage caused can also be determined by the rate at which energy is released on a biological tissue. In this regard, the damage caused is correlated both with the physical dose and the density of ionization that radiation causes in the tissue. Robkin (1987 : 19) refers to the combined effect of physical dose and ionization density as dose equivalent. The unit used to express dose equivalent is called rem in cgs system and sievert (Sv) in the SI system. One Sv equals 100 rem. Equal numbers of rems (or Sv) are intended to imply equal amounts of biological hazards (Robkin, 1987 : 19). These units are summarized in Table 1.5 where the use of "discontinued units" must be avoided and are only given for the purpose of conversion from old publications.

Physical parameter	SI Unit	Abbreviation	Discontinued unit	To convert from discontinued unit to new unit multiply by
Exposure to ionizing radiation (has been phased out)	coulomb per kilogram	C / kg	Roentgen (R)	2.58×10^{-4}
Dose	gray	Gy	rad	0.01
Dose rate	gray per second	Gy / s	rad / s	0.01
Equivalent dose to an organ or effective dose to the whole body	sievert	Sv	rem	0.01
Equivalent dose rate to an organ or effective dose rate to the whole body	sievert per second	Sv / s	rem / s	0.01

Table 1.5 : The units used in measuring the absorbed dose (Leuschner, 1992 : 44)

1.3.4 POTENTIAL ALPHA ENERGY CONCENTRATION

The potential alpha energy of an atom in the decay of radon is the total alpha energy emitted during the decay of this atom to ^{210}Pb which relatively long-lived(ICRP[4], 1993 : 3; UNSCEAR, 1992 : 143). However, the potential alpha energy concentration (PAEC) is the total energy that would be released per unit volume of air as alpha radiation if all the short-lived daughter atoms (RaA to RaC′) decay away (Ogden, 1974 : 25; ICRP,1993 : 3). The traditional unit of PAEC is the working level (WL), but in the SI unit PAEC is measured in J / m^3. One working level is equal to 2.06×10^{-8} J / m^3 of potential alpha energy (Fry, 1976 :16; NCRP,1988 : 17; Ogden, 1974 : 25).

1.3.5 WORKING LEVEL

The concept of working level was introduced to provide a better physical measure of the hazard of radon exposure. As the name suggests, the working level was taken at that time to represent the maximum concentration of airborne short-lived radon daughters to which uranium mine workers could be exposed (Robkin, 1987 : 24; NCRP, 1988 : 17). This unit is not only confined to uranium miners but also to the buildings occupied by the general population as well. Numerically, the working level is any combination of short-lived daughters in one litre of air that will result in emission of 1.3×10^5 MeV of potential alpha energy (NCRP, 1988 : 17; Fry, 1976 : 16).

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[4]International Commission on Radiological Protection

The total exposure of uranium miners is dependent both on the intensity of the exposure and its time duration. Resultantly, the exposure of uranium miners and other miners has been expressed in units of Working Level Month (WLM), which is an exposure rate of one working level for a working month of 170 hours (NCRP, 1988 : 17 ; Robkin, 1987 : 28). Mathematically WLM can be expressed as

$$WLM = WL \frac{(Hours\ Exposed)}{170}$$

The potential alpha energy exposure of workers is often expressed in the WLM, in which case one working level is expressed as the concentration of potential alpha energy associated with the radon in equilibrium with 100 pCi / l (3700 Bq / l).

CHAPTER 2 : THE HEALTH EFFECTS OF INHALED RADON AND ITS PROGENY

2.1 INTRODUCTION

A crucial factor in determining the potential hazard of a radon contaminated atmosphere is the relative amount of radon and each of its short-lived daughters. Continuous inhalation of radon daughters, unattached or attached to the surface of aerosols, dusts and smoke particles, irradiates the cells of the lungs on which they deposit and eventually culminate in lung cancer (Bodansky, 1987 : 10). Today, radon is recognised a factor contributing to the development of lung cancer.

Estimates of the relationship between lung cancer and the magnitude of radon exposure rely primarily on extrapolations from the past experience of miners in uranium and other mines. The observed correlations for miners are translated into a calculated rate of lung cancer increase per unit of radon exposure (Bodansky, 1987 : 10). It is then assumed that this rate (i.e cancer per unit dose) applies not only at high radon exposures typical of most miners but also at low radon exposures typical of most homes. Current findings have proved that the risk of radiation damage, at lower doses, is linearly proportional to the effective dose and that there is no lower threshold level below which the risk falls away (Rolle, 1991 : 1). Against this background, the U.S Environmental Protection Agency (EPA) suggests that, all homes in the U.S be tested for radon and wherever necessary, mitigating measures be implemented to alleviate the levels (EPA,1998 : 2).

The rate of lung cancer induction depends upon the kind, number and location of the radioactive atoms deposited in the lung. These in turn depend upon many factors, including radon concentration in air, the ratio of the concentration of the daughters to that of radon, the extent to which the daughters attach to the dust particles and the size of the particles, the rate of breathing and the deposition of radon daughters in various parts of the lung (Bodansky, 1987 : 10). Given the data on these factors and an adequate model of the lung, it is possible to calculate the radiation dose that provides the impact of radon on health, especially when comparisons are made with doses from other sources of radiation.

2.2 EARLY EXPERIENCE OF RADON INDUCED LUNG CANCER

The first identification of lung cancer in the miners was made in 1879 at Schneerburg (Germany) (Jackson, 1987 : 92; Fry, 1976 : 43). From 1869 to 1877, about 150 miners died of lung cancer. Investigations later proved that these deaths were due to lengthy exposure to high levels of radon in mines. The radon concentrations in the Schneerburg mines were estimated to be 2 900 pCi/l (107.3 Bq /m^3) in one estimate and 15 00 pCi/l (55.5 Bq /m^3) in another (Jackson, 1987 : 93).

Furthermore, it was discovered that, nine uranium miners who died of lung cancer in Colorado (U.S.A) between 1869 and 1877, was because of exposure to radon and its daughters (Jackson, 1987 : 93). The first studies, in which radon was measured for thirty four mines in Colorado showed radon concentration extending as high as 50000 pCi/l

(1850 Bq /m^3). It was subsequently recommended that the concentration be held below a newly adopted working level, equivalent to 100 pCi/l (3700 Bq /m^3) of radon in equilibrium with its daughters. It was further recommended that the permissible dose rate to the lungs of radiation workers be 15rem/year (0.15 Sv / year) (Fry, 1976 :19).

2.3 SYNERGISTIC EFFECTS OF SMOKING

The latest accumulated evidence proved that smoking accelerates the induction of lung cancer. This is supported by the observation that the latent period of induction of cancer appears to be six or seven years later for smokers than for non-smokers (Fry, 1976 : 19). In the U.S, the increase in lung cancer deaths (even from women surpassing breast cancer) has been attributed to cigarette smoking. The American Cancer Society estimates that smoking is responsible for 83% of all lung cancers (EPA, 1998 : 5).

Evidence from some of the epidemiological studies of underground miners, primarily U.S uranium miners, indicates that radon exposure and smoking may have synergistic relationships. Either smoking or radon exposure can independently increase the risk of lung cancer. However, exposure to both greatly enhances the risk (EPA, 1998 : 5). In essence, the use of tobacco enormously multiplies the risk of radon-induced lung cancer .

CHAPTER 3 : SECULAR EQUILIBRIUM AND THE EQUILIBRIUM FACTOR BETWEEN RADON AND ITS DAUGHTERS

3.1 SECULAR EQUILIBRIUM

Consider a system in which radon gas is emanating from radium-226 source into a volume V of air confined to an unventilated space (see Figure 3.1 below). Radon is assumed to be the only source of radioactivity in the space. Accordingly, the radon gas emanating into the air is practically free of decay products, but the activity of these daughter products builds up with time (UNSCEAR, 1982 : 142).

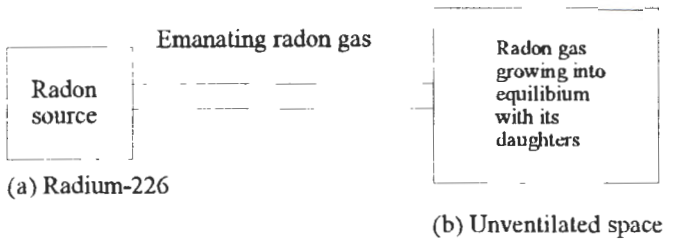

Figure 3.1 : (a) Radium-226 with activity $A_o(t)$ (b) Radon gas with activity A(t) confined to an unventilated space

Since radon is the only source of radioactivity in the space, and if it only looses radioactive particles by radioactive decay, then after a considerable period of time, a state of equilibrium will eventually be reached between radon and its daughter

products in the system. The equilibrium reached, is one in which the activities of the long-lived radon and each of its short-lived daughters are equal. This state of equilibrium, as pointed out by (Robkin, 1987 : 21), is called "secular equilibrium". The approximate time it takes to equilibrate radon with its daughters is given in Table 3.1 below.

Daughter	Half-life	Time to indicate Equilibrium			
		25%	50 %	90 %	99 %
Po-218	3 minutes	1	3	10	20
Pb-214	27 minute	16	31	95	180
Bi-214	20 minute	36	60	135	230
Po-214	<< 1 sec	36	60	135	230

Table 3.1 : Approximate time to equilibrate radon with daughters (in minutes) (Robkin, 1987 :22)

Suppose the space is ventilated with ventilation rate λ_v, then the increase in radon concentration in air follows the expression (UNSCEAR, 1982 : 143) :

$$C_{Rn}(t) = \frac{F_r A_o}{V(1 + \frac{\lambda_v}{\lambda})}(1 - e^{-(\lambda+\lambda_v)t}) \qquad (3.3)$$

where C_{Rn} is the ativity concentration of radon and F_r is the emanating power radon from the radium source

It can be seen from the above equation that the activity concentration of radon decreases as the ventilation rate increases. Figure3.2 shows the relative growth of radon concentration for several values of λ_v.

