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

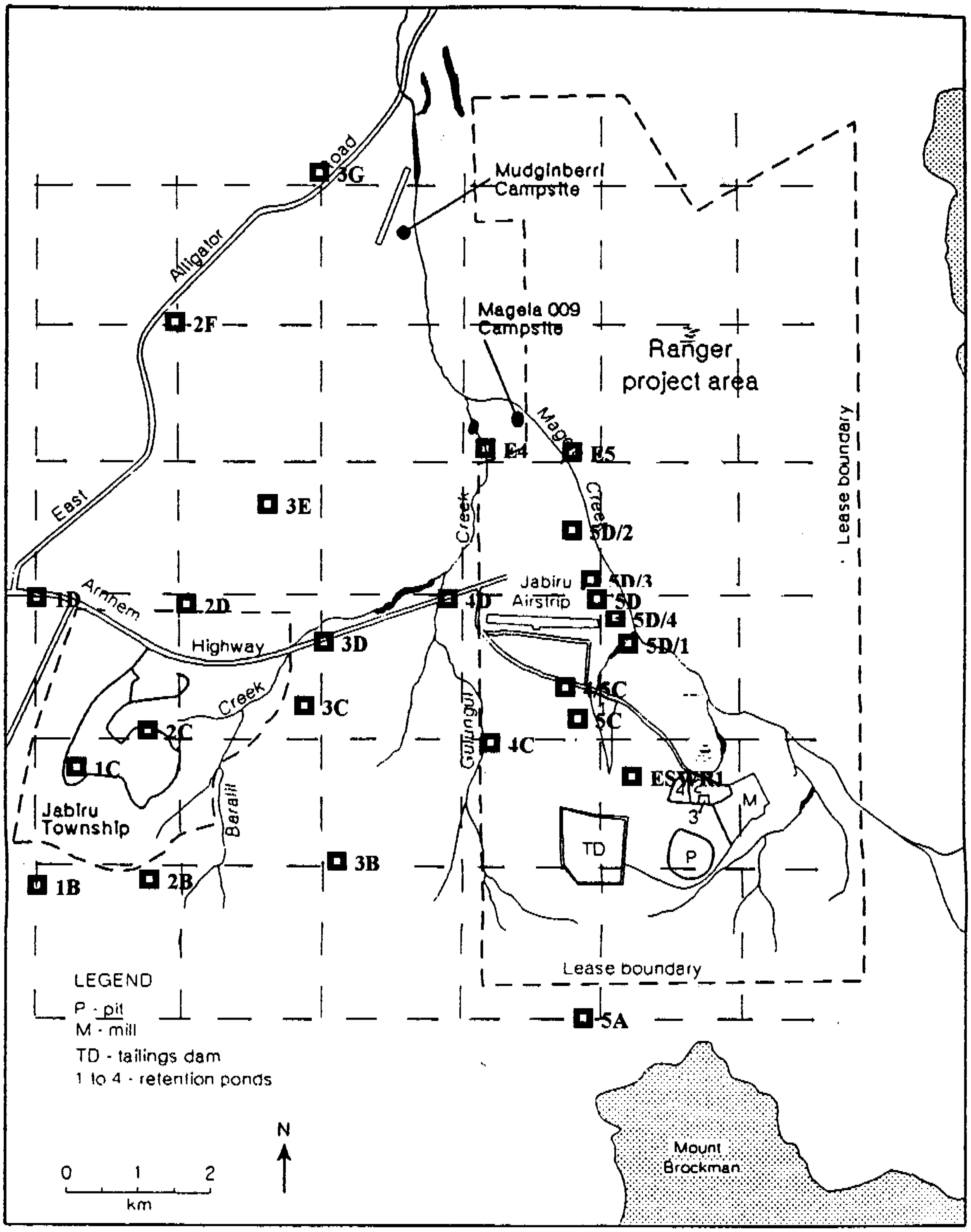

Figure 3.1 Measurement Sites for the ^{222}Rn and ^{220}Rn Activity Flux Survey

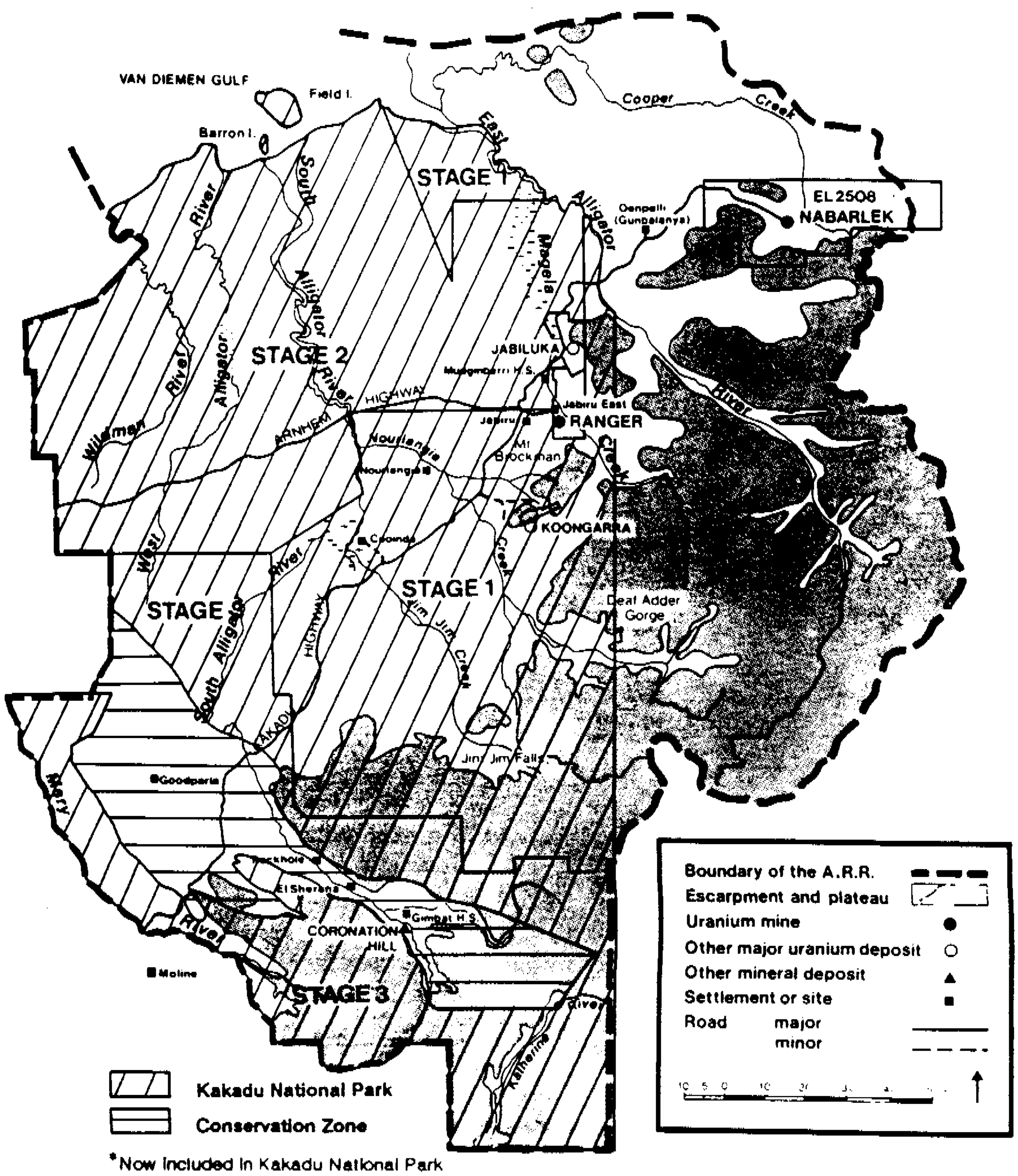

Figure 3.2 The Alligator Rivers Region (ARRRI, 1991)

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.

