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Abstract

Radon exhalation fluxes and radon exhalation rates have been determined for the late dry season at the rehabilitated Nabarlek uranium mine and environmental areas in the Nabarlek District using conventional charcoal canisters and a radon emanometer. Environmental background levels amount to 31±15 $mBq \cdot m^{-2} \cdot s^{-1}$. The radon exhalation fluxes within the fenced rehabilitated mine area show large variations. The highest average radon flux is estimated to 6500 $mBq\ m^{-2}\ s^{-1}$ at an area south of the former pit, where soils are relatively fine grained and are characterised by a high salinity and a disequilibrium between ^{226}Ra and ^{238}U. In addition, radon exhalation fluxes are comparatively high above the areas of the former pit (971 $mBq \cdot m^{-2} \cdot s^{-1}$) and waste rock dump (335 $mBq \cdot m^{-2} \cdot s^{-1}$).

Although pre- and post-mining radon exhalation fluxes are difficult to compare due to a lack of pre-mining data available, a comparison of radon exhalation rates suggests that pre- and post-mining radon exhalation fluxes from the site have not significantly changed. The total pre-mining radon exhalation rate above environmental background for the fenced area was estimated to above 170 $kBq \cdot s^{-1}$ originating from an area of approximately 98 ha, whereas the above background post mining exhalation rate amounts to 134 $kBq \cdot s^{-1}$ originating from an area of 62 ha. Applying an additional soil cover of 90 cm to the area of the former pit and waste rock dump, including the runoff pond, would result in a reduction of the total radon exhalation rate by almost 50 percent.

Our study highlights that the results of radon exhalation studies are vitally dependant on the selection of individual survey points. We suggest the use of a randomised system for both, the selection of survey points and the placement of charcoal canisters at each survey point, to avoid over estimation of the radon exhalation fluxes. In addition, our study underlines the importance of having reliable pre-mining radiological data available to assess the success of rehabilitation of a uranium mine site.

Geographic variability in radon exhalation at the rehabilitated Nabarlek uranium mine, Northern Territory

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1 Introduction

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 (figure 1). The Nabarlek orebody 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 orebody 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 meters. The design relied on the fact that tailings would be below ground water and approximately 13 m 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 aid consolidation. With final decommissioning of the mine in 1995, remaining contaminated material and unsaleable plant equipment were placed in the pit and covered with another layer of waste rock. 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.

Adams and Hose (1999) noted that the surface materials throughout the site are highly variable, with some areas having broken and crushed rock to depth, others with varying proportions of clays and silts. They arbitrarily divided the mine site into a 'dolerite area' (ore stockpile, evaporation ponds and clay and topsoil stockpiles – 'Ponds area') and a 'schist area' (pit and waste rock dump – 'Mine area').

The study described here is part of a larger program to investigate the radiological conditions of the rehabilitated Nabarlek sited. One of the aims of this program of work is to provide a detailed radiometric description of the rehabilitated Nabarlek mine site, so that future users of the area will have sufficient information to judge radiological risk and any future study of the site will have a baseline dataset available. In addition, it aims to provide information which may help in the rehabilitation of other mine sites, particularly the Ranger and Jabiluka mine sites which are located in Kakadu National Park and are subject to similar climatic conditions, with contrasting wet (approximately November to April) and dry (approximately May to October) seasons.

Figure 1 Location of the Nabarlek mine site

The present study was carried out to investigate geographic variability in radon-222 (^{222}Rn) exhalation rate over the site. It will provide valuable data for various radon transport and dispersion models that are in use (Petersen et al 1992, Martin 2000), their ultimate aim being to be able to predict radon and radon progeny concentration at various locations as a function of time.

Although the inhalation of ^{222}Rn (half-life 3.82 days) itself does not impose a major health risk, the subsequent ingrowth of its radioactive progeny in the air, and their inhalation by humans, is one of the major pathways for radiological impact on members of the public (e.g. Tubiana et al 1990). Therefore, following the ICRP guidelines (1991) that the non-natural radiation exposure of the public should be less than 1 mSv per year for a practice such as a U mining operation, it is essential, though difficult, to estimate the above natural airborne radon progeny concentration. This depends on the equilibrium factor E between radon and radon progeny, which has been estimated to be 0.45 ± 0.03 for the Alligator Rivers Region (Akber et al 1994) and local meteorological and geographical conditions, such as wind speed and direction, soil uranium content and soil porosity.

In this study charcoal canisters were used to measure radon exhalation from soils, which takes advantage of the adsorption of radon on to charcoal, which was first noted by Rutherford (1906). Charcoal canisters are a convenient screening technique which gives the average radon exhalation over the period that the canisters are on the site (generally about 1 to 3 days). The advantage of the charcoal canister technique is that a large number of canisters can be deployed at the same time. In the present study, a total of 313 individual charcoal canisters measurements were taken from within the fenced area, and more than 60 were taken from outside the fence. This capacity has enabled us to obtain data on geographic variability over the Nabarlek site.

In addition, a radon emanometer (Todd et al 1998) was used at selected sites for a comparison with the radon exhalation fluxes obtained with the charcoal canister method. The emanometer gives a reading of average radon exhalation rate at one site over about a half-hour period.

It is known that the exhalation rate of ^{222}Rn from the soils in the region varies considerably over the year, being higher in the dry season than in the wet season (Martin et al 2002), primarily due to the influence of soil moisture. The present study was carried out at dates varying from August to October, i.e. the late dry season. The reasons for this were:

- It is likely that soil moisture is at a minimum at this time of year, and at relatively stable levels. Hence radon exhalation rates at any one location could be expected to be relatively stable over the course of the study.
- The remote location of the site would have made access to sampling sites extremely difficult during the wet season.
- At present the site is uninhabited, and so access by other people also occurs primarily during the dry season. Hence for radiological impact assessment purposes, the dry season is the most relevant time of year.

Consequently, the radon exhalation rates measured here represent late dry season values only. Seasonal variations in radon exhalation rates are being investigated in detail in another, related study being carried out in the vicinity of the Ranger uranium mine.

2 Methods

2.1 Site selection

Nine areas on the former Nabarlek mine site were selected for a survey of radon exhalation rates during August, September and October 1999, 2001 and 2002, respectively. The locations selected covered the former pit, plant runoff pond, ore stockpile area, stockpile runoff pond, evaporation ponds and topsoil stockpile areas.

One commonly used method in surveying is to select points on a regular grid mapped onto the area to be surveyed. However, this method can introduce bias in the selection of points, when there are regularly repeating features in the survey landscape. Given this possibility, it was decided to use a randomised selection of survey points. A grid was mapped onto the nine survey locations and the x-y co-ordinates for each point in each square were randomly generated numbers. The x-y coordinates were transformed to (r, θ) coordinates to provide a range and bearing, so that a prismatic compass and tape measure could be used to approximately locate these points on site. The points were then marked by star pickets and their exact co-ordinates established as eastings and northings with a Global Positioning System (GPS) under the WGS84 system.

Once a survey point was chosen, three charcoal canisters were placed within 1 m^2 around this point to give an average exhalation rate. To ensure random placement of charcoal canisters at each survey point, one experimenter stood several metres distant, facing away from the point and then threw a stone back toward the point. The other experimenter noted where the stone first hit the ground, this being the selected location. Pebbles and other detritus on the ground were simply left where they were and the canister placed over them with the rim pushed into the ground as usual. If the point happened to be on a larger rock which was embedded in the ground, then the exhalation was measured from the surface of the rock; if, however, the rock was simply sitting on the ground surface then the rock was moved aside and the exhalation measured from the ground surface.

Control sites were chosen where exhalation fluxes were measured on a continuous basis to allow an estimate of the temporal stability of radon exhalation. In addition, environmental sites have been chosen and exhalation fluxes measured during the project to get an estimate of the environmental background radon exhalation fluxes in the area.

2.2 Radon exhalation measurements using charcoal canisters

2.2.1 Charcoal canisters

The charcoal canisters used were standard brass cylindrical design with an internal diameter of 0.070 m, depth 0.058 m and wall thickness 0.004 m. If the 'open face' of a brass charcoal canister is sealed against a surface, then all the radon emanating from the surface will diffuse into the canister and adsorb to the charcoal. With this configuration the canister functions as an emanometer. In addition, this method provides simultaneous measurements of numerous locations and was the method of choice in the current survey. The radon exhalation rate over the period of exposure can be estimated using the expression:

$$J = \frac{R \cdot t_c \cdot \lambda^2 \cdot \exp(\lambda t_d)}{\varepsilon \cdot a \cdot [1 - \exp(-\lambda t_e)] \cdot [1 - \exp(-\lambda t_c)]} \quad (1)$$

where J ($Bq \cdot m^{-2} \cdot s^{-1}$) is the average radon exhalation rate, R is the net count rate (s^{-1}) – after background subtraction – obtained during the counting period t_c (s), λ (s^{-1}) is the decay constant for radon, t_d (s) is the delay period from the end of exposure to the beginning of the counting interval, ε ($s^{-1} \cdot Bq^{-1}$) is the counting efficiency of the system, a (m^2) is the area of the canister, t_e (s) is the period of exposure of the charcoal in the canister (Spehr et al 1983).

