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PREDICTIONS FOR RADON SOURCES AND SOME RELATED CONCENTRATIONS FOR THE KOONGARRA URANIUM DEVELOPMENT, NORTHERN TERRITORY

THE AUSTRALIAN ATOMIC ENERGY COMMISSION

PREPARED BY D.R. DAVY

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PREDICTIONS FOR RADON SOURCES AND SOME RELATED CONCENTRATIONS FOR THE KOONGARRA URANIUM DEVELOPMENT (NORTHERN TERRITORY)

by

D.R. Davy

ABSTRACT

Estimates are provided for the total quantity of radon that would be released per day as a result of the proposed development of the Koongarra uranium deposit. The estimated quantity varies with the phase of development; it is greatest (560 GBq d^{-1}) during phase II, at which time the ore stockpile and the tailings dam contribute 70% of the total.

Predicted concentrations for radon daughters near the bottom of the openpit also vary with phase of development but, in this case, atmospheric stability is the major variable. During phase II, working level (WL) concentrations are expected to vary from 0.035 to 4.6 WL at a height of 1 m above the pit floor as atmospheric stability changes from unstable to neutral conditions.

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1. INTRODUCTION

This paper reports on the results of some calculations by the Australian Atomic Energy Commission (AAEC) on behalf of Noranda Australia Ltd. for the proposed development of the uranium deposit at Koongarra, N.T.

The results are in two parts. First, predictions for radon source terms arising from waste rock, ore stockpiles, tailings dam, evaporation pond and the mine are provided. Second, an attempt is made to predict the concentration of radon and its daughters that will develop in the operating openpit mine during typical daytime and nighttime conditions.

The predictions employ input data from two sources. Queen's University (Canada) measured diamond drill core samples for estimates of emanation rates and emanating power of the ore; in the text this work is credited explicitly. Second, the AAEC made field measurements of radon daughter concentrations and related quantities at Koongarra over a two week period during June 1978. A report on this work has been prepared [Davy et al. 1978]; in the text this work is often referred to implicitly.

The reader needs to be aware that the theory of radon diffusion is poorly developed. The application of analytical expressions involves assumptions and approximations that may not always be obvious. All radon diffusion calculations involve transcendental functions (the dependent variable of one relationship being the independent variable of another) so analytical solutions are obtained by assuming that constant relationships hold. Examples of interrelated variables from the topics included here are, with respect to prediction of radon daughter concentrations, the radon diffusion coefficient, the (atmospheric) coefficient of vertical turbulent diffusion, the heat flux and the (atmospheric) temperature gradient and, with respect to radon diffusion in soil, porosity, emanating power and the radon diffusion coefficient. Further, the boundary conditions used to reach the analytical solutions are not true under all conditions. For example, the condition that the radon concentration → zero at the soil-atmosphere interface does not hold under nighttime conditions.

2. SYMBOLS AND DEFINITIONS

Z	vertical distance into the medium: zero at the soil-atmosphere boundary; positive downwards when dealing with soil; positive upwards when dealing with the atmosphere.
D	pore diffusion coefficient for radon through the volume of the porous medium.
D_a	turbulent diffusion coefficient for radon in air.
S	porosity of the medium defined as the ratio of void volume to total volume.
k	bulk diffusion coefficient ($D = kS$).
λ	the radon decay constant (2.1×10^{-6} s^{-1}).
ρ	density of medium.
J_v	volume emanation rate of radon (Bq m^{-3} s^{-1}).
J_s	surface emanation rate of radon (Bq m^{-2} s^{-1}).
J_o	value of J_s at $Z = 0$.
G	grade of ore in % U_3O_8 (grade of U = 0.85 G).
A	specific activity of ore assumed to be in equilibrium (6.0×10^{-3} G in pCi g^{-1} s^{-1}; 2.22×10^{-4} G in Bq g^{-1} s^{-1})
β	emanating power of ore ($\beta = J_v/\rho A$).
$C(Z)$	concentration of radon per unit volume at height Z.
C_o	concentration of radon at Z = zero.
K_h	eddy heat exchange coefficient.
$T(Z)$	air temperature at height Z.
T_o	air temperature at ground surface.
Γ	adiabatic lapse rate.

