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PRACTICAL DIFFICULTIES IN DETERMINING ^{222}Rn FLUX DENSITY IN UNDERGROUND U MINES

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ABSTRACT

Radon-222 flux density, J, has been determined in a number of locations in an underground U mine. Measurements were conducted using two different methods, namely, the fluxmeter 'can' method and the Two Point Measurement (2PM) method consisting of measuring the ^{222}Rn concentration at two different points a distance apart within a given section of the mine. Several mine models were used for determining J by the 2PM method. The first method, i.e., fluxmeter method, provides J through the mine walls, whereas the second method (2PM) gives an estimate of the apparent J in the section of the mine under consideration. The 2PM method is sensitive to sources and sinks of ^{222}Rn other than mine walls, as well as mining operations and mining activities of a diverse nature. Although measurements by the two methods should be, in principle, reasonably close, significant differences between the two methods were found and also between the different mine models used in the 2PM method. The practical and theoretical difficulties in determining J by the two methods are discussed.

Key words: Radon; Flux density; Uranium; Mines.

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INTRODUCTION

Reliable experimental values of ^{222}Rn emanation rates, k, from underground U mine walls enable theoretical determination of ^{222}Rn and ^{222}Rn progeny levels in U mine atmospheres. Theoretical prediction of radioactivity levels in mine environments is important from the health physics standpoint, and provides a great engineering aid in the planning and design of underground mine ventilation systems.

Radon-222 flux density, J, across the mine wall/air interface is another very useful variable which is simply related to the emanation rate provided the geometry of the mine volume of interest, i.e., V, is known. In its simplest expression k and J are related to the total surface area, S, of V as follows: $k = JS$.

The ^{222}Rn flux density across the mine wall/air boundary can be experimentally determined by means of a fluxmeter, which in its simplest version assumes the shape of an open-ended cylinder or container sealed to, or driven, into the wall. The flux density, J, can be calculated from measurements of the ^{222}Rn concentration in the container versus time according to well established procedures (Kraner et al. 1964; Wilkening et al. 1972; Countess 1976; Fleisher 1980; Schiager 1980; Bigu 1984; Kearney and Krueger 1987).

Alternatively, J can be estimated by the two point measurement (2PM) method. This method consists of taking air samples at two different locations or points, a distance L apart, within the mine volume of interest, and measuring the ^{222}Rn concentration in the samples. From the geometry of the volume V and the values of the ^{222}Rn concentration upstream and downstream of V, the variable J can be determined (Bigu 1988). The reader should be aware that the downstream air sample should be taken a time L/v after the upstream

sample, where v is the air linear velocity. However, because of the relatively long radioactive half-life of ^{222}Rn (~3.8 d), the radioactive decay of ^{222}Rn in V is negligible provided L is not too large or v too small. Under these circumstances, the two measurements can be taken simultaneously for simplicity. Simultaneous air sampling results in a great simplification of the experimental procedure because measurement of v is not always straightforward and accurate under most field conditions.

Depending on the mine geometry, physical and chemical characteristics of the rock formation, underground environmental variables, mining operations and activities, or the absence thereof, and airflow conditions, it can be shown that reliable measurements of J are considerably more complex and uncertain than might appear at first glance.

This paper presents data of flux density measurements conducted by means of ^{222}Rn fluxmeters and by means of the 2PM method. Data by the two methods are compared. Although the discussion presented here accentuates measurements of ^{222}Rn flux density in U mines, the methods discussed are of general applicability to other situations such as non U mines or any other partially or totally enclosed environment.

THEORETICAL BACKGROUND

There is a significant conceptual difference between the quantities determined by means of a fluxmeter and the 2PM method, namely:

1. A fluxmeter, when properly used, will provide a measure of the amount of ^{222}Rn crossing the wall/air boundary of the mine opening covered by the fluxmeter's cross-sectional area. When the ^{222}Rn emanation rate is normalized to the total cross-sectional area of the fluxmeter, a measure of the ^{222}Rn flux density is obtained. However, ^{222}Rn emanation across the wall/air interface is affected by both diffusion and convective transport

phenomena. The former depends on ^{222}Rn concentration gradients, whereas the latter depends on factors such as pressure and temperature differentials, and water seepage, if any.

The accurate measurement of ^{222}Rn flux density when both transport and diffusion mechanisms are considered is considerably more complex than when diffusion is the only important ^{222}Rn emanation mechanism. Because of the significant influence that transport mechanisms have in ^{222}Rn emanation, care should be exercised to carry out flux density measurements under constant barometric pressure conditions, and in the absence of water seepage. This may, however, not be representative of actual field conditions and the ^{222}Rn flux density measured will, therefore, not be truly representative of ^{222}Rn emanation from mine walls. If transport phenomena are ignored for simplicity's sake, ^{222}Rn flux density measurements using fluxmeters will be nearly independent of mine environmental conditions. except for barometric pressure variations. But more importantly, the measurements will not be affected by unit mining operations and general mining activities.

