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RADIOACTIVE AND NON-RADIOACTIVE (TRACER) GAS TECHNIQUES FOR STUDYING VENTILATION CONDITIONS IN WORKING ENVIRONMENTS

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RADIOACTIVE AND NON-RADIOACTIVE (TRACER) GAS TECHNIQUES FOR STUDYING VENTILATION CONDITIONS IN UNDERGROUND WORKING ENVIRONMENTS

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Abstract: Ventilation conditions in working environments are usually studied by anemometry or, in complex cases, by using special tracer gases such as SF_6 and ^{85}Kr, in conjunction with chromatographic and radioactivity techniques, respectively. In some working environments, such as underground uranium mines, however, use can be made of the natural radioactivity environment (e.g., ^{222}Rn, ^{220}Rn, and their progeny) to investigate mine ventilation conditions of practical interest. Theoretical studies and experimental data in several underground uranium mines and mine locations show that certain thoron progeny to radon progeny concentration ratios are very good indicators of ventilation conditions. Furthermore, the growth and decay of radon progeny and thoron progeny provide valuable information on mine air residence and clearance times. Some specific examples have been analyzed, such as bacterially-assisted uranium leaching operations in a partially enclosed stope, and the effect on the underground environment of turning ventilation fans on and off for a period of time. Air residence times and other variables of interest, determined from the mine radioactivity environment, were compared with more traditional techniques, such as anemometry and tracer gas chromatography. These studies were also extended to a wet non-uranium mine which exhibited relatively high concentrations of radon and its progeny.

INTRODUCTION

One of the most common methods of controlling airborne pollutants is by forced mechanical ventilation. The intelligent use of such a control method requires an efficiency test of the ventilation system in order to determine such important variables as airflow, air residence time, and recirculation characteristics of the ventilation air at the location of interest.

Ventilation systems are extensively used in industrial, commercial and residential buildings, research, military, sports installations, medical and laboratory facilities, factory plants, and underground mines among other places and locations.

The efficiency of ventilation systems can often be determined by anemometry. However, in complex cases involving recirculation of return air into intake air, and air leakage, as well as a variety of other important cases encountered in mines, industrial fume hoods, and large buildings and installations, techniques more sophisticated and accurate than simple anemometry are not only desirable, but imperative. In such cases, the use of tracer gases such as SF_6, ^{85}Kr, and ^{41}Ar, and their associated tracer gas detection techniques (gas chromatography for SF_6, and β- and γ-radiation detection techniques for ^{85}Kr and ^{41}Ar, respectively), can provide an effective means of analyzing difficult ventilation problems and conditions. The tracer gases that can be used are not limited to those indicated above. Other tracer gases can also be used effectively such as BrF_3CH_4 and $Cl_2F_2CH_4$. In certain working locations such as underground uranium mines, however, the natural airborne radioactivity can provide an effective means to study mine ventilation conditions.

The radioactivity environment in an underground uranium mine consists mainly of an atmosphere of radon and its short-lived decay products (i.e., progeny). In some uranium mines, however, significant amounts of ^{232}Th in the ore are found. This radionuclide gives rise to thoron and its progeny, which also contribute to the mine air environment. It has been suggested (Rolle 1972, Thomas and Epps 1970, Schroeder and Evans 1969, Bigu 1985) that the F-equilibrium factor (defined by the ratio WL(Rn)/[^{222}Rn], where WL(Rn) stands for radon progeny Working Level and the square brackets are used to indicate activity concentration), the radon progeny disequilibrium ratios, and the growth and decay of radon progeny in underground mine atmospheres can be used to determine the 'age' of mine air, i.e., mine air residence and clearance times. Furthermore, it has also been suggested (Bigu 1985) that certain thoron progeny to radon progeny ratios, such as WL(Tn)/WL(Rn), are potentially excellent indicators of underground ventilation conditions.

In this paper, the potential uses of natural airborne radioactive tracers in uranium and non-uranium mines to determine underground ventilation conditions are examined. This method has been applied to some cases of practical interest, and in some specific cases it has been possible to conduct concurrent ventilation measurements using SF_6 tracer gas techniques (and conventional anemometry), and to compare the results from those measurements with data obtained using the natural radioactivity tracer technique.