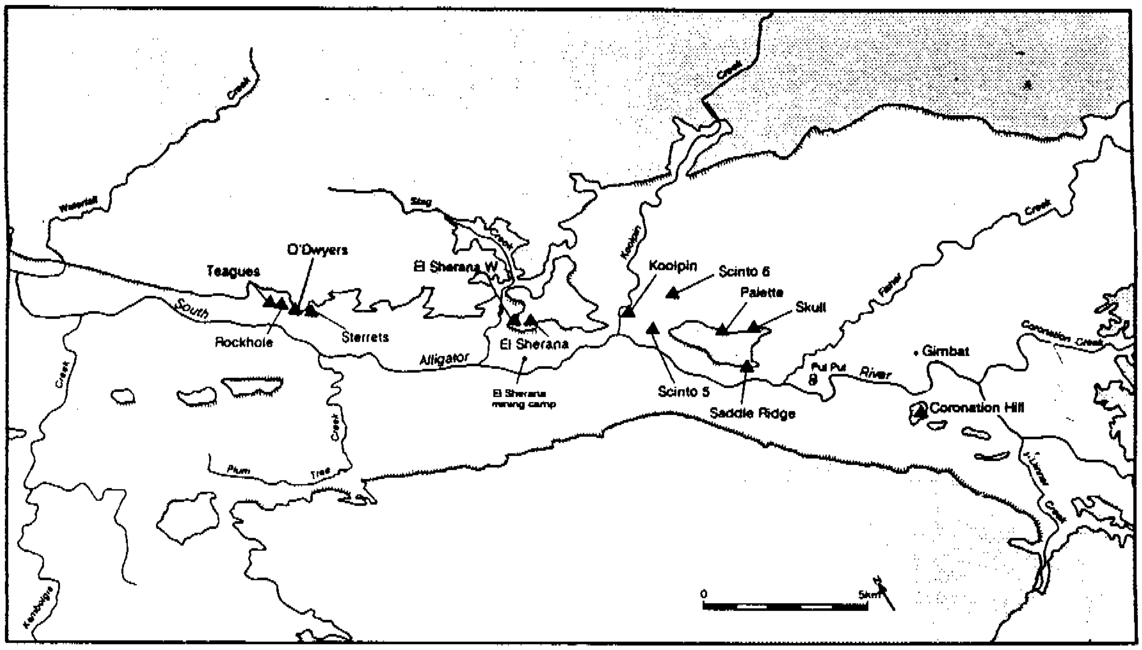

Figure 3.3 Upper South Alligator Valley Uranium Field (ARRR1, 1991)

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.

<u>Narbalek</u>

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.

<u>Ranger Uranium Mine</u>

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.

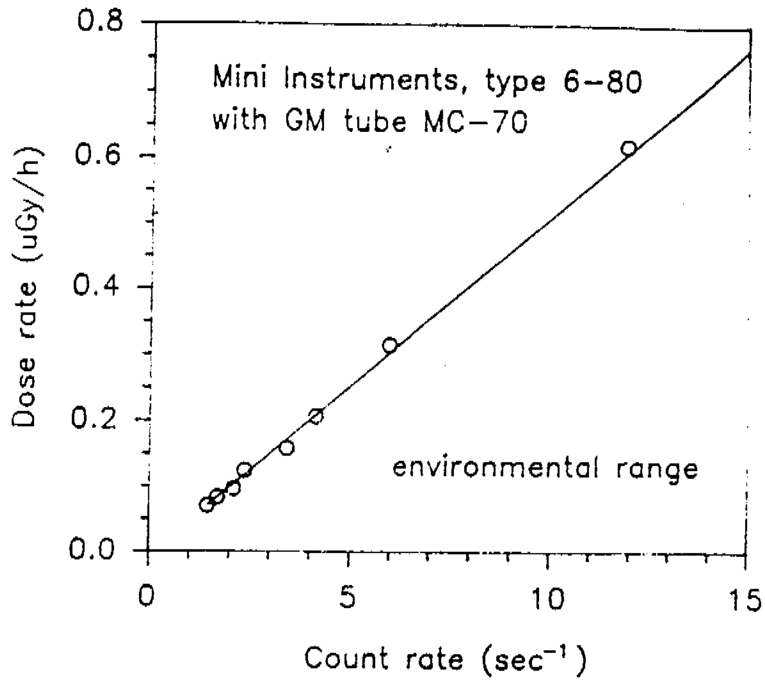

Figure 3.4 Absolute Sensitivity Calibration for the Gamma Dose Rate Meter (Marten, 1991)

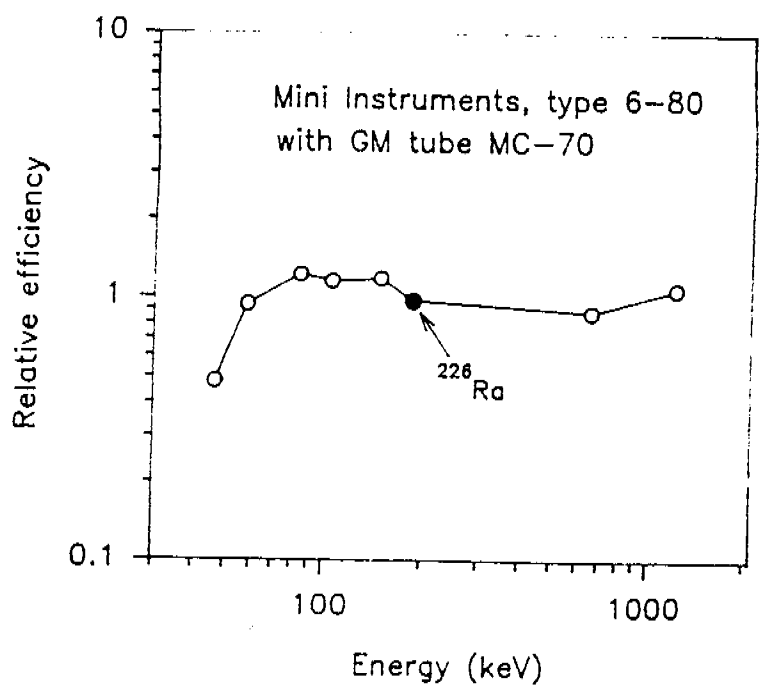

Figure 3.5 Relative Efficiency Calibration for the Gamma Dose Rate Survey Meter (Marten, 1991)

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

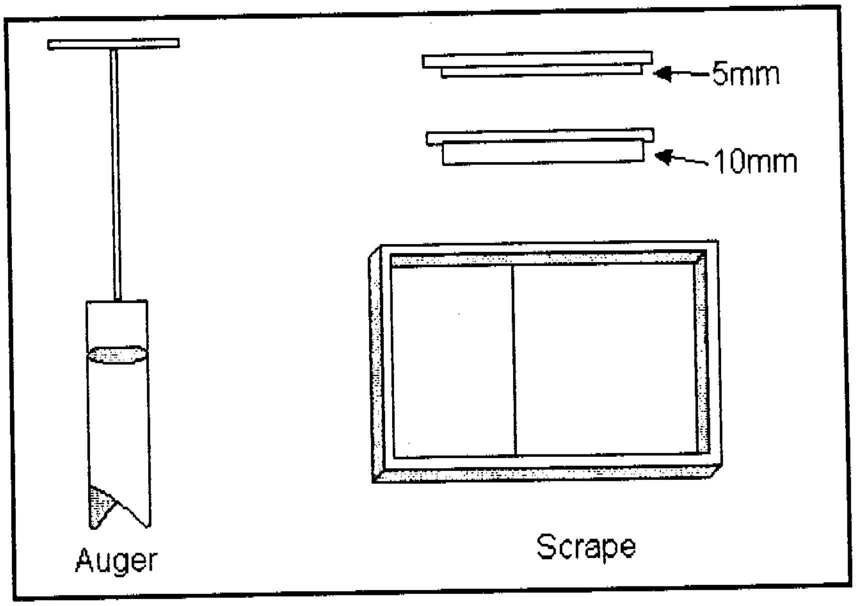

Figure 3.6 Auger and Scrape Used to Obtain Soil Samples

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

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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