2. The 2PM method gives 'apparent' values for the flux density only as opposed to true emanation flux density from mine walls as measured by the fluxmeter method. This is so because ^{222}Rn sources other than those from mine walls also contribute to the ^{222}Rn concentration measured in the mine volume. Several discrete, local, sources of ^{222}Rn, in addition to extended, i.e., uniformly distributed, ^{222}Rn sources contribute to the total ^{222}Rn concentration observed in the mine. Some of these sources are listed below:

   a) ^{222}Rn dissolved in water percolating through mine walls;

   b) ^{222}Rn dissolved in water entering mine openings;

   c) ^{222}Rn released in local underground U leaching operations and U leaching

by natural processes;

d) ^{222}Rn 'pushed' by vehicles into a particular area from adjacent sites; and

e) ^{222}Rn released in rock-breaking operations, and other mining operations such as blasting, drilling, mucking and ore transportation.

Discrete (local) ^{222}Rn sources may lead to flux density measurements by the 2PM method differing substantially from ^{222}Rn flux density measurements by the fluxmeter method. Furthermore, by its very nature, the contribution to the radiation level in the mine from discrete sources of ^{222}Rn cannot be quantified easily.

A main difficulty with the 2PM method of flux density determination is a theoretical one. It arises with regard to the range and limit of applicability of the kinetic equations derived for the calculation of the flux. It has been shown (Bigu 1985; Beckman and Holub 1979) that for an underground U mine the concentration of ^{222}Rn and its progeny increase from zero at t = 0, at the 'origin', to a maximum, constant, value when steady-state conditions are reached at a distance from the origin for which the rate of growth of radioactivity equals its rate of decay. The distance from the origin at which this conditions occurs depends on air flow conditions, i.e., mine air residence time, and the particular radioisotope under consideration. Hence for distances from the origin equal to, or greater than a given value, the ^{222}Rn concentration does not increase any more and the method is no longer valid (see Appendix A).

Items 1 and 2 emphasize the complexity associated with ^{222}Rn flux density measurements. In addition to the difficulties encountered with the 2PM method, fluxmeter measurements are also characterized by other practical and theoretical difficulties, namely:

a) Basic theoretical assumptions on which the calculations and the analytical

procedure are based (see Appendix B).

b) Optimum time interval and time span for which accuracy of measurements is optimized and, hence, render useful and reliable data (see Appendix B).

c) Practical difficulties associated with the installation of fluxmeters on mine walls. Securing a tight fit and a good seal between the base of the fluxmeter and the quite irregular and uneven face of the walls represents a major hurdle.

In addition to items a) to c), other considerations of concern are rock fracture, fissures and cracks, and water seepage which can, in principle, affect ^{222}Rn flux density measurements greatly over relatively small regions or sections of the wall.

Radon-222 flux density determinations were conducted using fluxmeters and by the 2PM method. In the latter case, several mine models were used. Analytical expressions for J based on these mine models are given in Appendix A. Appendix B presents a brief discussion on fluxmeter techniques and methodology.

EXPERIMENTAL CONSIDERATIONS AND PROCEDURES

Although mostly ^{222}Rn flux density measurements will be discussed here, the data presented in this paper are but a small part of the data obtained during the course of a major radiation and meteorological survey conducted at an underground (UG) U mine over a period of one year (Bigu 1988).

The main objectives of the above study were to investigate the effect on ^{222}Rn, ^{220}Rn, and their respective progenies, of:

1. UG meteorological variables such as airflow rate, temperature, relative humidity, and barometric pressure;
2. Seasonal variations regarding item 1; and
3. unit mining operations, and other mining activities.

In addition to items 1 to 3, the study was also aimed at determining radioactivity source terms, i.e., ^{222}Rn and ^{220}Rn flux densities which were later to be used as input parameters in (radiation) mine models. One of the ultimate goals of this study was one of a very practical nature, namely, to be able to predict UG radiation levels under a variety of environmental working and mining conditions.

It is worthwhile emphasizing that the study was designed with some important limitations dictated by economical and other practical considerations as viewed by mine personnel. No attempt was made, for the sake of the study, to change mining work schedules and mining activities, or to select the most promising sampling locations based on theoretical grounds, or on experimental evidence. This would have resulted, undoubtedly, in severe disruption of routine mine operations, and hence, to significant financial losses to the mining company. The work and sampling strategy was decided using best judgement subordinated to practical constraints and circumstances.

