Technical Memorandum 29

Concentrations of radon and radon daughters during semi-dry tailings deposition at Nabarlek (1985-88)

D. A. Woods

Supervising Scientist for
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Supervising Scientist for the Alligator Rivers Region
P.O. Box 387, Bondi Junction
N.S.W. 2022, Australia

This Technical Memorandum was prepared by:

D.A. Woods

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From June 1985 to June 1988 Queensland Mines Ltd operated a semi-dry system of tailings deposition in their Nabarlek mine pit. To confirm that radon and radon daughter concentrations did not become excessive, the Company carried out an intensive radon/radon daughter monitoring program. This report summarises the data from that program and also gives details of check measurements carried out by OSS.

OSS independent measurements indicate good agreement between instruments used and confirm QML's data. Dose assessments presented in this report indicate that safe working conditions were maintained and that the operations posed no hazard to members of the public.

1 INTRODUCTION

The Queensland Mine Ltd (QML) pit at Nabarlek was excavated between April and October 1979, when 606 700 tonnes of ore were mined and stockpiled. The stockpiled ore was processed to extract uranium oxide between May 1980 and June 1988 with the tailings from the milling operation being returned to the pit. From May 1980 to May 1985, the tailings were deposited under water (subaqueously) with water depths of the order of 10 m in 1981-82 and 4 m in 1983-84. In May 1985 removal of surface water from the tailings commenced and a semi-dry (sub-aerial) system of tailings deposition started. At this time the depth of tailings was some 58 m. By June 1988, following the exhaustion of the ore stockpile, the tailings surface was sufficiently dewatered and consolidated to allow the placement of geotextile and waste rock covers. Vertical dewatering wicks were also inserted to further enhance the consolidation of the tailings prior to the eventual final capping and rehabilitation.

In the early years of the mill, the perceived wisdom was to maintain a water cover over the tailings, primarily to inhibit radon emanation from the surface of the tailings. However, in the later years of the operation, experience and some experimental work (Marshman 1987) suggested that radon/radon daughter levels were not expected to be a problem under semi-dry operation and that the advantages in terms of decommissioning and rehabilitation far outweighed the continuance of the water cover. However, to confirm that radon and radon daughter concentrations did not become excessive, the Company initiated a more intensive radon/radon daughter monitoring program. This report summarises the data from that program and also gives details of check measurements carried out by OSS.

The relevant periods in terms of radon emanation from the tailings were:

May 1980 - May 1985	tailings under water
June 1985 - June 1988	moist to dry tailings varying progressively with time and season (Wet/Dry)
post June 1988	geotextile/waste rock cover

2 MONITORING METHODS

2.1 QML routine radon monitoring

From the outset of operations at Nabarlek, radon concentrations were routinely measured by QML using Eberline radon gas monitors. Generally, these automatic monitors were placed at various locations around the site and its environs for a week at a time taking hourly samples. Prior to semi-dry tailings operations, measurements at the pit were only carried out once or twice a year, greater emphasis being placed on measurements in and around the mill where most employees were located for most of the time. At the on-set of semi-dry tailings operations additional sampling in and around the pit (Fig. 1) was performed almost continuously and reported on a monthly basis.

Up until March 1987, radon concentrations were presented in a daily day/night summary format. Appendix 1 shows an example of this reporting format. For each 24-hour period a daytime mean and maximum and a night-time mean and maximum were given. For reporting purposes day and night were of equal duration i.e. 12 hours. From March 1987 onwards the reporting format changed. For a particular sampling location the total number of hourly samples taken, the mean and the maximum radon concentrations were given. Appendix 2 shows an example of this reporting format.

2.2 QML radon daughter monitoring

Up to late 1983 radon daughter measurements at Nabarlek pit were performed by QML using the Rolle grab sampling technique (Rolle 1972). Relatively few samples were taken and for the most part these were daytime samples. The mean result over this period was around 0.5 mWL with a range of 0.1-2 mWL. Since, as will be shown in this report, the maximum values occur in the early hours of the morning outside the daytime sampling period this mean will underestimate the true daily mean. From April 1984 onwards Eberline Working Level Monitors were employed. As with the radon gas monitors, these automatic monitors were placed at various locations around the site for a week at a time taking hourly samples.

2.3 OSS check measurements

To confirm independently that radon and radon daughter concentrations did not exceed acceptable levels and also to cross-check QML's reported measurements, OSS carried out radon daughter measurements using an alpha Nuclear automatic radon daughter monitor in Nabarlek pit in September 1986 and September 1987. In addition, QML provided detailed data printouts showing hourly measurements for sampling periods in October 1985, May 1986, September 1986, September 1987 and October 1988.

In September 1986 radon daughter measurements at Nabarlek pit were performed simultaneously using OSS, QML and Ranger Uranium Mine Ltd (RUM) who operate the Ranger mine near Jabiru) automatic radon daughter monitors, providing an intercomparison of the monitors in use in the Region. An OSS health physicist, in conjunction with the QML Radiation Safety Officer, carried out (over the week 18-24 September 1986) a series of continuous radon and radon daughter measurements in the Nabarlek pit. The following equipment was used in the intercomparison:

Monitor	Identification no.	Owner	Sampling period
Eberline Radon Gas Monitor RGM1	1	QML	3.9.86-24.4.86
Eberline Radon Gas Monitor RGM2	96	QML	4.9.86-24.9.86
Eberline Working Level Monitor WLM1	121	QML	3.9.86-10.9.86 13.9.86-20.9.86
Eberline Working Level Monitor WLM1	313	QML	17.9.86-24.9.86
alpha Nuclear 500	63	OSS	19.9.86-24.9.86
alpha Nuclear 500	26	RUM	18.9.86-24.9.86

The measurements were all taken near pit pump 1 at the end of the haul road in the pit (Fig. 1; OC06, Pit 1). The monitors were located on a sampling platform about 1 m above the ground (Plate 1). The RGM2 (Unit No. 96) is provided with legs so that it operates at waist level above the ground. The RGM1 (Unit No. 1) is similar to a large suitcase and was placed on top of the RGM2.

3 RESULTS

3.1 QML summary radon concentration data

Table 1 summarises the radon concentration results reported by QML for the pit area to November 1988. Mean values for results prior to March 1987 were obtained by taking the average of the day/night means reported for a particular sampling period and location. Figure 2 illustrates the monthly radon results reported by QML for the pit area. Although there were insufficient data prior to the semi-dry tailings operation to permit a definitive comparison of before and after semi-dry tailings operation results, particularly as there is a seasonal variation, the mean value in August 1983 is similar to the mean values in August 1985 and August 1986 suggesting that no significant increase in radon levels occurred. Over the four-year period of semi-dry tailings operations, radon levels peaked in August and dipped in February each year. Dry season results for 1985 and 1986 were similar; 1987 and 1988 Dry season results were also similar, but lower than the previous two years. This indicates that no dramatic increase in radon concentrations occurred as semi-dry tailings operations continued.

The mean radon concentrations in and around the pit did not exceed the 1980 Radiation Protection Code (Commonwealth of Australia 1980) derived limit for members of the public (3700 Bq/m^3) at any time during the semi-dry tailings operation. In fact the highest mean (360 Bq/m^3 in July 1985) was approximately one tenth of the public limit. The highest maximum result recorded during semi-dry tailings operation was 5843 Bq/m^3 in August 1988. The corresponding mean was 257 Bq/m^3.

3.2 QML summary radon daughter concentration data

Table 2 summarises the Working Level Monitor results for locations in and around Nabarlek pit. Figure 3 illustrates the mean and maximum values reported. During years of semi-dry tailings operations, the mean radon daughter concentration did not significantly increase or decrease in the Dry season (Fig. 3*a*). The overall mean for these data is around 7.3 mWL and includes elevated night time results and low Wet season results. This is less than the 1980 Radiation Protection Code derived limit for members of the public of 10 mWL, significantly less than the derived limit of 330 mWL for workers, and confirms that radon daughter levels during semi-dry tailings operations were not excessive.

Although mean values have remained similar, Fig. 3*b* suggests that maximum values may have increased since semi-dry operations started, with an isolated peak value of 445 mWL in August 1988, as the tailings dried out. The corresponding mean for the sampling period in which this peak was recorded was 17.6 mWL.

Figure 4 illustrates the variation in radon equilibrium factor at Nabarlek pit during semi-dry tailings operations based on corresponding mean radon and mean radon daughter values reported. The mean radon equilibrium factor over the period was 0.17.

3.3 OSS check measurements and QML detailed data

The results of OSS measurements and the more detailed QML data are presented in the sections below.

October 1985

At the request of OSS, QML carried out simultaneous radon and radon daughter automatic monitor measurements in October 1985 in the pit. October was chosen in expectation of higher readings towards the end of the Dry season in the first year of semi-dry tailings operation. QML provided OSS with the detailed (continuous hourly) results of these measurements taken at pit pump 2. Figure 5 shows radon and radon daughter concentrations measured simultaneously for the period 12-19 October 1985 at sump pump 2 in the pit and the corresponding radon equilibrium factor variation.

Figure 5 clearly illustrates low daytime results (~ 10 mWL, ~ 200 Bq/m^3) and higher night-time results (~ 25 mWL, ~ 700 Bq/m^3). The mean radon daughter and radon concentration values were 12.6 mWL and 336 Bq/m^3, respectively. The mean radon equilibrium factor for the sampling period was 0.15. At this stage in the operation the tailings were still quite wet (Plate 2).

May 1986

Figure 6 shows hourly radon daughter concentrations at pit pump 1 in the pit for the period 11.5.86 to 18.5.86. In this period the mean radon daughter concentration was 13.6 mWL, with a range of 0.7-67.4 mWL.

September 1986

Figure 7 shows hourly radon daughter concentrations at pit pump 1 for the period 17.9.86 to 24.9.86 using QML, OSS and Ranger instruments and indicates good agreement between monitors. Figure 8 shows the hourly radon and radon daughter concentrations and corresponding equilibrium factors for the period 3.9.86 to 24.9.86.

Table 3 gives the measurement statistics for each instrument used.

These measurements indicate that radon and radon daughter levels in the pit continued to remain low in comparison with derived limits for occupational exposures towards the end of the second Dry season of semi-dry tailings operations. The equilibrium factors (F), which were low during the day and peaked in the early hours of the morning, were derived by using the expression:

$$F = \frac{3.7 \times \text{radon daughter conc. (mWL)}}{\text{radon conc. (Bq/m}^3\text{)}}$$

The mean radon equilibrium factor for September 1986 was 0.13 with a range of 0.03-0.51 and a median of 0.09, indicating, as expected, fairly young air (i.e. an average of 7 to 8 minutes old).