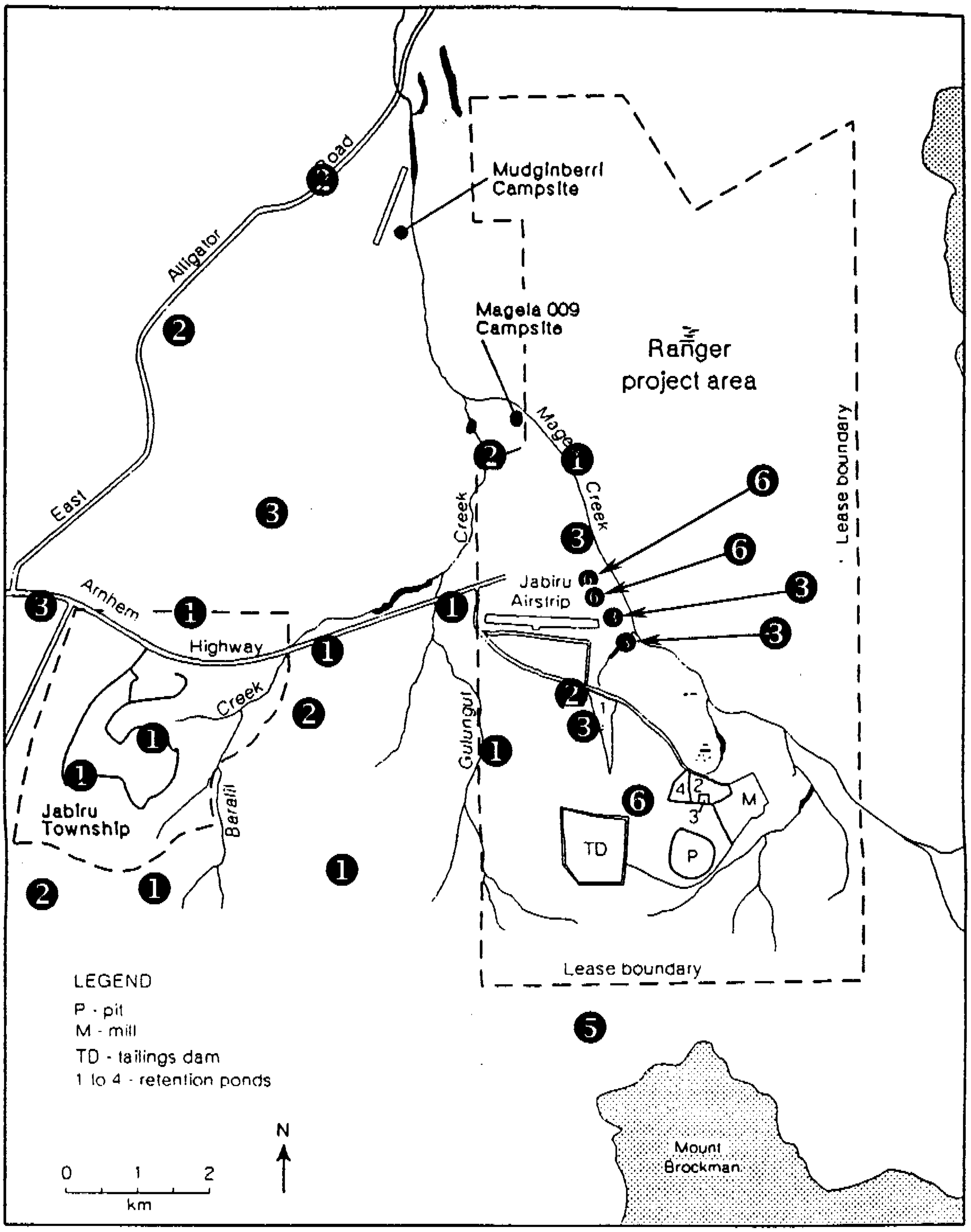
Firstly ^{222}Rn and ^{220}Rn activity flux values obtained were plotted onto maps of the survey region. Following this the distribution of the flux values and regional averages were determined. Finally detailed analysis into the association between activity flux and the various parameters measured was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

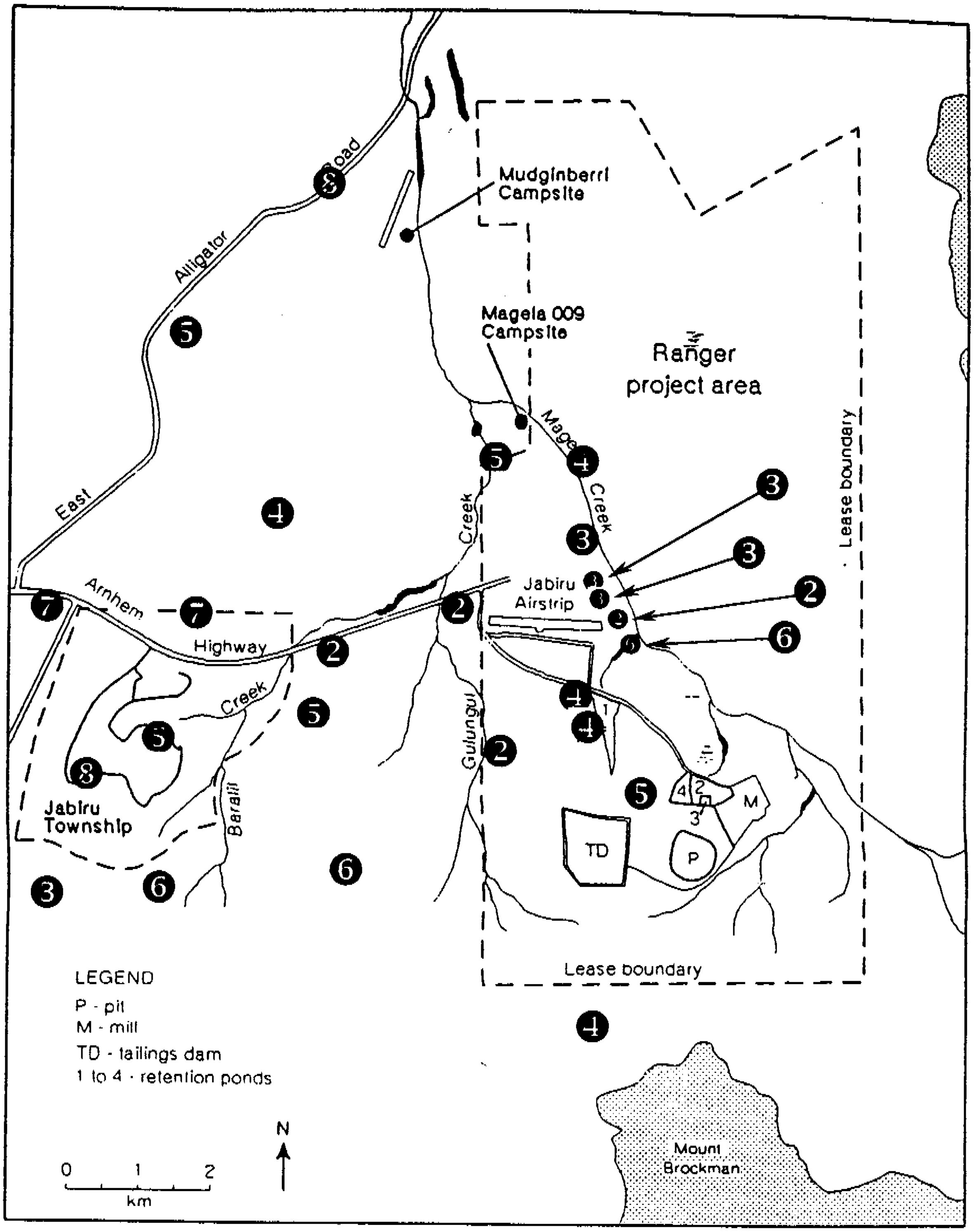
The ^{222}Rn flux at two sites approximately 10m east of the Magela Creek sand bed (ES5D and ES5D3) and on the waste rock dump at the Ranger Uranium Mine were all greater than 250 mBq.m^{-2}.s^{-1}. The high ^{222}Rn flux at the Magela Ck is not caused by water born contamination as the ^{226}Ra, ^{235}U 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 1500mBq.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 ($mBq.m^{-2}.s^{-1}$)