The above limitations are quite acceptable to mine personnel who strongly advocate that in most cases the only practical way to conduct research work underground is by not imposing artificial constraints, that is, experimental conditions, to the 'natural' mining environment. Hence, it is expected that the outcome will reflect this philosophy, where, often, economic considerations and scientific necessity may need to compromise.

The bulk of the experimental work, except for ^{222}Rn fluxmeter density measurements, was conducted by mine personnel, who also designed the sampling strategy. The analysis of the data is the responsibility of the author.

Underground measurements were divided into four main categories, namely, radioactivity measurements, meteorological measurements, physical and geometrical measurements of the mine or mine sections, and observations of interest regarding the physical appearance of working and inactive locations

of the mine where measurements were taken, such as water conditions, leaching operations, and the like. Measurements were conducted using grab-sampling techniques.

A wide variety of mine sampling sites was selected for radiation and meteorological monitoring purposes. This selection was as follows:

1. Main general areas (sections) of the mine;
2. Within each section a number of locations of interest were identified such as exhaust ways, travel ways, shafts, main ramps, stopes and leaching areas; and
3. Within most locations two or more stations were chosen.

The areas (sections), locations and stations chosen were based on the following parameters of interest:

1. ^{222}Rn emanation characteristics of the rock formation;
2. Mining operation or activity;
3. Ventilation conditions;
4. Ground, floor, back and wall conditions;
5. Mine water conditions; and
6. Unusual conditions.

A detailed description and analysis of all the data collected during this project has been published elsewhere (Bigu 1988).

EXPERIMENTAL RESULTS AND DISCUSSION

Some data of interest are shown in Fig. 1 and Tables 1 to 5.

Figure 1 shows ^{222}Rn concentration for six different underground mine locations, namely, a footwall drive, a jumbo development heading, a travel way, a ramp in waste, an exhaust airway, and an airway. The histograms shown in Fig. 1 represent the distribution of ^{222}Rn concentration levels, i.e., number of measurements (normalized) versus ^{222}Rn concentration, at each

location during a period of one year. As would be expected, the lowest concentration levels occurred in airways, which are in theory fresh air intakes, but which in fact serve sometimes as partial second pass air-passages because of unintentional air recirculation paths in the ventilation network. Similarly, the highest concentration levels are usually found, for obvious reasons, in air exhaust airways. As previously indicated, ^{222}Rn concentration levels partly depend on environmental factors such as airflow rate and barometric pressure, the presence (or absence) of mining operations, the circulation of vehicles and machinery, workmen's traffic, and the physical conditions of the mine location, e.g., water drainage, water seepage through walls and roof, and other conditions. The measurements shown in Fig. 1 were carried out at a fixed sampling station for each of the above locations. The data of Fig. 1 are representative of average UG conditions. The data show a relatively broad range of ^{222}Rn concentration levels which are related to the above variables.

Table 1 shows the average ^{222}Rn flux density, J, measured at several wall positions in two main locations, namely, airway/travel way and an exhaust way. Six fluxmeters randomly distributed were used in the walls of each location. Measurements were conducted for a period of one year. These measurements were conducted under steady-state conditions, i.e., after radioactive equilibrium in the fluxmeter had been reached.

Flux density measurements under steady-state conditions were necessary in our case because of experimental difficulties in following the linear growth of ^{222}Rn concentration versus time necessary for more accurate determination of J (see Appendix B), and other practical constraints such as:

1. Fluxmeters require delicate procedures for their proper installation, in mine walls, and performance. For example, the open end of the fluxmeter can must be perfectly sealed to the mine wall to avoid leaks in the system.

Although special sealing materials were used for the purpose, drying and curing of these materials were not instantaneous. Hence, a substantial time-lag developed between the end of the sealing operation and the beginning of the measurements.

2. Because of the mine wall roughness, and in spite of all reasonable precautions taken, it is not possible to ensure that the system was and/or would remain absolutely leakproof. Hence, there is always a definite possibility that microleaks of sufficient importance may develop in the sealant reducing significantly the accuracy of the measurements.
3. Continuous or intermittent water seepage through mine walls, and into the sealed joint between the fluxmeter and the walls, weakens the bond between these two surfaces at the contact points making the system susceptible to leaks.
4. The low porosity (<1%) of the host rock (granitic formation), and the low permeability of the rock to ^{222}Rn makes transport of the latter into the fluxmeter volume a relatively slow process.
5. The 'initial' ^{222}Rn concentration in the fluxmeter volume after installation was, for obvious reasons, that corresponding to the mine location where the fluxmeters were installed. Flushing the ^{222}Rn out of the fluxmeters with compressed air or N_2 to initiate measurements with zero ^{222}Rn concentration was not practical or reliable enough.