September 1987

OSS again carried out simultaneous radon and radon daughter measurements at the pit pump 1 location in conjunction with the QML Radiation Safety Officer. Figure 9 shows the radon and radon daughter concentrations measured simultaneously over the period 12-17 September 1987 and the corresponding radon equilibrium factor variation. Good agreement between the radon daughter monitors was once again achieved and similar results to those of the previous year obtained. Table 3 gives the measurement statistics for each instrument used.

By this stage, although ponding still continued around the sump pump a significant proportion of the tailings surface area was dry and cracking. (Plate 3)

October 1988

Figure 10 shows hourly radon and radon daughter concentrations at pit pump 1 for the period 6.10.88 to 29.10.88 and the corresponding equilibrium factors. The measurement statistics for these data are given in Table 3.

By this stage semi-dry tailings deposition had ceased and during this month a geotextile/waste rock cover was placed over the tailings and vertical dewatering wicks inserted (Plate 4).

4 DOSE ASSESSMENTS

The radon and radon daughter concentrations reported above demonstrate that no significant radiation exposure due to radon and radon daughters emanating from the tailings in the pit would be expected. However, to demonstrate this, the following dose estimates are presented:

- Designated employee working for 2000 hours per year in and around the pit; and
- Members of the public at the Mankinkinkani Aboriginal camp and at the Nabarlek accommodation camp (Fig. 11).

4.1 Designated employee dose estimates

The overall mean values for radon and radon daughter concentrations for the period of the semi-dry tailings operation (1985-1988) were 163 Bq/m^3 and 7.3 mWL, respectively. Work would normally be performed in and around the pit in daylight hours only, therefore, dose assessments based on these mean values (which include high night time results) will yield overestimates.

For radon-222, ICRP 47 (ICRP 1985) gives a dose conversion factor of 3.3×10^{-7} Svy^{-1}/Bqm^{-3} for designated employees working 2000 hours per year. Therefore, for exposure to a mean radon concentration of 163 Bq/m^3, the annual dose to a designated employee would be:

$$D(\text{radon}) = 163 \times 3.3 \times 10^{-7} \text{ Sv} = 0.054 \text{ mSv}$$

For radon daughters, the appropriate dose conversion factor for designated employees is 10 mSv/WLM (Commonwealth of Australia 1987*a,b*). A worker exposed to the mean radon daughter concentration of 7.3 mWL for 2000 working hours would receive an annual dose of:

$$D(\text{radon daughters}) = 7.3 \times 10^{-3} \times 10 \times 2000/170 = 0.86 \text{ mSv}$$

where 1 working month = 170 hours.

Therefore, the total annual dose, due to radon and radon daughters, to a designated employee working for 2000 hours per year in and around Nabarlek pit is less than 0.92 mSv. This is less than 2% of the annual dose limit of 50 mSv for workers.

Actual exposure times were significantly lower than 2000 hours. The QML Radiation Safety Officer estimated the highest pit occupancy to be 240 hours per year (Marshman typically of the order of 2 mWL or less. Using these data the annual dose to the most exposed designated employee becomes 0.03 mSv (0.06% of the annual dose limit), clearly demonstrating trivial occupational exposures due to radon and radon daughters from the pit.[1] (The IAEA indicates that trivial doses are in the order of some tens of microsieverts per year [IAEA 1988].)

4.2 Member of the public dose estimates

From the QML report 'Estimated dose equivalents and committed dose equivalents from operations at Nabarlek Mine' (Harrington 1985), two potential critical groups are indicated:

- 20 adults at the Aboriginal camp, Mankinkinkani, 3 km west of the pit.
- 20 adults (catering/cleaning staff) at the Nabarlek accommodation camp, 2 km north of the pit.

From the annual wind rose for Nabarlek, presented in the same report, the wind blows to the west 21% of the time and to the north 5% of the time. The report also presents the variation in stability category with wind direction. For the wind directions of interest this is given below:

	Stability category						
	A	B	C	D	E	F	G
East wind (to the west) (% time)	7.0	29.4	24.7	15.3	10.5	6.0	7.1
South wind (to the north) (% time)	3.6	4.8	9.6	24.1	30.7	13.9	13.3

For the purposes of calculation let us assume a C-D stability category for the Mankinkinkani group and an F stability category for the accommodation camp group. This will overestimate the dose to each group, but simplifies the mathematics.

As mean concentrations rather than emission rates are available let us assume that these concentrations occur at 100 m downwind from a point source. Using airborne dispersion curves for prolonged releases (Bryant 1964) yields:

- for category C-D at 3 km distance an airborne dispersion dilution factor of 2×10^{-3},
- for category F at 2 km distance an airborne dispersion dilution factor of 7×10^{-3}.

Overall dilution factors (ODF) are given by multiplying the wind direction factor by the aerial dispersion factor.

[1] In the September 1986 measurement campaign, an OSS external gamma integrating dosimeter was placed on a QML staff member working on the surface of the tailings (on a drill rig). This dosimeter indicated an average external gamma dose rate of 19 μSv/h. Therefore, external gamma radiation was potentially the principal source of occupational exposure in the pit. However, such exposures were low in actual practice as the time spent on the surface of the tailings was minimal, the most significant exposures occurring during the actual placement of the geotextile and waste rock covers. No measurements for airborne tailings dust were performed by OSS. This source of exposure was not considered likely to be significant due to the conditions of the surface (alternately moist and caking).

For Mankinkinkani this is: $ODF = 0.21 \times 2 \times 10^{-3} = 4.2 \times 10^{-4}$

For the accommodation camp this is: $ODF = 0.05 \times 7 \times 10^{-3} = 3.5 \times 10^{-4}$

From this it can be seen that the overall dilution factor is almost the same for the two locations, with the accommodation camp being slightly less restrictive. For the purpose of simplified calculations let us assume that they are the same at 4×10^{-4}.

Using this dilution factor, the mean radon daughter concentration of 7.3 mWL at the pit is reduced to $7.3 \times 4 \times 10^{-4} = 0.003$ mWL at the critical group location. This is an overestimate as radon daughter plate-out on surfaces over which the air passes has been ignored and radioactive decay of the radon daughters has been ignored.

In comparison with the dose estimate for radon daughters, that for radon is negligible. However, as the air travels towards the critical group more radon daughters are formed from radon. In the case of stability category C-D the wind speed is 5 m/s or 18 km/h and the air takes 10 minutes to reach the Aboriginal camp. Taking the mean radon concentration, 163 Bq/m^3, this is diluted in direction and distance to: $163 \times 4 \times 10^{-4} = 6.5 \times 10^{-2}$ Bq/m^3.

For 10-minute air the radon equilibrium factor is about 0.15. Therefore, $0.15 \times 6.5 \times 10^{-2}/3.7 = 0.003$ mWL of additional radon daughters are formed. This would yield from the original radon and radon daughter sources a total radon daughter concentration of 0.003 + 0.003 = 0.006 mWL at Mankinkinkani.

Using a similar argument for the accommodation camp with a wind speed of 2 m/s (7 km/h) and a radon equilibrium factor of 0.3, yields an effective radon daughter concentration of 0.008 mWL.

From the 1987 Draft Assessment of Doses Guideline (Commonwealth of Australia 1987*b*) the dose conversion factor for members of the public is 10 mSv/WLM. If continuous exposure is assumed, the exposure time is equivalent to $(365 \times 24)/170 = 51.5$ working months.

Therefore, the annual dose to a member of the public due to radon daughters from the pit is given by:

$D(public) = 0.006 \times 10^{-3} \times 51.5 \times 10 = 0.003$ mSv or 3 μSv for Mankinkinkani; and

$D(public) = 0.008 \times 10^{-3} \times 51.5 \times 10 = 0.004$ mSv or 4 μSv for the accommodation camp.

For the combined population of 40 adults the annual collective dose equivalent would be 1.4×10^{-4} person sieverts.

These doses are trivial, well below natural background levels, and are less than the deminimis levels (below regulatory concern) of 10 μSv and 1 person sievert recommended by the International Atomic Energy Agency (1988).

5 CONCLUSIONS

Radon and radon daughter measurements performed by QML in and around Nabarlek pit during semi-dry tailings operations from 1985-1988, confirmed that safe working conditions were maintained and that the operations posed no hazard to members of the public.

Independent measurements by OSS indicated good agreement between instruments used and confirmed QML's data.

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Table 1. Radon concentrations at Nabarlek pit

Pit 0 = Pit East; Pit 1 = Pit pump 1; Pit 6 = Pit pump road; Pit 7 = Pit Thickner; Pit 9 = Pit North; OC = Open Cut = Pit

Date	Location	Mean (Bq/m^3)	Maximum (Bq/m^3)
October 1981	In pit	70	-
January 1982	Top of pit	176	-
7.8.83-11.8.83	OC North	315	1135
11.3.84-24.3.84	OC North	87	547
9.7.84-15.7.84	OC North	250	961
22.11.84-28.11.84	OC North	92	326
8.3.85-10.3.85	OC Pump platform	81	221
29.3.85-4.4.85	OC North	195	657
24.5.85-27.5.85	OC North	84	257
3.6.85-10.6.85	OC North	140	558
7.6.85-10.6.85	OC Pump platform	92	304
10.7.85-27.7.85	OC North	344	1101
7.8.85-13.8.85	Pit pump road	337	1185
22.8.85-30.8.85	Pit pump road	260	997
13.9.85-19.9.85	Pit pump 1	270	1282
13.10.85-28.10.85	Pit pump 2	280	994
22.11.85-27.11.85	Pit pump 1	141	1392
22.11.85-27.11.85	Pit North	303	578
25.12.85-31.12.85	Pit Thickner	268	831
1.1.86	Pit Thickner	294	419
13.6.86-30.6.86	Pit Thickner	170	1059
1.7.86-31.7.86	Pit East	149	1467
26.7.86-31.7.86	Pit pump 1	181	597
17.8.86-31.8.86	Pit North	172	1044
1.8.86-17.8.86	Pit East	198	913
1.8.86-31.8.86	Pit pump 1	336	2190
1.9.86-4.9.86	Pit North	175	752
5.9.86-30.9.86	Pit pump 1	293	1569
1.9.86-30.9.86	Pit pump 1	268	1300
22.9.86-29.9.86	Pit Thickner	136	772
1.10.86-9.10.86	Pit pump 1	269	1093
1.10.86-28.10.86	Pit pump 1	170	1020
29.10.86-31.10.86	Pit Thickner	63	312
1.11.86-30.11.86	Pit Thickner	88	2060
1.12.86-31.12.86	Pit Thickner	59	319
1.1.87-31.1.87	Pit Thickner	44	240

(change in reporting format)

Date	No. of samples	Location	Mean (Bq/m^3)	Maximum (Bq/m^3)
March 1987	85	Pit 7	3	59
April 1987	612	Pit 7	190	956

Table 1. (continued)

Date	No. of samples	Location	Mean (Bq/m³)	Maximum (Bq/m³)
May 1987	744	Pit 7	183	1180
June 1987	720	Pit 7	199	1000
July 1987	677	Pit 7	208	955
August 1987	744	Pit 9	213	1190
September 1987	411	Pit 0/1/9	233	1540
October 1987	744	Pit 0	109	667
November 1987	720	Pit 0	80	318
December 1987	420	Pit 0	86	622
January 1988	665	Pit 0	80	306
February 1988	249	Pit 0	104	375
March 1988	740	Pit 0	52	327
April 1988	681	Pit 0	123	836
May 1988	566	Pit 0	114	722
June 1988	720	Pit 0	182	866
July 1988	743	Pit 0	147	1140
August 1988	931	Pit 0/6	257	5843
September 1988	494	Pit 0/1	123	902
October 1988	1311	Pit 0/1	146	2600
November 1988	1217	Pit 0/1	154	1660

Table 2. Radon daughter concentrations at Nabarlek pit

L200 = Tailings Dam area; OC01 = Open Cut North; Pit 0 = Pit East; Pit 1 = Pit pump 1; Pit 2 = Pit pump 2; Pit 6 = Pit pump road; Pit 7 = Pit Thickner; Pit 9 = Pit North.

