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The geographical variability of airborne radon concentration at the rehabilitated Nabarlek mine site during the dry season 2005

A Bollhöfer

1 Introduction

This report describes the results of a study aiming at measuring the geographical variability of airborne radon concentration at the rehabilitated Nabarlek mine site in Western Arnhem Land. Passive radon monitors (PRMs) were supplied by *Radiation Detection Systems*, Adelaide, and deployed at Nabarlek from June 7 to September 14, 2005, during a period of no rainfall.

This sub-project is part of the larger project *'Radiological impact assessment of the rehabilitated Nabarlek mine site'*, which aims at advancing Key Knowledge Need 4.2.1: *'Overall assessment of the rehabilitation success at Nabarlek'*. The measurements are required to develop a more comprehensive dose model for Nabarlek, which takes the geographical variability of airborne radon concentration into account. The temporal variability of radon concentrations on site has been measured earlier, for the best part of three years (1997-99) and results are published in a separate internal report (Bollhöfer et al 2004).

There is no permanent habitation close to the rehabilitated Nabarlek uranium mine site at present, but future occupancy of the site cannot be ruled out. Consequently, a radiological risk assessment, including all exposure pathways, is needed for planning purposes and to achieve closeout of the site. A radiological dose assessment requires integration of sub-tasks, or exposure pathways, such as:

1) External gamma dose rate
2) Radon exhalation rate and airborne radon concentration
3) Radionuclide concentration in surface soils and erosion/stability assessment
4) Bore water uranium and radium activity concentration measurements and
5) Measurement of radionuclide uptake into edible plants growing on and off site.

Sub tasks 1, 2, 3 and 4 are mostly complete, and results have been published in earlier reports and journal articles (Bollhöfer et al 2003, 2004, 2005; Hancock et al 2006, Martin et al 2006; Ryan and Bollhöfer, 2007). However, knowledge of the geographic variability of radon concentration was required for dose assessment.

Knowledge of site-use and site-use expectations of the local Aboriginal people is indispensable for an assessment of radiological exposure. At the time of this study the site was only infrequently accessed during the dry season for hunting, revegetation and planting activities by the general population and members of the Gunbalanya Community Rangers. Furthermore, staff from the Northern Territory Government, Hanson Pty Ltd, the Northern Land Council (NLC) and SSD access the site occasionally for site inspections or to ground truth remotely sensed data.

1.1 Location and climate

Nabarlek is located in the wet-dry tropics of northern Australia (Figure 1). The dry season extends from May to September and the wet season extends from November to March, with April and October being transition months. No long-term climatic records are available for Nabarlek itself, however, more than 60 years of weather data from Gunbalanya (Oenpelli), a small town 15 km west of Nabarlek uranium mine, exist. Over 90% of the total rainfall occurs between November and April and almost 60% within the three months of January, February and March. At Nabarlek airport the mean annual rainfall is 1389 mm (Grabham 2001).

Figure 1 Location of the Nabarlek mine site

The contrasting wet and dry seasons result in highly variable radon exhalation rates at Nabarlek over the year (Martin et al 2002) primarily due to the influence of soil moisture on radon exhalation (Lawrence 2005). Consequently, ambient radon concentration vary considerably (Bollhoefer et al 2004) between wet and dry seasons. From a dose assessment point of view, the dry season months are the relevant months for Nabarlek, as access to the site during the wet is restricted.

The Nabarlek mine site is located in Arnhem Land in the Northern Territory, 1 km south-east of the Gadjerigamundah Creek and 1 km north-west of the western arm of Cooper Creek, the latter being a tributary of the East Alligator River. The Nabarlek ore body 1 extended from the surface to a depth of 72 metres, with a length of 230 m and a variable thickness of about 10 m. It was a relatively compact, high-grade ore body and Queensland Mines Ltd (QML) mined it out during 4 months of the dry season of 1979. Approximately 600 000 t of average 2% grade ore were stockpiled, and subsequently milled and sold over an eight year period that ended in 1988 (UIC 1997). Rehabilitation of the Nabarlek site is described in detail in Waggitt and Woods (1998) and Adams and Hose (1999).

680 000 t of mill tailings, together with scraped sludge from the bottom surfaces of runoff and evaporation ponds, were placed in the pit. The tailings were covered by geotextile followed by a graded rock and leached sand layer of 1 to 3 metres. The design relied on the tailings being below the recovered level of the local groundwater table, and approximately 13 metres below the final ground surface to keep radon exhalation rates at the surface low (Waggitt & Woods 1998). Vertical 'wicks' to a maximum depth of 33 m were installed to drain the mass and accelerate consolidation. With final decommissioning of the mine in 1995, remaining contaminated material and unsaleable plant equipment were placed in the remaining pit void and covered with another layer of waste rock to ground surface. In addition to the pit area, other sites to be rehabilitated were the plant area, the evaporation ponds, the plant runoff pond, stockpile runoff pond, waste rock pad runoff pond, ore stockpile area, waste rock stockpile area and the topsoil stockpile area. Most of these areas were left covered with run-of-mine waste rock. This waste rock cover was then prepared for revegetation.

1.2 Radon

Radon is a natural radioactive noble gas and has three major isotopes. These isotopes are ^{219}Rn ('*Actinon'*), ^{220}Rn ('*Thoron*') and ^{222}Rn ('*Radon'*) with halflives of 3.96 seconds, 55.6 seconds and 3.82 days, respectively. ^{222}Rn is a member of the ^{238}U decay series (Figure 2), whereas ^{219}Rn and ^{220}Rn are members of the ^{235}U and ^{232}Th decay chains, respectively.

Radon is an inert gas and diffuses through and emanates from U rich soils and rocks without undergoing chemical reactions. The radon flux density depends on the type of soil (sandy, silty etc.), its porosity and moisture, the uranium and radium content, and the depth of the watertable, which impedes the flow of soil gas (eg Markkanen & Arvela 1992, Holkko & Liukkonen 1992, Porstendörfer 1994).

The majority of radon related research focuses on indoor environments because indoor exposure to radon, although it varies widely, can reach over 20 mSv per year in some cases (Tubiana et al 1990). This is 20 times higher than the annual dose limit from a practice recommended by the International Commission for Radiological Protection (ICRP60, 1991). Main sources of radon in indoor environments are building materials (such as materials based on granite or clay) and the type of soil a house is built on. In addition, it is largely influenced by the ventilation of inside air. In warm and subtropical regions such as the Alligator Rivers Region, homes are usually well ventilated and radon exhalation from building materials does not contribute significantly to radon exposure. This is reflected in the average radiation

exposure from radon, which is 1.2 mSv worldwide (UNSCEAR 2000) but only approximately 0.6 mSv in Australia (Langroo et al 1990).

Uranium mines exhibit elevated ^{222}Rn exhalation due to the high uranium and radium contents of stockpiles, waste rock dumps or tailings material, and their relative porosity as compared to the undisturbed areas nearby. A recent study at Nabarlek (Bollhöfer et al 2003, Bollhöfer et al 2005) has shown that radon exhalation rates, despite attempts to rehabilitate the former mine site, are relatively high (in some areas up to 200 times above environmental background). Akber et al (2004) and Lawrence (2005) have shown in a study around Ranger mine that the ratio of radon flux density to soil radium content is characteristic for certain geomorphic units and this can consequently be used to estimate average radon flux densities from their soil radium concentration.