For the reasons given above, and practical time constraints and limitations during a normal UG mine working shift, the growth in ^{222}Rn concentration from $t = 0$, for which the concentration is zero, could not be followed for a period long enough for reliable flux density measurements. Instead, measurements were conducted, as previously indicated, under steady-state conditions (i.e., for $t > \infty$ or $\lambda t >> 1$).

Inspection of Table 1 shows a great variability of J within a given

location for several wall positions. This is attributed to the different:

1. characteristics of the rock formation, i.e., presence or absence of fissures, cracks, and faults, and also of interface boundaries between different rock formations;
2. pore water content of the rock formation and water percolation through the rock;
3. ore grades;
4. fluxmeter leaks.

It should be noted that although exhaust airways have, in general, and for obvious reasons, higher ^{222}Rn concentrations than many other UG locations, this does not necessarily mean a high value for J because airways usually run through areas of low ore grade formations.

Table 2 shows the ^{222}Rn flux density calculated by the 2PM method using the Thomas-Epps Mine Model (TEMM) (see Appendix A) for three different mine locations. Calculations were done using the ^{222}Rn concentrations measured at pairs of points (i.e., sampling stations) such as A and B, N and O, and so on, situated a given distance, L, apart. Also shown in the Table are other variables that enter directly into the calculation of J, such as the airflow rate, Q, and the cross-sectional area, S, of the location, which is given by $S = Q/v$, where v is the linear air velocity. (Note: S was determined directly but is not reported in Table 2. However, it can be obtained according to the above simple relationship between Q and v.)

Comparison between Table 1 (i.e., 'true' ^{222}Rn flux density measurements) and Table 2 (i.e., apparent ^{222}Rn flux density values) show great discrepancies for the values of J determined in the same mine location. Furthermore, Table 2 shows a number of relevant and noticeable features, namely:

1. Large differences in the values for J for different pairs of points, i.e.,

stations, within the same mine location.

2. Large differences in the value for J for the same pairs of stations, within the same mine location, for different days.

Table 3 shows the J values calculated according to the three mine models presented here, namely, the Thomas-Epps Mine Model (TEMM), the Modified Thomas-Epps Mine Model (MTEMM), and the Mine Tunnel Model with Ventilation (MTMV) (see Appendix A), for several UG mine locations. Also shown in the Table are the ^{222}Rn concentrations measured at each pair of sampling stations chosen for the purpose, and the air transit time between these stations, i.e., time taken by mine air to travel from the upstream to the downstream sampling station.

A comparison between the values for J(MTEMM) and J(TEMM) shows that the former are substantially higher (~58%) than the values for the latter. The qualitative aspect of this result is not surprising because the MTEMM model takes into account, among other considerations, the radioactive growth and decay of ^{222}Rn during the air transit time between sampling stations.

The values for J(MTMV) are markedly higher than for the other two models. The ratio J(MTMV)/J(MTEMM) ranges from ~1.1 to >30, with most values in the range ~2 to 5. No satisfactory explanation can be offered at present to account for the large differences between this model and the MTEMM, except for the fact that the MTMV contains the ventilation rate, Q, explicitly in the physical description (i.e., differential kinetic equations) of the model.

Table 3 also shows some negative values for the models TEMM and MTEMM. This result will be discussed below. Table 4 shows geometrical and ventilation data for different mine locations. With these data and data in Table 3 it is very simple to verify the values of J for the different models.

Table 5 shows the increase in ^{222}Rn concentration, $\Delta[^{222}Rn]$, and Potential Alpha Energy Concentration (PAEC), i.e., Δ(PAEC), in some

underground locations brought about by some mining and human activities. These data are included here because they demonstrate that even vehicle traffic through certain areas can have a significant effect on ^{222}Rn concentration and the PAEC, and hence, help to understand some odd results obtained such as negative values for J, and the like. Some of these matters will be discussed briefly in the next section.

FURTHER DISCUSSION OF THE EXPERIMENTAL DATA

The values for J by the fluxmeter method are markedly lower than those obtained by the mine model methods used, i.e., 2PM method. Apart from potential leaks in the fluxmeter, and the presence of fissures, cracks, faults, and percolation of water in the rock formation, factors that have a pronounced effect on the J values measured by the fluxmeter, the data in Table 1 are significantly underestimated because measurements, as pointed out before, were conducted under steady-state conditions (i.e., $\lambda t >> 1$, or $t > \infty$). Furthermore, backdiffusion of ^{222}Rn was ignored and, most importantly, J depends on the ^{222}Rn concentration gradient between the rock pores and the fluxmeter can. If allowance for the latter phenomena is made, the expression for J becomes: $J = \beta h C(t_\alpha)$ where $\beta = (\alpha/h) + \lambda$, where α is a constant, and the symbol h is the height of the fluxmeter can. The parameter β has to be determined exponentially during the linear ^{222}Rn ingrowth period (Bigu 1984; Dave and Lim 1982). This operational procedure leads to the same difficulties as previously indicated. Complementary laboratory measurements show that the values for J in Table 1 should be at least a factor of 10, or more, higher. However, despite this correction, the values for J by the fluxmeter method are still significantly lower than those obtained by the 2PM method (compare Table 1 with data in Table 2 for the same UG mine locations).