The derivation of equation 1 is based on a number of assumptions, including that the radon exhalation rate from the ground is constant over the exposure period. The existing data indicate that diurnal variations in ^{222}Rn exhalation rates in the Alligator Rivers Region are small, probably less than 20% of the mean exhalation rate (Todd et al 1998, Martin et al

2002), and so an assumption of a constant radon exhalation rate is reasonable. In addition, our data are not corrected for the effects of water vapour uptake by the charcoal. The assumption that all of the radon is adsorbed and retained is reasonable, provided that adsorption of gases (primarily water vapour) does not lead to saturation of the charcoal. Consequently, correction for humidity should not be required.

The charcoal canisters were filled with 25 grams of charcoal that was heated overnight at ~110° C to drive out any residual radon adsorbed on the charcoal. Three canisters were deployed per survey point and collected again after a period of three days. To prevent leakage of radon the canisters were embedded in the earth to a depth of about 1 cm or – if the surface was too hard or irregular – the rim was sealed with mud or a 'putty'. At some sites, measurements were performed with a radon emanometer (RTE-2), and radon fluxes were compared with those calculated from equation 1.

At least 3 hours were allowed to elapse between the collection of the canisters from the site and the start of the count period to allow the progeny, ^{214}Pb (half-life 27 mins) and ^{214}Bi (half-life 20 mins), to in-grow towards a secular equilibrium with their progenitor, ^{222}Rn.

2.2.2 Counting system setup and efficiency calibration

A portable γ spectrometer (Geofyzika Brno, GS-256) with a 3' diameter x 3' thick NaI(Tl) crystal was used to determine the activity of radon progeny adsorbed on the charcoal. Depending on the activity of each sample count periods of 600 s to 900 s were used. The energy range for the spectrometer is 12 keV to 3 MeV collected in 256 channels, i.e. 12 keV per channel. The NaI(Tl) detector was housed in a lead castle to reduce background.

Four regions of interest (ROI) representing the photopeaks for Pb-214 at 242, 295 and 353 keV and for Bi-214 at 609 keV were used to determine the activity of radon progeny adsorbed onto the charcoal. The net count rate *R* was obtained by subtracting the background count rate from the gross count rate in those regions of interest. The system was calibrated against a calibration charcoal canister of known activity. This calibration canister was prepared using twenty-five grams of charcoal and a solution of a total of 327.0 Bq activity of radium-226 that was carefully dropped onto the charcoal in the canister. After the charcoal was dry, the canister was sealed and after an ingrowth period of 35 days, a counting efficiency of 4.83 ± 0.08 % (2σ) (1999) and 5.42 ± 0.08 (2σ) (2001), respectively, was obtained. Differences in the efficiency were due to a change in the geometric efficiencies of the system.

2.3 Radon emanometer

The RTE-2 emanometer includes a sampling drum with a specific sampling volume of 0.01846 m^3 and covering area of 0.259 m^2, the latter approximately 90 times the sampling area of a charcoal canister. The soil gas that emanates into the drum space is pumped at a rate of 1 $L{\cdot}min^{-1}$ through a ZnS(Ag) alpha scintillation detector, a delay line to remove thoron and into a second ZnS(Ag) scintillation detector. The RTE-2 measures the radon flux via thoron subtraction, according to the two sets of counts from the detectors. The soil gas is cycled through the chambers and back into the drum via an outlet hose, to maintain a constant atmospheric pressure under the drum.

Background counts before and after a run are derived by running the counting system without the inlet and outlet hoses connected to the drum, each run being 5 consecutive count intervals of 6 minutes duration. A fan underneath the drum mixes the soil gas within the volume covered by the drum. When sampling many sites, the survey sequence is to rank the sites from lowest through to successively higher fluxes. This minimises the plateout of radon progeny in the chambers during that run, which would add to the background of successive measurements. Radioactivity associated with plateout is removed by allowing the decay of any progeny attached to the detector before the RTE-2 is next used.

3 Results

To have control over seasonal and interannual variations in radon exhalation we chose several control sites where radon exhalation was estimated with every set of measurements. In addition, the extensive surveys were conducted at the end of the dry seasons, during similar climatic conditions, in 1999, 2001 and 2002. Due to the long duration of the project it was important to demonstrate that variations in radon exhalation between August and October, as well as interannual variations from 1999 to 2002, were low. Table 1 shows the results of measurements at the control sites. The Myra site is an environmental site in the Nabarlek District outside the fenced area whereas the Rn station and Plinth D are two sites within the fenced area exhibiting elevated radon exhalation fluxes.

Table 1 Radon exhalation fluxes J at the three control sites throughout the duration of the project. n: number of exposed charcoal cups

	J ($mBq\ m^{-2}\ s^{-1}$) mean ± s.d. (n)		
Date	Myra	Rn station	Plinth D
13.8 – 16.8.1999	12 ± 7 (2)	89 ± 6 (2)	–
20.8 – 23.8.1999	18 ± 3 (2)	93 ± 15 (3)	1106 ± 4 (2)
24.8 – 27.8.1999	–	94 ± 7 (3)	–
30.8 – 2.9.1999	22 ± 1 (3)	107 ± 7 (3)	839 ± 3 (3)
4.9 – 7.9.1999	–	91 ± 6 (3)	–
10.9 – 13.9.1999	16 ± 2 (3)	95 ± 10 (3)	849 ± 123 (3)
21.9 – 23.9.1999	19 ± 6 (2)	119 ± 3 (2)	–
17.8. – 20.8.2001	18 ± 5 (3)	94 ± 7 (3)	–
24.8. – 27.8.2001	29 ± 20 (3)	122 ± 22 (3)	839 ± 256 (3)
31.8. – 3.9.2001	18 ± 3 (3)	117 ± 11 (3)	–
7.9. – 10.9.2001	12 ± 2 (3)	117 ± 22 (3)	689 ± 187 (3)
28.9. – 1.10.2001	17 ± 3 (3)	99 ± 18 (3)	–
21.10 – 22.10.2002	15 ± 3 (3)	–	–
All readings	18 ± 7 (30)	102 ± 15 (34)	838 ± 188 (14)

On average, the variability of the radon exhalation measurements over the duration of the project at the control sites amounts to approximately 25 per cent. This variability is only slightly higher than the average standard deviation of a single measurement (using three cups per survey point) of approximately 20 per cent. We therefore assume that the variations at the control sites are caused by local rather than seasonal and interannual effects. It should be noted that although seasonal effects are low at this time of the year (late dry season), variations between the wet and dry season exhalation rates are quite large (Martin et al 2002).

To check for the accuracy of the radon exhalation measurements using the charcoal cups, radon exhalation rates have also been determined using the RTE-2 radon emanometer.

Table 2 shows the results of the radon exhalation fluxes and a comparison with the results determined using the charcoal canisters.

Table 2 Results of the intercomparison of charcoal cup and emanometer radon exhalation flux measurements

Site	Emanometer	Radon cups
	J (mBq m^{-2} s^{-1}) mean ± s.d.	
Myra	8 ± 4	16 ± 2
Rn-station	114 ± 8	91 ± 6

The results of the comparative measurements illustrate that within two standard deviations radon exhalation rates determined using the charcoal cups agree well with the measurements performed using the RTE-2 radon emanometer.

To estimate the natural background radon exhalation fluxes in the vicinity of the Nabarlek mine, several environmental sites were chosen. Results are shown in table 3. Environmental sites E5 and E6 exhibit naturally elevated radon exhalation fluxes, as does an area in the vicinity of E5, southeast of the wast rock dump retention pond. This area has previously been identified both in the original environmental impact statement (QML 1979) and from a recent airborne gamma survey (Martin 2000) as an area with a naturally high uranium series signal. It was surveyed extensively in 2001 using charcoal canisters, and results have been included in table 4 (U-anomaly SE of WRDRP). For the calculation of the environmental background radon exhalation flux in the Nabarlek district of 31±15 mBq $m^{-2}s^{-1}$ these areas have not been included.