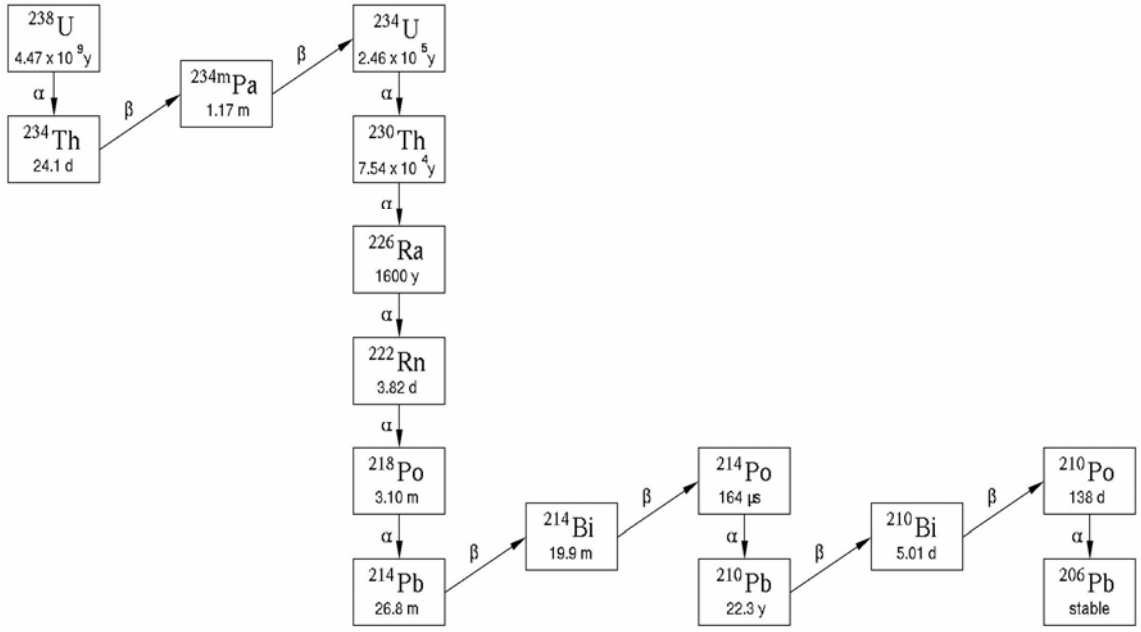

Figure 2 The ^{238}U decay chain

Following the ICRP guidelines (1991) the non-natural radiation exposure of the public should be less than 1 mSv per year from a practice such as uranium mining. This limit is for the total dose from all relevant practices but the dose constraint for a single source will generally be lower than this. ICRP (1997), paragraph 6.2.1 (a) states:

> The control of public exposure from waste disposal should be exercised by the use of the constrained optimisation of protection. To allow for exposures to multiple sources, the maximum value of the constraint used in the optimisation of protection for a single source should be less than 1 mSv in a year. A value of no more than about 0.3 mSv in a year would be appropriate.

It is essential to estimate the above natural component of radiation exposure. Therefore reliable pre-mining data are needed in order to assess the impact of a practice. Although radon in soil measurements were taken in 1975 (QML 1979) it has proven difficult to conduct a pre-post mining comparison of radon exhalation at the Nabarlek site because actual pre mining radon flux densities were not measured (Bollhöfer et al 2003). A study measuring pre-mining radon concentration at Nabarlek has been conducted by Davy et al (1978) however this report was confidential and data are not available up to this point in time.

1.3 Radon progeny

Although radon itself does not impose a major inhalation health risk, its short lived radioactive progeny, the metals ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (^{212}Pb, ^{212}Bi and ^{212}Po for thoron) can be deposited in the lungs and deliver a significant dose to the respiratory system (Tubiana et al., 1990). The most important parameters for dose estimation due to inhalation of radon progeny are the radon progeny potential alpha energy concentration (PAEC), the equilibrium factor (E), and the unattached fraction of radon progeny (f_p). With a knowledge of these factors radon concentration measurements can be used to estimate the average potential alpha energy concentration and the dose received due to the inhalation of radon progeny.

1.3.1 Potential alpha energy concentration and equilibrium factor

The potential energy originating from the alpha decays of $1.8 \cdot 10^8$ Bq/m^3 radon in air in equilibrium with its short-lived decay products is 1 J/m^3. This gives a measure of the total kinetic energy of all the alpha particles emitted by a mixture of radon and short lived radon decay products when all of the atoms in the mixture have completely decayed into ^{210}Pb. The alpha energy of one atom of ^{214}Po decaying to ^{210}Pb is 7.69 MeV. Although ^{214}Bi is a beta emitter, it has a potential alpha energy of 7.69 MeV as well, since its progeny is ^{214}Po, which eventually decays to ^{210}Pb via an alpha decay.

The actual potential alpha energy concentration, W_p, is the sum of the potential alpha particle energy of all the short-lived radon and thoron daughters in a unit volume of air. Looking at radon only, it is a measure of the total energy of the alpha particles emitted by radon progeny, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po, which are not necessarily in equilibrium with their progenitor radon.

The equilibrium factor describes the fraction of potential alpha decay energy of the actual short-lived radon decay products in air compared to the potential energy of the short-lived radon decay products, W_{eq}, in secular equilibrium with radon.

$$F = W_p / W_{eq} \qquad (1)$$

This equation can be expressed in terms of activity concentrations because:

$$W_p = \Sigma_i W_{p,i} = \Sigma_i N_{p,i} \cdot \varepsilon_{p,i} = \Sigma_i A_{p,i} \cdot \varepsilon_{p,i} / \lambda_i \qquad (2)$$

With:

W_p: potential alpha energy of mixture of short lived radon progeny in air

$W_{p,i}$: alpha energy of radon progeny i

$N_{p,i}$: number of atoms of radon progeny i per m^3

$\varepsilon_{p,i}$: potential alpha energy per atom i (13.69 MeV for ^{218}Po and 7.69MeV for ^{214}Pb,Bi,Po)

$A_{p,i}$: activity concentration of radon progeny i

λ_i : decay constant of radon progeny i

Therefore:

$$F = W_p / W_{eq} = (\Sigma_i A_{p,i} \cdot \varepsilon_{p,i} / \lambda_i) / (A_0 \cdot \Sigma_i \varepsilon_{p,i} / \lambda_i) = \Sigma_i (A_{p,i} / A_0 \cdot (\varepsilon_{p,i} / \lambda_i) / (\Sigma_i \varepsilon_{p,i} / \lambda_i))$$
$$= (0.105 \cdot A_1 + 0.516 \cdot A_2 + 0.379 \cdot A_3 + 5.254 \cdot 10^{-8} \cdot A_4) / A_0 \qquad (3)$$

Where A_0, A_1, A_2, A_3, and A_4 are the activity concentrations of ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po, respectively. The coefficients give the fractional contribution to the total alpha energy from the various decay products. The potential alpha energy of ^{214}Pb and ^{214}Bi (both are β

emitters) is 7.69 MeV per atom, as this is the alpha energy of a ^{214}Po atom decaying to ^{210}Pb; ^{218}Po possesses an additional potential 6 MeV due to its decay to ^{214}Po. At radioactive equilibrium, the equilibrium factor equals 1. UNSCEAR (2000) assume a default equilibrium factor of 0.6 for outdoor environments.