Date	No. of samples	Mean Location	Maximum (mWL)	(mWL)
May 1984	159	L200	2.2	20.8
September 1984	45	OCO1	3.8	49.0
February 1985	65	OCO1	3.5	8.5
May 1985	134	OCO1	4.4	30.9
June 1985	210	OCO1	6.4	30.2
July 1985	496	OCO1	11.0	93.5
September 1985	168	Pit 1	15.2	64.5
October 1985	168	Pit 2	12.5	34.4
February 1986	38	Pit 7	0.8	3.2
March 1986	130	Pit 7	1.7	16.1
May 1986	168	Pit 1	13.6	67.4
June 1986	335	Pit 7	7.5	48.9
July 1986	336	Pit 0	10.8	141.0
August 1986	1096	Pit 0.1/9	13.9	-
September 1986	752	Pit 1/7/9	10.2	98.6
October 1986	351	Pit 1/7	3.7	27.6
November 1986	657	Pit 7	3.6	30.0
December 1986	542	Pit 7	2.8	24.3
January 1987	298	Pit 7	1.9	14.7
February 1987	132	Pit 7	0.9	4.9
March 1987	372	Pit 7	3.2	16.1
April 1987	336	Pit 9	7.7	69.3
May 1987	543	Pit 9	6.4	72.4
June 1987	633	Pit 9	8.6	116.0
July 1987	209	Pit 9	6.4	66.1
August 1987	564	Pit 9	12.4	125.0
September 1987	780	Pit 0/1	11.3	139.0
October 1987	621	Pit 0	7.6	101.0
November 1987	447	Pit 0	2.9	22.4
December 1987	504	Pit 0	2.5	31.2
January 1988	336	Pit 0	2.6	17.9
February 1988	336	Pit 0	3.3	22.3
March 1988	153	Pit 0	2.8	107.0
April 1988	575	Pit 0	5.1	50.4
May 1988	650	Pit 0	6.5	108.0
June 1988	597	Pit 0	11.4	94.6
July 1988	1164	Pit 0/6	12.9	111.0
August 1988	773	Pit 0/9	17.6	445.0
September 1988	296	Pit 0	5.1	41.5
October 1988	1382	Pit 0/1	5.8	44.9
November 1988	738	Pit 0/1	3.5	31.5

Table 3. Measurement statistics for the instruments used

Monitor no.	No. of hourly samples	Mean	Min.	Max.	Median	Units
September 1986						
Radon monitors						
96	514	283	80	1300	174	Bq/m^3
1	478	302	69	1569	186	Bq/m^3
Radon daughter monitors						
121	336	13.5	0.8	98.6	3.6	mWL
313	168	11.3	0.7	62.6	3.5	mWL
63	120	9.4	1.0	55.0	3.0	mWL
26	114	11.4	0.0	68.0	3.0	mWL
Equilibrium factor		0.13	0.03	0.51	0.09	
September 1987						
Radon monitor						
96	92	236	87	695	136	Bq/m^3
Radon daughter monitors						
121	77	11.7	1.7	52.7	2.7	mWL
313	92	12.3	1.3	55.3	2.6	mWL
63	44	10.1	1.0	41.0	2.0	mWL
Equilibrium factor		0.14	0.04	0.38	0.08	
October 1988[a]						
Radon monitor						
3	504	198	30	756	120	Bq/m^3
Radon daughter monitor						
216	504	6.4	0.3	45	2.7	mWL
Equilibrium factor		0.11	0.01	0.3	0.1	

[a]New QML instruments used here: Unit No. 3, an Eberline Radon Gas Monitor RGM4 and Unit No. 216, an Eberline Working Level Monitor WLM1.

