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^{222}Rn and ^{220}Rn ACTIVITY FLUX FROM THE GROUND IN THE VICINITY OF RANGER URANIUM MINE

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SUMMARY

This report is prepared for submission to the Environmental Research Institute of the Supervising Scientist (ERISS) for part fulfillment of the requirement under a QUT-ERISS consultancy agreement.

The report contains up to date details of the work and measurements carried out to study the radon activity flux as a collaborative effort by QUT and ERISS staff. The main body of the text deals with the radon activity flux survey; chapter five describes an initial set up of a radon emanation measurement column and its application to study thoron emanation from a monazite sample; appendix one describes the field sites, appendix two is a site by site description of all measurements, appendix three includes the results of an intercalibration exercise of the equipment.

Extensive research into the production and transport of ^{222}Rn in the environment as been performed, however it is still not possible to determine what set of conditions will lead to elevated levels of ^{222}Rn. Very limited data is available for ^{220}Rn. The majority of studies have been performed in temperate climates with little data obtained in tropical regions. There are large variations in flux between regions. The relative importance of the various parameters on flux also varies between regions. Therefore it is difficult to apply results from previous studies to an unknown region.

A flow through accumulator technique was used to measure ^{222}Rn and ^{220}Rn flux in field and laboratory experiments. An activity flux survey was performed over an area of approximately 10 kilometres square, in the Jabiru region of the Northern Territory. The aim was to determine the association between radon flux and various soil characteristics and meteorological parameters in this tropical region. The average ^{222}Rn and ^{220}Rn flux in the region were

determined to be 64 ± 25 $mBq.m^{-2}.s^{-1}$ and 2.15 ± 0.21 $Bq.m^{-2}.s^{-1}$ respectively. The strongest correlation was found between radon activity flux and radium activity concentration in the soil. Weak non-linear relationships were observed between ^{222}Rn and ^{220}Rn flux and the ratio of the >2mm fraction to the <2mm fraction of a core soil sample (0-20cm deep) and with soil moisture. Strong correlation was found between gamma dose rate at 1m above ground and ^{220}Rn flux but not ^{222}Rn flux and no relationship was observed between ^{222}Rn and ^{220}Rn. Of the meteorological parameters observed weak correlation was observed between ^{222}Rn flux and air temperature. No significant effect was observed due to wind speed, barometric pressure, soil temperature or air soil temperature difference, and no significant correlation was found between ^{222}Rn flux and any of the meteorological parameters.

A study of the diurnal variations in flux was also performed. Significant diurnal variations were observed in both ^{222}Rn and ^{220}Rn flux. ^{222}Rn flux was lower through the middle of the day while ^{220}Rn flux was elevated at this time. No correlation was found between ^{222}Rn and ^{220}Rn flux, suggesting that different factors are dominating variations in these parameters.

A laboratory study was undertaken, into the effect of sample thickness and moisture on ^{220}Rn flux from a monazite sample. Flux increased rapidly with thickness to approximately 5cm after which no increase was observed. Soil Moisture had a large effect on flux, causing an increase in flux for water content less than approximately 6% by weight. This was followed by a dramatic decrease with little flux observed for water content over 10%.

A large part of this report constitutes the thesis submitted by Rebecca Todd for partial fulfillment of the requirements of the degree of Master of Applied Science (Medical Physics) at the Queensland University of Technology.

ACKNOWLEDGMENT

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CHAPTER 1. GENERAL INTRODUCTION

1.1 RADON IN THE ENVIRONMENT

Radon is a radioactive noble gas. There are three naturally occurring isotopes; ^{219}Rn, ^{220}Rn, and ^{222}Rn which are part of the actinium (^{235}U), thorium (^{232}Th), and uranium (^{238}U) primordial series. ^{219}Rn (actinon) is least significant due to it's short half-life and the limited abundance of ^{235}U which constitutes only 0.7% of natural uranium. The uranium and thorium decay series are illustrated in Figure1.1. ^{238}U and ^{232}Th are equally abundant in nature however, ^{222}Rn (radon) is generally considered to be a greater health risk than ^{220}Rn (thoron) due to its longer half life. In areas of elevated ^{220}Rn the dose due to the inhalation of its daughter ^{212}Pb may be significant. Some confusion may arise over the use of radon as it may refer to the element or the specific isotope ^{222}Rn. For the purpose of this paper the term radon will only be used when discussing the element while ^{222}Rn and ^{220}Rn will be used when referring to the specific isotopes.

Of primary concern are the possible health effects due to the dose to the lungs upon inhalation of radon's daughter products. Progeny concentrations in the atmosphere are determined primarily by atmospheric radon concentrations. In turn the concentration of atmospheric radon depends on the radon activity flux and dispersion of radon in the atmosphere. Radon's progeny are all heavy metals and are chemically reactive therefore their migration from soil to the atmosphere is insignificant.

Radon exposure is the single most significant source of natural radiation. The worldwide average annual effective dose due to the inhalation of radon progeny is estimated to be 1.3 mSv. The total average annual dose from all

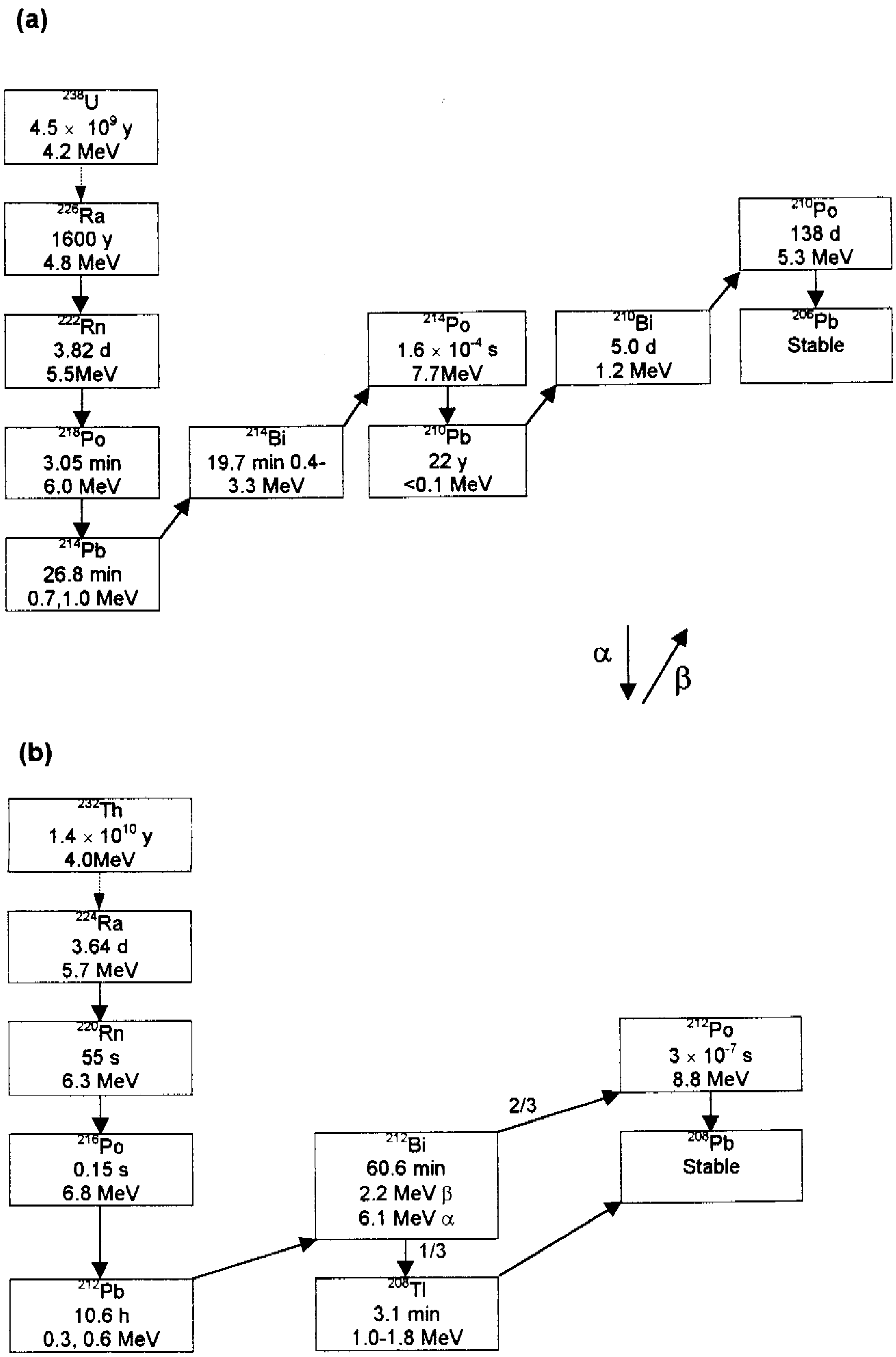


Figure 1.1 (a) Uranium and (b) Thorium Primordial Decay Series. For each isotope the half life and energy of the principal decay mode are shown.

natural sources is 2.4 mSv (UNSCEAR, 1993). Due to the large populations of China and India the results for these countries have a large influence on the world wide annual effective dose (UNSCEAR, 1993). In Australia the dose from radon progeny is one of the most important natural sources, along with terrestrial gamma radiation and cosmic radiation.

NCRP's report no.78 (1984) lists the major sources of global atmospheric radon. At least 80% of atmospheric radon originates from exhalation from soil and rock formations. The other major source is radon dissolved in groundwater, however the contribution to human exposure is generally small due to the low dose following ingestion as opposed to inhalation. Other minor sources include: emanation from oceans, phosphate residues, uranium mill tailings, coal residues, and natural gas. While, on a global scale, soil is clearly the most significant source of atmospheric radon, the relative significance of each source is site dependent.

1.2 PROPERTIES OF RADON AND IT'S PROGENY

Details of the properties of radon contained in the Handbook of Chemical Physics (1983) are summarised below. At room temperature radon is a colourless gas. As it is a noble gas it is essentially inert. It occupies the last place in the zero group of the periodic table and is the heaviest known gas. It has a boiling point of -61.8 °C, melting point of 71°C and a density in gaseous form of 9.73 g/l. It is readily soluble in water (230 $cm^3.kg^{-1}$ at 20°), and some organic compounds (eg toluene). Radon is readily absorbed onto charcoal, a property that is often used in radon concentration measurements. The principal radiation energies and intensities of the three isotopes are contained in Table 1.1. Radon progeny are all heavy metals, including a series of Bi, Po and Pb isotopes and finishing with a stable isotope of lead.

Upon the decay of atmospheric radon the progeny may, attach to aerosols or surfaces, or remain unattached.

Table 1.1 Properties of the Primordial Series Radon Isotopes. (NCRP, 1988)

Isotope	Half Life	Principal Radiation Energies and Intensities			
		Alpha		Gamma	
		MeV	%	MeV	%
^{219}Rn	3.96 s	6.819	81	0.271	10
		6.553	12		
^{220}Rn	55.60 s	6.288	100		
^{222}Rn	3.824 d	5.490	100		

1.3 RADON EMANATION AND TRANSPORT FROM SOIL GAS TO AIR

The movement of radon from the soil to the atmosphere consists of two stages, emanation and transport from the soil gas to the atmosphere. Soil can be thought of as a porous network of soil grains or particles. The isotopes preceding radon in the primordial series' are solids and migration from the soil grains to the pore space is generally negligible. Radon emanates from the soil grains into the pore space primarily by recoil upon the decay of its parent radium. This process is illustrated in Figure 1.2. The typical recoil range in minerals is of the order of 0.03 μm for ^{220}Rn atoms and 0.02-0.07 μm for ^{222}Rn (Tanner, 1980). Diffusion also occurs however the diffusion length in solids is in the range 10^{-7} to 10^{-26} μm (Nazaroff, 1992) making this mechanism of migration from soil particles negligible. The fraction of radon, which emanates into the pore space is termed the emanating fraction or emanation coefficient. Experimental results indicate emanating fractions in soil are in the range 0.05-0.7, which is considerably higher than expected from theoretical models (Nazaroff, 1992). This discrepancy has been explained in two ways. Firstly that the radium is distributed primarily on the surface of the grain (Morowska, 1993; Nazaroff, 1992). Secondly chemical and predominantly radiation damage due to previous decays facilitate the escape of radon (Nazaroff, 1992).

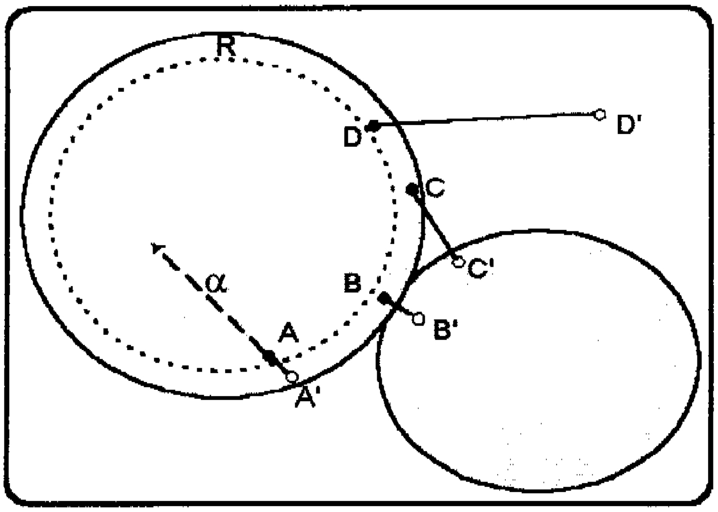


Figure 1.2 Emanation of Radon From Soil Grains
The above diagram is a schematic only and is not drawn to scale. Two soil grains surrounded by air are shown. They are depicted as circles to simplify the diagram. Radium atoms decay producing an alpha particle and a radon atom. The recoil range, R, of the radon atoms is shown. When inside this recoil range radon particles may emanate from the soil grain. The recoil range is air is considerably larger than in the soil grain.

Upon emanation the radon may : lodge in the pore space (D), be embedded in the adjacent grain leaving a track of damage (B or C), or remain in the original grain (A). Moisture has a large effect on the emanation coefficient as the small recoil range of radon in water increases the probability that the radon will lodge in the pore space.

Once in the pore space the isotopes migrate by forced advection and diffusion. Forced advection is a pressure driven flow of the soil gas, and is described by Fick's law. Diffusion, described by Darcy's law, is the flow of a component of the soil gas due to a concentration gradient. It is thought that on a long term basis diffusion is the dominant transport mechanism (Schery 1984). However this may not be true in the immediate vicinity of buildings due to sustained pressure differences induced by the buildings geometry and operation; and the blocking of molecular diffuison by the buildings structure (Nazeroff, 1992).

There are a number of similar equations quoted which describe the total transport process. One such equation, quoted by Schery (1984) is:

$$\frac{\partial C}{\partial t} = \frac{1}{\varepsilon}\frac{\partial}{\partial z}\left(D\frac{\partial C}{\partial z}\right) - \frac{1}{\varepsilon}\frac{\partial}{\partial z}(\upsilon C) - \lambda C + \varphi$$

Where: C= interstitial radon concentration in soil (atoms.m^{-3})

J= flux density (atoms.$m^{-2}.s^{-1}$)

ν= volume interstitial fluid flowing per unit area per unit time ($m.s^{-1}$)

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

ε= porosity (dimensionless)

λ= radon decay constant (s^{-1})

φ= source term (atoms.$m^{-3}.s^{-1}$)

The parameter, activity flux, is used to describe the rate which radon is emitted from the ground. Activity flux is the activity per unit area per unit time. The units that are generally used are $mBq.m^{-2}.s^{-1}$. Although concentrations of ^{238}U and ^{232}Th in the ground are comparable, ^{220}Rn activity flux is generally much greater than ^{222}Rn flux. The difference in flux is due to the difference in the half lives of the two isotopes. This is illustrated below.

Activity Flux = Activity /Area /Time

= λN /Area /Time

$$\lambda_{Rn\text{-}222} = 1.26 \times 10^{-4}\ s^{-1}$$

$$\lambda_{Rn\text{-}220} = 1.25 \times 10^{-2}\ s^{-1}$$

1.4 PROJECT JUSTIFICATION AND AIM

Extensive research into the production and transport of ^{222}Rn in the environment has been performed, covering the effects of radium distribution in soil grains, and the effect of meteorological parameters on flux, through to transport of radon and it's progeny in the atmosphere. However many of the studies present conflicting results and it is not yet possible to predict accurately what conditions will cause elevated ^{222}Rn concentrations. Very limited data is available for ^{220}Rn. For both isotopes the majority of studies have been performed in temperate climates. Details on radon flux from Australian soils and in particular tropical regions are sparse.

There is a large variety of factors which effect radon flux. As a result there a large variations in flux between regions. The relative importance of the various parameters is also site dependent, hence the conflicting reports from different studies. The relative importance of the various effects also depends on the size of the region and the time frame of interest. For example, barometric pressure may dominate variations in flux with time at one site, however on a regional scale it may not be significant in determining flux.

There are a number of points which are generally true. In general higher radium levels lead to higher flux, although some believe it is the emanating fraction not the radium content which is most important (Schery, 1989). Moisture content tends to increase flux to a maximum due to an increase in the emanation coefficient and then decrease with the decreasing diffusion length until no flux is observed (Schery 1984, Strong 1982, Ball 1991). Higher soil permeability and porosity increase emanation while soil density has no effect (Schery 1984 and 1989). The effect of other parameters such as; soil and air temperature, atmospheric pressure, wind, vegetation and humidity are not as clear.

Very few studies have been performed in tropical regions. It cannot be assumed that results from studies in temperate climates can be transferred to tropical climates. Australia's major uranium deposits are located in the regions of Jabiru (Northern Territory) and Roxby Downs (South Australia). It is therefore important to examine the transport of radon in these different climates.

Limited data is available for ^{220}Rn as it is generally not a domestic problem. However due to Australia's mineral sands industry there may be sites where ^{220}Rn is important.

The primary aim of this project was to examine the effects of various meteorological parameters and soil characteristics on ^{222}Rn and ^{220}Rn flux from the ground, in particular in tropical northern Australia. Analysis of the association between activity flux and: radium activity concentration, soil grain size, moisture content, atmospheric pressure, soil and air temperature and other relevant parameters was performed. This was achieved through an activity flux survey of the region surrounding Jabiru in the Northern Territory. A preliminary study into ^{220}Rn flux from a monazite sample was also performed.

1.5 PROJECT OUTLINE

This report consists of four components. Chapter 2 contains a description of the working principles behind and the specific design of the emanometer used to obtain flux measurements.

Chapter 3 contains a description of the ^{222}Rn and ^{220}Rn activity flux survey conducted in the Jabiru and Jabiru East Regions of the Northern Territory. It includes the experimental method, and the results of the survey.

An examination of the diurnal variations in ^{222}Rn and ^{220}Rn flux along with various meteorological parameters at a number sites is presented in Chapter 4.

Finally Chapter 5 details laboratory experiments performed to provide insight into ^{220}Rn exhalation.

CHAPTER 2. MEASUREMENT OF RADON FLUX

2.1 METHODS OF RADON MEASUREMENT

Due to it's unique properties there are many techniques which may be used to determine radon concentration. These techniques are all based on its radioactive properties. Ionisation chambers have low detection limits however they are not commonly used as they are costly and not practical for field work. Scintillation cells (typically zinc sulphide) may be used as closed or flow through types and provide either integrated or partially integrated results. They are commonly used as they are; rugged, versatile, sensitive, reliable, relatively low cost and simplistic (IAEA, 1992).

The adsorption of radon onto charcoal was first noticed by Rutherford in 1906 (Harley, 1992). Measurement of radon concentration with activated charcoal uses preweighed amounts of charcoal contained in canisters, which are exposed to the radon source for a few hours to days. After exposure they are sealed and later analysed by gamma spectroscopy. They are simple, flexible, rugged and low cost (IAEA,1992). There are practical problems such as desorption and decay which need to be considered when using this technique (Harley, 1992).

There are a number of less commonly used techniques. Nuclear track detectors may be used to measure radon by placing them in containers with a diffusion barrier to exclude solid decay products (Harley, 1992). They provide a passive, fully integrated result, however they are not suitable for flux measurements (IAEA, 1992). Solid state surface barrier detectors are suited to flux measurements however they are expensive and require high levels of care and maintenance (IAEA, 1992). Thermo luminescent detectors and electrets have also been used.

There are three methods commonly used to determine ^{222}Rn and ^{220}Rn flux from the soil: accumulation, flow-through, and adsorption. The accumulation technique uses a container placed over the test surface. The radon concentration inside the container at one time or at several specific times is used to determine the rate of radon accumulation. The concentration is measured using one of the instantaneous detectors mentioned above. NCRP (1988) lists a number of requirements which must be satisfied to obtain accurate results : the accumulation time must be short compared to radon's half life, the concentration inside the container must be less than the soil gas to prevent back diffusion, the measuring device should not significantly affect the exhalation, and good seal must be sustained around the edge of the container.

The flow through method is based on the same principals as the accumulation method however air in the container is continually replaced. The radon concentration in air drawn from the container is measured using a scintillation detector or other semi-integrating device (IAEA, 1992). The concentration of radon is proportional to the flux rate and the surface area (IAEA, 1992). This system reduces the build-up of radon and therefore has less effect on the concentration gradient than the accumulator technique. The flow rate must be high enough to prevent build up but low enough to ensure that the conditions under the container resemble natural conditions (IAEA, 1992).

Radon is readily adsorbed onto certain materials, for example activated charcoal. In the adsorption method a canister of this material is exposed for a known amount of time (typically 1-3 days). They are then sealed and analysed using gamma spectroscopy (IAEA, 1992). This technique is less sensitive than the other techniques to due the smaller sampling area. However it can be left to obtain and integrated value over a period of time. The flux is determined using the radon activity collected, surface area exposed, time of exposure and a correction for radon decay (IAEA, 1992).

NCRP's publication "Measurement of Radon and Radon Daughter in Air" (1998) describes some less commonly used techniques. The vertical profile method is based on the principal that the total amount of radon in a vertical column of fixed area represents the radon that has exhaled from the same area of soil. It is a large scale, costly technique requiring aircraft or balloons for measurements. Soil concentration gradient may be used to determine flux provided pressure conditions are stable and rain and wind do not interfere. This technique requires independent measurements of the diffusion constant in soil and soil radon concentrations.

2.2 EQUIPMENT DETAILS

Flux measurements were performed using a flow through type radon/thoron emanometer and accompanying software manufactured by ANSTO. The emanometer consists of a drum, which is placed over the surface to be measured, two pumps, two scintillation detectors and relevant supporting electronics and a lap top computer. The drum is approximately conical in shape with a volume of 0.01846 m^3 and covers an area of 0.259 m^2. To obtain accurate measurements; conditions in the drum must closely match those outside and the air in the drum must be well mixed (Schery et al, 1989). To achieve this air in the drum is continually replaced via inlet and outlet hoses at the top of the drum with a ventilation rate of approximately 1 $L.min^{-1}$. These hoses are approximately 10m long to allow the drum to be placed at a distance from the detectors. Two small pumps control the ventilation rate. A small 12V fan (dimensions: 82×82×25 mm) located in the centre of the drums interior ensured mixing of the air.

Air drawn from the outlet passes through two zinc sulphide alpha scintillation detectors which are separated by a length of pipe. As a result a sample of air reaches the second detector six minutes after passing through the first, allowing distinction of ^{222}Rn and ^{220}Rn counts. The first detector counts both ^{222}Rn and ^{220}Rn while the second detector counts predominantly ^{222}Rn. The delay time is more than 6half lives of ^{220}Rn. Figure 2.1 describes the flow of air through the emanometer.

To determine the flux from a particular surface the drum was placed over the area to be measured with the rim placed 1cm into the soil. Error in the placement of the drum is often the most important source of error in the measurements (Whittlestone). To minimise this error a specially designed cutting device was used to dig a circular hole 1cm deep, which the drum was placed in (Figure 2.2). The edge of the drum must be adequately sealed, and extra dirt was placed around the rim when required. The operation manual

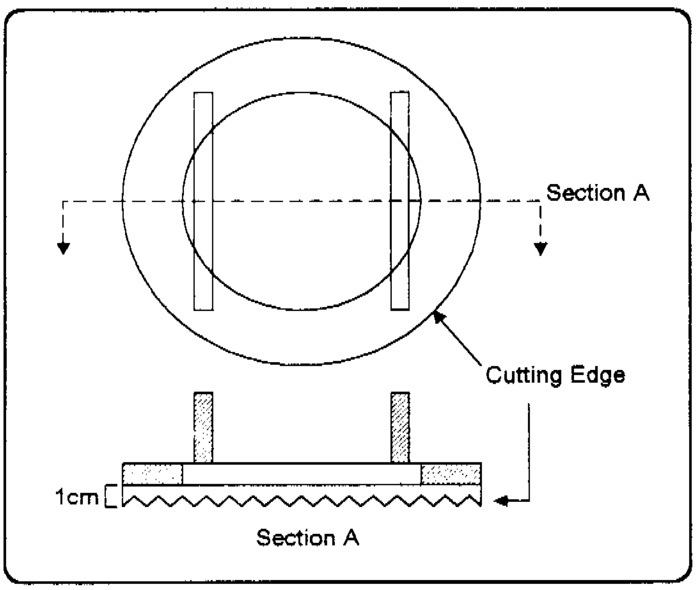
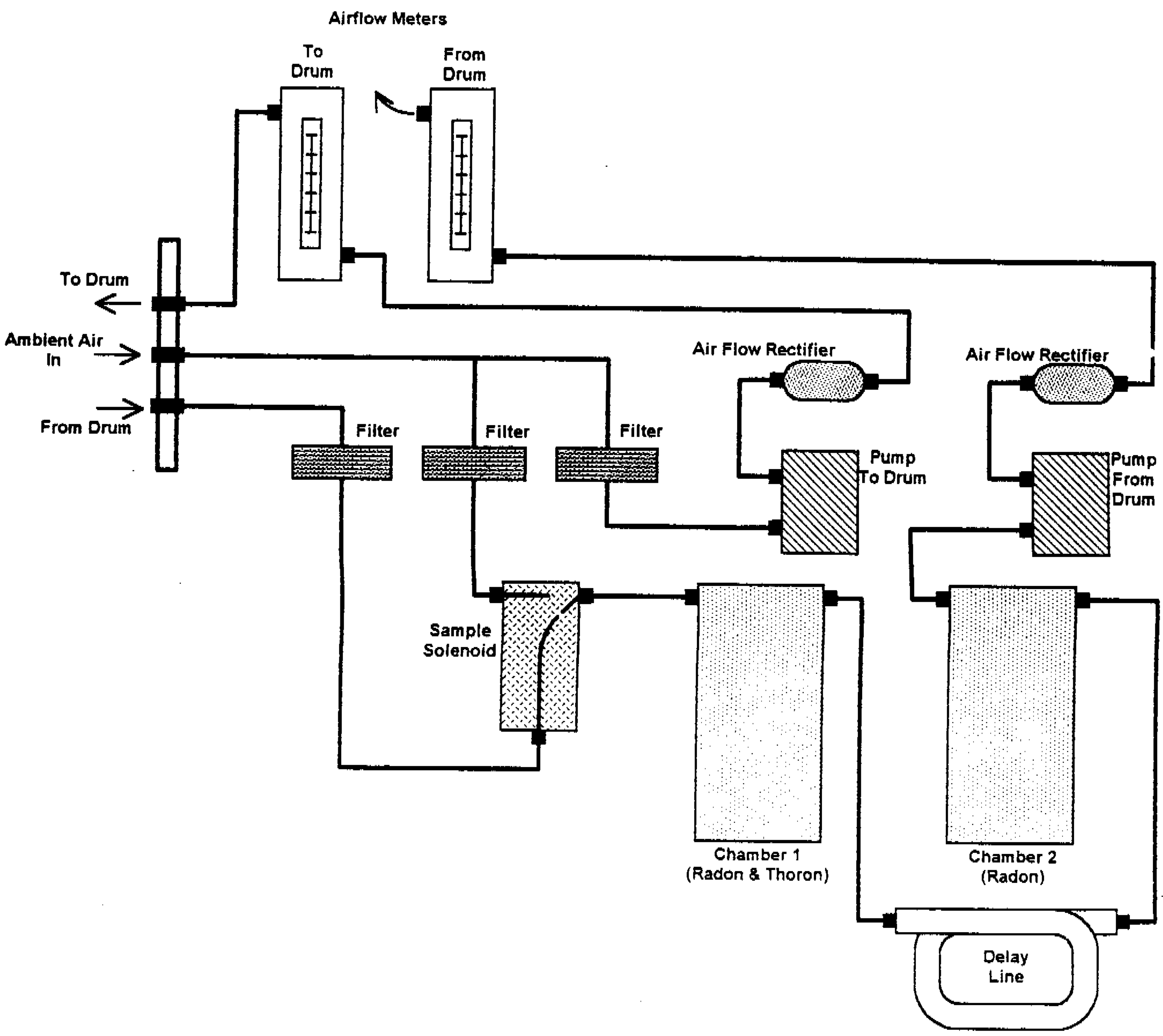


Figure 2.2 Schematic Diagram of the Cutting Device Used to Accurately Place the Emanometer

Figure 2.1 Schematic Diagram of Air Flow Through the Radon/Thoron Emanometer
Diagram Supplied by N. Giannakas,
Queensland University of Technology Centre for Medical and Health Physics



states that a tarpaulin may need to be placed over the drum in particularly windy conditions however this was never necessary.