Using the equilibrium factor the potential alpha energy concentration can be calculated from the measured radon concentration via:

$$C_{RDP} = F \cdot W_{eq} \cdot C_{Rn} \qquad (4)$$

With:

W_{eq} : PAEC per Bq of ^{222}Rn in equilibrium with short lived progeny, 5.6 nJ/Bq

F : equilibrium factor

C_{Rn}: radon activity concentration [Bq per m^3].

The following calculation is performed to estimate the effective dose resulting from exposure to radon progeny:

$$E_{RDP} = h_{RDP} \cdot C_{RDP} \cdot t \qquad (5)$$

With:

E_{RDP}: effective dose due to the inhalation of radon decay products [μSv]

h_{RDP}: dose conversion factor

C_{RDP}: radon progeny PAEC [μJ/m^3]

t: inhalation time.

The dose conversion factor h_{RDP} recommended by the International Commission on Radiation Protection (ICRP 1993) is 1.1 μSv·(μJ·h·m^{-3})$^{-1}$ (for radon in equilibrium with progeny) which translates to 6.18 nSv·(Bq·h·m^{-3})$^{-1}$. The dose conversion factor recommended by UNSCEAR (2000) is 9 nSv·(Bq·h·m^{-3})$^{-1}$ for dose calculations from the inhalation of radon in equilibrium with its progeny, assuming an average daily breathing rate of 22.2 m^3 per day for an adult male. This is approximately 45% higher than the ICRP (1993) recommended conversion factor, but similar to the value given by Porstendörfer (2001) for a f_p = 0 in indoor air, 9.7 nSv·(Bq·h·m^{-3})$^{-1}$.

1.3.2 Equilibrium factor in the Alligator Rivers Region

Whilst there have been many studies investigating the equilibrium factor, most of them have focussed on indoor radon concentration, since indoor radon is considered a much higher risk (see for instance Nazaroff & Nero 1988). Generally, indoor radon and radon progeny concentrations are higher in buildings than in the open atmosphere (Porstendörfer 1994) and can give rise to effective radiation doses of above 20 mSv per year (Tubiana et al 1990).

As the inhalation of radon progeny is one of the major pathways for radiological impact from uranium mining activities both, for workers and the general public, several studies have been carried out in the Alligator Rivers Region and, in particular, in the region around Ranger uranium mine measuring radon and/or radon progeny concentration in the air (Akber et al 1992a,b, Akber & Pfitzner 1994, Akber et al 1994a,b, Auty & Du Preez 1994, Martin et al 2004).

In general lower values for the equilibrium factor F occur when radon is young and transport of radon is limited. This situation occurs during periods of little atmospheric exchange, and low wind speeds, typically in the mornings when radon concentrations are relatively high.

The radon is then of 'local' origin rather than radon that has been transported from elsewhere, as is the case during periods of higher wind speeds. In those cases, generally in the afternoons, the equilibrium factor is higher. Akber and Pfitzner (1994) have reported average equilibrium factors of about 0.4 in the mornings in the dry season in Jabiru East, increasing to about 0.8 in the afternoon.

Martin (2002) has modelled radon and radon progeny concentrations in the Alligator Rivers Region using a moving grid dispersion model, and has calculated annual average equilibrium factors for Jabiru and Jabiru East of 0.16 and 0.09, respectively.

Woods (1989) reported an annual average equilibrium factor for Nabarlek of 0.17. These measurements were performed next to the Nabarlek pit during a period of semi-dry tailings deposition. Woods observed the same annual and diurnal pattern as the one observed at Jabiru East by Akber and Pfitzner (1994). However, equilibrium factors reported are on average a factor of approximately 2 lower. This is most likely due to the fact that measurements by Woods were taken close to the main source of radon at Nabarlek at a height of 1 m above the surface, whereas the height of the sampler inlet at Jabiru East, about 3 km north of the Ranger mine, was 15 m above the ground.

1.3.3 Attached and unattached fraction

Additional factors influencing the dose received from the inhalation of radon progeny are whether the radon progeny is attached to aerosol, and the size distribution of the aerosol.

After radon decays to ^{218}Po, radon progeny react with trace gases and air vapours and become small particles. This happens within less than 1 second after decay (Porstendörfer 1994) and the formed clusters with diameters of typically 0.5 to 2 nm are called unattached radon progeny. The ratio of unattached to total radon progeny is labelled f_p.

Unattached radon progeny can attach to existing aerosol particles in the atmosphere. These aerosols have a certain particle size distribution and the radon progeny attachment process is a function of the aerosol size and the particle density. Indoors, a higher particle concentration when ^{218}Po forms from the decay of ^{222}Rn increases the equilibrium factor, as plate out of radon progeny is reduced.

The size distribution of aerosols determine the behavior in the respiratory tract and thus the radiation dose received. Particle deposition in the lungs increases for particles with diameters ranging from 3–10 nm and decreases again as diameters increase toward 100 nm and larger. Particle deposition starts to increase again for particles above 500 nm but larger particles with diameter exceeding 3.5 µm deposit predominantly in the nose and mouth during inhalation, and thus the dose from inhalation is reduced. The dose conversion coefficient for the inhalation of radon progeny increases with an increase in the unattached fraction, f_p. For instance, for median aerosol diameters above ~200 nm the dose conversion coefficient increases by about two fold for an increase in the unattached fraction from 0.05 to 0.21 (UNSCEAR 2000).

Generally, most of the radon progeny attach to aerosols if the number of condensation nuclei is sufficient. A typical value of f_p given for indoor environments is 0.05 (meaning that 5% of the radon progeny is unattached) and f_p generally increases with decreasing particle density.

Akber and Pfitzner (1994) have measured f_p in outdoor air at Jabiru East and report a decreasing trend of the unattached fraction and an increase in the equilibrium factor with increasing particle density. They estimated an annual average of about 0.14 for the unattached fraction of radon progeny in Jabiru East and approximately 0.10 during the dry season. This is higher than values reported elsewhere, which Akber and Pfitzner related to lower condensation nuclei concentrations in the air at Jabiru East than at other places. Akber et al

(1994b) in particular demonstrate, that a default value of 0.05 for f_p is not applicable in the Alligator Rivers Region. Martin (2002) modelled radon and radon progeny transport in the Alligator Rivers Region and determined even higher unattached fractions of 0.24 and 0.29 at Jabiru and Mudginberri, respectively.

