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ABSTRACT

A survey of radon concentrations in groundwater, soil-air and the atmosphere was made at the Koongarra uranium deposit, Northern Territory. Radon daughter concentrations in the atmosphere were measured for a range of atmospheric stability categories and are expressed in working level units.

Surface radon emanation rates were measured over undisturbed sections of the ore body to provide an estimate of the daily rate of radon release from the ore body; this estimate was then compared with the value expected from an above-ground tailings dam constructed as a result of mining of the ore body.

Surface radon emanation rates were also measured for small mock heaps designed to be representative of waste rock and ore stockpile material.

Taken collectively, the data can be used to provide estimates of radon source terms and radon concentrations in and from a mining and milling operation based on the deposit.

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URANIUM ORES; GEOLOGIC DEPOSITS; NORTHERN TERRITORY; KOONGARRA DEPOSIT; DAUGHTER PRODUCTS; NATURAL RADIOACTIVITY; EARTH ATMOSPHERE; RADON; SOILS; GROUND WATER; QUANTITY RATIO; MINING; URANIUM; MILLING

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continued

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1. INTRODUCTION

During the period 19-30th June 1978, the Australian Atomic Energy Commission (AAEC), under a contract with Noranda Australia Limited, measured the prevailing levels of radon originating from the uranium deposit at Koongarra, NT. The program included measurements of the related concentration of radon in groundwater and soil-air, which in turn influence the measured rate at which radon emanates from ground surface and the way in which subsequent atmospheric dispersion controls the measured radon and radon daughter concentrations in air. As part of a different contractual agreement, the consultants Dames & Moore carried out meteorological studies at Koongarra during the period of AAEC involvement; references in this report to inversion climatology are from that source.

Officers of the Australian Radiation Laboratory (ARL) worked with the AAEC officers but not under the terms of the contractual agreement with Noranda. From ARL's point of view, the exercise allowed it to assess the performance of equipment and methods under field conditions and provided first hand experience in the range of values likely to be encountered. In the main, results obtained by ARL are not reported here, the only exceptions being referenced to V. Leach as a private communication.

2. EXPERIMENTAL METHODS AND SITES FOR MEASUREMENTS

2.1 Radon Dissolved in Water

Waters for which dissolved radon was determined and the methods employed were as follows.

Quiescent groundwater method

The groundwater could be supersaturated in CO_2 and N_2; if samples for radon determinations are not sealed at the point of collection, any escaping CO_2/N_2 would carry off some radon.

The groundwater sampler shown in Figure 1 is operated in the following manner. The stainless steel bomb is evacuated before sample collection. Two solenoids, operated electrically from ground surface, give positive operation even at high external pressures. After the solenoids are opened, water flows from the nozzle through stainless steel capillary tubes into the sample bomb. The amount of water collected (~ 600 mℓ) is determined after the completion of measurements.

Four samples were collected in this way: these were from hole

PH 11 (10200 N 10320 E) near the centre of the ore body and the new series of holes outside the proposed pit boundary at 10100 N 9840 E, 11270 N 10030 E and 11200 N 10680 E.

Hole PH 11 is cased to an unknown depth but indications are that the casing ceased above the prevailing height of the groundwater. The new series of bores are fully cased and slotted to a depth equivalent to that of the primary ore lode. Only the new series of bores, installed since the previous wet season, could provide groundwater known to be in equilibrium with the surrounding medium. Water from PH 11 would have been diluted to an unknown degree by rainwater.

Radon from the collected samples was transferred quantitatively to an evacuated zinc sulphide scintillation cup (see Figure 2) having a design similar to that of a 'Lucas' cup; transfer was effected by means of a 'Watson-Marlow' flow inducer with air as the carrier.

Pumped groundwater method

A commercial radon counter (INAX 531) was used to analyse pumped groundwater samples. An eight hundred millilitre sample was collected in a necked 1 ℓ bottle which was sealed immediately after inserting a sintered steel bubbling device. Air was recirculated from a zinc sulphide scintillation cup, through the bubbler and back to the cup. Although this instrument is designed mainly as an exploration tool, it can be calibrated to give reliable results when used in a reproducible manner. The unit was calibrated against a solution containing a known amount of ^{226}Ra and had a sensitivity of 21.6 count Bq^{-1} ℓ^{-1} of dissolved radon for the ten-minute counting interval employed. The greatest uncertainty in the method is the possible loss of some radon at the point of collection which, in this case, was the discharge line of the pump.

This method was used at two sites:

- one of the new series of bores (9670 N 10725 E) which was undergoing a seven-day pump-down test*, and
- the bore supplying potable water to the Noranda campsite.

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*Pump-down tests are used for estimated yields of aquifers. The chosen pump speed lowers the water table and the origin of the discharged water varies with time. The water with the highest dissolved radon would have originated in part from the ore body.

Spring water method

Most springs and seeps originating at Mt Brockman are radioactive. Two sites were studied - Leichhardt Springs (~ 12 km NNE of Koongarra) and X-anomaly (~ 7 km NE of Koongarra). As Leichhardt Springs gush from the escarpment, no significant loss of radon should have occurred prior to collection. At X-anomaly there is a series of seeps and hence sampling is more difficult. The INAX counter was used at these sites.

2.2 Radon in Soil-Air

A hollow metal pipe (o.d. ~ 1.5 cm) was driven into the soil to the required depth; this was replaced by PVC conduit of the same diameter and having a series of vent holes at the bottom. The INAX soil-air suction probe was then inserted and the combination 'sealed' with the INAX rubber housing (Figure 3). Air was then re-circulated in the sequence: suction probe → scintillation cup → rubber housing. The unit was calibrated in the field against zinc sulphide scintillation cups of known efficiency using the monitor drum (Section 2.3) as a source of radon. The sensitivity was 13.1 counts per Bq ℓ^{-1} for the ten-minute counting interval employed.

Results are reported in terms of the measured radon concentration. These values represent soil-air radon concentrations only to the degree that radon diffusion has led to an equilibrium concentration in the conduit-rubber housing volume (with dilution caused by the volume of the scintillation cup at the time of measurement). This was not the case for the spot measurements reported for sites 9950 N 10400 E, 10200 N 10420 E, 10200 N 10320 E and 10600 N 10630 E, since only 20 minutes was allowed to elapse between insertion and measurement. However, this was the case for the results on diurnal variation reported for site 10600 N 10630 E, for which the elapsed time was > six hours and the first measurement would break down any stratification within the probe. It was not possible to employ this method at sites with other than consolidated alluvium soil profiles because of the rocky nature of laterites.

2.3 Radon Emanation

Two general methods were used to measure radon emanation rates at the soil-atmosphere boundary and three classes of sites were investigated:

- the ore bodies and their vicinities,
- A mock waste heap, and

- a mock ore stockpile.

Both methods involved placing bottomless drums (volumes 60 ℓ and 200 ℓ respectively) on undisturbed ground (the ripe 'spear' grass could be brushed away) and sealing the rim with pressed soil obtained by surface scrapings remote from the drum. The smaller drums were used on the relatively small mock heaps.

In each case, the method used relied on measuring the rate of build-up of radon concentration in the drum. Provided that the radon concentration at the end of the build-up period was very much less than that for soil-air at the surface, then neither the concentration gradient nor the emanation rate was perturbed and the radon concentration varied linearly with time. The emanation rate was then estimated from a least squares fit of the data points. The methods varied according to the way the radon concentration was determined. In the first method, which has been fully investigated by Bernhardt *et al.* [1973], a 12 V fan was mounted in the drum to mix the gases. At half-hourly intervals over a three-hour period, using a series of valves and a vacuum line (Figure 4), a sample of air was transferred to the evacuated zinc sulphide scintillation cup (Figure 2). After about 2.5 hours' delay from the time of sampling, the radon in the cup had built up to equilibrium with its daughter products to yield three alpha decays per radon decay. The alpha activity was measured by placing the cup, without optical coupling, on an EMI type 6097B photomultiplier in a light-tight housing and feeding the pulses to an electronic scaler. Reproducibility of the counting arrangement was routinely checked with a standard ^{241}Am source and the system was operated under crude temperature-controlled conditions. Emanation rates at three sites could be determined daily by this method.

The second method involved the use of a two-filter system developed by Thomas & LeClare [1969]. Air passing through the first filter paper is relieved of its radon daughters. In the finite time taken to reach the second filter, some of the radon decays and the resultant daughters are trapped on the second filter paper. The measurement of this alpha activity is directly related to the radon concentration.

To determine radon emanation, air was recirculated from the drum, through the filter paper assembly and back to the drum, thus there was need for a circulation fan. A sampling rate of 11.5 ℓ min^{-1} was used; the sampling time was ten minutes and the counting time five minutes. There was a delay of one minute between the end of sampling and the start of counting. The activity was measured on a field scaler fitted with a zinc sulphide photomultiplier scintillation head designed at the UK Atomic Energy Authority Research Establishment, Harwell. Reproducibility was checked with a standard ^{241}Am source and random changes were within ± 3 per cent. The experimental procedure was calibrated daily against a zinc sulphide scintillation cup of known efficiency, using the monitor drum as the source of radon after it was measured with the two-filter system.

Generally the radon concentration was determined four times during a build-up period of ~ 3.5 hours; six emanation determinations were made per day.

Earlier work by Davy & O'Brien [AAEC report in preparation] on the Ranger I Ore Body I uranium deposit indicated that both methods give excellent values for the coefficient of determination (r^2) resulting from the least squares fit. Of the early values measured at Koongarra, $\bar{r}^2 > 0.97$. As a consequence, linearity in the rate of increase of radon concentration in the drum could be assumed.

Subsequently, many of the measurements using the second method involved the measurement of radon concentration change over a time interval of 60 to 150 minutes which allowed more sites to be measured per day. Other workers [*e.g.* Culot *et al.* 1973] have measured emanation rates with a single radon concentration determination. In all three methods, the combinations of chosen collection times and counting times were such as to lead to a standard deviation in the counting statistics of < 5 per cent or ± 0.05 Bq m^{-2} s^{-1}, whichever was the higher.

During the survey, a 200 ℓ drum was left in a fixed position. In this condition, the radon concentration in the drum would, if there were no changes in the emanation rate, reach an equilibrium level at which the rate of decay of radon balanced the emanation rate. Thus monitoring the radon concentration in the drum would provide an index of changes in the emanation rate. This technique was used to monitor for any slow but substantial change in emanation rate resulting from the seven-day pump-down test on groundwater. Note that because of the large surface soil-air temperature differentials accruing shortly after both sunrise and sunset, the response time of this monitor drum is much faster than the half-life of radon.

2.4 Radon Concentration in Air

Theoretically, the two-filter method should yield statistically meaningful results for radon concentrations in air that exceed 0.4 Bq dm^{-3} (~ 10 pCi ℓ^{-1}). However at Koongarra, the results, particularly for dawn, could not be believed. It is postulated that these errors are due to two factors:

- high humidity (dews occurred on most mornings), and
- the youth of the air (in the sense of the radon being in gross disequilibrium with its daughters).

These prevented the complete filtering of radon daughters (particularly unattached RaA (^{218}Po)) at the first filter. The results reported for this method are given in arbitrary units (counts per minute), as this provides an indication of the change in RaA concentration in air with time.

Most of the radon concentrations in air were obtained by opening an evacuated zinc sulphide cup at the time indicated. Subsequent measurements were as described in Section 2.1. The vertical profiles were obtained after fixing the cups at known heights on the meteorological tower and then opening them all more or less simultaneously.

Occasionally, as a cross check, radon in air concentration was measured by passing 20 ℓ of air at 2 ℓ min^{-1} through a molecular sieve (to remove water vapour) and then through an activated charcoal trap designed for use with an AAEC radium/radon rig to measure the quantity of absorbed radon.

2.5 Radon Daughter Concentration in Air

Spot working level (WL) measurements

For these measurements, air was sampled through Millipore 37 mm x 0.8 μm filters held in a standard Millipore holder for a sampling period of 10 minutes. Initially, a flow rate of 2 ℓ min^{-1} was used but, as levels were generally low and time variations were rapid, this was increased to 20 ℓ min^{-1} to improve the statistical accuracy (~ ± 10 per cent for 0.001 WL). The alpha activity of the particulate retained by the filter paper was measured on an AERE zinc sulphide/photomultiplier 'alpha drawer assembly' connected to an AAEC field scaler equipped with a built-in power supply. The EHT was set at the mid point of the voltage/countrate plateau determined with a standard ^{241}Am thin source. The geometrical counting efficiency was also measured with this source and found to agree with that estimated with a Monte Carlo code. The self absorption of alpha particles resulting from particulate being retained within the body of the filter rather than as a surface deposit was estimated, for a flow rate of 2 ℓ min^{-1}, from the front-to-back activity ratio and the attenuation resulting from a series of frontally placed blank filters of the same type. The self-absorption factor was 0.98 and the overall counting efficiency was 0.217 [A.C. Svenson, AAEC private communication]. The same values were used for a sampling rate of 20 ℓ min^{-1}.

The influence of sample collection, delay and counting times on the estimation of WLs for a range of possible radon daughter disequilibria was discussed by Rolle [1972]. The times used for the Koongarra results (10, 4.35 and 5 minutes respectively) are consistent with his recommendations for minimising the effect of disequilibria on WL determinations.

Most measurements were made at the meteorological tower (10262 N 10743 E) but some were also made at the site proposed for the waste rock dump and at a site initially proposed for the tailings dam but since abandoned.