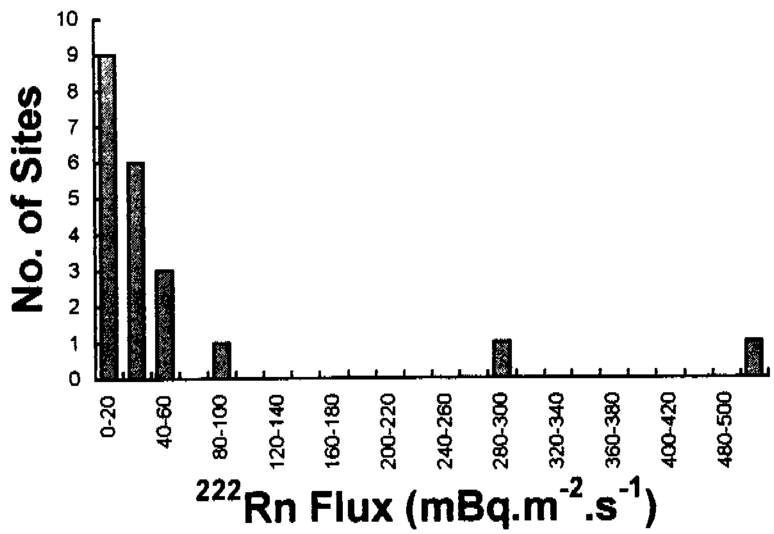
Figure 3.7 seems to show a lower value trend in ^{220}Rn activity flux in close proximity to creeks. Only one site with ^{220}Rn activity flux less than 1500mBq.m^{-2}.s^{-1} is not located near a creek. Conversely all sites with ^{220}Rn flux greater than 3000 Bq.m^{-2}.s^{-1} were at a distance from 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)

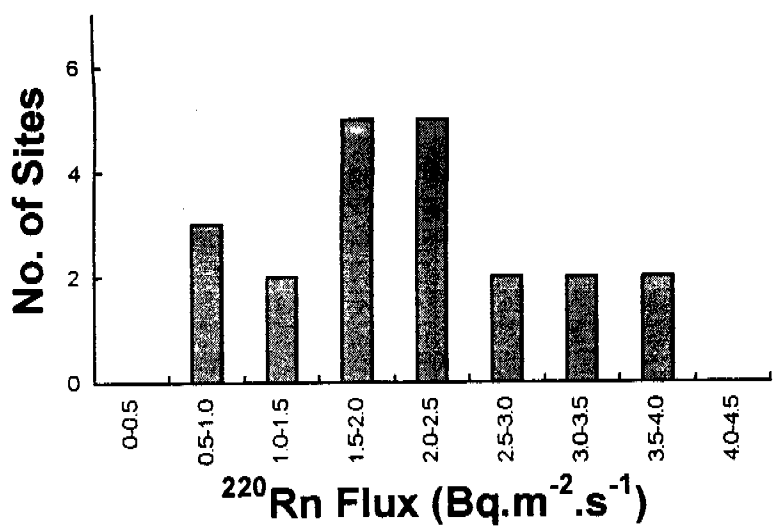


Figure 3.9 Histograms of the (a) ^{222}Rn and (b) ^{220}Rn Flux

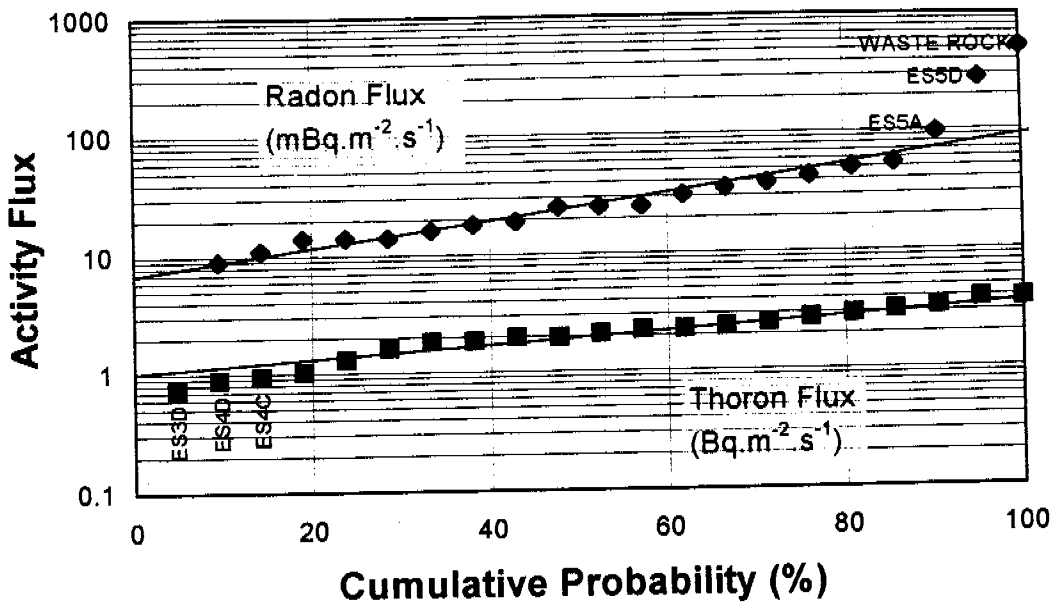


Figure 3.10 Plot of the Logarithm of ^{222}Rn and ^{220}Rn Flux Versus Cumulative

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.