Table 3 Radon exhalation fluxes at environmental sites

Location code	J (mBq·m^{-2}·s^{-1}) mean ± sd (n)
E2	43 ± 4 (3)
E3	33 ± 7 (3)
E4	20 ± 31 (2)
E5	408 ± 54 (3)
E6	124 ± 34 (3)
E7	49 ± 4 (3)
E8	21 ± 3 (3)
E9	16 ± 6 (3)

Figure 2 shows the results of the radon exhalation measurements on the rehabilitated Nabarlek mine site and the area south east of the waste rock dump retention pond with the naturally elevated U signal, superimposed on a map of the site. Shown on the plot are the relative radon exhalation fluxes with the maximum representing 12 600 mBq$m^{-2}s^{-1}$. A total of 125 locations within or in the vicinity of the fenced area were surveyed using 356 radon cups. The areas covered on the mine site were the waste rock dump and waste rock dump runoff pond (WRD), pit, plant runoff pond (PROP), ore stockpile (OSP), ore stockpile runoff pond (OSP-ROP), evaporation pond 1 (EP1), evaporation pond 2 (EP2), and the topsoil stockpile (TSP).

Table 4 gives means, standard deviations, maxima, minima and the number of individual measurements of the radon exhalation fluxes at the different locations within the fenced area of the former Nabarlek mine site.

Hancock et al (2003) identified an area adjacent to the pit with highly saline soils and erosion rates up to 300 times higher than natural erosion rates. The soils from this area, called erosion unit 7, exhibit a pronounced radioactive disequilibrium between ^{226}Ra and ^{238}U, and soil radionuclide concentrations up to 15400 Bq kg^{-1} and 6800 Bq kg^{-1}, respectively. As the area can clearly be distinguished from surrounding areas by visual inspection and upon their radionuclide content, we introduce a separate area in our radon exhalation study, south of the former pit, called unit 7, in accordance with the paper by Hancock et al (2003).

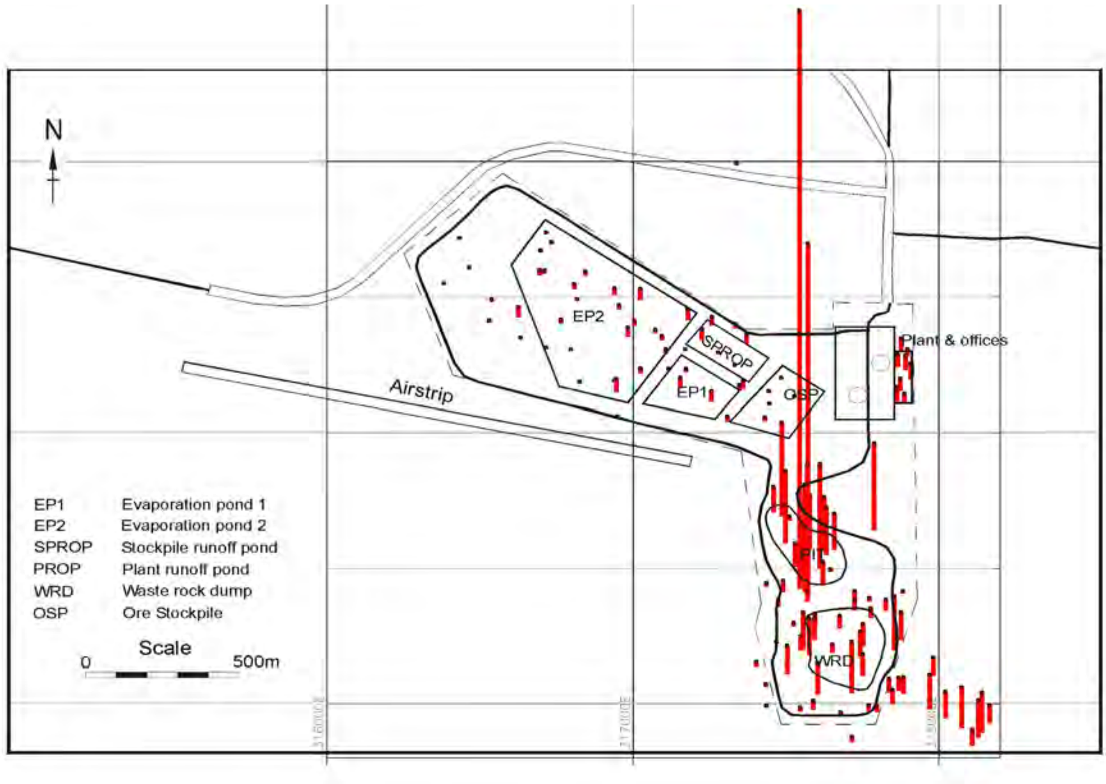

Figure 2 Radon exhalation fluxes superimposed on a map of the Nabarlek mine site

Kvasnicka (1996) reports average post-rehabilitation radon exhalation fluxes measured in August 1996 of 4710, 1390, and 840 $mBqm^{-2}s^{-1}$ for pit, waste rock dump, and evaporation pond, respectively. The fluxes reported are on average 4–5 times higher than the fluxes determined in our study. The difference is most likely due to the different methods of the selection of survey points.

The radon exhalation depends on the soil (or rock) radium content, the porosity of the soil and the vegetation cover, which can vary on a very localised scale. The ratio of radon exhalation fluxes measured on rocks and off rocks in the former pit has been determined in our study and amounts to 0.16 (0.19 for the ore stockpile, 0.15 for the ore stockpile runoff pond). Kvasnicka's (1996) method of burying each individual charcoal canister in an approximately 2 cm deep hole in the soil does not take into account the influence of rocky terrain on the radon exhalation fluxes and therefore is prone to overestimating the radon exhalation.

Due to the randomised, bias free selection of survey points in our study, the charcoal canisters may be exposed to rather large variations in the local radon exhalation fluxes, however averages are more likely to represent true radon exhalation rates for an area. The general trend however is similar in both studies, with the former pit and waste rock dump exhibiting the highest radon exhalation fluxes.

Table 4 Measured post-rehabilitation radon exhalation rates for major areas of the rehabilitated Nabarlek mine site. n: number of radon cups

Location	Date	^{222}Rn exhalation rate ($mBq \cdot m^{-2} \cdot s^{-1}$) Mean Arith. (geom.)	Standard deviation	n	Min	Max
Unit 7 (Hancock et al 2003)	21.10 – 22.10.2002	6508 (4605)	6831	12	1944	25410
Pit	13.8 – 23.8.1999	971 (541)	739	42	1	2428
U-anomaly SE of WRDRP (natural)	28.9 – 1.10.2001	446 (362)	255	30	24	1044
Waste Rock Dump + Runoff Pond	17.8 – 10.9.2001	335 (224)	318	77	15	1923
Plant Runoff Pond	24.8 – 27.8.1999	278 (194)	203	24	6	924
Evaporation Pond 1	4.9 – 7.9.1999	169 (148)	86	12	69	314
Stockpile Runoff Pond	30.8 – 2.9.1999	137 (83)	120	18	12	335
Evaporation Pond 2	10.9 – 24.9.1999	105 (68)	102	82	0	507
Ore Stockpile	4.9 – 7.9.1999	77 (55)	59	21	13	213
Topsoil Stockpiles	21.9 – 23.9.1999	31 (22)	28	17	4	109

Table 5 gives a comparison of the mean ^{222}Rn exhalation rate with estimated ^{226}Ra soil concentrations for a number of areas of the site. The last column shows the ratio of exhalation rate to estimated ^{226}Ra soil concentration. The highest ratio was obtained for the pit area. It is unlikely (although possible) that this higher ratio is due to radon sourced from the tailings, since these are approximately 13 metres below the final ground surface, and are below the ground water level (Waggitt & Woods 1998). A more likely reason is the substantially greater depth of waste rock over the pit, compared with the other areas.

The high ratios obtained for unit 7 and for the plant runoff pond may be due in part the fact that the surface material of these two areas is relatively fine-grained. The relatively low ratios for the EP1 and EP2 areas may be due to the fact that these areas were scraped to remove sediment and then covered with a relatively thin layer of waste rock.

Table 5 Comparison of mean Rn-222 exhalation rate with estimated mean Ra-226 soil concentrations for major areas of the rehabilitated Nabarlek mine site

Location	Mean ^{222}Rn exhalation rate ($mBq \cdot m^{-2} \cdot s^{-1}$)	Estimated ^{226}Ra soil concentration ($Bq \cdot kg^{-1}$)	Ratio ^{222}Rn exh/^{226}Ra conc ($mBq \cdot m^{-2} \cdot s^{-1}$ per $Bq \cdot kg^{-1}$)
Unit 7 [a]	6508	15400	0.42
Pit [b]	971	1526	0.64
Waste Rock Dump + Runoff Pond [b]	335	1062	0.32
Plant Runoff Pond [b]	278	737	0.38
Evaporation Pond 1 [b]	169	1369	0.12
Stockpile Runoff Pond [b]	137	607	0.23
Evaporation Pond 2 [b]	105	663	0.16
Ore Stockpile [b]	77	248	0.31
Topsoil Stockpiles [a]	31	101	0.31

a ^{226}Ra concentration estimates from Hancock et al (2003)

b ^{226}Ra concentration estimates from Martin et al (in prep)

4 Discussion

4.1 Statistical distribution of radon exhalation fluxes

Figure 3 shows the frequency distribution of radon exhalation fluxes from the different areas on the rehabilitated mine site. Figure 4 shows the frequency distributions of the natural logarithms of radon exhalation fluxes from the individual areas. In addition, a normal distribution is fitted to the logarithmic data. Figure 5 shows the natural logarithmic distribution plotted over the whole rehabilitated Nabarlek site.