3. PREDICTION OF RADON DAUGHTER CONCENTRATIONS IN THE MINE PIT

Opencut mining practices create a pit floor that is composed of extensively shattered rock to a depth of $\geqslant 1$ m. This, together with the fact that the Koongarra pit is designed to place the high grade ore (0.5% U_3O_8 for phase I, 1.54% for phase II, 1.08% for phase III and 0.64% for phase IV) at the centre of the pit, means that estimates for occupational exposure can be based on calculations that only consider the floor of the pit.

3.1 Factors Influencing Radon Concentrations

The list of factors influencing radon emanation and air concentrations in an operating pit is shorter than that for the surface of the earth. Because of the slowness in changes to the gross weather patterns, barometric pressure effects can be ignored; so too can effects due to location and motion of the ground water table, since the pit will be maintained in a depression cone. For at least the second and subsequent phases, wind stress can also be ignored since the scale of the eddies generated by the rim of the pit will be small compared with the depth of the pit. There are then three main variables influencing the air concentration of radon in the pit: the solar heat flux (H); the concentration (C_o) of radon at the air-soil boundary of the pit floor; and the air temperature gradient within the pit. In turn C_o is controlled by the porosity of the ore (S), its grade (G), its pore diffusion coefficient (D) and its emanating power (ß) since these determine the magnitude of the surface emanation (J_o) from the pit floor. Approximate relationships between the main variables are [Ta-Yung Li 1974]:

$$C(Z) = C_o + \frac{\rho_a C_p J_o}{H \chi} \left[T(Z) - T_o + \Gamma Z \right] , \qquad \ldots \qquad (1)$$

where χ (0.1) is a constant, C_p is the specific heat of air (0.24 cal g^{-1}), ρ its density (10^{-3} t m^{-3}) and H, for nighttime, has a value of approximately -10^{-3} cal cm^{-2} s^{-1} for neutral and stable atmospheric conditions [Mann 1966].

The major assumptions leading to equation (1) is that $D_a = \chi K_h$ and that, for unstable atmospheric conditions, H = constant $(\Delta T)^{3/2}$.

3.2 Values of Variables

3.2.1 Value for C_o

An estimate for C_o for stable conditions can be obtained in two ways. First, the vertical profile of radon concentration was measured on two occasions at Koongarra. This curve can be extrapolated to Z = zero and normalised to account for ore grade using measured and calculated surface emanation rates. Unfortunately, both vertical profiles were measured at times when atmospheric stability was decreasing. Thus C_o values arrived at in this way would be underestimates. Alternatively, values of C at Z = 40 cm (above ground) during stable conditions can be extrapolated to Z = zero. This extrapolation is uncertain.

The vertical profiles lead to extrapolated values of C_o of 93 and 130 mBq dm^{-3}. The emanation rate measured at the location of these measurements was 0.7 Bq m^{-2} s^{-1}.

Twelve measured values for radon concentration at a site near the centre of the ore body (10200 N 10320 E), where J = 22.4 Bq m^{-2} s^{-1} and Z = 40 cm, ranged from 0.7 to 25.4 Bq dm^{-3} with an average of 5.7 Bq dm^{-3}. Using the vertical profile curve for 0630 hours on 28/6/1978 suggests that C_o would be in the region of 9.7 Bq dm^{-3} whereas that for 1840 hours on 27/6/1978 leads to 6.3 Bq dm^{-3}. If direct proportionality between J_o and C_o is assumed, then the vertical profile data suggest that C_o = 3.6 Bq dm^{-3} when J_o = 22.4 Bq m^{-2} s^{-1}. As previously mentioned, this value is expected to be too low.

If the highest value of C (Z = 40) is discarded as being of short duration origin the remaining 11 values average at 3.9 Bq dm^{-3} which suggests C_o values of 6.6 and 4.3 Bq dm^{-3} for the 2 measured profiles. In the following discussion, C_o for J = 22.4 Bq m^{-2} s^{-1} is taken as 5.5 Bq dm^{-3} under stable conditions.