As previously indicated, however, the differences observed for J

measured by the fluxmeter method and the 2PM method are more apparent than real because of the conceptual difference between the two measurement approaches. Furthermore, the distance from a reference origin for each pair of sampling stations, and their mutual distance, cannot be chosen at random for the reasons given in Appendix A, namely, and among other things, because of the very nature of the growth and decay of ^{222}Rn in partially enclosed environments (Bigu 1988).

CONCLUSIONS

The main conclusions to be drawn from this study are the following:

1. There is poor agreement between the values for J obtained by the 2PM method using different mine models. Part of the disagreement arises from the different assumptions on which each model is based. The data obtained suggest that the distance between pairs of sampling stations and their distance to a proper reference origin can be important (see Appendix A). Furthermore, discrete ^{222}Rn sources, as opposed to more or less uniformly distributed sources (such as those in an UG U-mine), mining operations, and other activities can act as 'extra' sources of ^{222}Rn or sinks of ^{222}Rn, e.g., water drainage, etc.
2. Measurements of J by the fluxmeter method gave the lowest values, i.e., substantially lower than the values obtained by the 2PM method. Part of the problem can be attributed to microscopic air leaks in the fluxmeter seals to the wall, to fractures, cracks and fissures at the rock face, and behind the rock face, and to water seepage (percolation) through the rock formation. Most of these situations are not immediately obvious to the naked eye. The experimental values obtained are also affected by the fact that because of practical limitations and constraints, measurements had to be carried out when the ^{222}Rn concentration in the fluxmeter can had

reached radioactive equilibrium.

3. Measurements by the 2PM method provide only an apparent value for the flux density, which in turn can be strongly affected by a number of factors (see item 1). This type of measurement is conceptually different from fluxmeter measurements. However, only the latter, in principle, can be used in the kinetic equations to predict ^{222}Rn levels in working environments.

In conclusion, the data presented here emphasize the difficulty in obtaining reliable measurements of ^{222}Rn flux density in complex environments.

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APPENDIX A

Three mine models for ^{222}Rn are briefly discussed here, namely, the Thomas-Epps Mine Model (TEMM), the Modified Thomas-Epps Mine Model (MTEMM), and the Mine Tunnel Model with Ventilation (MTMV) (Thomas and Epps 1970; Bigu 1985; Beckman and Holub 1979). The mine models have been used here to determine the ^{222}Rn flux density, J, in an UG U-mine. The above, and other mine models, have been discussed and adapted to ^{220}Rn by the author elsewhere (Bigu 1985).

1. THE TEMM

It can be shown (Thomas and Epps 1970) that the ^{222}Rn atom concentration, N, for this model is given by:

$$N = JPL/\upsilon A_c\lambda = (JP/A_c\lambda)t = JS/Q \qquad (A.1)$$

where, in the above expression:

υ = mine air velocity (υ = L/t)

P = perimeter of the mine section under consideration

A_c = cross-sectional area

S = surface area of the mine section under consideration (S = PL)

L = length of mine section under consideration

Q = airflow rate ($Q = \upsilon A_c$)

If measurements of ^{222}Rn activity concentration, $[^{222}Rn]$, are conducted at two different sampling stations a distance L apart, it is easy to verify that:

$$J = \Delta[^{222}Rn](Q/s) \qquad (A.2)$$

where, Δ stands for increment. It should be noted that $[^{222}Rn] = N\lambda$, where λ is the ^{222}Rn radioactive decay constant. (Equation A.2 can also be obtained by applying mass-conservation principles to a differential mine volume element, i.e., differential control volume, followed by Taylor's expansion.

and integration between L = 0 and L = L.)

Equation A.1 is obviously incorrect because it means that N increases indefinitely with increasing S, i.e., no radioactive steady-state is reached!

2. THE MTEMM

It can be shown in this case (Bigu 1985) that:

$$N = \frac{JP}{A_c \lambda^2} (1-e^{-\lambda t}) \qquad (A.3)$$

Following the same reasoning as before, it is easy to verify that:

$$Jn = \frac{\Delta[^{222}Rn]\lambda V}{S(1-e^{-\lambda t})} \qquad (A-4)$$

where, $V = A_c L$

Equation A.3 shows that as $t \to \infty$, N tends to a constant value given by $JP/A_c\lambda^2$. Also, for $\lambda t << 1$, Eq. A.4 becomes Eq. A.2.