Porstendörfer (2001) suggests that the dominant parameter influencing the fraction of the unattached progeny is the attachment rate, which depends on the number concentration of aerosol and gives the following empirical equation to calculate f_p in outdoor air:

f_p = 414/Z[cm^{-3}] (see Porstendörfer 2001 for details) (6)

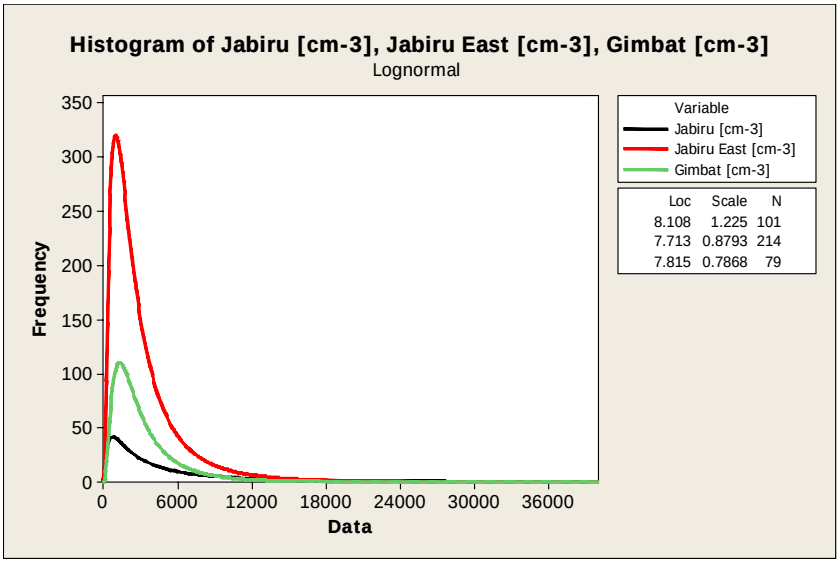

Figure 3 Aerosol number [cm^{-3}] distribution at Jabiru, Jabiru East and Gimbat, 1998

Porstendörfer (2001) furthermore calculates the dose conversion factor [mSv·WLM^{-1}] for outdoor air, for a person breathing through the nose at a rate of 1.2 m^3·hr^{-1}. For the equilibrium equivalent radon concentration this equation can be written as:

DCF [nSv·(Bq·h·m^{-3})$^{-1}$] = 14.5 + 101.7·f_p (7)

The particle number and size distribution at Nabarlek is not known. However, Thomas et al (1999) have measured aerosol size distribution at Jabiru and Gimbat, and also at Jabiru East (not published). Figure 3 shows the number distribution for the three sites. The geometric means for the three sites are 3321, 2237, and 2477 cm^{-3}, respectively. Consequently, the unattached fraction f_p of radon progeny using equation 6 for these sites is between 0.12–0.18 although the Jabiru (higher) value was influenced by domestic aerosol (cooking) (Thomas et al 1999). These f_p values are in agreement with the measurements by Akber and Pfitzner (1994) but lower than values reported by Quintarelli et al (1998).

Assuming an f_p value for Nabarlek between 0.12 and 0.18, the dose conversion factor can be calculated using equation 7, assuming light to moderate activities performed on site. The DCF inferred from this equation is higher yet again (26.7–32.8 nSv·(Bq·h·m^{-3})$^{-1}$) due to the faster breathing rate assumed by Porstendörfer (2001) compared to ICRP (1993) and UNSCEAR (2000) values, and the higher unattached radon progeny.

2 Methods

Track etch detectors have been used in this study to determine the airborne radon activity concentration. This method has been widely used, and it is relatively simple and low cost, and ideal for geographical surveys where integration of the radon concentration over a certain time period is sufficient. Detection limits for the method vary typically at around 10 Bq per m^3 and uncertainties for low activities are generally ± 40% (Kvasnicka, pers comm).

2.1 Survey sites

Locations of the survey sites are marked by the grey squares in Figure 4. Black triangles (environmental sites) and black dots (control sites) represent sampling locations from a radon exhalation survey (Bollhöfer et al 2003, 2005). Appendix A gives the GPS coordinates of the individual survey points and the associated exposure times.

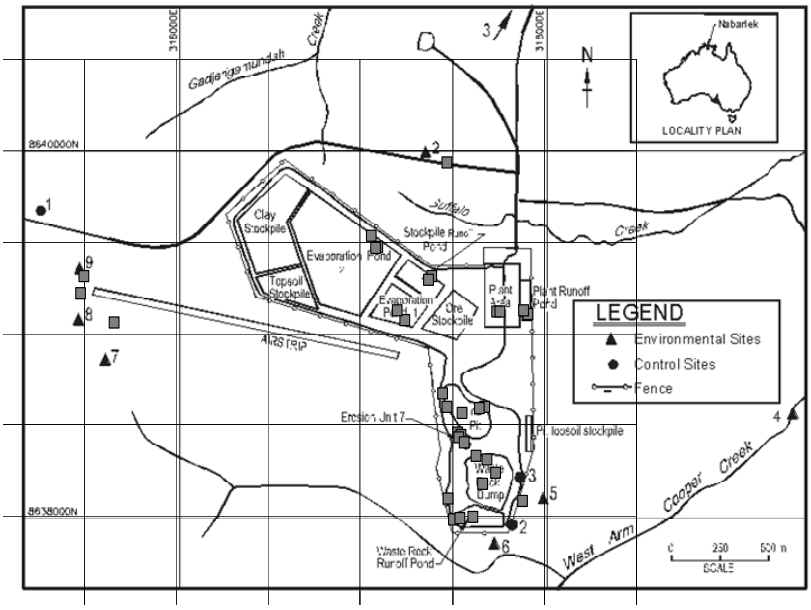

Figure 4 Location of the airborne radon concentration survey sites (grey squares)

Figure 5 shows a photograph of one of the sampling locations. Track etch detectors were deployed in pairs at each site. A plastic star picket was used to attach the plastic bags containing the passive radon monitor (PRM). The plastic bags had holes to allow easy airflow. The height of the PRMs was 1 m above the ground surface. As the response of the track etch film typically decreases when exposed to direct sunlight and excessive heat, a shade was installed. This shade consisted of a white styrofoam food container.

A total of 80 PRMs were deployed at a total of 36 sites. 3 PRMs each were deployed at both Plinth D and the former radon station site, and 4 PRMs were deployed at unit 7, at various heights above the ground to investigate the effects of height onto radon concentration. Three of those four PRMs were found lying on the ground (PRM #70, 73, and 52) upon collection, and the data are not included in this report.

The radon station site was the site of an active radon station, where radon concentrations were measured using a continuous radon gas monitor (Tims 1999) from1997–1999 (Bollhöfer et al 2004).

Figure 5 Sampling location

2.2 Track etch detectors

Track etch detectors rely on the fact that charged particles, which pass through a dielectric material, ionise the molecules in the dielectric and this transfer of energy results in a trail of damaged molecules.

The track can be made visible by etching the material in strong acidic or basic solutions, as the tracks generated by the charged particles are etched at a faster rate than the remaining material. This leads to small 'pits' forming on the material's surface upon etching, which can be counted using a conventional optical microscope (Knoll 1979). Today, plastic track etch detectors are the most common method to measure radon (Durrani & Ilic 1997).

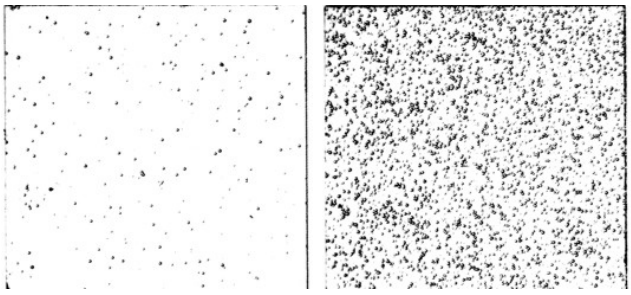

Figure 6 Photograph of a track etch film as seen through a microcope

Figure 6 shows a typical photograph of a track etch film as seen through a microcope. The left side was exposed to a lower airborne alpha activity concentration than the right side, thus showing a lower track density. Track etch detectors require particles to have a specific energy loss per length travelled before the damage to the dielectric is visible upon etching. This excludes electrons and gamma particles from producing a track severe enough to be etched. Thus track etch detectors are useful for the detection of alpha radiation only and ideal for radon applications, as they are insensitive to gamma and cosmic rays (Knoll 1979). Typical responses of track etch detectors vary between 0.5 to approximately 7 (tracks/cm^2) per (kBq/m^3·h) (Durrani & Ilic, 1997).