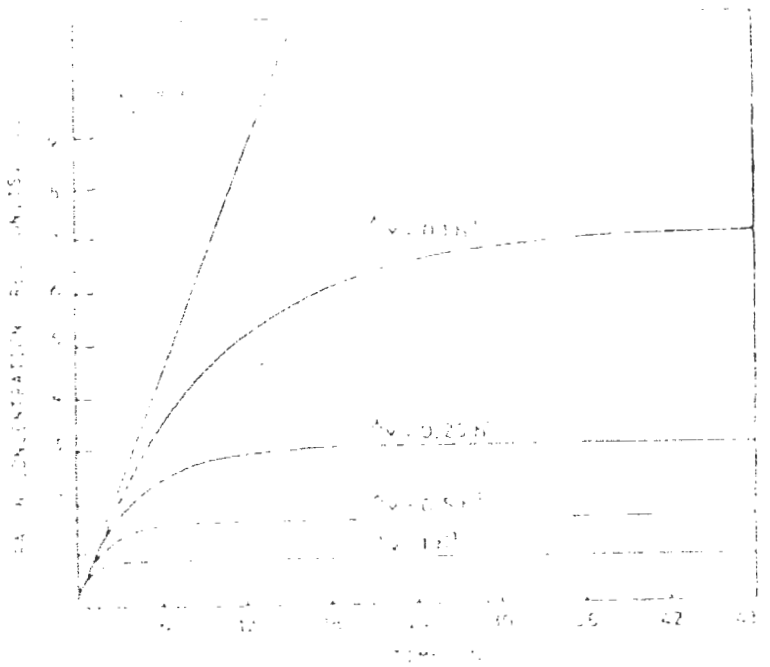

Figure 3.2 : The relative growth of radon concentration in a confined space as a percentage of the equilibrium value for no ventilation versus time for different ventilation rates (USCEAR, 1982 : 144)

Increased ventilation will increase the rate of deposition of radon daughters on the surface and the walls of the confinement. Consequently, the state of secular equilibrium will never be attained. This deposition removes daughters from secular equilibrium and hence reduces the daughter concentrations in the air. A single quantity which describes the extent to which the short-lived daughters have concentrations less than the values in secular equilibrium with radon is called the "equilibrium factor or the F factor" (Robkin, 1987 : 23). The definition of the F factor is given in the following section

3.2 THE EQUILIBRIUM FACTOR

Consider a system consisting of radioactive radon gas whose activity concentration as a function of time in air is denoted by C_{Rn} (see Figure 3.3 below) . The radon daughter activities will build up with time and eventually there will be an equilibrium mixture of radon and its daughters in the system.

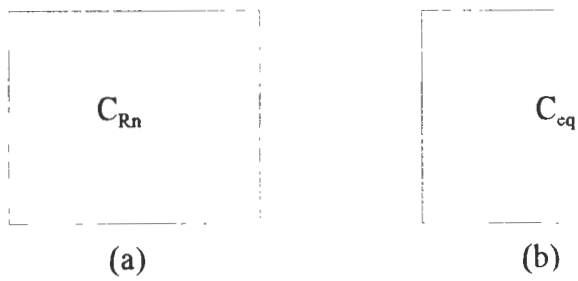

Figure 3.3 : (a) Radon gas of concentration C_{Rn} enclosed in an unventilated space. (b) *Radon in equilibrium with its daughters with the equilibrium concentration C_{eq}*

Let C_{eq} (this quantity is commonly known as the "equivalent equilibrium concentration") denotes the concentration with which radon is in equilibrium with its daughters. The equivalent equilibrium concentration (C_{eq}) is defined as the concentration of radon, in equilibrium with its daughters that would have the same potential alpha energy per unit volume as the existing mixture (Swedjemark, 1983 : 454; NCRP, 1988 :17). Numerically, C_{eq} can be calculated from measured concentrations of each of the daughter products using the equation:

$$C_{eq} = \sum_{j=1}^{4} c_j f_j \qquad (3.5)$$

where c_j is the radon daughter concentration, and f_j is a constant that can be calculated using the expression:

$$f_j = \frac{E_j}{k\lambda_j} \qquad (3.6)$$

where E_j is the potential alpha energy (MeV) for the radon daughter *j* and ***k*** is the ratio of the total potential alpha energy (U) to volume (V) in m^3 . If all concentrations, c, are 1 Bq / m^3, the ratio U / V (or k) = 34565 MeV / m^3. λ_j is the decay or disintegration constant for the radon daughter j. Numerically, the disintegration constants for the radon daughters ^{218} Po, ^{214} Pb, ^{214} Bi and ^{214} Po are given by, $\lambda_1 = 0.003788\ s^{-1}$, $\lambda_2 = 0.000433\ s^{-1}$, $\lambda_3 = 0.000586\ s^{-1}$ and $\lambda_4 = 4234\ s^{-1}$ respectively. Table 3.2 summarizes all the constants used in equation (3.6) :

Isotope	E_j (MeV)	λ_j (s^{-1})	E_j / λ_j (MeV / Bq)	f_j
^{222}Rn (Rn)	13.690	2.093×10^{-6}	-	-
^{218} Po (RaA)	13.690	0.0037877	3614.2	0.1046
^{214} Pb (RaB)	7.687	0.00043106	17832.9	0.5159
^{214}Bi (RaC)	7.687	0.00005864	13117.9	0.3795
^{214} Po (RaC')	7.687	4234.2	0.00182	5.27×10^{-8}

Table 3.2 : The constants used in equation (2.3)

Then, the equilibrium or the F factor is given by the ratio of equivalent equilibrium concentration to radon concentration in the air. Mathematically, this can be expressed as :

$$F = \frac{C_{eq}}{C_{Rn}} \qquad (3.4)$$

It can be seen from the above equation that, if the system is in secular equilibrium, then the F factor is unity. Practically, the state of secular equilibrium is never attained due to environmental factors, such as ventilation and plateout, that remove daughter products from the air, therefore the value of F in air is always less than one.
By neglecting the small value $f_4 = 5.27 \times 10^{-8}$, equations (1.1) and (1.2) give the formula for the equilibrium factor (Planinic, 1989 : 552) :

$$F = \frac{f_1 c_1 + f_2 c_2 + f_3 c_3}{C_{Rn}} \qquad (3.7)$$

where c_1, c_2 and c_3 are the concentrations of Po-218, Pb-214 and Bi-214 respectively. To calculate the value of F using equation (3.7) for a particular environment, it is imperative to measure concurrently the concentration of radon as well as that of its individual daughters due to spatial and temporal variability of radon and air.

3.3 FACTORS AFFECTING THE EQUILIBRIUM FACTOR

The relative abundance of radon and its daughters in air is altered by removal processes such as ventilation, plateout of radon daughters on surfaces and attachment of these daughters on the atmospheric aerosol. Since the F factor is the ratio of the concentrations of the daughters to that of the parent radon, any alteration caused by these process will alter the value of the F factor as well. Accordingly, these removal processes reduce the concentrations of radon daughters in the air (Robkin, 1987 : 22). Since it is these daughters which determine the breathing hazard, it is important to know which factors influence their concentrations in the air.

3.3.1 VENTILATION AND PLATEOUT

Ventilation can increase or decrease the concentrations of radon and that of its daughters (and hence the F factor) in air. On the one hand, if ventilating air is fresh for a given mixture of radon and its daughters in the air, it would dilute radon and its daughters to lower concentrations. On the other hand, if ventilating air is contaminated with radon and its daughters (for example, if houses closer to mine tailings containing traces of uranium are only ventilated by opening doors and windows during the day), it would add to the existing concentrations in the existing mixture of radon and its daughters in the air.

Furthermore, radon daughters can readily plate themselves out on the walls or any available surface (see 3.3.2 below). Therefore, the increased rate of ventilation may accelerate the rate at which the daughters plate out on the surfaces. This plateout of radon daughters removes the daughters from secular equilibrium and ensures that the daughter concentrations are always less than that of radon in the air. Knowledge about how much of the daughters have been removed from secular equilibrium by plating out on the surfaces, gives us a better estimation of the F factor in the air.

3.3.2 ATTACHMENT OF RADON DAUGHTERS TO ATMOSPHERIC AEROSOL

At the moment of decay of Rn-222, Po-218 is formed with two excess electrons. However, the excess electrons are stripped away by recoil of the nucleus and, usually, one or more of the orbital electrons is also lost. This makes Po-218 appear as a singly charged positive ion (NCRP, 1988 : 74). Very rapidly, the charged ion becomes neutralized and begins to grow from the initial atomic dimensions. One growth mechanism is the adsorption of water vapor molecules and trace gases (George and Breslin, 1980 : 1272). In another, the polonium atom also combines with oxygen or other substances such as nitrate or sulfate to become a simple compound. Within a very short time, this molecule plus its accompanying shell of water vapor becomes attached to particles in the ambient aerosol present in the atmosphere. While the attachment process tends to remove these small clusters, they are continually being renewed by decay of the atmospheric radon (NCRP,1988 : 19). The successive daughters of Po-218, which are Pb-214 and Bi-214 behave likewise. Consequently,

these daughters exist as both the unattached and attached species in any environment (NCRP, 1988 : 74). The unattached species are called "unattached fraction" by various authors, and the attached species are called attached fraction. Therefore, the radon daughters in the air occur as a mixture of attached and unattached fractions. Robkin (1987 : 23) defines the attached fraction as those daughters that are adsorbed to atmospheric aerosol. It is important to know the concentration of the attached fraction (and of the unattached fraction as well) because it helps us estimate by how much the daughter concentrations in the air fall below the equilibrium values. The concentration of the attached fraction plays a major role in assessing the radiation damage caused on the lung tissues because it is the attached fraction which deposits on the tissues and irradiates them (NCRP, 1988 : 74). The process of attachment of radon daughters on the aerosols explains why this daughters can readily plateout on walls and surfaces and also why they easily deposit on the respiratory tract.

3.4 STATEMENT OF THE PROBLEM

A given level of radon concentration corresponds to concentrations of airborne radon daughter products in varying states of radioactive equilibrium with the parent radon gas. The equilibrium state of the short-lived daughters is described by the equilibrium factor or the F factor. This factor is determined by various environmental parameters such as ventilation rate, plateout, aerosol concentration and size. The radiological dose associated with a certain level of radon is determined by the daughter mixture in equilibrium with radon. Consequently, a study should be undertaken to quantify the F factor, its variability as well as its dependence on various environmental parameters.

Usually, a default value for the equilibrium factor is assumed, but this will be different in South African mining environments. The equilibrium factor and its variability have been well quantified in countries such as Canada (average F = 0.52), Italy (average F = 0.3) and USA (average F = 0.5) (Farid, 1993 : 60) . However, ventilation conditions of buildings in these countries are expected to be different from those in South Africa due to different climatic conditions. Additionally, the aerosol characteristics in South African atmosphere are different from those of the above mentioned countries. These facts imply that the value of the F factor may be different for South African environments.

The first systematic survey of radiation levels of radon in South African gold mines, producing uranium, suggests that, mines with high uranium grades have the highest levels of concentration of radon and that of its short-lived daughter products (Haasbroek, 1973 : 49-50). Once produced in higher levels, radon daughters can be taken mainly by air movement into neighbouring buildings and areas. Consequently, the mining industry in South Africa is probably the cause of elevated radon levels in certain buildings and areas. It further implies that mine workers, in South African gold mines with high grades of uranium, are exposed to higher doses of radon.