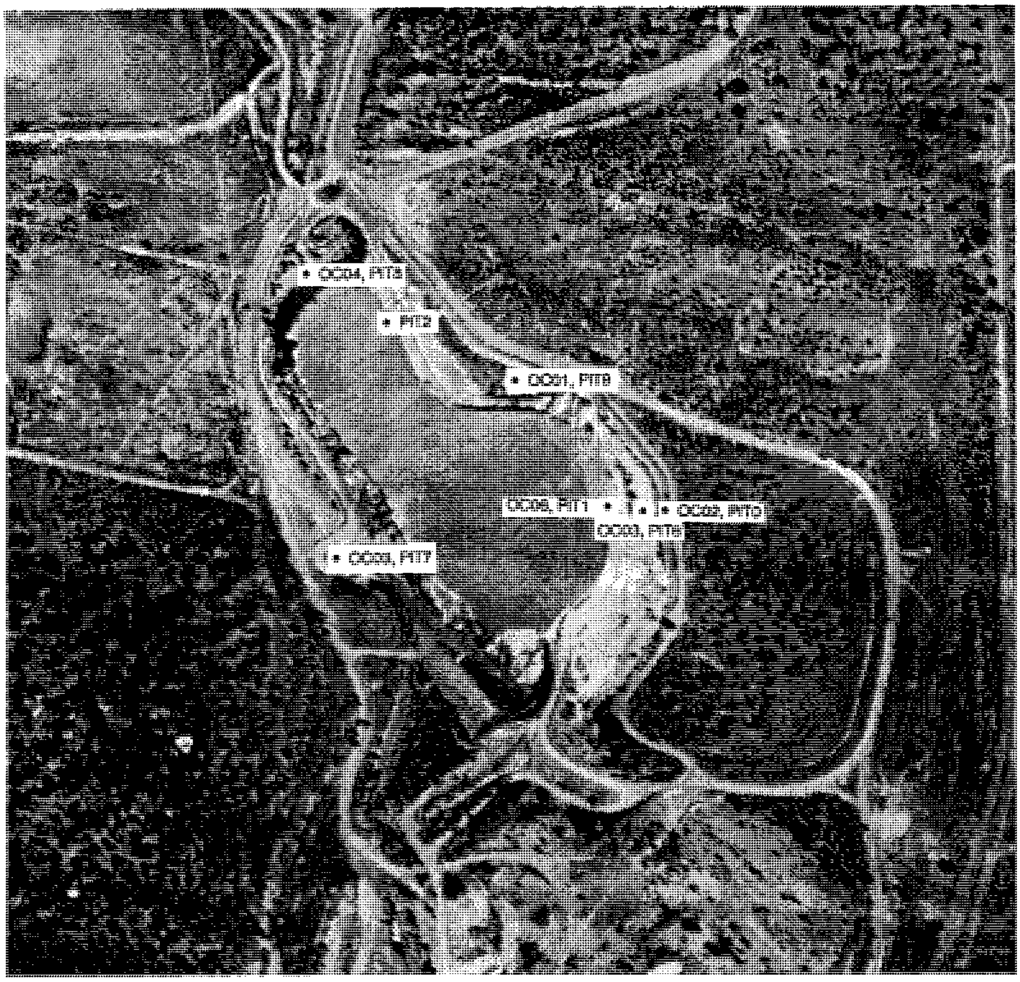


Figure 1. Location of the sampling sites

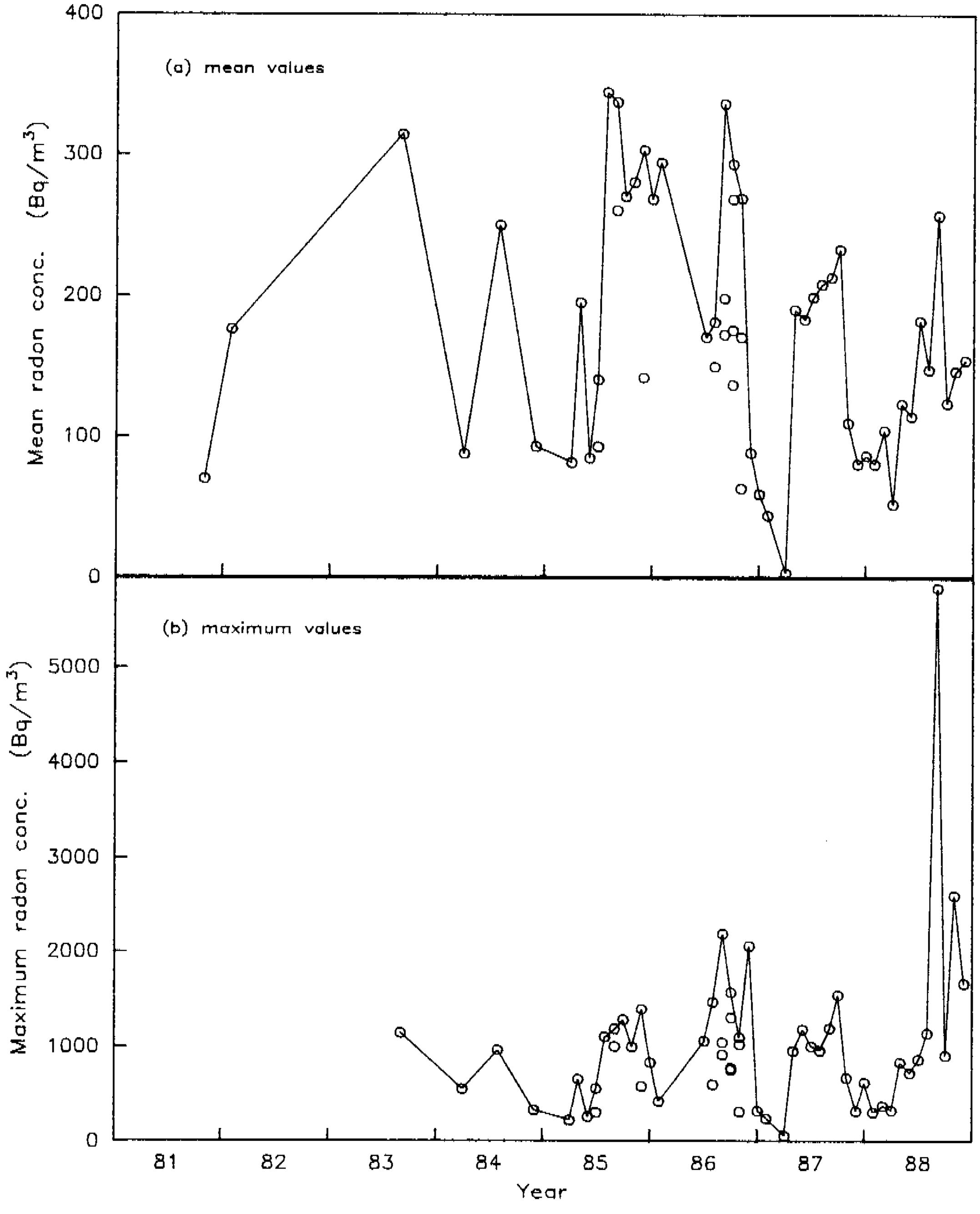


Figure 2. Monthly radon concentrations at Nabarlek pit

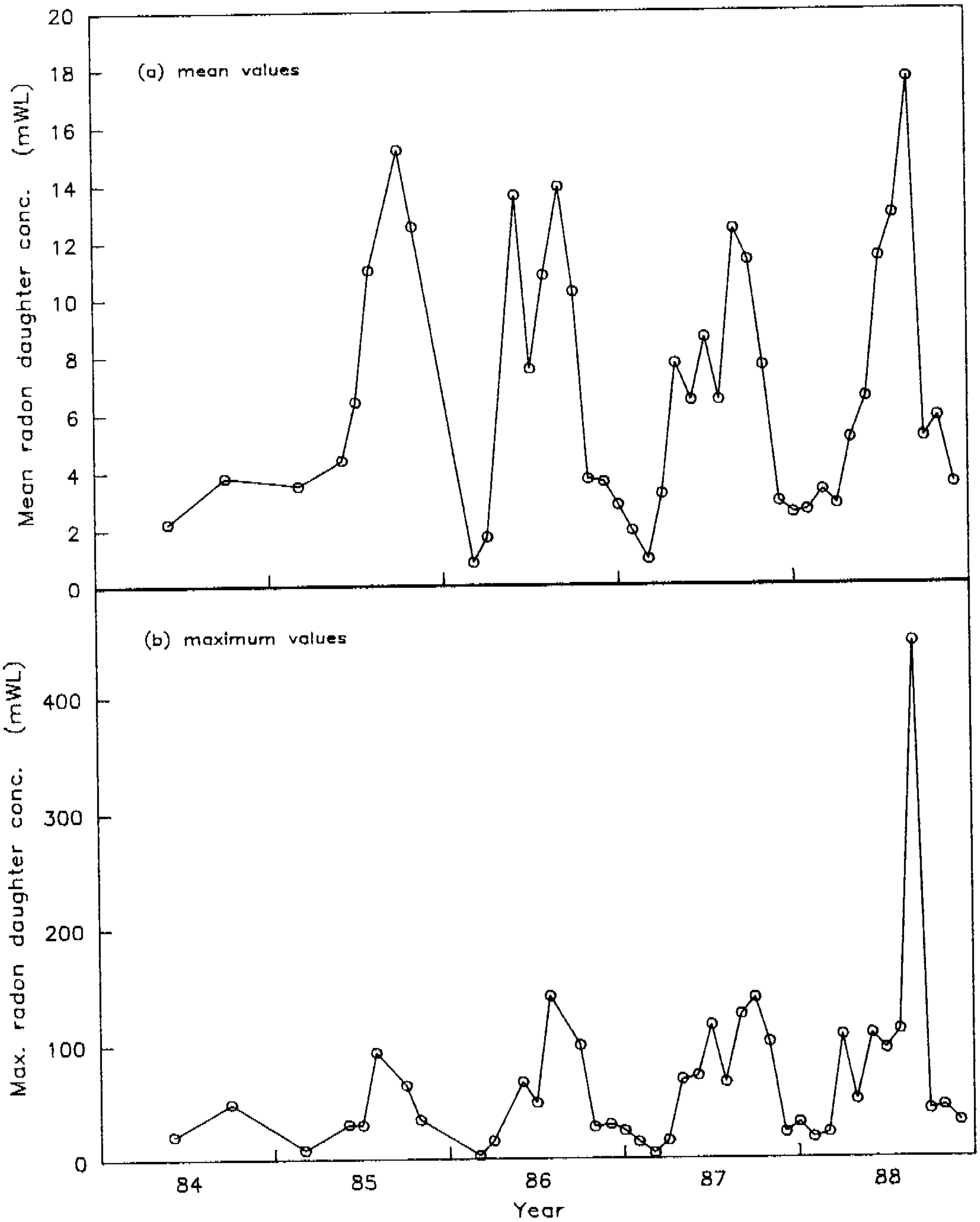


Figure 3. Monthly radon daughter concentrations at Nabarlek pit

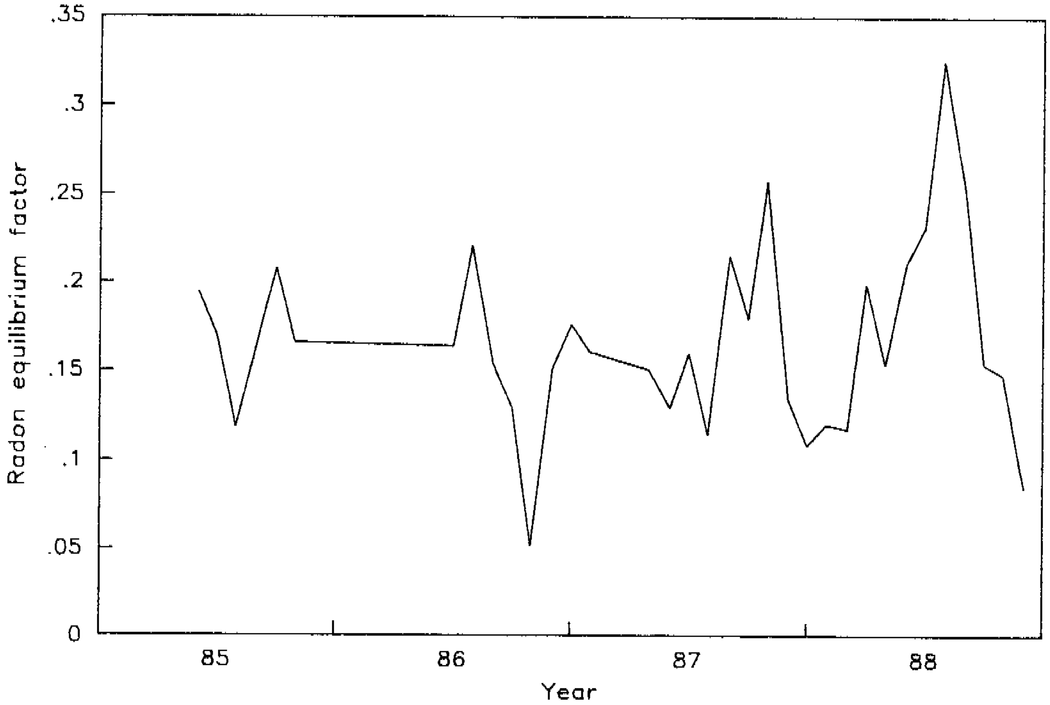


Figure 4. Monthly variation in the radon equilibrium factor at Nabarlek based on monthly mean data from automatic radon and radon daughter monitors

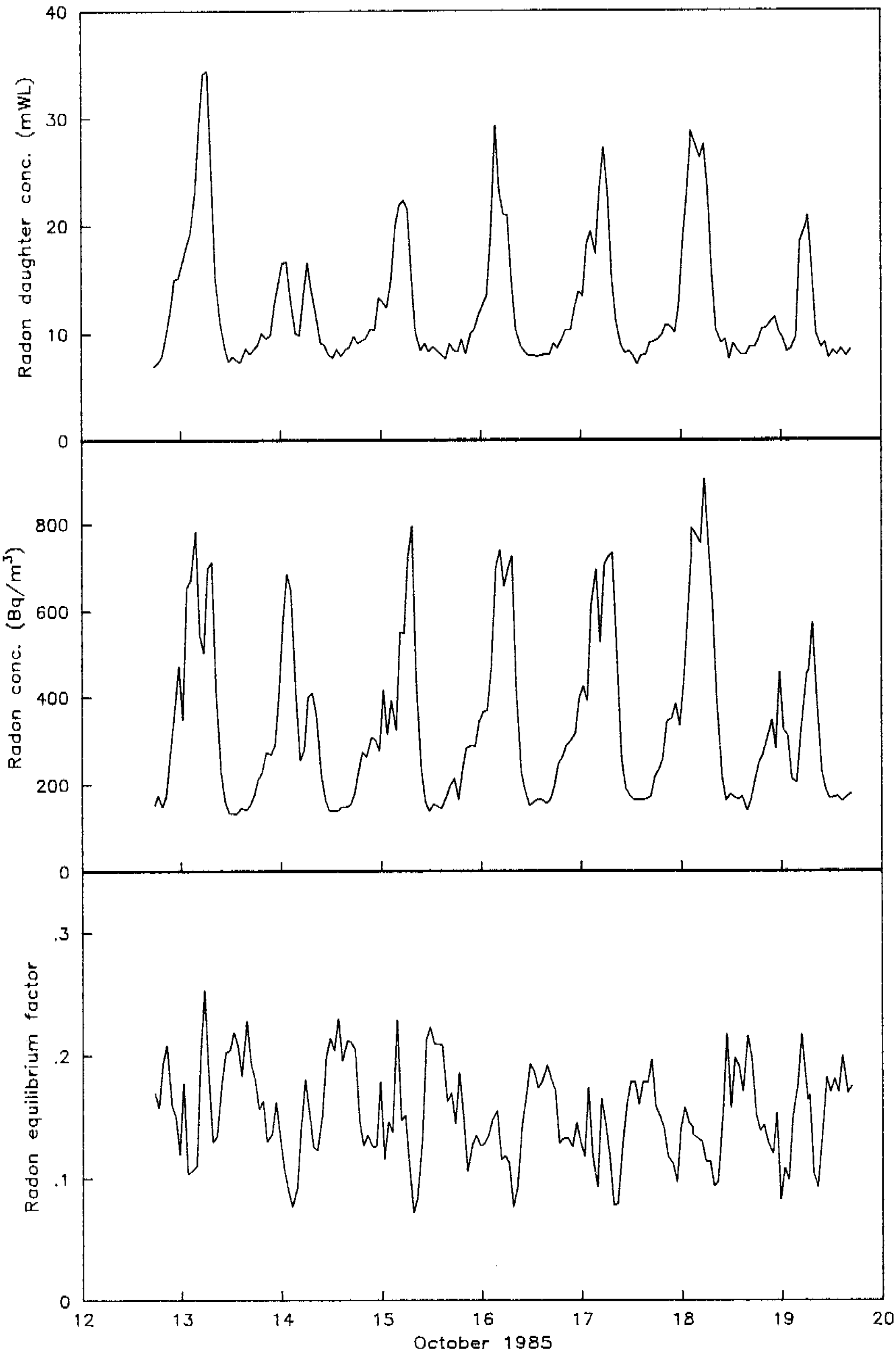


Figure 5. Hourly radon and radon daughter concentrations and corresponding equilibrium factors in Nabarlek pit - October 1985