The equipment may be run in two modes: background mode, where ambient air is drawn from an inlet on the side of the electronics box, or drum mode where air is drawn from the drum. This allows background measurements to be performed. Sources of background are: ^{222}Rn or ^{220}Rn daughters remaining in the cells after a cycle, radon in the ambient air, contamination of the air lines and drum, and ^{210}Pb which has built up in the scintillation cells (Whittlestone). Background is only a problem when measuring sites with particularly high flux. To determine activity flux a number of background measurements are taken followed by an emanation cycle. The number of count periods per cycle, nc, and the length of these (the count time), cp, may be adjusted. During the last count period ambient air is sampled. This allows the sample of air in the first detector to reach the second detector before the cycle is complete. After each measurement the equipment is left to count in background mode until the background reaches a suitable level. This assists in reducing the concentration of daughter products remaining in the detector after a measurement.

The same basic procedure was used at each site and during laboratory work. At least two ambient cycles were performed before each measurement. Each emanation cycle consisted of 6 count periods of 6 minutes each. Following each cycle the detector was run in background mode until the counts reached a suitable level (typically 30 min).

From the count rates measured the ^{220}Rn and ^{222}Rn flux densities are determined using the accompanying software.

Whilst performing preliminary measurements it was found the high voltage supplied to the detectors increased with temperature. Before determining the effect of temperature on the emanometer's performance the effect of variations in high voltage was determined. Therefore the effect of voltage supply on the emanometer's performance was examined. A radium source of approximately 180Bq (radon emanation rate of 1.5 Bq/g/s) electrostatically deposited on a metal disk was placed centrally under the drum. Emanation cycles were run with the usual six steps but a count period of only 1min. This prevented excessive build up of background in the detectors. The high voltage was increased from approximately 700V to 850 V. The total counts measured in the first detector over the six count periods was examined as a function of the high voltage (Figure 2.3).

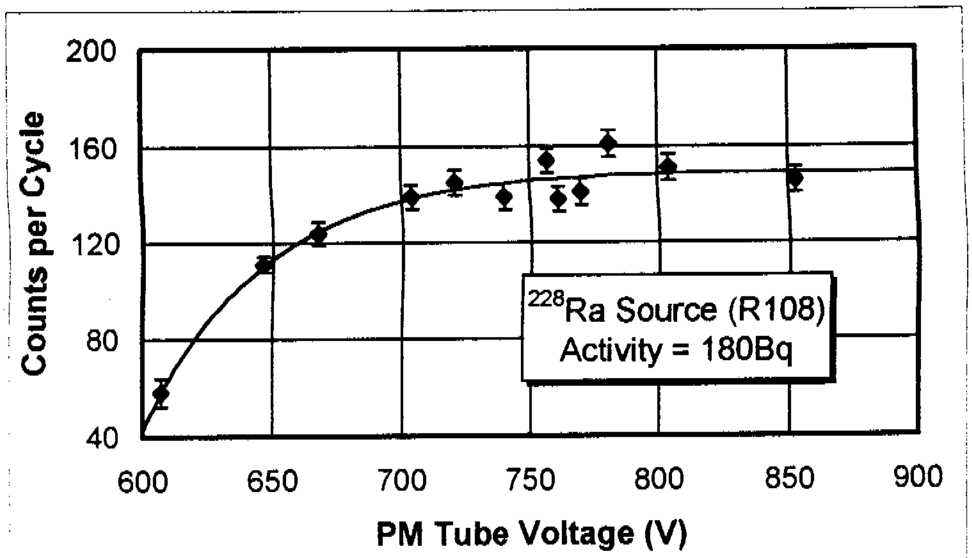


Figure 2.3 Detector Response to Variations in the High Voltage Supplied to the Photomultiplier Tube.

In the range 720V to 850V there is no significant variation in the total counts. It can therefore be inferred that in this voltage range there would be no significant variation in emanation results due high voltage variations. Throughout subsequent use the high voltage range was limited to 740-780V.

This was achieved by covering the equipment to reduce heating when in the field and by adjusting the gain.

Regular test of the detectors response to high voltage variations and flux from a standard source should be performed. These provide an indication of any system variations or faults (Conversation with Whittlestone).

CHAPTER 3. ^{222}Rn AND ^{220}Rn ACTIVITY FLUX SURVEY

3.1 INTRODUCTION

A ^{222}Rn and ^{220}Rn activity flux survey was performed over a region, approximately 10 kilometres square, encompassing Jabiru township, Jabiru East and the Aboriginal campsites; Magela 009, Mudginberri, Manaburduma and Gulungul Creek. Figure 3.1 is a map of the survey region. Various environmental and radiological parameters were also examined. The aim was to determine the association between the measured parameters and activity flux in this tropical region.

Locality

The survey area is approximately 260km east of Darwin, within the Alligator Rivers Region (Figure 3.2). An excellent account of the locality is given in various reports published by the Supervising Scientist of the Alligator Rivers Region. A brief summary given below is based upon the information contained in the Proceedings of the Land Application Workshop (ARRRI, 1991) which was extracted from the Alligator Rivers Research Institute Annual Research Summary for 1987-88. The Alligator Rivers Region (ARR) is broadly defined by the catchments of the East, South and West Alligator Rivers. The first stage of Kakadu National Park was declared in 1979, it has since grown through stages two and three to cover 19 804 km^2 of the ARR. The exceptional cultural and natural significance of the region was recognised internationally, when Stages 1 and 2 of Kakadu National Park were included on the World Heritage List. An abundance of flora and fauna, aboriginal rock art and it's vastly contrasting landscapes make the region unique. The ARR is composed of a variety of ecosystems including, sandstone heathlands, open woodlands, flood plains, seasonal watercourses and permanent billabongs. The survey area however, was predominantly

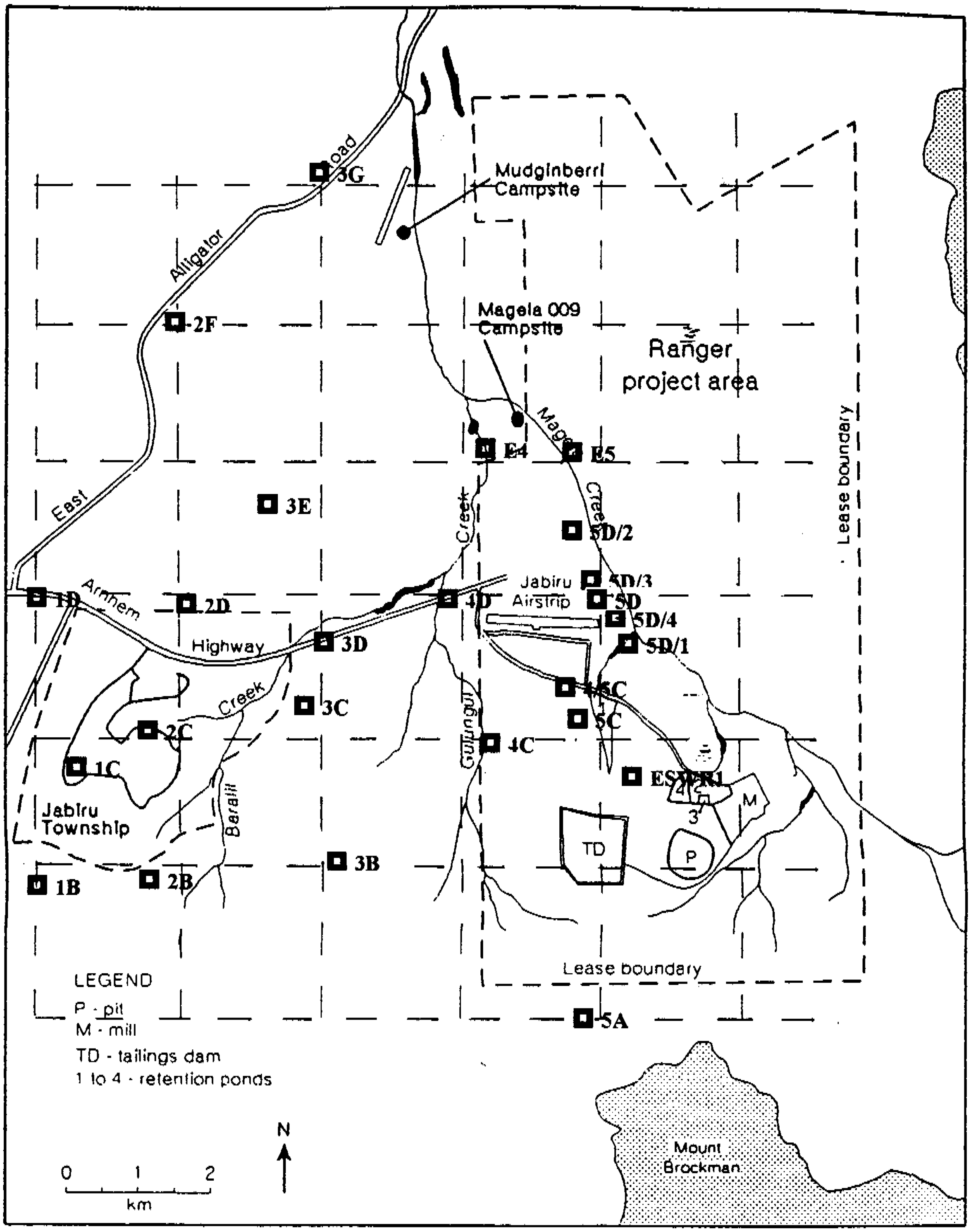


Figure 3.1 Measurement Sites for the ^{222}Rn and ^{220}Rn Activity Flux Survey

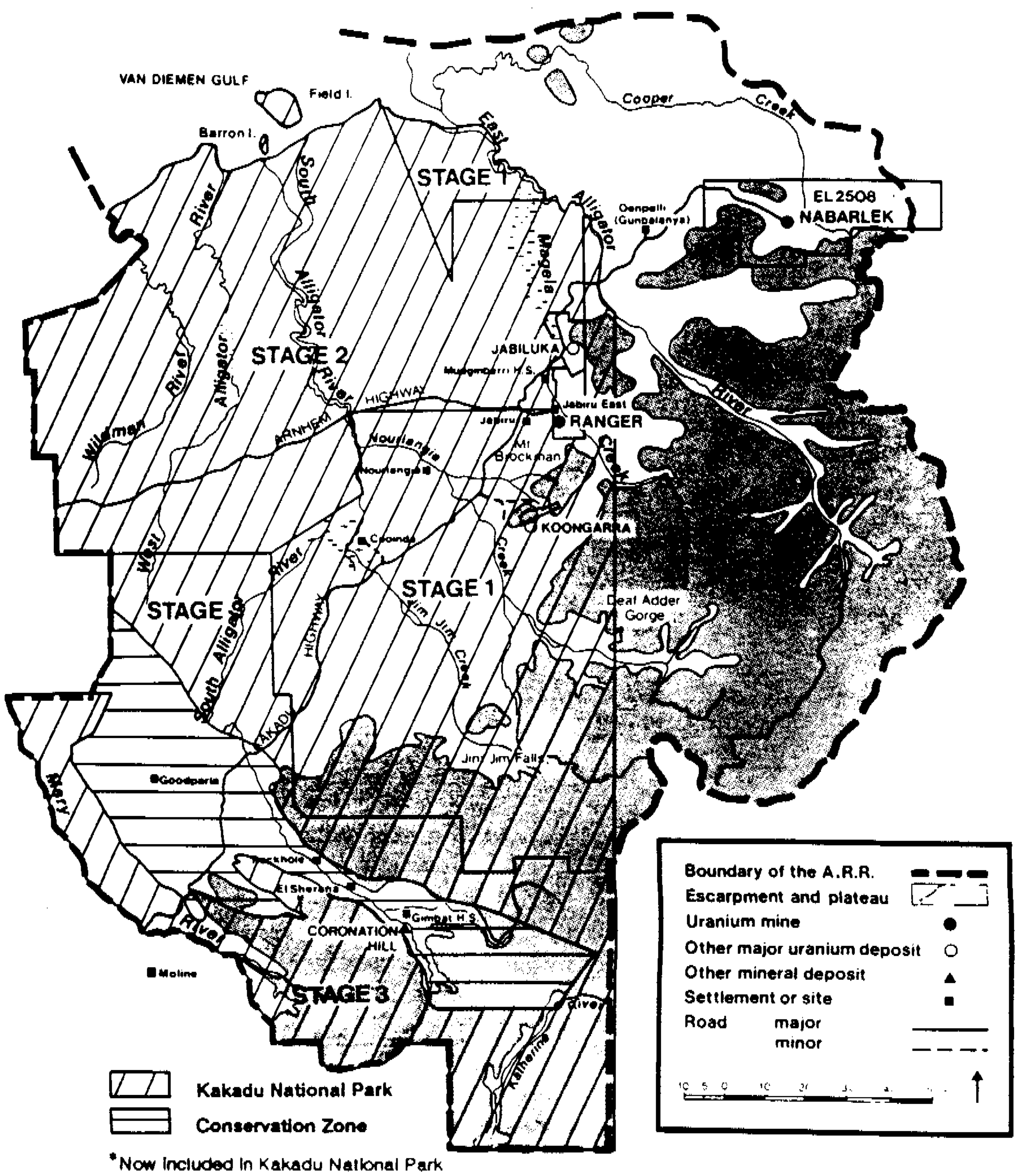


Figure 3.2 The Alligator Rivers Region (ARRRI, 1991)

open woodland with some floodplain areas near creek beds. The ARR also has many large mineral reserves including uranium, gold and platinum.

Demographics

As previously mentioned the survey region encompasses a number of settlements. The township of Jabiru was originally designed to service mining activity in the region it has also developed into a centre for the region and for tourists visiting the park. Tourism is now a major contributor to the region's economy. The population is constantly changing as most people live in the town for work only. It had an estimated population of 1356 in 1994 (Australian Bureau of Statistics). The estimated total population for the 1997/98 financial year is 1913 (provided by the Jabiru Town Council). This estimate is based on a forecast increase in staff at the ERA Ranger Mine, associated support staff, tourism industry staff and includes visitors and tourists at any given time. The town area is leased from the Australian Nature Conservation Agency (ANCA) who is responsible for the upkeep of the park. Although surrounded by Kakadu the town itself is not part of the national park.

Jabiru East is a working centre with the Ranger Mine, ERISS Laboratories and the Airport. Therefore it is predominantly occupied during working hours with some shift workers operating at the mine.

The Aboriginal communities in the region are located at the Manaburduma (Jabiru Town Camp Site), Gulungul Creek, Magela 009 and Mudginberri campsites. The indigenous population of Jabiru is estimated to be 8
% of the total population (Australian Bureau of Statistics).

Climate

The region has a monsoon-like climate with virtually all the rainfall occurring in the wet season from approximately November to March. October and April are typically transitional months with the dry season from May to September. The following summary is derived from details contained in the Climatological Summary for Jabiru Airport (Lat 12° 39' 39"S Long 132° 53' 34"E) provided by the Bureau of Meteorology. It has an annual rainfall of approximately 1473mm. Total annual evaporation levels are well in excess of the annual rainfall. Relative Humidity levels are high with averages of 68% and 42% for measurement times of 9am and 3pm respectively. The mean daily maximum and minimum temperatures are 34.0°C and 22.4°C. Winds are predominantly from the east and south east from April to September. November to February have more variable winds with frequent strong westerly and northern components while March and October are transitional months (ARRRI, 1991). The region is also affected by tropical cyclones which develop over the sea, however it is highly unlikely that a tropical cyclone would travel as far inland as the survey region (ARRRI, 1991).

Mining in the Region

A summary of, the history of mining and the mineral potential of the region are contained in the Proceedings of the Land Application Workshop (ARRRI, 1991) along with other details on the region. The following details are drawn from this publication, unless otherwise referenced.

The Alligator Rivers Region is located in an ancient basin called the Pine Creek Geosyncline, which is estimated to have approximately 360 000 tonnes of contained U_3O_8. Mining in the region can be dated back to 1865 with 16 metals extracted, including silver, gold, uranium, tungsten and zinc. Uranium was found to be the only economically viable mining resource in the ARR.

Uranium was discovered at Rum Jungle, approximately 100 km south of Darwin, in 1949. This stimulated extensive exploration for uranium in the ARR due to similar geology of the region. The ARR contains two areas in which uranium mines have been established, the Upper South Alligator River Valley and the East Alligator River.

Upper South Alligator River Valley

A uranium rush in this region followed the discovery of uranium deposits at Coronation Hill and Sliesbeck in 1953. At least 16 deposits or radiometric anomalies were identified and eventually 13 mines were established in the region. The mines were: Coronation Hill, Saddle Ridge, Skull, Palette, Scinto 6, Scinto 5, Koolpin, El Sharana, El Sharana West, Sterrets, O'Dwyers, Rockhole, and Teagues. The region is illustrated in Figure 3.3.

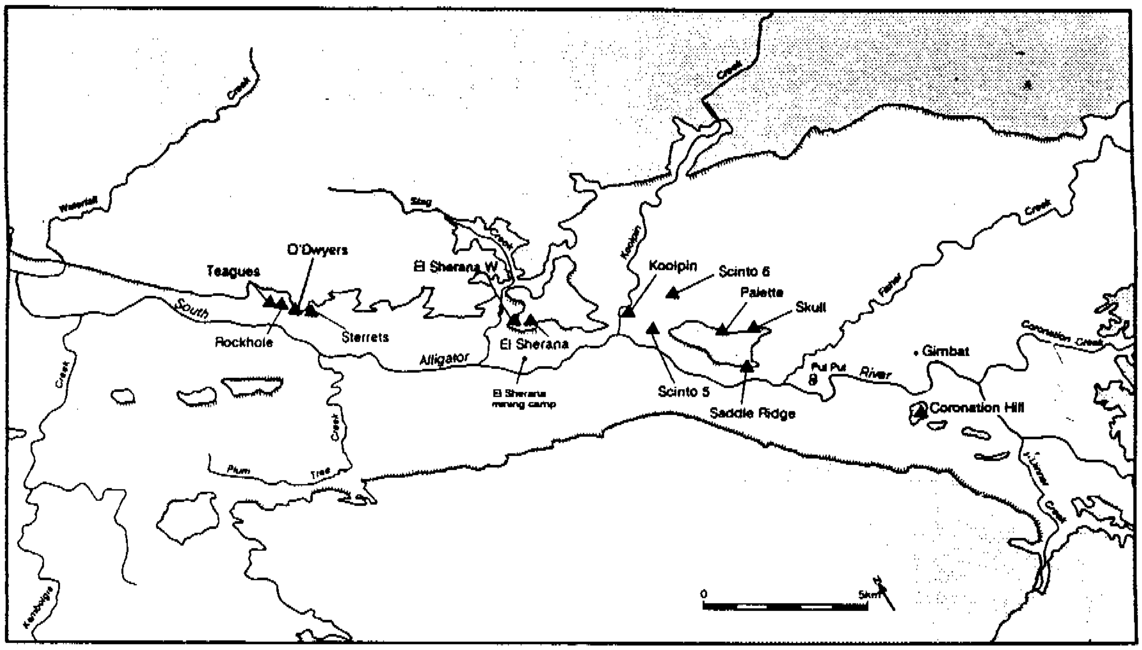


Figure 3.3 Upper South Alligator Valley Uranium Field (ARRR1, 1991)

Coronation Hill was operational from 1956-1964 producing approximately 75 tonnes of U_3O_8. Further south Sliesbeck was mined in 1956, producing only 3 tonnes of U_3O_8. The mine at El Sharana was the most productive in region with 411 tonnes of U_3O_8 obtained in 1958-59. Mining in the region was generally by the open cut method with some glory hole and cut and fill stoping from small shafts. All mines and processing plants in the region were abandoned in 1964. Mining in the region over the period 1954-1964 produced a total of approximately 975 tonnes of U_3O_8.

Surveys in 1986 and 1988 by the Commonwealth Department of Housing and Construction lead to proposals to rehabilitate the abandoned mine sites. The aim was to reduce the physical and radiological hazards, posed by the sites to park visitors. To provide protection from radiological hazards the goal was to obtain a dose rate less than 1mSv/yr on cleared areas and an average gamma dose rate over the site of less than 1 μGy/hr with no single site over 1.5 μGy/hr. These were all achieved as confirmed by various surveys since (Anon, 1996).

East Alligator Rivers Uranium

The East Alligator Rivers Region covers an area of 22 500km^2 east of the South Alligator River. It includes the uranium deposits of Ranger, Koongarra, Jabiluka and Narbalek.

Narbalek

The deposit at Narbalek was mined from April to October of 1979 by open cut method. Approximately 14 000 tonnes of U_3O_8 with an average grade of 2.3% was recovered. Milling of the recovered ore was completed in 1988.

Ranger Uranium Mine

The deposit at Ranger was discovered 1969 by airborne radiometric surveys and confirmed in the mid 70's by drilling. The Ranger Uranium Environmental Inquiry (Fox Inquiry) was established 1975, to review the implications of uranium mining in the ARR (ERA, 1996b). Following the completion of the final report in 1977, an agreement was signed by Northern Land Council

(NLC), on behalf of Aboriginals in the region, allowing mining at the site (ERA, 1996b). Energy Resources of Australia Ltd (ERA) commenced mining operations in 1980.

The reserves are estimated to be 5.8 million tonnes at 0.27% U_3O_8 in Orebody 1 and, 21.6 million tonnes at 0.28% U_3O_8 in Orebody 3 at a cut off grade of 0.12% U_3O_8 (ERA, 1996a). Orebody 1 was mined from 1980 -1994 by the open cut method. The remaining stockpiles are expected to last to 1999. Orebody 3 was approved in May 1996 and open cut mining is expected to commence in July 1997.

Other facilities at the Ranger site include an ore treatment plant, acid plant and power plant. The Ore Treatment Plant was originally designed to produce 3000 tonnes U_3O_8 a year (ERA, 1996a). It is currently being expanded to produce 5000 tonnes U_3O_8 a year by July 1997. An Acid Plant produces the sulfuric acid required for leaching from elemental sulfur. The Electric Power Plant supplies both the mine and Jabiru township.

Jabiluka

The history Jabiluak and proposal for it's future are contained in detail in the Draft Environmental Impact Statement (ERA, 1996b) as summary of important points is contained below. The orebody at Jabiluka was discovered in 1971. It was also considered in the Fox report and following the submission of an Environmental Impact Statement a mineral lease was granted to Pancontinental in 1982. An agreement was reached in 1982 with the NLC to allowing mining to commence. However the ALP Federal Government's 'Three Mine Uranium Policy' limited mining development in the region. The Jabiluka mineral lease was purchased by ERA in 1991. The election of a coalition government in 1996 lead to further consideration of the Jabiluka project.

The current proposal for the lease is to commence construction in 1997 with the first U_3O_8 recovery in 1999. The mine will be underground, with tailings backfilled into the mine. ERA expect to recover a total of approximately 19.5 million tonnes of ore.

Koongarra

The Koongarra deposit is located 20km south of Ranger uranium mine. It is a relatively small resource, containing approximately 15 300 tonnes U_3O_8 (ARRRI, 1991). Government approval to mine has not yet been obtained.

3.2 EXPERIMENTAL PROCEDURE

3.2.1 Selection of the Survey Sites

The primary objective in site selection was to give reasonable coverage of the survey region, an area of approximately 10km^2. Initially it was planned to perform measurements in a 2km grid over the area, however this was limited by site accessibility and time restraints.

Several factors influenced the choice of site locations, these are listed in order of importance.

a) Where possible sites were located at points in a 2km grid, whether the area was natural or altered.

b) Sites used in a previous study into the transport of dust from the Ranger Mine were also included. The results from the previous study provided additional information, particularly about the history of the sites, and allowed cross-validation of results.

c) At each site an attempt was made to place the drum over a representative area of ground cover. Placement was limited by the size of the emanometer, for example trees/shrubs were not included.

Figure 3.1 is a map of the survey region showing the survey sites and 2km grid. Extra measurements were performed along the Magela Creek where a site with particularly high ^{222}Rn flux was found. The number of sites was limited by the required measurement and analysis time.