Because no meaningful value for C(Z) under unstable conditions was obtained in the field with the methods and counting periods employed, the following predictions for unstable conditions are based on measured concentrations of radon daughters over areas of measured J_s during still neutral conditions; these are then normalised to calculated J_s values for the pit floor and the effect of temperature gradients is then inferred from equation 1.

3.2.2 Value for J

Queen's University measured the volume emanation rates of 62 quarter core samples of unweathered ore. Using grade estimates based on γ activity measured with a monitor designed for exploration use, they reported a correlation of:

$$(J_v)\ \mathrm{Ci\ cm^{-3}\ s^{-1}} \times 10^{-16} = 12 + 4.94\ G(\%U_3O_8)$$

with $r^2 = 0.69$.

Uranium assays on 12 of the samples revealed substantial differences between estimated grade and the uranium content (e.g. estimated 2.72% measured 0.39%). The 12 samples were reassayed using the delayed fission neutron method and the chemical results were confirmed. A probable explanation is that some of the samples have marked ^{238}U-^{226}Ra disequilibrium, particularly as some samples have an emanation power of > 100% inferred from the U content. Within the time restraints placed on the survey, the question of disequilibria could not be investigated. However results on 'run-of-mine' samples indicate that on average the Koongarra orebody is in U-Ra equilibrium.

Under these circumstances, the assessment of the relationship between grade and volume emanation rate was restricted to the 12 samples for which grade values were available. A power series fit yielded:

$$J_v = 25.5\ G^{0.425} \qquad r^2 = 0.685$$

in units of Ci $cm^{-2}\ s^{-1} \times 10^{-16}$ and % U_3O_8,
whereas a linear regression yielded:

$$J_v = 6.0 + 61G \qquad r^2 = 0.81$$

in units of Bq $m^{-3}\ s^{-1}$ and % U_3O_8.

The latter relationship was used to estimate J_o via the expression [Kramer et al. 1964]:

$$J = DC_A \sqrt{\frac{\lambda}{D/S}}\ \exp\left(\left(-\frac{\lambda}{D/S}\right)^{\frac{1}{2}} z\right),$$

where $k = \frac{D}{S}$, $C_A = \frac{J_v}{S\lambda}$ and $Z = 0$ for J_o,

therefore $J_o = \frac{k}{\lambda} J_v \sqrt{\frac{\lambda}{k}}$.

In the field, k was estimated at $1.0 \times 10^{-6}\ m^2\ s^{-1}$, so J_o values for the various phases of pit development are:

Predicted Ore Grade (% U_3O_8)	J_v (Bq $m^{-3}\ s^{-1}$)	J_o (Bq $m^{-2}\ s^{-1}$)	C_o (Bq dm^{-3})
0.5	37	26	6.4
1.54	100	69	17
1.08	72	50	12.3
0.64	45	31	7.6

3.3 Predicted Radon Concentration

The predictions were made for Z = 1 m since Noranda proposes to mine during one shift (daytime) per day and blast at the end of shift, and because 1 m is a reasonable approximation to the height of the breathing zone for a powder monkey.

Predictions are supplied for four temperature gradients:

$-\ 0.03^{o}C\ m^{-1}$ (3Γ)	Unstable atmospheric conditions
$-\ 0.01^{o}C\ m^{-1}$	Neutral atmospheric conditions
$+\ 0.01^{o}C\ m^{-1}$	Stable conditions (Pasquill Class F)
$+\ 0.05^{o}C\ m^{-1}$	Stable conditions (Pasquill Class G)

For unstable conditions, the inferred radon concentration was derived from the measured working level (WL) concentration after normalising for J_o and assuming the working level ratio (WLR, the ratio between existing and equilibrium WL concentrations) to be 0.1. This value is greater than WLR values measured in the field under very light breeze neutral conditions (0.08).

Table 1 lists the predicted values. Note that C(Z) decreases with increasing height for both stable (H -ve ΔT +ve) and unstable (H +ve ΔT -ve) conditions.