3 Results

Table 1 shows the results of the measurements of radon concentration in the air at Nabarlek.

Table 1 Results of airborne radon concentration [Bq·m^{-3}] (±stdev) measured by the individual track etch detectors deployed at Nabarlek

SITE	ERISS PRM Number	PRM number on detectors				Rn-222 [Bq·m^{-3}]			Rn-222 ave [Bq·m^{-3}]
Darwin	1, 2	1	2			33	41		37 ± 6
PlinthD	79, 78, 43	79	78	43		51	47	41	46 ± 3
Rn-station	52, 62, A	5	62	47		155	210	237	201 ± 42
Unit 7-1	69, 42	69	42			174	213		194 ± 28
Unit 7-2	50, 41	50	41			270	330		300 ± 42
Unit 7-3	60, 67	60	67			348	416		382 ± 48
Unit 7-4	63, 70, 73, 52	63	~~70~~	~~73~~	~~52~~	322			322 ±129
PROP-1	56, 68	56	68			48	54		51 ± 4
PROP-2	54, B	54	15			65	57		61 ± 6
PROP-3	65, C	65	57			96	77		87 ± 13
SPROP-1	72, 49	72	49			257	187		222 ± 49
SPROP-2	58, 76	58	76			194	356		275 ± 115
EP2-1	74, 79	74	61			159	174		167 ± 11
EP2-2	59, 77	59	77			426	408		417 ± 13
EP2-3	51, 48	48	51			572	426		499 ± 103
EP1-2	80, 64	80	64			200	252		226 ± 37
EP1-1	66, 77	66	71			73	83		78 ± 7
PIT-1	16, 39	16	39			70	96		83 ± 18
PIT-2	24, 45	24	45			213	174		194 ± 28
PIT-3	55, 13	55	31			107	312		210 ± 145
WRD-1	07, 30	7	30			90	122		106 ± 23
WRD-2	26, D	26	13			109	113		111 ± 3
WRDROP-1	21, 14	21	14			86	107		97 ± 15
WRDROP-2	06, 31	6	10			86	113		100 ± 19
WRDROP-3	32, 10	32	75			155	129		142 ± 18
WRDROP-4	29, 11	29	11			286	278		282 ± 6
WRD-3	22, 19	22	19			100	96		98 ± 3
WRD-4	36, E	36	40			127	145		136 ± 13
PIT-4	34, 09	34	9			90	81		86 ± 6
PIT-5	03, 33	3	33			127	96		112 ± 22
ENV.5	38, 17	38	17			126	117		122 ± 6
ENV.2	F, G	44	46			23	34		29 ± 8
ENV.9	H, I	12	37			55	55		55 ± 0
ENV.8	20, J	20	18			49	62		56 ± 9
ENV.7	08, 04	8	4			41	39		40 ± 1
MYRA-1	27, 36	27	28			18	31		25 ± 9
Top Tank	35, 15	35	15			67	65		66 ± 1
Bund Tank	23, K	23	25			37	29		33 ± 6

Radon concentrations measured at individual sites ranged from a minmum of 25±9 Bq·m^{-3} at the environmental control site close to the Myra camp turn-off (Myra-1) up to a maximum of 500±100 Bq·m^{-3} at evaporation pond 2. Radon concentration were also high at unit-7 (maximum 382±48 Bq·m^{-3}) a relatively bare area, which has previously been identified as an

area of high soil radium activity concentration (Hancock et al 2006) and radon flux densities (Bollhöfer et al 2005).

At unit-7 (Hancock et al 2006), also called the radiological anomalous area, soils exhibit a pronounced radioactive disequilibrium between ^{226}Ra and ^{238}U, and soil radionuclide activity concentrations up to 15 400 $Bq \cdot kg^{-1}$ and 6800 $Bq \cdot kg^{-1}$, respectively. The area can clearly be distinguished from surrounding areas by both visual inspection and by radionuclide content. The area exhibits the highest radon exhalation, with a mean radon exhalation flux density of 6.5 $Bq \cdot m^{-2} \cdot s^{-1}$. Four sampling sites were situated on the area. Upon collection of the exposed PRMs, numbers 70, 73 and 52 were lying on the ground. Radon concentrations measured by these PRMs were thus not used when calculating the average at the sampling site.

Other areas exhibiting relatively high airborne radon concentrations were the stockpile runoff pond area and areas on the footprint of former evaporation pond 2. The area of the former pit and waste rock dump show a radon concentration of 100–200 $Bq \cdot m^{-3}$.

4 Discussion

Area-averaged concentrations of radon in air at Nabarlek were compared with average terrestrial gamma dose rates determined from groundtruthing of an airborne gamma survey (Martin et al 2006), from a detailed survey of unit-7 in 2005, and with radon flux densities determined across the site (Bollhöfer et al 2005). The comparison indicates that terrstrial gamma dose rates (ultimately, soil radionuclide activity concentrations) influence the airborne radon concentration at specific locations (Table 2). Generally, higher soil radionuclide concentrations lead to elevated average radon concentrations (Figure 7). This was observed at the pit, WRD, WRDRP, unit-7, EP1 and PROP. However, both EP2 and SPROP stand out in this comparison. These sites had a significantly denser vegetation cover at the time of deployment of the PRMs as compared to the other sites. The monitors were deployed amongst dense stands of weeds (red natal grass, and para and mission grasses), which may have inhibited air flow and promoted a build up of radon and its progeny during the night and in the early morning hours, and inhibited an effective convective air exchange during the day.

Table 2 Average airborne radon concentrations and a comparison with terrestrial gamma dose rates and radon flux densities at Nabarlek. The average radon concentration given for the total area is an area weighted average, assuming that the area not investigated on site exhibits an environmental airborne radon concentration of 41±15 $Bq \cdot m^{-3}$ (average of Myra site and environmental sites 2, 7, 8 and 9).

	Area [ha]	Radon concentration [$Bq \cdot m^{-3}$]	Gamma dose rate[a] [$uGy \cdot hr^{-1}$]	Radon exhalation[b] [$mBq \cdot m^{-2} \cdot s^{-1}$]
EP-2	25	361 ± 162	0.37	105 ± 102
Unit 7	0.4	296 ± 83	0.98	6508 ± 6831
PROP	1.1	66 ± 18	0.36	278 ± 203
SPROP	4	249 ± 78	0.36	137 ± 120
EP-1	6	152 ± 88	0.48	169 ± 86
PIT	4	137 ± 76	0.51	971 ± 739
WRD	8	113 ± 18	0.46	335 ± 318
WRDROP	1.9	138 ± 92	0.47	335 ± 318
remainder	89.6	41 ± 15	0.05-0.09	31 ± 15
Total area	**140**	**118**	**0.31**	**124**
Environmental background		41 ± 15	0.05-0.09	31 ± 15

a Martin et al (2006), b Bollhöfer et al (2005)