3.2.2 Measurements

The survey was conducted in the period from July to early September 1996, during the dry season. Measurements were all during daylight hours and predominantly mid morning or mid afternoon. ^{222}Rn and ^{220}Rn flux were measured using the equipment and procedures described in Chapter 2. In addition to the radon activity flux the following parameters were measured either on site or at the Institute.

Terrestrial Gamma Dose Rate

Gamma dose rate at 1m above the ground was measured using an Environmental Meter type 6-80, manufactured by Mini Instruments Ltd., with compensated Geiger Muller tube type MC-70. These instruments are proven to operate satisfactorily under the climatic conditions of the region (Marten, 1991).

The dose rate may be obtained directly from an analogue scale or more accurately from a digital reading. The integrated count obtained from the digital reading may be converted to dose rate using a calibration curve supplied by the manufacturers. Figure 3.4 is the absolute calibration for sensitivity (c/s to μGy/h) for the detector. This was obtained using gamma radiation from ^{226}Ra and it's short lived daughters (Marten, 1991). The results lead to a calibration factor of 0.056 $c.s^{-1}/\mu Gy.h^{-1}$. Calibration of similar instruments at QUT with ^{137}Cs (E= 661.6 keV) and ^{60}Co (E= 1173 and 1332 keV) leads to a calibration factor quite close to this value.

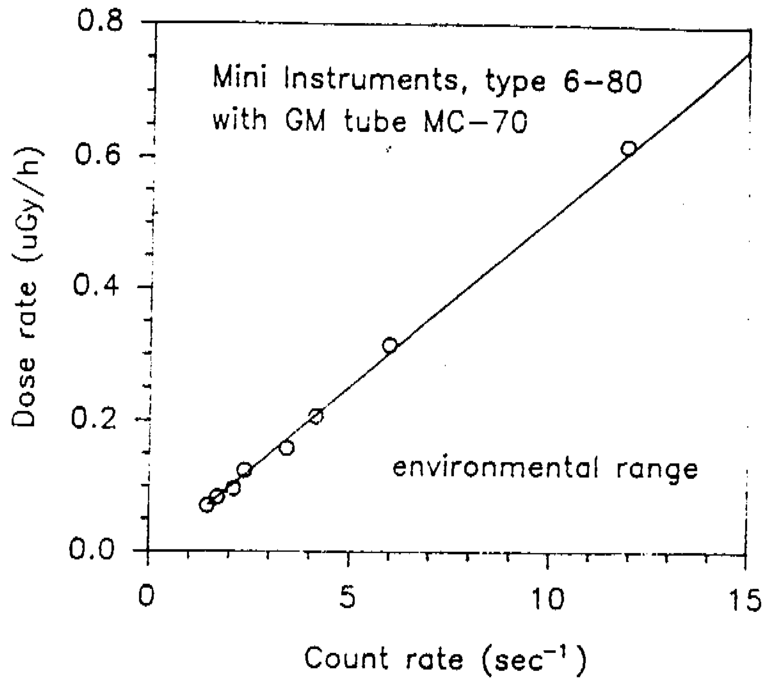


Figure 3.4 Absolute Sensitivity Calibration for the Gamma Dose Rate Meter (Marten, 1991)

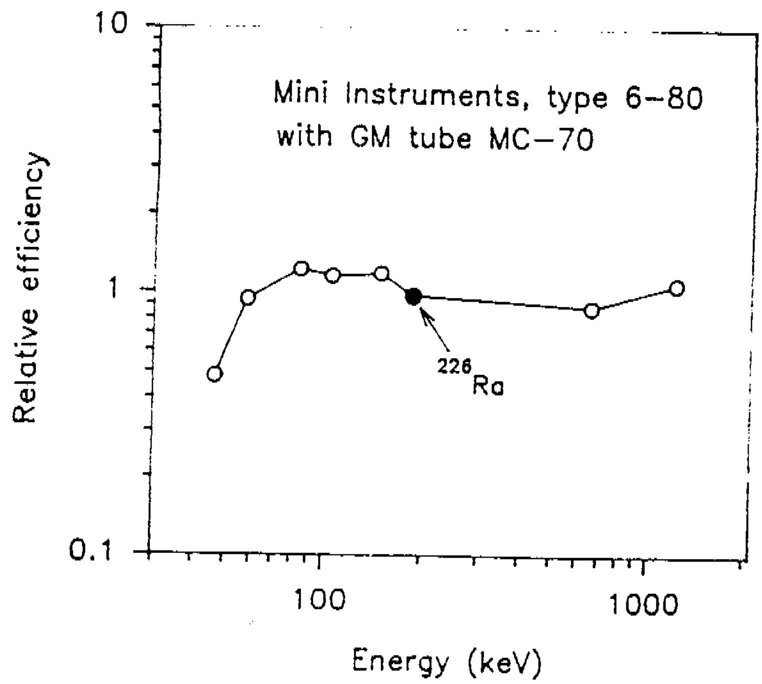


Figure 3.5 Relative Efficiency Calibration for the Gamma Dose Rate Survey Meter (Marten, 1991)

The detector has been designed to reduce the non-linearity that is typical of GM tubes with a deviation from linearity no greater than 25% for radiation normal to the detector axis in the energy range 55keV to 4MeV (Figure 3.5).

It was necessary to subtract the cosmic background from all measurements. Marten (1991) found the average dose rate from cosmic background to be 0.066 μGy/h. This was determined by taking a series of measurements on the Jabiru Lake at a water depth of 4m to shield gamma radiation from the ground. The cosmic background was determined in early June.

For the purpose of this study four measurements were performed around the emanometer, at a distance of approximately 2m, as it was running. The count time was 600s, providing approximately 1000 counts. Therefore the results obtained had a statistical error no greater than ±3%. The average count was converted to dose rate using the manufacturer's calibration curve before subtracting cosmic background.

Meteorological Parameters

Shaded air temperature and humidity were measured on site using a Max instruments portable probe. Soil temperature at approximately 2cm deep was measured at three points around the base of the emanometer drum using an Environ Data Automatic Weather Station. These parameters were measured every half-hour during background and activity flux measurements.

A Monitor Sensors Automatic Weather Station, with GLX Series Data Logger, located at Jabiru East behind the Institute was used to obtain meteorological data. Wind speed and direction at approximately 2m above the ground, and barometric pressure were all measured half hourly during flux measurements.

Table 3.1 Summary of ^{222}Rn and ^{220}Rn Flux Survey Sites

Identifier	People Present	GPS	Description	Vegetation	Radon Flux Thoron Flux
ES4/5C	BR	S 12°39.778' E 132°53.575'	Jabiru East- Rear of institute Site1 of dust project	Open woodland-mainly Eucalypts, sparse ground covering	28 ± 3 1546 ± 92
ES5D	BR	S 12°39.316' E 132°54.233'	Approx. 10m west of Magela Ck, 0.7 km along track at end of airport	Open grassland, approx. 5m from Pandanus and lush vegetation, dense dry grass covering ground.	280 ± 10 1292 ± 142
ES4D	BR	S 12°39.244' E 132°52.685'	EST of Gulungul ck, approx. 350m along tack from Arnhem Hwy.	Open Woodland, on the edge of flood plain, ground covering: small grassy shrubs.	18 ± 3 885 ± 77
ES2D	BR	S 12°39.608' E 132°50.481	STH of Telecom Operations Centre, opposite side of road.	Open woodland- mainly Eucalypts, small shrubs covering ground, fairly recently burnt.	9 ± 2 3339 ± 117
ES1D	BR	S 12°39.127' E 132°48.940'	NTH Est side of corner of Oenpilly Rd and Arnhem Hwy, approx. 10m from road.	Very recently burnt, large trees have not yet recovered, very little ground coverage.	43 ± 4 3097 ± 121
ES1B	BR	S 12°40.940' E 132°49.600'	20m from Pine Ck Rd on NTH side, along dirt section STH of Jabiru.	Open grassland (spear grass), Pandanus, Livestonia, Eucalypts and Acacias, low flood plain.	25 ± 3 1014 ± 76
ES3G	BR	S 12°35.532' E 132°51.482'	WST side of East Alligator Rd opposite Mudginberri airstrip, Dust site 7.	Eucalypts, no low vegetation due to burning.	25 ± 3 3836 ± 129
ES2F	BR	S 12° 36.185 E 132°50.865'	EST side of East Alligator Rd, approx. 7km from Arnhem Hwy.	Woodland, mostly large Eucalypts, small Acacias and Eucalypts, grass covering ground.	38 ± 4 2211 ± 104
ES4E	JH	S 12°37.757' E 132°53.107'	WST of Magela 009 campsite, near Gulungul ck.	Creek flood plain, open area with short grass, Paperbarks in the background.	25 ± 3 2311 ± 106
ES1C	BR	S 12°40.357' E 132°49.773'	Behind town water tower, Dust site 2.	Open grass area, approx. 70% ground cover.	19 ± 3 3834 ± 126
ES2C	BR	S 12° 40.573' E 132°50.230'	Wooded area in Jabiru township, Dust site 4.	Eucalypts, sparse grass covering.	14 ± 2 2489 ± 102
ES2B	JH	S 12°41.121' E 132°49.934'	NTH of golf course, approx. 1km site ES1B along track.	Spear grass (sparse) and Calytrix.	14 ± 3 2728 ± 108

Identifier	People Present	GPS	Description	Vegetation	Radon Flux Thoron Flux
ES3D	JH	S 12° 39.393' E 132°52.343'	STH of Baralil Billabong, approx. 5m from waters edge.	Mostly Spear Grass, small flowering plants, Paperbarks and some Pandanus near by.	-3 ± 0 725 ± 55
ES4C	PM	S 12°40.182' E 132°53.074'	EST of Gulungul Ck, approx. 2 km along Radon Springs track.	Open woodland, primarily Eucalypts, some Pandanus and Acacias.	14 ± 2 922 ± 67
ES5E	PM	S 12° 38.394' E 132°54.040'	EST of Magela ck, approx. 1km along track NTH after sandy crossing.	Flood plain area, Pandanus and Paperbark.	16 ± 2 1824 ± 92
ES3C	BR	S 12°40.639' E 132°51.357'	Approx. 1km STH of Arnhem Hwy along track EST of Baralil ck.	Mainly Eucalypts, little under growth in sample area.	31 ± 3 2231 ± 103
ES3E	BR	S 12°39.049' E 132°50.907'	NE from road near telecom operations centre.	Mainly Eucalypts, some Livestonia, very little undergrowth, recently burnt.	54 ± 4 1805 ± 105
ES5C	BR	S 12°40.200' E 132°53.875'	WST of RP1, near pipeline.	Spear grass, with a few Acacias and Eucalypts surrounding the sample area.	50 ± 4 1947 ± 104
ES5A	DJ	S 12°41.578' E 132°53.330'	Ranger lease boundary, Dust site 10.	Open woodland, mainly Eucalypts, and few Acacias.	96 ± 6 1946 ± 113
ES5D/1	BR	S 12°39.522' E 132°54.274'	WST of Magela ck, STH of site ES5D, near junction in creek.	Open grassland near the edge of the Pandanus and Paperbarks.	53 ± 4 2791 ± 119
ES5D/2	BR,PM	S 12°39.119' E 132°54.165'	WST of Magela ck, NTH of sites ES5D and ES5D/3.	As for other ES5D sites.	60 ± 5 1292 ± 92
ES3B	BR,PM	S 12°41.259' E 132°51.258	STH of Arnhem Hwy along track near Baralil Ck, STH of site ES3C.	Eucalypts and Pandanus.	11 ± 3 2909 ± 122
ES5D/3	PM	S 12°39.251' E 132°54.179'	Approx. 100m NTH of site ES5D.	As for other ES5D sites.	275 ± 10 1182 ± 145
ES5D/4	PM	S 12°39.311' E 132°54.220'	Approx. 100m STH of ES5D	As for other ES5D sites.	58 ± 7 819 ± 112
ESWR1			Top WST side of the northern waste rock dump.	None.	525 ± 14 2126 ± 196
ESWR2			Approx. 50 SE of site 1.	Edge of revegetation area, spear grass.	513 ± 16 2021 ± 237

It was also used to check to validity of the on site measurements of relative humidity, air and soil temperatures.

Site Details

A detailed explanation of the site's location including GPS coordinates was recorded. This enabled accurate mapping and a reference for future work. Broad descriptions of the site, in particular the vegetation and percentage ground cover were also noted. These are summarised in Table 3.1. The percentage ground cover was estimated by sight. Site labels were developed using the nearest grid coordinates (Figure 3.1). In addition to the written site description a minimum of three photographs were taken at each site, usually including a picture of the ground around and under the emanometer. These photographs are contained in Appendix 1 along with a site description. The sites were marked using yellow spray paint markings on easily identifiable tree/s (also included in photographs).

Soil Samples

Up to four soil samples were obtained at each location. Core samples from 0-10cm and 10-20cm were taken at all sites using an auger. ^{222}Rn is expected to originate from depths of up to 4m however the equipment available for sample collection limited the sampling depth. Surface scrapes, usually 0-5mm and 5-10mm, were collected using an ERISS designed and manufactured device (Figure 3.6). The soil samples were placed into labelled plastic bags immediately and sealed.

Soil moisture from 0-10cm and 10-20 cm was determined by drying a representative portion of each core sample immediately upon returning to the Institute. The sample was mixed thoroughly and approximately 50-100g was placed in an aluminium dish. The soil was dried at 80 °C for a minimum of 24 hours, then desiccated until cool before reweighing. The two core samples

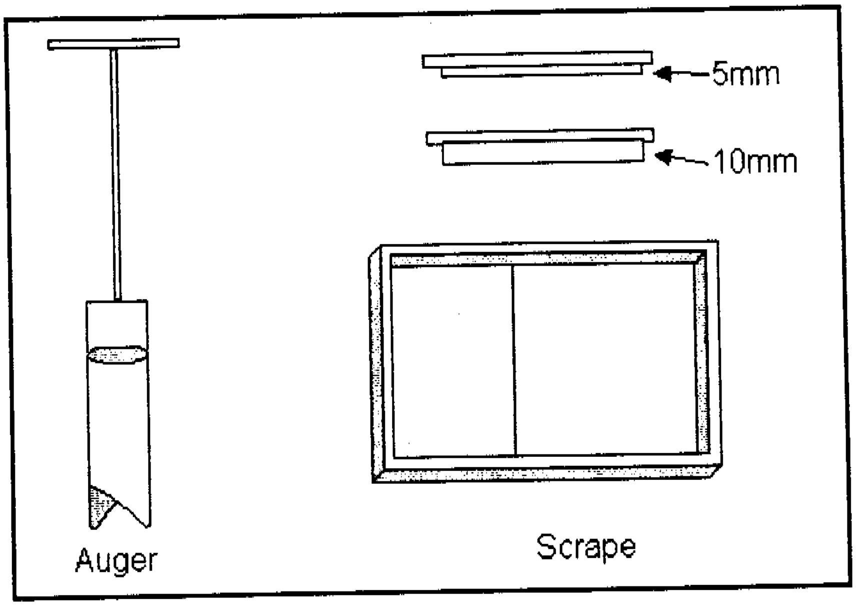


Figure 3.6 Auger and Scrape Used to Obtain Soil Samples

were then combined and mixed completely. It was necessary to combine the cores due to the number of samples and the limited analysis time available.

The samples were then prepared for radionuclide analysis. Samples were cast in polyester resin in moulds of dimensions calibrated for gamma spectroscopy radionuclide analysis. The final geometry was a disc of diameter 65mm and approximately 10mm thick containing 15-30g of the sample. The resin holds the samples homogeneously in a radon tight matrix (Pfitzner, 1994). This is particularly important for this study where radon is the primary focus and any loss would cause an error in analysis.

There are a number of steps required to prepare the soil for casting. Firstly the samples were weighed, and dried in ovens at 80°C for a minimum of 24 hrs. 80°C is used as a standard as Polonium isotope removal may become significant above 85 °C (Pfitzner, 1994). Another isotope likely to sublimate at higher temperatures is ^{210}Pb. Once dry the soil is desiccated until cool before reweighing. It is important that the samples be completely dry or they do not grind adequately and the subsequent analysis is incorrect (Pfitzner, 1994). They are then placed in airtight containers.

Once dried the samples are separated into two size fractions, greater than and less than 2mm. This was achieved by sieving in a sieve shaker for 30mins (sufficient time for the sample to completely separate).

To ensure the cast is homogeneous the samples must be ground to less than 200 μm (Pfitzner, 1994). This was achieved using a disc-type grinding mill. To prevent cross contamination of samples the mill was cleaned between each site's samples using a sand matrix, known to be low in radioactivity, obtained from the Flying Fox Creek in Kakadu National Park. Samples, too large to grind, were separated using a gravimetric separator to ensure no bias in the component taken. Any excess sample was discarded.

The soil samples were then cast and stored for 23 days, to allow the sample to reach equilibrium between ^{226}Ra and its short lived progeny, before performing analysis for ^{238}U, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{210}Pb, and ^{40}K. Radionuclide analysis was performed using a HPGe detector. The techniques of sample preparation and analysis were based on the paper "Analysis for Naturally Occurring Radionuclides at Environmental Concentration by Gamma Spectrometry" Murray et al (1987).

3.3 RESULTS

A comprehensive summary of the data set for each site is contained in Appendix 2, with all sites listed in alphabetic order. This includes the average and standard deviation for all parameters measured. The GPS coordinates only are used to describe the location in this appendix. More detailed site descriptions are contained in Table 3.1 and Figure 3.1. Site descriptions along with photographs taken for each site are contained in Appendix 1.

The date and starting time that the flux measurement commenced along with the results obtained are contained under the heading, activity flux. The average terrestrial gamma dose rate measured at 1m above the ground is also listed.

Meteorological data, for each site, is quoted as the mean plus or minus the standard deviation. The standard deviation is not an indication of the error in a single measurement or in the mean, it simply demonstrates the variability of the parameter during the sampling period (typically 2 hours surrounding the flux measurement). For the majority of sites there was no significant difference in the air temperature and relative humidity measured on site and at the Institute. The relationship between the soil temperature on site and at the Institute was more variable. This is expected due to the site dependence of this parameter. Barometric pressure was virtually constant over the time required for a measurement, with standard deviation not exceeding 0.1% in any sampling period. The wind direction quoted is a half hourly average of measurements recorded every 6 minutes, during the flux measurement.

All soil samples were given a sample code using the protocol of the Environmental Radiation group at ERISS. The first two letters are a code for the site. This is followed by the last two digits of the year in reverse and finally the sample number. The sample description includes the date, sample type, initials of people present and a general description of the experiment and/or sample.

eg.

The first sample of 1996 — Soil Sample — General Sample Description

JT6901 960716 SOI RLT,BR Emanation Study 0-10mm scrape

Jabiru Township — YYMMDD — Rebecca Todd and Bruce Ryan Present

The date and starting time that the flux measurement commenced along with the results obtained are contained under the heading, activity flux. The average terrestrial gamma dose rate measured at 1m above the ground is also listed.

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eg.

The first sample of 1996   ↓Soil Sample   ↓General Sample Description

JT6901   960716 SOI RLT,BR Emanation Study 0-10mm scrape

Jabiru Township   ↑YYMMDD   ↑Rebecca Todd and Bruce Ryan Present

Due to time constraints not all soil samples could be processed and analysed. For most sites the core samples have been analysed and the activity concentration of the various nuclides are listed. In some cases only one fraction of the sample (>2mm or <2mm) has been analysed. All the details of samples which have been analysed are quoted. A description of the samples which are yet to be analysed is also listed.

Table 3.2 contains the arithmetic mean and relevant statistical data for ^{222}Rn and ^{220}Rn activity flux and the other environmental and radiological parameters. It should be noted that the meteorological data quoted is not an average for the region, nor is it a seasonal average, it is simply an average during sampling times. The table is designed to provide an indication of the conditions under which measurements were performed. Similarly the average values of the flux and activity concentration included in the table are not a regional average but an average for the sites surveyed. The general survey sites did not include sites from the Ranger mine site or the extra sites along the Magela Creek. An attempt will be made to estimate the regional average for ^{222}Rn and ^{220}Rn activity flux in the analysis section. The standard deviation in all cases provides an indication of the variability of the parameters measured during sampling periods.

There is a large variation in the activity flux of both ^{222}Rn and ^{220}Rn, even in this relatively small region. The range of ^{222}Rn activity flux values may be due to the abundance of uranium deposits in the region and the large range in soil moisture at the sites. A study performed by Badr and Durrani (1993) into the spatial variation of soil radon found significant variation in concentrations within 10m. It is these relatively small-scale variations and the large variety of contributing factors which make it so difficult to determine the association between activity flux and any one variable. ^{222}Rn flux was at a level that could be measured with acceptable accuracy in a reasonable time frame.

Table 3.2 Summary of Results Obtained in the $^{222}Rn/^{220}Rn$ Flux Survey

PARAMETER	MEAN	STANDARD DEVIATION	MAXIMUM	MINIMUM	NUMBER OF SITES
ACTIVITY FLUX					
Radon Flux ($mBq.m^{-2}.s^{-1}$)	41	60	280	0	20
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2147	941	3834	725	20
Gamma Dose Rate (uGy/hr)	0.130	0.021	0.185	0.0868	20
ACTIVITY CONCENTRATIONS (Bq/kg)					
>2mm Fraction					
^{226}Ra	81.1	49.2	225.92	46.30	13
^{228}Ra	87.9	41.4	30.51	176.83	13
^{238}U	78.6	71.6	304.70	17.63	13
^{210}Pb	74.7	50.1	227.57	29.86	13
^{40}K	105.4	140.3	437.39	24.06	13
<2mm Fraction					
^{226}Ra	35.2	9.6	43.17	19.17	18
^{228}Ra	36.3	14.3	20.06	59.76	18
^{238}U	37.8	14.0	61.40	15.24	18
^{210}Pb	51.9	16.6	78.94	20.41	18
^{40}K	47.3	29.1	101.96	11.34	18
SOIL PARAMETERS					
Soil Moisture (% by weight)					
0-10 cm Core	3.1	4.8	19.4	0.3	19
0-20cm Core	3.4	3.1	16.5	0.3	20
Ratio of >2mm Fraction to <2mm Fraction (0-20cm)	0.46	0.47	1.51	0	19
METEOROLOGICAL PARAMETERS - ON SITE					
Air Temperature (C)	33.5	2.8	37.1	28.6	20
Soil Temperature (C)	37.8	4.9	47.7	31.5	18
Relative Humidity (%)	37	14	69	21	20
METEOROLOGICAL PARAMETERS- INSTITUTE					
Air Temperature (C)	30.8	3.0	35.4	25.6	20
Soil Temperature (C)	33.8	4.1	40.7	27.0	20
Relative Humidity (%)	37	13	38	12	20
Wind Speed	10	4	18	2	20
Barometric Pressure (hPa)	1013	3	1017	1009	20
Solar Radiation (kJ/m^2)	2408	3955	10100	707	19

In contrast to the radon flux measurements the gamma dose rate showed little variation. The average gamma dose rate, 0.13 ± 0.02 μGy/hr, is not significantly larger than the average value which Schery et. al. determined in their survey of Australia, 0.093 ± 0.027 μGy/hr.

For all isotopes analysed the average activity concentration of the >2mm grain size fraction was considerably higher than the <2 mm fraction. This may be a result of the different size ranges originating from different sources. The ratio of the fraction of the 0-20cm core sample which is greater than 2mm to the fraction which was less than 2mm, by weight, is also quoted. A small value describes a sample with predominantly fine grains while a large value describes a course, rocky sample. The ratio of the >2mm to <2mm size fractions may provide more insight into the expected flux when combined with the measured concentration than the concentrations alone.

The meteorological parameters were all fairly stable. This is typical of the region in the dry season. In particular the barometric pressure was almost constant with a standard deviation of approximately 0.3%. The bias towards daytime measurements, with most performed either mid-afternoon or mid-morning also limited the range of these values. A survey over a full cycle of the seasons would provide a much larger variation in these parameters. During the months in which sampling took place there was no rainfall in the region. This is reflected in the low average soil moisture obtained.

3.4 ANALYSIS AND DISCUSSION

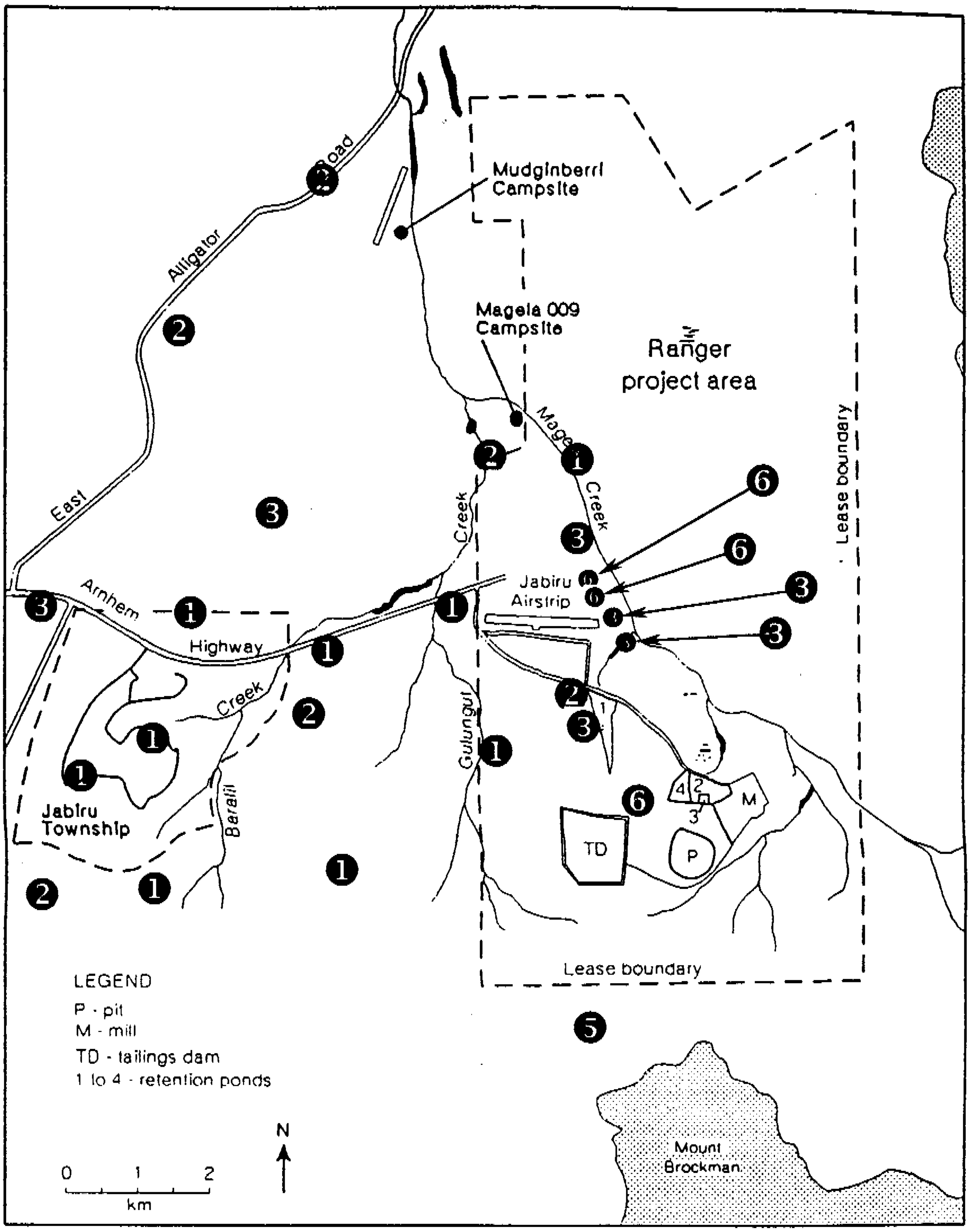
Firstly ^{222}Rn and ^{220}Rn activity flux values obtained were plotted onto maps of the survey region. Following this the distribution of the flux values and regional averages were determined. Finally detailed analysis into the association between activity flux and the various parameters measured was performed.