The *Theory of Successive Random Dilutions* (Ott 1990) states that a concentration undergoing a series of independent random dilutions tends to be lognormally distributed. This theory is especially appropriate for representing inert substances and gases released at very high concentrations into carrier media (air, water, soil) undergoing physical movement and agitation before they are measured (Ott 1995).

This situation applies in our case as variables having an influence on radon exhalation from soils, such as radium content, soil moisture, atmospheric pressure etc. are independent variables. Therefore, the distribution of radon exhalation fluxes is right skewed for most of the sites, except for the stockpile runoff pond, as shown in figure 3. The stockpile runoff pond exhibits two maxima, one at environmental exhalation levels at about 20–40 $mBqm^{-2}s^{-1}$ and a second one at approximately ten times background levels.

Fitting a normal distribution to the natural logarithms of radon exhalation rates at the different areas on the site (figure 4) exhibits reasonable fits especially for the evaporation ponds and waste rock dump and waste rock dump retention pond areas. This may mainly be attributed to the larger number of sampling points at those sites in comparison with the other sites.

Figure 5 shows the natural log-normal distribution for individual measurements across the site as a whole. The average of the natural logarithms of the radon exhalation fluxes from within the fenced area amounts to 5.011 (stdev. = 1.469), therefore the median radon exhalation rate calculated from our survey amounts to 150 $mBqm^{-2}s^{-1}$.

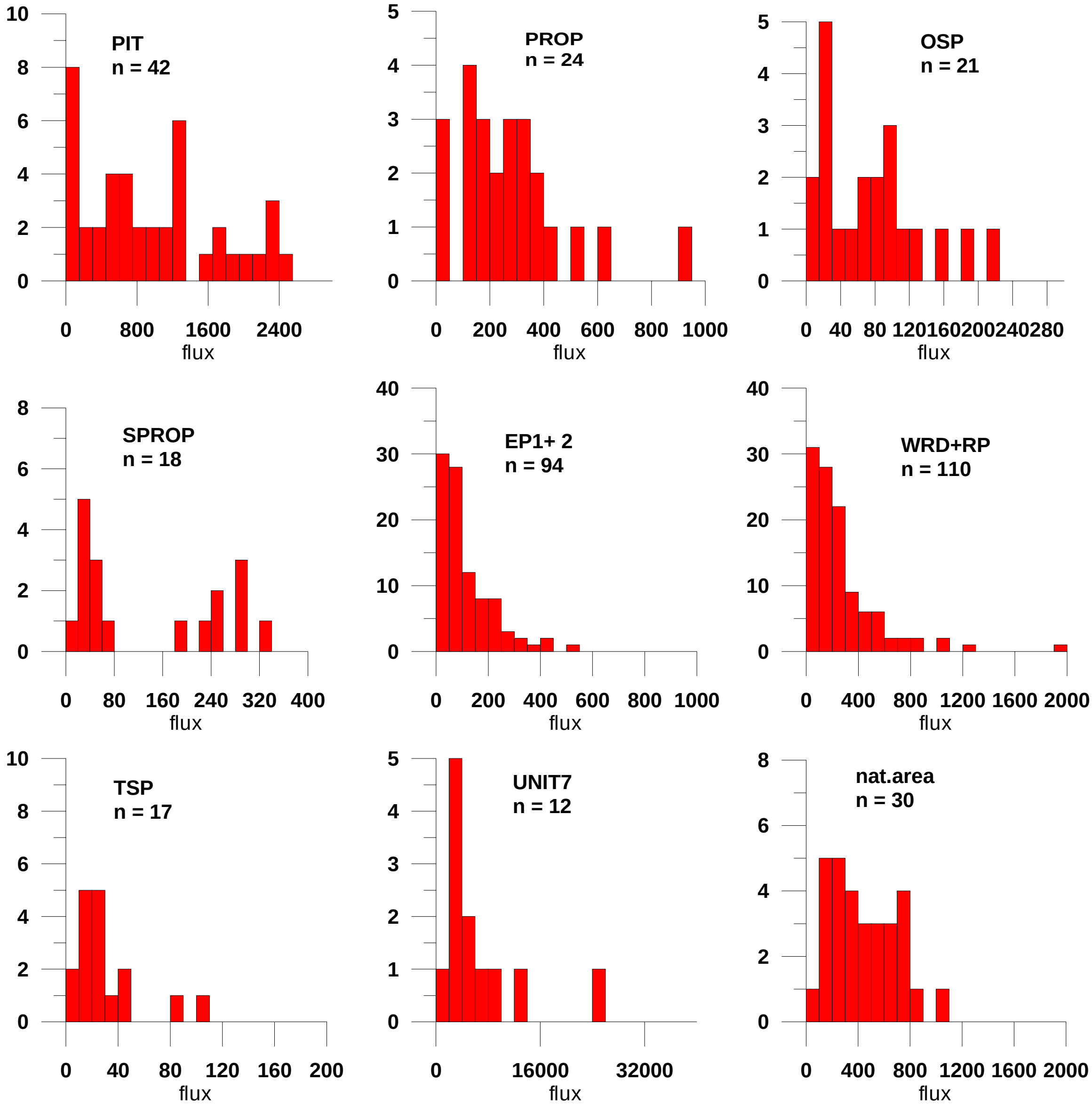

Figure 3 Histograms of the natural radon exhalation fluxes from the various areas