Radon hazards must be assessed in mines and related industries (e.g building materials). In all these investigations, the value of the F factor becomes very important. The focus of this study was to measure the concentrations of radon and that of its daughter products in different locations underground. These concentrations were subsequently used to calculate the equilibrium factor between radon and its

daughters using equation (3.7). The radiological dose associated with a certain level of radon is determined by the daughter mixture equilibrium with radon. Knowledge about the distribution of the F factor is therefore essential to an understanding of radon dosimetry (especially in the underground mines with higher levels of radon and its daughters) and for the development of measuring techniques which will give a good physical correlative of radiological dose for the mine workers who are mostly the victims of ionising radiation. This suggests that, the F factor may be useful for assessment of radon dose in the underground mining environment and this assessment must later be extended to indoor and outdoor exposure, of the general public, to radon.

3.5 MOTIVATION

The health impact of radon has attracted attention of health officers worldwide, and therefore nationwide surveys on radon and its daughters have been carried out in many countries of the world. The equilibrium factor between radon and its daughters had been measured in the indoor, outdoor and underground mining environments in these countries. As an example, Table 3.3 shows the values of the F factor in underground mines for different countries.

Mine	Country	Average F factor
Uranium	USA	0.29 - 0.32
Uranium	France	0.17
Non-uranium	Norway	0.5 - 0.6
Non-uranium	Sweden	0.7
Non-coal	U K	0.3
Non-coal	Poland	0.3

Table 3.3 : The values of the F factor in underground mines for indicated countries (UNSCEAR, 1982 : 164)

In South Africa, not much attention is given to radon problem. This is supported by the fact that only a few industries and academic institutions are conducting research on radon and also that there is less data on concentrations of radon and its daughters in different environments in the country. The surveys on the levels of concentration of radon and its daughters are regularly conducted by different radiation departments in different underground mines in South Africa. However, their data are never published for public perusal, instead these are kept for use only by the mines.

This study was therefore undertaken to measure the concentrations of radon and its daughters in different locations underground and also to calculate the F factor from the measured concentrations. The result obtained will be presented at seminars, workshops and conferences in order to establish public awareness about the health impact of radon and its daughter products. It is also envisaged that, proper arrangement including consultation with different stakeholders will be sought in order to publish the results of this study.

3.6 GENERAL OBJECTIVES

The aim of this project was to calculate the F factor at different locations in the underground mining.

3.7 SPECIFIC OBJECTIVES

1 To measure the concentrations of radon and that of each of its daughters at different locations in the underground mining environment.

2 To calculate the equilibrium factor or the F factor from the measured concentration of radon and that of each of its daughters at different locations in the underground mining environment.

CHAPTER 4 : TECHNIQUES FOR THE DETECTION OF RADON AND ITS DAUGHTER PRODUCTS

4.1 INTRODUCTION

The fundamental quantity in measurement of a radioactive material is the number of atoms decaying per unit time. In general, the activity of radon in a sample is monitored by measuring the number of alpha particles emitted by both radon and its progeny which build up in the sample collected. The instruments and methods of detection of the radon gas and its daughter products will be discussed in this chapter.

4.2 SAMPLING

The field collection of air for the analysis of radon is usually an instantaneous or grab sample in a relatively small vessel holding one litre or less. In this project, grab samples of air containing radon were collected into a scintillation cell for analysis. Due to spatial and temporal variations of radon concentration, a choice must be made on the length of the sampling period, based on the type of information desired and the time available (NCRP, 1987 : 40). The period of sampling can vary from a matter of seconds to a continuous period of up to a year. In the latter case, one obtains full information of exposure. However, instantaneous sampling method has been chosen for the sake of obtaining prompt information.

4.3 CALIBRATION

All radioactivity measurements require a proper calibration of measuring devices. It is seldom possible to make an absolute measurement of the activity but rather it is necessary to obtain a calibration factor for the detection system based on a standard of the same substance (NCRP, 1987 : 41). Improper calibration of a detection system is the most prevalent cause of erroneous activity measurements. It is therefore important to ensure that the detection system is properly calibrated in order to obtain accurate activity measurements. Proper calibration of the detection system depends upon the determination of the background as well as the counting efficiency of each detector in use.

4.4 METHODS OF COLLECTION AND MEASUREMENT

The methods of collection and measurements of radon in air are divided into two categories namely, instantaneous and integrating methods. These methods can further be subdivided into active and passive methods, which either depend upon the direct measurement of Rn-222 only, or measurement of Rn-222 and its short-lived daughter products, or the measurement of short-lived daughter products for the estimation of the radon gas concentration (NCRP, 1987 : 43). In the active method, a pump is used to draw air into a measuring device. The concentration of the radioactive substance is most often determined by counting scintillations caused by alpha particle radiation in zinc sulphide (ZnS) or sodium iodide (NaI) chamber (Leuschner, 1992 : 48). Compared to others, these techniques are relatively sensitive. In passive

methods, radon is allowed to diffuse naturally into the measuring chamber. With these techniques, only time- integrated measurements are possible because of the slow diffusion rate of the radon gas. Although both methods will be described in more details in the following sections, only the instantaneous method will be used in this project.

4.5 INTEGRATING TECHNIQUES FOR MEASUREMENT OF RADON

Most commonly, these techniques are used for long periods of monitoring (usually for several months). Integrating technique instruments record events which occur over a full monitoring period and which constitute an integration of the α-particle decays. Examples of the integrating technique instruments are etched track, thermoluminiscent and charcoal detectors, as well as electrect techniques which are actually ionisation systems.

4.5.1 ETCHED TRACK DETECTORS

This method was originally developed to detect heavy particles in nuclear physics experiments and those coming from cosmic rays, and was subsequently applied to the specific problem of radon detection. The method exploits the fact that a heavy atomic particle, such as an alpha particle, leaves a track of damage when passing through a certain radiation-sensitive plastic. The tracks are later enlarged by chemical etching and counted under a microscope. Nevissi (1987:37) points out that the number of tracks per unit area is proportional to radon concentration. Radon

daughters in the air sample are excluded using a filter membrane which admits radon only.

4.5.2 THERMOLUMINISCENT DETECTORS

In one form, a thermoluminiscent detector (TLD) consists of a battery powered with stabilized air flow. A pump is connected to the detector by a tube with the sampling and detector head (Huber et al, 1978 :142). The detector has a membrane filter with an effective area of 95 mm^2. The TLD has two identical chips, the first is located 3.5 mm above the filter membrane surface and the second is shielded against alpha radiation from the filter membrane by an aluminium sheet of 0.1 - 0.2 mm thickness. The first chip is exposed to alpha and beta particles and gamma rays emitted by radon and its decay products and the second chip is usually used for monitoring the gamma ray background radiation (Nevissi*, 1987 : 37). The principle of detection of the TLD is based on the fact that ionizing radiation can cause atomic or molecular disturbances in some materials such that they subsequently emit light when heated (Nevissi*, 1987 : 37). To measure the activity of radon daughter products, air is drawn through a filter on which the daughters are deposited. After sampling, the thermoluminescence of both chips is measured with the TLD-reader (Huber et al, 1978 :143).

4.5.3 CHARCOAL ADSORPTION DETECTORS

The charcoal adsorption method exploits the fact that, like a number of other gases, radon can be adsorbed on charcoal. In the use of this technique, radon gas accumulates on a bed of charcoal and the gamma-ray activity from the decay of radon daughters is counted (Nevissi, 1987 : 38). The detector is useful for the integration of radon concentrations over a period of a week. Counting is carried out with the sodium iodide (NaI) detection system, set to detect the 295 keV and 352 keV gamma rays from the decays of Pb-214 and the 609 keV gamma rays from the decay of Bi-214 (Nevissi, 1987 : 38).

4.6 INSTANTANEOUS TECHNIQUES FOR MEASUREMENT OF RADON AND ITS DAUGHTER PRODUCTS

Instantaneous techniques are used for short periods of monitoring (usually several hours). When these techniques are used, a grab sample of air is collected in a container and brought back to the laboratory for analysis. The examples of instantaneous technique instruments are scintillation cells, ionisation chamber counters and the ML98B radiation spectrometer for radon. As mentioned in chapter 1, only scintillation cells and the ML98B RSR were used in this study.

4.6.1 INSTANTANEOUS TECHNIQUES FOR MEASUREMENT OF RADON

4.6.1.1 IONISATION CHAMBERS

Ionization chambers are usually brass or steel cylinders with a central collecting anode. In these chambers, an electrical signal is produced without the intermediary of scintillation counting (NCRP, 1988 : 45). They can be used either to count electrical pulses from individual decay events or to measure currents resulting from integrated effect of all decays. The chambers are usually operated at or slightly above atmospheric pressure.

Sealed and flow-through chambers with sensitive volumes of one to several hundred litres have been constructed. With these chambers, the air to be measured is filtered before it enters the sensitive volume to remove atmospheric aerosol including radon daughters (NCRP, 1988 : 45). In sealed chambers, the short-lived daughters formed are allowed to attain radioactive equilibrium with the gas, while in flow-through chambers, only a fraction of the equilibrium daughter concentration is attained.

4.6.1.2 SCINTILLATION CELLS

One of the oldest and simplest technique for the measurement of radon concentration is the one developed by Lucas H L (1977 : 69). In the use of this technique, a radon gas sample is introduced into a counting cell called the scintillation or Lucas cell. The

inside of this cell is coated with silver-activated zinc sulphide (ZnS), except for its one end which is covered with a transparent window used to couple it to a photomultiplier tube (NCRP, 1988 : 48; Nevissi, 1987 : 33). When an alpha particle from the decay of the radon gas strikes the wall of the cell, a flash of light will be emitted from the ZnS coating. This flash of light will then be detected by the photomultiplier tube and be translated into an electrical signal (NCRP, 1988 : 48). Both the scintillation cell and the photomultiplier tube are covered with light tight tubes to prevent unwanted light from entering. The silver-activated ZnS is essentially insensitive to any form of natural background radiation other than alpha particles (NCRP, 1988 : 47). This implies that only the activity which envolves the emission of alpha particles will be detected by the cell. The background rates in typical scintillation cells are low, about, 0.1 to 0.2 count per minute (cpm) and the efficiency of these cells is typically 70 to 80 % (Nevissi, 1987 : 33). In order to evacuate and fill the cell with air samples, a single port is situated on top of the cell.

The scintillation cells used in this project were supplied with RDA-200 system. The system was used for measuring ambient levels of radon in a variety of environments. It operates with a linear response over a wide range and with high sensitivity. Therefore, it can be used to measure levels of radon in normal residential areas as well as high levels associated with uranium mining and milling operations (Scintrex, 1993 : 1).