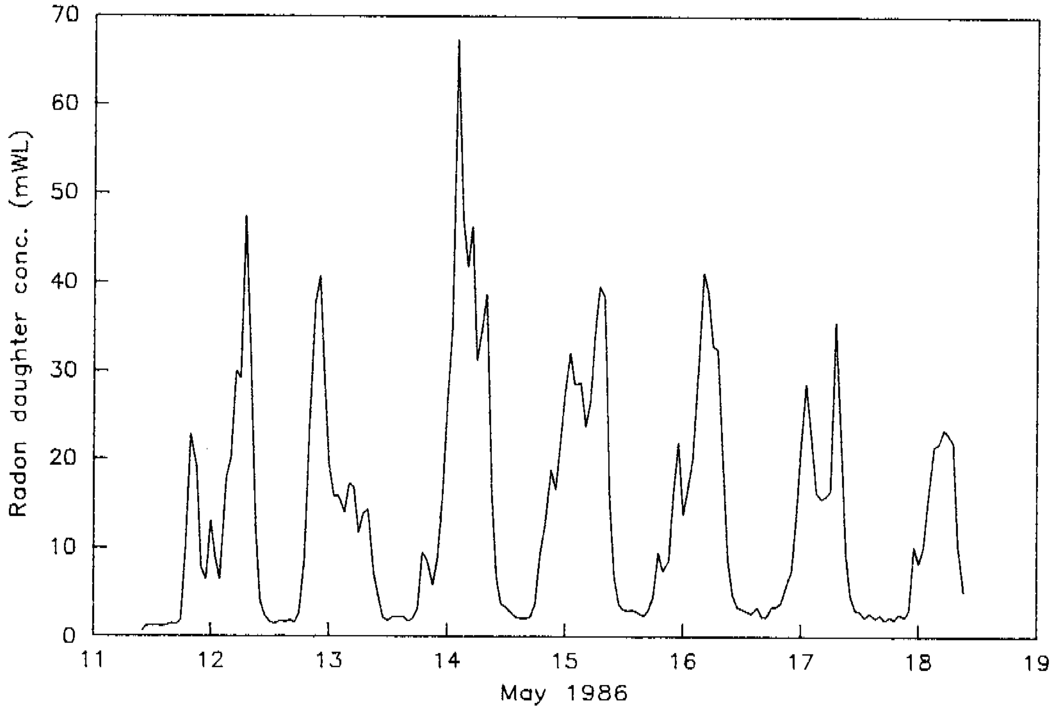


Figure 6. Hourly radon daughter concentrations in Nabarlek pit - May 1986

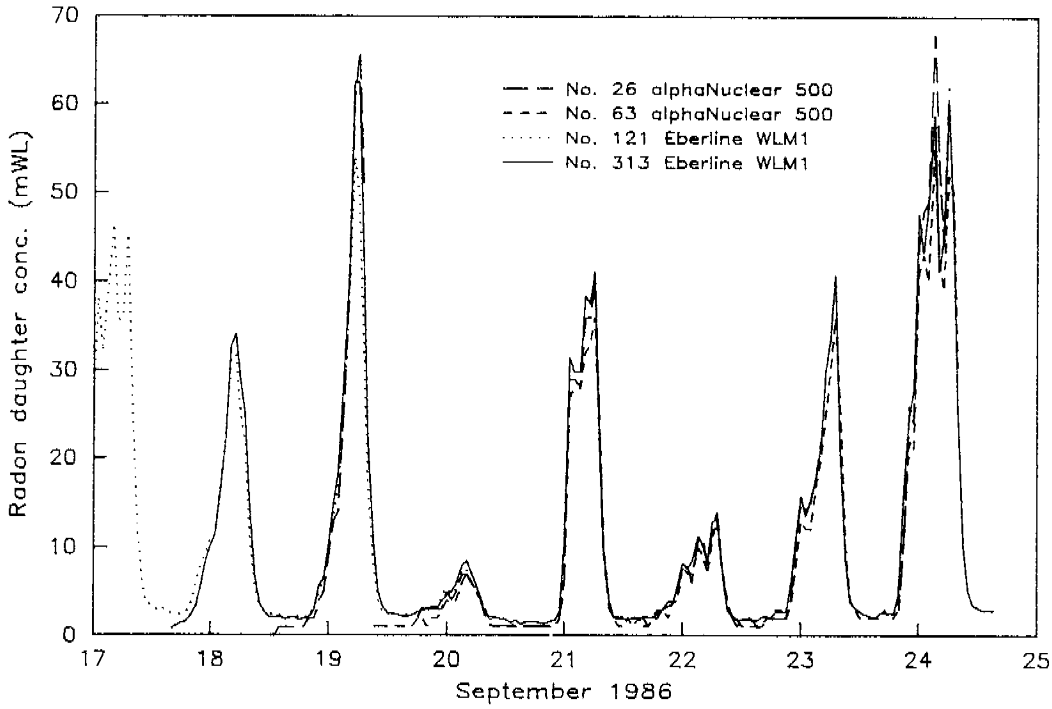


Figure 7. Hourly radon daughter concentrations in Nabarlek pit - intercomparison of automatic radon daughter monitors - September 1986

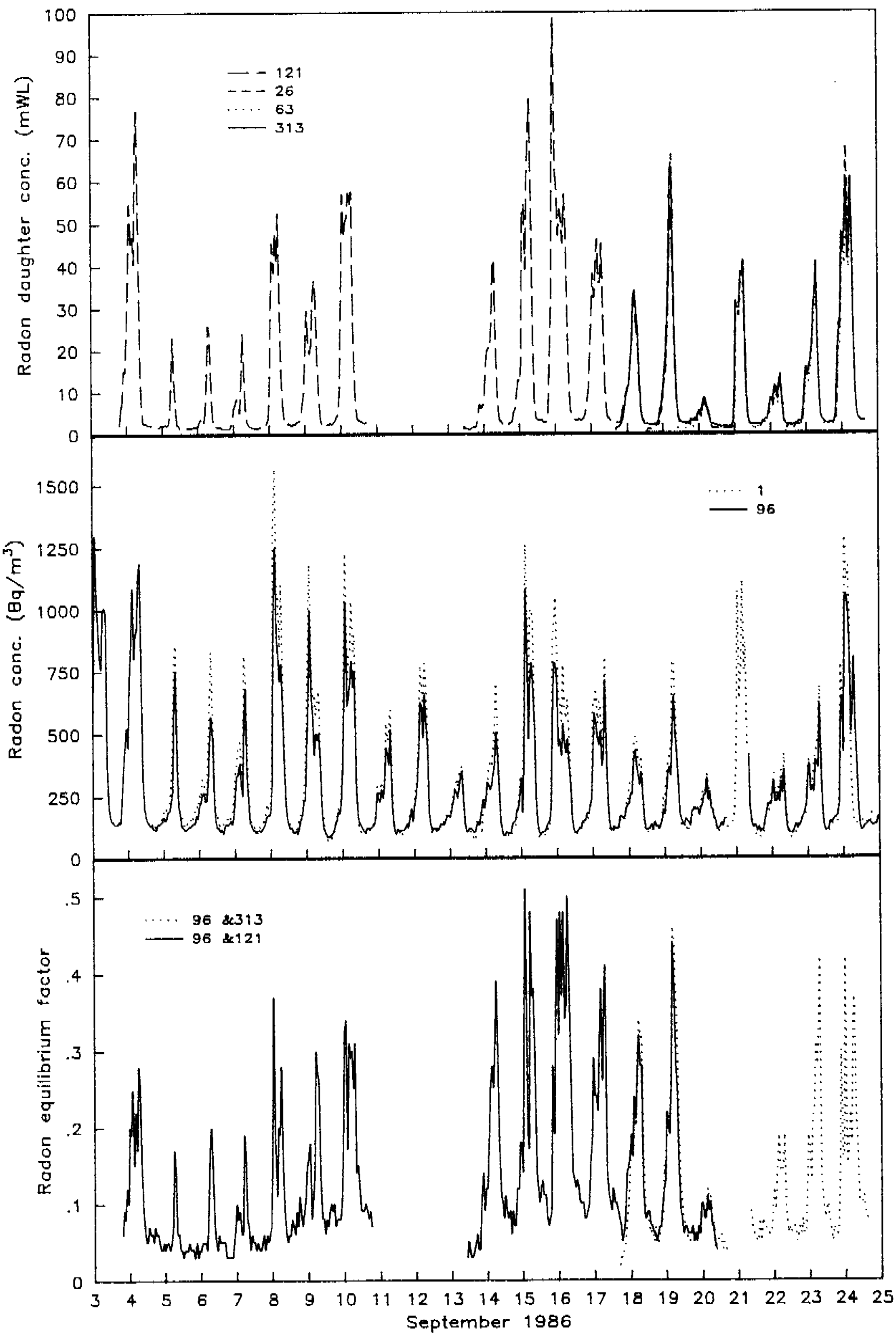


Figure 8. Hourly radon and radon daughter concentrations and corresponding equilibrium factors in Nabarlek pit - September 1986