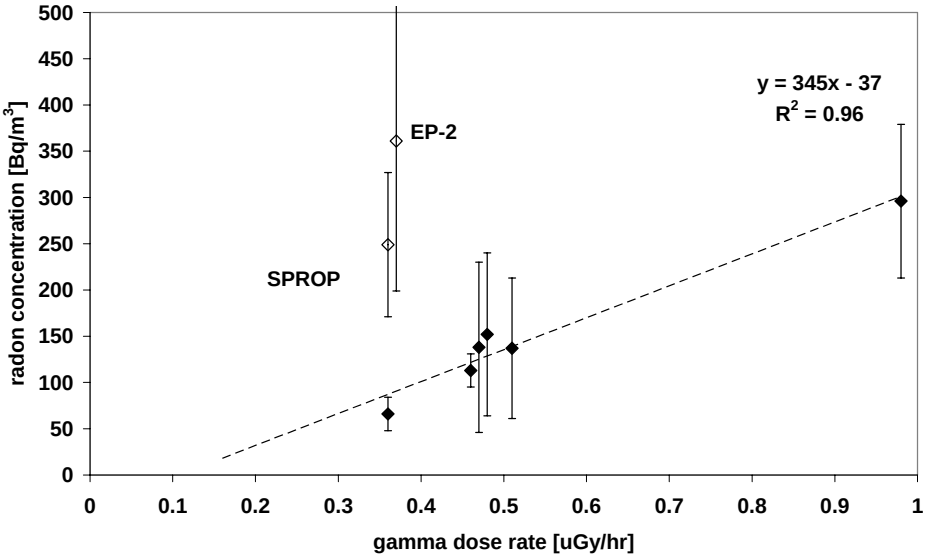

Figure 7 Airborne radon concentration plotted versus terrestrial gamma dose rates averaged over areas on the Nabarlek site given in Table 2

Continuous measurements conducted at Nabarlek from 1997–99 using a radon gas monitor showed that average radon concentration during the mid dry-season (July-September) at the radon station site ranged from 100–140 Bq·m^{-3} (Bollhöfer et al 2003). The value of 201 ± 42 Bq·m^{-3} found for the radon monitor used in this study (Table 1) is higher within the given uncertainties. The most likely reason for this difference again is the denser vegetation cover of the site during the time of deployment of the track etch detectors. In contrast, when the radon gas monitor was operated at Nabarlek between 1997–1999, the area in the vicinity of the instrument was kept reasonably clear to prevent it from being damaged by fire. Environmental site 5 approximately 100 metres NE of the radon station site, exhibits a radon concentration of 122 Bq·m^{-3}, which is similar to the averaged values from 1997–99.

The accumulation of radon in 'dead zones' has potentially important implications for assessing human exposure on rehabilitated mine landforms. In particular, measurements made in well flushed open environments may underestimate exposure that would occur in an area with denser mid-story or canopy development, and vice versa. Moreover, humans are typically much closer to the ground (sleeping) during the night and early morning hours when the potential for radon accumulation will be the greatest. Addditional work was planned to investigate near ground surface concentrations of radon in vegetated areas at Nabarlek during the 2006 dry season. However, the occurrence of Cyclone Monica and subsequent fires meant that this follow-up work could not be performed.

Figure 8 shows the frequency distribution and a log-normal fit to the measured airborne radon concentration data, and the probability function for all measurements conducted on site. The arithmetic mean of the radon concentration is 151 Bq·m^{-3}. The median and 1st and 3rd quartiles, respectively, are 109, 65 and 210 Bq·m^{-3}. Calculating an area averaged mean radon concentration (see Table 2) yields 118 Bq·m^{-3}.

The US Environmental Protection Agency's *Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings* (US EPA 2004) recommends that annual average concentration of radon-222 in air at or above any location outside a disposal site (the pit could in general be considered as such) should not exceed the background by more than one-half picocurie per liter; this is equivalent to 18.5 Bq·m^{-3}. Assuming an environmental background of 41 Bq·m^{-3} this would result in a total radon concentration of 60 Bq·m^{-3}. More than 75% of

the sites investigated would therefore not comply with the standard set by the US EPA. However, it is difficult to estimate the pre mining airborne radon concentrations which is considered background at the Nabarlek mine site. Davy et al (1978) investigated the pre mining radon concentration at Nabarlek. However, these data are not available.

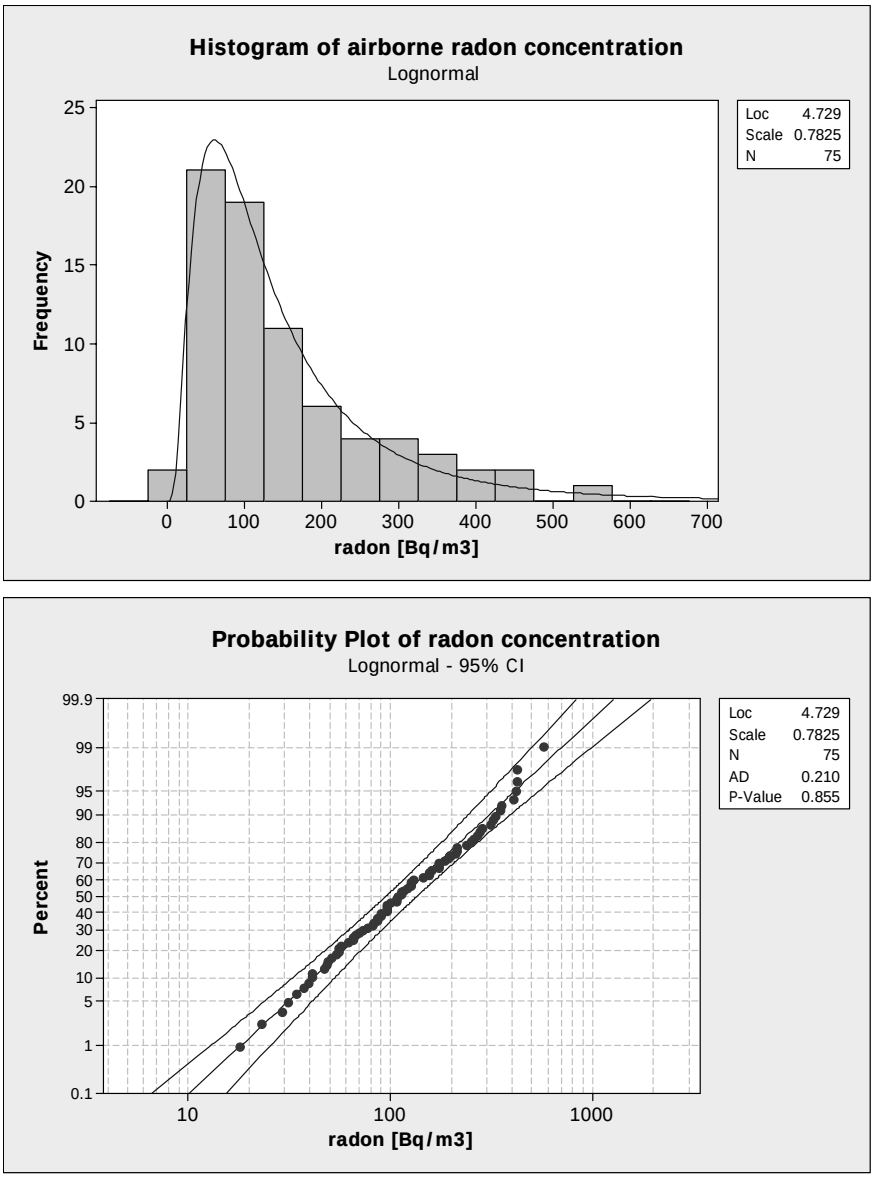

Figure 8 Frequency distribution and probability plot of the airborne radon concentration [Bq·m^{-3}] measured at the rehabilitated Nabarlek mine site

Most countries also have reference levels for radon concentration in dwellings, above which measures should be taken to reduce the risk from inhalation of radon progeny. The Australian reference level is 200 Bq·m^{-3}. This applies to all homes and is the same for existing and new dwellings. Regarding an Aboriginal camp site within the fenced area as a new dwelling, 26% of the area investigated on the Nabarlek site would not comply with this reference level during dry season conditions and would thus be unsuitable for permanent occupation. This would in particular include the rehabilitated evaporation pond 2.