There were five scintillation cells supplied with the RDA-200 system. The shell of each cell was made of chromate coated aluminum. To avoid the need for the evacuation of the cells, each cell had been outfitted with a second port. The double

port scintillation cells provided a flow-through operation. These scintillation cells were designed to yield the average concentration of radon during measurement periods. Each of the two ports was fitted with a single end shut-off female swagelok connector including quick release couplings. The base of each cell was sealed with a transparent pelxiglass viewing window for optical coupling to the photomultipier tube. A removable black cap had been provided to protect the window and shield the interior of the cell from light. The interior of each cell was coated with a silver-activated ZnS phosphor. The intrinsic scintillation property of the phosphor is that, it is highly sensitive to alpha particles in the 5.5 MeV energy range, and this results from the decay of isotopic radon in its gaseous phase (Scintrex, 1993 : 5). The volume of each cell was 160×10^{-6} m^3. Although these cells had the same volume, it is known that scintillation cells are not all the same because they have nonuniform layers of ZnS and this may result in different efficiencies. Due to this fact, the author deemed it necessary to calibrate each cell separately and obtain the calibration factor for each. Additionally, each cell was given a number to avoid mixing them up during field work.

In addition to the five scintillation cells, the RDA-200 was also supplied with a test cell meant to check the sensitivity of the photomultiplier tube rapidly. The test cell was similar in its dimensions to those scintillation cells described earlier. The only physical difference of the test cell was that the exterior position had a knob rather than a swagelok connector. The cell was essentially doped with a known quantity of a dilute standard solution of radium.

4.6.2 INSTANTANEOUS TECHNIQUES FOR MEASUREMENT OF RADON DAUGHTERS

4.6.2.1 SCINTILLATION CELL TECHNIQUE

Unlike the gaseous parent radon which is inert, the daughter products can readily deposit on dust particles and other surfaces. Therefore, the measurement of daughter concentrations is done by drawing volumes of air through a filter and counting the deposited activity (Nevissi*, 1987 : 34). The scintillation cell technique is based on this approach for the measurement of radon daughters. Air is passed through a filter to collect radon daughter products. The filter containing radon daughters can be covered with a thin sheet of ZnS phosphor and then be placed on a photomultiplier tube for counting. At the start of counting, each Po-218 atom on the filter will give rise to a 6.00 MeV and a 7.69 MeV alpha particles although not all the alphas are recorded by the detector. This is the method originally developed by Kutznet (1956 : 65). The method uses a five minute sampling period at a flow rate of two liters per minute. It allows the sample to decay for forty minutes, and then counts the total number of alpha particles for two minutes (NEA[5], 1985 : 35) . Figure 4.1 shows a typical scintillation cell similar to the one used in this project.

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[5]NEA - Nuclear Energy Agency

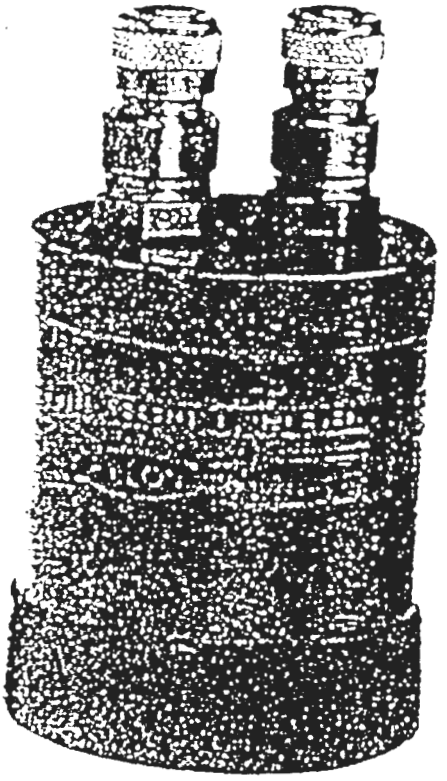

Figure 4.1 scintillation cell (Lenzen, 1997 : 2901)

4.6.2.2 ML98B RADIATION SPECTROMETER FOR RADON

Conventionally, radon daughters are filtered from the air and the activity of only two daughters (Po-218 and Pb-214) is measured. The activity of the third daughter (Bi-214) is determined indirectly by known decay rates. However, the new portable ML98B RSR has been designed to measure all the three daughters directly and simultaneously. The ML98B RSR is an intrinsically safe, portable, continuous flow-through spectrometer of mass 1.2 kg. It has 32 character display , 4 x 4 key board and a pump connector. It also has a matching flow-control pump weighing as little as 0.6 kg and its controlled flow rate is 2 litres per minute (Rolle : 1997 : 2). The

instrument uses 0.8μm polycarbonate filters to trap radon daughters. A silicon detector is incorporated in the instrument to differentiate radon daughters spectrally. There is also a Nickel Cadmium battery which needs to be charged prior to its use in field work. The efficiency of the instrument is 0.33 counts per radon daughter alpha disintegration. Schematic presentation the ML98B RSR is shown in figure 4.2 below.

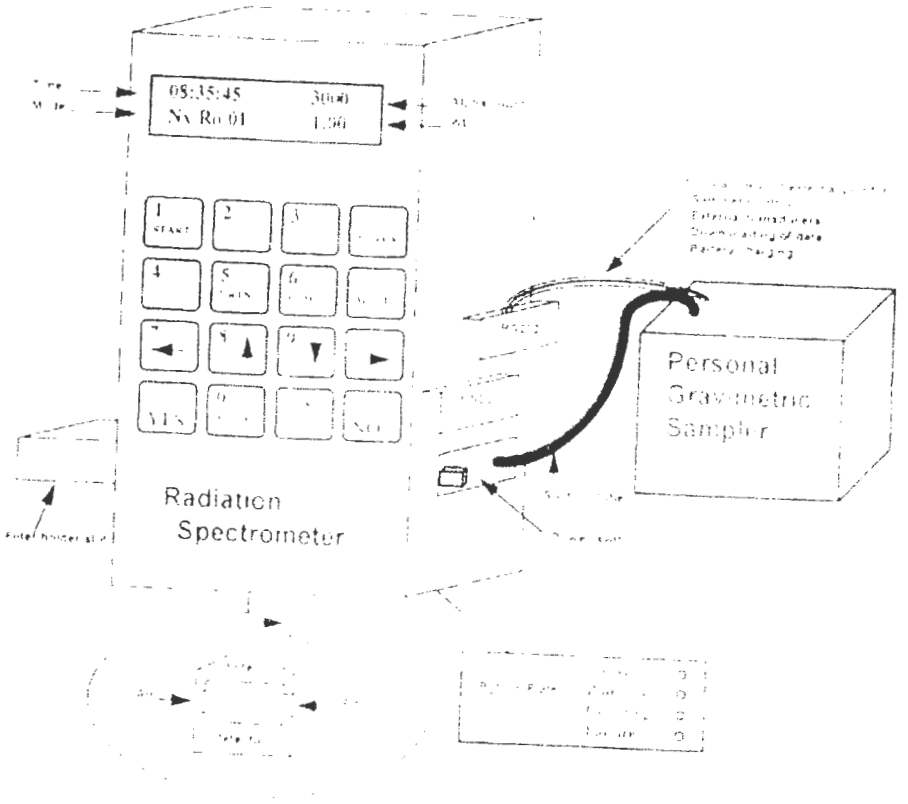

Figure 4.2 : schematic presentation of the ML98B RSR and personal gravimetric sampling assembly (RPPM, 1994 : 1)

The ML98B RSR can be operated in various modes, with or without an operator input, to survey different sections of the chosen site. These modes are Rolle, Batch, Ogden, Tsivoglou, Ogden, continuous and manual. Except for the batch (and

sometimes the manual) , in these modes ,filters are not regularly changed to allow the detection of up to ten times more of the decay of a sample. However, the expected improvement in precision is slightly offset by more convoluted data (Rolle, 1991 : 4). In the batch mode, filters are changed regularly to allow adequate flow-control. For this reason, the batch mode has been selected as the mode of operation for the underground measurements radon daughters. The timing procedure pertaining to the Batch mode includes a one minute background counting, a four minute sampling and a four minute measuring at the end of sampling.

For a rapid inspection of the sensitivity of the ML98B RSR, there are two check sources supplied per instrument. The first one is a primary check source and the second one is a secondary check source. The secondary check source is used on a daily basis before any measurements can be taken to confirm if the instrument is in proper conditions and the primary check source is used monthly. The purpose of using the primary check source is to confirm the integrity of the secondary check source which may be exposed to harsh environments during measurements. Check sources supplied for a particular ML98B RSR and identified as being for that instrument by the check source number, cannot be used in other instruments as they will not give the same alpha readings(RPPM, 1994 : 9). A check source count lasts for five minutes.

The instrument is interfaced to a computer by a program called Radiation Monitoring Operating System (Ramos). This program allows the initialization of the ML98B RSR for the next survey. At the end of sampling the data are downloaded into the database via this program. The ML98B RSR can log about 240 full spectra of 240

channels (Rolle, 1997 : 4). Radon daughters can be differentiated by alpha spectrometry. Each radon daughter can be spectrally noticed by its characteristic alpha-particle energy. Examples of typical underground spectra are given in figures 4.3 below.

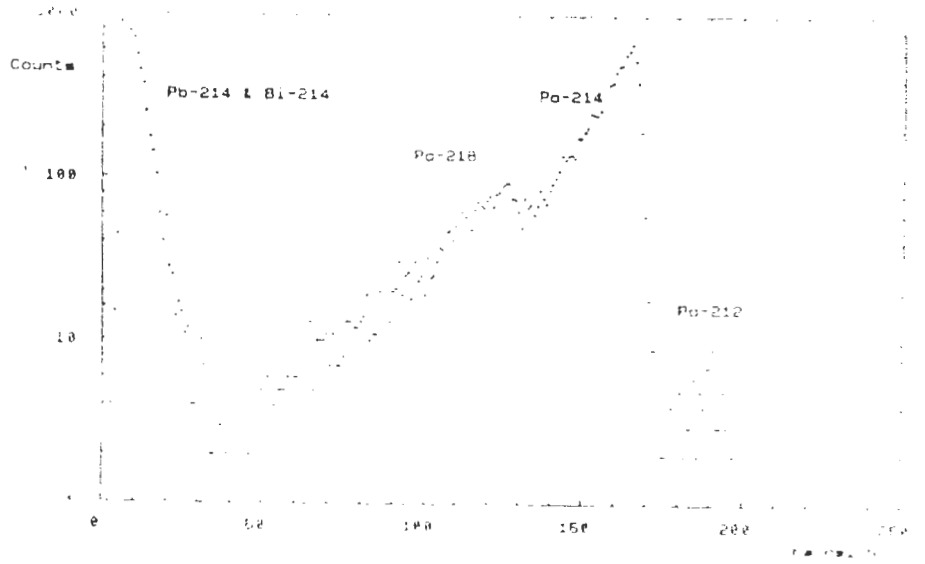

Figure 4.3 : Typical underground radon daughter spectrum obtained during 170-172 minute sampling

Although the ML98B RSR is designed to measure radon daughter products only, the following information is also available from the instrument : the working level, the age of air, potential alpha energy concentration, radon concentration and the F factor. The radon concentration and the F factor are not directly measured by the instrument, it calculates the concentration and the F factor through the use of a standard decay equation incorporated in its microprocessor. Because of this, the results of radon concentrations and the F factor obtained from the ML98B RSR were not considered for analysis in this study. However, the radon concentrations obtained by the scintillation cells and the F factors calculated in this projected were compared to the values calculated by the ML98B RSR.