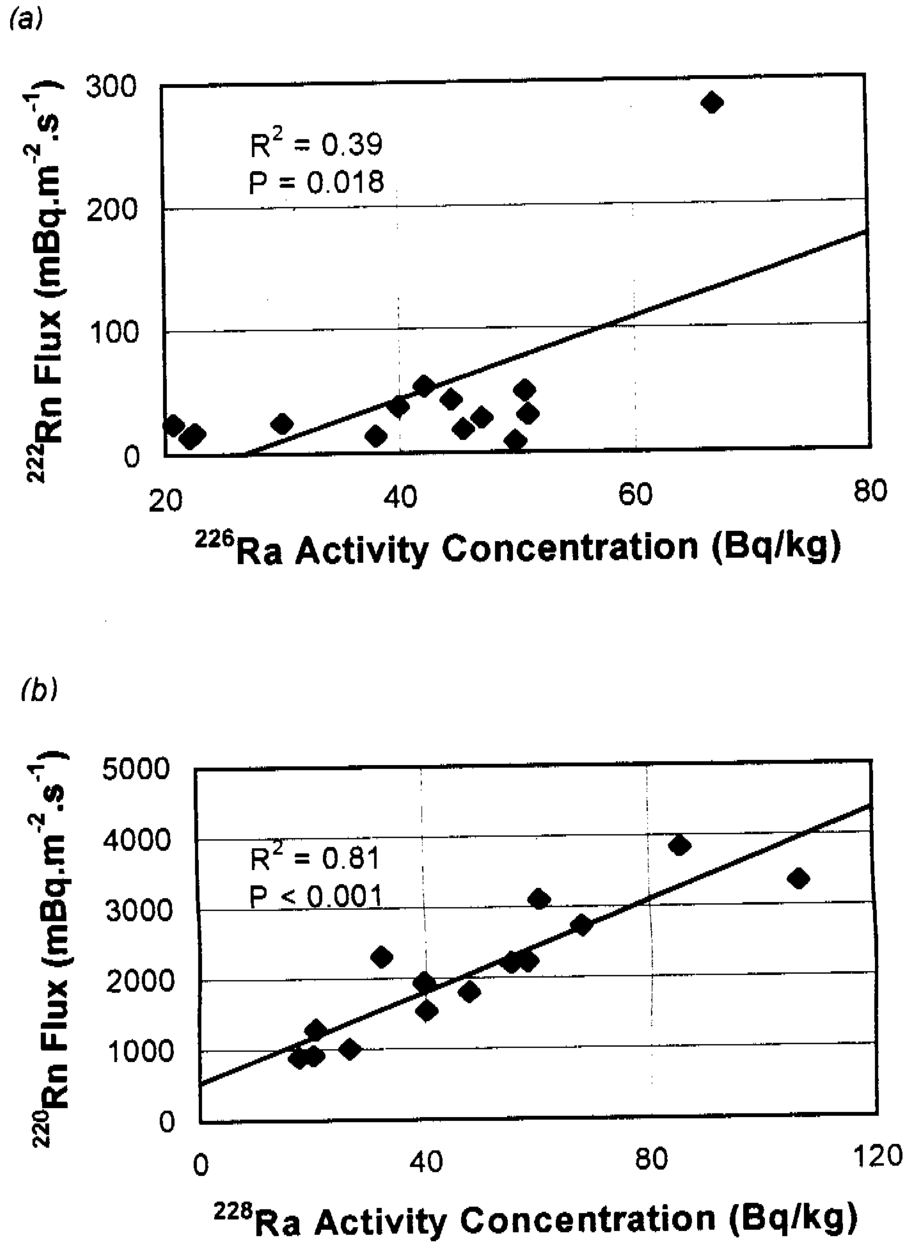


Figure 3.11 Flux Versus Radium Activity Concentration of the 0-20cm Core

(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

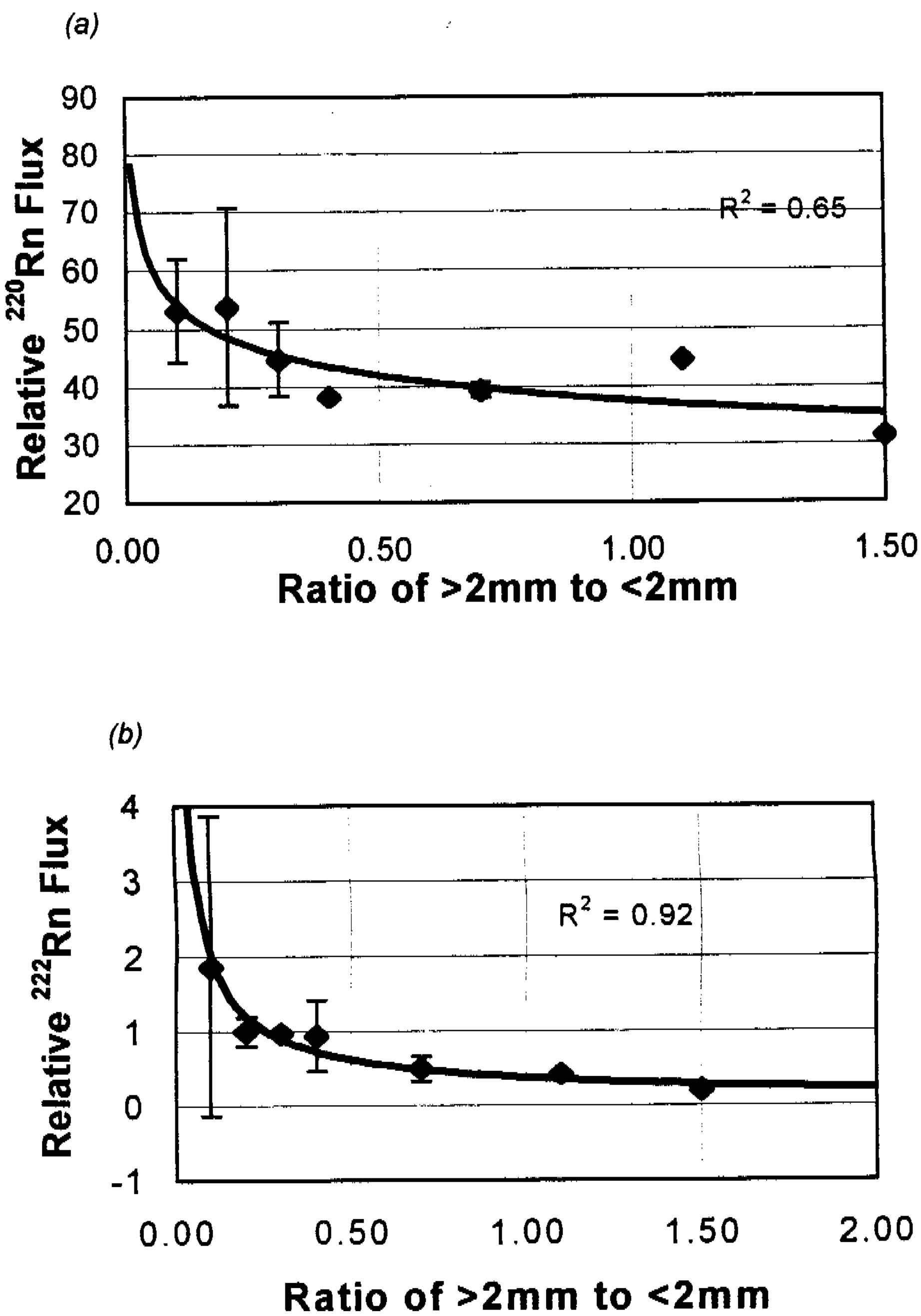


Figure 3.12 Relative Flux as a Function of the Ratio of the >2mm Fraction to the <2mm Fraction for the Core Sample (a) ^{222}Rn, (b) ^{220}Rn

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.

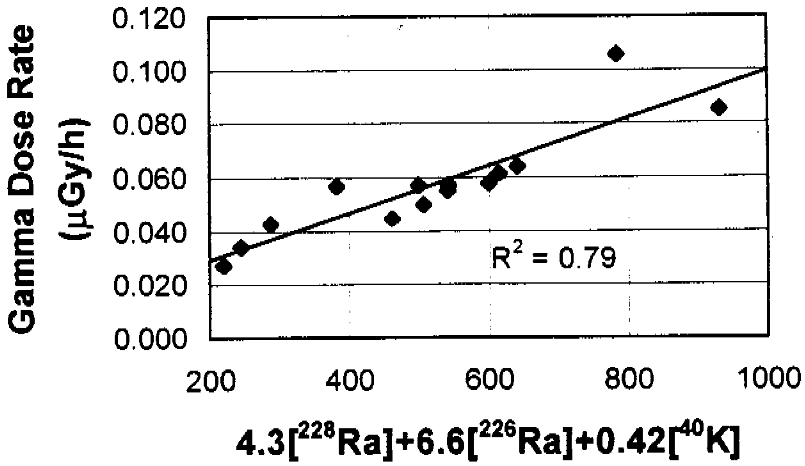


Figure 3.13 Gamma Dose Rate Versus Approximation of Formula

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.

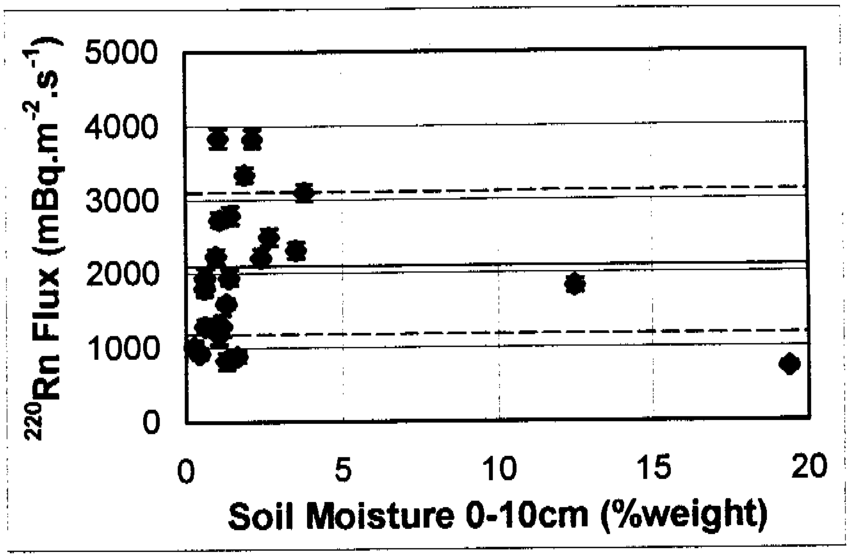


Figure 3.14 ^{220}Rn Flux as a Function of Soil Moisture in the Top 10cm of Soil
The average flux is marked by a solid line with dotted lines marking one standard deviation either side of the average

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.

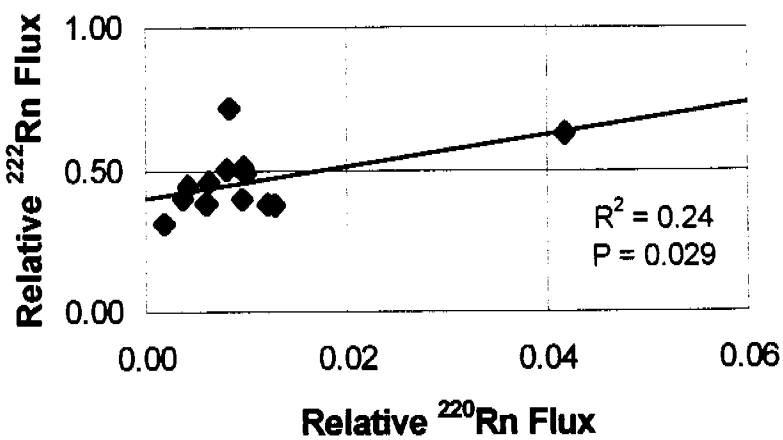


Figure 3.15 Relative ^{222}Rn Flux versus Relative ^{220}Rn Flux
(Relative Flux = Radon Flux / Radium Concentration)

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.