Average WL measurement

A commercial instrument manufactured by CEA-Steppe (France) was used to integrate the WL exposure over a three-week period. It was positioned in the Stevenson screen at the meteorological tower.

Air entering the head unit was filtered through a membrane which retained the radon daughters on the surface. The emitted α-particles passed through a collimator and then through moderating films to reduce the energy of the α-particles to about 3.5 MeV. Different thicknesses of moderating films distinguished between α-particles from RaA (^{218}Po) and RaC' (^{214}Po) decays. The resulting α-particles then passed through the cellulose nitrate film (Kodak-Pathe LR115) to produce a track in the film. The film was later removed, etched and the number of tracks counted. This method is described more fully by Pradel *et al.* [1977].

3. RESULTS

3.1 Radon Concentration in Water

Table 1 gives the results for radon concentration in quiescent groundwater, pumped groundwater at the camp site, pumped groundwater from the seven-day pump-down test and spring water from Leichhardt Springs and X-anomaly (Map 1). On the basis of these results, a reasonable value to assign to the level of radon dissolved in groundwater remote from uranium ore bodies is 0.05 to 0.1 kBq dm^{-3} (1-2 nCi $ℓ^{-1}$).

Leichhardt Springs and X-anomaly are not in this category. The value for water downstream of Leichhardt Springs indicates the rapid rate at which radon is lost.

Although it is important to be aware of the location of sampling bores in relation to the ore body, a comparison of different ore bodies is of interest when comparing the respective bulk emanating powers:

Ore Body	Sampled Bore	Radon Concentration ($kBq\ dm^{-3}$)	Reference
Ranger I/I	S1/3 - static - pump-down	14.8 3.5-4.8	Davy [1974]
Yeelirrie	H - static	1.2	Brownscombe & Davy [1978]
Koongarra	External to ore body	0.6	
	Predominantly from ore body (?)	1.7	

Ideally, the above comparison should be corrected for the grade and emanation power of ore samples and hence provide guidance on the degree of dilution at Koongarra during the pump-down test. Unfortunately, although the emanation power of the Ranger I Ore Body I and Koongarra material has been determined using split core samples, and the emanation power of ground ore has been determined for the Ranger I Ore Body I and Yeelirrie samples, no sets of data have yet been obtained with the same technique; this is being rectified.

3.2 Radon Concentration in Soil-Air

Table 2(a) gives data on the radon concentration in ground air at different locations. As mentioned earlier, equilibrium would not have been reached in these measurements, therefore they should be regarded as arbitrary units and used only for site to site comparisons at the *same* depth.

Table 2(b) and Figure 5 deal with the diurnal variation in the radon concentration in soil-air and because of the time involved relate to equilibrium conditions although, in this sense, the first measurement taken at 122 cm depth is in doubt. The measuring process introduces dilution factors of 1.62 and 1.48 for the 50 cm and 122 cm depth measurements. When combined with the reported concentrations of the plateau regions of Figure 5, these factors yield a ratio of 2.7 between the soil-air radon concentrations for these depths; coincidentally, this is a relaxation length of 72 cm.

It should be recalled that the site of these measurements comprises consolidated alluvium (so that any assumption about homogeneity would be reasonable) and is external to the primary ore. For a homogeneous medium without primary mineralisation there are two possibilities: either the distribution of radon in soil-air results from a homogeneous source and emanation of radon at the soil-atmosphere interface, or below the measuring depth (122 cm) there is a uniform plane source with barren material above it and free emanation of radon from the surface.

The one-dimensional diffusion equation for a homogeneous semi-infinite medium is

$$\frac{\partial c}{\partial t} = \frac{D}{S} \frac{\partial^2 c}{\partial x^2} - c\lambda + \beta \quad , \qquad (1)$$

where S is the porosity of the medium, defined as the ratio of soil volume to total volume, λ is the Rn decay constant (2.1×10^{-6} s^{-1}), β is a constant related to the emanating power of the medium into the interstitial volume, and c is the concentration of Rn in the interstitial gas.

Kramer *et al.* [1964] provided a solution to Equation (1) under steady state conditions for a uniform source with the boundary conditions $c \to o$ at $x = o$ and $c = c_o$ at $x = \infty$:

$$c = c_o \, (1-e^{-ux}) \quad \text{where} \quad u = \left(\frac{\lambda}{D/S}\right)^{\frac{1}{2}} \quad . \qquad (2)$$

For alluvium, S is > 0.02 and D must be less than its value for air (0.1 cm^2 s^{-1}), so u must be greater than 10^{-3}. For x values of 50 and 122 cm, the ratio c_{122}/c_{50} is $\leqslant$ 2.4 compared to the experimental value of 2.7. Thus the radon concentrations measured in soil-air do not result from a uniform source at the measurement sites.

Tanner [1969] gives a solution to Equation (1) for the movement of radon upwards through the soil from a subsurface source of infinite lateral extent:

$$c = c_o \, e^{-ux} \quad \text{where} \quad u = \left(\frac{\lambda}{D/S}\right)^{\frac{1}{2}} \qquad (3)$$

(Note that S is included here for the reasons discussed by Culot *et al.* [1973] but it was not used by Tanner.)

Thus if $D/S = 1.0 \times 10^{-2}\ cm^2\ s^{-1}$, a relaxation length of 72 cm would result. This implied value for effective diffusion coefficient can be compared with measured values of $1.8 \times 10^{-2}\ cm^2\ s^{-1}$ for diluvium of metamorphic rocks, $1.5 \times 10^{-2}\ cm^2\ s^{-1}$ for eluvial detrital deposits of granite reported by Tanner, and a value of 1.7 to $6.0 \times 10^{-2}\ cm^2\ s^{-1}$ inferred from results for the calcrete valley fill at Yeelirrie, Western Australia [Brownscombe & Davy 1978].

The depth to the water table could not be measured at site 10600 N 10650 E but it was measured 150 m east at hole PH 58 (3.09 m), which has about the same altitude, and at hole PH 139 (5.06 m) which is hydrologically downslope at 75 m south.

From Equation (3), if $D/S = 10^{-2}\ cm^2\ s^{-1}$ and $x = Z-50$, where Z is the depth to the water table, then for Z = 3, 4 and 5 m, $c_o = 5.5 \times 10^2$, 2.3×10^3 and 9.9×10^3 nCi ℓ^{-1} respectively.

Alternatively, if c_o is taken as the highest concentration of radon measured in groundwater, 1.67 kBq dm^{-3} (45 nCi ℓ^{-1}), as given in Table 1, then Z = 128 cm. This value is too low and suggests that the highest value of radon dissolved in groundwater encountered during the pump-down test still represents a significant dilution (> factor of 3)* of ore body water. A value of ~ 11 kBq dm^{-3} (300 nCi ℓ^{-1}) for undiluted ore body groundwater from Koongarra is more in keeping with results from Ranger I Ore Body I, given the higher grade (0.58 per cent *vs* 0.22 per cent) and the greater emanating power of Koongarra ore [R.W. Thomkinson - private communication].

The shape of the diurnal variation in the radon concentration in soil-air (Figure 5) and its possible significance is discussed in Section 4.

3.3 Surface Radon Emanation Rates

3.3.1 Ore body

Table 3 presents results for the surface emanation rates measured over Koongarra Ore Body I (Map 2). Results for emanation rates over Ore Body II are not included since with the methods used they were essentially zero ($J < 0.05$ Bq $m^{-2}\ s^{-1}$). Three sites measured with the scintillation cup method were again measured with the two-filter method. Agreement was good: -1.5, +5 and +9 per cent for J values of ~ 23, 8, 2 Bq $m^{-2}\ s^{-1}$ respectively.

* The ratio of the concentration of radon in groundwater to that in the pore air immediately above it (C_o) is not known; it could be as high as 1:3.

At each site where the emanation rate was measured, the surface gamma activity was also measured with the same type of instrument as that used by Noranda to derive the 'isodose' contours for the ore body (1000 counts s^{-1}, ~ 1.1 μG h^{-1}). These results are given in Table 3 in counts per second.

The least squares fit between J (fCi cm^{-2} s^{-1}) and the gamma response (counts s^{-1}) was

$$J = 1.33 + 0.055 \text{ (counts } s^{-1})$$

with $r^2 = 0.82$.

General observations on this relationship include:

- For a given surface γ response, the emanation rate was lowest at the northern boundary (near the Kambolgie formation) and highest at the southern boundary (over alluvium).
- On the ore body proper the emanation rate was not affected by the existing depth of top soil to the weathered schists.
- The presence of the quartzite outcrop and the existence of the subsurface hard bands and schist bedrock had no apparent influence on the measured emanation rate.

These observations are illustrated in Figure 6, which is a composite of the soil profile of Line 10325 N reported by Noranda, the isodose contours and the measured emanation rates.

Emanation rate measurements made over backfilled costeans in the region of 10240 N 10200-10600 E were in the range of 70-200 Bq m^{-2} s^{-1}; these results are not included in Table 3. Two other measurements (10100 N 10200 E and 10100 N 10300 E), at sites which were intended to be just clear of backfilled costeans (Map 2), were anomalously high (6.6 and 98 Bq m^{-2} s^{-1} respectively) and were discarded from Table 3.

Emanation rate from the ore body

The emanation rate measurements were made at sites that were undisturbed by exploration so that they could be used to estimate the quantity of radon given off by the undeveloped ore body. This was done in the following way:

- For those isodose areas entirely within the proposed pit outline, the radon emanation was the relationship of the product of the isodose area and the emanation rate, obtained from the least squares fit, to the mid-range of the isodose area.
- All of the 50-100 isodose area (some of which lies outside the

proposed pit outline at the southern boundary (Map 2)) was included since, according to the interpretation given in Section 3.3, the radon originates from the groundwater which in turn originates from the ore body.

- For the < 50 isodose area, which lies within the proposed pit outline near the escarpment, only the average of the measured emanation rates was used since the least squares fit was somewhat overestimated for this area because it also contains data taken over consolidated alluvium. Table 4 gives details of the estimate.

This method of estimation was chosen in preference to using the measured emanation rates directly because the data base leading to the isodose contouring (by computer methods) is very much larger than that for emanation rates and, most importantly, the isodose data were obtained before any major drilling or costeaning operations.

Comparison with estimates for the proposed tailings dam

No previous uranium mining venture in Australia has neutralised the tailings materials, therefore estimates for radon emanation from the proposed tailings dam at Koongarra after abandonment had to be based on measurements over acid tailings at Port Pirie and Rum Jungle (the Morleen mill was used for other extractions after it was abandoned for uranium extraction; the Mary Kathleen tailings dam is still in use).

Measurements of radon emanation from the Port Pirie tailings dam were made four times over a 12 month span in a joint venture by the South Australian Department of Public Health, Australian Mineral Development Laboratories, and Australian Atomic Energy Commission. No seasonality was found but there was a marked tidal effect, the Port Pirie tailings dam being sited on tidal flats. The average of 60 measurements taken over the area containing most of the tailings material was 4.9 Bq m^{-2} s^{-1} (13.2 fCi cm^{-2} s^{-1}). The average ^{226}Ra grade of the Port Pirie tailings is 46 Bq g^{-1} (1200 pCi g^{-1}) [D.R. Davy & L. Wilkinson - unpublished data].

Davy & O'Brien have measured the radon emanation rate of the Rum Jungle tailings and found no signficant difference in values for the end of the dry season (November) or for the end of the wet season (March). The average of 24 measurements was 2.1 Bq m^{-2} s^{-1} (5.7 fCi cm^{-2} s^{-1}). The bulk radium grade of the Rum Jungle tailings material (averaged over 85 measurements) was 26.5 Bq g^{-1} [J. Castelyn & D.R. Davy - unpublished data].

The erosion fines in the surface tailings material at Rum Jungle have been somewhat depleted. The average radium concentration of 12 surface samples is 12.2 Bq g^{-1} (*i.e.* about half the bulk average) but the average for 20 samples taken for the depth intervals 0-15 cm and 15-30 cm was the same as that for the bulk average. Thus although erosion would have decreased the surface radon emanation rate, the change would not have been large. The reduction is assumed to have been 20 per cent.

The average radium grade of the Koongarra tailings is expected to be 61.4 Bq g^{-1} (1660 pCi g^{-1}). Thus, on the basis of the Port Pirie and Rum Jungle data, the radon emanation rate is expected to be about 6.2 Bq m^{-2} s^{-1} (17 fCi cm^{-2} s^{-1}). The effect of neutralisation (15.5 kg of lime per tonne of ore) on the radon emanation rate from the tailings is unknown, but the crystallisation of calcium and magnesium sulphates could well reduce both the porosity and radon diffusion coefficient, thereby reducing the radon emanation rate.

If abandonment of the above-ground tailings dam is allowed, it will need to be revegetated. One possible action would be to create a series of beaches as the free water, which initially is over the tailings dam, recedes. The beach benches could be stabilised with waste rock and then top dressed and planted. If it is assumed that ~ 30 cm of top dressing is used and that the effective diffusion coefficient of the laterites used for top dressing is ~ 0.015 cm^2 s^{-1}, then the top dressing would reduce the radon emanation by about 30 per cent, *i.e.* to an estimated 4.3 Bq m^{-2} s^{-1} (3.7 GBq ha^{-1} d^{-1}).

3.3.2 Waste rock

A mock waste rock 'heap' was constructed with material drawn from the boundary of the proposed pit. The base dimensions of the heap were 6 x 4 m, the height was 1.6 m and the flat area of the top was 3 x 1 m. The angle of repose for the sides was ~ 45°.