For heights greater than some tens of metres, the diurnal variation in radon concentration will not peak under neutral atmospheric conditions but will when inversion conditions are breaking up. This is illustrated in figure 1 which has been redrawn from Ta-Yung Li [1974].

The reasonableness of the predicted values listed in table 1 can, to some extent, be judged on the highest concentration of radon detected 40 cm above the ore body; this was 25.4 Bq dm^{-3} (690 pCi ℓ^{-1}).

3.4 Predicted Working Level Concentrations

It takes some time for the radon daughters to grow into equilibrium with the radon gas. Evans [1969] provides, in a convenient form, equations and curves for WL per 100 pCi ℓ^{-1} as a function of time from initially pure radon. By way of illustration, some of these values are: 12 min, 0.2; 28 min, 0.4; 50 min, 0.6; 85 min, 0.8. Thus, in the context of this section, the average WL concentration in the openpit under stable atmospheric conditions can be taken to be 0.01 times the average radon concentration in pCi ℓ^{-1}. During phase II of the pit development, working levels 1 m above the pit floor would be in the region of 5 WL compared with ∿ 2 WL in phase I. Again, field measurements provide some confidence in these numbers; for a seven-day period in late June, when inversion conditions were frequent, the average nighttime WL at 40 cm above the surface of the ore body was about 1.3 WL.

4. PREDICTION OF RADON SOURCE TERMS

4.1 Waste Rock

Queen's University measured volume emanation rates from 24 samples of weathered ore for which assay grades are available. As in the case of unweathered ore, there were considerable discrepancies between measured and estimated grades; again, there is uncertainty in the degree of disequilibrium between ^{238}U and ^{226}Ra for each sample. When determining the relationship between ore grade (G) in % U_3O_8 and J_v (in Bq m^{-3} s^{-1}), three results were deleted since their grades (1.3, 2.45 and 3.2% U_3O_8 were well outside the planned grade limit for waste rock (0.015%). A power curve fit to the remaining 21 samples yielded:

$$J_v = 75\ G^{0.675} \qquad (r^2 = 0.515)$$

and a linear regression yielded:

$$J_v = 3.5 + 141\ G \qquad (r^2 = 0.486)$$

Thus a relationship between J_v and G is tenuous at best so this estimation of radon released from waste rock assumes that all waste has a grade of 0.015% which is the planned limit for separating waste from ore.

Three field measurements on a mock heap of overburden material of average grade 0.015% gave estimates for J_o of 0.5, 0.7 and 3 Bq m^{-2} s^{-1}; direct measurements at three locations from which material for the mock heap had been taken gave values for J_o of 1.2, 4.1 and 3.4 Bq m^{-2} s^{-1}.

The power curve fit to the J_v data predicts J_v = 4.4 Bq cm^{-3} s^{-1} for a grade of 0.015%. Two measurements on material with grades near this value were made by Queen's University:

$$0.012\%\ J_v = 7; \quad 0.017\%\ J_v = 2.9\ \text{Bq m}^{-3}\ \text{s}^{-1}.$$

Using the 4.4 Bq m^{-3} s^{-1} value (which corresponds to an emanation power of 70%):

$$J_o = \frac{k}{\lambda} \cdot J_v \sqrt{\frac{\lambda}{k}} \qquad (k = 10^{-6}\ \text{m}^2\ \text{s}^{-1})$$

$$= 3\ \text{Bq m}^{-2}\ \text{s}^{-1}.$$

All the field work, and probably the Queen's University data for grades near 0.015%, relate to extremely weathered material. It could be expected that waste material characterised as 'weathered schist' and 'fresh schist' would have lower emanating powers and therefore lower J_v and J_o values. Porosity is a measurable quantity that could be used to adjust values of J_o.

Porosity of the mock waste heap was measured at 0.28; that for weathered schist is derived from the 'Tailings Retention Study' (Table E8-II, Vol 5) presented to the Ranger Inquiry and yields a value of 0.13. In the case of fresh schist, no laboratory measurements seem to be available, but its porosity can be equated to the water content (0.03) of the saturated material.