3.4.1 Measurement Sites

Figures 3.7 and 3.8 are maps of the survey region with the measured flux range for each site. They provide an overall picture of the ^{222}Rn and ^{220}Rn flux observed. This map includes all sites where data was collected. In addition to the 20 general survey sites there are six sites, where a subset of the total data set was obtained. Four sites (ES5D1, ES5D2, ES5D3, ES5D4) in close proximity to site ES5D along the Magela Creek were investigated to provide insight into the high ^{222}Rn flux at ES5D. Measurements were also taken at two sites on the Ranger Uranium Mine waste rock dump. The six extra sites are only used selectively in further analysis.

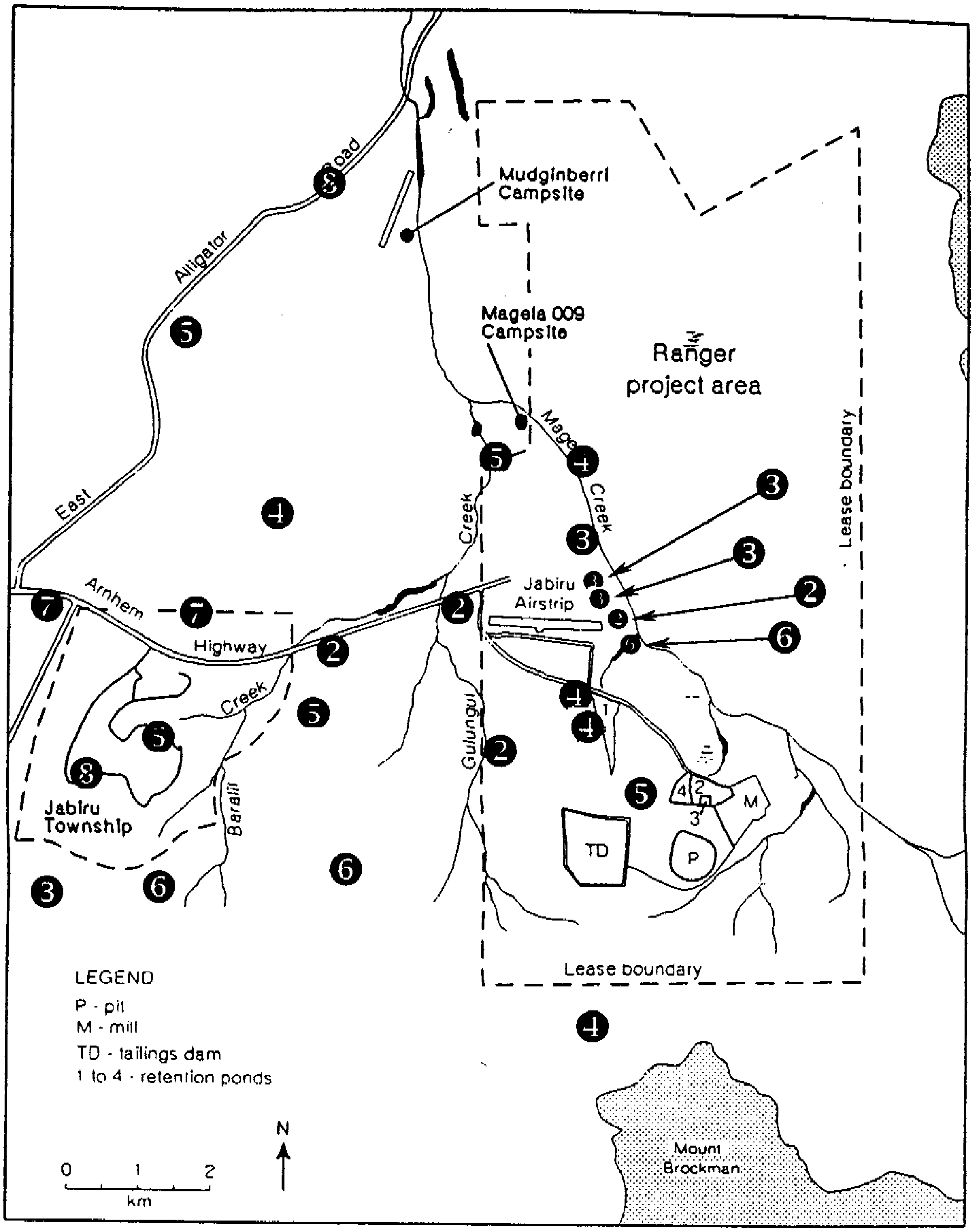
The ^{222}Rn flux at two sites approximately 10m east of the Magela Creek sand bed (ES5D and ES5D3) and on the waste rock dump at the Ranger Uranium Mine were all greater than 250 $mBq.m^{-2}.s^{-1}$. The high ^{222}Rn flux at the Magela Ck is not caused by water born contamination as the ^{226}Ra, ^{235}U and ^{210}Pb concentrations are approximately equal. It is most likely due to an outcrop of uranium. Site ES5A, on the southern boundary of the Ranger lease, also had relatively high ^{222}Rn flux (96 ± 6 $mBq.m^{-2}.s^{-1}$). These sites are all fairly close to the Ranger mine site however there does not seem to be a general trend of increasing ^{222}Rn activity flux in proximity to the mine. All other sites had a ^{222}Rn activity flux of less than 80 $Bq.m^{-2}.s^{-1}$, and show no trends in their location. Comparison of the two maps (Figures 3.7 and 3.8) reveals no obvious relationship between ^{222}Rn and ^{220}Rn activity flux.

Figure 3.7 seems to show a lower value trend in ^{220}Rn activity flux in close proximity to creeks. Only one site with ^{220}Rn activity flux less than 1500$mBq.m^{-2}.s^{-1}$ is not located near a creek. Conversely all sites with ^{220}Rn



❶ 0 - 20	❹ 60 - 80
❷ 20 - 40	❺ 80 - 100
❸ 40 - 60	❻ >100

Figure 3.7 Map of ^{222}Rn Activity Flux ($mBq.m^{-2}.s^{-1}$)



❶ 0 - 500	❺ 2000 - 2500
❷ 500 - 1000	❻ 2500 - 3000
❸ 1000 - 1500	❼ 3000 - 3500
❹ 1500 - 2000	❽ 3500 - 4000

Figure 3.8 Map of ^{220}Rn Activity Flux ($mBq.m^{-2}.s^{-1}$)

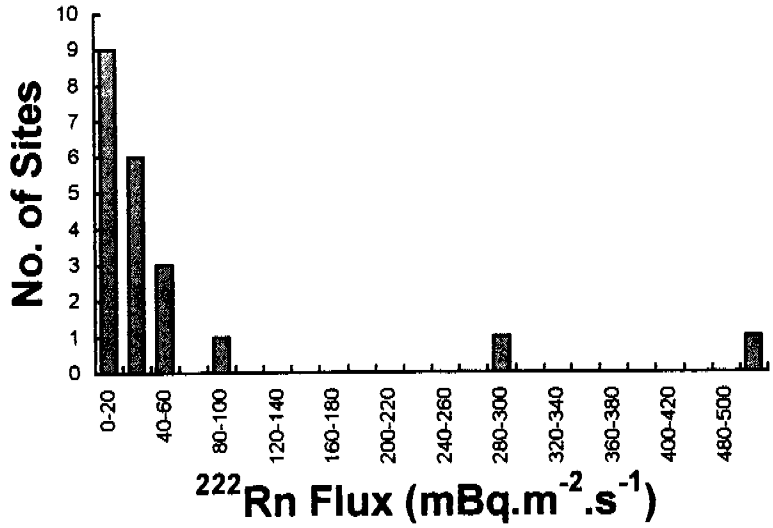
Figure 3.7 seems to show a lower value trend in ^{220}Rn activity flux in close proximity to creeks. Only one site with ^{220}Rn activity flux less than $1500mBq.m^{-2}.s^{-1}$ is not located near a creek. Conversely all sites with ^{220}Rn flux greater than 3000 $Bq.m^{-2}.s^{-1}$ were at a distance from any creeks. This apparent trend will be investigated further when determining the association between ^{220}Rn flux and the various parameters. This trend is due to differences in soil types between the two regions, and the variations in the ^{228}Ra concentration.

3.4.2 Activity Flux Distributions

Figure 3.9 contains histograms of the measured ^{222}Rn and ^{220}Rn activity flux. An average value for the two waste rock dump sites, which were approximately 50m apart was included in these distributions. The extra sites along Magela Creek (ES5D1-ES5D4) were not included, as the large concentration of sites in one area would have produced unrealistic distributions for the region. An average of these sites was not used due to the spatial distribution (approximately 2km between the two extreme points) compared to the small scale which significant radon variation can occur.

Most random events can be described by the normal distribution. It is a symmmetrical bell shaped distribution centred on an average value. A random event is equally likely to be greater than or less than the average value. The lognormal distribution is effectively a skewed normal distribution. There is a greater probability that an event will be in the lower range. Figure 3.10 is a plot of the logarithm of the flux versus cumulative probability. The cumulative probability is the percentage of sites with activity flux less than or equal to a particular value. A lognormal distribution would be a straight line on this graph. It can be seen that the distributions are approximately lognormal with some deviation at either end.

(a)



(b)

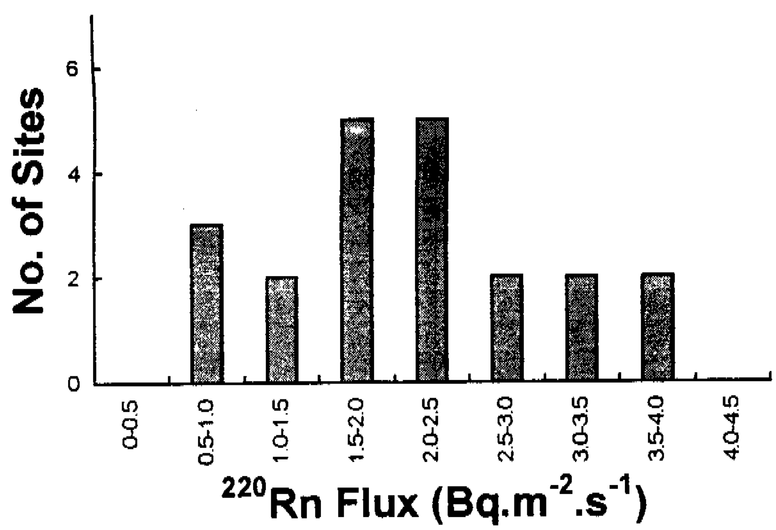


Figure 3.9 Histograms of the (a) ^{222}Rn and (b) ^{220}Rn Flux

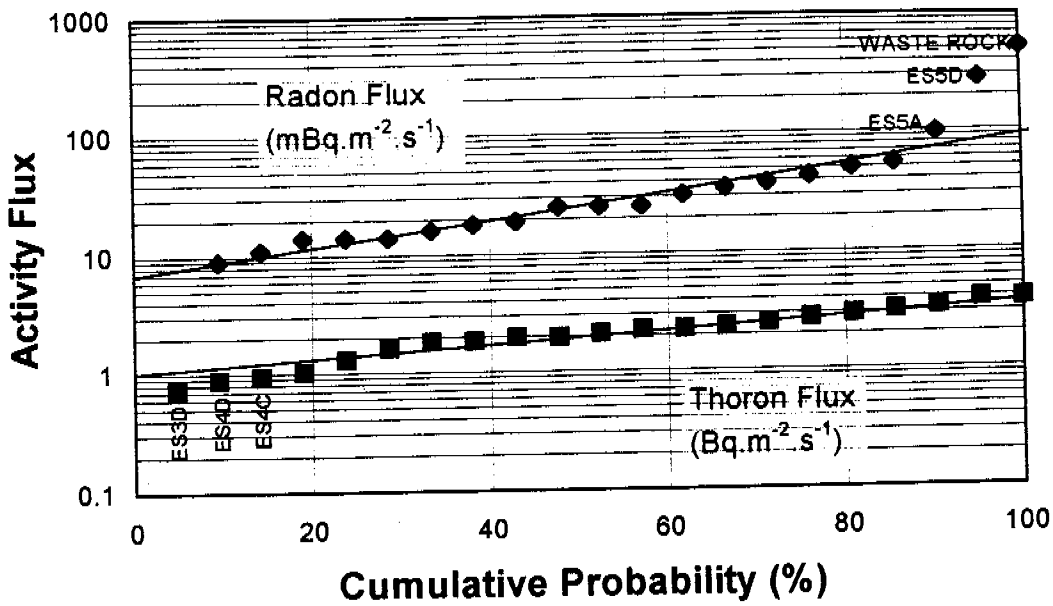


Figure 3.10 Plot of the Logarithm of ^{222}Rn and ^{220}Rn Flux Versus Cumulative

UNSCEAR's 1993 report states that distributions of radon concentrations in air are usually reported to be lognormal. Schery et al (1989) in their survey of the radon and thoron flux from Australian soils found both distributions to be approximately lognormal.

The data points representing the waste rock dump and ES5D (Magela Creek high site) in the ^{222}Rn distribution deviate significantly from the lognormal distribution. These are uncharacteristically high for the region due to the high ^{226}Ra activity concentrations of these sites. For ^{220}Rn the most significant deviation occurred at the lower end of the distribution. The lowest flux value observed was at site ES3D that had very high soil moisture (17%), particularly in comparison to the rest of the region at this time of year. It should be noted that the data point corresponding to this site could not be included in the ^{222}Rn distribution as the flux was 0 $mBq.m^{-2}.s^{-1}$ and this cannot be plotted on the logarithmic scale. The next two data points in the ^{220}Rn distribution correspond to sites ES4D and ES4C. There is no obvious reason for their deviation however they both have below average ^{228}Ra concentration and ratios of >2mm to <2mm of much less than one (0.004734 and 0.02876 respectively).

Schery et al (1989) also found that deviations occurred at either end of the distributions. In particular the ^{222}Rn flux values observed at the upper end of the distribution where lower than would be expected for a pure lognormal distribution. Therefore they had less sites with high ^{222}Rn flux than is predicted by a lognormal distribution.

3.4.3 Average Values of ^{222}Rn and ^{220}Rn Activity Flux

An average value for the waste rock dump was included in calculations of the average flux of both ^{222}Rn and ^{220}Rn while the extra sites along Magela Creek were excluded. The average ^{222}Rn flux for the region was determined to be 64 ± 25 mBq.m^{-2}.s^{-1}. This regional average is well above the estimated range for the world average flux of 15 to 23 mBq.m^{-2}.s^{-1} (UNSCEAR, 1982) and the arithmetic mean flux for Australia obtained by Schery et. al. (1989) of 25 ± 5 mBq.m^{-2}.s^{-1}. If the average value of the waste rock dump is excluded from the calculations the average is found to be 41 ± 13 mBq.m^{-2}.s^{-1}. The average ^{220}Rn flux (2.15 ± 0.21 Bq.m^{-2}.s^{-1}) is not significantly different to the world wide average which is in the range 0.9-1.9 Bq.m^{-2}.s^{-1} (UNSCEAR, 1982). This world average is poorly determined due to the lack of available data. Schery et. al. (1989) found the Australian average to be 2.1 ± 0.4 Bq.m^{-2}.s^{-1} which is not significantly different to the result obtained for this study.

Restrictions to the mine site due to construction activities at the time of the survey limited flux measurements to two localities, both on the northern waste rock dump. The first site had no vegetation and only limited weathering of the rock was evident. The second site was on the edge of a revegetation area. ^{222}Rn activity flux observed at these sites were 525 ± 14 $mBq.m^{-2}.s^{-1}$ and 513 ± 16 $mBq.m^{-2}.s^{-1}$ respectively.

The true seasonal average flux may be somewhat lower than the average obtained during the dry season. Due to the large amount of rainfall, which occurs during the wet season, soil moisture would be high therefore reducing flux due to capping of the soil pore space. However greater porosity of freshly deposited rocks on the waste rock dump may result in prompt infiltration of rain water and the capping effect may not be long lasting.

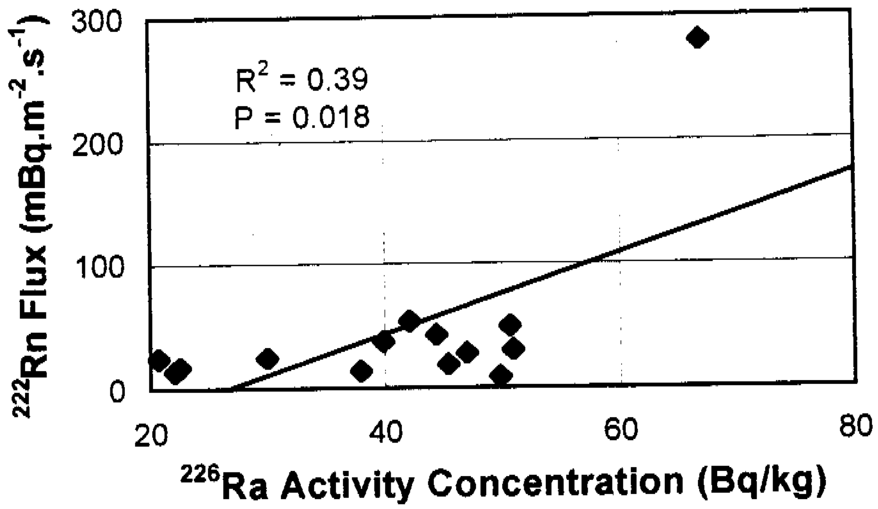
3.4.4 Factors Affecting Activity Flux

Simple linear regression analysis was used as the first step in determining the association between flux and the various parameters measured. Linear dependence was not assumed, this statistical technique was simply used to provide and indication of general trends. Both r-squared values and correlation coefficients were determined. Correlation between variables does not necessarily imply cause. Conversely a lack of correlation does not necessarily mean there is no relationship between flux and the variable observed, it may be a non-linear relationship or the relationship may be masked by other dominant factors. To limit analysis, non-linear relationships were examined by visual inspection of plots of the experimental data.

The only sites excluded from the following analysis were the two waste rock dump sites. However due to equipment failure not all parameters were determined for all sites.

The strongest correlation found was between radon activity flux and radium activity concentration in the soil. This is illustrated in Figure 3.11. Correlation coefficients of 0.622 and 0.901 were found with ^{222}Rn and ^{220}Rn respectively. There was no correlation between ^{222}Rn and ^{220}Rn activity flux.

(a)



(b)

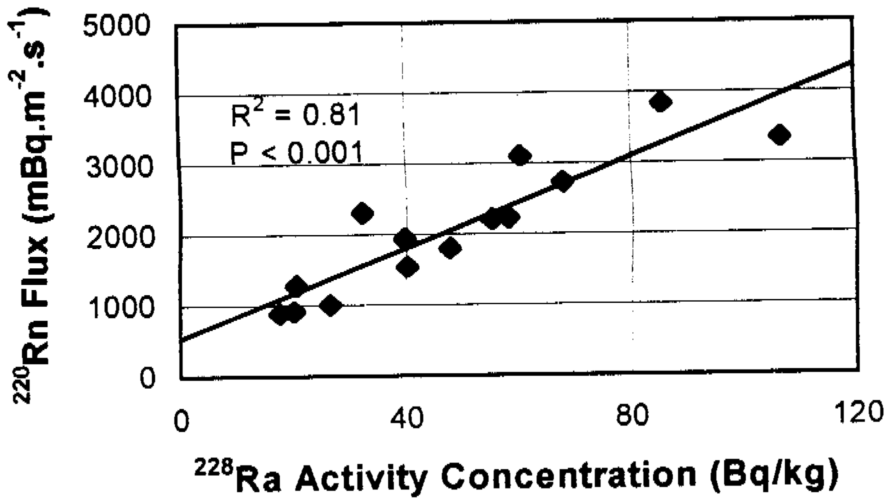


Figure 3.11 Flux Versus Radium Activity Concentration of the 0-20cm Core

(a) ^{222}Rn Flux Versus ^{226}Ra Concentration

(b) ^{220}Rn Flux Versus ^{228}Ra Concentration

For ^{222}Rn the next best, but significantly weaker correlations, where with air temperature (-0.421), ratio of >2mm fraction to <2mm fraction in the core sample (-0.313), and terrestrial gamma dose rate at 1m above ground (0.301).

Significant correlation was found between ^{220}Rn flux and terrestrial gamma dose rate at 1m above the ground, with a correlation coefficient of 0.621. Weaker correlation was also observed with the ratio of >2mm fraction to <2mm fraction for the core sample (0.344).

For both isotopes the linear correlation with soil moisture was weak. This will be discussed in detail. Soil temperature, air soil temperature difference, barometric pressure, wind speed and solar radiation had very low correlation coefficients.

The correlation between air temperature on site and at the Institute was very strong (correlation coefficient 0.88). Linear regression analysis of air temperature on site as a function of air temperature at the Institute produces an equation of gradient 0.94 and x-intercept -0.8. Similarly there was a strong correlation between relative humidity on site and at the Institute. The equation for this line had a gradient of 0.81 and an intercept of 7. Relative humidity on site was generally higher than measured at the Institute, however for the purpose of determining correlations the results obtained are suitable. These results validate the data collected by the portable probes on site.

Parent Nuclide Activity Concentrations

The radium activity concentration of the 0-20 cm core soil sample was found to be the best predictor of radon flux. Radionuclide analysis was performed on the >2mm fraction, and the <2mm fraction. The activity concentration of the sample was determined using the concentrations of the two fractions and the >2mm/<2mm ratio.

For ^{222}Rn, the concentration of ^{226}Ra in the >2mm portion of the core sample provided the best correlation with a coefficient of 0.97. This is significantly better than the correlation coefficients determined for the <2mm fraction and the whole sample of 0.67 and 0.62 respectively. This may be due to the statistics as the activity concentration in the >2mm fraction was significantly larger than in the <2mm fraction for all samples analysed. The site at Magela Ck which had unusually high ^{222}Rn flux (280 $mBq.m^{-2}.s^{-1}$) seems to have a large effect on the correlation of ^{222}Rn flux to ^{226}Ra concentration (Figure 3.11a). The P-value however is 0.0182. This is the probability that the observed data could have come from an uncorrelated data set. As this value is small it is likely that ^{222}Rn flux and ^{226}Ra are correlated.

In contrast the correlation between ^{220}Rn and ^{228}Ra concentration in the whole core sample was very strong (linear correlation coefficient = 0.90, P-value < 0.001). Though present, correlations with the >2mm and < 2mm fraction were significantly weaker.

In their study of flux from Australian soils, Schery et al (1989) found only weak correlation between flux and radium concentrations. They have suggested that it is the emanating fraction, not parent concentrations, which are most important. A survey of radon in Canada (Grasty, 1994) found no significant correlation between ^{222}Rn and uranium concentration determined by airborne gamma-ray spectrometry and concluded that other major factors were controlling the flux.

Ratio of the Fraction >2mm to the Fraction <2mm for the Core Sample

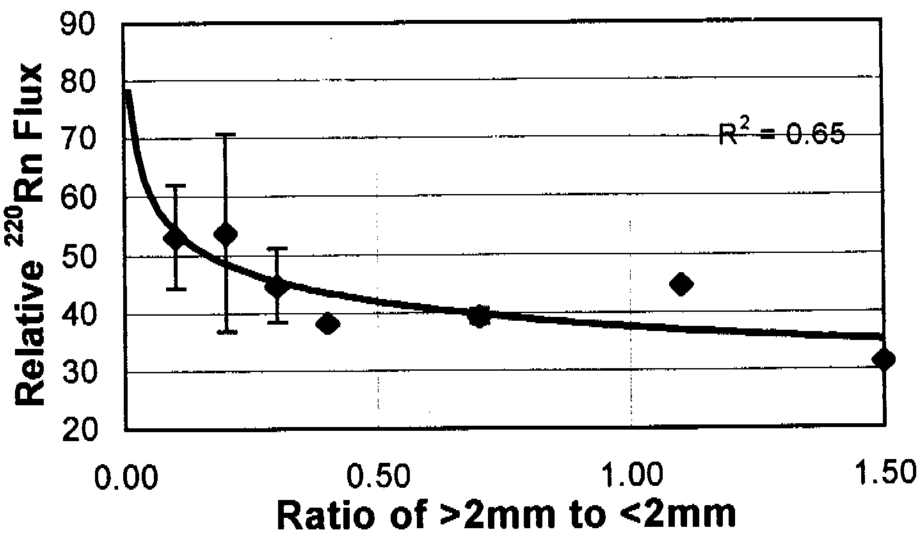
It has been shown that radon emanation rate is greater for smaller mineral grains (Amin et al, 1995; 1993; Strong and Levins, 1982). Amin et al found that a plot of emanation rate as a function of grain size correlated well the surface to volume ratio, for mineral grain sizes in the range 63-250 μm. For the purpose of this survey all soil samples were separated into two fractions, greater than and less than 2mm. The ratio of the >2mm to the <2mm fractions by weight was determined for each sample.

Weak correlation was found between ^{222}Rn and ^{220}Rn activity flux and the ratio >2mm /<2mm with correlation coefficients of -0.31 and 0.34 respectively. The true relationship between the flux and this ratio seems to be masked by other dominant factors. Due to the strong correlation between flux and radium activity concentration it was decided to 'normalise' the data for radium concentration. The term relative flux is used here to describe the ratio of the activity flux to radium activity concentration in the soil. For example the relative ^{222}Rn flux is the ratio of the ^{222}Rn flux to the ^{226}Ra concentration measured at a particular site. Figure 3.12 demonstrates the association between relative flux and the ratio of the >2mm fraction to the <2mm fraction. A binned plot was used as it provides a clearer representation of the data. It can be seen that the flux decreases as the grain size increases. This is most likely due to an increase in emanation as the ratio of the surface area to volume increases (ie as grain size decreases).