The radon emanation rates were measured at three locations on the top surface at 1 m from each other. The results were respectively 0.26, 0.45 and 1.6 Bq m^{-2} s^{-1} (0.69, 1.2 and 4.3 fCi cm^{-2} s^{-1}). Because of the finite and relatively small size of the heap, measured emanation rates are lower than those expected for the same material in a more realistic heap. Correction factors can be calculated with computer transport models. This was not done, but a set of calculations for cylindrical geometry [B. Clancy - AAEC private communication] was normalised by the square root of the effective diffusion coefficients. The 'corrected' emanation rates give 0.5, 0.7 and 3 Bq m^{-2} s^{-1} respectively. The uranium content of a composite made up from material of the heap was 0.015 per cent U_3O_8.

Material for the mock heap was drawn from six sites external to the proposed pit boundary. Emanation rates were measured in the vicinity of three of these - 10500 N 10100 E, 10100 N 10600 E, 10100 N 10200 E - and the results were respectively 1.2, 4.1 and 3.4 Bq m^{-2} s^{-1} (3.2, 11 and 9.1 fCi cm^{-2} s^{-1}).

Workers at Queen's University, Canada, have measured the volume emanation rate of 24 weathered ore cores of known uranium grade [Noranda Australia Limited - private communication]. The correlation of volume emanation rate with ore grade is relatively poor, the power curve fit for the data being:

$$J_V(\text{Bq m}^{-3}\text{ s}^{-1}) = 75.1\ (\text{grade \% } U_3O_8)^{0.675}$$

with $r^2 = 0.51$.

This fit is equivalent, for 0.015 per cent U_3O_8, to a volume emanation rate of 4.4 Bq m^{-3} s^{-1}.

Since $$J = \frac{k}{\lambda} J_V \sqrt{\frac{\lambda}{k}}$$

the expected surface emanation rate is 3 Bq m^{-3} s^{-1}.

3.3.3 Mock ore heap

Noranda Australia Limited has on site a heap of weathered ore used previously for leach testing. The base dimensions of the heap are 4 x 3.5 m, height 0.8 m and the flat top has dimensions of 1.8 x 1.4 m. The measured radon emanation rate at the centre of the top of the heap was 27.3 Bq m^{-2} s^{-1} (74 fCi cm^{-2} s^{-1}). No field measurements were made that would indicate an appropriate value for the effective diffusion coefficient applicable for this heap and it is difficult to apply the numerical factors for cylindrical geometry directly. The effective diffusion coefficient value for these calculations was 0.12 cm^{-2} s^{-1}, so the correction factor applied to the mock heap was less than five (the value for a cylinder with height (H) and radius (R) of 1 m) but greater than 2 (the value for R = H = 3).

The concentration of radon in the interstitial air of the heap was measured at each corner of the top plane to a depth of 50 cm. Concentrations were uniform at 3.55 kBq dm^{-3} (96 nCi ℓ^{-1}). Some of the data from Tables 2(a) and 3 are again listed below:

Site		Soil-Air Concentration (c) ($Bq\ dm^{-3}$)*	Emanation Rate (J) ($Bq\ m^{-2}\ s^{-1}$)
9950 N	10400 E	67.3	3.6
10200 N	10420 E	218	7.4
10200 N	10320 E	792	22.4
10600 N	10630 E	133	6.0

* *see Sections 2.2 and 3.2 for discussion of these values.*

A linear regression through these points yields:

$$J = 2.1 + 0.0256\ c \quad \text{with} \quad r^2 = 0.998 \ .$$

On this basis, the expected emanation rate is 93 $Bq\ m^{-2}\ s^{-1}$ (250 $fCi\ cm^{-2}\ s^{-1}$).

The weighted average grade of the heap has been reported at 8.6 lb/short ton (1971) and 9.12 lb/short ton (1972) of U_3O_8, *i.e.* ~ 0.44 per cent U_3O_8.

3.4 Radon Concentration in Air

The field methods used by the ARL and the AAEC for the measurement of radon concentration in air were essentially identical and, in each case, the calibration of the zinc sulphide scintillation cups was traceable to a standard radium solution from the US National Bureau of Standards.

Although all the AAEC measurements of radon in air were made at the site of the meteorological tower, most of the ARL measurements were made closer to the centre of the ore body where the surface of response was highest (10200 N 10320 E). Combined ARL and AAEC radon concentration data are given in Table 5; these data are for instantaneous (~ 1 s) concentrations in air at a height of ~ 75 cm above the ground.

The vertical distribution of radon concentration in air in the 0-10 m interval was twice determined. The sampling times (1830 hours on 27.6.78 and 0630 hours on 28.6.78) were meant to coincide with the morning and afternoon peaks in WL (see Section 3.5) but, in retrospect, these were not well chosen (see Figure 8). The results are indicated in Figure 7 together with error bars indicating one standard deviation.

3.5 Working Level Measurements

3.5.1 Spot determinations

Table 6 lists the recorded WL values at four sites - the meteorological station, the escarpment embayments proposed as sites for the waste rock dump, the tailings dam and the base camp site. This table also includes results for the instantaneous radon in air concentrations taken at the meteorological station, together with the differential air temperature measurement (53-13 m) at half-hourly intervals (as an index of atmospheric stability class), and the wind speed and direction at hourly intervals taken at a height of 13 m. The subjective notation of wind conditions refers to the measurement sites.

A discussion of the results is most conveniently represented in Figure 8 which displays results obtained from 1600 h on 27.6.78 to 0800 h on 28.6.78, and which are representative of cause-effect relationships.

A late afternoon peak in WL occurred on each day but one. This peak was characterised by a rapid rise and fall in WL. This can be summarised:

Date (1978)	Approx. Time of Peak	$\frac{\delta}{\delta t}(\Delta T)$*	$\frac{\delta}{\delta t}(WL)$†	Wind Velocity	
				$\bar{u}(ms^{-1})$	Direction (°)
20.6	18.50	0	2.4×10^{-4}	~ 1.1	74
21.6	18.14	6.7×10^{-3}	7.1	~ 0.9	96
22.6	19.11	2.0×10^{-2}	7.2	~ 0.1	15
23.6	18.24	0	17	~ 0.6	~ 65
26.6	18.40	1.3×10^{-2}	15	~ 0.7	140-315
27.6	18.28	0	24	~ 1.1	160-50
28.6	18.03	2.0×10^{-2}	44	~ 0.7	48

† *Rate of change in WL between neighbouring measurements.*

* *Change in 53-13 m air temperature difference divided by the time interval (30 min.).*

General observations based on these data and Figure 8 include the following:

- The afternoon peak occurs at about sunset but is not definitively related to either the regional or the local time of sunset.
- Neutral or stable atmospheric conditions are apparently a prerequisite for the development of the afternoon WL peak but there is no cause-effect relationship. Low wind speeds appear to be in the same category.

- Wind direction may affect the magnitude of the peak but there is no cause-effect relationship.
- The working level ratio (WLR) at the peak is low (~ 0.08). The rate of increase in the measured WL is not inconsistent with the growing in of RaA into initially daughter-free air.
- There is no apparent meteorological factor that could explain the very rapid fall of WL during the afternoon peak.

The top section of the 'Millipore' filter paper holder used for WL determinations acts like a cascade impactor. It was observed that during periods of WL peaks there was a good correlation between the size and intensity of the impacted particulate material (having a tar-like colour) and the rise and fall of WL. Bush fires were common in the region at the time but none were burning in the valley where Koongarra is located. This observation suggests that vertical mixing over a limited height was occurring during the afternoon WL peaks. This and other speculations are discussed in Section 4.

The 'no breeze' condition

The meteorological station is outside the boundary of the ore body and at a location with a relatively low radon emanation rate (0.7 Bq m^{-2} s^{-1}). Thus, under perfectly still conditions WL values will be low. It is to be expected that the age of the air would be relatively old under these conditions but perhaps the data are internally inconsistent in this respect. The distribution of RaA : RaB : RaC determined by a modified Tsivoglou method was 1 : 0.65 : 0.43 at 0151 hours and 1 : 0.88 : 0.47 at 0313 hours [V. Leach - private communication]. However, the WLR values at the time of measuring radon in air concentrations were:

Time	2220	0135	0310	0400
WLR	0.13	0.06	0.1	0.13

which indicate younger air than is apparent from the RaA : RaB : RaC ratios. Apparently measurements of WL by the ARL and the AAEC were consistent during these periods, so the discrepancy remains unexplained.

The strong NW breeze condition

The onset of a strong breeze off Nourlangie Rock lasting an hour or so and initiated sometime between 2200 and 0200 hours is a common occurrence. It suppresses the WL values by reducing both the radon concentration and the build-up of daughter products.

Inversion conditions

Before and after the strong breeze condition, atmospheric inversions form, break up and reform. The structure of the WL *versus* time curve reflects these changes, whereas the magnitudes of the various peaks within the structure reflect the origin of the air mass relative to that part of the ore body having the highest emanation rates. For a northeasterly breeze of 0.2 m s^{-1}, radon originating from that place would be 10-15 minutes old by the time it reached the meteorological tower, and have a WLR $\leqslant$ 0.2. At 0600 hours on the 28.6.78 there was about a four- to five-fold increase in wind speed at a height of 13 m. If this change also occurred near the ground, the age of the air would drop to 3-4 minutes with a WLR $\leqslant$ 0.08. This could account for the drop in WL from 0.225 to 0.075 at that time.

3.5.2 Average WL determinations

The average value of WL prevailing at the meteorological station at a height of ~ 1.2 m for the period 3.6.78 to 1.7.78 was 0.15 WL.

The ARL [V. Leach - private communication] also assessed average WL values using a prototype dosimeter that involved triplicated detectors - thermoluminescent chips of LiF and CaF_2 and track etch material. These measurements were done at a height of 40 cm above the ore body (10200 N 10350 E) and at the meteorological station. The integrating periods were 19 to 22.6.78 and 26 to 29.6.78 inclusive. The thermoluminescent chips yielded consistent results; the WL over the ore body was 1.24 and that at the meteorological tower was 0.37 (CaF_2 chip only). The differing results for the meteorological station are probably due, in the main, to the differing heights of the ARL and AAEC measurements.

4. DISCUSSION

The results again demonstrate the importance of atmospheric stability when determining the prevailing WL concentrations [Ta-Yung Li 1974]. This effect will be even more marked in open pits. Further, as the solid angle subtended by ore will be greater on the floor of the pit than it is on the surface of the undeveloped ore body and the grade of ore will be higher, the average WL at the working faces of the pit during the night hours could well exceed the annual average occupational level of 0.33 WL. During the daylight hours, the WL concentrations should not be substantially greater than that measured at ground surface over the ore body during 'no wind' periods, *i.e.* ~ 0.01 WL.

The apparent prerequisites for the afternoon peak - neutral stability and low wind speeds - could occur in an open pit at a time earlier than regional sunset.

Limited radon surveys have been carried out at Ranger I Ore Body I, Port Pirie, Rum Jungle and Koongarra; variations of the late afternoon WL peak were observed at all locations. Some generalisations are:

- The probability of occurrence and its magnitude (both absolute and relative to the early morning inversion 'peaks') decrease rapidly with increasing distance from the radon source.
- The magnitude is greater over ore bodies than it is over tailings dams when the ore grades are similar. One could speculate that this is because the water table is higher in the tailings dam than in the ore bodies.
- The development of the atmospheric stability prerequisites is controlled by the local sunset (when the radon source is in full shade).

A study of the phenomenon would be labour intensive and rather complex. Several models are proposed for the phenomenon which could produce appropriate types of measurements.

Limited atmospheric mixing model

At the time of the local sunset, the radon source (ground surface) is in full shade but the atmosphere some metres above the ground is in full sun. An atmospheric mixing mechanism then develops that is akin to fumigation conditions that develop after sunrise except, in this case, it is the thermal lag of the ground surface temperature that provides the convective motion rather than the incident solar energy which is responsible for true fumigation conditions. The mechanism is short-lived, in part because of decreasing ground surface temperatures, and in part because of an increasing mixing height in the atmosphere. The increase in WL is due mostly to an increase in WLR, the increase in radon concentration being secondary.

Wind regulated surface emanation rate model

Near sunset the wind speed drops. This effect is more marked over ore than over tailings material because of the much greater surface roughness of the former. The radon concentration at the ground-atmosphere boundary increases: this suppresses radon emanation which in turn leads to an increase in the radon concentration in soil-air near ground surface. Subsequently, the wind speed increases sufficiently to break down the ground-atmosphere boundary layer, which leads to a temporary increase in emanation rate until the exponential relationship for the radon concentration in soil-air is restored. For such a case, the WL peak would occur predominantly as a result of a peak in radon in air concentration.

Groundwater regulated surface emanation rate model

Referring to Figure 5, the failure of the radon concentration in soil-air at a depth of 50 cm to return, after 24 hours, to the initial value was due to the effect of the pump-down test (the monitor drum - see Section 2.3 - was stable (± 2 per cent) until 28.6.78 but it increased by 12 per cent between 1630 hours on 28.6.78 and 1700 hours on 29.6.78. The radon dissolved in water from the pump-down test increased markedly during the same period - Table 1(a)). Thus, what is seen is a broad minimum in the radon in soil-air concentration which sharpens up as the depth of measurement approaches the height of the groundwater.

The height of the groundwater near the centre of the ore body was measured at 2.72 m (average for PDH 6, 8, 10 and 11).