3. THE MTMV

It can be shown that for this model (Beckman and Holub 1979):

$$N = N_o e^{-\Lambda t} + \frac{JS}{\Lambda} (1-e^{-\Lambda t}) \qquad (A.5)$$

where, $N_o = N(t=0)$ and $\Lambda = \lambda + Q/V$.

It is easy to show from Eq. A.5 that:

$$J = \left[\frac{[^{222}Rn]_2 - [^{222}Rn]_1 \, e^{-\Lambda t}}{S(1 - e^{-\Lambda t})}\right] \Lambda V \qquad (A.6)$$

where, the indices 1 and 2 are used to indicate the ^{222}Rn activity concentration at sampling stations 1 and 2, respectively, a distance L apart.

It is easy to show that if $N_o = 0$ at $t = 0$, Eq. A.6 reduces to Eq. A.4, except that λ in the MTEMM becomes Λ in the MTMV, or vice versa.

It is not difficult to realize that for sufficiently large values of t, i.e., sufficiently large distance of the sampling station(s) from the origin, N becomes constant (see Eqs. A.3 and A.5). Hence, measurement of $[^{222}Rn]$ under these conditions will give $\Delta[^{222}Rn] \sim 0$. Hence, L cannot be chosen

arbitrarily otherwise large errors in the determination of J will result.

APPENDIX B

The differential equation describing the growth of ^{222}Rn in a fluxmeter can is a particular example of the more general case of a mine model with Q=0, i.e., enclosed volume with no airflow. It can be shown (Bigu 1988) that:

$$\text{a) for } \lambda t << 1, \quad J = h[^{222}Rn]/t \ , \tag{B.1}$$

$$\text{b) for } t \to \infty, \quad J = \lambda h[^{222}Rn]_{\alpha} \tag{B.2}$$

where, in the above expressions h is the height of the fluxmeter can.

However, the above expressions have been derived under the following assumptions:

a) there is no ^{222}Rn backdiffusion mechanisms;

b) J is independent of the ^{222}Rn concentration gradient between interstitial pore volume below the rock surface and the fluxmeter can volume.

If item b) is taken into account then it can be shown (Dave and Lim 1982) that:

$$J = \beta h[^{222}Rn]_{\alpha} \tag{B.3}$$

where $\beta = \frac{\alpha}{h} + \lambda$

In the above expression α is a constant that relates J and the ^{222}Rn concentration gradient between the rock pore volume and the fluxmeter can volume. The variable β can be obtained experimentally using different analytical expressions depending upon the method of measurement employed (Bigu 1984).

Barometric pressure variations, ΔP, affect the values of J because significant transport (convection) of ^{222}Rn takes place (Bigu 1984). Hence, J measurement should be conducted preferably during periods for which $\Delta P = 0$.

Table 1. Average ^{222}Rn flux density, J, measurements at several wall positions in two underground mine locations by the fluxmeter can method.

Location	Fluxmeter No.	J x 10^3 Bqm^{-2} s^{-1}
Travelway	1	26.6
	2	6.7
	3	75.1
	4	82.5
	5	104.0
	6	50.3
Exhaust airway	11	8.5
	12	4.4
	13	8.1
	14	1.8
	15	2.6
	16	6.7

Table 2. Rn-222 flux density and other variables measured at several sampling stations in three mine locations.

Location	Station	J ($Bqm^{-2}s^{-1}$)	$[^{222}Rn]_1$ (Bqm^{-3})	$[^{222}Rn]_2$ (Bqm^{-3})	L (m)	Q (m^3s^{-1})	υ (ms^{-1})	Date
Travelway	A,B	0.22	373	396	171	39	1.4	04/12/86
	B,C	1.59	396	544	148	39	1.1	
	A,C	0.86	373	544	319	39	1.2	
	A,C	2.35	431	929	319	35	1.1	04/03/87
Exhaust Airway	P,Q	12.98	3082	3636	155	77	3.0	18/12/86
	P,Q	9.84	2924	3381	155	70	2.8	05/03/87
	P,Q	2.86	3053	3169	155	80	3.2	05/05/87
Ramp	M,N	11.64	297	707	55	24	1.6	28/04/87
	M,O	2.54	297	449	83	23	-	
	N,O	-10.18	707	449	28	23	1.0	
	M,O	15.35	125	1133	83	23	-	27/04/87
	M,N	5.34	241	440	55	23	1.8	30/12/86

Note: $[^{222}Rn]$ stands for ^{222}Rn concentration. The subindices 1 and 2 are used to indicate first and second sampling stations, respectively. The symbols L, Q, and υ, stand respectively, for the distance between sampling stations, the airflow rate and air velocity measured at these stations. The letters A, B, C, P, Q, M, N, and O are used to indicate the position of the sampling station within each location. J denotes ^{222}Rn flux density.