Gamma Dose Rate

Terrestrial gamma dose rate at 1m above ground correlated well with ^{220}Rn activity flux but not with ^{222}Rn. Linear correlation coefficients of 0.62 and -0.29 were calculated. The negative correlation obtained with ^{222}Rn flux is due to the high values at Magela Creek. If these are excluded from the analysis a linear correlation coefficient of -0.055 is found. Therefore no

(a)



(b)

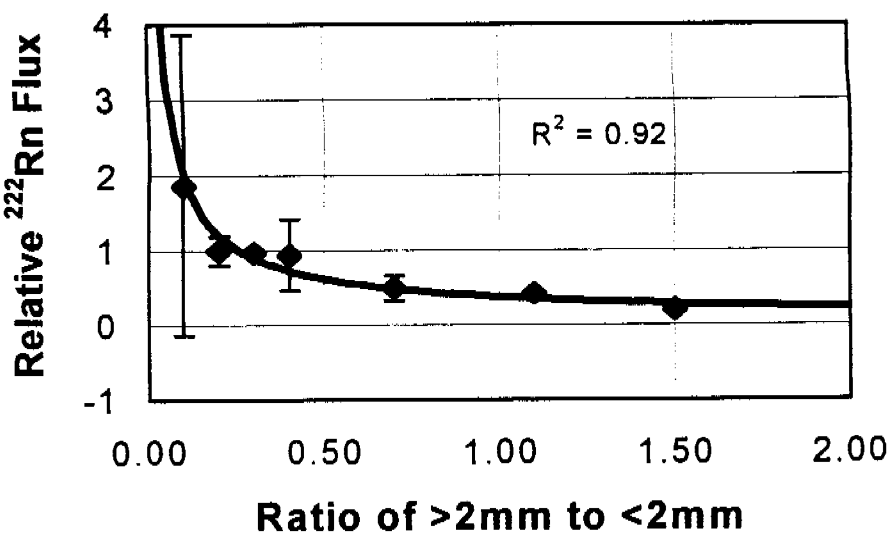


Figure 3.12 Relative Flux as a Function of the Ratio of the >2mm Fraction to the <2mm Fraction for the Core Sample (a) ^{222}Rn, (b) ^{220}Rn

relationship between ^{222}Rn flux and gamma dose rate was observed. These results may be due to the origin of the various parameters. The top layers of soil would contribute most significantly to the ^{220}Rn flux and the gamma dose rate, however ^{222}Rn may exhale from the top few metres of soil.

The correlation between terrestrial gamma dose rate at 1m above ground and the activity concentration of ^{226}Ra, ^{228}Ra, and ^{40}K in the core samples were also examined. No correlation was found with ^{226}Ra or ^{40}K, however very good correlation was observed with ^{228}Ra (correlation coefficient 0.88).

Kvasnicka and Bywater (1991) quote the following equation that may be used to calculate terrestrial gamma radiation. Considering a homogeneous distribution of radionuclides in a semi-infinite source the gamma dose rate ($D^{\cdot}$ in $Gy.h^{-1}$) in air at one metre above the ground may be calculated approximately by the following:

$$D^{\cdot} = (4.3E\text{-}10\ a_{U\text{-}238} + 6.6E\text{-}10\ a_{Th\text{-}232} + 4.2E\text{-}11\ a_{K\text{-}40})\ (1\text{-}P)\ \rho/\rho_s$$

Where a - specific activities of ^{238}U, ^{232}Th and ^{40}K in dry soil ($Bq.kg^{-1}$)

ρ - soil density ($kg.m^{-3}$)

ρ_s - soil bulk density ($kg.m^{-3}$)

P - soil porosity

Soil porosity, bulk density, and density, were not determined in the current study. AS an approximation the correlation between the terrestrial gamma dose rate at 1m above ground and the function: ($4.3\ a_{U\text{-}238} + 6.6\ a_{Th\text{-}232} + 0.42\ a_{K\text{-}40}$) was determined. A very good correlation was obtained (correlation coefficient 0.89) as can be seen in Figure 3.13.

Schery et al (1989) found that gamma dose rate gave the strongest correlation with radon flux, significantly better than any other variable.

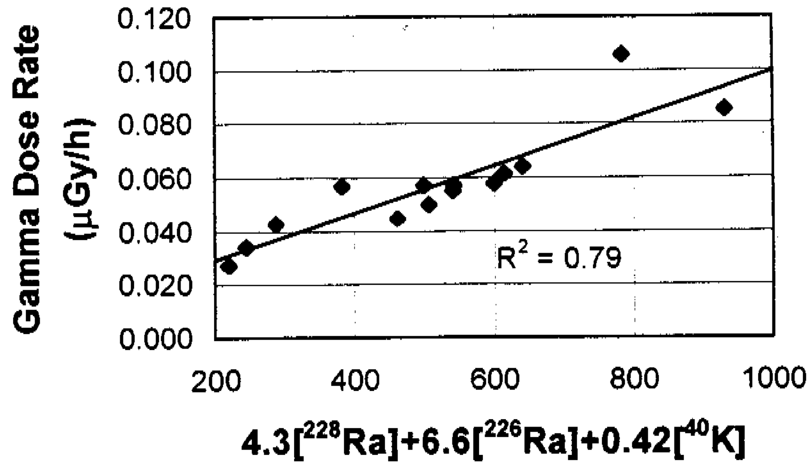


Figure 3.13 Gamma Dose Rate Versus Approximation of Formula

Soil Moisture

Many studies agree that soil moisture initially causes an increase in flux due to an increase in the emanation fraction. As the pore spaces fill with water the diffusion length decreases causing a decrease in flux and eventually no flux is observed. This is demonstrated in an experiment into the effect of moisture on uranium mill tailings by Strong and Levins (1982). How soil moisture should be used in predicting flux is not clear.

No linear correlation was observed between ^{222}Rn and ^{220}Rn flux and soil moisture (with linear correlation coefficients less than -0.07). This is not surprising as a non-linear relationship is expected. Visual inspection reveals no obvious relationship between ^{222}Rn and soil moisture. Figure 3.14 is a plot of ^{220}Rn flux as a function of soil moisture in the top 10cm of soil. The moisture in the top 10cm was used as the majority of the ^{220}Rn would originate in this zone. It can be seen that above average flux values lie in the moisture range from 2 to 4%. All data points with soil moisture greater than 4% have reduced flux.

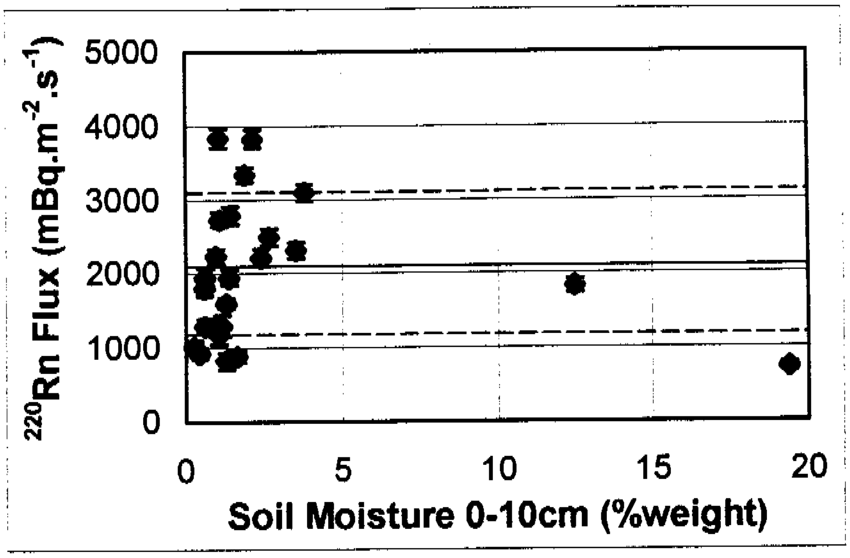


Figure 3.14 ^{220}Rn Flux as a Function of Soil Moisture in the Top 10cm of Soil The average flux is marked by a solid line with dotted lines marking one standard deviation either side of the average

Relative flux (the ratio of radon flux to radium concentration) was observed as a function of soil moisture. No relationship is observed between the relative ^{222}Rn flux and soil moisture while a slight increase in ^{220}Rn flux with soil moisture is observed. This data set is limited due to the number of samples that have been analysed for radium activity concentration. The maximum soil moisture in this data set is less than 4%. A significant reduction in flux would be expected for soil moisture approximately greater than 8% (Schery et al , 1989; Strong and Levins, 1983).

Meteorological Parameters

Studies into the influence of meteorological parameters on flux have produced conflicting reports. The effect, if any, of the various parameters and their relative significance are not agreed upon. Studies performed at one site with time have found significant correlation between ^{222}Rn flux and barometric pressure (Duenas and Fernandez, 1987; Schery and Pertschek, 1983; Schery et al, 1984;). In general and increasing atmospheric pressure causes a decrease in flux. Significant effects have been observed in both instantaneous and long term flux measurements. Model calculations of flux also predict an effect due to changes in atmospheric pressure (Edwards and Bates, 1980). The survey of Australian soils by Schery et al (1989) however found only a very weak effect due to pressure variations.

The effect of soil and air temperature is not clear. Studies performed at one site with time found no correlation with flux (Schery et al, 1984; Tidjani, 1988). Schery et al (1989) found significant correlation between flux and soil temperature but only weak correlation with air temperature. It is thought that a possible temperature effect could be explained by changes in the emanating fraction or sorption-related effects (Schery et al, 1984). This is supported by Markkanen et al (1992) who found an increase in emanation with increasing temperature. Temperature variations may have more effect on ^{220}Rn as changes will effect the top few decimetres of soil.

The effect of wind speed is also unclear. It has been postulated that the high frequency pressure changes induced by wind may have an effect on flux. Experimentally wind speed seems to have little or no effect on flux from a region (Schery et al, 1989) but may contribute to diurnal and seasonal variations at one site (Duenas and Fernandez, 1987).

Of the meteorological parameters measured in the current study, air temperature and relative humidity had the best correlation with ^{222}Rn however these were significantly weaker than the effect of ^{226}Ra activity concentration. No significant effect was observed due to wind speed, barometric pressure, soil temperature or air soil temperature difference. No significant correlation was found between ^{220}Rn flux and any of the meteorological parameters.

^{222}Rn Flux as a Function of ^{220}Rn Flux

No correlation was found between ^{222}Rn and ^{220}Rn activity flux. The linear correlation coefficient (-0.287) was negative however this is due to the high ^{222}Rn flux values at the Magela Creek location. If these sites are excluded a correlation coefficient of -0.12 is obtained. Only a weak correlation is found between the relative ^{222}Rn and ^{220}Rn flux.

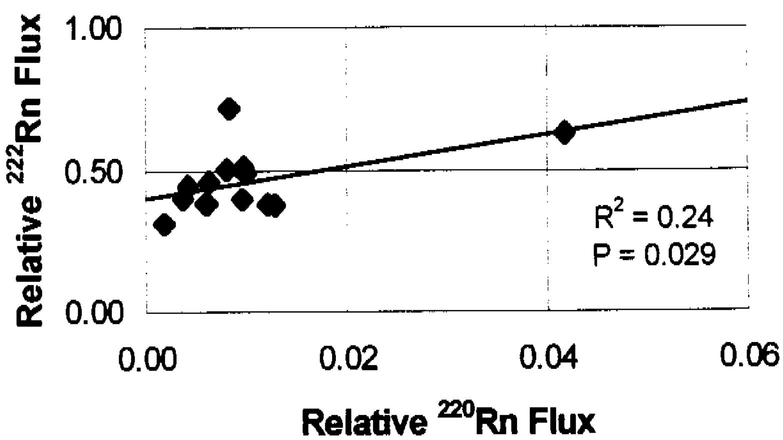


Figure 3.15 Relative ^{222}Rn Flux versus Relative ^{220}Rn Flux
(Relative Flux = Radon Flux / Radium Concentration)

Very few studies have compared ^{222}Rn and ^{220}Rn flux in this way as most studies focus on ^{222}Rn and a number are observing the variation in radon flux at only one site. Schery et al (1989) found significant correlation between radon and thoron (linear correlation coefficient 0.51). Their study covered a large portion of Australia and had a maximum ^{222}Rn flux of only 118mBq.m^{-2}.s^{-1} which is just over half the maximum observed in this survey (280 mBq.m^{-2}.s^{-1}). It is expected that the various environmental parameters would effect both ^{222}Rn and ^{220}Rn flux in the same way. However in this survey no correlation was found between ^{222}Rn and ^{220}Rn flux and only weak correlation was observed between the relative flux values (which take into account the dominance of radium activity concentration).

3.5 CONCLUSION

The average ^{222}Rn flux for the region was determined to be 64 ± 25 $mBq.m^{-2}.s^{-1}$. This is considerably higher than estimates of Australian and World averages and is dominated by the presence of the Ranger Uranium Mine. The average ^{220}Rn flux, 2.15 ± 0.21 $Bq.m^{-2}.s^{-1}$, was not significantly different to the estimated world and Australian averages. For both isotopes the distributions were approximately lognormal.

The type of study performed seems to have a large effect on the relative significance of the various parameters. The effects also seem to be very site dependent. In this study the effect of radium concentration on both ^{222}Rn and ^{220}Rn dominated variations in flux. Tables 3.3 and 3.4 contain a summary of all correlations obtained. Soil moisture and the ratio of >2mm and <2mm fraction also had some effect on flux observed. No significant correlation was found with any of the meteorological parameters. However this may be due to the limited range of these parameters during the survey period. This lack of correlation does not mean that the parameters have no effect on flux, however the effect is not significant compared to other dominating factors. Caution would be applied before extending these results for comparison in another region. The unique properties of the region make it difficult to compare to other areas.

No correlation was observed between ^{222}Rn and ^{220}Rn flux. This may indicate that the various parameters are affecting ^{222}Rn and ^{220}Rn in different ways due to their different origins.

Table 3.3 Summary of Correlations Obtained for Environmental Parameters

	^{222}Rn Flux (mBq.m^{-2}.s^{-1})	^{220}Rn Flux (mBq.m^{-2}.s^{-1})	Gamma Dose Rate (uGy/h)	Soil Moisture (%) 0-10cm	Soil Moisture (%) 0-20cm	Air Temperature - Site (C)	Air Temperature - Institute (C)	Soil Temperature (C)	Air Soil Temp Difference (C)	Barometric Pressure (hPa)	Wind Speed (km/h)	Relative Humidity Site (%)
^{220}Rn Flux (mBq.m^{-2}.s^{-1})	-0.287	1										
Gamma Dose Rate (uGy/h)	0.301	0.621	1									
Soil Moisture (%) 0-10cm	-0.236	-0.182	-0.252	1								
Soil Moisture (%) 0-20cm	-0.255	-0.116	-0.237	0.997	1							
Air Temperature - Sita (C)	-0.421	0.250	-0.171	0.091	0.106	1						
Air Temperature - Institute (C)	-0.329	0.052	-0.208	0.368	0.360	0.878	1					
Soil Temperature (C)	-0.165	0.134	0.005	-0.387	-0.400	0.600	0.239	1				
Air Soil Temp Difference (C)	-0.150	-0.037	-0.177	0.569	0.579	-0.082	0.261	-0.846	1			
Barometric Pressure (hPa)	0.140	-0.086	0.107	-0.243	-0.242	-0.773	-0.888	-0.170	-0.265	1		
Wind Speed (km/h)	0.141	0.115	-0.067	-0.015	0.038	0.063	0.056	-0.085	0.177	-0.136	1	
Relative Humidity -Site (%)	0.306	-0.251	0.278	-0.036	-0.076	-0.492	-0.424	-0.139	-0.146	0.517	-0.539	1
Relative Humidity - Institute (%)	0.025	0.000	0.281	-0.201	-0.223	-0.459	-0.622	0.101	-0.383	0.680	-0.540	0.900
>2mm/<2mm Core	-0.313	0.344	0.622	-	-	-	-	-	-	-	-	-

Table 3.4 Summary of Correlations Obatianed with Radiometric Data

	^{222}Rn Flux (mBq.m^{-2}.s^{-1})	^{220}Rn Flux (mBq.m^{-2}.s^{-1})	Gamma Dose Rate (uGy/h)	^{238}U Concentration	^{226}Ra Concentration	^{210}Pb Concentration	^{40}K Concentration	^{228}Ra Concentration
^{238}U Concentration	0.371	0.574	0.631	1				
^{226}Ra Concentration	0.622	0.375	0.422	0.784	1			
^{210}Pb Concentration	0.497	0.229	0.259	0.736	0.644	1		
^{40}K Concentration	0.303	-0.058	0.049	0.446	0.305	0.415	1	
^{228}Ra Concentration	-0.338	0.901	0.879	0.488	0.361	0.256	-0.231	1
4.3[^{238}Ra]+6.6[^{228}Ra]+[^{40}K]	-0.092	0.884	0.887	0.683	0.622	0.439	-0.032	0.952

CHAPTER 4. DIURNAL VARIATIONS IN RADON ACTIVITY FLUX

4.1 EXPERIMENTAL METHOD AND RESULTS

The aim of this experiment was to examine possible diurnal variation in ^{222}Rn and ^{220}Rn activity flux. Activity flux was measured with time at the one site. Various meteorological parameters were also examined including air and soil temperature, relative humidity, wind speed and direction, and barometric pressure. The data was examined to determine if significant diurnal variation occurred. Analysis was then performed to determine if any association existed between flux and the meteorological parameters.

Three separate trials were performed. Details of these trials are contained in Table 4.1. Trial 1 was performed at Jabiru East behind the Institute, near the automatic weather station. Measurements were taken approximately hourly from 8:30 am to 6:00 pm, ie during daylight hours. The second trial was at a site ES5D near the Magela Creek which had particularly high ^{222}Rn Flux. Measurements were taken hourly from 7:30am to 4:30pm. Trial 3 was performed at the same site as trial 1 however measurements were taken every 3 hours for a 24 hour period.

^{222}Rn and ^{220}Rn flux measurements were performed as described in Chapter 2. The drum was placed in the same position when performing the measurements for each trial. Flux data was collected a minimum of one hour apart to ensure the background in the detectors had reduced to a reasonable level. To limit the build up of radon under the drum, it was removed from the ground and aired between measurements. Meteorological measurements

Table 4.1 Summary of Trials Performed Into the Diurnal Variation of ^{222}Rn and ^{220}Rn Activity Flux

Trial Number	1	2	3
Site	Institute	Magela Ck (ES5D)	Institute
Time Of Measurements			
Start of First Measurement	8:30 10-7-96	7:30 30-8-96	8:12 12-9-96
Start of Last Measurement	18:00 10-7-96	16:30 30-8-96	4:22 13-9-96
Number of Flux Measurements	10	9	7
Frequency	Approximately hourly	Hourly	3 Hourly
^{222}Rn Activity Flux (mBq.m^{-2}.s^{-1})			
Average	34	292	38
Standard Deviation	6	122	9
Maximum	44 ± 5 at 18:02	400 ± 12 at 10:30	50 ± 4 at 20:00
Minimum	26 ± 4 at 13:01	72 ± 7 at 15:30	27 ± 5 at 8:12
^{220}Rn Activity Flux (mBq.m^{-2}.s^{-1})			
Average	2820	899	2449
Standard Deviation	234	402	373
Maximum	3196 ± 127 at 13:01	1386 ± 160 at 16:30	2979 ± 122 at 13:56
Minimum	2460 ± 135 at 18:02	635 ± 193 at 8:30	1962 ± 114 at 4:22

were performed with the Monitor Sensor Automatic Weather Station used in the activity flux survey.

There was a significant difference in the maximum and minimum flux of both the ^{222}Rn and ^{220}Rn flux observed in all three trials. The greatest variation in ^{222}Rn flux was observed at the Magela Creek site. No significant difference was observed in the average, maximum or minimum ^{222}Rn flux found in the two trials at the institute. There was a slight difference in the ^{220}Rn flux observed during the two trials. The first trial, during daylight hours only, had slightly higher average ^{220}Rn flux than trial 3, over 24 hours.

4.2 ANALYSIS AND DISCUSSION

The diurnal variation in ^{222}Rn flux for the three trials is illustrated in Figure 4.1. In all three trials below average flux was observed through the middle of the day. Changes in ^{222}Rn for trial 3 are not as clear as the other trials. More frequent measurements may be required to accurately examine the diurnal variations. Figure 4.2 contains the results obtained for ^{220}Rn flux. In contrast to ^{222}Rn there seems to be a trend towards higher ^{220}Rn flux through the middle of the day.

No correlation was found between ^{222}Rn and ^{220}Rn flux at the Magela Creek Site, while quite a strong negative correlation was found between these parameters at the site behind the Institute (correlation coefficients of -0.69 and -0.42 for trial 1 and 3 respectively). It is expected that the parameters controlling any variations in flux at the one site with time would affect ^{222}Rn and ^{220}Rn in the same way. Therefore a strong positive correlation between ^{222}Rn and ^{220}Rn flux is expected. The negative correlation may indicate that different parameters dominate the variations in ^{222}Rn and ^{220}Rn.

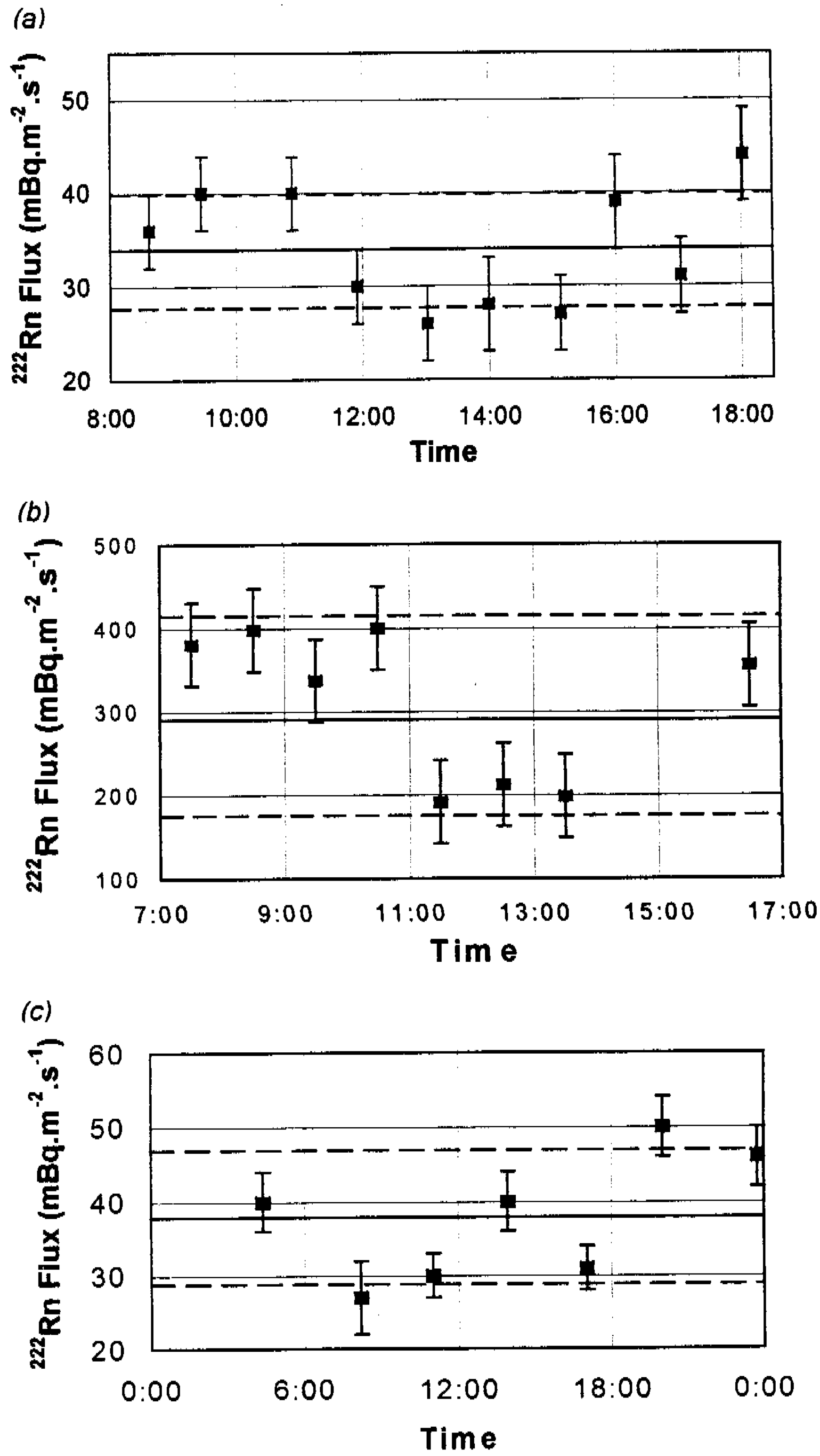


Figure 4.1 Diurnal Variation in ^{222}Rn Flux (a) Trial 1: Institute (b) Trial 2 : Magela Creek (c) Trial 3 : Institute over 24 hours. The solid line marks the average flux, while dashed lines are at ± one standard deviation

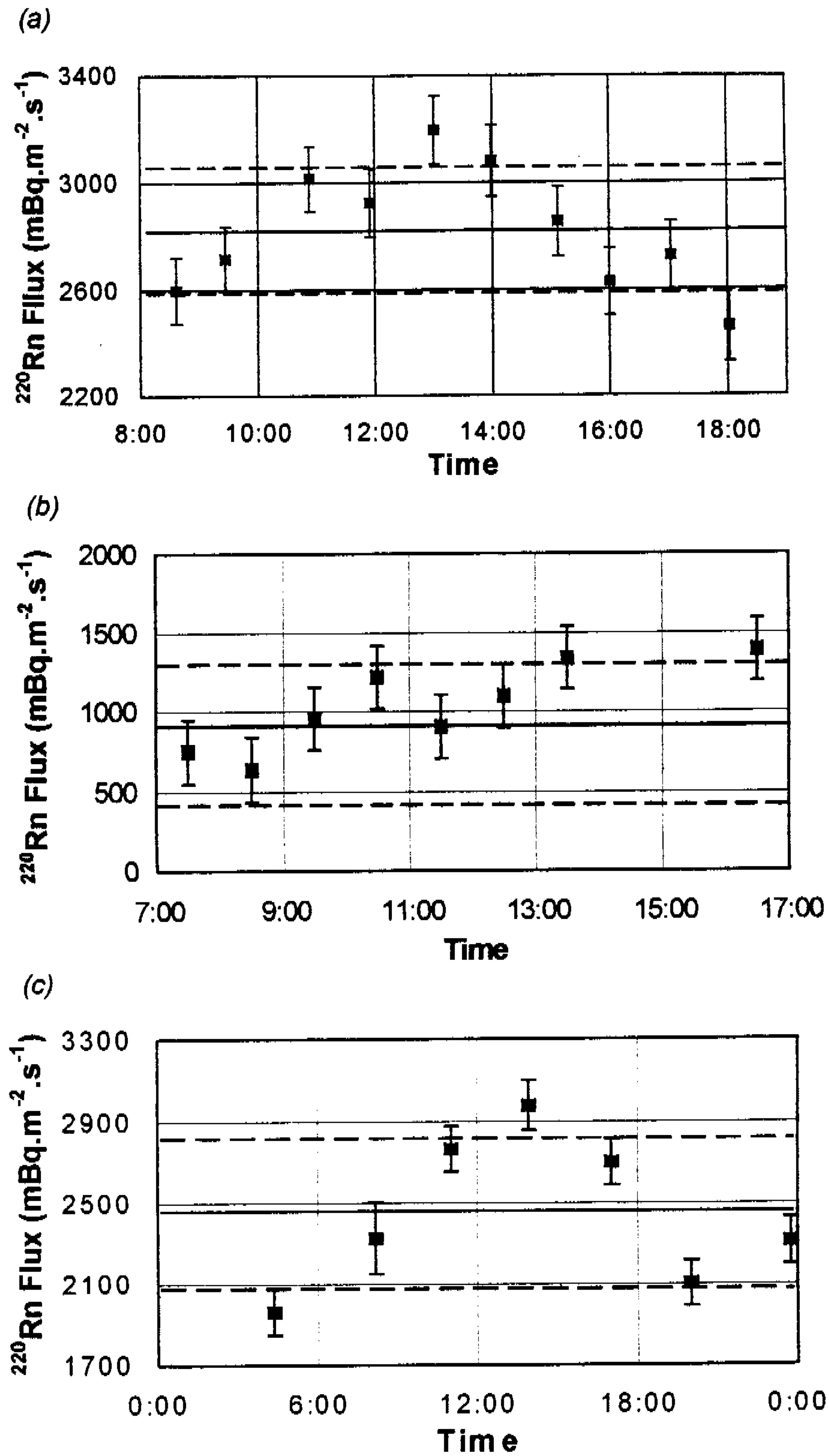


Figure 4.2 Diurnal Variations in ^{220}Rn Flux (a) Trial 1 : Institute (b) Trial 2 : Magela Creek (c) Trial 3 : Institute over 24 hours The solid line marks the average flux, while dashed lines are at ± one standard deviation

Table 4.2 Correlations Obtained in Diurnal Trials

Trial 1

Parameter	^{222}Rn Flux		^{220}Rn Flux	
	Correlation Coefficient	P-value	Correlation Coefficient	P-value
^{220}Rn Flux	-0.691	0.029	1.000	-
Air Temperature	-0.512	0.13	0.184	>0.5
Soil Temperature	-0.536	0.11	0.368	0.31
Air- Soil Temperature Difference	0.467	0.18	-0.108	>0.5
Barometric Pressure	0.176	>0.5	0.188	>0.5
Wind Speed	-0.215	>0.5	0.627	0.053

Trial 2

Parameter	^{222}Rn Flux		^{220}Rn Flux	
	Correlation Coefficient	P-value	Correlation Coefficient	P-value
^{220}Rn Flux	0.0758	>0.5	1.00	-
Air Temperature	-0.672	0.048	0.564	0.058
Soil Temperature	-0.735	0.025	0.562	0.059
Air- Soil Temperature Difference	0.655	0.057	-0.384	0.32
Barometric Pressure	0.428	0.26	-0.482	0.19
Wind Speed	-0.665	0.051	0.570	0.11

Due to equipment problems no meteorological data was collected for trial 3, behind the institute. Table 4.2 contains the correlation coefficients and P-values found for trials one and two. Strong negative correlations were observed between both air and soil temperature and ^{222}Rn flux. A weaker correlation was found between flux and the difference between air and soil temperature. A reasonable negative correlation was observed with wind speed at the Magela Ck site. This is surprising as the wind speed only varied between 0 and 3 km/hr in this trial. The weak correlations observed with barometric pressure are probably due to the limited variations in this parameter.