It is postulated that the diurnal variation in radon in soil-air results from the convective movement of soil-air within the soil profile. If this is so, the important parameters would then be the diurnal variation in ground surface temperature and the constant temperature of the groundwater (35°C). It is further postulated that the late afternoon values of WL increase because of the onset of stable atmospheric conditions and then decrease because of reduced emanation rates resulting from thermal gradients within the soil profile.

The positive value of the intercept (significant at the 95 per cent confidence level) in the linear regression between surface emanation rate and the concentration of radon in soil-air (measured around midday) could be interpreted as indicating that, at some time, surface emanation rates are greater than those measured during the daylight hours. If the late afternoon WL peak is due, directly or indirectly, to the water table then the phenomenon will not occur in an operating de-watered open pit mine.

5. SUMMARY

The major conclusions for this survey of radon levels at Koongarra are as follows:

(i) The regional level of radon dissolved in groundwater is 0.05-0.1 kBq dm^{-3} (1-2 nCi ℓ^{-1}). Spring water from X-anomaly and Leichhardt Springs is anomalous in its dissolved radon concentration.

(ii) The concentration of radon in groundwater from the ore body could not be measured directly but the value inferred from the pump-down test external to the ore body, and the measurement of radon in soil-air at the southern boundary of the ore body, lies in the range 2-20 kBq dm^{-3} with 11 kBq dm^{-3} being a reasonable estimate.

(iii) The daily release of radon from the undeveloped Koongarra ore bodies is estimated to be ~ 26 GBq. The corresponding estimate for the radon release from an above ground tailings dam resulting from development of the ore body is 3.7 GBq ha^{-1} d^{-1}.

(iv) The estimated surface radon emanation rate from waste rock arising from development of the Koongarra deposits is 2.0 Bq m^{-2} s^{-1} when the grade of the waste rock is 0.015 per cent U_3O_8.

(v) The estimated effective diffusion coefficient for radon in the overburden is 1.0×10^{-2} cm^2 s^{-1}.

(vi) The estimated emanation rate from crushed oxidised ore of grade 0.44 per cent U_3O_8 is 93 Bq m^{-2} s^{-1}.

(vii) The radon concentration in air in the vicinity of the ore body fluctuates directly with the prevailing atmospheric stability.

(viii) The WL concentration in air in the vicinity of the ore body reflects atmospheric stability (convective mixing) wind direction (origin of the air mass) and wind speed (age of the air).

(ix) The mechanism leading to a frequently intense short duration peak in WL at about the time of sunset is unexplained.

6. ACKNOWLEDGEMENTS

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TABLE 1

RADON CONCENTRATION IN GROUND AND SPRING WATERS

(a) Pump-Down Test (9670N 10725E)

Start of test : 0900 25.6.78

Date	Time (h)	Radon Concentration	
		kBq dm^{-3}	nCi ℓ^{-1}
25.6.78	1115	0.455	12.3
	1645	0.396	10.7
26.6.78	0830	0.10	2.7
	1710	0.12	3.1
27.6.78	0830	0.300	8.2
	1700	0.160	4.3
29.6.78	0830	0.063	1.7
	1705	1.39	37.5
	2020	1.35	36.5
30.6.78	0750	1.67	45.0
1.7.78	0945	1.57	42.5

(b) Other groundwaters

Date	Site and Depth (m) below Water Table	Radon Concentration	
		kBq dm^{-3}	nCi ℓ^{-1}
27.6.78	10100N 9840E (0.5)	0.072	1.9
27.6.78	11270N 10030E (0.5)	0.11	3.0
27.6.78	11200N 10680E (0.5)	0.59	15.9
27.6.78	10200N 10300E (0.5)	0.044	1.2
1.7.78	Koongarra Camp	0.044	1.2

TABLE 1 (contd.)

(c) Spring Waters

Date	Site	Radon Concentration	
		kBq dm^{-3}	nCi ℓ^{-1}
24.6.78	Leichhardt Springs - at source	0.464	12.5
	- 200 m downstream	0.044	1.2
29.6.78	X-anomaly*		
	- 1	0.17	4.5
	- 2	0.37	10.0
	- 3	0.77	21
	- 4	0.15	4.0
	- 5	0.046	1.2
	- 6	0.041	1.1
	- 7	0.042	1.1
	- 8	0.02	0.6
	- 9	0.15	4.0

* See Map 1 for locations

TABLE 2(a)

RADON CONCENTRATION IN SOIL AIR (See Sections 2.2 and 3.2)

Site	Depth (cm)	Radon Concentration	
		Bq dm^{-3}	nCi ℓ^{-1}
9950N 10400E	50	67	1.8
	122	30	0.8
10200N 10420E	50	220	5.9
10200N 10320E	50	790	21.4
10600N 10630E	50	133	3.6
	122	83	2.2

TABLE 2(b)

DIURNAL VARIATION IN CONCENTRATION OF GROUND AIR

(10600N 10630E)

Depth : 50 cm				Depth : 122 cm			
Date	Time (h)	Radon Concentration		Date	Time (h)	Radon Concentration	
		nCi ℓ^{-1}	Bq dm^{-3}			nCi ℓ^{-1}	Bq dm^{-3}
30.6.78	20.83	7.18	266	2.7.78	10.28	17.8	669
1.7.78	00.5	6.84	253		11.13	26.0	960
	04.42	7.24	268		11.73	23.0	850
	06.20	6.53	242		13.17	20.0	740
	07.45	5.22	193		14.47	25.0	930
	08.83	4.94	183		15.77	24.0	890
	09.83	4.73	175		16.62	26.4	980
	10.83	4.50	167		17.72	27.0	1000
	11.75	5.48	203		19.5	28.3	1050
	13.00	6.38	236				
	14.25	7.23	268				
	15.50	7.48	277				
	16.58	8.15	302				
	17.72	8.94	331				
	19.00	9.08	336				
	20.83	9.20	340				

TABLE 3

RADON EMANATION RATES FROM ORE BODY I

Location	Emanation Rate		Gamma Response
(Mine coordinates)	(Bq m^{-2} s^{-1})	(fCi cm^{-2} s^{-1})	(Counts s^{-1})
9600N 10420E	0.44	1.2	35
9800N 10400E	1.95	5.0	60
9910N 10400E	2.3	6.2	110
9950N 10400E	3.6	9.8	130
10000N 10090E	0.3	0.7	12
10000N 10200E	0.2	0.5	55
10000N 10280E	0.48	1.3	60
10000N 10350E	4.3	11.6	170
10000N 10400E	3.9	10.4	170
10000N 10740E	0.6	1.5	58
10000N 10750E	1.6	4.2	40
10100N 10100E	1.3	3.4	45
10100N 10200E	3.4	9.1	95
10100N 10500E	8.6	23.3	150
10100N 10600E	4.1	11.1	180
10200N 10000E	0.8	2.1	13
10200N 10100E	1.4	3.7	46
10200N 10320E	22.4	60.5	1000
10200N 10420E	7.4	20.0	660
10200N 10780E	0.7	1.9	54
10300N 10200E	0.8	2.2	85
10300N 10600E	3.7	10.0	115
10300N 10700E	1.7	4.6	80
10350N 10520E	6.7	18.1	180
10400N 10000E	0.3	0.9	25
10400N 10090E	4.9	13.2	230
10400N 10100E	1.1	3.1	40
10400N 10200E	1.6	4.2	80
10400N 10330E	12.2	33.0	520
10400N 10420E	9.3	25.0	230

TABLE 3 (contd.)

Location	Emanation Rate		Gamma Response
(Mine coordinates)	$(Bq\ m^{-2}\ s^{-1})$	$(fCi\ cm^{-2}\ s^{-1})$	$(Counts\ s^{-1})$
10400N 10520E	6.6	17.8	250
10400N, 10600E	4.7	12.7	110
10400N 10680E	3.3	8.9	90
10400N 10800E	0.3	0.8	30
10500N, 10100E	1.2	3.2	12
10600N 10000E	0.1	0.3	24
10600N 10100E	0.67	1.8	38
10600N 10190E	3.4	9.2	78
10600N 10290E	3.8	10.4	250
10600N, 10350E	4.8	13.0	200
10600N 10400E	5.2	14.0	230
10600N 10620E	2.2	6.0	60
10600N 10680E	2.5	6.7	54
10600N 10800E	0.67	1.8	30
10600N 10900E	0.3	0.7	34
10600N 11000E	0.2	0.5	17
10800N 10035E	0.07	0.2	10
10800N, 10100E	0.07	0.2	12
10800N 10200E	0.93	2.5	23
10800N 10700E	4.0	10.9	60
10850N 10450E	7.6	20.6	320
10860N 10380E	4.0	10.7	350
10950N 10400E	9.7	26.3	330
11090N 10406E	4.1	11.0	170
11100N 10485E	1.6	4.3	94
11100N 10570E	1.5	4.0	44
11200N 10380E	1.9	5.0	110
11400N 10100E	0.15	0.4	23
11600N 10200E	0.15	0.4	20
11700N 10200E	0.07	0.2	13

Least squares fit: $J\ (fCi\ cm^{-2}\ s^{-1}) = 1.33 + 0.055\ (counts\ s^{-1})$
(coefficient of determination $r^2 = 0.82$)

TABLE 4

ESTIMATE OF DAILY RELEASE RATE OF RADON FROM ORE BODY I

Isodose Contour (Map 1)	Area	J	Daily Release	
Area (counts s^{-1})	(ha)	(fCi cm^{-2} s^{-1})	(Ci)	(G Bq)
< 50	5.29	1.55	0.071	2.62
50 - 100	3.69	5.46	0.174	6.44
100 - 250	2.57	11.0	0.244	9.04
250 - 500	0.79	22.0	0.150	5.56
500 - 750	0.13	35.7	0.040	1.48
> 750	0.063	56.3	0.031	1.13
		TOTAL	0.71	26.3

TABLE 5

RADON CONCENTRATION IN AIR

(a) Scintillation cup measurements

Site: Meteorological Station

Date	Time	pCi ℓ^{-1}	mBq dm^{-3}	σ%
20.6.78	0647	14	520	14
	0734	22	810	11
21.6.78	0516	11	410	15
	0710	12	440	15
	0732	16	590	13
22.6.78	0525	77	2850	6
	0615	40	1480	8
	0801	4	150	27
23.6.78	0505	5	190	18
	0623	16	590	10
	0808	9	330	14
25.6.78	1817	33	1220	8
	1846	11	410	19
	1925	43	1590	11
	1950	17	630	19
	2023	29	1070	11
26.6.78	0500	13	480	22
	0547	22	810	10
	0623	32	1180	12
	1754	27	1000	15
	1810	19	700	21
	1923	26	960	15
	1947	10	370	29
	1952	16	590	13
27.6.78	0452	49	1810	11
	0652	16	590	20
	1835	66	2440	8
	2220	16	590	19
28.6.78	0133	54	2000	3
	0325	60	2220	9
	0400	45	1670	9
	0440	11	410	29
	1809	61	2260	5
	1825	17	630	22
	1835	17	630	23

TABLE 5 (contd.)

Date	Time	pCi ℓ^{-1}	mBq dm^{-3}	σ%
29.6.78	0601	6	220	12
	0637	6	220	10
	0718	10	370	9
	1807	20	740	7
	1819	27	1000	7
	1850	42	1550	6
30.6.78	0630	24	890	7
	0638	14	520	6
	0648	27	1000	7
	1930	3	110	-
	1945	12	440	-
	2000	5	190	-

Site: Ore Body

Date	Time	pCi ℓ^{-1}	mBq dm^{-3}	σ%
21.6.78	1813	126	4660	5
	1833	686	25380	3
	1856	45	1670	10
	1920	19	700	21
	1957	55	2040	8
	2038	50	1850	10
22.6.78	0602	162	5990	5
	0616	117	4330	5
	0712	218	8070	5
	1905	95	3520	7
	2008	239	8840	5
	2043	34	1260	12

TABLE 5 (Contd.)