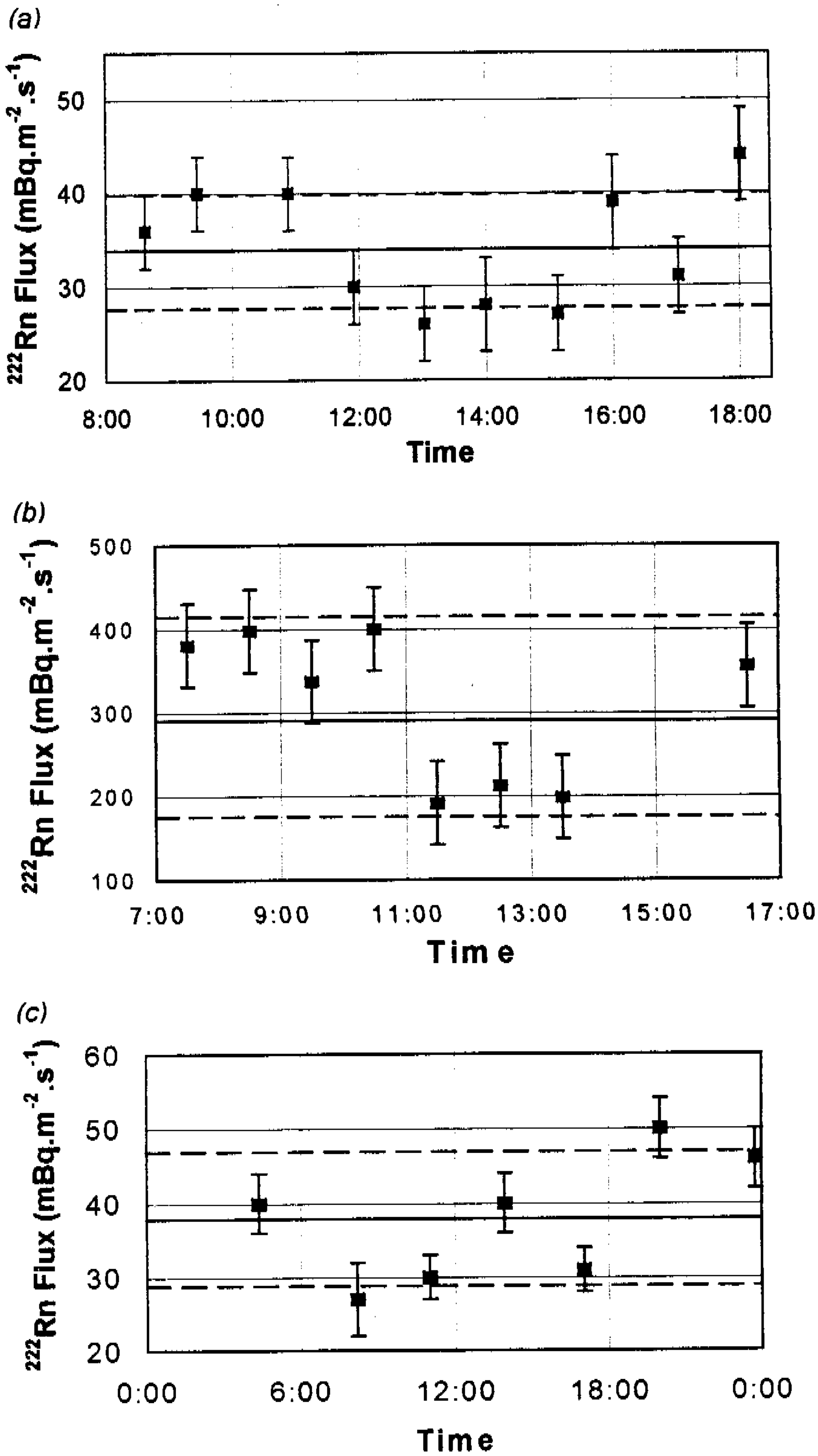


Figure 4.1 Diurnal Variation in ^{222}Rn Flux (a) Trial 1: Institute (b) Trial 2 : Magela Creek (c) Trial 3 : Institute over 24 hours. The solid line marks the average flux, while dashed lines are at ± one standard deviation

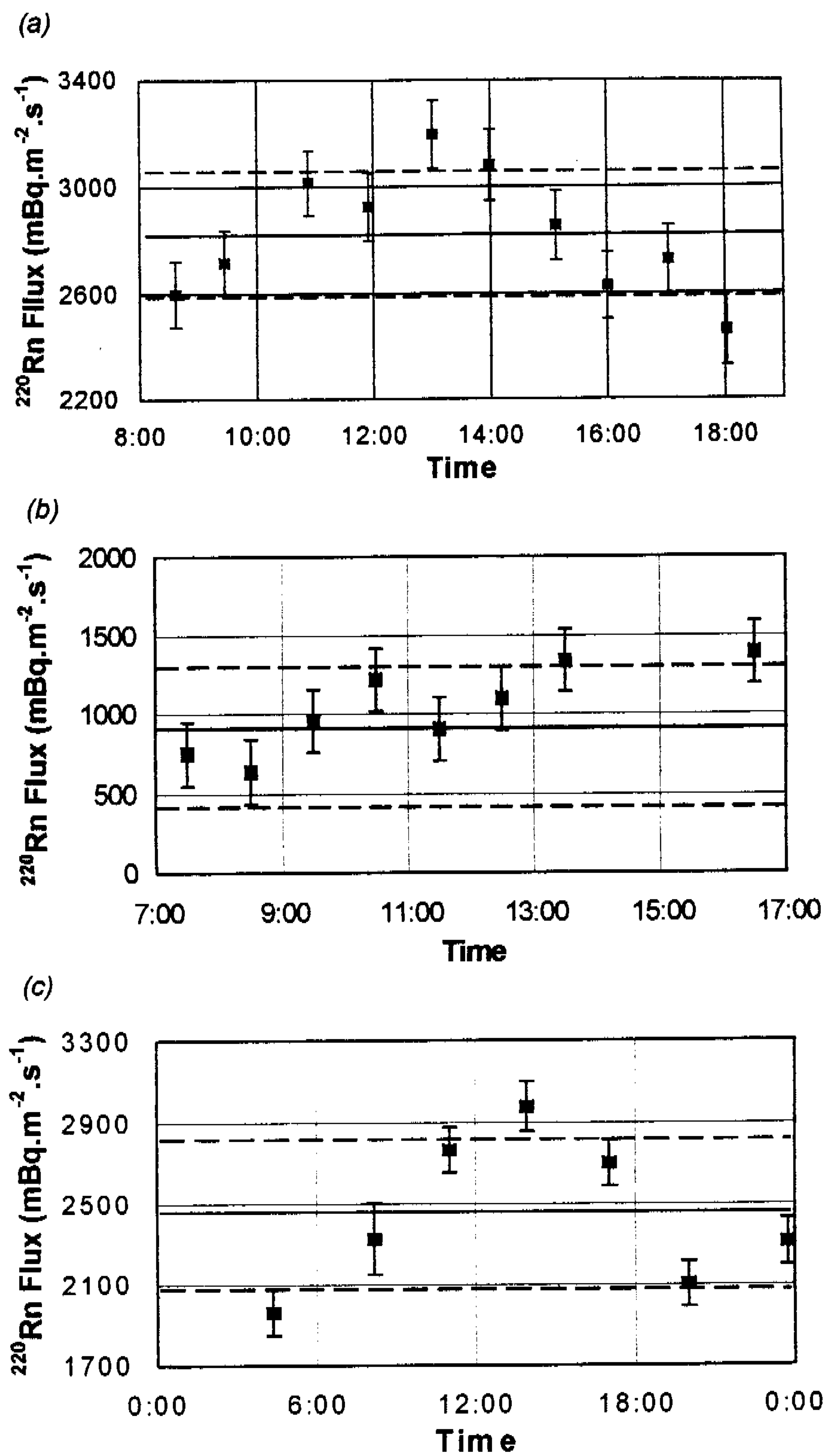


Figure 4.2 Diurnal Variations in ^{220}Rn Flux (a) Trial 1 : Institute (b) Trial 2 : Magela Creek (c) Trial 3 : Institute over 24 hours The solid line marks the average flux, while dashed lines are at ± one standard deviation

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.