In this context it is necessary to note that there is a large difference in radon concentration between the wet and dry seasons. The average wet season concentration is only 40% of the average dry season concentration and coupled with the lower equilibrium factors during the

wet season, wet season radon dose rates due to the inhalation of radon progeny are only 25% of the dry season value (Bollhöfer et al 2004).

5 Dose assessment

In this assessment, occupation during the dry season only is assumed. This assumption is reasonable, as access to the mine site during the wet season is restricted due to poor road conditions.

For dose calculations, due to the lack of data at Nabarlek, an average equilibrium factor of 0.55 for the dry season is assumed. The daytime dose conversion factor is assumed to be 27 nSv $(Bq \cdot h \cdot m^{-3})^{-1}$ equilibrium equivalent radon concentration. This was calculated using equation 6 and assumes an f_p of 0.12 for Nabarlek, and a nose breather (1.2 $m^3 \cdot hr^{-1}$) undertaking light to moderate activities (such as hunting or planting) on site. For the night time, a dose conversion factor of 9 nSv $(Bq \cdot h \cdot m^{-3})^{-1}$ equilibrium equivalent radon concentration is assumed as suggested by UNSCEAR (2000). Effective doses were then calculated using equations 4 and 5.

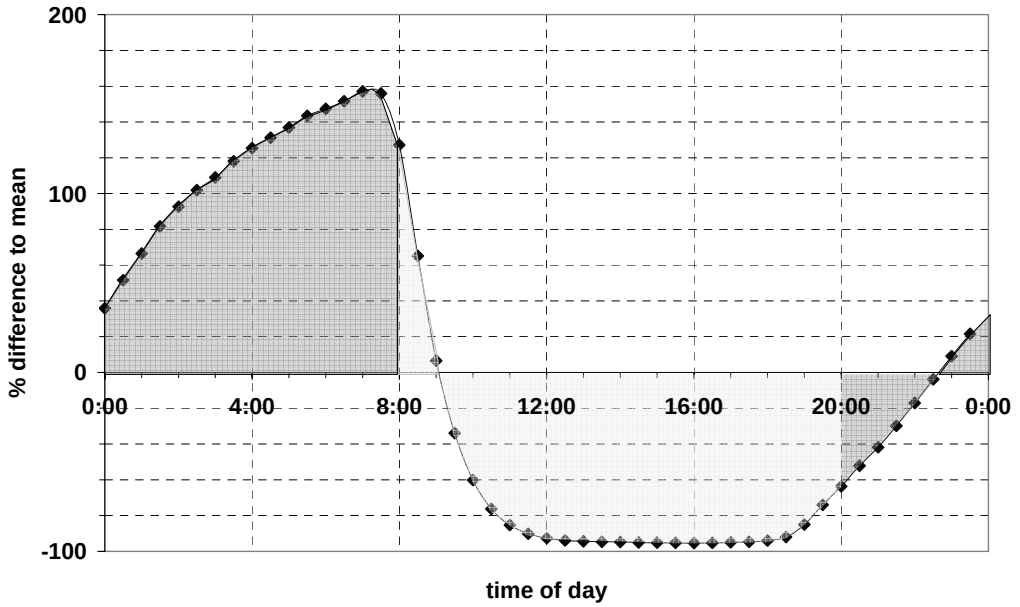

Figure 9 Variation of the daily radon concentration at Nabarlek during the dry season, 1997-1999 (Bollhöfer et al 2003). Light grey shaded area indicates daytime occupation (8:00–20:00), dark grey shaded area nighttime occupation (20:00–8:00), respectively.

Previous studies (Pfitzner & Akber 1994, Martin et al 2002) have shown that the diurnal variation of outdoor radon and radon progeny concentrations in the ARR is quite large. A previous study at Nabarlek (Bollhöfer et al 2004) showed that for the months July-September the radon concentration in the middle of the day (between 12:00 and 16:00) is only 5% (which equals 6 $Bq \cdot m^{-3}$) of the daily average, whereas during the night time concentrations can be up to 2.5 times higher than the average. Figure 9 shows the percentage difference of radon concentration as compared to the daily average at Nabarlek. Between 8:00–20:00 the radon concentration is on average only 25% of the average, whereas between 20:00–8:00 the concentration is about 75% higher on average.

Table 3 shows the calculated effective doses per day for the inhalation of radon and its progeny at Nabarlek during the dry season 2005, using the dose conversion, equilibrium and

unattached radon progeny factors given above, and taking into account the variation of the radon concentration during the day.

Table 3 Effective dose per day for the inhalation of radon and its progeny for various areas on the rehabilitated Nabarlek mine site. Daytime and nighttime doses are calculated assuming 12 hours spent on site (8:00–20:00 and 20:00–8:00, respectively).

	Area [ha]	Radon concentration [Bq·m^{-3}]	Effective dose per 24 hrs [uSv/d]	Effective daytime dose per 12 hrs [uSv/d]	Effective nighttime dose per 12 hrs [uSv/d]
EP-2	25	361 ± 162	53 ± 24	16 ± 7	38 ± 17
Unit 7	0.4	296 ± 83	44 ± 12	13 ± 4	31 ± 9
PROP	1.1	66 ± 18	10 ± 3	3 ± 1	7 ± 2
SPROP	4	249 ± 78	37 ± 12	11 ± 3	26 ± 8
EP-1	6	152 ± 88	22 ± 13	7 ± 4	16 ± 9
PIT	4	137 ± 76	20 ± 11	6 ± 3	14 ± 8
WRD	8	113 ± 18	17 ± 3	5 ± 1	12 ± 2
WRDROP	1.9	138 ± 92	20 ± 14	6 ± 4	14 ± 10
remainder	89.6	41 ± 15	6 ± 2	2 ± 1	4 ± 2
Total area	**140**	**118**	**17**	**5**	**12**
ENV		41 ± 15	6 ± 2	2 ± 1	4 ± 2

Doses are representative for access during the day time for 12 hours (for hunting activities for instance, or activities such as planting, maintenance of fences etc.) and overnight camping on site for 12 hours, respectively.

Accessing the site for hunting purposes during the daytime (12 hrs) for instance would result in an above environmental background dose of ~3 μSv, whereas the night time dose would strongly depend on where the camp was situated, and range from 0–34 μSv. Averaged over the whole site, the dose for night time occupation amounts to ~8 μSv above background.

The total above background dose for occupancy for 1 day (24 hrs) thus amounts to ~11 μSv. However, it should be noted that the assessment assumes that a background of 41 ± 15 Bq·m^{-3} existed at the Nabarlek site before mining started. This is highly unlikely due to the mineralised nature of the area and the ore body outcropping at some areas on site. Consequently, airborne radon concentrations may have been much larger pre-mining, Unfortunately, pre-mining data for the site are not available.