(b) Two Filter Tube - Arbitrary Units

Site: Ore body - Meteorological Station

Date	Time	RaA 'activity' (arbitrary units) (counts min^{-1})	Wind Condition
22.6.78	1648	4	VL (NE)
	1736	40	" "
	1815	31	L (N)
	1856	36	VL (N)
	1931	148	No wind
	2014	43	"
23.6.78	0419	37	VL (NE)
	0500	62	" "
	0540	61	No wind
	0617	72	VL (NE)
	0657	114	No wind
	0738	106	VL (E)
	1642	< 1	L (NE)
	1733	22	" "
	1807	104	VL (NE)
	1850	48	" "
	1930	23	" "
24.6.78	0550	135	VL (NE)
	0625	112	" "
	0705	73	VL (E)
	0743	64	" "
25.6.78	1722	< 1	L (NE)
	1810	16	" "
	1857	34	VL (NE)
	1944	28	No wind
26.6.78	0419	174	VL (NE)
	0446	55	" "
	0509	122	No wind
	0530	69	"
	0552	71	"
	0613	173	"
	0635	155	VL (NE)
	0655	166	VL (SW)
	0718	101	" "
	0740	53	" "

VL = calm, very light
L = light

TABLE 6

WL CONCENTRATION AT FOUR SITES

Site: Ore Body - Meteorological Station

Date	Time	WL	σ (%)	ΔT (°C)	Wind Condition (Subjective)	Speed (m s^{-1})	Direction (°)
20.6.78	0435	0.014	12		VL		
	0530	0.007	15	3.8	"	0.33	75
	0558	0.011	13	4.6	"		105
	0617	0.028	9		"		
	0640	0.014	11	5.2	"		
	0647	Radon in air concentration 14 pCi ℓ^{-1} (520 mBq dm^{-3})					
	0705	0.02	10	4.8	VL		
	0725	0.038	7	3.6	"		
	0734	Radon in air concentration 22 pCi ℓ^{-1} (810 mBq dm^{-3})					
	1610	< 0.001	-		L	2.75	48
	1631	0.001	32		"		
	1655	0.002	26	-1.6	"	1.81	114
	1716	0.002	25		"		
	1737	0.001	30	-2.0	L to VL		
	1804	0.003	24	-1.6	VL	1.11	117
	1850	0.014	12	-1.2	"	1.08	74
	1914	0.003	15		"		
	1935	0.007	13	-1.2	"	1.25	75
21.6.78	0420	0.021	10		VL	0.44	42
	0450	0.023	9	3.4	"	0.33	42
	0510	0.022	9		"		
	0516	Radon in air concentration 11 pCi ℓ^{-1} (410 mBq dm^{-3})					
	0555	0.016	11	2.8	VL	0.36	279
	0616	0.008	14		VL to L		
	0640	0.017	10	3.4	No wind		
	0705	0.037	7	4.4	VL	0.44	48
	0710	Radon in air concentration 12 pCi ℓ^{-1} (440 mBq dm^{-3})					
	0727	0.038	7	0.4	VL		
	0732	Radon in air concentration 16 pCi ℓ^{-1} (590 mBq dm^{-3})					

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (^{o}C)	Wind Condition (Subjective)	Speed (m s^{-1})	Direction (^{o})
21.6.78	1657	< 0.001	-	-1.6	VL	1.33	92
	1725	< 0.001	-	-1.2	"		
	1750	0.007	5	-1.2	"	0.89	96
	1814	0.024	3		"		
	1838	0.011	4	-1.0	"		
	1900	0.009	5	-0.6	VL to L	1.03	96
	1922	0.006	6	-0.8	VL		
	1945	0.009	5	-0.6	"	1.50	96
22.6.78	0434	0.081	2		VL	0.44	120
	0455	0.124	1	-1.2	"	0.22	9
	0517	0.063	2		"		
	0525	Radon in air concentration 77 pCi ℓ^{-1} (2850 mBq dm^{-3})					
	0559	0.067	2	0.2	VL	0.31	9
	0615	Radon in air concentration 40 pCi ℓ^{-1} (1480 mBq dm^{-3})					
	0623	0.045	2	1.6	VL		
	0647	0.017	3		"		
	0710	0.051	2	3.2	"	0.58	9
	0730	0.051	2	2.4	"		
	0755	0.051	2	1.0	"	0.56	251
	0801	Radon in air concentration 4 pCi ℓ^{-1} (150 mBq dm^{-3})					
	1615	0.001	14		L	0.94	6
	1635	0.001	15		"		
	1715	0.004	7	-1.6	VL	1.14	69
	1755	0.002	9	-1.8	VL to L	0.92	8
	1835	0.011	4	-1.6	VL		
	1911	0.037	2	0.4	No wind	0.11	15
	1950	0.069	2	1.2	"	0.61	15

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (^{o}C)	Wind Condition (Subjective)	Speed (m s^{-1})	Direction (^{o})
23.6.78	0437	0.029	3		VL	0.78	60
	0505	Radon in air concentration 5 pCi ℓ^{-1} (190 mBq dm^{-3})					
	0518	0.044	2	2.0	VL	0.14	60
	0556	0.056	2	3.2	No wind	0.03	60
		Radon in air concentration 16 pCi ℓ^{-1} (590 mBq dm^{-3})					
	0636	0.064	2	3.8	No wind		
	0718	0.060	2	3.2	"	0.78	69
	0750	0.043	2	3.4	VL	0.78	69
	0808	Radon in air concentration 9 pCi ℓ^{-1} (330 mBq dm^{-3})					
	1620	<0.001	-		L	1.89	107
	1705	0.001	13	-1.6	"	0.69	60
	1749	0.022	3	-0.4	VL	0.56	75
	1824	0.081	2	-0.4	"		
	1906	0.012	4	1.6	"	0.64	54
	1948	0.016	4	3.4	"	0.36	62
24.6.78	0440	0.027	3		VL		
	0505	0.025	3	-1.4	"	0.44	56
	0525	0.030	3	0.0	"		
	0605	0.037	2	1.4	"	0.22	60
	0644	0.096	1	1.6	"	0.56	84
	0723	0.032	3	1.0	"		
25.6.78	1655	<0.001	-	-1.6	L	1.50	72
	1817	Radon in air concentration 33 pCi ℓ^{-1} (1220 mBq dm^{-3})					
	1832	0.027	3	-0.6	VL	1.31	47
	1846	Radon in air concentration 11 pCi ℓ^{-1} (410 mBq dm^{-3})					
	1919	0.039	2	1.0	No wind	1.33	50
	1925	Radon in air concentration 43 pCi ℓ^{-1} (1590 mBq dm^{-3})					
	1950	" " " " 17 pCi ℓ^{-1} (630 mBq dm^{-3})					
	2006	0.013	4	0.6	VL	0.92	62
	2023	Radon in air concentration 29 pCi ℓ^{-1} (1070 mBq dm^{-3})					
	2029	0.028	3		VL		

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (°C)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (°)
26.6.78	0419	0.064	2		VL		
	0446	0.026	4		"		
	0500	Radon in air concentration 13 pCi ℓ^{-1} (480 mBq dm^{-3})					
	0509	0.010	6	4.4	No wind	0.64	54
	0530	0.013	5	4.4	"		
	0547	Radon in air concentration 22 pCi ℓ^{-1} (810 mBq dm^{-3})					
	0552	0.022	4	2.4	No wind	0.78	36
	0613	0.049	3		"		
	0623	Radon in air concentration 32 pCi ℓ^{-1} (1180 mBq dm^{-3})					
	0635	0.050	3	3.2	VL		
	0655	0.043	3	3.8	"	1.03	258
	0718	0.025	4		"		
	0740	0.017	5	5.2	"	1.00	261
	1635	<0.001	-		"		
	1656	0.001	13	-1.8	"	0.50	144
	1716	0.003	9		"		
	1738	0.012	4	-2.0	"		
	1754	Radon in air concentration 27 pCi ℓ^{-1} (1000 mBq dm^{-3})					
	1800	0.018	3	-0.8	VL	0.64	141
	1810	Radon in air concentration 19 pCi ℓ^{-1} (700 mBq dm^{-3})					
	1820	0.018	3	-1.2	VL		
	1840	0.048	2		No wind		
	1902	0.034	2	-0.8	"	0.72	315
	1923	0.021	3	0.4	VL		
	1923	Radon in air concentration 26 pCi ℓ^{-1} (960 mBq dm^{-3})					
	1944	0.024	3	2.2	VL	0.47	351
	1947	Radon in air concentration 10 pCi ℓ^{-1} (370 mBq dm^{-3})					
	1952	Radon in air concentration 16 pCi ℓ^{-1} (590 mBq dm^{-3})					

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (^{o}C)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (^{o})
27.6.78	0440	0.057	2		No wind		
	0449	0.084	2		"		
	0452	Radon in air concentration 49 pCi ℓ^{-1} (1810 mBq dm^{-3})					
	0505	0.054	2	2.0	No wind	0.42	54
	0514	0.070	2		"		
	0525	0.032	2		"		
	0535	0.045	2	1.2	"		
	0544	0.037	2		"		
	0557	0.051	2		VL	0.39	54
	0606	0.042	2	1.0	"		
	0617	0.028	3		"		
	0627	0.031	2	1.8	"		
	0639	0.031	3		"		
	0647	0.024	3		"		
	0652	Radon in air concentration 16 pCi ℓ^{-1} (590 mBq dm^{-3})					
	0700	0.037	2	2.0	VL	0.28	54
	0708	0.034	2		"		
	0720	0.050	2		No wind		
	0729	0.060	2	1.8	"		
	0741	0.048	2		"		
	0752	0.029	2		"		
	0802	0.033	2	1.2	VL	0.75	54
	1642	<0.001	-		L		
	1652	0.001	13		"		
	1703	<0.001	-	-1.4	"	1.19	119
	1713	<0.001	-		"		
	1723	<0.001	-	-2.0	VL		
	1739	<0.001	-		"		
	1749	0.005	6		"		
	1800	0.020	3	-1.0	"	1.06	159
	1808	0.038	2		"		
	1821	0.035	2		"		
	1828	0.052	2	-1.2	"		

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (^oC)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (^{o})
27.6.78	1835	Radon in air concentration 66 pCi ℓ^{-1} (2440 mBq dm^{-3})					
	1844	0.009	4		VL		
	1851	0.010	4		"		
	1905	0.004	6	-0.8	"	1.25	50
	1913	0.009	5		"		
	1925	0.005	6	-1.2	"		
	1935	0.011	4		No wind		
	1947	0.005	5		"		
	1957	0.009	5	-1.0	"	1.36	45
	2024	0.006	5		"		
	2039	0.012	4		"		
	2055	0.012	4		VL	1.14	39
	2109	0.011	4		"		
	2125	0.011	4		No wind		
	2145	0.014	4		"		
	2155	0.010	4		"		57
	2210	0.017	4		"		
	2220	Radon in air concentration 16 pCi ℓ^{-1} (590 mBq dm^{-3})					
	2225	0.021	3		No wind		
	2236	0.020	3		G		
	2256	0.001	10		S		
28.6.78	0052	0.012	4		No wind		
	0133	Radon in air concentration 54 pCi ℓ^{-1} (2000 mBq dm^{-3})					
	0203	0.038	2		No wind		
	0218	0.034	2		"		
	0252	0.057	2		"		
	0308	0.106	1		"		
	0318	0.065	2		"		
	0325	Radon in air concentration 60 pCi ℓ^{-1} (2220 mBq dm^{-3})					

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (^{o}C)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (^{o})
28.6.78	0329	0.064	2		No wind		
	0340	0.070	2		"		
	0350	0.058	2		"		
	0400	Radon in air concentration 45 pCi ℓ^{-1} (1670 mBq dm^{-3})					
	0402	0.055	2		No wind		
	0419	0.039	2		"		
	0425	0.037	2		"		
	0437	0.035	2		"		
	0440	Radon in air concentration 11 pCi ℓ^{-1} (410 mBq dm^{-3})					
	0446	0.038	2		VL		
	0458	0.049	2	1.2	"	0.11	36
	0507	0.077	2		"		
	0519	0.093	1		"		
	0527	0.112	1	0.8	"		
	0540	0.177	1		"		
	0548	0.225	1		"		
	0600	0.076	1	1.4	"	0.86	36
	0610	0.072	2		"		
	0621	0.082	1		No wind		
	0630	0.065	2	1.2	"		
	0642	0.045	2		"		
	0650	0.048	2		"		
	0702	0.035	2	1.2	"	0.25	36
	0711	0.042	2		"		
	0723	0.035	2		"		
	0732	0.031	3	3.2	"		
	0747	0.019	3	0.4	VL	1.97	105

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (°C)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (°)
28.6.78	1650	<0.001	-		VL		
	1703	<0.001	-	-1.4	"	0.89	108
	1713	<0.001	-		"		
	1723	<0.001	-	-2.8	"		
	1745	0.009	4		"		
	1755	0.013	4		"		
	1803	0.048	2	-1.4	No wind	0.67	48
	1809	Radon in air concentration 61 pCi ℓ^{-1} (2260 mBq dm^{-3})					
	1815	0.021	3		No wind		
	1825	Radon in air concentration 17 pCi ℓ^{-1} (630 mBq dm^{-3})					
	1825	0.012	3	-0.8	No wind		
	1835	Radon in air concentration 17 pCi ℓ^{-1} (630 mBq dm^{-3})					
	1837	0.014	4		No wind		
	1845	0.013	3		"		
	1858	0.009	5	-0.6	"	0.61	15
	1908	0.010	4		"		
	1920	0.011	4		"		
	1930	0.013	3	2.4	"		
	1940	0.028	3	1.6	"	0.86	15
29.6.78	0512	0.002	9	-1.8	L	2.17	120
	0528	0.002	9	-1.8	"		
	0535	0.001	13		"		
	0549	0.002	9		"		
	0558	0.003	8	-1.4	"		59
	0601	Radon in air concentration 6 pCi ℓ^{-1} (220 mBq dm^{-3})					
	0610	0.004	6		L		
	0619	0.003	8		"		
	0632	0.003	7	-1.2	"		
	0637	Radon in air concentration 6 pCi ℓ^{-1} (220 mBq dm^{-3})					

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (^{o}C)	Wind Condition (Subjective)	Speed (m s^{-1})	Direction (^{o})
29.6.78	0642	0.004	7		L		
	0654	0.003	7		VL		
	0703	0.003	8	-1.4	"		
	0714	0.004	6		L		
	0718	Radon in air concentration 10 pCi ℓ^{-1} (370 mBq dm^{-3})					
	0723	0.004	7		L		
	0735	0.002	8	-1.4	VL		
	0744	0.002	10	-2.0	"		
	1610	<0.001	-		L		
	1619	<0.001	-		"		
	1629	<0.001	-		VL		
	1710	0.001	15		"		
	1720	0.002	10		"		
	1732	0.010	4		"		
	1742	0.030	3		"		
	1754	0.019	3		"		
	1802	0.015	4		"		
	1807	Radon in air concentration 20 pCi ℓ^{-1} (740 mBq dm^{-3})					
	1814	0.016	3		VL		
	1819	Radon in air concentration 27 pCi ℓ^{-1} (1000 mBq dm^{-3})					
	1845	0.029	2		VL		
	1850	Radon in air concentration 42 pCi ℓ^{-1} (1550 mBq dm^{-3})					
	1855	0.026	3		No wind		
	1902	0.019	3		"		
	1915	0.015	4		"		
	1929	0.028	2		"		
	1938	0.027	3		"		
	1947	0.035	2		"		