CHAPTER 5 : EXPERIMENTAL STRATEGIES AND METHODS

5.1 INTRODUCTION

This chapter summarises the experiments that were performed to measure concentration of radon and that of its short-lived daughter. In this chapter, the methods used for the measurement are described. The description of these methods includes, calibration of the four scintillation cells and the ML98B RSR, as well as the actual measurements.

5.2 EMPIRICAL INVESTIGATION

Two techniques were used to measure the concentrations of radon and that of its daughters simultaneously. These are alpha particle scintillation counting with zinc sulphide (ZnS) for the determination of radon concentration and the ML98B Radiation Spectrometer for Radon (ML98B RSR) for the determination of concentrations of radon daughters.

In the alpha particle scintillation counting technique, the radon gas sample is introduced into a scintillation cell coated with ZnS. When an alpha particle strikes the wall of the cell, a flash of light is emitted from the ZnS coating on the wall of the cell (Nevissi, 1987 : 32). The light is amplified by the photomultiplier tube and translated into an electrical signal. The concentration of radon will then be determined from the count rate of pulses.

The ML98B RSR is a rugged, lightweight, portable alpha spectrometer. It has versatile operating modes for measuring concentrations of the individual short-lived radon daughters (RPPM [6], 1994). It is used along with a GILAIR personal sampler to collect air samples. This instrument uses a polycarbonated filters to trap radon daughters from the air samples. The alpha particles emitted by radon progeny on the filter will be measured via a solid state surface barrier detector incorporated in the instrument.

The experiments were conducted at different locations in the underground mining environment. Making use of equation (3.7), the measured concentration of radon and that of its short-lived daughters were later used in calculation of the F factor.

5.3 CALIBRATION OF SCINTILLATION CELLS

Essentially, the purpose of calibration was to determine the relationship between radon concentration and counts per minute. The relationship established will be used to determine the concentration of radon in the air sampled from an underground environment.

The calibration experiment was conducted at the Council of Scientific and Industrial Research (CSIR) through the use of radon chamber. Radon concentration in the chamber was measured with a computer controlled electronic measurement system and

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[6]Radiation Protection Procedure for Mines

ML98B RSR instrument. The calibration of this instrument was done at an internationally accredited chamber at the National Radiological Protection Board (NRPB) in the United Kingdom.

A known concentration of radon from the chamber was sampled into the scintillation cells that were to be calibrated. This concentration was noted as the initial concentration, C_o, of the chamber and its value was 40811 Bq / m^3. This value was the same for all the four cells used. Sampling was achieved by filling one cell with the gas at a time. The sampling was done via a pump that was set at 1.74 liter per minute and it was run for about 3 minutes. There were two tubing connectors to the pump, namely, the inlet and the outlet. These connectors were in turn connected to the inlet and the outlet ports of the scintillation cell onto which the gas was to be sampled. The inlet connector came from the chamber into the pump and the outlet connector connected the pump to the inlet port of the scintillation cell into which the gas was to be sampled. For it to be complete, this tubing was then run from the outlet port of the cell to the outside air (Figure 5.1below) . This type of connection provided a flow-through collection of the radon gas. To prevent radon daughters from entering the cell, an in-line filter was placed on the outlet connector that joined the pump to the cell.

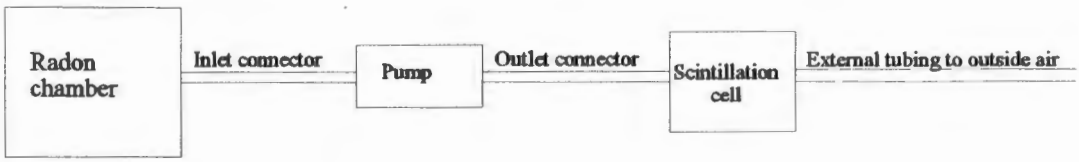
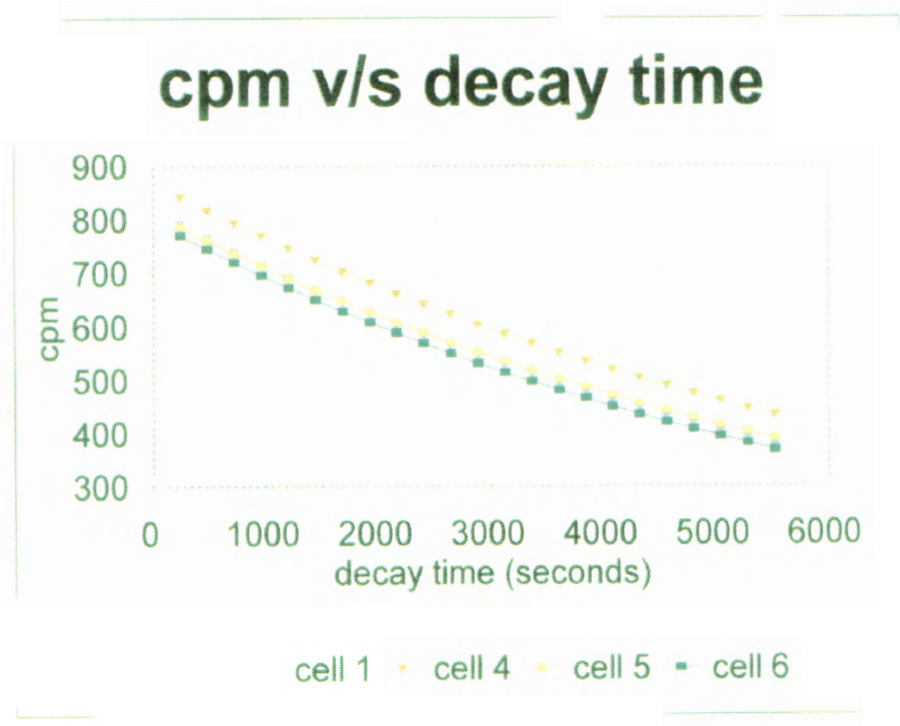


Figure 5.1 : Schematic represantation of the tubing connection during sampling of radon gas from radon chamber at CSIR.

To allow radon daughters to grow into equilibrium, counting of the scintillations was delayed for at least four hours. All the scintillation cells were then counted at intervals of four hours with each counting lasting for fifteen minutes. The counting was done by placing one cell at a time into the photomultiplier tube which was in turn connected to a counter. After introducing the cell into the photomultiplier tube, a sixty seconds delay time was allowed before counting could start. This was intended to eliminate possible accidental light exposure which could influence the counts. The counting process lasted for a period of 3.83 days which is equivalent to the half-life of radon. The counts obtained for each cell were converted into counts per minute(cpm) (see table 5.1 for details) and these were subsequently plotted against the decay time to illustrate the decay rate of the radon gas. The plot of cpm versus decay time in Figure 5.1 below illustrates the exponential decay law for radon gas.



Fiure 5.2 : Exponential curve which illustrates the decay law of the radon gas.

Assuming that the count rate changed according to the radon decay rate because there was no leakage from the cells, the decrease in the activity concentration of radon can be calculated using the following equation

$$C = C_o e^{-\lambda t} \qquad (5.1)$$

Where C = activity concentration of radon

C_o = initial activity concentration of radon

λ = the decay constant of radon

t = the decay time of radon

The decay constant (λ) can be calculated from the following equation

$$\lambda = \frac{0.693}{t_{\frac{1}{2}}} \qquad (5.2)$$

where $t_{\frac{1}{2}}$ is the half-life of radon gas and is equal to 3.83 days ≈ 92 hours.

Substituting for $t_{\frac{1}{2}}$ in equation (5.2), the value of λ is found to be 7.53×10^{-3} per hour. Using C_o = 40811 Bq / m^{-3} and $\lambda = 7.53 \times 10^{-3}$ per hour, it can be shown (using equation (5.1)), that the initial activity calculated on the basis of measurements over the first four hours was 39600 Bq / m^3 . The activity concentration of radon was then calculated at intervals of four hours in succession. The results are shown in Table 5.1 below. The given standard deviation expresses the precision or the reproducibility of the measurement. The general equation to calculate the standard deviation (σ) in nuclear counting statistics is

$$\sigma(N) = \sqrt{\overline{N}} \qquad (5.3)$$

where N is the number of events recorded by a nuclear detector and $\overline{N}$ is the mean value. However, if only one experiment with one outcome N is performed, the best estimate of the standard deviation is

$$\sigma(N) = \sqrt{N} \qquad (5.4)$$

In this study, the two equations (i.e (5.3) and (5.4)) were used to estimate the standard deviation depending on the number of events recorded for a given experiment.

COUNT PER MINUTE				Decay time (Minutes)	Activity Concentration of Radon (Bq / m^3)	Standard Deviation (Bq / m^3)
cell 1	cell 4	cell 5	cell 6			
778	792	771	783	240	39587	± 199
729	787	741	728	480	38362	± 196
680	782	727	689	720	37138	± 193
746	789	730	663	960	36322	± 190
703	709	695	659	1200	35097	± 187
687	729	649	667	1440	34281	± 185
662	746	652	650	1680	33057	± 182
648	699	661	644	1920	32241	± 180
606	689	628	618	2160	31016	± 176
584	642	591	593	2400	30200	± 174
577	658	608	549	2600	29384	± 171
543	601	561	538	2880	28160	± 168
522	599	522	513	3120	27751	± 167
513	585	509	511	3360	26935	± 164
491	566	513	456	3600	26119	± 162
470	529	469	445	3840	25303	± 159
465	496	460	439	4080	24078	± 155
457	495	453	427	4320	23670	± 154
449	494	442	422	4560	22854	± 151
430	472	430	417	4800	22446	± 150
411	452	424	388	5040	21630	± 147
331	439	398	382	5280	21222	± 146
385	427	389	373	5520	20406	± 143

Table 5.1 : *The decay time , the activity concentration of radon and counts per minute for the four scintillation cells.*

The purpose of this calibration was to evaluate the relationship between radon concentration and counts per minute. The results of calibration are plotted in Figure 5.3 below. The plot illustrates the variation of the activity concentration with counts

per minute. Calibration factors of the scintillation cells are given in the following table

SCINTILLATION CELL NUMBER	CALIBRATION FACTOR (cpm per $Bq.m^{-3}$)
1	0.021 ± 0.14
4	0.020 ± 0.14
5	0.020 ± 0.14
6	0.020 ± 0.14

Table 5.2 : Calibration factors for different scintillation cells.