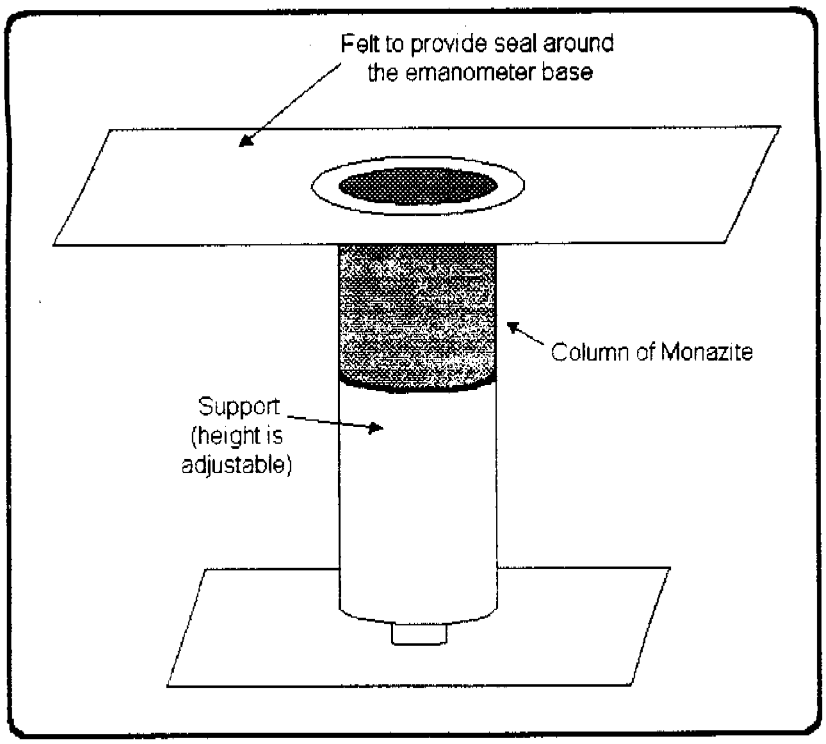


Figure 5.1 Schematic Diagram of Experimental Arrangement

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).

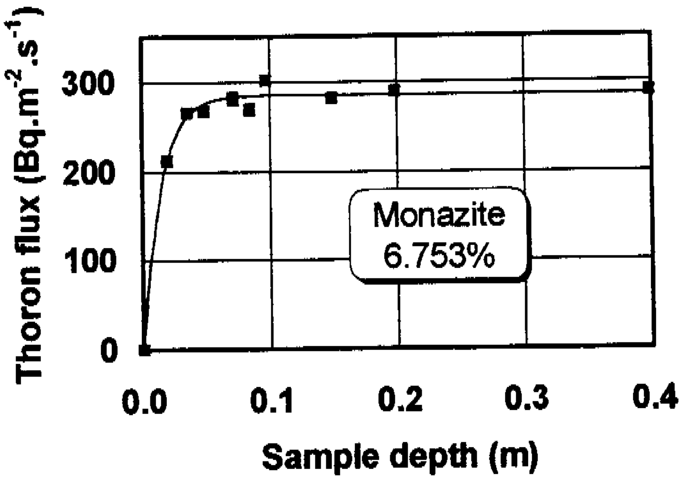


Figure 5.2 ^{220}Rn Activity Flux as a Function of Coulmn Thickness

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.

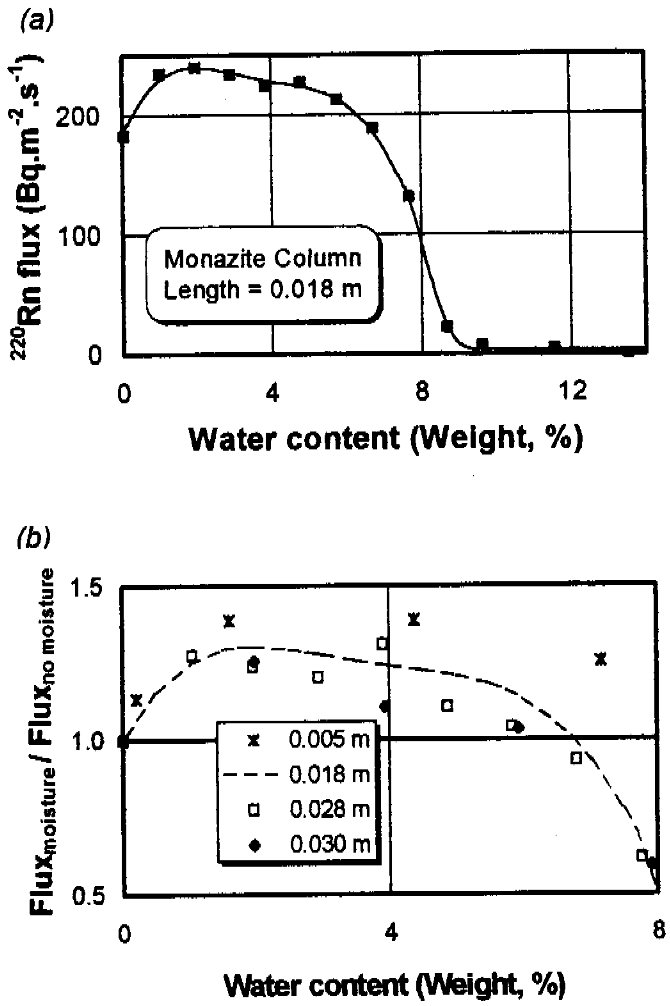


Figure 5.3 ^{220}Rn Flux Versus Water Content (a) An Example of Results Obtained (b) As a Ratio of Moist Flux to Dry Flux

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.

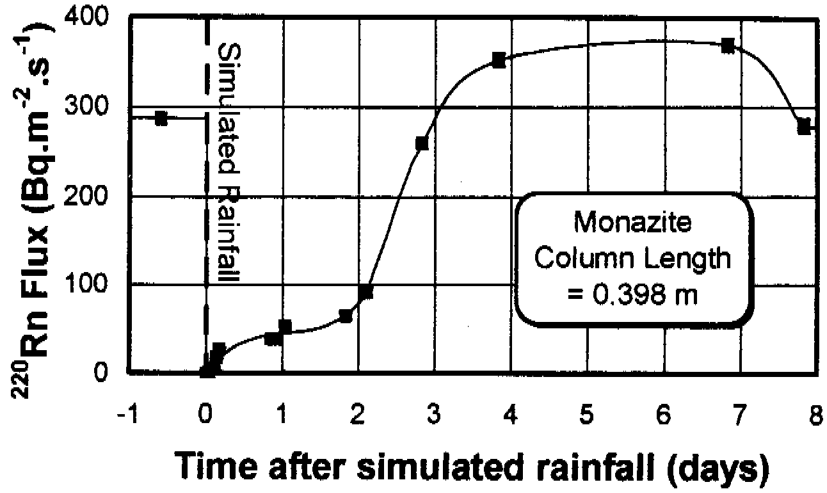


Figure 5.4 ^{220}Rn Flux Response to Simulated Rainfall

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.

BIBLIOGRAPHY

Amin, Y.M., Mahat, R.H., Doraisamy, S.J. and Subramaniam, S.Y. (1995). The Effect of Grain Size on the Radon Emanation Rate. *Appl. Radiat. Isot.*, 46(6/7): 621-622.

Anon (1996). History of Mining Operations in the Upper South Alligator Valley. *Information Sheet Provided at RARCS, Jabiru.*

ARRRI, Alligator Rivers Region Research Institute (1991). Alligator Rivers Region. *Proceedings, Land Application Workshop Jabiru.*

Australian Bureau of Statistics (1995) Regional Statistics Northern Territory ABS Catalogue No 1362.7.

Badr, I. and Durrani, S.A. (1993). Combing Nested and Linear Sampling for Determining the Scale and Form of the Spatial Variation of Soil Radon in the Midlands of England. *Nucl. Tracks Radiat. Meas.*, 22(1-4): 267-272.

Ball, T.K., Cameron, D.G., Colman, T.B. and Roberts, P.D. (1991). Behaviour of Radon in the Geological Enviroment: A Review. *Quart. J. Eng. Geol.*, 24: 169-182.

Becker, E. and Kaletsch, K. (1993). Function of Radon Emanation in Dosimetric Calculations. *Health Phys.*, 65(1): 103.