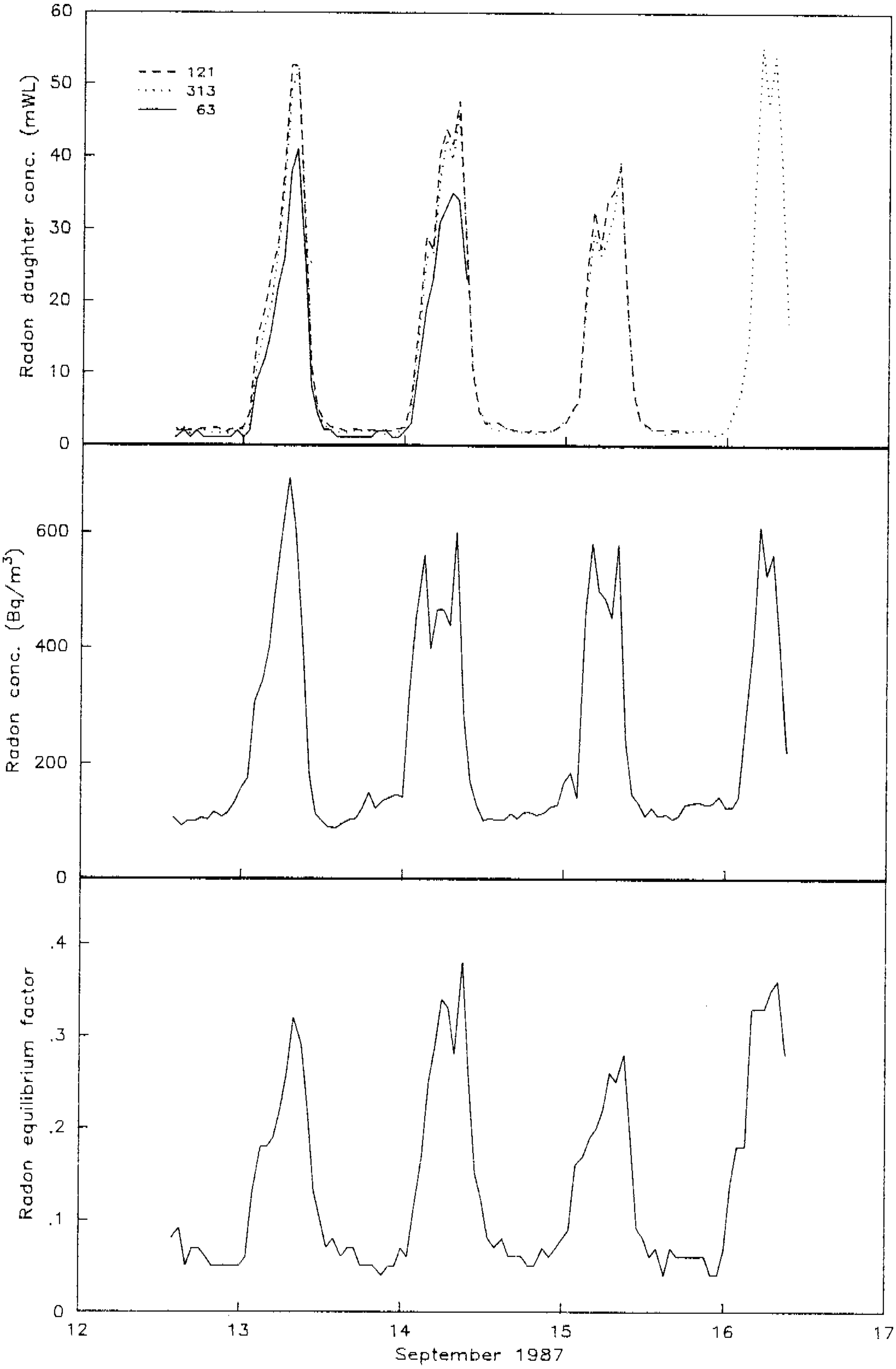


Figure 9. Hourly radon and radon daughter concentrations and corresponding equilibrium factors in Nabarlek pit - September 1987

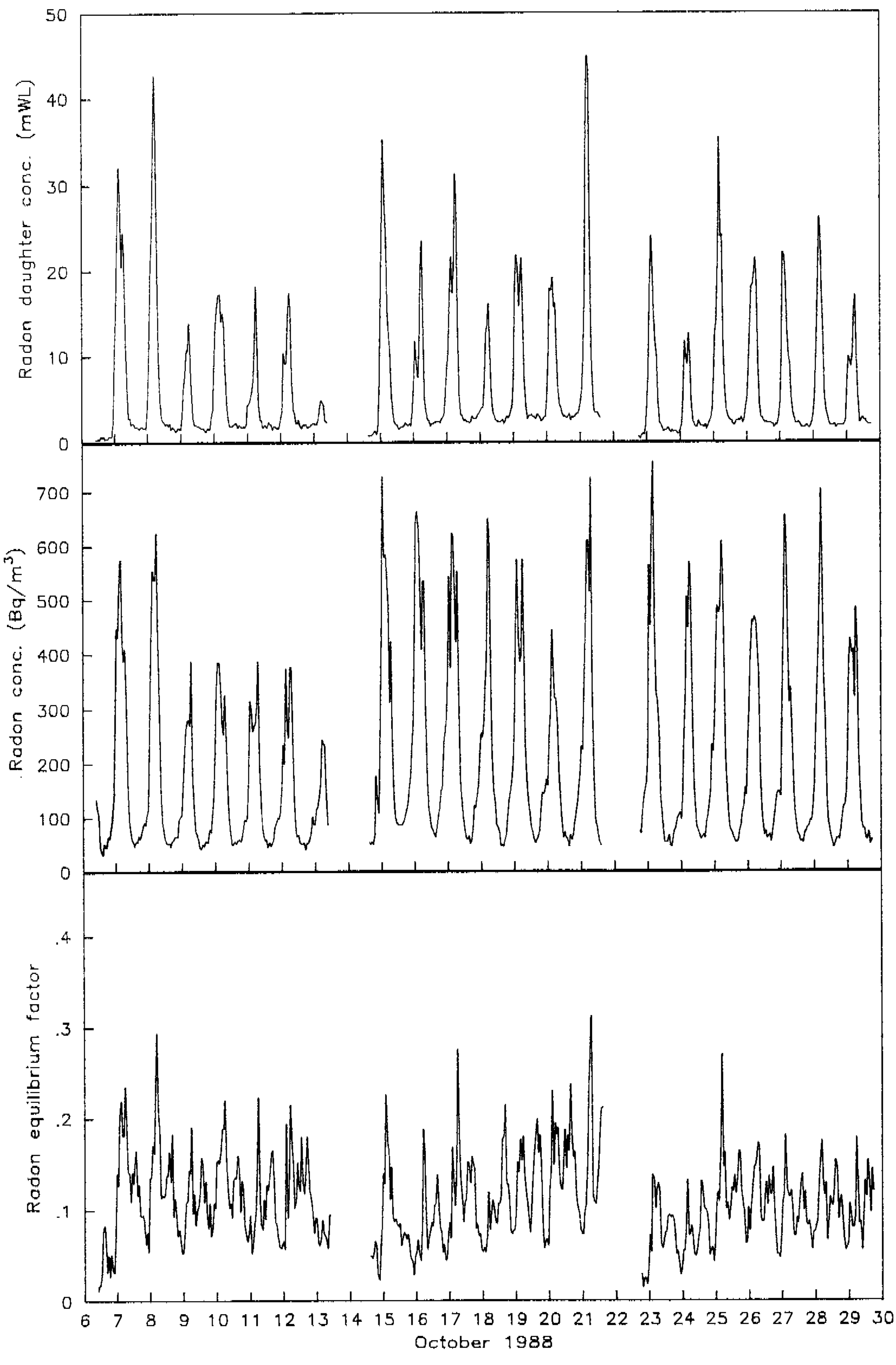


Figure 10. Hourly radon and radon daughter concentrations and corresponding equilibrium factors in Nabarlek pit - October 1988

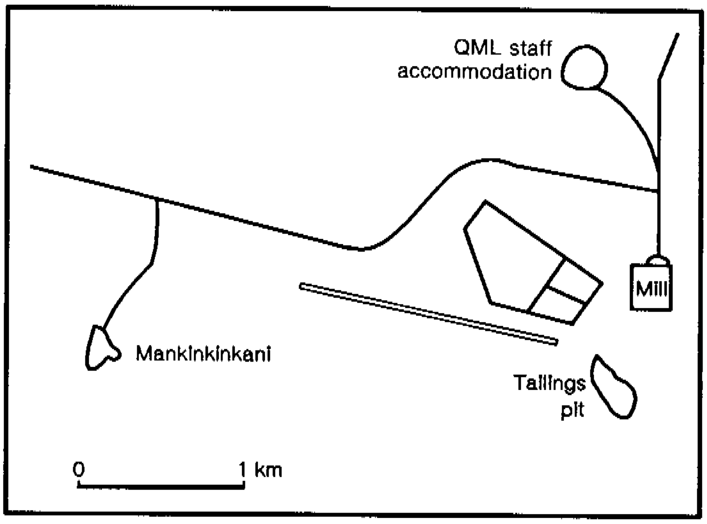
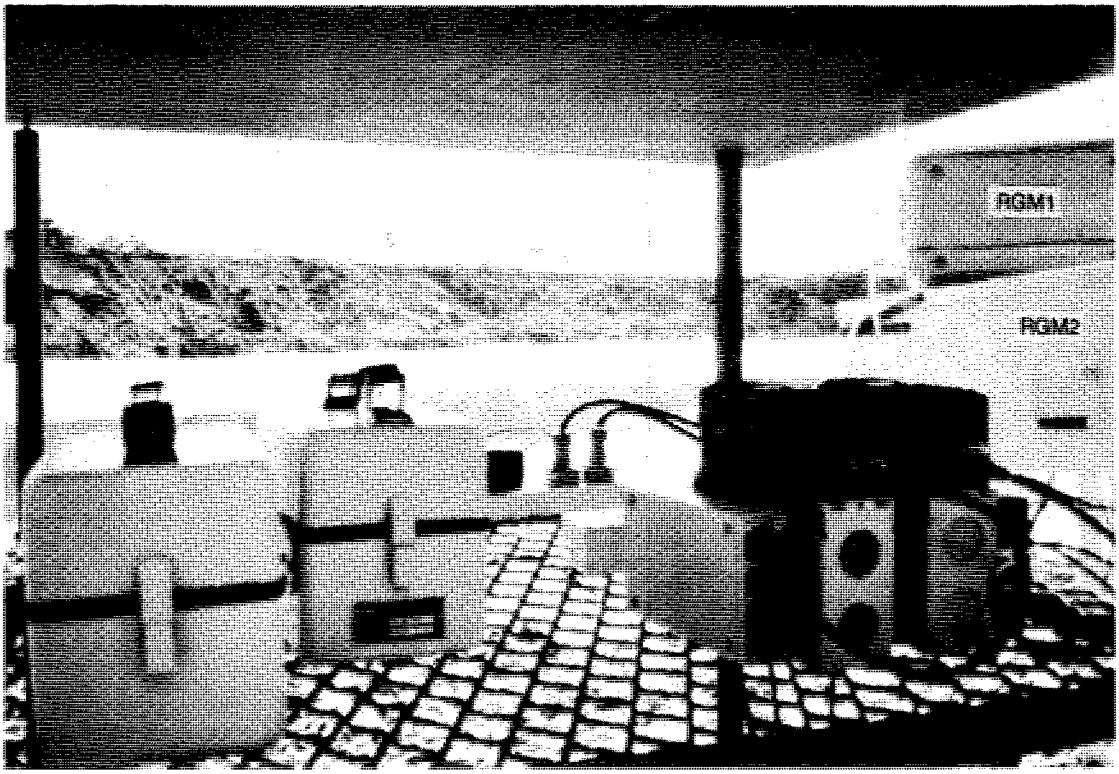