The calibration results indicate that there is a linear relationship between the activity concentration of radon and the cpm, and hence the calibration plots can be extrapolated and used to measure lower activity concentrations. The calibration information was later used to evaluate the radon concentration of the air sampled from different locations in the underground mining environment.

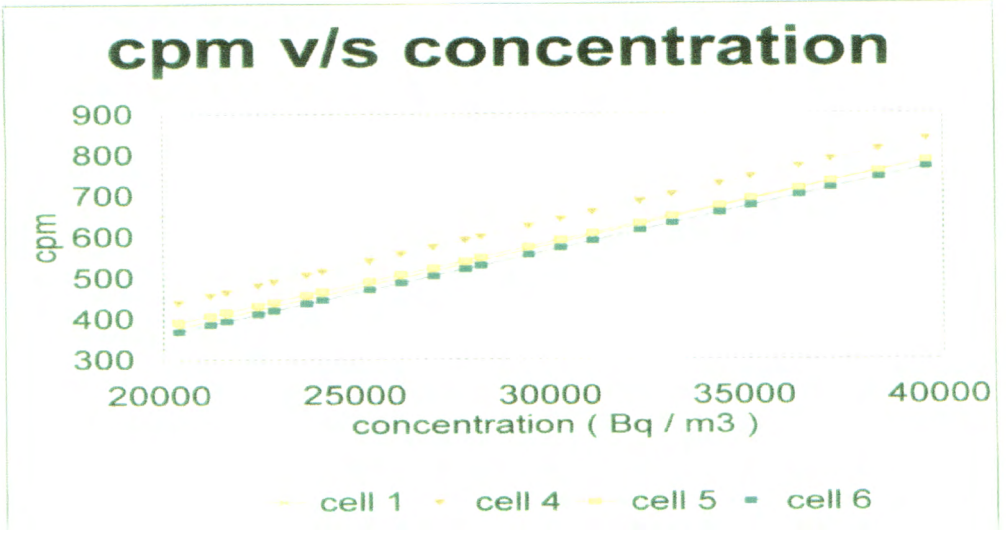


Figure 5. 3: The results of calibration experiments which show the relationship between concentration and cpm

5.4 CALIBRATION OF THE ML98B RADIATION SPECTROMETER FOR RADON

The ML98B RSR radon daughter monitor was calibrated against a Standard ML98 which was in turn calibrated against the internationally recognized reference chamber at the NRPB in the United Kingdom.

The Reference ML98 together with the ML98B instrument to be calibrated were placed in the Radon Chamber at AEC and a minimum of two Batch measurements for each instrument were taken. Each group of measurement was done at the same time to ensure that the chamber environment is the same for each instrument. The spectra for both the instrument were downloaded into the database using the Ramos (Radiation Monitoring Operating System) program. Spectral data of each instrument were then imported into a spreadsheet. The spectra for the measuring phase of each instrument in the group were graphed to check that the F factor was the same for each instrument (See the plots below). From the plots, the difference in count ratios between the 6 MeV and 7.8 MeV alphas is readily apparent, although not so obvious for the betas.

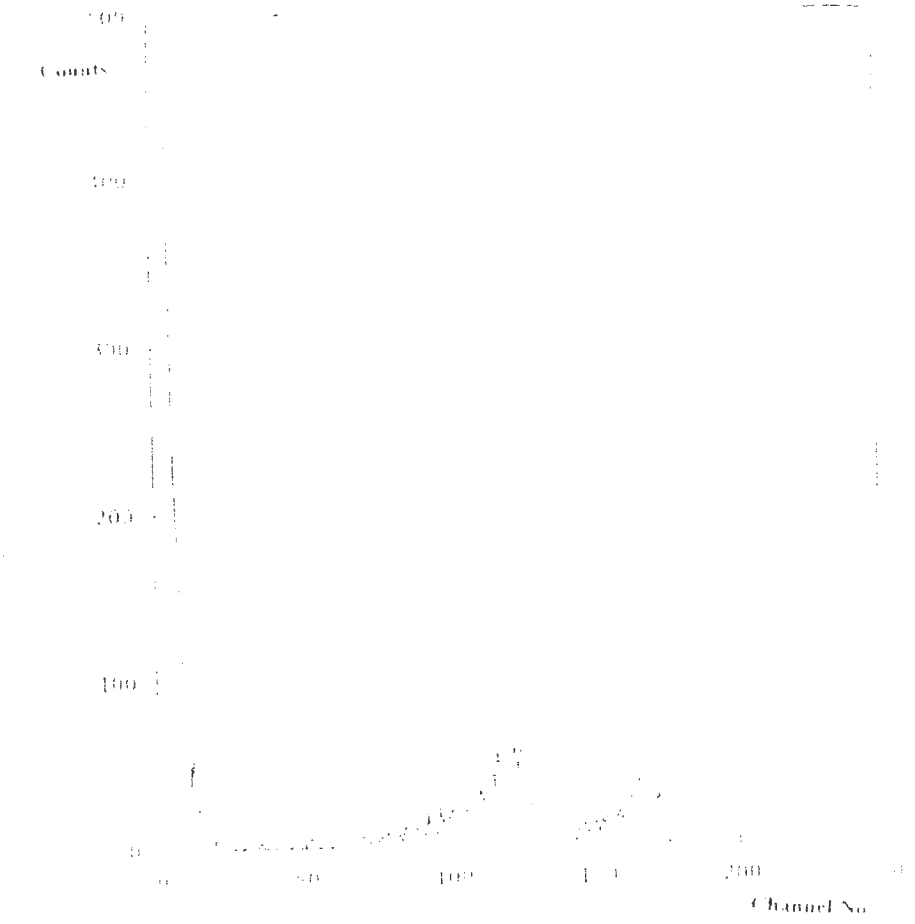


Figure 5.4 : Calibration spectrum - first in ramos print out (F factor = 0.31)

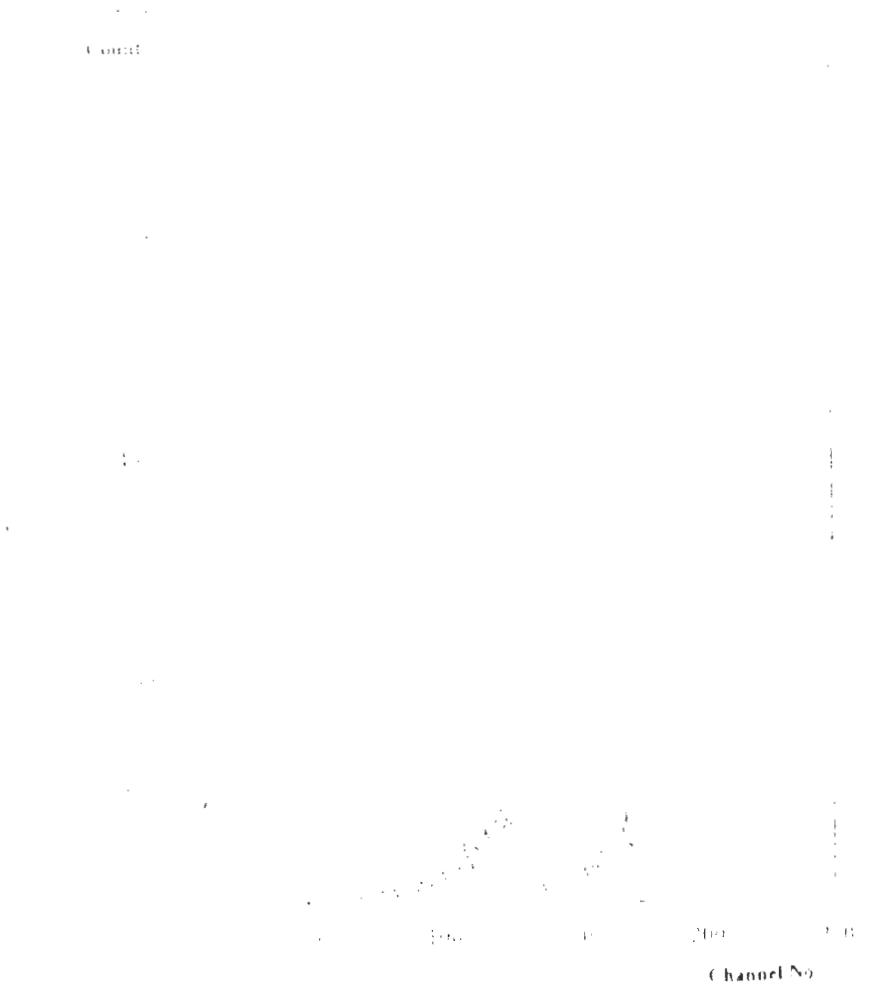


Figure 5.5 : Calibration spectrum - last in ramos print out (F-factor = 0.41)

Counting windows of the instrument being calibrated were selected by inspection based on spectral data and graphs to ensure that the beta lower channel is above the detector and electronic noise, and that the alpha 1 and 2 (i.e alphas from Po-218 and Po214 respectively) channels were adequately separated. The total counts within these channels were summed in the spreadsheet. The standard reference instrument channels are fixed. With the knowledge of the beta and alpha efficiencies of the standard reference instrument in mind, the total Disintegration Per Minute (D.P.M) for each channel of this instrument was then calculated. Since the D.P.M of both instruments is

the same for a group of measurements done simultaneously, the efficiency of the ML98B was then readily calculated. At the time of calibration, the alpha efficiency for energy less than 4 MeV was 28% , and it was 32% for energy greater than 6 MeV. The beta efficiency was 18 %.

5.5 DESCRIPTION OF THE SITE

The site surveyed was shaft number 6 of Driefontein Gold Mine. Measurements of the concentration of radon and that of its short-lived daughters (Po-218, Pb-214 and Bi-241) were taken at levels 18, 20 and 36 whose elevations below ground level were 1803 m, 1919 m and 2469 m respectively. Each level consists of numerous stopes (step like excavations underground meant for the removal of ore that is formed as the ore is mined in successive layers). In this study, only one stope per level was assessed . Those stopes were 18.43, 20.27 and 36.31 for levels 18, 20 and 36 respectively. It should be noted that there is no any specific reason why these stopes were selected for experimental work, except that by the time the experiment was performed, these stopes were being assessed by the radiation department as part of the routine of the mine. In each stope, measurements were taken at three different locations namely, the intake airways (the path through which fresh ventilating air enters the stope), the stope face (the working area where ore is extracted) and the return airways (the path through which contaminated air leaves a stope to complete air circulation through the stope). On the one hand, radon concentration in a particular stope depends on the grade of uranium of the reef provided that uranium and radium are in secular equilibrium in the rocks. On the other hand, concentration of short-lived radon daughters depends on the ventilation of the stope. Consequently, knowledge about uranium grades and the

ventilation control of stopes give us a better understanding of the activity of the radioactive nuclides present in air.