Much weaker correlations were observed between ^{220}Rn flux and the various meteorological parameters. At both sites the strongest correlation was with wind speed, followed by air and soil temperature. Weak correlation with barometric pressure was also observed at Magela Ck.

In general, barometric pressure is quoted as the major factor affecting variations with time at a particular site. Schery, Gaeddert and Wilkening (1984) found that pressure, rain and wind variations were generally sufficient in explaining observed diurnal, semi-diurnal and long term variations in flux. They found barometric pressure and rainfall were the major factors while wind was of minor importance. No effects due to air or soil temperature variations were observed. However they have postulated a number of processes by which temperature may affect flux. From kinetic theory of diffusion one expects $J_{diffusion} \propto T^{1/2}$, however this effect is typically small and would only apply to the top few decimeters of soil. Thermal expansion of the soil would also occur leading to an enhancement of flux. Once again only the top few decimters of soil would be affected while ^{222}Rn travels metres through the soil. Thermally induced convection has been ruled out as a significant effect (Schery and Petsheck, 1983). Emanation is also known to increase with temperature. Temperature may have a greater affect on ^{220}Rn flux due to greater variations in the top layers of soil.

4.3 CONCLUSION

Significant variation in both ^{222}Rn and ^{220}Rn flux was found in all three trials. It is important to understand diurnal variations which may occur in activity flux as it provides and insight into the effects of the meteorological parameters on flux in the region which can't be obtained through a survey of the region.

The results of the current study are surprising. A strong positive correlation was expected between ^{222}Rn and ^{220}Rn however at the institute a strong negative correlation was found, while there was no correlation between the two at the Magela Ck site. Correlations found with meteorological parameters are contained in Table 4.2. The fact that correlations were found with these parameters does not imply that they caused the variations in flux. For example it is not likely that increased temperatures caused a decrease in ^{222}Rn flux as the correlations would suggest. A more detailed study of the diurnal variations need to be performed to determine what effects are causing the changes in flux.

A study of variations in flux over a full cylce of the seasons would also be useful in providing insight into the effects of the various meteorological parameters on flux. The relationship between ^{222}Rn and ^{220}Rn also requires further investigation.

CHAPTER 5. STUDY OF ^{220}RN EMANATION FROM A MONAZITE SAMPLE

5.1 INTRODUCTION

To date few studies have been performed on ^{220}Rn as it is generally considered an insignificant risk compared to ^{222}Rn, due to it's short half life. However in regions with elevated ^{232}Th radioactivity, for example areas containing mineral sand deposits or at sites contaminated with mineral sand derivatives, the dose due to ^{212}Pb may be significant (NCRP, 1988; Steinhausler et al, 1994).

^{220}Rn in the atmosphere originates principally from the top few centimetres of soil. It was originally assumed that, with such a short half life, ^{220}Rn from the soil would not contribute significantly to indoor concentrations. However Li, Schery and Turk (1992) have published data which indicates that soil is a significant source of indoor ^{220}Rn.

There is also a statistical advantage in studying ^{220}Rn as it's flux is much greater than ^{222}Rn flux (due to it's half life). Therefore it is simple to obtain more accurate results in a shorter time frame.

This study aimed to examine, for a particular monazite sample, the depth from which ^{220}Rn emanates and the effect of moisture on flux.

5.2 EXPERIMENTAL METHOD

The sample chosen was a monazite sample obtained from Consolidated Rutile Limited Qld. It had elevated ^{232}Th levels making it simple to perform accurate measurements of ^{220}Rn flux. Monazite is a product of the mineral sands industry which is important throughout south east Queensland and in Western Australia.

The monazite content in mineral sand deposits is typically 0.1% and approximately 1% in heavy mineral concentrates. Australian monazite typically contains 5-7% Thorium and 0.1-0.3% Uranium (Koperski, 1993).

Radionuclide analysis was performed using a HPGe well detector. The amount of ^{232}Th present was determined from activity concentration measurements of the daughters ^{228}Ac, ^{212}Pb and ^{212}Bi assuming secular equilibrium. The sample contained 6.753 ± 0.003 % ^{232}Th by weight.

A column of monazite of known thickness between 0 and 40cm, was used to observe the variation in flux with sample thickness (Figure 5.1). Throughout the measurements the surface level and surface area (6.6E-3 m^2) remained constant. Flux from a selected set of columns was also measured with time from approximately 5 min after filling for up to 5 days.

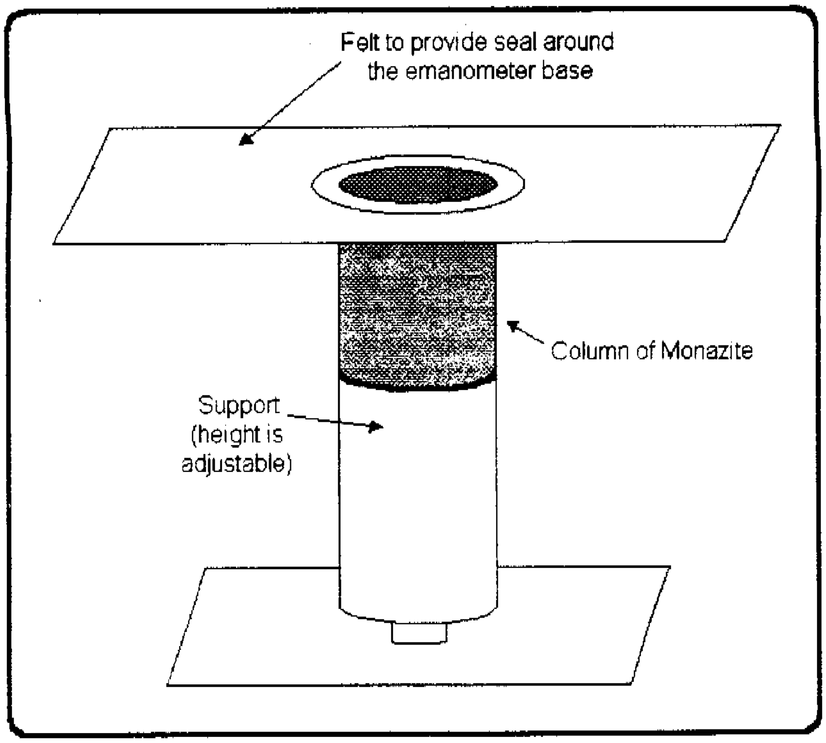


Figure 5.1 Schematic Diagram of Experimental Arrangement

The effect of water content on flux was studied in two ways. Firstly known amounts of deionised water were added homogeneously to four monazite samples of various depth and surface area. Secondly the column was filled to 0.398m and rainfall was simulated by sprinkling 50mL of water over the surface with a burette over approximately 2min. This corresponds to a shower of approximately 7mm. This corresponds to a rainfall rate of approximately 200mm/h. This is a very high rate however in the monsoonal climate of the Northern Territory showers of this nature do occur. The average recurrence interval of a shower of this intensity for a duration of 5min is 5 years (ERA, 1996b). That over 100 years approximately 20 showers of this nature would occur. Flux was measured at various intervals for 8 days after the event. Temperature and humidity remained fairly constant at approximately 23.5° and 60% respectively.

5.3 RESULTS AND DISCUSSION

Results of the column experiments show that the flux increased with thickness to approximately 5cm, after which no significant change occurred (Figure 5.2). It was also found that there was no significant change in the measured flux with time from 5 minutes after filling.

These results suggest that ^{220}Rn originating in only a few centimetre layer of surface mineral contribute significantly to the surface flux. The thickness of surface soil contributing to ^{220}Rn concentrations is significantly less than the reported values for radon. For example, a review of ^{222}Rn flux from uranium mill tailings (IAEA, 1992) indicates that the thickness of tailing has no effect on ^{222}Rn flux beyond about 2m for wet tailings and about 4m for dry tailings. ^{222}Rn to ^{220}Rn ratio can therefore, vary with the thickness of the contributing layer. The difference in the thickness of the contributing is primarily due to the difference in the isotopes half lives (UNSCEAR, 1993; Schery, 1990).

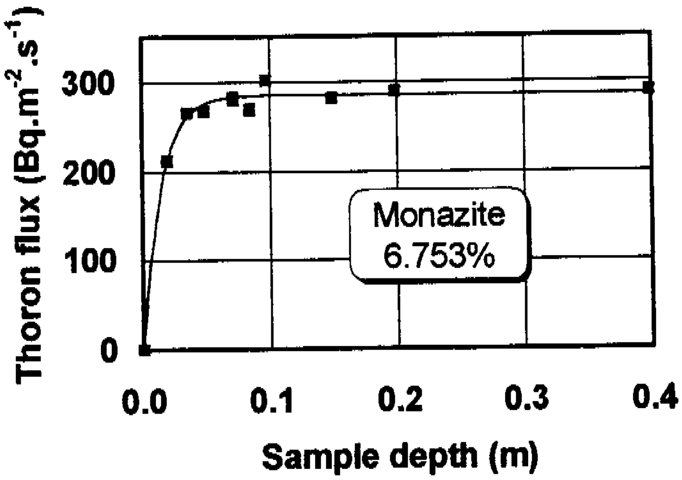


Figure 5.2 ^{220}Rn Activity Flux as a Function of Coulmn Thickness

The flux initially increased with water content, with elevated levels to approximately 6% water by weight. This has been illustrated in Figure 5.3a Through a representative result for a sample 0.018m thick. The region where virtually no flux was measured corresponds to the point where a thin film of water covered the surface. The initial increase was greater for samples of smaller thickness (Figure 5.3b).

These findings can be explained by the combined effect of emanation and transport. The recoil range of ^{220}Rn in water is considerably smaller than in air, in the order of 0.1μm and 83μm respectively (Tanner, 1980). Therefore as the water content increases the probability that any ^{220}Rn which escapes from the soil grains will stop in the pore space increases. However as water content increases the diffusion length decreases until 'capping' occurs and virtually no flux in observed. The greater increase for samples of smaller depths suggests that the sample thicknesses were less than the average diffusion length therefore any decrease in diffusion had less effect on the surface flux.

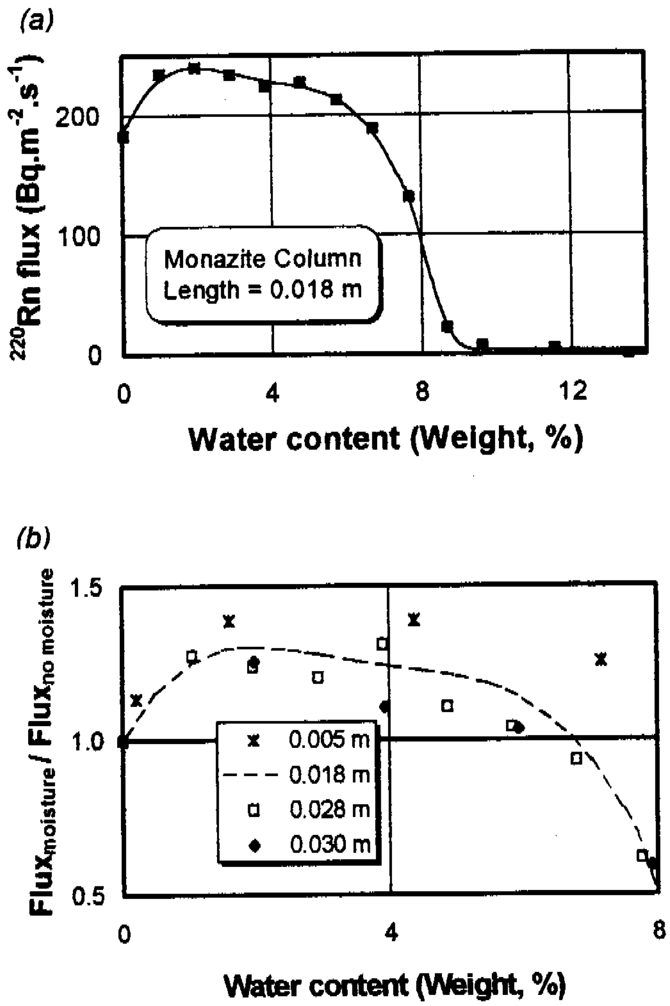


Figure 5.3 ^{220}Rn Flux Versus Water Content (a) An Example of Results Obtained (b) As a Ratio of Moist Flux to Dry Flux

The results of the simulated rainfall experiment are presented in Figure 5.4 where the variation in ^{220}Rn flux is plotted as a function of time. Initially the flux rapidly reduces to near zero, corresponding to a situation when the sample is covered with water. Following this, the moisture content of the surface layers decreases as the water seeps to the deeper layers and evaporates form the surface. This is reflected as a gradual increase in the ^{220}Rn flux over approximately 3 days. The flux actually reaches a value about 20% above the dry flux for four days, suggesting 1-6% moisture in the surface layers of mineral (refer to Figure 5.3(b)). The flux then decreases to its initial value.

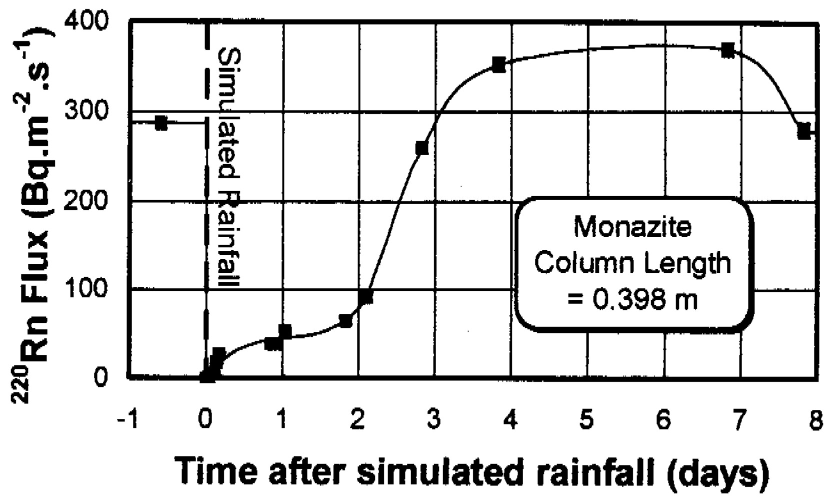


Figure 5.4 ^{220}Rn Flux Response to Simulated Rainfall

5.4 CONCLUSION

For the given monazite sample, the ^{220}Rn flux increases with the column thickness, reaching a steady state value at about 0.05m. The steady state flux corresponds to 2Bq.m^{-2}.s^{-1}. The water content changes ^{220}Rn flux, reducing it rapidly from about 6% water by weight reducing to nearly zero from about 10% water by weight. Water content between 1-5% by weight, the flux is enhanced by 10-40% compared to dry conditions. ^{220}Rn flux variations with the soil moisture can be explained as the combined effect of two processes; a change in ^{220}Rn recoil range in the pore spaces and, a change in the diffusion length.

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APPENDIX 1 SITE DESCRIPTION AND PHOTOGRAPHS

Only two photographs which best represent each site are included.

SITE IDENTIFICATION : ES1B

Date :	17/07/96
Starting time :	10:30
GPS Location :	S12°40.940' E132° 49.600'
Location :	20m from Pin Creek Rd on the North Side, dirt section south of Jabiru Township
Vegetation :	Open grassland in a low floodplain area, mostly Livestonia with some Eucalypts, Pandanus and Acacia, approximately 90% ground cover
Flux :	^{222}Rn : 25 ± 3 mBq.m^{-2}.s^{-1} ^{220}Rn : 1014 ± 74 mBq.m^{-2}.s^{-1}

SITE IDENTIFICATION : ES1C

Date :	19/07/96
Starting time :	11:01
GPS Location :	S12°40.357' E132° 49.773'
Location :	Behind Jabiru water tower, Dust site No. 2
Vegetation :	Open grass area, approximately 70% ground cover
Flux :	^{222}Rn : 19 ± 3 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 3834 ± 126 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES1D

Date :	16/07/96
Starting time :	13:55
GPS Location :	S12°39.127' E132° 48.940'
Location :	North east side of the comer of East Alligator Rd and the Arnhem Hwy, approximately 10m from the road
Vegetation :	Very newly burnt, even large trees have not recovered, approximately 5% ground cover
Flux :	^{222}Rn : 43 ± 4 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 3097 ± 121 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES2B

Date :	22/07/96
Starting time :	10:31
GPS Location :	S12°41.121' E132° 49.134'
Location :	North of the golf club, approximately 1km east of site ES1B
Vegetation :	Predominantly Calytrix with Spear Grass (sparse), approximately 10% ground coverage
Flux :	^{222}Rn : 14 ± 3 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 2728 ± 108 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES2C

Date :	19/07/96
Starting time :	15:14
GPS Location :	S12°40.573' E132° 50.230'
Location :	Wooded area, Jabiru Township, end of Carrington St, Dust Site 4
Vegetation :	Eucalypts, sparse ground cover
Flux :	^{222}Rn : 14 ± 2 mBq.m^{-2}.s^{-1}
	^{220}Rn : 2489 ± 102 mBq.m^{-2}.s^{-1}

SITE IDENTIFICATION : ES2D

Date :	16/07/96
Starting time :	10:27
GPS Location :	S12°39.608' E132° 50.481'
Location :	South of the Telecom operations centre, opposite side of the road
Vegetation :	Open woodland, small shrubs covering the ground, fairly recently burnt, approximately 10% coverage under the drum
Flux :	^{222}Rn : 9 ± 2 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 3339 ± 117 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES2F

Date :	18/07/96
Starting time :	10:27
GPS Location :	S12°36.185' E132° 50.365'
Location :	Approximately 7km along the East Alligator Rd from the Arnhem Hwy, eastern side of the road
Vegetation :	Predominantly Eucalypts with some Acacias
Flux :	^{222}Rn : 38 ± 4 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 2211 ± 104 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES3B

Date :	10/09/96
Starting time :	12:32
GPS Location :	S12°41.259' E132° 51.258'
Location :	South along track east of Baralil Ck
Vegetation :	Eucalypts and Pandanus
Flux :	^{222}Rn : 11 ± 3 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 2909 ± 122 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES3C

Date :	24/07/96
Starting time :	14:22
GPS Location :	S12°40.639' E132° 51.357'
Location :	Approximately 1km south of the Arnhem Hwy along track east of Baralil Ck
Vegetation :	Open woodland, mainly Eucalypts, little undergrowth in sample area, approximately 5% coverage under drum
Flux :	^{222}Rn : 31 ± 3 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 2231 ± 103 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES3D

Date :	22/07/96
Starting time :	15:22
GPS Location :	S12°39.393' E132° 52.343'
Location :	South of Baralil Billabong
Vegetation :	Mostly Spear Grass in immediate area, small flowering plants, Paperbarks and some Pandanus
Flux :	^{222}Rn : 0 ± 0 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 725 ± 55 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES3E

Date :	25/07/96
Starting time :	10:31
GPS Location :	S12°39.049' E132° 50.907'
Location :	North east along track west of Telecom Operations Centre
Vegetation :	Mainly Eucalypts, some Livestonia, recently burnt, very little undergrowth, approximately 1-2% ground cover
Flux :	^{222}Rn : 54 ± 4 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 1805 ± 105 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES3G

Date :	17/07/96
Starting time :	14:48
GPS Location :	S12°35.532' E132° 51.482'
Location :	Western side of the East Alligator Rd opposite Mudginberri airstrip, Dust Site 7
Vegetation :	Eucalypts, no low vegetation due to recent burning
Flux :	^{222}Rn : 25 ± 3 mBq.m^{-2}.s^{-1}
	^{220}Rn : 3836 ± 129 mBq.m^{-2}.s^{-1}

SITE IDENTIFICATION : ES4C

Date :	23/07/96
Starting time :	11:11
GPS Location :	S12°40.182' E132° 53.074'
Location :	Eastern side of Gulungul Ck, approximately 2km along the radon spring track
Vegetation :	Open woodland, primarily Eucalypts, some Pandanus and Acacias, approximately 5% ground cover
Flux :	^{222}Rn : 14 ± 2 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 922 ± 67 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES4D

Date :	15/07/96
Starting time :	13:58
GPS Location :	S12°39.244' E132° 52.685'
Location :	East of Gulungul Ck, approximately 350 north of the Arhnem Hwy
Vegetation :	Open woodland, on the edge of the floodplain with Paper barks on the other side of the track
Flux :	^{222}Rn : 18 ± 3 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 885 ± 77 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES4E

Date :	18/07/96
Starting time :	14:19
GPS Location :	S12°37.757' E132° 53.107'
Location :	West of Magela 009 Campsite near Gulungul Ck
Vegetation :	Floodplain, open area with short grass, Paperbarks in background
Flux :	^{222}Rn : 25 ± 3 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 2311 ± 106 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES4/5C

Date :	12/07/96
Starting time :	11:19
GPS Location :	S12°39.778' E132° 53.575'
Location :	Jabiru East at the rear of the Institute
Vegetation :	Open woodland, very little ground cover
Flux :	^{222}Rn : 45 ± 4 mBq.m^{-2}.s^{-1}
	^{220}Rn : 1663 ± 103 mBq.m^{-2}.s^{-1}

SITE IDENTIFICATION : ES5A

Date :	28/08/96
Starting time :	15:06
GPS Location :	S12°41.578' E132° 53.330'
Location :	Range lease boundary, Dust Site 10
Vegetation :	Open woodland, mainly Eucalypts with a few Acacias
Flux :	^{222}Rn : 96 ± 6 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 1946 ± 113 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES5C

Date :	25/07/96
Starting time :	13:56
GPS Location :	S12°40.200' E132° 53.875'
Location :	West of Retention Pond 1 (RP1)
Vegetation :	Spear grass with a few Acacias and Eucalypts at a distance to the sample area
Flux :	^{222}Rn : 50 ± 4 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 1947 ± 104 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES5D

Date :	15/07/96
Starting time :	10:27
GPS Location :	S12°39.316' E132° 54.233'
Location :	Approximately 10m west of the Magela Ck, about 0.7km along the track from the end of the airport
Vegetation :	Open grassland, close the lush vegetation by the creek
Flux :	^{222}Rn : 280 ± 10 mBq.m^{-2}.s^{-1} ^{220}Rn : 1292 ± 142 mBq.m^{-2}.s^{-1}

SITE IDENTIFICATION : ES5E

Date :	23/07/96
Starting time :	15:51
GPS Location :	S12°38.394' E132° 54.040'
Location :	East of Magela Ck, approximately 1km north of Sandy Crossing
Vegetation :	Floodplain area, Pandanus and Paperbarks
Flux :	^{222}Rn : 16 ± 2 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 1824 ± 92 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES5D1

Date :	06/09/96
Starting time :	11:46
GPS Location :	S12°39.522' E132° 54.274'
Location :	Near junction in Magela Ck, south of ES5D and ES5D4
Vegetation :	Open grassland
Flux :	^{222}Rn : 53 ± 4 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 2791 ± 119 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES5D2