Figure 11. Location of potential radiological critical groups at Nabarlek



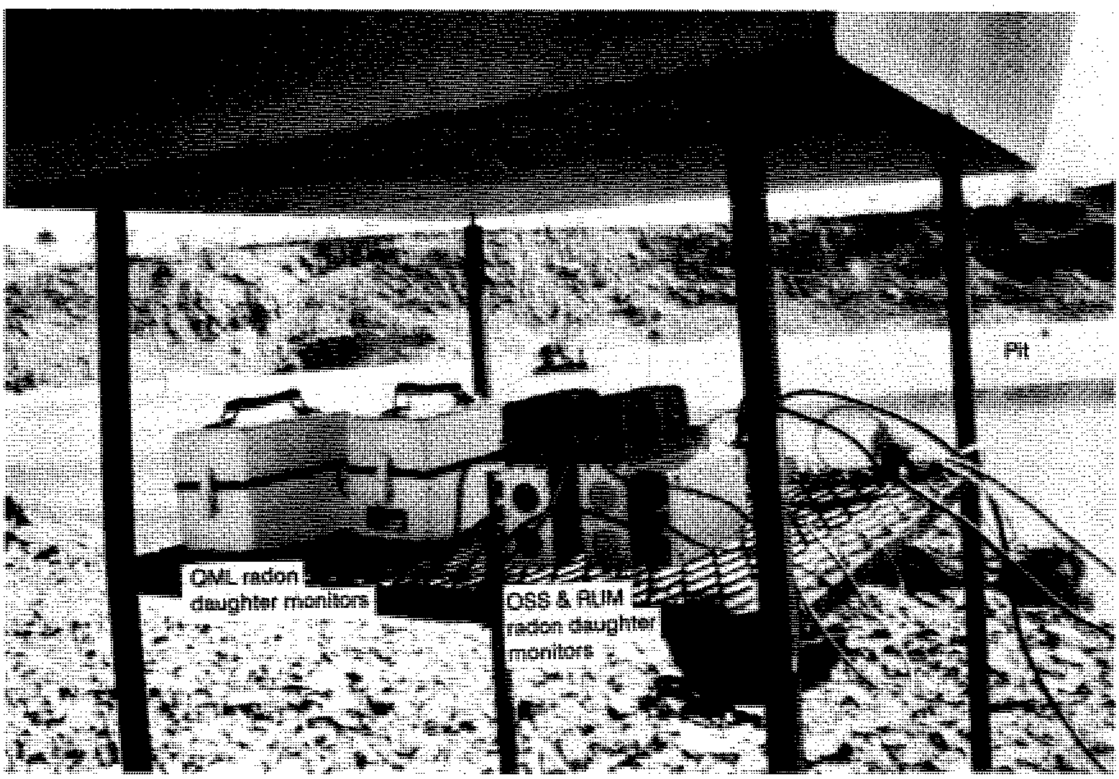


Plate 1. Equipment used in the radon/radon daughter monitor intercomparison, September 1986

Radon daughter monitors are on a specially constructed sampling frame which raises the monitors of the ground and provides shade from the sun. For Wet season use, the roof of this frame is inverted so that it is gabled, sheds water and protects the monitor from the rain.