5.5.1 VENTILATION CONTROL OF STOPES

Since stopes are the main production areas in a mine, the majority of the labour force is concentrated there and it is therefore essential that adequate quantities of air are provided therein and controlled to maintain safe and healthy environmental conditions (Thorp, 1981 : 279). Ventilating air is usually delivered to stopes via electric fans and pipes. The air is delivered to the stopes through the intake airways and leaves through return airways (see figure 5.1 below) . Since a higher emanation of radon gas from the rock faces is expected at the faces of stopes , it therefore suggests that the return air has higher concentration of radon than the intake air. Thus, it implies that radon concentration must be highest at the return airway followed by the stope face and the intake airway respectively.

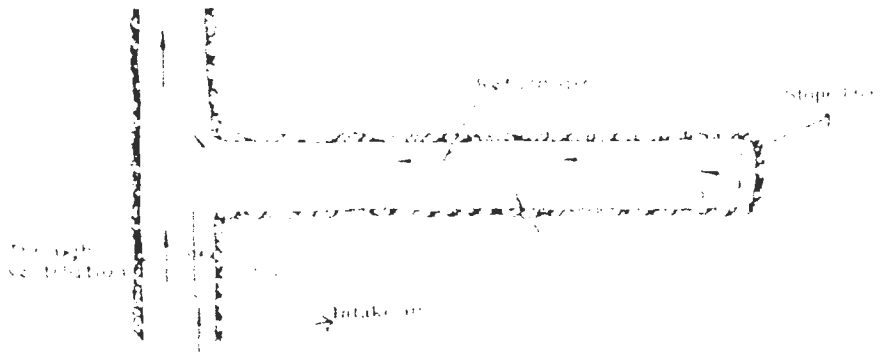


Figure 5.1 : section of a stope showing the path taken by ventilating air through the stope.

The policy of the ventilation department of the Driefontein Gold Mine was to inspect ventilation operations of all shafts after every three months. At the time this experiment was performed (that is, from 22 September 1999 to 27 September 1999), the ventilation operation of shaft number 6 had last been inspected on 01 September 1999. At that time, air volume allocations at the faces of the three stopes under consideration were as indicated in table 5.3 below :

Stope	Air quantity at the stope face (m^3/s)	Speed of air (m/s)
20.27	7.1	0.6
18.43	5.8	0.5
36.31	8.4	0.6

Table 5.3 : The air volumes delivered at the faces of stopes 18.43, 20.27 and 36.31

By law, a minimum amount of air of 0.15 m^3/s per square meter of average cross sectional area at the face must be delivered to the end (Thorp, 1981 : 279). However, this limit is substantially exceeded in most cases, particularly in hot mines. The given values of air quantity in table 5.3 indicate that this limit was also exceeded at the Driefontein Gold Mine.

5.5.2 URANIUM GRADES

Uranium grades vary widely in various groups of reefs. In typical South African Gold Mines, the principal uranium bearing reefs are the Main Reef Group (e.g Carbon Leader reef), the Bird reef, Ventersdorp Contact Reef (VCR), Vaal Reef, Dominion Reef, and others (CNS, 1998, 6). Among others, the higher grade uranium bearing reefs are the Main, Bird and Dominion reefs. Since radon emanation from the rock faces is proportional to the content of uranium in the reef, the higher grade uranium bearing reefs are expected to yield higher levels of radon concentration. Out of the three stopes assessed, 20.27 and 36.31 were Carbon Leader reefs, whereas 18.43 was VCR. Therefore, higher yields of radon concentration were expected at stopes 20.27 and 36.31.

5.6 MEASUREMENTS OF CONCENTRATIONS OF RADON AND THAT OF ITS DAUGHTERS

5.6.1 INTRODUCTION

This section is about the experimental procedure on how the concentration of radon and that of its short-lived daughters were measured. As mentioned in chapter 1, two techniques were used to take measurements. Radon concentration was measured with scintillation cells while radon daughter concentrations were measured with the ML98B RSR. Measurements of the scintillation cells and the ML98B RSR were taken simultaneously to ensure that the F-factor is the same for both instruments.

5.6.2 MEASUREMENTS OF RADON CONCENTRATION : SCINTILLATION CELL TECHNIQUE

The four calibrated scintillation cells were used to collect grab samples of air from the underground. At every level, the samples were collected at the station, the intake airways, the stope face and the return airways. Sampling was done manually via a tube that was connected to the inlet port of the scintillation cell. This tube had a rubber bulb which was used to inflate the cell with air sample. The outlet port of the scintillation cell was kept open during sampling to allow an adequate flow-through operation. This operation was intended to establish equilibrium between the air inside the cell and that outside the cell. Sampling time was about five to ten minutes. The radioactivity of the samples was counted after four hours at the end of sampling in order to allow radon daughters to grow into equilibrium. The counting time was fifteen minutes. The counts obtained were eventually converted into cpm by dividing each by fifteen. Radon concentration corresponding to each cpm was then obtained using the above plotted calibration curve. The results obtained are presented in chapter 6 (tables 6.1 to 6.3).

5.6.3 MEASUREMENTS OF CONCENTRATIONS OF RADON DAUGHTERS : ML98B RSR TECHNIQUE

A check source measurement lasting for five minutes was daily taken to confirm that the instrument was in good conditions. All check source measurements were taken on the surface of the shaft before going underground. The specified range for the secondary check source provided with the ML98B RSR (used in this project) was

0.44 - 0.54 WL. It is recommended that if the check source reading is outside its specified range, the instrument should not be used. However, all measurements taken, in this instance, were within the specified range for the check source provided. This confirmed that the instrument was always in good operational conditions.

The batch mode was selected as the operational mode to take measurements underground . The timing procedure for this mode includes background measurement for one minute, four minutes of sampling and four minutes of counting at the end of decay. Three to five measurements were taken at every location. To allow adequate flow-control, filters were changed regularly, that is, a new filter was used for every measurement. At the end of sampling, the data were downloaded, with the use of the ramos program, into the database for computational purposes. The information obtained from the ramos printout included the working level, the age of air, the concentration of radon daughters (Po-218, Pb-214 and Bi-214), the concentration of radon and the F factor. For the purpose of this study, only the concentration of radon daughters will be considered. However, radon concentration (and the F factor) will be noted for comparison with those obtained by the scintillation cells. The results of the concentration of radon daughters are tabled in the following chapter.

CHAPTER 6 : RESULTS AND DISCUSSION

6.1 INTRODUCTION

This chapter presents the results of the measured concentrations of radon and that of its short-lived daughters obtained from different locations in the underground environment. Due to a simultaneous collection of air samples with the use of scintillation cells and the ML98B RSR at every location, for every set of radon concentration measured with the scintillation cells, there is a corresponding set of the concentration of its short-lived daughters measured with the ML98B RSR. The results of radon concentration and the F factor calculated by the ML98B RSR are also given for comparison to those obtained by the scintillation cells.

6.2 CONCENTRATIONS OF RADON MEASURED WITH SCINTILLATION CELLS

LEVEL 20 -STOPE 20.27

LOCATION	SCINTILLATION CELL NUMBERS	COUNTS PER MINUTE	Rn-222 CONCENTRATION ± SD (Bq / m ^{3})
Station	1	1	48 ± 7
Intake	6	64	3048 ± 55
Stope face	4	72	3429 ± 58
Return	5	88	4400 ± 66

Table 6.1 - Radon concentrations measured with scintillation cells at level 20 - stope 20.27.

LEVEL 18 STOPE 18.43

LOCATION	SCINTILLATION CELL NUMBERS	COUNTS PER MINUTE	Rn-222 CONCENTRATION ± SD (Bq / m ^{3})
Station	6	1	48 ± 7
Intake	1	10	476 ± 22
Stope face	#	#	#
Return	5	11	550 ± 23

Table 6.2 - Radon concentrations measured with scintillation cells at level 18-stope 18.43.

: Entrance to the site was temporarily barricaded.

LEVEL 36 STOPE 36.31

LOCATION	SCINTILLATION CELL NUMBERS	COUNTS PER MINUTE	Rn-222 CONCENTRATION ± SD (Bq / m ^{3})
Station	5	1	48 ± 7
Intake	1	26	1238 ± 35
Stope face	4	28	1333 ± 37
Return	#	#	#

Table 6.3 - Radon concentrations measured with the scintillation cells at level 36 - stope 36.31.

- access to the site was temporarily barricated

6.3 CONCENTRATIONS OF RADON DAUGHTERS MEASURED WITH THE ML98B RSR

LEVEL 20 - STOPE 20.27

LOCATION	AVERAGE CONCENTRATIONS ± SD		
	Po-218 (Bq / m ^{3})	Pb-214 (Bq / m ^{3})	Bi-214 (Bq / m ^{3})
Station	*	*	*
Intake	2218 ± 47	1401 ± 37	774 ± 28
Stope face	3249 ± 57	2431 ± 49	1219 ± 35
Return	3581 ± 60	2498 ± 50	1309 ± 36

Table 6.4 : Concentration of radon daughters at level 20 - stope 20.27

** Values obtained were below the Least Level of Detection (LLD) of the instrument.*

LEVEL 18 -STOPE 18.43

LOCATION	AVERAGE CONCENTRATIONS ± SD		
	Po-218 (Bq / m ^{3})	Pb-214 (Bq /m ^{3})	Bi-214 (Bq/ m ^{3})
Station	*	*	*
Intake	412 ± 20	424 ± 21	167 ± 13
Stope face	#	#	#
Return	523 ± 23	574 ± 24	199 ± 14

Table 6.5 : Concentration of radon daughters at level at level 18- stope 18.43.

LEVEL 36 - STOPE 36.31

LOCATION	AVERAGE CONCENTRATIONS ± SD		
	Po-218 (Bq / m ^{3})	Pb-214 (Bq / m ^{3})	Bi-214 (Bq / m ^{3})
Station	*	*	*
Intake	1181 ± 34	816 ± 29	268 ± 16
Stope face	1329 ± 36	718 ± 27	279 ± 17
Return	#	#	#

Table 6.6 - Radon and its short-lived daughters' concentrations and the F-factor measured with ML-98B RSR at level 36 - stope 36.31.

6.4 CALCULATION OF THE F FACTOR

The above given concentration of radon and the corresponding concentration of the short-lived daughters were used to calculate the F factor using equation (3.7). For example, if we take the values of the concentration of radon and that of its daughters for the intake of stope 20.27 (see table 6.6 below), that is C_{Rn} = 3014 Bq / m ^{3}, C_1 = 2218 Bq / m ^{3}, C_2 = 1401 Bq / m ^{3} and C_3 = 774 Bq / m ^{3}(C_1, C_2 and C_3 are the concentrations of Po-218, Pb-214 and Bi-214 respectively, and C_{Rn} is the concentration of radon), and the constants f_1 = 0.1046, f_2 = 0.5159, f_3 = 0.3795 (see table 3.3),the value of the F factor at the intake airway of stope 20.27 can be calculated as follows

$$F = \frac{(0.1046 \times 2218) + (0.5159 \times 1401) + (0.3795 \times 774)}{3014} = 0.41$$

The F factors calculated in the same manner are presented in tables 6.6, 6.7 and 6.8 below.