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (°C)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (°)
30.6.78	0436	0.044	2		VL		
	0445	0.039	2		"		
	0458	0.046	2		"		
	0508	0.041	2		"		
	0520	0.038	2		"		
	0530	0.033	2		"		
	0540	0.036	2		No wind		
	0550	0.038	2		"		
	0600	0.067	2		"		
	0610	0.123	1		VL		
	0620	0.108	1		"		
	0630	Radon in air concentration 24 pCi ℓ^{-1} (890 mBq dm^{-3})					
	0630	0.062	2		VL		
	0638	Radon in air concentration 14 pCi ℓ^{-1} (520 mBq dm^{-3})					
	0642	0.084	2		VL		
	0648	Radon in air concentration 27 pCi ℓ^{-1} (1000 mBq dm^{-3})					
	0654	0.120	1		VL		
	0703	0.234	1		No wind		
	0715	0.117	1.		"		
	0725	0.086	2		"		
	0735	0.087	1		"		
	1645	<0.001	-		L		
	1655	<0.001	-		"		
	1705	<0.001	-		"		
	1720	0.001	15		"		
	1740	0.001	15		"		
	1750	0.001	12		"		
	1800	0.003	8		VL		
	1811	0.004	6		"		
	1821	0.001	12		"		
	1831	0.001	13		L		
	1842	0.001	14		"		
	1857	0.001	10		"		
	1903	0.001	12		"		
	1914	0.003	7		VL		
	1924	0.004	7		"		

TABLE 6 (contd.)

Date	Time	WL	σ (%)	ΔT (^{o}C)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (^{o})
30.6.78	1930	Radon in air concentration 3 pCi ℓ^{-1} (110 mBq dm^{-3})					
	1935	0.006	5		No wind		
	1944	0.005	6		VL		
	1945	Radon in air concentration 12 pCi ℓ^{-1} (440 mBq dm^{-3})					
	1955	0.005	5		VL		
	2000	Radon in air concentration 5 pCi ℓ^{-1} (190 mBq dm^{-3})					

VL = calm, very light

L = light

S = strong

G = gusts

TABLE 6 (contd.)

Site: Waste Rock

Date	Time	WL	σ (%)	ΔT (^{o}C)	Wind Condition (Subjective)	Speed ($m\ s^{-1}$)	Direction (^{o})
24.6.78	0445	0.037	2	-1.4	VL	0.44	56
	0528	0.046	2	0.0	"		
	0552	0.048	2	1.4	"	0.22	60
	0617	0.025	3	1.6	"		
	0655	0.017	3	0.8	"	0.56	84
	0708	0.035	2		"		
	0724	0.096	1	1.0	"		
	0739	0.035	2		"		
	0757	0.019	3	0.6	"	0.78	162
25.6.78	1715	0.0010	13	-1.6	L	1.50	72
	1727	0.0009	12	-2.4	"		
	1740	0.0010	12		"		
	1752	0.0013	11		"		
	1803	0.0009	13	-1.0	"	1.31	47
	1815	0.0007	14		"		
	1827	0.0011	12	-0.6	"		
	1839	0.0010	12		"		
	1851	0.0008	12		"		
	1902	0.0008	13	-0.4	"	1.33	50
	1914	0.0011	12		"		
	1929	0.0018	10	1.0	"		

VL = calm, very light

L = light

TABLE 6 (contd.)

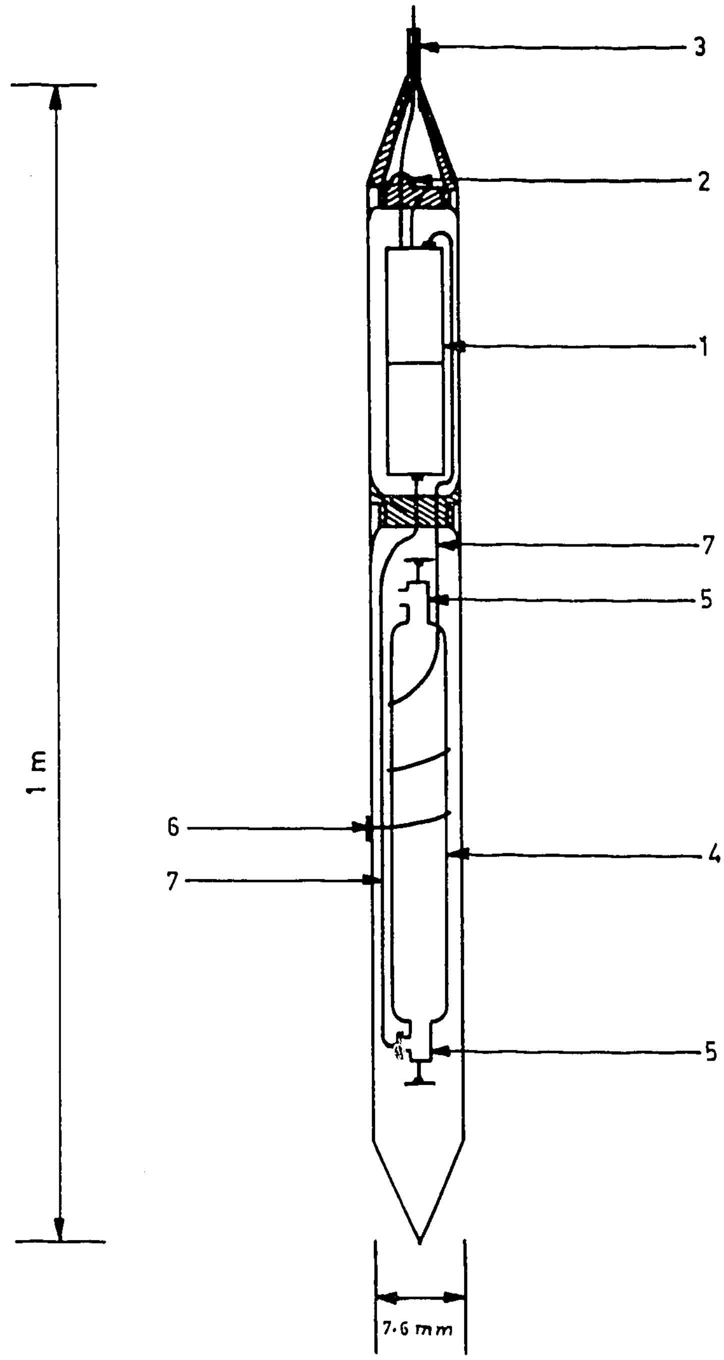
Site: Base Camp

Date	Time	WL	σ (%)	ΔT (°C)	Wind Condition (Subjective)	Speed (m s⁻¹)	Direction (°)
24.6.78	0430	0.021	3		VL	1.17	9
	0455	0.021	3	-1.4	"	0.44	56
	0513	0.021	3		"		
	0535	0.021	3	0.0	"		
	0555	0.013	4	1.4	"	0.22	60
	0615	0.024	3		"		
	0635	0.016	3	1.6	"		
	0656	0.019	3	0.8	"	0.56	84
	0717	0.018	3		"		
	0738	0.017	3	1.0	"		
	0801	0.016	3	0.6	"	0.78	162

Site: (b) Tailings Dam

Date	Time	WL	σ (%)	Wind Condition (subjective)
30.6.78	0448	0.0024	8	VL
	0510	0.0024	8	"
	0530	0.0027	8	"
	0550	0.0026	8	"
	0610	0.0022	8	"
	0630	0.0022	8	"
	0655	0.0021	9	"
	0713	0.0032	7	"
	0733	0.0032	7	"

VL = calm, very light



1 - 12 V, 0·5A Solenoid valves
2 - Lead - in seat
3 - Support cable & 12 V supply
4 - 0·5 l Stainless steel bomb
5 - Valves
6 - Inlet
7 - Stainless steel capillary