THEORETICAL BACKGROUND

In what follows the presence of ^{222}Rn in mine air will be assumed to arise from the radioactive decay of $^{238}U/^{226}Ra$ mineral ores in the mine walls (extended source case), or from ^{222}Rn dissolved in ground or surface water entering the mine (discrete source). Broadly speaking, underground mines fall into the extended ^{222}Rn source category case, whereas wet non-uranium underground mines fall into the discrete ^{222}Rn source category case. (The reader should be aware that the arguments used in this paper for ^{222}Rn are equally applicable to thoron, i.e., ^{220}Rn.)

For an arbitrary section of an underground uranium mine (assume this section to be cylindrically shaped with volume V, surface area S, and length L), the kinetic equations describing the growth of ^{222}Rn and/or ^{220}Rn, and their respective progeny can be written (Beckman and Holub 1979, Bigu 1985) as follows:

$dN_n/dt = k_n - \Lambda_n N_n$, and (1)

$dN_i/dt = \lambda_{i-1} N_{i-1} - \Lambda_i N_i$ (2)

where, $\Lambda_n = \lambda_n + \lambda_v$; $\lambda_v = Q/V$; $\Lambda_i = \lambda_i + \lambda_v + \lambda_{ai}$ (3)

In the above expressions, the symbols N_n and N_i represent, respectively, the atom concentration (in V) of the radioactive parent gas (^{222}Rn and ^{220}Rn) and of i-type progeny. The symbols λ_n and λ_i stand for the radioactive half-lives of the radioactive gas and of i-type progeny, respectively. The symbol Q is used to indicate the air flowrate in the mine section of interest. The symbol λ_{ai} stands for the losses of ^{222}Rn (^{220}Rn) progeny by plate-out to mine walls and other large surfaces. The ^{222}Rn (^{220}Rn) emanation rate from mine walls is represented by k_n. This quantity is related to the radioactive gas flux, J_n, by the expression $k_n = J_n S$.

Dynamic conditions can be determined by solving equations 1 and 2 (Bigu 1985). Steady-state conditions can be calculated by setting $dN_n/dt = dN_i/dt = 0$ in equations 1 and 2.

Activity concentrations, A, can be obtained by using the well known expressions: $A_n = N_n \lambda_n$ and $A_i = N_i \lambda_i$. In this paper the activity concentration of a given radioisotope will be denoted by square brackets. A useful quantity, frequently quoted in this paper, is the Working Level, WL, which can be derived from the progeny activity concentrations. The Working Level is defined as the amount of radon progeny, or thoron progeny, which upon radioactive decay releases an energy of 1.3×10^5 MeV/L.

It should be noted that in writing equations 1 and 2, a number of important simplifying assumptions have been made as discussed elsewhere (Bigu 1988a).

For the discrete radioactive source case, e.g., wet, non-uranium mines, the analytical solutions to equations 1 and 2 assume a significantly different form because k_n can no longer be represented by $k_n = J_n S$. The solutions to equations 1 and 2 for the extended and discrete radioactive source cases have been given and discussed elsewhere (Bigu 1985, 1988a, 1988b).

The solutions to equations 1 and 2 for an underground uranium mine (i.e., extended radioactive source case) shows that unless Q=0 (no air flow) and the volume of the section of the mine V is bulkheaded so that air is confined to V (no air leakage), the ^{222}Rn progeny formed by the radioactive decay of ^{222}Rn do not attain radioactive equilibrium with each other or with the parent gas. In other words, the following conditions exist: $[^{222}Rn] > [^{218}Po] > [^{214}Pb] > [^{214}Bi] = [^{214}Po]$, where the radioisotopes ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po are the short-lived decay products (progeny) of ^{222}Rn.

Also the so-called F-factor, defined by the ratio $WL(Rn) \times 10^2/[^{222}Rn]$, is less than unity. (In this expression the ^{222}Rn concentration is given in pCi/L and WL(Rn) stands for radon progeny Working Level.)