Date :	06/09/96
Starting time :	15:26
GPS Location :	S12°39.119' E132° 54.165'
Location :	West of Magela Ck, north of ES5D and ES5D3
Vegetation :	Open grassland
Flux :	^{222}Rn : 60 ± 5 mBq.m^{-2}.s^{-1}
	^{220}Rn : 1292 ± 92 mBq.m^{-2}.s^{-1}

SITE IDENTIFICATION : ES5D3

Date :	11/09/96
Starting time :	9:08
GPS Location :	S12°39.251' E132° 54.179'
Location :	Approximately 100m north of ES5D, south of ES5D2
Vegetation :	Open grassland
Flux :	^{222}Rn : 275 ± 10 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 1182 ± 145 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES5D4

Date :	11/09/96
Starting time :	10:21
GPS Location :	S12°39.311' E132° 54.220'
Location :	Approximately 100m south of ES5D
Vegetation :	Open grassland
Flux :	^{222}Rn : 58 ± 7 mBq.m^{-2}.s^{-1}
	^{220}Rn : 819 ± 112 mBq.m^{-2}.s^{-1}

SITE IDENTIFICATION : ESWR1

Date :	11/09/96
Starting time :	14:04
GPS Location :	—
Location :	Top western side of the northern waste rock dump
Vegetation :	None
Flux :	^{222}Rn : 525 ± 14 $mBq.m^{-2}.s^{-1}$
	^{220}Rn : 2126 ± 196 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ESWR2

Date :	11/09/96
Starting time :	15:14
GPS Location :	—
Location :	Approximately 50m south east of site ESWR1, edge of the revegetation area
Vegetation :	Spear grass, Acacias in revegetation area
Flux :	^{222}Rn : 513 ± 16 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 2021 ± 237 $mBq.m^{-2}.s^{-1}$

SITE IDENTIFICATION : ES5E

Date :	23/07/96
Starting time :	15:51
GPS Location :	S12°38.394' E132° 54.040'
Location :	East of Magela Ck, approximately 1km north of Sandy Crossing
Vegetation :	Floodplain area, Pandanus and Paperbarks
Flux :	^{222}Rn : 16 ± 2 $mBq.m^{-2}.s^{-1}$ ^{220}Rn : 1824 ± 92 $mBq.m^{-2}.s^{-1}$

APPENDIX 2 SUMMARY OF DATA SET FOR EACH SITE

SITE IDENTIFICATION : ES1B

GPS Location	S 12°40.940′
	E 132°49.600′

ACTIVITY FLUX

Date and Starting Time	17/07/96 10:30
Radon Flux ($mBq.m^{-2}.s^{-1}$)	25 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1014 ± 76
Terrestrial Gamma Dose Rate at 1m above ground (μGy/hr)	0.115 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	29.9 ± 1.4	27.3 ± 1.8
Soil Temperature (°C)	—	28.2 ± 1.8
Air-Soil Temperature Difference	—	—
Relative Humidity (%)	43 ± 11	46 ± 10
Barometric Pressure (hPa)	—	1016 ± 1
Wind Speed (km/hr)	—	8 ± 4
Wind Direction (°)	—	226
Wind Direction Standard Deviation (σ_θ)	—	69
Solar Radiation ($kJ.m^{-2}$)	—	910 ± 561

SOIL MOISTURE

0-10cm Core Sample (%)	0.27
10-20cm Core Sample (%)	0.29

SOIL SAMPLES

Code: JT6902 Description: 960716 COR RLT, BR Emanation Study **0-20cm Core**

≥2mm/<2mm : 0.1401

Activity Concentration (Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226 :	31.8 ± 1.4	Ra-226 :	19.2 ± 1.3
Ra-228 :	64.4 ± 3.0	Ra-228 :	21.2 ± 2.5
U-238 :	18 ± 16	U-238 :	34 ± 16
Pb-210 :	29.9 ± 7.7	Pb-210 :	60.7 ± 7.7
K-40 :	38.5 ± 9.1	K-40 :	54.6 ± 9.4
Cs-137 :	1.69 ± 0.70	Cs-137 :	1.95 ± 0.69

ADDITIONAL SAMPLES NOT ANALYSED

Code : JT6901 Description : 960716 SOI RLT, BR Emanation Study **0-10mm Scrape**

≥2mm/<2mm : 0.3278

SITE IDENTIFICATION : ES1C

GPS Location	S 12° 40.357′
	E 132° 49.773′

ACTIVITY FLUX

Date and Starting Time	19/07/96 11:01
Radon Flux ($mBq.m^{-2}.s^{-1}$)	19 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	3834 ± 126
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.178 ± 0.002

METEOROLOGICAL PARAMETERS	ON SITE	INSTITUTE
Air Temperature (°C)	33.6 ± 1.7	28.8 ± 1.0
Soil Temperature (°C)	42.6 ± 2.0	31.1 ± 1.8
Air-Soil Temperature Difference	-9.0	
Relative Humidity (%)	53 ± 8	60 ± 6
Barometric Pressure (hPa)		1014 ± 1
Wind Speed (km/hr)		6 ± 1
Wind Direction (°)		264
Wind Direction Standard Deviation (σ_θ)		51
Solar Radiation ($kJ.m^{-2}$)		1238 ± 134

SOIL MOISTURE

0-10cm Core Sample (%)	2.16
10-20cm Core Sample (%)	2.87

SOIL SAMPLES

Code: JT6906 Description : 960719 COR RLT, BR Dust Site 2 **0-20cm Core**

≥2mm/<2mm : 1.0880

Activity Concentration (Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	52.4 ± 1.8	Ra-226	37.6 ± 1.6
Ra-228	118.6 ± 3.9	Ra-228	49.9 ± 3.1
U-238	61 ± 19	U-238	61 ± 18
Pb-210	41.8 ± 9.1	Pb-210	56.0 ± 8.8
K-40	58 ± 11	K-40	58 ± 10
Cs-137	2.20 ± 0.85	Cs-137	1.52 ± 0.75

Additional Samples Not Analysed

Code: JT6904 Description : 960719 SOI RLT, BR Dust Site 2 **0-5mm Scrape**

≥2mm/<2mm : 0.9223

Code : JT6905 Description: 960719 SOI RLT, BR Dust Site 2 **5-10mm Scrape**

≥2mm/<2mm : -

SITE IDENTIFICATION : ES1D

GPS Location	S 12° 39.127′
	E 132° 48.940′

ACTIVITY FLUX

Date and Starting Time	16/07/96 13:55
Radon Flux ($mBq.m^{-2}.s^{-1}$)	43 ± 4
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	3097 ± 121
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.132 ± 0.002

METEOROLOGICAL PARAMETERS	ON SITE	INSTITUTE
Air Temperature (°C)	34.2 ± 0.3	30.9 ± 0.7
Soil Temperature (°C)	33.2 ± 4.3	35.1 ± 0.7
Air-Soil Temperature Difference	-1.0	
Relative Humidity (%)	7 ± 1	21 ± 2
Barometric Pressure (hPa)		1012 ± 1
Wind Speed (km/hr)		11 ± 1
Wind Direction (°)		227
Wind Direction Standard Deviation (σ_θ)		40
Solar Radiation ($kJ.m^{-2}$)		1375 ± 112

SOIL MOISTURE

0-10cm Core Sample (%)	3.80
10-20cm Core Sample (%)	4.58

SOIL SAMPLES

Code : ER6902 Description: 960716 COR RLT, BR Emanation Study **0-20cm Core**

>2mm/<2mm : 0.1475

Activity Concentration (Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	72.9 ± 2.1	Ra-226	40.1 ± 1.6
Ra-228	77.2 ± 3.8	Ra-228	58.0 ± 3.2
U-238	58 ± 21	U-238	49 ± 18
Pb-210	76 ± 10	Pb-210	54.9 ± 8.5
K-40	24 ± 11	K-40	24.8 ± 9.7
Cs-137	2.72 ± 0.91	Cs-137	0.63 ± 0.76

ADDITIONAL SAMPLES NOT ANALYSED

Code : ER6901 Description: 960716 SOI RLT, BR Emanation Study **0-10mm Scrape**

>2mm/<2mm: 0.6574

SITE IDENTIFICATION : ES2B

GPS Location	S 12° 41.121′
	E 132° 49.934′

ACTIVITY FLUX

Date and Starting Time	22/07/96 10:31
Radon Flux ($mBq.m^{-2}.s^{-1}$)	14 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2728 ± 108
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.139 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	32.3 ± 1.2	28.8 ± 1.5
Soil Temperature (°C)	38.7 ± 3.9	30.2 ± 1.7
Air-Soil Temperature Difference	-6.4	
Relative Humidity (%)	54.5 ± 8.4	53 ± 8
Barometric Pressure (hPa)		1017 ± 1
Wind Speed (km/hr)		9 ± 1
Wind Direction (°)		222
Wind Direction Standard Deviation (σ_θ)		80
Solar Radiation ($kJ.m^{-2}$)		1178 ± 185

SOIL MOISTURE

0-10cm Core Sample (%)	1.10
10-20cm Core Sample (%)	1.84

SOIL SAMPLES

Code: JT6914 Description: 960722 COR RLT, JH Emanation Study **0-20cm Core**
>2mm/<2mm: 0.6456

Activity Concentration (Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	46.3 ± 1.7	Ra-226	35.6 ± 1.6
Ra-228	111.3 ± 3.8	Ra-228	39.7 ± 3.0
U-238	46 ± 18	U-238	31 ± 18
Pb-210	40.8 ± 8.7	Pb-210	78.9 ± 8.8
K-40	77 ± 11	K-40	72 ± 11
Cs-137	1.1 ± 1.1	Cs-137	2.55 ± 0.82

ADDITIONAL SAMPLES NOT ANALYSED

Code: JT6912 Description: 960722 SOI RLT, JH Emanation Study **0-5mm Scrape**
>2mm/<2mm: 11.242

Code: JT6913 Description: 960722 SOI RLT, JH Emanation Study **5-10mm Scrape**
>2mm/<2mm: -

SITE IDENTIFICATION : ES2C

GPS Location	S 12°40.573′
	E 132°50.230′

ACTIVITY FLUX

Date and Starting Time	19/07/96 15:14
Radon Flux ($mBq.m^{-2}.s^{-1}$)	14 ± 2
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2489 ± 102
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.135 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	36.3 ± 0.3	33.4 ± 0.4
Soil Temperature (°C)	38.0 ± 1.7	36.0 ± 0.8
Air-Soil Temperature Difference	-1.7	
Relative Humidity (%)	38.2 ± 1.7	38 ± 1
Barometric Pressure (hPa)		1010 ± 1
Wind Speed (km/hr)		12 ± 1
Wind Direction (°)		231
Wind Direction Standard Deviation (σ_θ)		16
Solar Radiation ($kJ.m^{-2}$)		858 ± 201

SOIL MOISTURE

0-10cm Core Sample (%)	2.67
10-20cm Core Sample (%)	2.64

SOIL SAMPLES

Code: JT6908 Description: 960719 SOI RLT, BR Dust Site 4 **0-5mm Scrape**

>2mm/<2mm: 0.6654

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	39.4 ± 1.7
Ra-228		Ra-228	47.3 ± 3.2
U-238		U-238	55 ± 19
Pb-210		Pb-210	99.1 ± 9.7
K-40		K-40	63 ± 11
Cs-137		Cs-137	1.01 ± 0.78

Code: JT6910 Description: 960719 COR RLT, BR Dust Site 4 **0-20cm Core**

>2mm/<2mm: 0.4830

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	34.8 ± 1.6
Ra-228		Ra-228	52.8 ± 3.1
U-238		U-238	55 ± 17

Pb-210		Pb-210	41.9 ± 8.4
K-40		K-40	75 ± 11
Cs-137		Cs-137	0.3 ± 0.7

ADDITIONAL SAMPLES NOT ANALYSED

Code: JT6909 Description: 960719 SOI RLT,BR Dust Site 4 **5-10mm Scrape**

>2mm/<2mm: -

SITE IDENTIFICATION : ES2D

GPS Location	S 12° 39.608′
	E 132° 50.481′

ACTIVITY FLUX

Date and Starting Time	16/07/96 10:27
Radon Flux ($mBq.m^{-2}.s^{-1}$)	9 ± 2
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	3339 ± 117
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.162 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	28.6 ± 0.6	26.8 ± 1.4
Soil Temperature (°C)	29.5 ± 1.4	27.3 ± 1.9
Air-Soil Temperature Difference	-0.9	
Relative Humidity (%)	36.5 ± 6.3	34 ± 5
Barometric Pressure (hPa)		1016 ± 1
Wind Speed (km/hr)		10 ± 1
Wind Direction (°)		322
Wind Direction Standard Deviation (σ_θ)		72
Solar Radiation ($kJ.m^{-2}$)		1165 ± 179

SOIL MOISTURE

0-10cm Core Sample (%)	1.91
10-20cm Core Sample (%)	2.99

SOIL SAMPLES

Code : JI6902

Description : 960716 COR RLT, BR Emanation Study **0-20cm Core**

≥2mm/<2mm : 1.4760

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	56.4 ± 1.9	Ra-226	39.9 ± 1.6
Ra-228	138.7 ± 4.2	Ra-228	59.8 ± 3.1
U-238	54 ± 20	U-238	48 ± 17
Pb-210	65.1 ± 9.7	Pb-210	64.6 ± 8.3
K-40	35 ± 10	K-40	19.7 ± 9.1
Cs-137	2.27 ± 0.88	Cs-137	1.39 ± 0.73

ADDITIONAL SAMPLES NOT ANALYSED

Code : JI6901

Description: 960716 SOI RLT, BR Emanation Study **0-10mm Scrape**

≥2mm/<2mm: 8.8899

SITE IDENTIFICATION : ES2F

GPS Location	S 12°36.185′
	E 132°50.865′

ACTIVITY FLUX

Date and Starting Time	18/07/96 10:27
Radon Flux ($mBq.m^{-2}.s^{-1}$)	38 ± 4
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2211 ± 104
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.131 ± 0.002

METEOROLOGICAL PARAMETERS	ON SITE	INSTITUTE
Air Temperature (°C)	29.3 ± 0.9	28.4 ± 1.2
Soil Temperature (°C)	31.8 ± 2.8	29.0 ± 1.8
Air-Soil Temperature Difference	-2.5	
Relative Humidity (%)	51.4 ± 5.2	47 ± 9
Barometric Pressure (hPa)		1016 ± 1
Wind Speed (km/hr)		7 ± 1
Wind Direction (°)		227
Wind Direction Standard Deviation (σ_θ)		70
Solar Radiation ($kJ.m^{-2}$)		1143 ± 172

SOIL MOISTURE

0-10cm Core Sample (%)	2.41
10-20cm Core Sample (%)	3.65

SOIL SAMPLES

Code : ER6905 Description : 960718 COR RLT, BR Emanation Study **0-20 cm Core**

≥2mm/<2mm : 0.2065

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	85.1 ± 2.2	Ra-226	30.6 ± 1.5
Ra-228	176.8 ± 4.7	Ra-228	30.0 ± 2.7
U-238	76 ± 22	U-238	40 ± 16
Pb-210	82 ± 10	Pb-210	45.8 ± 7.8
K-40	27.1 ± 9.6	K-40	16.1 ± 8.9
Cs-137	2.82 ± 0.93	Cs-137	1.28 ± 0.72

ADDITIONAL SAMPLES NOT ANALYSED

Code: ER6904 Description: 960718 SOI RLT, BR Emanation Study **0-10mm Scrape**

≥2mm/<2mm: 0.4116

SITE IDENTIFICATION : ES3B

GPS Location	S 12° 41.259′
	E 132° 51.258′

ACTIVITY FLUX

Date and Starting Time	10/09/96 12:32
Radon Flux ($mBq.m^{-2}.s^{-1}$)	11 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2909 ± 122
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.138 ± 0.002

METEOROLOGICAL PARAMETERS	ON SITE	INSTITUTE
Air Temperature (°C)	35.9 ± 1.3	34.3 ± 0.7
Soil Temperature (°C)	36.9 ± 4.2	39.0 ± 1.1
Air-Soil Temperature Difference	-1.0	
Relative Humidity (%)	35 ± 10	24 ± 3
Barometric Pressure (hPa)		1009 ± 1
Wind Speed (km/hr)		18 ± 3
Wind Direction (°)		4
Wind Direction Standard Deviation (σ_θ)		1
Solar Radiation ($kJ.m^{-2}$)		16900 ± 503

SOIL MOISTURE

0-10cm Core Sample (%)	Sample Spilled
10-20cm Core Sample (%)	4.18

SOIL SAMPLES NOT ANALYSED

Code : BL6908 — Description: 960910 SOI RLT Emanation Study **0-5mm Scrape**
>2mm/<2mm : -

Code : BI6909 — Description : 960910 SOI RLT Emanation Study **5-10mm Scrape**
>2mm/<2mm : -

Code : BL6910 — Description : 960910 COR RLT Emanation Study **0-20cm Core**
>2mm/<2mm : -

SITE IDENTIFICATION : ES3C

GPS Location	S 12°40.639′
	E 132°51.357′

ACTIVITY FLUX

Date and Starting Time	24/07/96 14:22
Radon Flux ($mBq.m^{-2}.s^{-1}$)	31 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2231 ± 103
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.136 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	35.7 ± 1.0	33.3 ± 0.7
Soil Temperature (°C)	47.7 ± 7.1	38.2 ± 0.5
Air-Soil Temperature Difference	-12.0	
Relative Humidity (%)	40.9 ± 0.6	37 ± 4
Barometric Pressure (hPa)		1012 ± 1
Wind Speed (km/hr)		8 ± 1
Wind Direction (°)		291
Wind Direction Standard Deviation (σ_θ)		73
Solar Radiation ($kJ.m^{-2}$)		1273 ± 154

SOIL MOISTURE

0-10cm Core Sample (%)	0.97
10-20cm Core Sample (%)	1.41

SOIL SAMPLES

Code : BL6907 Description : 960724 COR RLT, BR Dust Site 3 **0-20cm Core**

≥2mm/<2mm : 0.6834

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	73.6 ± 2.0	Ra-226	35.4 ± 1.5
Ra-228	99.2 ± 3.7	Ra-228	29.9 ± 2.7
U-238	52 ± 19	U-238	26 ± 16
Pb-210	60.1 ± 9.4	Pb-210	40.9 ± 8.0
K-40	36.8 ± 9.9	K-40	26.4 ± 9.3
Cs-137	0.4 ± 0.8	Cs-137	0.6 ± 0.8

ADDITIONAL SAMPLES NOT ANALYSED

Code : BL6905 Description : 960724 SOI RLT, BR Dust Site 3 **0-5mm Scrape**

≥2mm/<2mm: 9.6412

Code : BL6906 Description : 960724 SOI RLT, BR Dust Site 3 **5-10mm Scrape**

≥2mm/<2mm : -

SITE IDENTIFICATION: ES3D

GPS Location	S 12° 39.393′
	E 132° 52.343′

ACTIVITY FLUX

Date and Starting Time	22/07/96 15:22
Radon Flux ($mBq.m^{-2}.s^{-1}$)	0 ± 0
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	725 ± 55
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.117 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	33.5 ± 0.7	33.9 ± 0.4
Soil Temperature (°C)	33.6 ± 4.5	37.3 ± 1.1
Air-Soil Temperature Difference	-0.1	
Relative Humidity (%)	41.2 ± 5.6	29 ± 1
Barometric Pressure (hPa)		1012 ± 0
Wind Speed (km/hr)		10 ± 2
Wind Direction (°)		354
Wind Direction Standard Deviation (σ_θ)		46
Solar Radiation ($kJ.m^{-2}$)		962 ± 261

SOIL MOISTURE

0-10cm Core Sample (%)	19.4
10-20cm Core Sample (%)	13.5

SOIL SAMPLES

Code: BL6903 Description : 960722 COR RLT, JH Emanation Study **0-20cm Core**

≥2mm/<2mm : 1.5065

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	40.6 ± 1.7
Ra-228		Ra-228	51.3 ± 3.3
U-238		U-238	41 ± 19
Pb-210		Pb-210	69.4 ± 9.3
K-40		K-40	47 ± 11
Cs-137		Cs-137	1.19 ± 0.81

ADDITIONAL SAMPLES NOT ANALYSED

Code: BL6901 Description : 960722 SOI RLT, JH Emanation Study **0-5mm Scrape**

≥2mm/<2mm : 0.00511

Code: BL6902 Description : 960722 SOI RLT, JH Emanation Study **5-10mm Scrape**

≥2mm/<2mm : -

SITE IDENTIFICATION: ES3E

GPS Location	S 12° 39.049′
	E 132° 50.907′

ACTIVITY FLUX

Date and Starting Time	25/07/96 10:31
Radon Flux ($mBq.m^{-2}.s^{-1}$)	54 ± 4
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1805 ± 105
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.123 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	31.2 ± 0.8	26.8 ± 1.0
Soil Temperature (°C)	40.2 ± 2.8	30.1 ± 1.5
Air-Soil Temperature Difference	-9.0	
Relative Humidity (%)	65.7 ± 3.8	69 ± 5
Barometric Pressure (hPa)		1017 ± 1
Wind Speed (km/hr)		6 ± 1
Wind Direction (°)		235
Wind Direction Standard Deviation (σ_θ)		25
Solar Radiation ($kJ.m^{-2}$)		1055 ± 281

SOIL MOISTURE

0-10cm Core Sample (%)	0.61
10-20cm Core Sample (%)	1.79

SOIL SAMPLES

Code : XX6905

Description : 960725 SOI RLT, BR Emanation Study **0-5mm Scrape**

≥2mm/<2mm : 1.8728

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	29.4 ± 1.5
Ra-228		Ra-228	21.8 ± 2.7
U-238		U-238	1 ± 17
Pb-210		Pb-210	105.3 ± 9.2
K-40		K-40	14.8 ± 9.2
Cs-137		Cs-137	1.81 ± 0.74

Code : XX6907 Description : 960725 COR RLT, BR Emanation Study 0-**20cm Scrape**

≥2mm/<2mm : 0.3442

Activity Concentration(Bq/kg)

>2mm Fraction		**<2mm Fraction**	
Ra-226	77.7 ± 1.7	Ra-226	29.8 ± 1.5
Ra-228	96.6 ± 2.7	Ra-228	30.9 ± 2.9
U-238	37 ± 14	U-238	25 ± 17
Pb-210	65.7 ± 6.7	Pb-210	20.4 ± 8.3
K-40	46.1 ± 7.5	K-40	20.3 ± 9.7
Cs-137	0.1 ± 0.6	Cs-137	0.7 ± 0.7

ADDITIONAL SAMPLES NOT ANALYSED

Code : XX6906 Description : 960725 SOI RLT, BR Emanation Study 5-**10mm Scrape**

≥2mm/<2mm : 0.3442

SITE IDENTIFICATION: ES3G

GPS Location	S 12° 35.532′
	E 132° 51.482′

ACTIVITY FLUX

Date and Starting Time	17/07/96 14:28
Radon Flux ($mBq.m^{-2}.s^{-1}$)	25 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	3836 ± 129
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.151 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	37.0 ± 0.4	32.8 ± 0.4
Soil Temperature (°C)	46.7 ± 3.4	36.1 ± 0.4
Air-Soil Temperature Difference	-9.7	
Relative Humidity (%)	17.2 ± 1.4	23 ± 1
Barometric Pressure (hPa)		1012 ± 1
Wind Speed (km/hr)		12 ± 3
Wind Direction (°)		226
Wind Direction Standard Deviation (σ_θ)		70
Solar Radiation ($kJ.m^{-2}$)		1268 ± 147

SOIL MOISTURE

0-10cm Core Sample (%)	1.06
10-20cm Core Sample (%)	2.00

SOIL SAMPLES

Code : MI6903 Description : 960717 COR RLT, BR Dust Site 7 **0-20cm Core**

>2mm/<2mm : 0.5567

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	37.6 ± 1.6
Ra-228		Ra-228	52.2 ± 3.1
U-238		U-238	36 ± 18
Pb-210		Pb-210	65.4 ± 8.8
K-40		K-40	11.3 ± 9.6
Cs-137		Cs-137	0.5 ± 0.7

ADDITIONAL SAMPLES NON ANALYSED

Code : MI6901 Description : 960717 SOI RLT, BR Dust Site 7 **0-5mm Scrape**

>2mm/<2mm : 1.9267

Code : MI6902 Description : 960717 SOI RLT, BR Dust Site 7 **5-10mm Scrape**

>2mm/<2mm : -

SITE IDENTIFICATION: ES4C

GPS Location	S 12° 40.182′
	E 132° 53.074′

ACTIVITY FLUX

Date and Starting Time	23/07/96 11:11
Radon Flux ($mBq.m^{-2}.s^{-1}$)	14 ± 2
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	922 ± 67
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.106 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	35.1 ± 0.6	31.4 ± 0.7
Soil Temperature (°C)	40.7 ± 4.9	33.0 ± 1.8
Air-Soil Temperature Difference	-5.6	
Relative Humidity (%)	37.2 ± 1.4	37 ± 2
Barometric Pressure (hPa)		1015 ± 1
Wind Speed (km/hr)		9 ± 2
Wind Direction (°)		227
Wind Direction Standard Deviation (σ_θ)		71
Solar Radiation ($kJ.m^{-2}$)		1395 ± 115

SOIL MOISTURE

0-10cm Core Sample (%)	0.45
10-20cm Core Sample (%)	0.99

SOIL SAMPLES

Code : GL6909 Description : 960723 COR RLT, PM Emanation Study **0-20cm Core**
≥2mm/<2mm : 0.00638

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	22.1 ± 1.5
Ra-228		Ra-228	20.1 ± 2.8
U-238		U-238	16 ± 18
Pb-210		Pb-210	29.9 ± 8.2
K-40		K-40	40 ± 11
Cs-137		Cs-137	1 ± 1

ADDITIONAL SAMPLES NON ANALYSED

Code : GL6907 Description : 960723 SOI RLT, PM Emanation Study **0-5mm Scrape**
≥2mm/<2mm : 0.02876

Code : GL6908 Description : 960723 SOI RLT, PM Emanation Study **5-10mm Scrape**

$\geq 2mm / \leq 2mm$: -

SITE IDENTIFICATION: ES4D

GPS Location	S 12° 39.244′
	E 132° 52.685′

ACTIVITY FLUX

Date and Starting Time	15/07/96 13:58
Radon Flux ($mBq.m^{-2}.s^{-1}$)	18 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	885 ± 77
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.098 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	31.6 ± 0.3	29.7 ± 0.6
Soil Temperature (°C)	34.3 ± 1.1	34.7 ± 0.7
Air-Soil Temperature Difference	-2.7	
Relative Humidity (%)	33.2 ± 3.6	30 ± 1
Barometric Pressure (hPa)		1013 ± 0
Wind Speed (km/hr)		11 ± 2
Wind Direction (°)		248
Wind Direction Standard Deviation (σ_θ)		64
Solar Radiation ($kJ.m^{-2}$)		1398 ± 114