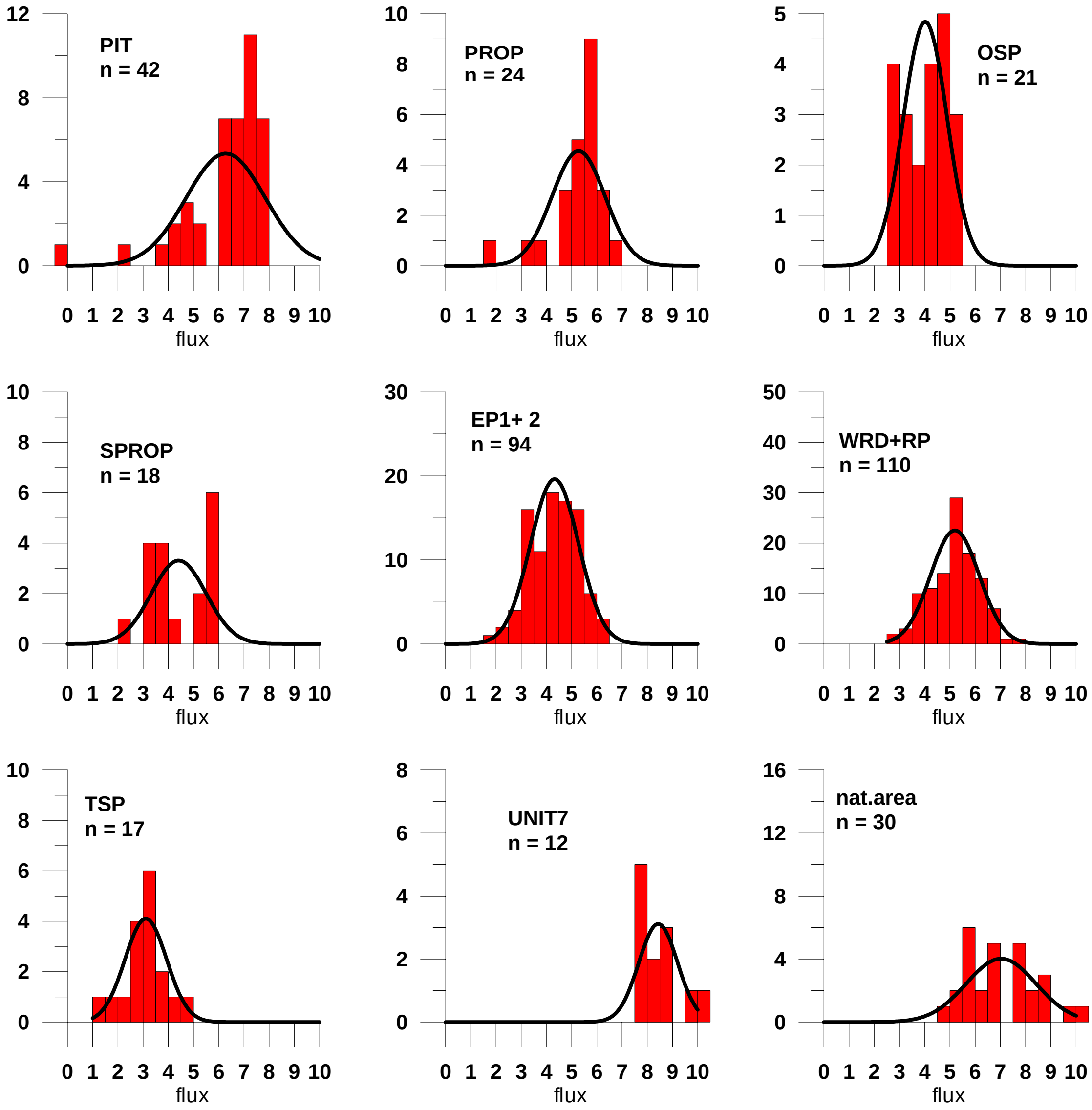

Figure 4 Histograms of the natural logarithms of the radon exhalation fluxes from the various areas

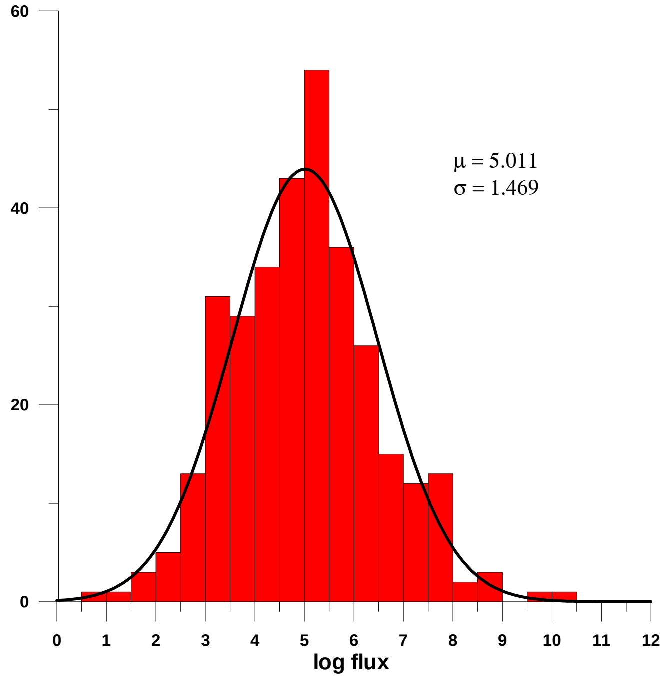

Figure 5 Lognormal fit to the radon exhalation fluxes across the fenced area at Nabarlek mine site

With the distributions shown in figure 4 and 5 we are able to calculate cumulative distribution functions (CDF) and probabilities for the percentage area within the fenced area (or for individual areas) that may exceed any given radon exhalation values using (Ott 1995, p 185):

$$F(z) = 1 - f(z) \cdot [b_1 \cdot t + b_2 \cdot t^2 + b_3 \cdot t^3 + b_4 \cdot t^4 + b_5 \cdot t^5] \quad (2)$$

With:

$$f(z) = 1/\sqrt{(2\pi)} \cdot \exp(-z^2/2) \quad (3)$$

Where:

$z = [\ln(x)-\mu]/\sigma$ $t = 1/(1 + a|z|)$

$a = 0.2316419$ $b_4 = -1.821255978$

$b_1 = 0.31938153$ $b_5 = 1.330274429$

$b_2 = -0.356563782$ μ = mean of logarithms

$b_3 = 1.781477937$ σ = standard deviation of logarithms

The US Environmental Protection Agency recommend that radon exhalation fluxes from uranium mine tailings should not exceed 20 pCi m^{-2} s^{-1}, which equals 740 mBq m^{-2} s^{-1} (U.S. EPA: 40 CFR, Part 192). This recommended value does not have any legislative or regulatory force in Australia. Rather, the Australian approach is based on a site radiological risk assessment methodology based upon estimates of the dose to people, summed over all pathways. Nevertheless, the U.S. EPA criterion does provide a useful reference value for comparison with the results obtained in our survey. Table 6 gives cumulative frequencies for respective radon exhalation fluxes. From the log-normal fit we can calculate that approximately 14%of the total surveyed area of the rehabilitated Nabarlek mine would be above 740 mBq m^{-2} s^{-1} and hence would not comply with U.S. EPA criteria for soil clean up.

Exhalation fluxes above the evaporation pond areas, the most likely and convenient areas on site for any future human habitation, would fall within those recommendations.

Table 6 Cumulative frequencies at various radon exhalation rates within fenced area and for evaporation ponds 1 and 2

Radon exhalation MBq $m^2 \cdot s^{-1}$	76	150	200	500	740	1000
CDF (total area)	0.32	0.50	0.58	0.79	0.86	0.90
CDF (EP1 + 2)	0.50	0.76	0.85	0.98	0.99	1.00

4.2 Pre and post mining radon exhalation rates

In order to estimate the total radon exhalation from the rehabilitated Nabarlek uranium mine site during the dry season, average radon exhalation fluxes were multiplied with the areas of the different locations on the mine site. For the calculation of radon exhalation fluxes above typical environmental background we subtract a radon exhalation flux of 31±15 mBq $m^{-2}s^{-1}$ estimated at the environmental sites (E2-E4 and E7-E9). In addition, the locations are assumed to have a uniform radon exhalation. Changes in the surface area of different sections on site due to ripping have been considered, but have proven to be trivial. Results of the exhalation rates are shown in table 7.

The total area of the fenced mine site amounts to 142 ha (Martin, 2000). The post mining total radon flux from the site above environmental background is determined to be 134 kBq s^{-1} emanating from an area of approximately 62 ha. The remaining portion within the fenced area is assumed to exhibit environmental background radon exhalation fluxes.

Table 7 Radon exhalation rates from the different locations on the rehabilitated Nabarlek mine site. Total areas of the different locations on the mine from Martin (2000) and Hancock et al (2003). Given areas do not take into account the effect of ripping and surface roughness.

Location	Area [ha]	^{222}Rn exhalation rate [kBq s^{-1}]		
		total	Above background	%
Unit 7	0.4	26	26	19
Pit	5	49	47	35
WRD + WRDROP	9	29	28	21
Plant Runoff Pond	1.1	3	3	2
Evaporation Pond 1	5	8	7	5
Stockpile ROP	3	4	3	2
Evaporation Pond 2	25	26	18	13
Ore Stockpile	6	5	3	2
Topsoil Stockpiles	7	2	0	0
Total	62	152	134	100

Three quarters of the above-background radon exhalation rate from the site originates from the former pit (including unit 7), the waste rock dump and waste rock dump runoff pond with a total area of approximately 15 ha. The remaining portion originates from an area three times that size. By far the highest exhalation rate in relation to its size is exhibited by unit 7 adjacent to the south-western edge of the pit. This area only has a size of less than one per cent of the total area, however it is responsible for approximately 20 per cent of the total radon flux. Its soils are elatively fine-grained and are characterised by a very high salinity, ^{226}Ra activity concentrations of on average 15400 Bq/kg and a pronounced ^{226}Ra/^{238}U disequilibrium (Hancock et al 2003). Due to the high salinity of the soils, vegetation on the area is scarce.

Figure 6 shows a satellite picture of the rehabilitated mine site, highlighting the location of unit 7. Figure 7 shows a picture taken on the ground in 2002. It is obvious that the area is devoid of vegetation and characterised by pronounced erosion gullies.

In their Environmental Impact Statement (QML, 1979) Queensland Mines Limited give a rough estimate of pre-mining radon concentrations in soil for the Nabarlek district. The magnitude of radon concentrations is given as background, above 3 times background and above 9 times background, however the absolute magnitude of the background concentration is not given.

Figure 6 Satelite picture of the rehabilitated Nabarlek uranium mine (2002)

By integrating over the radon in soil concentration figure in the Environmental Impact Statement (QML 1979) we estimate that approximately 26 % of the fenced area (38 ha) exhibited pre mining radon exhalation fluxes above 3 times background, and 41 % (60 ha) of the area were above 9 times background, respectively. This is assuming, as a best estimate, that the radon exhalation rate is a linear function of the radon in soil concentration. The remaining portion of the fenced area (44 ha) is assumed to have exhibited background radon exhalation fluxes.