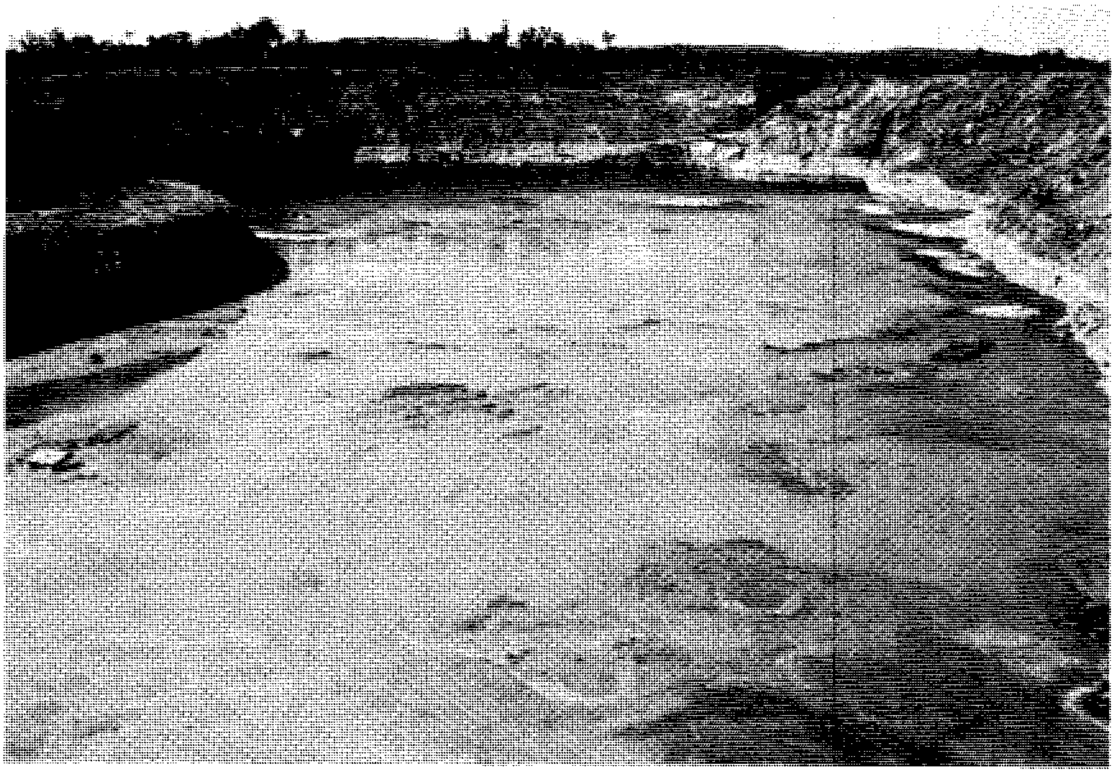


Plate 2. The beginning of semi-dry tailings deposition: Dry season 1985

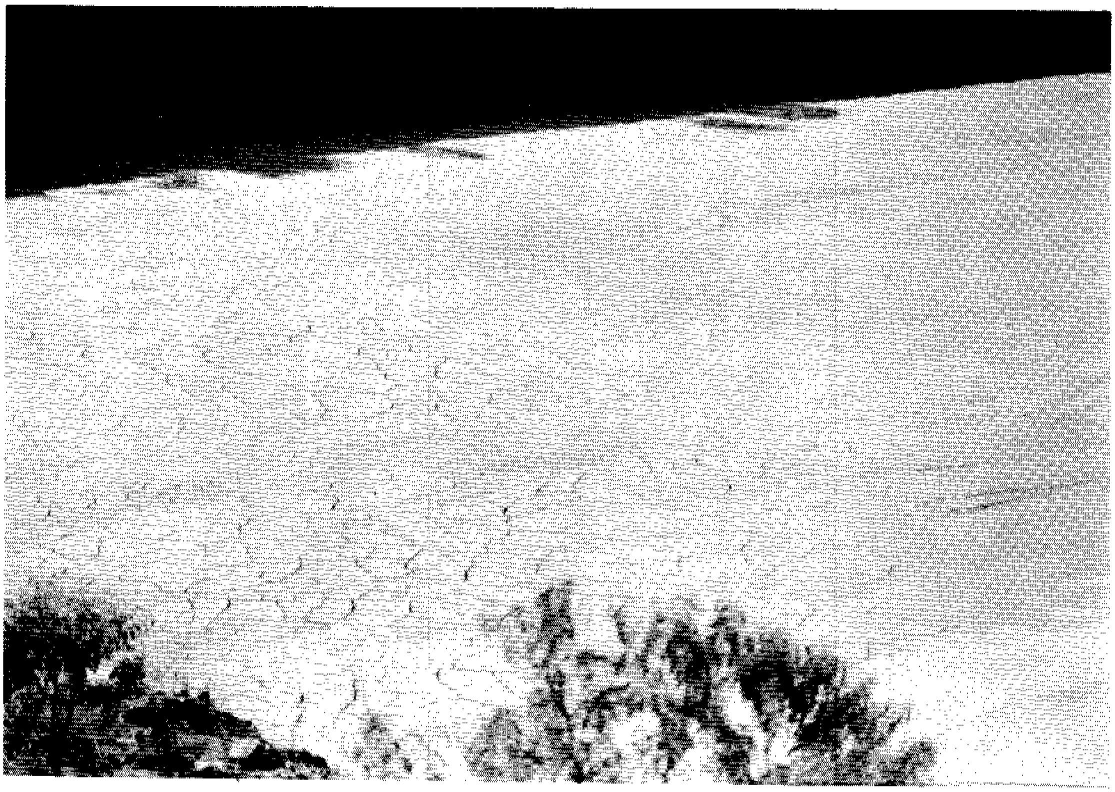


Plate 3. Shrinkage cracks in the tailings surface: Dry season 1987

Plate 4. Placement of geotextile and waste rock cover: Dry season 1988

APPENDIX 1

Example of QML radon measurement summary reporting format prior to March 1987

QUEENSLAND MINES LIMITED
NABARLEK URANIUM
CONTINUOUS RADON MONITOR SUMMARY

PERIOD FROM: 1/07/84 TO 31/07/84

MONITOR NO. 01

	NIGHT				DAY				
	BECQUEREL PER CUBIC METRE				BECQUEREL PER CUBIC METRE				
DATE	AVERAGE	STD.DEV.	PEAK	TIME	AVERAGE	STD.DEV.	PEAK	TIME	LOCATION
1/07/84					2	6	16	12:43	BOREFIELD D TB38
2/07/84	12	13	32	03:43	8	10	22	07:43	BOREFIELD D TB38
3/07/84	50	30	109	20:43	24	24	67	07:43	BOREFIELD D TB38
4/07/84					0	0	0	07:43	BOREFIELD D TB38
5/07/84	58	32	114	22:01	28	34	103	07:01	BOREFIELD D TB38
6/07/84	114	44	174	01:01	17	17	55	07:01	BOREFIELD D TB38
7/07/84	92	40	155	01:01	20	24	67	08:01	BOREFIELD D TB38
8/07/84	100	36	132	00:01	0	0	0	08:01	BOREFIELD D TB38
8/07/84					53	28	85	18:20	OPEN CUT NORTH
9/07/84	622	134	782	04:20	178	212	713	07:20	OPEN CUT NORTH
10/07/84	629	176	901	03:20	231	308	961	07:20	OPEN CUT NORTH
11/07/84	589	244	921	02:20	205	275	821	08:20	OPEN CUT NORTH
12/07/84	409	209	690	01:20	87	71	240	08:20	OPEN CUT NORTH
13/07/84	93	23	144	06:20	74	42	167	07:20	OPEN CUT NORTH
14/07/84	99	27	135	23:20	50	14	72	07:20	OPEN CUT NORTH
15/07/84	94	29	159	06:20	143	19	144	07:20	OPEN CUT NORTH
15/07/84					19	13	42	10:20	SECURITY GATE
16/07/84	19	12	36	06:20	10	12	30	07:20	SECURITY GATE
17/07/84	12	12	29	22:20	3	7	19	07:20	SECURITY GATE
18/07/84	5	10	24	04:20	9	11	30	07:20	SECURITY GATE
19/07/84	24	19	61	05:20	10	17	55	07:20	SECURITY GATE
20/07/84	28	14	51	05:20	12	17	49	07:20	SECURITY GATE
21/07/84	9	15	48	06:20	15	17	47	07:20	SECURITY GATE
22/07/84	24	14	37	23:22	52	9	52	07:22	SECURITY GATE
25/07/84					0	0	0	07:22	OFFICES - ADMIN
26/07/84					0	0	0	07:22	OFFICES - ADMIN
27/07/84	1	4	15	06:21	5	11	34	18:21	OFFICES - ADMIN
28/07/84	95	39	181	20:21	21	35	96	07:21	OFFICES - ADMIN
29/07/84	88	43	155	02:59	40	60	177	08:59	OFFICES - ADMIN
30/07/84	92	74	207	06:59	48	86	231	07:59	OFFICES - ADMIN
31/07/84	16	23	68	22:59	1	5	17	07:59	OFFICES - ADMIN

APPENDIX 2

Example of QML radon measurement summary reporting format post March 1987

CONTINUOUS RADON MONITOR SUMMARY

AUGUST 1988

AREA CODE	NUMBER OF SAMPLES	MEAN $Bq.m^{-3}$	MAX $Bq.m^{-3}$
L200	931	257	5843
L400	330	128	397
M104	633	41	422

EMPL CODE	NUMBER OF SAMPLES	MEAN $Bq.m^{-3}$	MAX $Bq.m^{-3}$
AF B	330	128	397
AFCO	963	71	422
CAOS	330	128	397
ENVS	1261	223	5843
EXPO	330	128	397
FETA	963	71	422
LAST	330	128	397
MIST	633	41	422
MPOP	633	41	422
PITT	931	257	5843
RDTN	1564	169	5843
STOR	330	128	397
WORM	963	71	422

LOWEST LEVEL OF DETECTION (LLD)

MONITOR	DATE FROM	DATE TO	LOCATION	LLD ($Bq.m^{-3}$)
EBERLINE RGM1#01	01/08/88	31/08/88	P009	31.6
EBERLINE RGM4#01	01/08/88	09/08/88	PIT6	17.7
EBERLINE RGM4#01	14/08/88	28/08/88	SG01	17.7
EBERLINE RGM2#96	01/08/88	31/08/88	PIT0	23.6

SUPERVISING SCIENTIST FOR THE ALLIGATOR RIVERS REGION

RESEARCH PUBLICATIONS

Alligator Rivers Region Research Institute Research Report 1983-84
Alligator Rivers Region Research Institute Annual Research Summary 1984-85
Alligator Rivers Region Research Institute Annual Research Summary 1985-86
Alligator Rivers Region Research Institute Annual Research Summary 1986-87
Alligator Rivers Region Research Institute Annual Research Summary 1987-88
Alligator Rivers Region Research Institute Annual Research Summary 1988-89 (in press)

Research Reports (RR) and Technical Memoranda (TM)

RR 1	The macroinvertebrates of Magela Creek, Northern Territory. April 1982 (pb, mf - 46 pp.)	R. Marchant
RR 2	Water quality characteristics of eight billabongs in the Magela Creek catchment. December 1982 (pb, mf - 60 pp.)	B.T. Hart & R.J. McGregor
RR 3	A limnological survey of the Alligator Rivers Region. I. Diatoms (Bacillariophyceae) of the Region. August 1983 (pb, mf - 160 pp.)	D.P. Thomas
	*A limnological survey of the Alligator Rivers Region. II. Freshwater algae, exclusive of diatoms. 1986 (pb, mf - 176 pp.)	H.U. Ling & P.A. Tyler
RR 4	*Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory. Volume I. Outline of the study, summary, conclusions and recommendations. 1986 (pb, mf - 63 pp.)	K.A. Bishop, S.A. Allen, D.A. Pollard & M.G. Cook
	Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory. Volume II. (in press)	K.A. Bishop, S.A. Allen, D.A. Pollard & M.G. Cook
	Ecological studies on the freshwater fishes of the Alligator Rivers Region, Northern Territory. Volume III. (in press)	K.A. Bishop, S.A. Allen, D.A. Pollard & M.G. Cook
RR 5	Macrophyte vegetation of the Magela Creek flood plain, Alligator Rivers Region, Northern Territory. March 1989 (pb - 41 pp.)	C.M. Finlayson, B.J. Bailey & I.D. Cowie
TM 1	Transport of trace metals in the Magela Creek system, Northern Territory. I. Concentrations and loads of iron, manganese, cadmium, copper, lead and zinc during flood periods in the 1978-1979 Wet season. December 1981 (pb, mf - 27 pp.)	B.T. Hart, S.H.R. Davies & P.A. Thomas
TM 2	Transport of trace metals in the Magela Creek system, Northern Territory. II. Trace metals in the Magela Creek billabongs at the end of the 1978 Dry season. December 1981 (pb, mf - 23 pp.)	S.H.R. Davies & B.T. Hart
TM 3	Transport of trace metals in the Magela Creek system, Northern Territory. III. Billabong sediments. December 1981 (pb, mf - 24 pp.)	P.A. Thomas, S.H.R. Davies & B.T. Hart
TM 4	The foraging behaviour of herons and egrets on the Magela Creek flood plain, Northern Territory. March 1982 (pb, mf - 20 pp.)	H.R. Recher & R.T. Holmes
TM 5	Flocculation of retention pond water. May 1982 (pb, mf - 8 pp.)	B.T. Hart & R.J. McGregor
TM 6	Dietary pathways through lizards of the Alligator Rivers Region Northern Territory. July 1984 (pb, mf - 15 pp.)	C.D. James, S.R. Morton, R.W. Braithwaite & J.C. Wombey
TM 7	Capacity of waters in the Magela Creek system, Northern Territory, to complex copper and cadmium. August 1984 (pb, mf - 42 pp.)	B.T. Hart & S.H.R. Davies

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pb = available as paperback; mf = available as microfiche

TM 8	Acute toxicity of copper and zinc to three fish species from the Alligator Rivers Region. August 1984 (pb, mf - 31 pp.)	L. Baker & D. Walden
TM 9	Textural characteristics and heavy metal concentrations in billabong sediments from the Magela Creek system, northern Australia. October 1984 (pb, mf - 39 pp.)	P.A. Thomas & B.T. Hart
TM 10	Oxidation of manganese(II) in Island Billabong water. October 1984 (pb, mf - 11 pp.)	B.T. Hart & M.J. Jones
TM 11	*In situ* experiments to determine the uptake of copper by the aquatic macrophyte *Najas tenuifolia* R.Br. December 1984 (pb, mf - 13 pp.)	B.T. Hart, M.J. Jones & P. Breen
TM 12	Use of plastic enclosures in determining the effects of heavy metals added to Gulungul Billabong. January 1985 (pb, mf - 25 pp.)	B.T. Hart, M.J. Jones & P. Bek
TM 13	Fate, of heavy metals in the Magela Creek system, northern Australia. I. Experiments with plastic enclosures placed in Island Billabong during the 1980 Dry Season: heavy metals. May 1985 (pb, mf - 46 pp.)	B.T. Hart, M.J. Jones & P. Bek
TM 14	Fate of heavy metals in the Magela Creek system, northern Australia. II. Experiments with plastic enclosures placed in Island Billabong during the 1980 Dry season: limnology and phytoplankton. May 1985 (pb, mf - 32 pp.)	B.T. Hart, M.J. Jones, P. Bek & J. Kessell
TM 15	Use of fluorometric dye tracing to simulate dispersion of discharge from a mine site. A study of the Magela Creek system, March 1978. January 1986 (pb, mf - 51 pp.)	D.I. Smith, P.C. Young & R.J. Goldberg
TM 16	Diets and abundances of aquatic and semi-aquatic reptiles in the Alligator Rivers Region. July 1986 (pb, mf - 57 pp.)	R. Shine
TM 17	Plants of the Alligator Rivers Region, Northern Territory. August 1986 (pb, mf - 54 pp.)	I.E. Cowie & C.M. Finlayson
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TM 19	Frogs of the Magela Creek system. January 1987 (pb, mf - 46 pp.)	M.J. Tyler & G.A. Crook
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TM 23	Alien plants in the Alligator Rivers Region, Northern Territory, Australia. September 1988 (pb - 34 pp.)	I.D. Cowie, C.M. Finlayson & B.J. Bailey
TM 24	The determination of zinc in Magela Creek water April 1989 (pb - 26 pp.)	C.A.A. LeGras & B.N. Noller
TM 25	Element concentrations in the freshwater mussel, *Velesunio angasi*, in the Alligator Rivers Region June 1989 (pb - 262 pp.)	H.E. Allison & R.D. Simpson
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TM27	Annual rainfall statistics for stations in the Top End of Australia: normal and log-normal distribution analysis (In press)	I.M. Vardavas
TM28	A study of the reproducibility of water conditions between small enclosures and a tropical waterbody November 1989	B.N. Noller, T.P. McBride, C.W. Hunt & B.T. Hart

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