It can be shown that F and the ratios $[^{214}Pb]/[^{218}Po]$ and $[^{214}Bi]/[^{218}Po]$ depend on the airflow (ventilation conditions), and hence, to the mine air residency time, RT = V/Q.

A similar study for thoron (^{220}Rn) and its progeny indicates that under the same conditions as those indicated above for ^{222}Rn and its progeny, the following conditions apply: $[^{220}Rn] = [^{216}Po]$, $[^{212}Bi] < [^{212}Pb]$. Hence, the ratios $[^{212}Bi]/[^{212}Pb]$ and WL(Tn)/WL(Rn) are also dependent on Q, and hence, RT. (The radioisotopes ^{216}Po, ^{212}Bi and ^{212}Pb are the short-lived decay products (progeny) of ^{220}Rn.)

Because of the dependence of F, and the ratios $[^{214}Pb]/[^{218}Po]$, $[^{214}Bi]/[^{218}Po]$, $[^{212}Bi]/[^{212}Pb]$ and WL(Tn)/WL(Rn) on Q, it suggests itself that these variables can readily be used to determine ventilation conditions in the mine, such as mine air residence time, and clearance time, among other important practical quantities.

Because several mine models have been developed based on different simplifying assumptions, some difficulty should be expected when comparing theoretical data by a given mine model and experimental data. Although qualitatively speaking most models are basically correct, substantial quantitative differences between mine models persist to warrant some caution about their limits of practical applicability. For this reason, it is important to validate the mine model experimentally before using it for quantitative analysis and predictions in practical field situations.

Irrespective of the mine model used, however, there are experimental procedures available which will often enable a mine model to circumvent the above difficulties. Four such experimental procedures are indicated below. Assuming that the ventilation and other characteristics, e.g., residency time (RT), for an arbitrary section of the mine of volume V are to be determined, the following practical alternatives are possible:

a) enclose V at t=0 and let activity grow until radioactive equilibrium (steady-state) is reached:

b) enclose V at t=0, let activity grow (see item a), and then remove physical enclosure, flush V at the desired flowrate, Q, and let activity decay;

c) flush V to reduce the initial activity concentration in V to as low a value as possible, and then continue as indicated in item a): and

d) flush V to reduce the initial activity concentration in V to as low a value as possible and then continue as indicated in item b).

It should be noted that the state of radioactive equilibrium referred to in item a) is desirable although not strictly necessary. Furthermore, it is assumed that a sufficient degree of air mixing in V exists arising by natural diffusion and convective processes so that a reasonably constant radioactivity concentration throughout V prevails.

Items a) to d) permit radiation dynamics to be investigated as well as the determination of the ^{222}Rn emanation rate and the ^{222}Rn flux from mine walls. Items b) and d) allow the ventilation conditions, e.g., RT and clearance time, in V to be determined.

The experimental procedures outlined above are equally applicable to non-uranium mines, where discrete radioactive source conditions prevail, or to uranium mines where the ^{222}Rn contribution from the walls is small compared with the release of ^{222}Rn from special mining operations (e.g., uranium leaching) going on at a particular mine location. One case of practical interest will be illustrated here, namely uranium leaching by the flooding technique in a leaching stope. The analytical solution of this particular operation will also be given below.

The uranium leaching operation basically consists of the following steps:

1. The stope is drilled and blasted to ensure that enough fragmented uranium ore is available for the leaching operation;
2. A bulkhead is built to contain the water added to the stope for flooding purposes;
3. Compressed air is injected into the stope for a period of time to ensure adequate aeration for oxidation to take place:
4. The stope is flooded with water containing a liquid solution of the bacteria Thiobacillus ferroxidans:
5. The stope is drained after a given time (~1 week) in order to separate the liberated oxidized uranium salt from the pyritic uranium ore (the drainage operation takes about one week):
6. The leaching cycle is initiated again starting at item 3.