FIGURE 1. BORE WATER SAMPLER

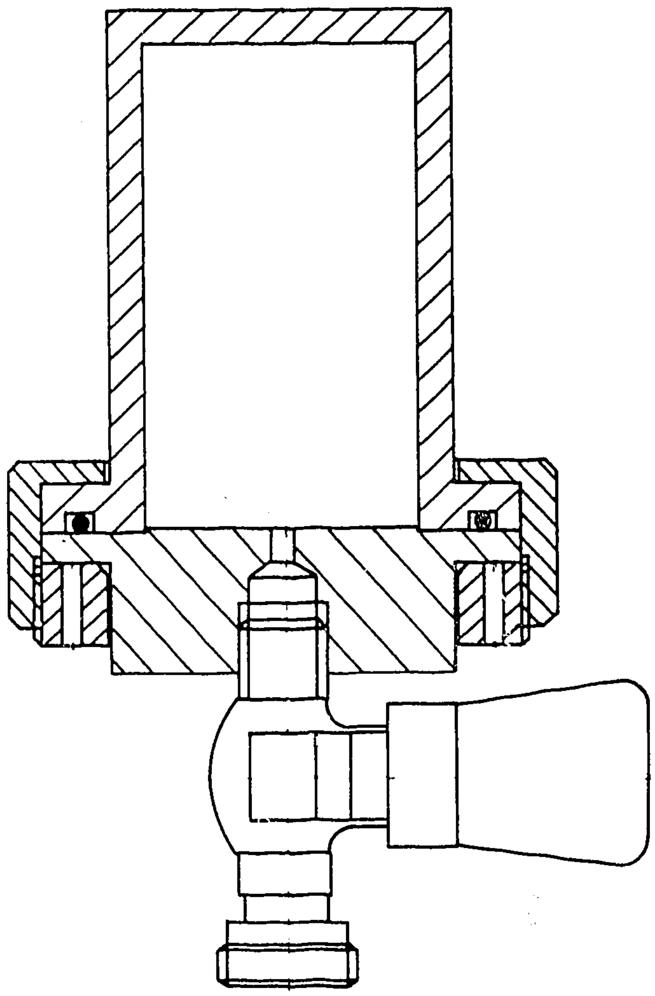


FIGURE 2. ZINC SULPHIDE SCINTILLATION CUP

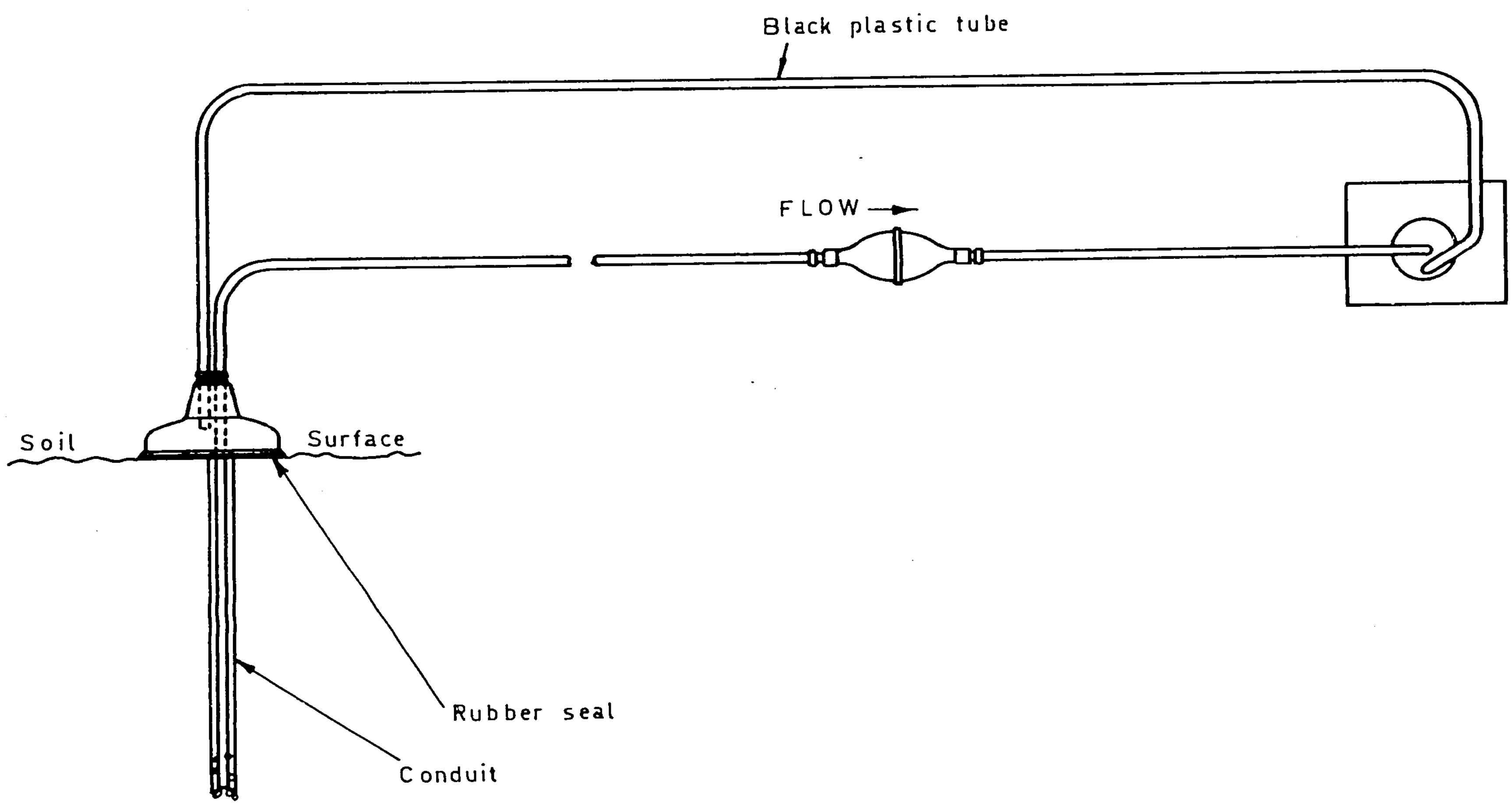


FIGURE 3. SOIL-AIR PROBE

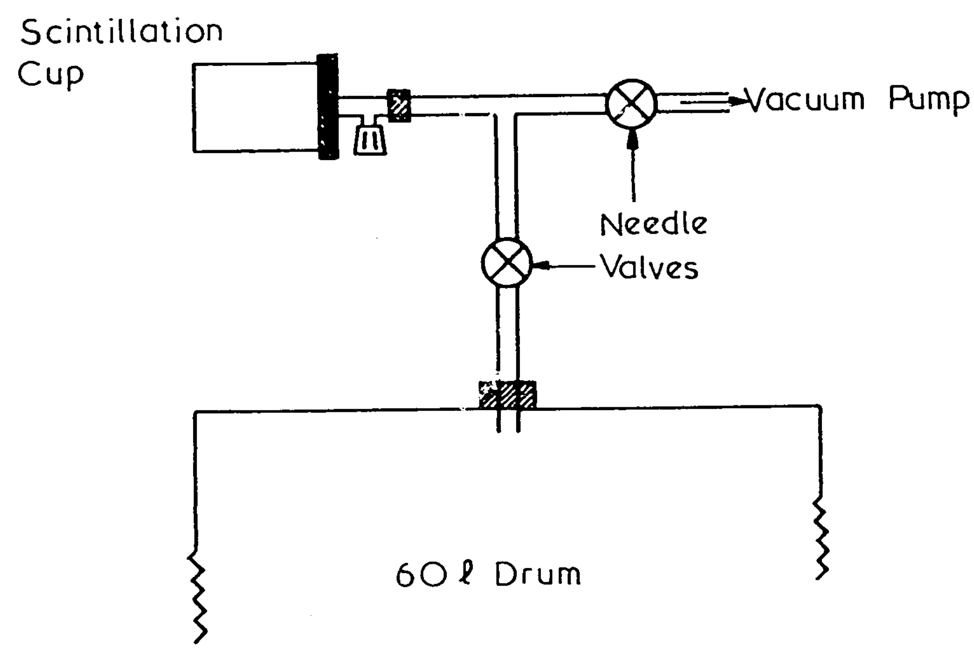


FIGURE 4. METHOD FOR SAMPLING IN SURFACE EMANATION RATE MEASUREMENTS

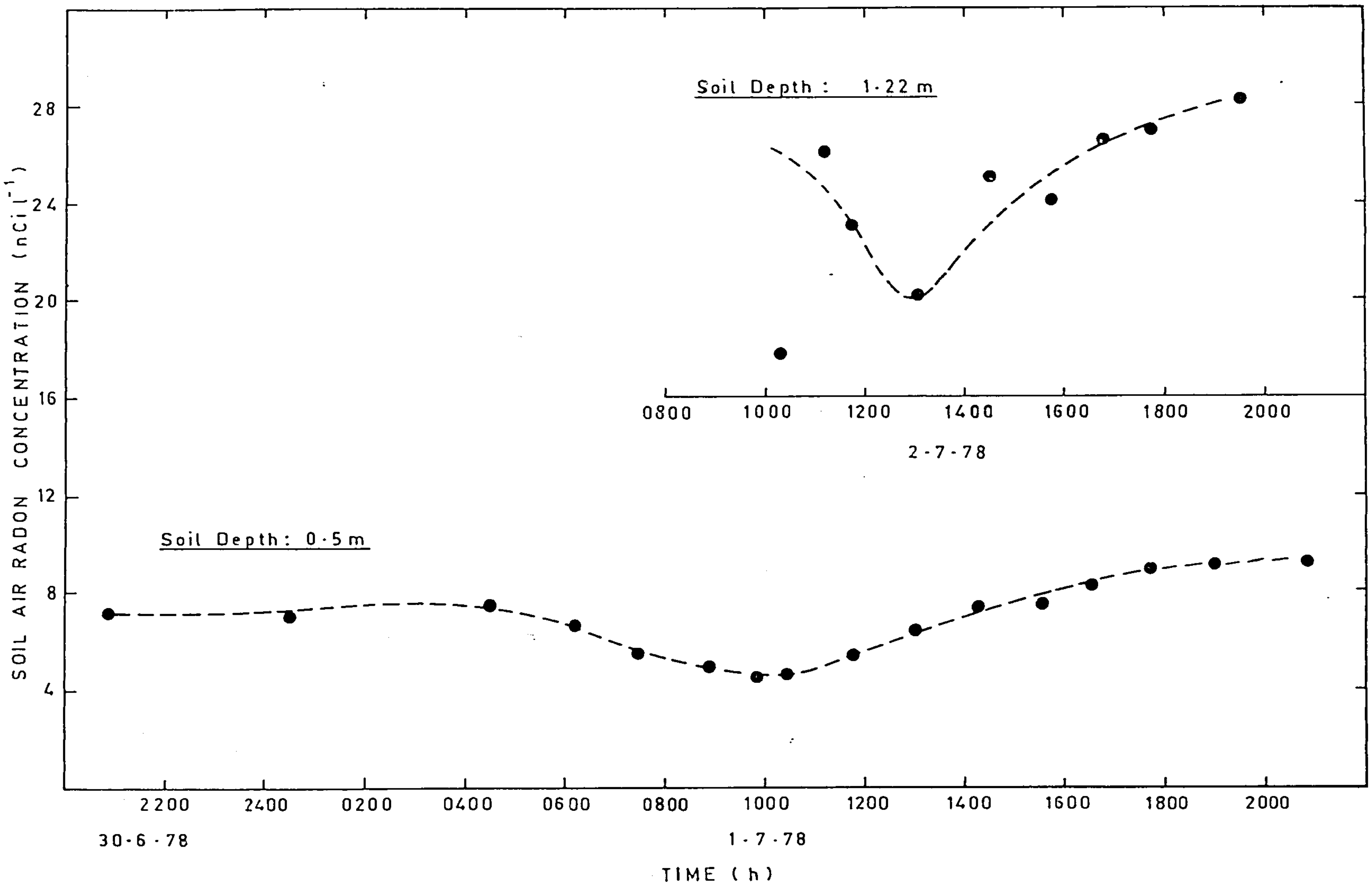


FIGURE 5. DIURNAL VARIATION IN THE RADON CONCENTRATION IN SOIL-AIR

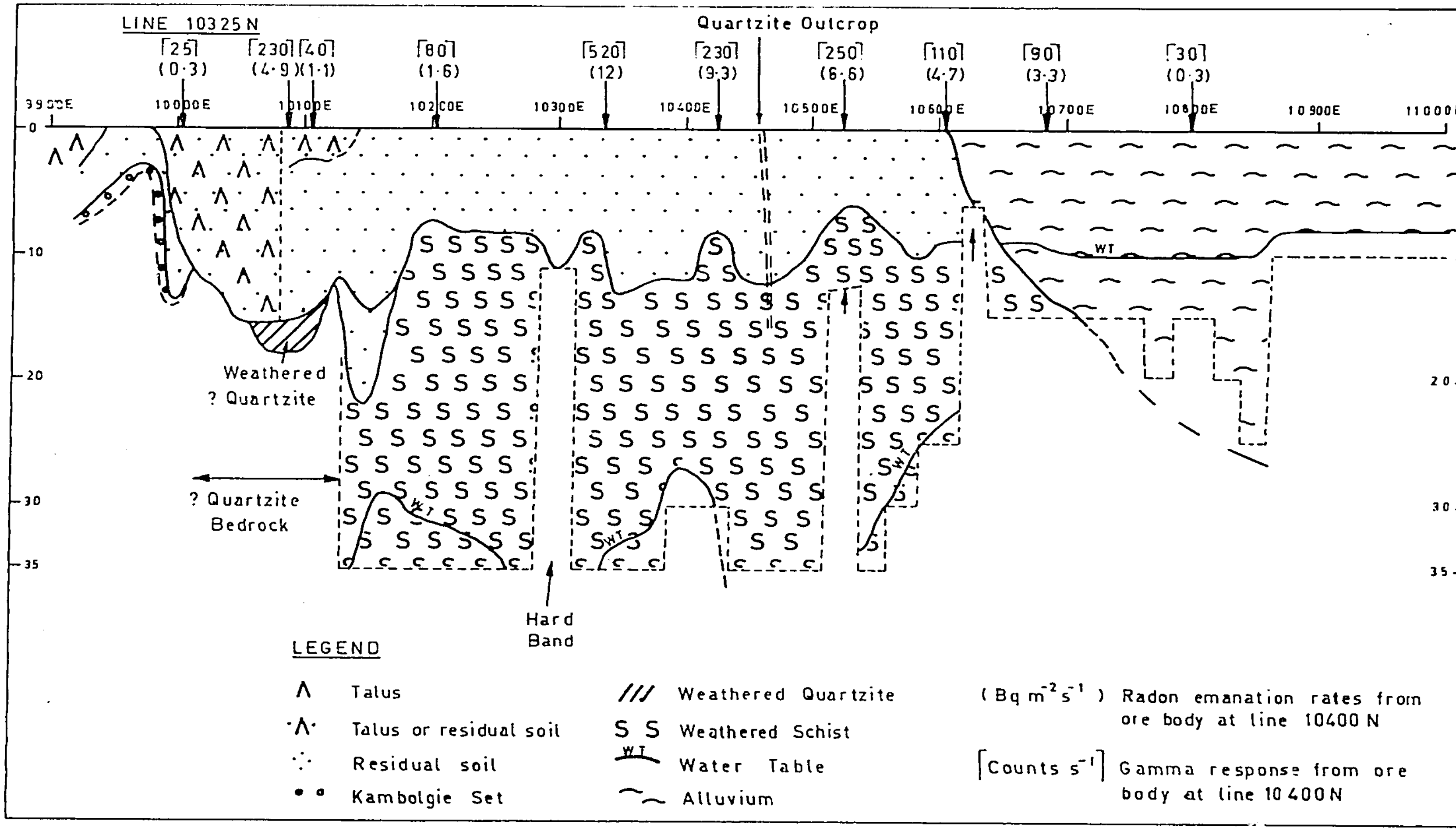


FIGURE 6. SOIL PROFILE OF LINE 10325N WITH GAMMA RESPONSE AND RADON EMANATION VALUES