Assuming a background exhalation of 31±15 mBq $m^{-2}s^{-1}$ estimated in our study, we can estimate a minimum pre-mining radon exhalation rate above environmental background, which amounts to approximately 170 kBq s^{-1} and originates from an area of approximately 98 ha. Due to a lack of pre mining data available, it is impossible to estimate an upper limit for the total pre mining radon exhalation flux from the Nabarlek mine.

Figure 7 Photograph of unit 7 (B Ryan)

Although maximum pre mining radon exhalation rates have been reported by Clark et al (1981), who report a range from 3700 up to 44 000 mBq $m^{-2}s^{-1}$ directly above the orebody, the upper maximum is certainly not representative for the entire area as the orebody was relatively small and exposed at only a few places. The average above orebody 1 at the Koongarra uranium deposit in the Alligator Rivers Region can be calculated for example to 2429 mBq $m^{-2}s^{-1}$ (Davy et al 1978). The maximum natural radon exhalation flux measured during our study at an undisturbed site within the fenced area was 1904 mBq $m^{-2}s^{-1}$. If we assume a maximum radon exhalation of 3700 mBq $m^{-2}s^{-1}$ we can estimate the upper limit for the pre-mining radon exhalation rate to be approximately 2300 kBq s^{-1}. We conclude that it is unlikely that the post-mining radon exhalation rate from the Nabarlek site is higher than pre-mining rates. However, we are not able to reliably determine the pre-mining upper limit of the radon exhalation from the site and emphasise that this is purely an estimate.

Our comparison of pre- and post-mining radon exhalation rates emphasises the importance of a good baseline data set to be available before a mine starts operating. Once mining is finished and the mine site is rehabilitated it may turn out to be difficult to decide whether or not the rehabilitation has been successful and overall radiation levels are back to pre-mining values. Although mining of the orebody at Nabarlek may have reduced the total radon flux from the site as all the uranium ore has been excavated, radon exhalation fluxes are still relatively high at some of the sites, especially at the former pit area and the adjacent unit 7, and could be further reduced.

4.3 Possible management of radon fluxes

The relatively high radon exhalation fluxes estimated for unit 7 are most likely due to the relatively fine grained, saline soils (possibly tailings) which are exposed at the surface and show a high ^{226}Ra concentration (Hancock et al 2003). In contrast, elevated exhalation fluxes above the former pit area may be due the substantially greater depth of waste rock and cracks and voids that allow radon to escape from the deeper areas.

Although the rehabilitation of the Nabarlek uranium mine relied on the fact that tailings would be below ground water and approximately 13 meters below the final ground surface to keep radon exhalation rates at the surface low (Waggit & Woods 1998), some material was placed in the pit with final decommissioning of the mine in 1995 and was only covered with a layer of waste rock. Queensland Mines Limited (QML 1979) report that seasonal variations of the groundwater level near the original deposit can be from 1m to 18m, which may additionally cause increased radon fluxes when ground water levels are low during the dry season.

Excavating the radioactive tailings material exposed at unit 7 and resurfacing the the area would reduce the total radon exhalation rate by 20%. However, at this stage it is not known how deep the material extends below the surface. In addition, erosion of radioactive material into the Cooper Creek catchment as described in Hancock et al (2003) could be reduced by a substantial amount. Excavating is certainly not a feasible option for the pit and waste rock dump area. Yet, resurfacing of the area may prove efficient, although erosion rates are extremely high at Nabarlek in the wet season and a new surface cover over the pit may not last long. Nonetheless a theoretical approach on how exhalation rates could be reduced is presented.

In order to estimate the effectiveness as a barrier of various surface covers for the pit, the following assumptions are made: radon fluxes are uniform above the pit and waste rock dump areas, the cover does not add to the radon flux and radon diffusion in the overburden is the only transport process, although this assumption may not be valid due to cracks and voids within the surface cover.

Jha et al (2001) give diffusion coefficients in soil, clay and concrete of $3 \cdot 10^{-6}$, $3 \cdot 10^{-7}$, and $3.1 \cdot 10^{-9}$ $s \cdot m^{-1}$, respectively. At steady state conditions, the diffusion of radon through the surface barrier is described via:

$$C = C_0 \cdot \exp[-\sqrt{(\lambda/D)} \cdot Z] \quad (4)$$

With

C:	radon concentration at height Z
C_0:	radon concentration at bottom of surface cover
λ:	decay constant of radon, 2.1×10^{-6} 1/s
D:	diffusion coefficient through surface barrier.

Diffusion is occurring along the strongest concentration gradient and applying Fick's 1st law, radon exhalation fluxes in Z-direction are given multiplying the diffusion coefficient with the magnitude of the radon concentration gradient, i.e.:

$$J = D \cdot gradC = - D \cdot \delta C/\delta Z \quad (5)$$

Combining the solutions of both equations yields, that a thickness of 4.1 m of soil, 1.3 m of clay and 0.1 m of concrete would results in a reduction of the radon exhalation from the former pit area to environmental background levels of 31 Bq m^{-2} s^{-1}, whereas a cover with 90 cm of soil, 30 cm of clay and 3 cm of concrete, respectively, would result in a reduction of radon exhalation flux to a pre mining level of 450 Bq m^{-2} s^{-1} estimated at the natural U anomaly southeast of the waste rock dump retention pond. To comply with U.S. EPA standards (740 Bq m^{-2} s^{-1}) 0.3 m of soil, 0.1 m of clay and 0.01 m of concrete would be required. The same surface barrier thicknesses would reduce the radon exhalation fluxes from the adjacent waste rock dump to 11 Bq m^{-2} s^{-1}, 160 Bq m^{-2} $s^{-1}$and 265 Bq m^{-2} s^{-1}, respectively.

On radiological grounds, following the recommendations of ICRP and the fact that pre mining levels of radon exhalation were most likely higher prior to the mining of the orebody than they are now, there is no need to further rehabilitate the area and reduce radon exhalation fluxes. However, following ALARA, exhalation rates could be reduced by excavating unit 7 and applying an additional soil cover of 90 cm to the pit and former waste rock dump areas. This would result in a reduction of the total radon exhalation rate (including background) from the fenced mine area by approximately 50 per cent.

5 Conclusion

Our radon exhalation survey emphasises the importance of a randomised selection of survey points and randomised placement of charcoal canisters at each individual survey point, in order to estimate a mean radon exhalation flux; averaging the results of survey points following a regular grid or topographical features may not reflect the true value. In addition, placement of individual radon cups at 'convenient' spots, where cups can be easily deployed (for example, in soft earth) may result in an overestimation of the radon exhalation fluxes. For instance, on and off rock exhalation measurements in the former pit have shown to differ up to a factor of five in our study. Hence it is important to have an experimental design in which choice of the specific measurement point is not left to the subjective judgment of the investigator.

In addition, our study emphasises that it is very important to have a good radiological baseline data set available, before a mining operation starts. It may otherwise turn out to be very difficult to assess the success of mine rehabilitation on radiological grounds. Although it was possible in our study to give an estimate of the lower pre-mining limit of radon exhalation from the site, it proved impossible to estimate the true pre-mining radon flux from the site.

The application of approximately 90 cm of soil as an additional surface barrier would result in the reduction of the radon exhalation rate from the fenced mine area by approximately 50 per cent, however its feasibility remains questionable. For example, topsoils rather than waste rock, may be more susceptible to cause problems with invasive weeds. In addition, high erosion rates around the location of unit 7 south of the pit, reported by Hancock et al (2003), may result in a quick denudation of the additional cover.