Brill, A.B., Becker, D.V., Donahoe, K., Goldsmith, S.J., Greenspan, B., Kase, K., Royal, H., Silberstein, E.B. and Webster, E.W. (1994). Radon Update: Facts Concerning Enviromental Radon: level, Mitigation Strategies, Dosimetry, Effects and Guidelines. *J. Nucl. Med.*, 35: 368-385.

Bureau of Meteorology. (1997). Climatological Summary for Jabiru Airport AWS.

Cui, L.-P (1990). Radiometric Methods in Regional Radon Hazard Mapping. *Nucl. Geophys.*, 4(3): 353-364.

Damkjaer, A. and Karsbech, U. (1988). A Search for Correlation Between Local Geology and Indoor Radon Concentration. *Radiat. Protect. Dosim.*, 24(1/4): 51-54.

Duenas, C. and Fernandez, M.C. (1987). Dependence of Radon 222 Flux on Concentrations of Soil Gas and Air Gas and an Analysis of the Effects Produced by Several Atmospheric Variables. *Annales Geophysicae*, 5B(6): 533-540.

ERA, Energy Resources Australia (1996a) *The Ranger Operation*, Jabiru : ERA

ERA, Energy Resources Australi (1996b) *The Jabiluka Project Environmental Impact Statement*, Brisbane : Kinhill.

Fleischer, R.L. (1987). Moisture and ^{222}Rn Emanation. *Health Phys.*, 52(6): 797-799.

Grasty, R.L. (1994). Summer Outdoor Radon Variations in Canada and Their Relation to Soil Moisture. *Health Phys.*, 66(2): 185-193.

Harley, J.H. (1992). Measurement of ^{222}Rn: A Brief History. *Radiat. Protect. Dosim.*, 45(1/4):13-18.

Hinton, T.G. and Whicker, F.W. (1985). A Field Experiment on Rn Flux From Reclaimed Uranium Mill Tailings. *Health Phys.*, 48(4): 421-427.

Howard, A.J., Simsarian, J.E. and Strange, W.P. (1995). Measurements of ^{220}Rn Emanation From Rocks. *Health Phys.*, 69(6): 936-943.

IAEA, International Atomic Energy Agency (1992) *Measurement and Calculation of Radon Releases From Uranium Mill Tailings Technical Reports Series No.333,* Vienna: IAEA.

ICRP, Internationl Commission on Radiological Protection. (1986) *ICRP47: Rdiation Protection of Workers in Mines*, Oxford: Pergamon Press.

ICRP, Internationl Commission on Radiological Protection. (1993) *ICRP 65: Protection Against Radon-222 at Home and Work*, New York: Pergamon Press.

Koperski, J. (1993). Radiation Protection in the Mining and Milling of Mineral Sands. *Radiat. Protect. Aust.*, 11(2): 46-52.

Kullman, F. (1994). Radon Risk Mapping- A Method of Predicting Problem Areas on Geological Grounds. *Radiat. Protect. Dosim.*, 56(1-4): 221-224.

Kvasnicka, J. and Bywater, J. (1991) Preliminary Assessment of Radiological Conditions at the Ranger Land Application Area. *Proceedings of the Land Application Workshop.*

Labed, V., Witschger, O., Robe, M.C. and Sanchez, B. (1994). ^{222}Rn Emission Flux and Soil-Atmosphere Interface: Comparative Analysis of Different Measurement Techniques. *Radiat. Protect. Dosim.*, 56(1-4): 271-273.

Li, Y., Schery, S.D. and Turk, B. (1992). Soil as a Source of Indoor ^{220}Rn. *Health Phys.*, 62(5): 453-457.

Li, Y. and Schery, S.D. (1993). A Coincidence Counter for Simultaneous Measurements of Low Levels of Radon and Thoron. *Radioactivity and Radiochemistry*, 4(2): 42-51.

Markkanen, M. and Arvela, H. (1992). Radon Emanation From Soils. *Radiat. Protect. Dosim.*, 45(1/4): 269-272.

Marten, R. (1991). External Dose Rate Survey of the Ranger Uranium Mine Land Application Plot. *Proceedings Land Application Workshop Jabiru.*

Morawska, L. and Phillips, C.R. (1993). Dependence of Radon Emanation on Radium Distribution and Internal Structure of the Material. *Geochimica et Cosmochimica Acta*, 57: 1783-1797.

Murray, A.S., Marten, R, Johnston A. and Martin P. (1987) Anlysis for Naturally Occuring Radionuclides at Environmental Concentrations by Gamma Spectrometry. *Journal of Radioanalytical and Nuclear Chemistry, Articles,* 115(2): 263-288.

NCRP, National Council on Radiation Protection and Measurements (1988), *Measurement of Radon and Radon Daughters in Air, NCRP Report No. 97,* Bethseda: NCRP.

Nazaroff, W.W. (1992). Radon Transport From Soil to Air. *Reviews of Geophysics*, 30(2): 137-160.

Owczarski, P.C., Holford, D.J., Freeman, H.D and Gee, G.W. (1990). Effects of Changing Water Content and Atmospheric Pressure on Radon Flux From Surfaces of Five Soil Types. *Geophysical Research Letters*, 17(6): 817-820.

Pfitzner, J. (1994) *Sample Collection and Preperation Manual for Gamm-Ray Spectrometry Analysis*, Internal Report IR69 Supervising Scientist for the Alligator Rivers Region.

Porstendorfer, J., Butterwick, G. and Reineking, A. (1991). Diurnal Variation of the Concentrations of Radon and its Short-Lived Daughters in the Atmosphere Near the Ground. *Atmos. Environ.*, 25A(3/4): 709-713.

Schery, S.D. and Petschek, A.G. (1983). Exhalation of Radon and Thoron: The Question of Thermal Gradients in Soil. *Earth and Planetary Science Letters*, 64(1): 56-60.

Schery, S.D., Gaeddert, D.H. and Wilkening, M.H. (1984). Factors Affecting Exhalation of Radon From a Gravelly Sandy Loam. *J. Geophys. Res.*, 89(D5): 7299-7309.

Schery, S.D. and Siegel, D. (1986). The Role of Channels in the Transport of Radon From the Soil. *J. Geophys. Res.*, 91(B12): 12366-12374.

Schery, S.D., Whittlestone, S., Hart, K.P. and Hill, S.E. (1989). The Flux of Radon and Thoron From Australian Soils. *J. Geophys. Res.*, 94(D4): 8567-8576.

Schery, S.D. (1990). Thoron in the Enviroment. *J. Air Waste Manag. Assoc.*, 40(4): 493-497.

Schery, S.D., Wang, R., Eack, K. and Whittlestone, S. (1992). New Models for Radon Progeny Near the Earth's Surface. *Radiat. Protect. Dosim.*, 45(1/4): 343-347.

Singh, B., Singh, S. and Virk, H.S. (1993). Radon Diffusion Studies in Air, Gravel, Sand, Soil and Water. *Nucl. Tracks Radiat. Meas.*, 22(1-4): 455-458.

Steinhausler, F., Hofmann, W. and Lettner, H. (1994). Thoron Exposure of Man: A Negligible Issue? *Radiat. Protect. Dosim.*, 56(1-4): 127-131.

Strong, K.P. and Levins, D.M. (1982). Effect of Moisture Content on Radon Emanation From Uranium Ore and Tailings. *Health Phys.*, 42(1): 27-32.

Tanner, A.B. (1980). Radon Migration in the Ground: A Supplementary Review. *The Natural Radiation Environment*, 3:5-56.

Thompson, A.W. (1995). Radiation Exposure to the Population of Perth, Western Australia. *Radiat. Protect. Dosim.*, 13(2): 64-69.

Tidjani, A. (1988). Study of the Effects of Atmospheric Parameters on Ground Radon Concentration by Track Technique. *Int. J. Radiat. Appl. Meas.*, 14(4): 457-460.

UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation. (1982) *Ionizing Radiation : Sources and Billogical Effects,* United Nations Publication E. 82, IX, 8-06300P, New York.

UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation. (1993) *Sources and Effects of Ionizing Radiation*, United Nations Publication No. E94.IX.2, New York.

Weast, R.C. (1983). *Handbook of Chemical Physics 64th Edition,* CRC Press Inc., Florida.

Whittlestone, S. Radon\Thoron Emanometer Operator's Instructions.