SOIL MOISTURE

0-10cm Core Sample (%)	1.64
10-20cm Core Sample (%)	2.62

SOIL SAMPLES

Code : GL6901

Description : 960715 COR RLT, BR Emanation Study **0-20cm Core**

>2mm/<2mm : 0.004734

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	22.5 ± 1.4
Ra-228		Ra-228	17.5 ± 2.7
U-238		U-238	15 ± 17
Pb-210		Pb-210	40.1 ± 7.8
K-40		K-40	17.5 ± 9.5
Cs-137		Cs-137	0.6 ± 0.7

ADDITIONAL SAMPLES NOT ANALYSED

Nil

SITE IDENTIFICATION: ES4E

GPS Location	S 12° 37.757′
	E 132° 53.107′

ACTIVITY FLUX

Date and Starting Time	18/07/96 14:19
Radon Flux ($mBq.m^{-2}.s^{-1}$)	25 ± 3
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2311 ± 106
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.113 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	35.7 ± 0.2	33.7 ± 0
Soil Temperature (°C)	39.0 ± 0.9.	36.6 ± 0.4
Air-Soil Temperature Difference	-3.3	
Relative Humidity (%)	19.8 ± 1.5	21 ± 1
Barometric Pressure (hPa)		1012 ± 1
Wind Speed (km/hr)		11 ± 3
Wind Direction (°)		258
Wind Direction Standard Deviation (σ_θ)		63
Solar Radiation ($kJ.m^{-2}$)		1255 ± 138

SOIL MOISTURE

0-10cm Core Sample (%)	3.52
10-20cm Core Sample (%)	4.32

SOIL SAMPLES

Code : GL6905 Description : 960718 COR RLT, JH Emanation Study **0-20cm Core**

≥2mm/<2mm : 0.1119

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	48.0 ± 1.9	Ra-226	28.0 ± 1.6
Ra-228	57.8 ± 3.5	Ra-228	29.3 ± 3.1
U-238	48 ± 20	U-238	27 ± 18
Pb-210	47.5 ± 9.5	Pb-210	39.0 ± 8.7
K-40	54 ± 11	K-40	102 ± 12
Cs-137	0.8 ± 0.8	Cs-137	0.88 ± 0.77

ADDITIONAL SAMPLES NOT ANALYSED

Code : GL6903 Description : 960718 SOI RLT, JH Emanation Study **0-5mm Scrape**

≥2mm/<2mm : 0.8614

Code : GL6904 Description : 960718 SOI RLT, JH Emanation Study **5-10mm Scrape**

≥2mm/<2mm : -

SITE IDENTIFICATION: ES4/5C

GPS Location	S 12° 39.778′
	E 132° 54.233′

ACTIVITY FLUX

Date and Starting Time	12/07/96 11:19
Radon Flux ($mBq.m^{-2}.s^{-1}$)	35 ± 2
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1601 ± 67
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.131 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	33.6 ± 1.3	28.6 ± 0.7
Soil Temperature (°C)	39.2 ± 6.9	32.1 ± 1.6
Air-Soil Temperature Difference	-5.6	
Relative Humidity (%)	17.6 ± 2.6	32 ± 3
Barometric Pressure (hPa)		1015 ± 1
Wind Speed (km/hr)		15 ± 1
Wind Direction (°)		228
Wind Direction Standard Deviation (σ_θ)		38
Solar Radiation ($kJ.m^{-2}$)		1438 ± 71

SOIL MOISTURE

0-10cm Core Sample (%)	1.30
10-20cm Core Sample (%)	2.32

SOIL SAMPLES

Code : JE6903   Description : 960712 COR RLT, BR Dust Site 1 **0-20cm Core**

>2mm/<2mm : 0.3401

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	76.5 ± 2.1	Ra-226	36.9 ± 1.7
Ra-228	79.4 ± 3.6	Ra-228	26.9 ± 3.1
U-238	79 ± 20	U-238	28 ± 28
Pb-210	54 ± 10	Pb-210	56.9 ± 8.8
K-40	86 ± 12	K-40	75 ± 12
Cs-137	1.49 ± 0.84	Cs-137	1.79 ± 0.79

ADDITIONAL SAMPLES NOT ANALYSED

Code : JE6901   Description : 960712 SOI RLT, BR Dust Site 1 **0-5mm Scrape**

>2mm/<2mm : 1.8899

Code : JE6902   Description : 960712 SOI RLT, BR Dust Site 1 **5-10mm Scrape**

>2mm/<2mm : -

SITE IDENTIFICATION: ES5A

GPS Location	S 12° 41.578′
	E 132° 53.330′

ACTIVITY FLUX

Date and Starting Time	28/08/96 15:06
Radon Flux ($mBq.m^{-2}.s^{-1}$)	96 ± 6
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1946 ± 113
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.138 ± 0.002

METEOROLOGICAL PARAMETERS :	ON SITE	INSTITUTE
Air Temperature (°C)	37.1 ± 0.8	35.4 ± 0.3
Soil Temperature (°C)	—	40.7 ± 0.3
Air-Soil Temperature Difference	—	
Relative Humidity (%)	33.3 ± 3.9	29 ± 1
Barometric Pressure (hPa)		1009 ± 1
Wind Speed (km/hr)		2 ± 1
Wind Direction (°)		12
Wind Direction Standard Deviation (σ_θ)		4
Solar Radiation ($kJ.m^{-2}$)		10100 ± 1900

SOIL MOISTURE

0-10cm Core Sample (%)	0.63
10-20cm Core Sample (%)	1.05

SOIL SAMPLES

Code : RX6903 Description : 960828 COR RLT, DJ Dust Site 10 **0-20cm Core**

≥2mm/<2mm : 0.5055

Activity Concentration (Bq/kg)

>2mm Fraction		**<2mm Fraction**	
Ra-226	123.2 ± 2.6	Ra-226	
Ra-228	55.0 ± 3.2	Ra-228	
U-238	107 ± 20	U-238	
Pb-210	101.8 ± 9.6	Pb-210	
K-40	51 ± 11	K-40	
Cs-137	—	Cs-137	

SOIL SAMPLES NOT ANALYSED

Code : RX6901 Description : 960828 SOI RLT, DJ Dust Site 10 **0-5mm Scrape**

≥2mm/<2mm : 0.9795

Code : RX6902 Description : 960828 SOI RLT, DJ Dust Site 10 **5-10mm Scrape**

≥2mm/<2mm : -

SITE IDENTIFICATION: ES5C

GPS Location	S 12° 40.200′
	E 132° 53.875′

ACTIVITY FLUX

Date and Starting Time	25/07/96 13:56
Radon Flux ($mBq.m^{-2}.s^{-1}$)	50 ± 4
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1947 ± 104
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.129 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	35.6 ± 1.3	31.2 ± 0.7
Soil Temperature (°C)	39.8 ± 6.2	37.0 ± 0.8
Air-Soil Temperature Difference	-4.2	
Relative Humidity (%)	41.9 ± 5.7	44 ± 6
Barometric Pressure (hPa)		1013 ± 1
Wind Speed (km/hr)		8 ± 1
Wind Direction (°)		225
Wind Direction Standard Deviation (σ_θ)		104
Solar Radiation ($kJ.m^{-2}$)		1343 ± 86

SOIL MOISTURE

0-10cm Core Sample (%)	1.38
10-20cm Core Sample (%)	2.62

SOIL SAMPLES

Code : RO6903 Description : 960725 COR RLT, BR Emanation Study **0-20cm Core**

>2mm/<2mm : 0.2229

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	83.9 ± 1.8	Ra-226	43.2 ± 1.7
Ra-228	39.9 ± 2.3	Ra-228	39.5 ± 3.0
U-238	81 ± 14	U-238	61 ± 18
Pb-210	77.8 ± 7.0	Pb-210	60.5 ± 8.4
K-40	437 ± 13	K-40	86 ± 12
Cs-137	0.34 ± 0.54	Cs-137	0.5 ± 0.7

ADDITIONAL SAMPLES NOT ANALYSED

Code : RO6901 Description : 960725 SOI RLT, BR Emanation Study **0-5mm Scrape**

>2mm/<2mm : 0.3249

Code : RO6902 Description : 960725 SOI RLT, BR Emanation Study **5-10mm Scrape**

>2mm/<2mm : -

SITE IDENTIFICATION: ES5D

GPS Location	S 12° 39.316′
	E 132° 54.233′

ACTIVITY FLUX

Date and Starting Time	15/07/96 10:27
Radon Flux ($mBq.m^{-2}.s^{-1}$)	280 ± 10
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1292 ± 142
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.133 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	28.6 ±0.5	25.6 ± 0.6
Soil Temperature (°C)	36.6 ± 6.3	27.0 ± 1.8
Air-Soil Temperature Difference	-8.0	
Relative Humidity (%)	37 ± 6	39 ± 6
Barometric Pressure (hPa)		1016 ± 1
Wind Speed (km/hr)		15 ± 2
Wind Direction (°)		225
Wind Direction Standard Deviation (σ_θ)		43
Solar Radiation ($kJ.m^{-2}$)		1195 ± 182

SOIL MOISTURE

0-10cm Core Sample (%)	1.17
10-20cm Core Sample (%)	2.42

SOIL SAMPLES

Code : MK6901

Description : 960715 SOI RLT, BR Emanation Study **0-20cm Core**

≥2mm/<2mm : 0.03324

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226	225.9 ± 4.3	Ra-226	61.6 ± 1.8
Ra-228	30.5 ± 3.8	Ra-228	20.1 ± 2.7
U-238	305 ± 29	U-238	50 ± 17
Pb-210	228 ± 14	Pb-210	71.2 ± 8.4
K-40	400 ± 21	K-40	83 ± 11
Cs-137	0.4 ± 1	Cs-137	0.8 ± 0.7

ADDITIONAL SAMPLES NOT ANALYSED

Nil

SITE IDENTIFICATION: ES5D1

GPS Location	S 12° 39.522′
	E 132° 54.274′

ACTIVITY FLUX

Date and Starting Time	06/09/96 11:46
Radon Flux ($mBq.m^{-2}.s^{-1}$)	53 ± 4
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2791 ± 119
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.126 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	35.4 ± 1.0	32.8 ± 0.6
Soil Temperature (°C)	—	37.3 ± 1.9
Air-Soil Temperature Difference	—	
Relative Humidity (%)	17.3 ± 4.8	12 ± 1
Barometric Pressure (hPa)		1012 ± 1
Wind Speed (km/hr)		21 ± 4
Wind Direction (°)		4
Wind Direction Standard Deviation (σ_θ)		5
Solar Radiation ($kJ.m^{-2}$)		17450 ± 526

SOIL MOISTURE

0-10cm Core Sample (%)	1.43
10-20cm Core Sample (%)	2.83

SOIL SAMPLES NOT ANALYSED

Code : MK6906 Description : 960906 SOI RLT Emanation Study **0-5mm Scrape**
≥2mm/<2mm : -

Code : MK6907 Description : 960906 SOI RLT Emanation Study **5-10mm Scrape**
≥2mm/<2mm : -

Code : MK6908 Description : 960906 COR RLT Emanation Study **0-20cm Core**
≥2mm/<2mm : 0.07615

SITE IDENTIFICATION: ES5D2

GPS Location	S12° 39.119′
	E 132° 54.179′

ACTIVITY FLUX

Date and Starting Time	06/09/96 15:26
Radon Flux ($mBq.m^{-2}.s^{-1}$)	60 ± 5
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1292 ± 92
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.116 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	34.8 ± 0.5	32.8 ± 0.4
Soil Temperature (°C)	42.6 ± 1.5	37.5 ± 0.8
Air-Soil Temperature Difference	-7.8	
Relative Humidity (%)	19.7 ± 1.1	15 ± 1
Barometric Pressure (hPa)		1009 ± 1
Wind Speed (km/hr)		11 ± 4
Wind Direction (°)		230
Wind Direction Standard Deviation (σ_θ)		34
Solar Radiation ($kJ.m^{-2}$)		7175 ± 2721

SOIL MOISTURE

0-10cm Core Sample (%)	0.63
10-20cm Core Sample (%)	1.23

SOIL SAMPLES

Code : MK6909 — Description : 960906 SOI RLT Emanation Study **0-5mm Scrape**
≥2mm/<2mm : 0.3020

Code : MK6910 — Description : 960906 SOI RLT Emanation Study **5-10mm Scrape**
≥2mm/<2mm : -

Code : MK6911 — Description : 960906 COR RLT Emanation Study **0-20cm Core**
≥2mm/<2mm : 0.04174

SITE IDENTIFICATION: ES5D3

GPS Location	S 12° 39.251′
	E 132° 54.179′

ACTIVITY FLUX

Date and Starting Time	11/09/96 9:08
Radon Flux ($mBq.m^{-2}.s^{-1}$)	275 ± 10
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1182 ± 145
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.172 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	29.5 ± 1.7	—
Soil Temperature (°C)	32.1 ± 2.3	—
Air-Soil Temperature Difference	-2.6	
Relative Humidity (%)	75.0 ± 3.5	—
Barometric Pressure (hPa)		—
Wind Speed (km/hr)		—
Wind Direction (°)		—
Wind Direction Standard Deviation (σ_θ)		—
Solar Radiation ($kJ.m^{-2}$)		—

SOIL MOISTURE

0-10cm Core Sample (%)	Sample Spilled
10-20cm Core Sample (%)	1.07

SOIL SAMPLES NOT ANALYSED

Code : MK6912 Description : 960911 SOI RLT Emanation Study **0-5mm Scrape**
≥2mm/<2mm : -

Code : MK6913 Description : 960911 SOI RLT Emanation Study **5-10mm Scrape**
≥2mm/<2mm : -

Code : MK6914 Description : 960911 COR RLT Emanation Study **0-20cm Core**
≥2mm/<2mm : -

SITE IDENTIFICATION: ES5D4

GPS Location	S12° 39.311′
	E 132° 54.220′

ACTIVITY FLUX

Date and Starting Time	11/09/96 10:21
Radon Flux ($mBq.m^{-2}.s^{-1}$)	58 ± 7
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	819 ± 112
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.114 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	33.7 ± 0.8	—
Soil Temperature (°C)	42.3 ± 5.9	—
Air-Soil Temperature Difference	-8.6	
Relative Humidity (%)	59.3 ± 4.0	—
Barometric Pressure (hPa)		—
Wind Speed (km/hr)		—
Wind Direction (°)		—
Wind Direction Standard Deviation (σ_θ)		—
Solar Radiation ($kJ.m^{-2}$)		—

SOIL MOISTURE

0-10cm Core Sample (%)	1.30
10-20cm Core Sample (%)	1.71

SOIL SAMPLES NOT ANALYSED

Code : MK6915 Description : 960911 SOI RLT Emanation Study **0-5mm Scrape**
≥2mm/<2mm : -

Code : MK6916 Description : 960911 SOI RLT Emanation Study **5-10mm Scrape**
≥2mm/<2mm : -

Code : MK6917 Description : 960911 COR RLT Emanation Study **0-20cm Core**
≥2mm/<2mm : -

SITE IDENTIFICATION: ES5E

GPS Location	S 12° 38.394′
	E 132° 54.040′

ACTIVITY FLUX

Date and Starting Time	23/07/96 15:51
Radon Flux ($mBq.m^{-2}.s^{-1}$)	16 ± 2
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	1824 ± 92
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.103 ± 0.002

METEOROLOGICAL PARAMETERS -	ON SITE	INSTITUTE
Air Temperature (°C)	34.9 ± 0.9	33.9 ± 0.5
Soil Temperature (°C)	32.6 ± 2.0	36.4 ± 1.1
Air-Soil Temperature Difference	2.3	
Relative Humidity (%)	37.2 ± 2.6	27 ± 1
Barometric Pressure (hPa)		1011 ± 1
Wind Speed (km/hr)		9 ± 3
Wind Direction (°)		228
Wind Direction Standard Deviation (σ_θ)		44
Solar Radiation ($kJ.m^{-2}$)		707 ± 398

SOIL MOISTURE

0-10cm Core Sample (%)	12.5
10-20cm Core Sample (%)	9.45

SOIL SAMPLES

Code : MK6905 Description : 960723 COR RLT, PM Emanatlon Study **0-20cm Core**

>2mm/<2mm : 0.02660

Activity Concentration(Bq/kg)

>2mm Fraction		<2mm Fraction	
Ra-226		Ra-226	40.7 ± 1.6
Ra-228		Ra-228	24.7 ± 2.8
U-238		U-238	37 ± 17
Pb-210		Pb-210	49.8 ± 8.4
K-40		K-40	22.3 ± 9.4
Cs-137		Cs-137	1.95 ± 0.70

ADDITIONAL SAMPLES NOT ANALYSED

Code : MK6903 Description : 960723 SOI RLT, PM Emanation Study **0-5mm Scrape**

>2mm/<2mm : 0.3589

Code : MK6904 Description : 960723 SOI RLT, PM Emanation Study **5-10mm Scrape**

>2mm/<2mm : -

SITE IDENTIFICATION: ESWR1

ACTIVITY FLUX

Date and Starting Time	11/09/96 14:04
Radon Flux ($mBq.m^{-2}.s^{-1}$)	525 ± 14
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2126 ± 196
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.596 ± 0.004

SITE IDENTIFICATION: ESWR2

ACTIVITY FLUX

Date and Starting Time	11/09/96 15:14
Radon Flux ($mBq.m^{-2}.s^{-1}$)	513 ± 16
Thoron Flux ($mBq.m^{-2}.s^{-1}$)	2021 ± 237
Terrestrial Gamma Dose Rate at 1m Above Ground (μGy/hr)	0.609 ± 0.004

APPENDIX 3

ACTIVITY FLUX INTERCOMPARISON AND CALIBRATION

APPENDIX 3 : ACTIVITY FLUX INTERCOMPARISON AND CALIBRATION

Emanometers

Three ANSTO designed flow through accumulator type emanometers were used. Two of these emanometers, RTE2 Serial Number 001 and RTE2 Serial Number 002, were used for measurements in ERISS Jabiru / Jabiru East area and in the QUT Laboratory, respectively. The third emanometer belonged to the radon laboratory in ANSTO, where the intercalibration exercise was carried out on 4 and 5 November 1996 utilising a QUT AINSE grant.

The emanometers had identical shape drums. Also, the two RTE2 series emanometers had identical scintillation chambers design but the recommended operational PM tube voltage and lower discriminator levels were somewhat different. ANSTO emanometer scintillation chamber size was larger with better counting efficiency.

The activity flux values obtained were compared with the activity flux values expected due to radon and thoron gas injection into individual emanometers from certified sources. Three different set up modes, radon (^{222}Rn) only, thoron (^{220}Rn) only, and radon and thoron combined were used.

Radon and Thoron Sources

The following sources were used.

Radon : Pylon Electronic Corporation Radon Source Serial # A-261
Strength: 2.7 Bq.min^{-1} or 45 mBq.s^{-1} (±3%).
The source is aired continuously at a flow rate of 30 mL.min^{-1} using a pump with a regulated power supply (a pot of silica gel is used in the inlet to avoid condensation).

Thoron: Pylon Electronic Corporation Source Serial # B-140,
Strength: ^{228}Th activity 21.2 kBq on 15 Nov 1993.
7.22 kBq on 4 Nov 1996.
Assuming 100% ^{220}Rn emission, this leads to ^{220}Rn strength of 7.22 x 10^{3} atoms per second, or 83.0 Bq.s^{-1}.

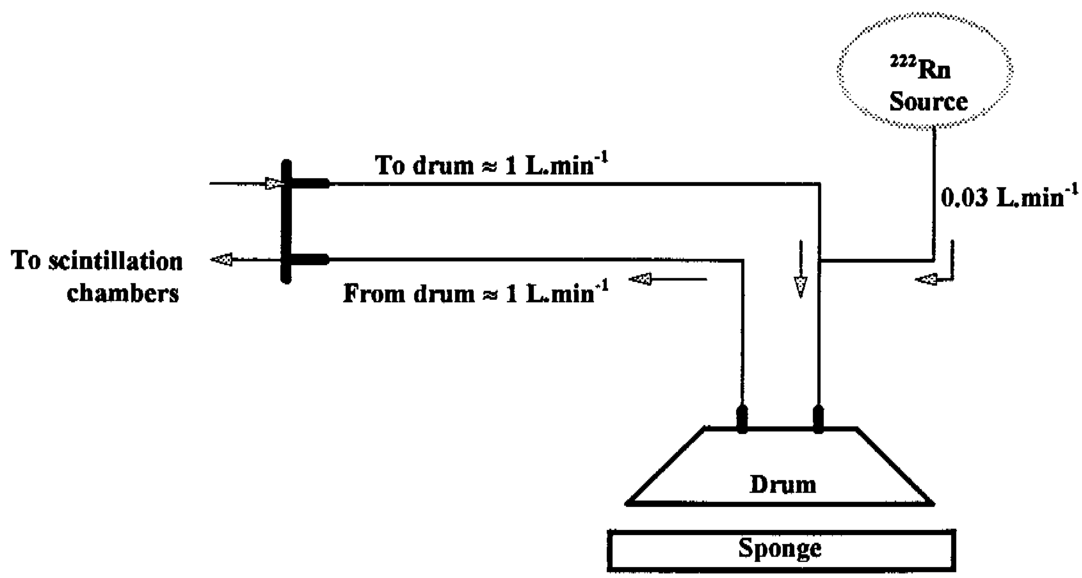
A 3.03L delay line was used between the source and the drum. The flow rate through the drum was determined when both ^{220}Rn and ^{222}Rn sources were in use for simultaneous measurement. As the flow rates for the three emanometer systems turned out to be somewhat different from one another, the corresponding delay times and ^{220}Rn activity reduction correction factors were also different. The values are given in the table below.

Table A3.1: Corrected ^{220}Rn source strength for the three emanometers.

Emanometer	Flow rate ($L.min^{-1}$)	Delay (seconds)	Corrected ^{220}Rn source strength ($Bq.s^{-1}$)
ANSTO	1.137	160	11.3
RTE2 001	1.010	180	8.80
RTE2 002	1.058	172	9.73

Set up

Radon and thoron injection from the calibrated sources in the air stream of emanometer drum simulated the emanation (see the illustration below, radon injection).



The surface area of the three drums was the same, 0.259 m^2. The drums were placed in turns on an approximately 0.1 m thick sponge cushion (covered with a polythene sheet) on the lab floor. A lead brick was placed as weight on the drum to ensure a firm contact at the drum edge to minimise leakage. This arrangement caused sponge compression near the edge and a bulge away from it, resulting in an estimated average rise of $6x10^{-3}$ m of sponge surface inside the drum. The calculation of air volume underneath the drum was corrected accordingly.

The expected activity flux values in Table A3.2 were obtained by dividing the corrected source strength (as in Table A3.1) by the surface area.

Table A3.2 : Expected ^{220}Rn and ^{222}Rn activity flux.

Emanometer	^{220}Rn		^{222}Rn	
	Source strength ($Bq.s^{-1}$)	Activity Flux ($Bq.s^{-1}.m^2$)	Source strength ($mBq.s^{-1}$)	Activity Flux ($mBq.s^{-1}.m^2$)
ANSTO	11.3	43.6	45	174
RTE2 001	8.80	34.0	45	174
RTE2 002	9.73	37.6	45	174

Results

Analyses programs for routine use were modified by (Dr. Vlodek Zahorowski, from ANSTO) to accommodate changes due to a different mixing volume of the drum .

Tables A3.3 and A3.4 summarise the results.

The three ^{222}Rn obtained activity flux readings for both RTE2 emanometers agree within the calculated uncertainties. The same is true for the two ^{220}Rn obtained activity flux readings for RTE2 002 and ANSTO emanometers. One of the ^{222}Rn readings for ANSTO emanometer is lower, outside the calculated uncertainty range and the two ^{220}Rn readings for RTE2 001 do not agree. This behaviour may be attributed to an intermittent leakage of activity from the system but this is not conclusive.

When the average values of ^{222}Rn obtained activity flux are compared with the expected activity flux, RTE2 measurements are lower, 73 ± 4 % and 80 ± 5 % of the expected value. ANSTO emanometer measurement is higher 115 ± 5 % of the expected value.

ANSTO emanometer also measured higher ^{220}Rn activity flux, 124 ± 1 % of the expected values. The RTE2 002 average ^{220}Rn measured activity flux value and the lower of the two RTE2 001 value agreed well with the expected value.

The expected ^{220}Rn activity flux was zero ^{222}Rn source activity was injected in an emanometer and vise vera. The corresponding calculated values (Tables A3.3 and A3.4) essentially reflect this situation, where calculated values are significantly less than those obtained for the average natural soils.

Overall, for the emanometers used in the present study, ^{220}Rn activity flux agreed with the expected value from a certified source. The instruments, however, underestimated the ^{222}Rn activity flux by about 25%. It is difficult to predict that when and how such deviation could have been introduced; the instruments were essentially supplied programmed and calibrated at ANSTO prior to their application. The results in the main body of the report are not corrected on the basis of this single intercomparison exercise. Further frequent lab and field calibrations and intercomparisons are recommended.

Table A3.3: Radon (^{222}Rn) obtained activity flux $mBq.m^{-2}.s^{-1}$

Set up	ANSTO	RTE2 001	RTE2 002
^{222}Rn only	163 ± 5	123 ± 7	138 ± 10
^{222}Rn only	194 ± 6	127 ± 9	145 ± 12
^{220}Rn + ^{222}Rn	206 ± 6	133 ± 9	136 ± 12
Average	*200 ± 4*	*127 ± 5*	*140 ± 6*
Expected value	*174 ± 5*	*174 ± 5*	*174 ± 5*
^{220}Rn only	-4 ± 4	-9 ± 6	-13 ± 8
Expected value	*zero*	*zero*	*zero*

Table A3.4: Thoron (^{220}Rn) obtained activity flux $Bq.m^{-2}.s^{-1}$

Set up	ANSTO	RTE2 001	RTE2 002
^{220}Rn only	55.3±0.3	54.4 ± 0.5	37.7 ± 0.5
^{220}Rn + ^{222}Rn	53.1±0.3	35.6± 0.4	39.1 ± 0.5
Average	*54.2 ± 0.2*	-	*38.4 ± 0.4*
Expected value	*43.6*	*34.0*	*37.6*
^{222}Rn only	0.04 ± 0.06	0.25 ± 0.09	-0.09 ± 0.09
^{222}Rn only	-0.05 ± 0.08	0.15 ± 0.11	0.03 ± 0.12
Average (std)	*0.00 ± 0.05*	*0.21 ± 0.07*	*-0.04 ± 0.07*
Expected value	*zero*	*zero*	*zero*