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Appendix A.1 Eastings, northings and individual radon exhalation fluxes determined during the study within and outside the fenced area of the rehabilitated mine-site

	Location		Date	Flux		mean	stdev
	survey point						
Can #	Easting	northing	Deployed	mBq/m2/s	err	mBq/m2/s	
	Pit – north						
14	10		13-Aug-99	670	6		
6	317658	8638570	13-Aug-99	614	5	799	272
26			13-Aug-99	1111	7		
7	9		13-Aug-99	1263	13		
13	317625	8638565	13-Aug-99	1033	12	1182	129
22			13-Aug-99	1251	13		
20	8		13-Aug-99	1227	7		
11	317578	8638571	13-Aug-99	2306	18	1193	1131
15			13-Aug-99	45	2		
24	4		13-Aug-99	73	3		
3	317511	8638677	13-Aug-99	142	5	97	39
17			13-Aug-99	78	4		
28	5		13-Aug-99	1966	12		
8	317486	8638693	13-Aug-99	2391	13	2047	311
23			13-Aug-99	1785	11		
29	1		13-Aug-99	536	9		
9	317460	8638709	13-Aug-99	698	10	556	132
5			13-Aug-99	435	6		
2	7		13-Aug-99	1853	16		
18	317499	8638593	13-Aug-99	1318	14	1579	268
21			13-Aug-99	1567	15		
	Pit-south						
1	14		17-Aug-99	1345	8		
2	317632	8638550	17-Aug-99	428	5	1041	530
3			17-Aug-99	1348	9		
4	17		17-Aug-99	2166	12		
5	317611	8638500	17-Aug-99	2428	12	2293	131
6			17-Aug-99	2285	12		
7	18		17-Aug-99	1	2		
8	317646	8638489	17-Aug-99	175	4	61	98
9			17-Aug-99	8	2		
11	20		17-Aug-99	140	4		
12	317621	8638438	17-Aug-99	674	7	525	336
13			17-Aug-99	760	7		
32	16		30-Aug-99	1691	9		
33	317550	8638451	30-Aug-99	948	6	1269	382
34			30-Aug-99	1169	7		
35	12		30-Aug-99	204	3		
36	317554	8638502	30-Aug-99	570	5	444	208
28			30-Aug-99	557	5		
29	11		30-Aug-99	801	6		
30	317530	8638507	30-Aug-99	140	3	508	336
22			30-Aug-99	582	6		

	Prop						
1	2		24-Aug-99	6	1		
2	317876	8639298	24-Aug-99	269	4	297	305
3			24-Aug-99	614	5		
7	4		24-Aug-99	229	3		
8	317897	8639282	24-Aug-99	141	3	168	53
9			24-Aug-99	135	3		
10	5		24-Aug-99	400	5		
11	317865	8639242	24-Aug-99	192	4	285	106
12			24-Aug-99	262	4		
13	7		24-Aug-99	328	5		
14	317891	8639232	24-Aug-99	320	5	323	4
15			24-Aug-99	320	5		
16	12		24-Aug-99	924	8		
17	317908	8639196	24-Aug-99	101	3	353	495
18			24-Aug-99	36	2		
19	10		24-Aug-99	199	4		
20	317874	8639154	24-Aug-99	395	5	281	102
21			24-Aug-99	249	4		
22	13		24-Aug-99	517	5		
23	317863	8639116	24-Aug-99	28	2	319	257
24			24-Aug-99	411	4		
25	15		24-Aug-99	188	3		
26	317887	8639112	24-Aug-99	149	3	198	54
27			24-Aug-99	256	4		
	Ore Stockpile						
1	116		30-Aug-99	163	3		
2	317360	8639163	30-Aug-99	131	3	169	42
3			30-Aug-99	213	3		
4	169		30-Aug-99	185	4		
5	317348	8639155	30-Aug-99	105	3	129	49
6			30-Aug-99	98	3		
7	176		30-Aug-99	79	3		
8	317432	8639044	30-Aug-99	112	3	90	19
9			30-Aug-99	78	3		
10	126		30-Aug-99	67	3		
11	317447	8639102	30-Aug-99	25	2	38	26
12			30-Aug-99	21	2		
13	125		30-Aug-99	100	3		
14	317444	8639147	30-Aug-99	27	2	59	37
15			30-Aug-99	50	3		
16	129		30-Aug-99	13	2		
17	317528	8639132	30-Aug-99	17	2	16	3
18			30-Aug-99	19	2		
19	124		30-Aug-99	15	2		
20	317485	8639198	30-Aug-99	38	2	39	25
21			30-Aug-99	65	3		
	Ore Stockpile ROP						
1	197		4-Sep-99	245	4		
2	317335	8639384	4-Sep-99	44	2	107	120
3			4-Sep-99	32	2		
4	99		4-Sep-99	12	2		

5	317333	8639246	4-Sep-99	40	2	28	14
6			4-Sep-99	31	2		
7		98	4-Sep-99	335	5		
8	317372	8639329	4-Sep-99	21	2	194	159
9			4-Sep-99	225	4		
10		95	4-Sep-99	34	2		
11	317279	8639292	4-Sep-99	42	2	36	6
12			4-Sep-99	30	2		
13		93	4-Sep-99	285	5		
14	317225	8639342	4-Sep-99	298	5	254	65
15			4-Sep-99	180	4		
16		92	4-Sep-99	79	3		
17	317258	8639395	4-Sep-99	253	4	205	109
18			4-Sep-99	282	5		
		EP1					
19		105	4-Sep-99	77	3		
20	317174	8639223	4-Sep-99	75	3	78	5
21			4-Sep-99	84	3		
22		172	4-Sep-99	101	3		
23	317309	8639042	4-Sep-99	196	4	122	66
24			4-Sep-99	69	3		
28		165	4-Sep-99	217	4		
29	317257	8639114	4-Sep-99	267	5	245	25
30			4-Sep-99	252	4		
37		158	4-Sep-99	189	4		
38	317155	8639164	4-Sep-99	314	5	232	72
39			4-Sep-99	192	4		
		EP 2					
4		83	10-Sep-99	51	2		
5	316951	8639053	10-Sep-99	71	3	63	10
6			10-Sep-99	66	3		
13		75	10-Sep-99	507	6		
14	317180	8639415	10-Sep-99	204	4	247	242
15			10-Sep-99	29	2		
16		86	10-Sep-99	22	2		
17	317172	8639307	10-Sep-99	18	2	19	3
18			10-Sep-99	17	2		
19		87	10-Sep-99	215	4		
20	317108	8639291	10-Sep-99	8	2	108	104
21			10-Sep-99	101	3		
22		77	10-Sep-99	49	2		
23	317095	8639341	10-Sep-99	126	3	100	44
24			10-Sep-99	124	3		
28		68	10-Sep-99	35	2		
29	317073	8639368	10-Sep-99	6	2	92	124
30			10-Sep-99	235	4		
31		88	10-Sep-99	54	2		
32	317117	8639230	10-Sep-99	28	2	40	13
33			10-Sep-99	37	2		
34		80	10-Sep-99	142	3		
35	317025	8639219	10-Sep-99	93	3	118	25
36			10-Sep-99	118	3		

37		72	10-Sep-99	22	2		
38	316939	8639189	10-Sep-99	40	2	28	11
39			10-Sep-99	21	2		
40		73	10-Sep-99	415	6		
41	316946	8639150	10-Sep-99	132	3	290	144
42			10-Sep-99	322	5		
43		60	10-Sep-99	206	4		
44	316984	8639354	10-Sep-99	237	4	207	29
45			10-Sep-99	179	4		
47		59	10-Sep-99	66	3	129	88
48	317005	8639392	10-Sep-99	191	4		
1		210	17-Sep-99	26	2		
2	316717	8639736	17-Sep-99	52	2	31	19
3			17-Sep-99	15	2		
4		179	17-Sep-99	66	3		
5	316734	8639695	17-Sep-99	28	2	60	29
6			17-Sep-99	85	3		
7		202	17-Sep-99	27	2		
8	316698	8639665	17-Sep-99	86	3	55	30
9			17-Sep-99	50	2		
10		181	17-Sep-99	32	2		
11	316711	8639588	17-Sep-99	67	3	72	43
12			17-Sep-99	117	3		
13		204	17-Sep-99	47	2		
14	316695	8639581	17-Sep-99	77	3	127	113
15			17-Sep-99	256	4		
16		49	17-Sep-99	161	4		
17	317024	8639489	17-Sep-99	385	5	255	117
18			17-Sep-99	219	4		
19		34	17-Sep-99	211	4		
20	316940	8639507	17-Sep-99	98	3	160	57
21			17-Sep-99	172	4		
22		42	17-Sep-99	91	3		
23	316955	8639454	17-Sep-99	114	3	107	14
24			17-Sep-99	115	3		
25		19	17-Sep-99	22	2		
26	316818	8639489	17-Sep-99	22	2	25	7
27			17-Sep-99	33	2		
28		11	17-Sep-99	186	4		
29	316808	8639530	17-Sep-99	77	3	119	58
30			17-Sep-99	93	3		
31		10	17-Sep-99	70	3		
32	316845	8639579	17-Sep-99	139	3	102	35
33			17-Sep-99	96	3		
10		56	21-Sep-99	24	3		
11	316826	8639181	21-Sep-99	27	3	46	35
12			21-Sep-99	86	4		
19		31	21-Sep-99	43	3		
20	316717	8639309	21-Sep-99	9	3	42	32
21			21-Sep-99	74	4		
13		38	21-Sep-99	23	3		
14	316797	8639305	21-Sep-99	30	3	23	7