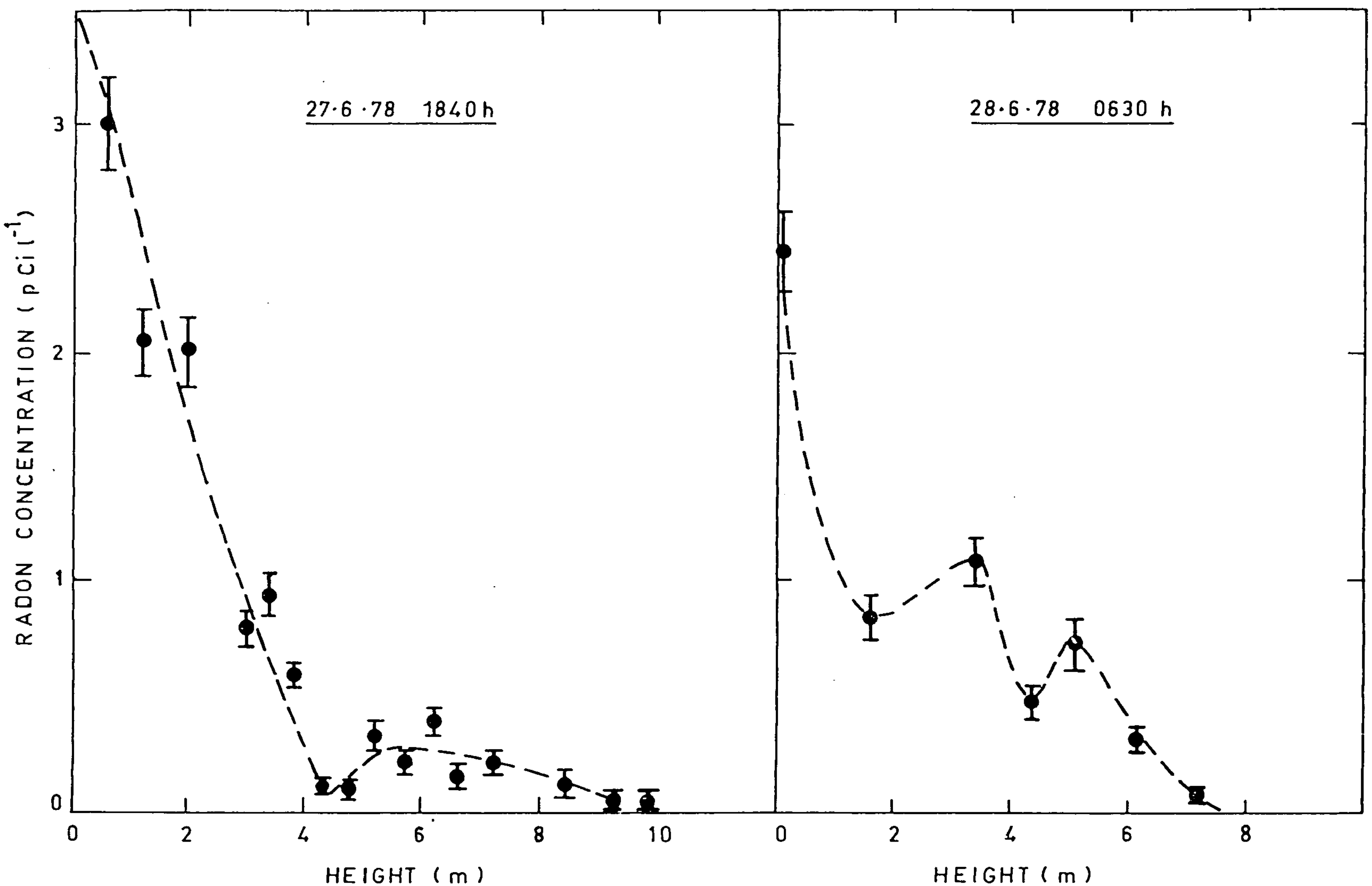


FIGURE 7. VERTICAL DISTRIBUTION OF RADON CONCENTRATION IN AIR

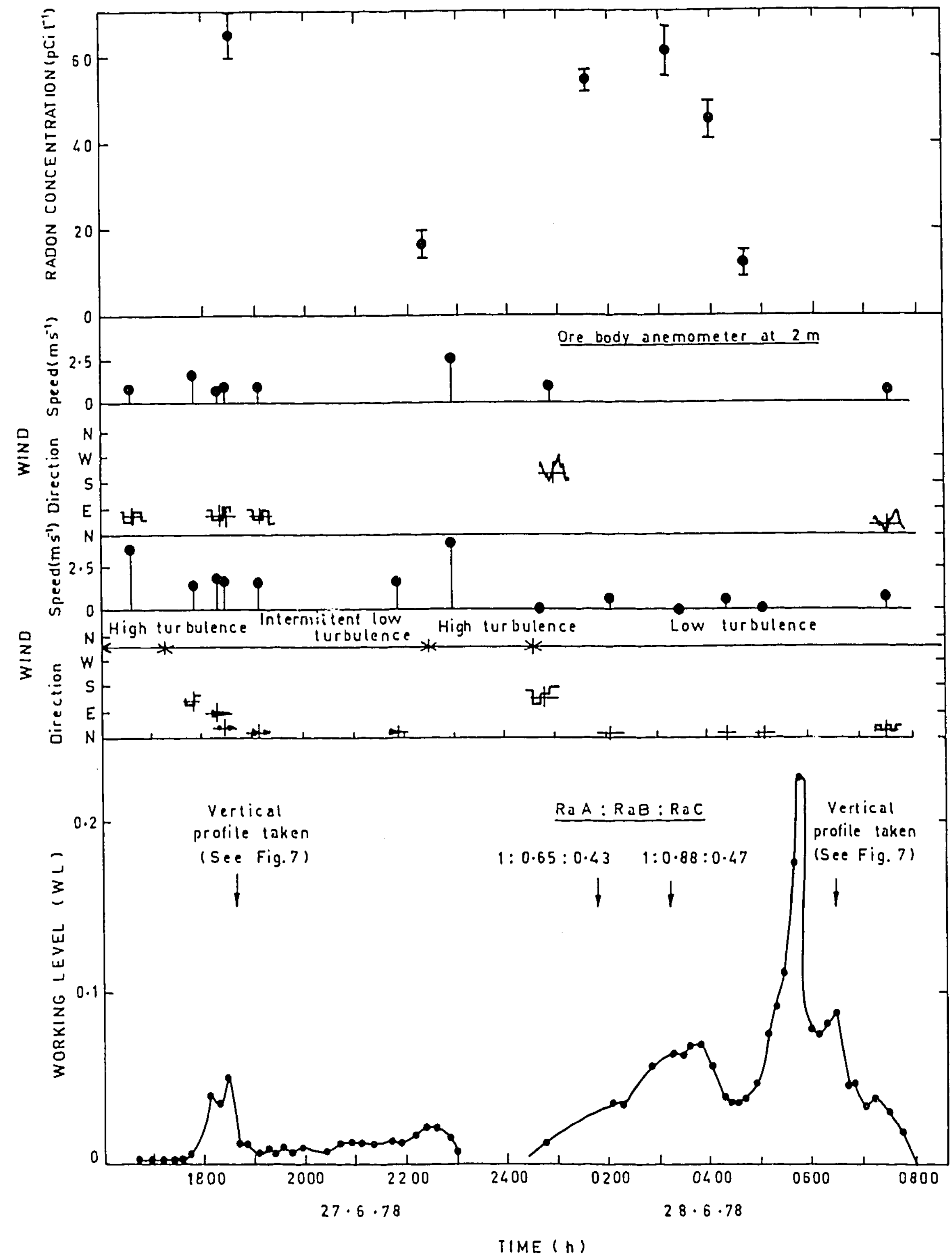
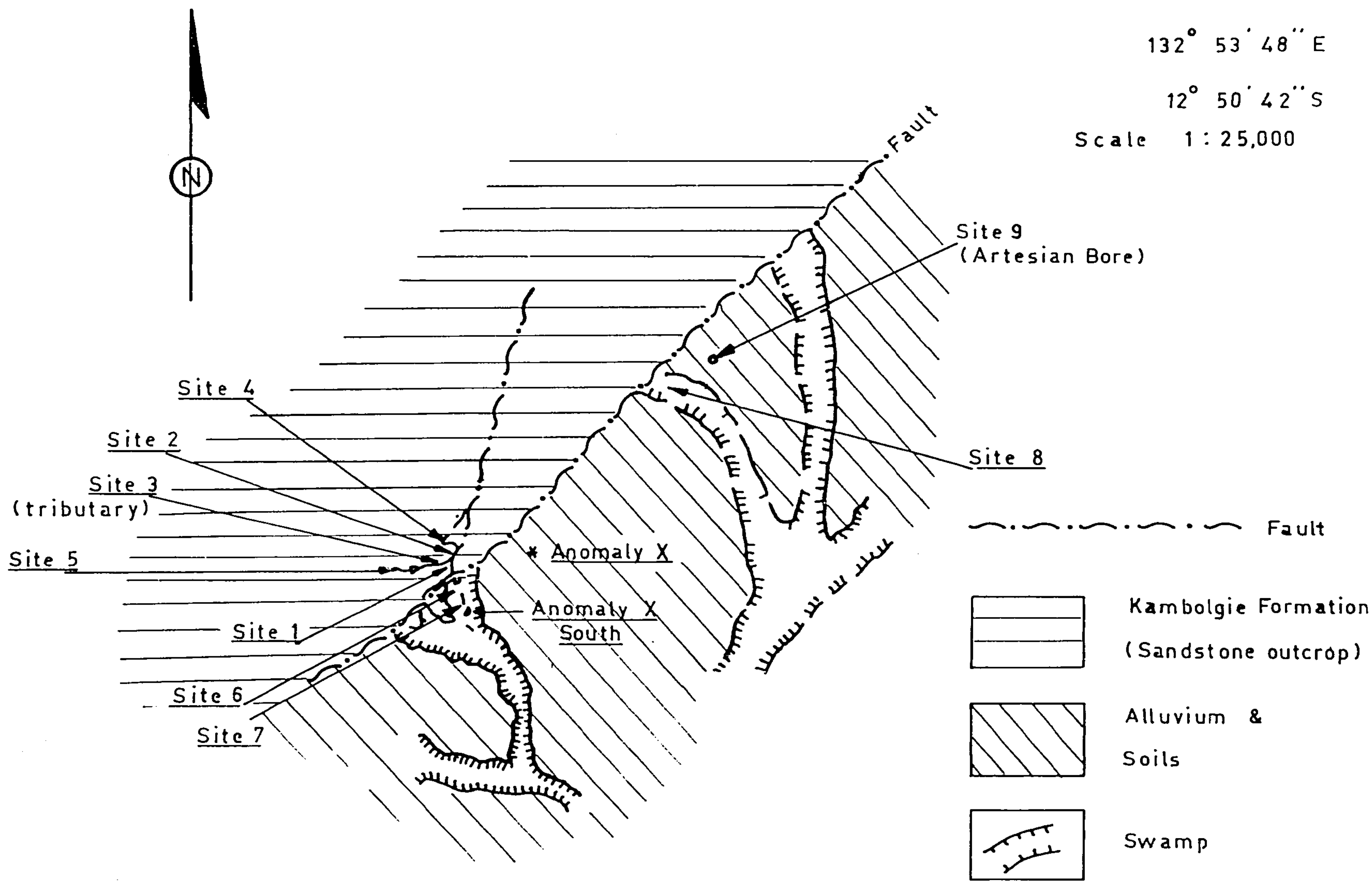
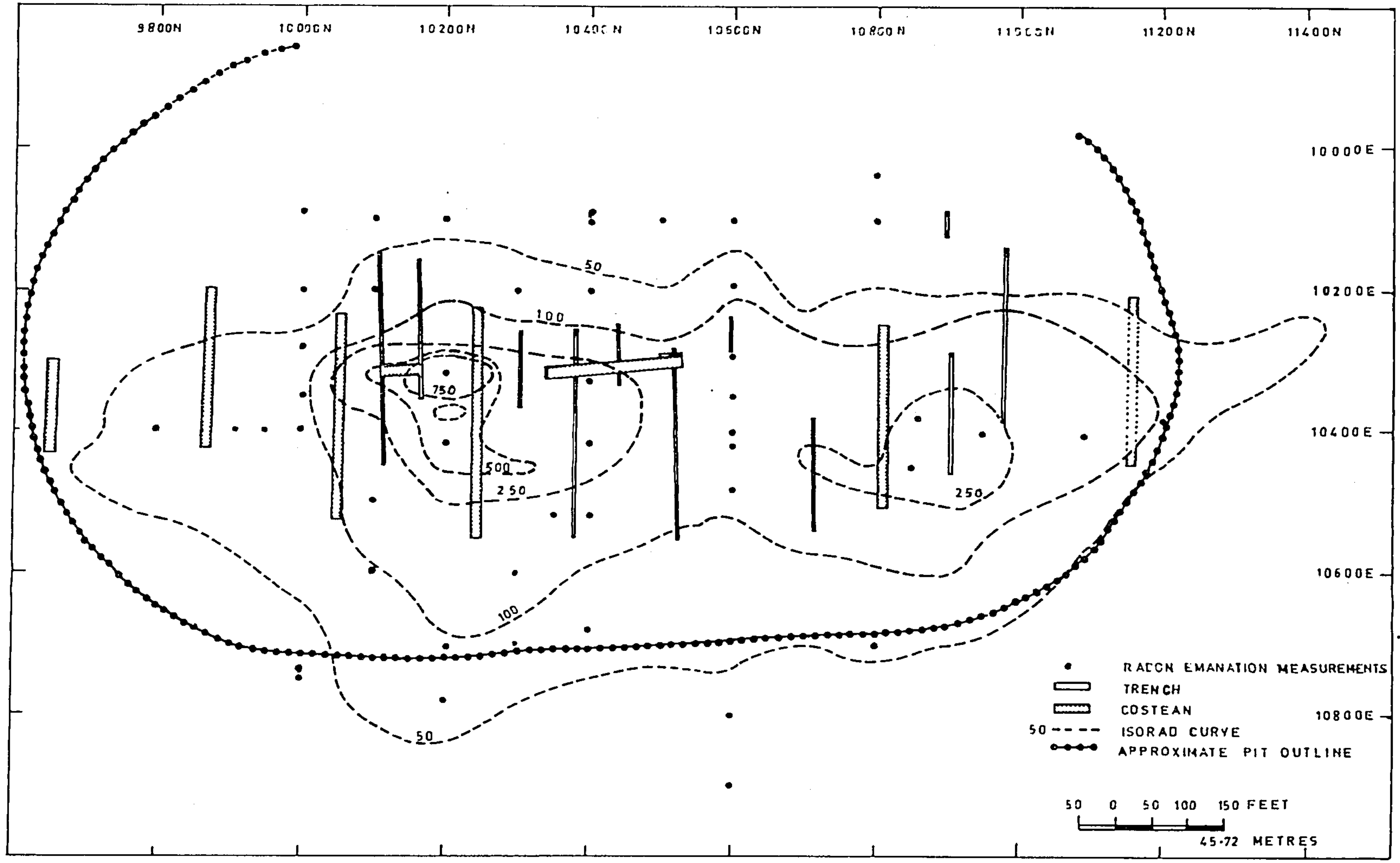


FIGURE 8. VARIATION OF WL AND RADON IN AIR CONCENTRATION DURING THE NIGHT 27-28/7/78



MAP 1. LOCATION OF SAMPLING SITES AT X-ANOMALY



MAP 2. KOONGARRA ORE BODY I SHOWING LOCATION OF COSTEANS AND SITES OF RADON EMANATION RATE MEASUREMENTS

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