Since J_v is assumed to be essentially unknown for weathered and fresh schist waste rock, the method adopted was to normalise the measured value of J_o for the overburden by $\sqrt{S}$ since

$$J_o = DC_A \sqrt{\frac{\lambda}{D/S}}$$

This normalisation is certainly not exact since both D and C_A also have some dependence on S; in effect, it is being assumed that these dependencies are self cancelling.

Thus the values assumed for surface emanation (in Bq m^{-2} s^{-1}) of waste rock of 0.015% U_3O_8 are:

Material	S	J_o
Overburden	0.28	2.0
Weathered schist	0.13	1.4
Fresh schist	0.03	0.7

Table 2 summarises the radon release from waste rock based on these estimates. It can be assumed to occur uniformly during a 24 hour day.

4.2 Weathered Ore Stock Pile

The surface emanation rate for a mock pile of weathered ore of grade 0.44% was measured in the field at 27.3 Bq m^{-2} s^{-1}. Because of the small size of the heap, a correction to this value was determined, in part, from a transport computer code and, in part, from a measurement of the concentration of radon in ore air at 50 cm depth. This led to a predicted surface emanation of 93 Bq m^{-2} s^{-1}.

The power curve fit to the Queen's University data for J_v of weathered ore predicts a value of 43 Bq m^{-3} s^{-1}. The one experimental point for grades near 0.44% is in agreement with this value (0.43% J_v = 47 Bq m^{-3} s^{-1}). Thus the predicted value for J_o is $\sim$ 30 Bq m^{-2} s^{-1}. This agrees with the actual experimental result but not with the corrected value.

A further check against the field data is available through comparison of the concentration of radon in the ore air. With J_v = 43 Bq m^{-3} s^{-1} and S $\sim$ 0.4 the predicted value for C is $\sim$ 50 kBq dm^{-3}. Since

$$C(Z) = C_o \left(1-e^{-\left(\frac{\lambda}{k}\right)^{\frac{1}{2}} Z}\right)$$

the expected value at Z = 50 cm is 26 kBq dm^{-3}. The measured value was 14.6 kBq dm^{-3}. Thus a correction for the smallness of the mock heap is necessary. A further indication of the magnitude of the correction factor is to calculate the factor applicable to an infinite homogeneous source of depth equal to the depth of the mock heap (80 cm). An appropriate equation for the Z dependence [following Culot et al. 1973] is:

$$J_o \propto kq \operatorname{Tanh}(qZ) ,$$

$$\text{where} \quad q = \left(\frac{\lambda}{k}\right)^{\frac{1}{2}}$$

Thus, the correction factor for depth only is $\sim$ 1.3, whereas the factor applied to account for the finite area and depth was 3.4.

It is assumed that both the inferred surface emanation rates from the mock heap and the Queen's University data on J_v are correct and that the difference is accounted for by ageing of the ore (e.g. surface adsorption of leached ^{226}Ra) since the mock heap has existed for approximately seven years. The Noranda proposal calls for the oxidised ore to be stockpiled at the beginning of the operation (phases I and II) and subsequently used as a blend feed to the mill over the next 12 years. Below it is assumed that for phase I of the operation J_o is as calculated from J_v, for phase II it is 1.6 times higher and for phases III and IV it is 3.4 times higher. Thus for the weathered ore stockpile:

Phase	Grade (% U_3O_8)	J_v (Bq m^{-3} s^{-1})	J_o (Bq m^{-2} s^{-1})
I	0.074	13	9
II	0.082	14	15
III	0.066	12	26
IV	0.037	8	17

Table 3 summarises the daily radon release from the weathered ore stockpile calculated in this way.

4.3 Openpit

Using the methods for estimating the required J_o as outlined for waste rock and ore stockpile, the quantity of radon released daily from the openpit can be estimated. Table 4 contains the details.