15			21-Sep-99	17	3		
34	29		21-Sep-99	83	4		
35	316765	8639403	21-Sep-99	112	4	93	17
36			21-Sep-99	83	4		
7	6		21-Sep-99	53	3	237	260
9	316626	8639425	21-Sep-99	421	7		
	Topsoil Stockpile						
2	15		21-Sep-99	17	3	20	5
3	316634	8639349	21-Sep-99	24	3		
4	186		21-Sep-99	26	3		
5	316530	8639406	21-Sep-99	44	3	53	33
6			21-Sep-99	89	4		
31	206		21-Sep-99	109	4		
32	316539	8639484	21-Sep-99	45	3	57	47
33			21-Sep-99	16	3		
25	234		21-Sep-99	26	3		
26	316383	8639550	21-Sep-99	23	3	20	8
27			21-Sep-99	12	3		
28	223		21-Sep-99	13	3		
29	316466	8639610	21-Sep-99	4	3	7	5
30			21-Sep-99	6	3		
16	230		21-Sep-99	25	3		
17	316434	8639715	21-Sep-99	18	3	25	7
18			21-Sep-99	31	3		
	WRDRP and WRD						
18	1 (outside fenced area)		17-Aug-01	18	2		
19	317437	8637991	17-Aug-01	26	2	22	4
5			17-Aug-01	22	2		
43	2		17-Aug-01	103	3	75	40
V	317547	8637974	17-Aug-01	47	2		
20	3		17-Aug-01	92	2		
23	317589	8637980	17-Aug-01	39	2	58	30
25			17-Aug-01	42	2		
40	4		17-Aug-01	47	2		
41	317679	8637961	17-Aug-01	90	2	51	38
46			17-Aug-01	15	2		
38	5		17-Aug-01	143	3		
39	317771	8637975	17-Aug-01	75	2	107	34
42			17-Aug-01	102	3		
6	6		17-Aug-01	244	3		
14	317848	8637999	17-Aug-01	195	3	270	91
16	outside fence east		17-Aug-01	371	4		
4	7		17-Aug-01	256	4		
9	317837	8638042	17-Aug-01	290	4	261	28
10	outside fence east		17-Aug-01	236	3		
13	8		17-Aug-01	585	5		
11	317751	8638103	17-Aug-01	340	4	399	165
24			17-Aug-01	271	4		
1	9		17-Aug-01	1923	9		
12	317715	8638040	17-Aug-01	437	4	928	862
X	WRDRP next to WRD		17-Aug-01	422	5		
21	10		17-Aug-01	623	5		

22	317604	8638036	17-Aug-01	691	6	567	159
27	WRDRP next to WRD		17-Aug-01	387	4		
18	3		24-Aug-01	173	3		
19	317589	8637980	24-Aug-01	84	2	161	71
22	WRDRP		24-Aug-01	225	4		
15	11		24-Aug-01	338	4		
26	317505	8638111	24-Aug-01	280	4	510	325
42	outside WRD area		24-Aug-01	740	6		
40	12		24-Aug-01	52	2		
44	317435	8638065	24-Aug-01	57	2	52	6
46	outside fence west		24-Aug-01	46	2		
17	13		24-Aug-01	80	2		
41	317404	8638138	24-Aug-01	55	2	91	43
43	outside fence west		24-Aug-01	139	3		
14	14		24-Aug-01	164	3		
16	317548	8638199	24-Aug-01	353	4	262	95
21	WRD		24-Aug-01	269	4		
10	15		24-Aug-01	216	3		
12	317556	8638203	24-Aug-01	745	6	667	418
27	WRD		24-Aug-01	1041	7		
6	16		24-Aug-01	1049	7		
7	317576	8638182	24-Aug-01	539	5	657	348
8	WRD		24-Aug-01	384	4		
4	23		24-Aug-01	495	5		
11	317593	8638237	24-Aug-01	405	4	377	133
V	WRD		24-Aug-01	232	3		
2	24		24-Aug-01	303	4		
3	317469	8638224	24-Aug-01	215	4	249	47
X	next to WRD		24-Aug-01	229	4		
2	30		31-Aug-01	49	5		
25	317882	8638409	31-Aug-01	46	5	45	5
39	outside WRD, NW		31-Aug-01	39	5		
3	29		31-Aug-01	217	5		
24	317826	8638344	31-Aug-01	164	5	210	65
40	outside WRD, W		31-Aug-01	256	5		
1	20		31-Aug-01	465	7		
16	317876	8638237	31-Aug-01	571	7	497	64
43	outside WRD, W		31-Aug-01	456	7		
4	19		31-Aug-01	817	8		
15	317854	8638198	31-Aug-01	1275	9	973	262
27	outside WRD, W		31-Aug-01	826	9		
12	21		31-Aug-01	595	7		
26	317752	8638214	31-Aug-01	287	6	403	168
42	WRD		31-Aug-01	326	7		
5	18		31-Aug-01	556	8		
14	317743	8638176	31-Aug-01	268	6	447	156
44	WRD		31-Aug-01	516	7		
V	17		31-Aug-01	87	6		
6	317652	8638190	31-Aug-01	173	6	154	60
21	WRD		31-Aug-01	201	6		
B	22		31-Aug-01	392	6		
X	317676	8638279	31-Aug-01	160	5	232	140

8	WRD		31-Aug-01	143	6		
9	25		31-Aug-01	24	4		
19	317525	8638288	31-Aug-01	69	6	64	38
20	outside WRD, E		31-Aug-01	100	7		
7	26		31-Aug-01	238	6		
11	317595	8638293	31-Aug-01	173	6	197	35
18	WRD		31-Aug-01	182	7		
8	28		7-Sep-01	193	4		
12	317777	8638318	7-Sep-01	189	4	184	13
23	WRD		7-Sep-01	170	3		
B	27		7-Sep-01	199	4		
17	317725	8638344	7-Sep-01	203	3	203	3
46	WRD		7-Sep-01	206	4		
X	31		7-Sep-01	58	2		
13	317773	8638379	7-Sep-01	87	3	70	15
21	Outside WRD, N		7-Sep-01	66	2		
V	32		7-Sep-01	132	3		
6	317725	8638389	7-Sep-01	153	3	140	11
9	Outside WRD, N		7-Sep-01	135	3		
2	34		7-Sep-01	197	3		
26	317491	8638414	7-Sep-01	258	4	209	44
41	Outside WRD, N		7-Sep-01	172	3		
4	35		7-Sep-01	84	2		
42	317437	8638432	7-Sep-01	54	2	80	24
44	Outside WRD, N		7-Sep-01	103	2		
1	36		7-Sep-01	144	3		
15	317475	8638359	7-Sep-01	138	3	138	6
16	Outside WRD, NW		7-Sep-01	131	3		
7	33		7-Sep-01	184	3		
14	317570	8638379	7-Sep-01	220	3	180	42
20	just outside WRD, N		7-Sep-01	136	3		
	Transect SE outside fenced area						
21	1		28-Sep-01	186	3		
39	317868	8638050	28-Sep-01	312	4	238	66
46			28-Sep-01	216	3		
26	2		28-Sep-01	24	2		
41	317884	8638039	28-Sep-01	325	5	295	41
43			28-Sep-01	266	4		
2	3		28-Sep-01	613	6		
25	317970	8637982	28-Sep-01	191	4	616	427
40			28-Sep-01	1044	8		
1	4		28-Sep-01	470	5		
9	318021	8637948	28-Sep-01	445	5	479	40
18			28-Sep-01	522	5		
B	5		28-Sep-01	865	6		
7	318074	8637912	28-Sep-01	582	5	735	143
16			28-Sep-01	758	6		
8	6		28-Sep-01	558	5		
12	318129	8637876	28-Sep-01	672	6	675	118
23			28-Sep-01	794	6		
11	7		28-Sep-01	637	5		

17	318141	8637895	28-Sep-01	798	6	721	81
44			28-Sep-01	727	5		
V	8		28-Sep-01	306	4		
5	318165	8637930	28-Sep-01	400	4	333	59
10			28-Sep-01	291	4		
3	9		28-Sep-01	285	4		
13	318109	8637846	28-Sep-01	338	4	295	38
14			28-Sep-01	264	4		
15	10		28-Sep-01	178	3		
20	318066	8637781	28-Sep-01	127	3	165	33
27			28-Sep-01	189	3		
	Unit-7						
10	1		7-Sep-01	2154	10		
11	317570	8638399	7-Sep-01	2595	10	2355	223
38			7-Sep-01	2317	10		
61	2		21-Oct-02	8028	50		
66	317544	8638426	21-Oct-02	25410	88	12606	11238
98			21-Oct-02	4379	37		
79	3		21-Oct-02	5448	41		
85	317562	8638413	21-Oct-02	2767	30	3386	1832
99			21-Oct-02	1944	25		
67	4		21-Oct-02	6449	45		
69	317572	8638399	21-Oct-02	3068	31	7687	5346
93			21-Oct-02	13543	64		