LEVEL 20 - STOPE 20.27

LOCATION	AVERAGE CONCENTRATIONS ± SD				F FACTOR
	SCINTILLATION CELLS	ML-98B RSR			
	Rn - 222	Po - 218	Pb - 214	Bi - 214	
Station	48 ± 7	*	*	*	
Intake	3048 ± 55	2218 ± 47	1401 ± 37	774 ± 28	0.41
Stope face	3429 ± 58	3249 ± 57	2431 ± 49	1219 ± 35	0.60
Return	4400 ± 64	3581 ± 60	2498 ± 50	1309 ± 36	0.49

Table 6.6 : The values of the F factor at level 20 - stope 20.27.

LEVEL 18 - STOPE 18.43

LOCATION	AVERAGE CONCENTRATIONS ± SD				F - FACTOR
	SCINTILLATION CELLS	ML-98B RSR			
	Rn - 222	Po - 218	Pb - 214	Bi - 214	
Station	48 ± 7	*	*	*	
Intake	476 ± 22	412 ± 20	424 ± 21	167 ± 13	0.68
Return	550 ± 23	523 ± 23	574 ± 24	199 ± 14	0.78

Table 6.7 : The values of the F factor at level 18 - stope 18.43.

LEVEL 36 - STOPE 36.31

LOCATION	AVERAGE CONCENTRATIONS ± SD				F - FACTOR
	SCINTILLATION CELLS	ML-98B RSR			
	Rn - 222	Po - 218	Pb - 214	Bi - 214	
Station	48 ± 7	*	*	*	
Intake	1238 ± 35	1181 ± 34	816 ± 28	268 ± 16	0.52
Stope face	1333 ± 37	1329 ± 36	718 ± 27	279 ± 17	0.46

Table 6.8 - The values of the F factor at level 36 - stope 36.31

6.5 DISCUSSION

The results indicate that the concentration of radon and its daughters was distinctly higher at stope 20.27 and was followed by stopes 36.31 and 18.43 respectively. This situation is supported by the fact that stopes 20.27 and 36.31 were carbon leaders and as such, had higher grades of uranium and hence higher yields of the radon gas. On the other hand, stope 18.43 was VCR and therefore the yield of the radon gas therein was comparatively low.

Although stopes 20.27 and 36.31 were both carbon leaders, the higher levels of radon concentration and that of its daughters concentration was obtained at stope 20.27. The differences could be attributed to ventilation and porosity of the rock faces. If rocks are less porous, the liberation of radon and daughter products will be decreased. It was therefore likely that the rocks at 20.27 were more porous than those at 36.31. Another possibility is that, uranium grades could be a bit higher at 20.27 than it did at 36.31 regardless of the two stopes being in the same uranium grade category. Table 5.3 shows that the air quantity delivered at stope 36.31 was higher than that delivered at stope 20.27. This suggests that the dilution of the radon gas to lower concentration was faster at stope 36.31 than at stope 20.27

At all station areas of the levels assessed, the radon concentrations measured with the scintillation cells were relatively low. It is not unusual to have low concentrations of radon at the station areas because good quality air is continuously supplied to these areas. Additionally, these areas are farther away from the stope faces where the radon

gas emanates, and therefore the diffusion rate of the emanating gas from rock faces was very low. The ML98B RSR was unable to give reasonable values of the concentrations of radon daughters at the station areas. Instead, values below zero were recorded by the instrument. This indicates that the concentrations of radon daughters were below the least level of detection (LLD) of the instrument.

The general observation pertaining to the three stopes is that, the concentrations of radon and that of its daughters were highest at the return airways, and lower at the stope faces and the intake airways. It is not surprising to have this situation because the return air is mostly contaminated with radioactive nuclides emanating from the rock faces in the stope whereas the intake air is mostly fresh ventilating air delivered to the stope face.

Generally, the values of the equilibrium factor as low as 0.41 and as high as 0.78 were obtained. The results indicate that there is a variation of the F factor from one location to the other. This variation could be due to temporal and spatial variations of radon in air, as well as its age in the air. Ventilation also has a direct impact on the F factor because it removes radon from air before the daughters could be formed and it also encourages plateout of the daughters onto walls and other surfaces. This attachment of radon daughters causes a disequilibrium between radon and its daughters in air. The average F factor for stopes 20.27', 18.43 and 36.31 are 0.47 ± 0.69, 0.73 ± 0.85 and 0.49 ± 0.7 respectively. The high average value of F at stope 18.43 indicates that the concentrations of radon and that of its daughters in the air were closest to equilibrium. Generally, the average value of the F factor for the three stopes is 0.56 ± 0.75 which is

almost equal to that of Norway (see Table 3.3, page 37).

6.6 COMPARISON OF SCINTILLATION CELL WITH ML98B RSR FOR MEASUREMENT OF RADON CONCENTRATION AND THE F FACTOR

In this section, the F factors calculated using equation 3.7 (see example in section 6.3) and the radon concentration measured with the scintillation cells are compared to the F factor and the radon concentration calculated by the standard decay equation incorporated in the ML98B RSR. Although three stopes were assessed, only one stope (i.e 20.27) has been selected for this comparison.

LOCATION	RADON CONCENTRATION		F FACTOR	
	SCINTILLATION CELL	ML98B RSR	SCINTILLTION CELLS	ML98B RSR
Station	48	*	*	*
Intake	3048	2230	0.41	0.55
Stope face	3429	3271	0.61	0.62
Return	4400	3603	0.49	0.59

Table 6.9 : The F factor and the radon concentration given by the ML98B compared to those obtained by the scintillation cells.

The results show that the values of the radon concentration measured with the scintillation cells are higher than those calculated by the ML98B RSR. It should be noted that the scintillation cells measure the alpha particles emitted by the radon gas

directly, whereas the ML98B RSR does not. Rather it calculates radon concentration through the use of the standard decay equation incorporated in its microprocessor. This instrument only measures the concentrations of radon daughters, and hence calculates back the concentration of radon using the standard decay equation. It therefore implies that the radon concentration calculated therefrom is dependent on the concentration of its daughters in air. For the fact that the values obtained by the scintillation cells are higher than those given by the ML98B, it can be concluded that the scintillation cells were more sensitive than the ML98B RSR. This can also be supported by the inability of the ML98B RSR to give reasonable measurements at the stations where the levels of concentration of radon and that of its daughters were too low.

The F factors given by the ML98B RSR are higher than those calculated as explained in section 6.3. The F factor is the ratio of concentration of radon daughters to that of radon, it is therefore mathematically correct to obtain the F factors given by the ML98B RSR higher than those calculated because the concentration of radon measured by the scintillation cells is indisputably higher than that given by the ML98B RSR. This is also attributable to the difference in the LLD's of the two instruments used to take measurements.

CHAPTER 7 : CONCLUSION AND RECOMMENDATIONS

7.1 CONCLUSION

The experiments conducted and the experimental results obtained therefrom indicate that, simultaneous determination of concentrations of radon and that of its daughters is possible. The measured concentrations made the calculation of the F factor possible.

It was discovered that the levels of radon concentration were low at the stations and higher at the stopes. Also in agreement with the circulation of ventilating air through a stope, it was established that the concentrations of radon and that of its daughters were higher at the return airways, and low at the stope faces and the intake airways successively. Good quality air enters the stope face through the intake airways, it then gets contaminated at the stope face where there is higher emanation of radon from the rock faces, and eventually leaves the stope as contaminated air through the return airways. It is therefore reasonable to have higher levels of radon concentration and perhaps that of its daughters at the return airways than it does at the intake airways or the stope faces.

The calculated values of the F factor vary from one place to the other. This variation may be due to various rates of ventilation in various stopes, attachment of radon daughters to aerosol, walls and other surfaces, as well as the age of radon in the air. On the one hand, increased ventilation accelerates the attachment of radon daughters on the aerosols, walls and other surfaces and this increases the degree of disequilibrium

between the concentration of radon and that of its daughters in the air. On the other hand, the longer the radon gas stays in a particular sample of air, the greater will be the chances for the daughters to build up and reach equilibrium with the parent radon. It is therefore reasonable to conclude that increased ventilation decreases the F factor and thus the longer the radon gas stays in the air, the higher will be the F factor.

The results of the measured concentrations prove that the scintillation cells were sensitive enough to record cpm as low as 1 and this made it possible for one to measure radon concentration even in areas like stations where the levels of concentration were very low. However, the ML98B RSR was unable to measure the concentration of radon daughters at the stations because the levels were low. It therefore suffices to conclude that, with the ML98B RSR, convincing results can only be obtain if the concentration of radon daughters in the air is sufficiently high.

Generally, the levels of concentration of radon (and that of its daughters) obtained are very high at all the stopes assessed. The average value of radon concentration for the three stopes is 2068 ± 45 Bq / m^3 . This suggests that stope workers are exposed to higher levels of radon. Although there is no stipulated action level of radiation for mines in South Africa, the new radiation legislation for the mining industry requires that the radiation exposure be controlled to levels As Low As Reasonably Achievable (ALARA principle) (Rolle, 1991 : 2). There is therefore a growing need for all the mines with higher levels of radiation to work hard to keep the levels down in order to create a hygienically safer working environment.

7.2 RECOMMENDATIONS

To determine the distribution of the F factor in South African gold mines, the author recommends that an expanded study be undertaken in future. To obtain accurate values of the F factor, it is recommended that attention be given to the following factors which have an impact on the value of the F factor

a. Ventilation control of stopes

b. Uranium contents on rock faces

c. Geological formation of the underground environments

Furthermore, it is imperative that the quality and the age of air as well as the aerosol distribution be reflected in measurements since the attached and unattached components of radon daughters in the aerosol(and hence the F factor) are influenced by these factors.

In future, more sensitive detectors must be used in order to measure the concentration of radon daughters even if their level of concentration is very low. Alternatively the same ML98 RSR can be used but its LLD must be increased. To measure relatively low radon concentrations it is advisable for one to use large scintillation cells because with these, large samples of air per area of interest can be collected for analysis. As a result, the concentration of radon obtained will serve as the average for that particular area, unlike collecting small volumes with very small cells and taking that as the average for the site under assessment.

It should be noted that, not all the envisaged objectives stipulated in this study have been achieved and to make up for this, it is recommended that a further study be undertaken in which a particular attention shall be given to the following :

1. Factors affecting the F factor, for example, concentration and particle size distribution of aerosol, ventilation and plateout of radon progeny on surface, and attached and unattached fractions of the progeny.
4. Spatial and temporal variation of F
5. The relationship between the F factor and the radon dose delivered to the lungs of human beings.

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