4.4 Tailings Dam

Davy et al. [1978] estimate that the daily release of radon from the tailings dam will be 3.7 GBq ha^{-1} d^{-1}. The area of the proposed dam is 70 ha. Thus the estimated release is $\sim$ 260 GBq d^{-1} (7 Ci d^{-1}). This estimate takes no account of the proposed 2 m of water over the tailings during the operating phase. In evidence to the Fox Inquiry (e.g. as given by R.M. Fry), a substantial reduction factor was claimed for the water cover although estimates of the daily release assumed that only the tailings were saturated with water.

Reasons for not including in this report any reduction factor arising from the presence of water cover are:

- More than 99% of the radium is not dissolved from the ore during the sulphuric acid leach milling process. Experimental evidence with ground ore indicates that emanating power is independent of percentage saturation, except perhaps in the 0-3% and 95-100% ranges where reductions in emanating power may occur [Austin & Droullard undated].
- The estimate is based on measurements of existing tailings dams which are characterised by an air dry surface, a dry surface crust of a few centimetres thickness and a saturated slurry below it which liquefies (i.e. separates free water on disturbance).
- Convective and wind driven currents will ensure the water is well mixed.
- There is no experimental evidence for a reduction in radon emanation from tailings material as a result of a water cover.

For the same reasons, it is assumed that the long-term management of the tailings, which involves topsoil over a clay cover, sloped to provide runoff and minimise seepage, will not significantly change the radon emanation rate over and above that due to the presence of the barren clay and topsoil.

4.5 Pit Dewatering

It is estimated that 4 x 10^3 m^3 of water will be transferred daily to the evaporation pond and that the majority of this water would be from pit dewatering.

The radon concentration in water from the ore body is not known but field work provided an estimate of 11 kBq dm^{-3}. Thus the daily release of radon from this source is expected to be in the region of 40 GBq d^{-1}.

4.6 Evaporation Pond

Dames and Moore, the consultants working on behalf of Noranda Australia Ltd measured the concentration of ^{226}Ra in six samples of bore water from the ore body. Their results have a mean of 13.1 pCi ℓ^{-1} ($\sim$ 0.5 Bq dm^{-3}) with a standard deviation of 8.3 pCi ℓ^{-1}. During 1972, the AAEC measured the ^{226}Ra in artesian water encountered during the diamond drilling exploration program at 26 pCi ℓ^{-1}. A further bore water sample assayed 16 pCi ℓ^{-1}. (Co-ordinates 646755, 1:50000 map series).

The total dissolved solid (TDS) content of water reaching the evaporation pond is difficult to predict. Since the TDS of bore water is $\sim$ 120 mg ℓ^{-1}, it will be low; therefore the percentage of radon generated by the radium contained in the water arising from pit dewatering that will reach the atmosphere will be high. A lower limit to this percentage is 50%, i.e. the figure applicable to the peat formed where seeps occur at the foot of the escarpment [Conway & Davy 1974]. Since the evaporation pond will be shallow and wind-driven motion will provide an efficient mechanism for emanation of radon, it has been assumed that all radon generated from the contained radium will be released irrespective of the existing water status of the pond. Thus, the daily radon release from this source will increase linearly with time, with the annual increase being the volume of water added (1.5 x 10^6 m^3) multiplied by its ^{226}Ra content ($\sim$ 0.6 Bq dm^{-3}) and the radon production rate (0.18 Bq d^{-1} per Bq ^{226}Ra. i.e. 0.16 GBq d^{-1}).

4.7 Milling Process

The milling proposals call for the treatment of 1000 tonnes of ore per day at an average feed grade of 0.306%. Some of the radon contained in the ore will be lost to the atmosphere during the ore grinding process. An estimate of this quantity was arrived at in the following way.

The linear regression to Queen's University data for unweathered schist yields $J_v = 25$ Bq m^{-3} s^{-1} for a corresponding $\beta = 13.5\%$ when $G = 0.306\%$.

The power curve fit to Queen's University data for weathered schist yields $J_v = 34$ Bq m^{-3} s^{-1} for a corresponding $\beta = 18.4\%$.