6 Conclusion

The Nabarlek site is not accessible during the wet season. Consequently, only dry season doses from the inhalation of radon and its progeny have been determined. Conservative dose conversion and equilibrium factors have been used in this assessment. During the dry season, occupation of the site for one month is possible before reaching the maximum value (300 μSv) of the constraint used in the optimisation of protection from radiation for a single source (ICRP 1997).

The area is accessed by Traditional Owners and SSD, NLC and NTG staff, respectively, for occasional hunting, maintenance of revegetation plots, maintenance of fences, and research and monitoring activities such as groundtruthing of remotely sensed data. Daytime inhalation doses are very low, due to the relatively lower radon concentration caused by effective mixing of air masses. Intermittent camps within the fenced area may give rise to a higher effective dose received via the inhalation pathway during the night, mainly due to the build up of radon and its progeny during the early morning hours. However, camps on site are highly unlikely

as areas nearby in the vicinity of Cooper Creek will be preferred owing to ready access to fresh water.

Denser stands of vegetation are associated with higher radon concentrations at areas with relatively low soil radium activity concentrations. These areas are difficult to access due to the dense stands of weeds, and thus would be less likely accessed for hunting or camping activities. Clearing of the areas will likely result in lower radon concentrations.

It is difficult to determine the pre mining airborne radon concentration for Nabarlek, as there are no pre-mining data available. However, in a previous study (Bollhöfer et al 2005) post-mining radon exhalation fluxes across the site were compared with the upper and lower limits for the pre-mining case, inferred from integration of a contour diagram of radon in soil concentration given in QML (1979). This comparison indicated that the post-mining radon flux from the Nabarlek site is unlikely to be higher than pre-mining. Consequently, it is unlikely that airborne radon concentrations post rehabilitation at Nabarlek are higher than pre-mining.

Our study emphasises the importance of a good baseline data set being available before a mine starts operating. Once mining ceases and the mine site is rehabilitated it may turn out to be difficult to decide whether or not the rehabilitation has been successful and whether or not overall radiation levels are back to or below pre-mining values.

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Appendix 1 Coordinates of the track etch detector sites and duration of deployment

RADON SURVEY SHEET 1		WGS84						
SITE	DETECTORS	EASTING	NORTHING	SET DATE	TIME	PICKUP DATE	TIME	NOTES
Darwin	C1, C2, C3			6/06/2005	13:00	14/09/2005		Top of EnRad count that, next to RM2 inlet
Darwin	1, 2			6/06/2005	13:00	14/09/2005		
PlinthD	79, 78, 43			7/06/2005	13:15	14/09/2005	12:18	
Rn-station	52, 62, A			7/06/2005	13:22	14/09/2005	12:50	
Unit 7-1	69, 42	53317532	8638453	7/06/2005	16:30	14/09/2005	13:30	WPT 146
Unit 7-2	50, 41	53317552	8638441	7/06/2005	16:40	14/09/2005	13:30	WPT 147
Unit 7-3	60, 67	53317541	8638431	7/06/2005	16:55	14/09/2005	13:30	WPT 148
Unit 7-4*	63, 70, 73, 52	53317568	8638404	7/06/2005	17:05	14/09/2005	13:30	WPT 149 (63 top, 70, 73, 52 bottom)
PROP-1	56, 68	53317909	8639096	8/06/2005	8:40	14/09/2005	12:04	WPT 150
PROP-2	54, B	53317915	8639103	8/06/2005	8:45	14/09/2005	12:04	WPT 151
PROP-3	65, C	53317890	8639121	8/06/2005	8:46	14/09/2005	12:04	WPT 152
SPROP-1	72, 49	53317392	8639309	8/06/2005	9:00	14/09/2005	14:47	WPT 153
SPROP-2	58, 76	53317376	8639290	8/06/2005	9:04	14/09/2005	14:47	WPT 154
EP2-1	74, 79	53317061	8639533	8/06/2005	9:18	14/09/2005	14:30	WPT 155
EP2-2	59, 77	53317101	8639470	8/06/2005	9:28	14/09/2005	14:30	WPT 156
EP2-3	51, 48	53317086	8639463	8/06/2005	9:30	14/09/2005	14:30	WPT 157

*On collection Unit 7-4: 70, 73 & 52 were lying on the ground.

RADON SURVEY SHEET 2

SITE	DETECTORS	EASTING	NORTHING	SET DATE	TIME	PICKUP DATE	TIME	NOTES	
EP1-2	80, 64	53317246	8639069	8/06/2005	9:57	14/09/2005	14:07	WPT 158	
EP1-1	66, 77	53317206	8639121	8/06/2005	10:00	14/09/2005	14:07	WPT 159	
PIT-1	16, 39	53317452	8638666	8/06/2005	10:19	14/09/2005	14:00	WPT 160	
PIT-2	24, 45	53317473	8638599	8/06/2005	10:22	14/09/2005	14:00	WPT 161	
PIT-3	55, 13	53317555	8638563	8/06/2005	10:26	14/09/2005	14:00	WPT 162	
WRD-1	07, 30	53317631	8638331	8/06/2005	10:56	14/09/2005	13:30	WPT 163	(TN 7)
WRD-2	26, D	53317667	8638177	8/06/2005	11:05	14/09/2005	12:25	WPT 164	
WRDROP-1	21, 14	53317481	8638095	8/06/2005	11:18	14/09/2005	13:00	WPT 165	
WRDROP-2	06, 31	53317511	8637980	8/06/2005	11:23	14/09/2005	12:55	WPT 166	
WRDROP-3	32, 10	53317546	8637991	8/06/2005	11:26	14/09/2005	12:55	WPT 167	
WRDROP-4	29, 11	53317616	8637995	8/06/2005	11:34	14/09/2005	12:55	WPT 168	
WRD-3	22, 19	53317739	8638236	8/06/2005	11:46	14/09/2005	12:25	WPT 169	
WRD-4	36, E	53317688	8638310	8/06/2005	11:50	14/09/2005	12:44	WPT 170	
PIT-4	34, 09	53317678	8638597	8/06/2005	12:07	14/09/2005	12:12	WPT 172	
PIT-5	03, 33	53317647	8638591	8/06/2005	12:10	14/09/2005	12:33	WPT 173	

RADON SURVEY SHEET 3

SITE	DETECTORS	EASTING	NORTHING	SET DATE	TIME	PICKUP DATE	TIME	NOTES
ENV.5	38, 17	53317886	8638080	8/06/2005	12:25	14/09/2005	14:57	
ENV.2	F, G	53317473	8639932	8/06/2005	14:00	14/09/2005	15:40	
ENV.9	H, I	53315503	8639314	8/06/2005	14:14	14/09/2005	15:45	
ENV.8	20, J	53315483	8639217	8/06/2005	14:17	14/09/2005	15:45	
ENV.7	08, 04	53315670	8639057	8/06/2005	14:30	14/09/2005	16:00	
MYRA-1	27, 36	53314727	8639765	8/06/2005	14:52	14/09/2005	16:15	WPT 179, Myra Site
Top Tank	35, 15	53317746	8639116	8/06/2005	15:17	14/09/2005	11:55	
Bund Tank	23, K	53317760	8639115	8/06/2005	15:28	14/09/2005	11:52	WPT 181