Table 3. Comparison of ^{222}Rn flux density according to three different mine models. Also shown are other data of interest.

Location	Transit Time (s)	$[^{222}Rn]_2$ (Bqm^{-3})	$[^{222}Rn]_1$ (Bqm^{-3})	J(TEMM) ($Bqm^{-2}s^{-1}$)	J(MTEMM) ($Bqm^{-2}s^{-1}$)	J(MTMV) ($Bqm^{-2}s^{-1}$)
Mining area	135.4	1382.7	1341.6	0.37	0.58	12.62
Jumbo stope	81.8	929.1	772.6	2.05	3.24	13.34
	529.2	1712.4	1342.0	0.89	1.41	4.64
Jumbo dev.	189.3	1013.4	940.5	0.54	0.86	7.88
heading	213.1	836.9	692.6	1.19	1.88	7.59
	260.4	1142.9	709.3	2.92	4.63	9.41
Jackleg stope	159.7	1530.7	916.1	4.08	6.45	12.53
	88.0	1842.6	1105.6	8.23	13.02	25.36
	132.1	2464.2	1474.1	7.36	11.65	22.62
Idle stope	860.5	14763.0	2099.0	14.91	23.61	26.09
	1215.4	11397.5	6670.0	3.81	6.03	11.41
Ramp	14.8	904.6	312.3	22.37	35.39	47.19
	18.2	281.6	340.8	-3.11	-4.93	13.00
	19.9	238.6	296.7	-2.79	-4.41	9.82
	12.5	633.8	281.6	26.65	42.16	63.47
Exhaust airway	51.3	3635.6	3082.5	12.99	20.55	92.94
	56.0	3381.4	2924.1	9.84	15.57	78.51
	49.3	3125.0	3072.1	1.29	2.05	77.21
Airway/	242.1	417.4	431.4	-0.10	-0.15	2.80
travelway	23.2	553.1	417.4	7.77	12.29	36.18
	19.6	928.7	553.1	25.86	40.91	79.00

Note: The square brackets are used to denote activity concentration. The subindices 1 and 2 indicate measurements conducted at sampling stations 1 and 2, respectively. The short forms TEMM, MTEMM and MTMV stand, respectively, for Thomas-Epps Mine Model, Modified Thomas-Epps Mine Model and Mine Tunnel Model with Ventilation. The transit time is the time taken by ventilation air to travel between the sampling stations 1 and 2. The symbol J is used to denote ^{222}Rn flux density.

Table 4. Geometrical characteristics and airflow conditions for some underground mine locations.

Location	ν (ms^{-1})	Q (m^3s^{-1})	V (m^3)	L (m)	S (m^2)
Mining area	1.44	46.5	6292	195	32.2
Jumbo Stope	0.63	13.2	1080	52	20.8
	0.23	9.7	5118	119	42.8
Jumbo Dev. Head.	0.31	13.6	2580	59	43.4
	0.23	16.5	3520	49	72.2
	0.19	13.5	3520	49	72.2
Jackleg Stope	0.50	11.3	1809	79	22.8
	0.52	9.2	810	46	17.7
	0.35	6.1	810	46	17.7
Idle Stope	0.02	0.46	396	18.6	21.3
	0.02	0.46	559	30	18.7
Ramp	3.69	21.7	321	55	5.9
	1.76	25.8	468	32	14.6
	1.61	23.5	468	32	14.6
	1.81	25.8	321	22.6	14.2
Exhaust Airway	3.03	76.9	3948	155	25.4
	2.78	70.5	3948	155	25.4
	3.16	80.1	3948	155	25.4
Airway/Travelway	0.41	35.5	8597	98	87.6
	1.18	35.5	824	27.4	30.0
	1.14	35.5	695	22.3	31.2

Notes: The symbols ν, Q, V, L and S stand for air velocity (ν), and airflow rate (Q) through a location of volume V and cross-sectional area, S, between two sampling stations a distance L apart.

Table 5. Effect of mining operations or activities on airborne radioactivity (^{222}Rn concentration and Potential Alpha Energy Concentration (PAEC)) for several underground mine locations.