It is assumed that the grinding process would liberate that quantity of radon which represents the quantity of radon held in the pores of the unweathered schist, i.e. C_A S/ρ per tonne. At a 1000 t d^{-1} throughput, this corresponds to 4.4 GBq d^{-1}. Note that this amount is ∿ 12% of the radon that would be contained in the ore at equilibrium. Since the quantity of radon held in the pores of weathered schist would exceed that held by unweathered schist, the release is seen to occur immediately on grinding.

4.8 Total Daily Release

Table 5 provides the estimates for the total daily release of radon from the various phases proposed for the development of the Koongarra uranium deposit. The component with the greatest uncertainty is that related to pit dewatering since there is limited knowledge not only of the present concentration of radon in groundwater from the ore body, but also of the degree by which it will change during the mining operation.

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TABLE 1

PREDICTED RADON CONCENTRATION 1 m ABOVE THE FLOOR OF THE OPENPIT

Phase of development	Temperature Gradient ($^oC\ m^{-1}$)	C_o ($Bq\ \ell^{-1}$)	Predicted C ($Bq\ \ell^{-1}$)
I	- 0.03	6.4	0.4
	- 0.01		6.4
	0.015		6.0
	0.04		4.5
II	- 0.03	17	1.3
	- 0.01		17
	0.015		16
	0.04		12
III	- 0.03	12.3	0.9
	- 0.01		12.3
	0.015		11.7
	0.04		8.7
IV	- 0.03	7.6	0.5
	- 0.01		7.6
	0.015		7.2
	0.04		5.4

TABLE 2

PREDICTED DAILY RADON RELEASE FROM THE WASTE ROCK

Development Phase	Material	Area (m^2)	Daily Release GBq d^{-1}	Daily Release Ci d^{-1}
I	Overburden	3.6×10^4	6.2	0.17
	Weathered	1.43×10^5	17.3	0.47
		Total	24	0.64
II	Overburden	8.9×10^4	15.4	0.42
	Weathered	3.0×10^5	36.3	0.98
	Fresh	2.1×10^5	12.7	0.34
		Total	64	1.74
III	Overburden	3.6×10^4	6.2	0.17
	Weathered	2.0×10^4	2.5	0.07
	Fresh	2.36×10^5	14.3	0.39
		Total	23	0.63
IV	Overburden	3.6×10^4	6.2	0.17
	Weathered	2.0×10^4	2.5	0.07
	Fresh	2.5×10^5	15.1	0.41
		Total	24	0.65

TABLE 3

PREDICTED DAILY RADON RELEASE FROM THE WEATHERED ORE STOCKPILE

Development Phase	Area (m^2)	Daily Release GBq d^{-1}	Daily Release Ci d^{-1}
I	9.0×10^4	70	1.9
II	1.0×10^5	130	3.5
III	8.2×10^4	184	5.0
IV	5.9×10^4	87	2.3

TABLE 4

PREDICTED DAILY RADON RELEASE FROM THE OPENPIT

Development Phase	Material	Grade	J_V	J_o	Area	Daily Release	
		(% U_3O_8)	(Bq $m^{-3}s^{-1}$)	(Bq $m^{-2}s^{-1}$)	(m^2)	(GBq d^{-1})	(Ci d^{-1})
I	WS	0.005	2.1	1.5	3.8x10^4	4.9	0.13
	"	0.01	3.4	2.3	2.7x10^4	5.4	0.15
	"	0.029	6.9	4.8	1.6x10^4	6.6	0.18
	"	0.093	15.	10.4	2.2x10^4	20.	0.53
	"	0.497	47	32	5.3x10^3	14.7	0.40
					Total	52	1.4
II	WS	0.005	2.1	1.5	2.9x10^4	3.8	0.10
	"	0.01	3.4	2.3	7.1x10^3	1.4	0.04
	"	0.029	6.9	4.8	2.6x10^3	1.1	0.03
	FS	0.005	0.7	0.5	1.0x10^4	0.4	0.01
	"	0.01	1.1	0.8	3.5x10^4	2.4	0.07
	"	0.028	2.2	1.5	5.7x10^3	0.7	0.02
	"	0.108	12.6	8.7	9.5x10^3	7.1	0.19
	"	1.54	100	69	6.7x10^3	40	1.08
					Total	57	1.5
III	WS	0.005	2.1	1.5	2.9x10^4	3.8	0.10
	"	0.01	3.4	2.3	1.4x10^4	2.8	0.08
	"	0.029	6.9	4.8	2.6x10^3	1.1	0.03
	FS	0.005	0.7	0.5	1.7x10^4	0.7	0.02
	"	0.01	1.1	0.8	5.0x10^4	3.5	0.09
	"	0.028	2.2	1.5	4.9x10^3	0.6	0.02
	"	0.097	11.5	7.9	1.1x10^4	7.5	0.20
	"	1.08	72	50	4.9x10^3	21	0.57
					Total	41	1.1
IV	WS	0.005	2.1	1.5	2.9x10^4	3.8	0.10
	"	0.10	3.4	2.3	1.4x10^4	2.8	0.08
	"	0.029	6.9	4.8	2.6x10^3	1.1	0.03
	FS	0.005	0.7	0.5	1.6x10^4	0.7	0.02
	"	0.01	1.1	0.8	7.2x10^4	5.0	0.14
	"	0.028	2.2	1.5	6.1x10^3	0.8	0.02
	"	0.1	12	8.3	7.4x10^3	5.3	0.14
	"	0.64	45	31	1.4x10^3	3.8	0.10
					Total	23	0.6

WS	weathered schist
FS	fresh schist

TABLE 5

TOTAL DAILY RADON RELEASE (GBq d^{-1})

Stage of Development		I	II	III	IV
Source	- waste rock	24	64	23	24
	- ore stockpile	70	130	184	87
	- openpit	52	57	21	23
	- tailings dam	260	260	260	260
	- dewatering	40	40	40	40
	- evaporation pond	0.2	1.0	1.8	2.6
	- mill	4.4	4.4	4.4	4.4
Total		451	556	534	441

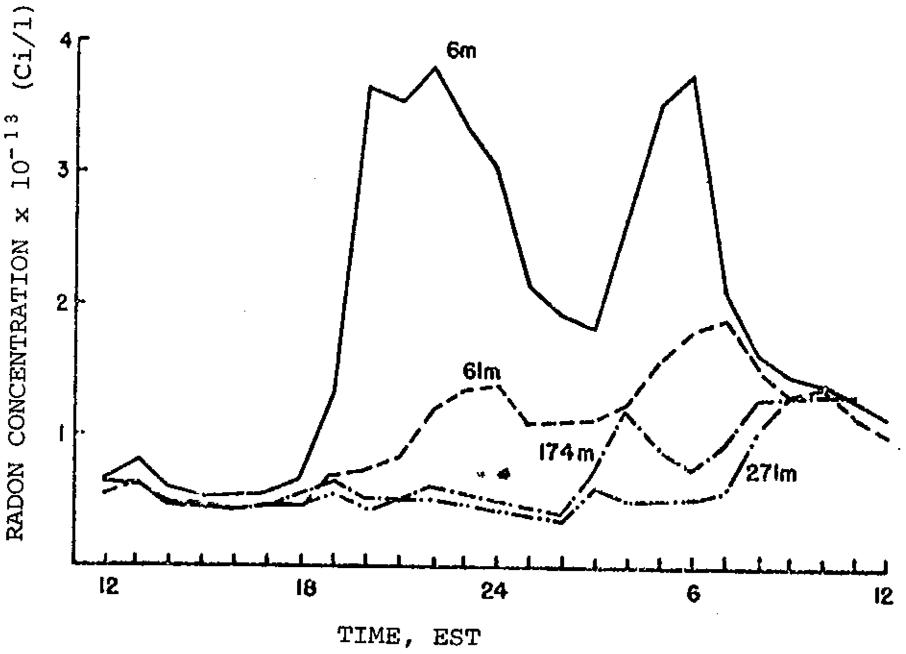

Fig.1 The curves represent hourly values of radon concentrations measured at heights of 6, 61, 174 271 m above the ground from noon to noon of June 7-8 1970.
(from Ta-Yung Li [1974])