Location	Mine Operation or Activity	$\Delta[^{222}Rn]^{+}$ %	$\Delta(PEAC)^{+}$ %
Jackleg Stope	Drilling on face > slushing	67	149
Jackleg Stope	No traffic > setting up	21	12
Jackleg Stope	No traffic > drilling on face	200	0
Travelway	No traffic > setting up	53	0
Travelway	No traffic > traffic	83	33
Crusher Decline	No traffic > traffic	19	0
Exhaust Airway	No traffic > traffic	32	21

$^{+}$ the symbol Δ is used to indicate percentage (%) increment.

LIST OF CAPTIONS

Figure 1 - ^{222}Rn concentration, [^{222}Rn], frequency histogram for several UG U mine locations, clockwise: exhaust airway, footwall drive, airway, ramp in waste, jumbo development heading and travelway. Units are given in Bqm^{-3} (lower x-axis scale) and $pCiL^{-1}$ (upper x-axis scale).

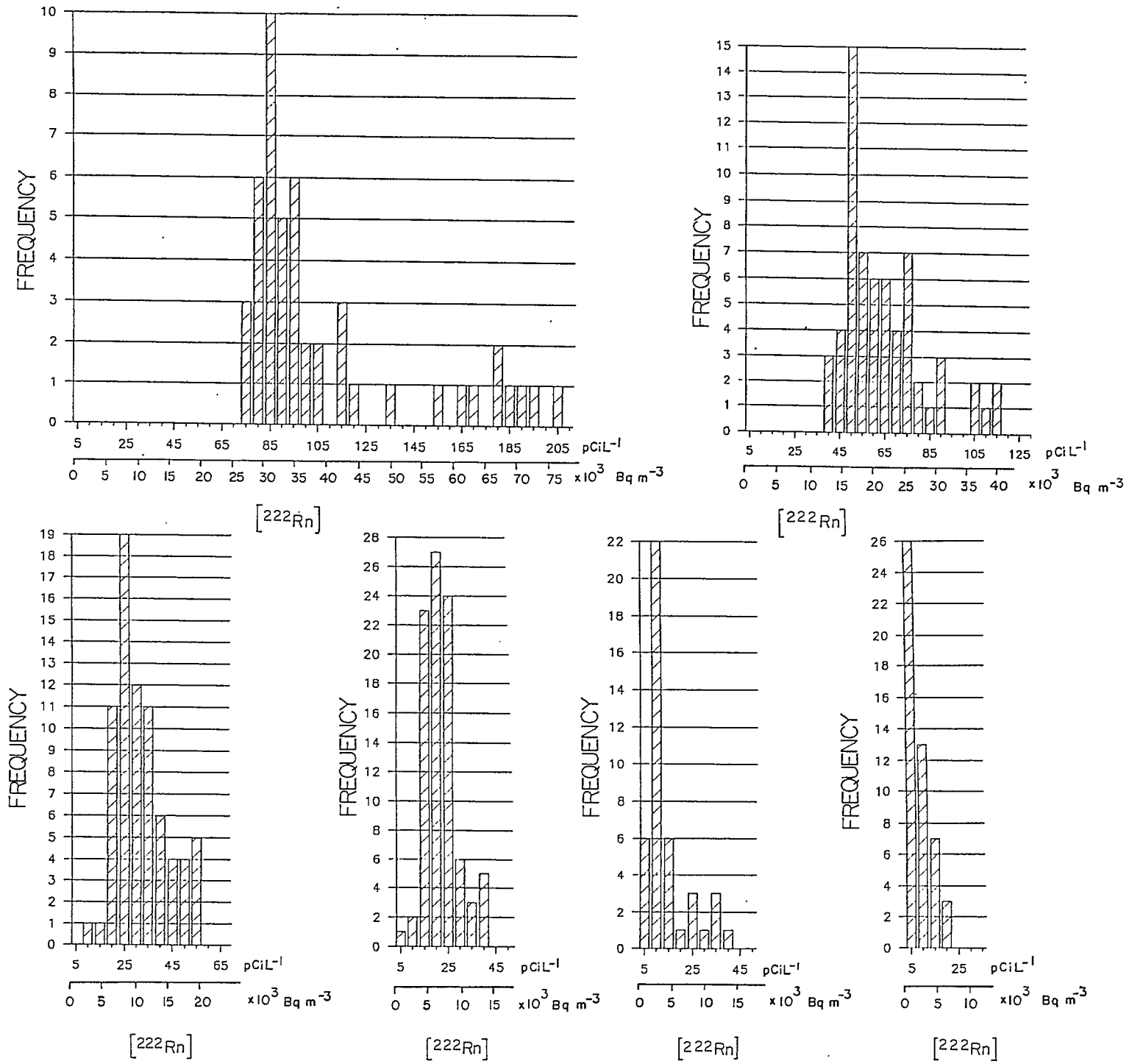

Figure 1.