Part of the ^{222}Rn formed during the leaching operation is dissolved in the aqueous solution (uranium leachate) and is removed during the draining operation whereas the rest of the ^{222}Rn is released from the solution, before and during draining, into the air volume of the stope. The equations describing the growth and decay of ^{222}Rn in the leaching stope are given by Bigu (1988b):

$$dN/dt = -N\Lambda \qquad (4)$$

with solution:

$$N(t) = N_0 e^{-\Lambda t} \qquad (5)$$

In equation 5, N_0 represents the number of ^{222}Rn atoms in V at the end of the draining operation under no air flow conditions, i.e., Q=0. It is not difficult to show from equation 5 (Bigu 1988b), after some manipulation, that:

$$RT = t_{50}/(0.693 - \lambda_n t_{50}) \qquad (6)$$

where t_{50} represents the time at which the $[^{222}Rn]$ is reduced to half of its original value. The relatively simple experimental and analytical procedure discussed above provides a means for determining the (stope) air residence time which is an important quantity in the aeration/leaching process.

The experimental results obtained from such a leaching operation as that previously discussed will be presented later on when a comparison is made with other air residence time measurements carried out concurrently at the same location using tracer gas (SF_6) techniques in conjunction with a gas chromatograph, and conventional anemometry (Hardcastle and Butler 1986).

THEORETICAL RESULTS

Some theoretical results obtained using a particular mine model, namely, the mine tunnel model with ventilation (MTMV), as described elsewhere (Bigu 1985), are shown in Figures 1 to 5. The data show the potential practical applications of naturally occurring radioactive tracers in underground environments for determining mine air residence times (RT) and clearance times.

Figure 1 shows the (normalized) radon progeny Working Level, WL(Rn), versus residence time, RT. The radon progeny Working Level has been normalized to 3.7 Bq/L (100 pCi/L) of ^{222}Rn representing decay products (progeny) necessary to release a total α-particle energy of 1.3×10^5 MeV/L (=1 WL). The graph shows that WL(Rn) increases with increasing RT. However, the rate of increase decreases as RT increases until, eventually, a steady-state or constant value for WL(Rn) is attained at sufficiently long residence times.

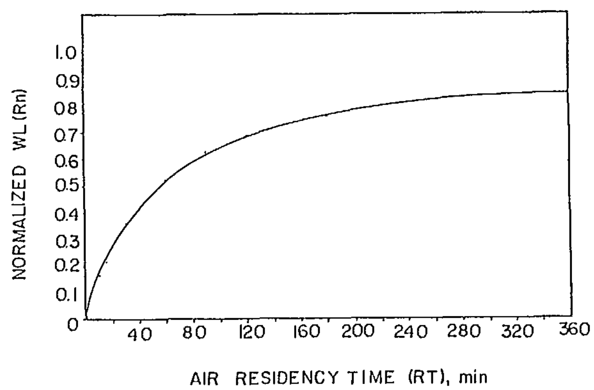

FIGURE 1. Normalized radon progeny Working Level versus air residence time.

Figure 2 shows the ratio $[^{214}Bi]/[^{218}Po]$ versus the ratio $[^{214}Pb]/[^{218}Po]$ for different residence times, which are indicated on the right hand side of the graph. The radon progeny ratios increase with increasing residence time reaching values close to unity at sufficiently long residence times. However, because of (selective) plate-out of radon progeny to large surfaces, and other phenomena, no radon progeny equilibrium is ever reached, i.e., $[^{214}Bi]/[^{218}Po] = [^{214}Pb]/[^{218}Po] =$ 1 even for very long values of RT. For 'young' mine air, the above ratios are vey low because there is not sufficient time for ^{218}Po to decay into its decay products. The two progeny ratios above provide a good indication of mine air residence times under underground conditions where selective plate-out is not significant, i.e., at sufficiently high submicron aerosol concentrations.

Figure 3 shows the (normalized) thoron progeny Working Level, WL(Tn), versus residence time, RT. The thoron progeny Working Level has been normalized to 0.277 Bq/L (7.5 pCi/L) of ^{220}Rn representing thoron progeny necessary to release a total α-particle energy of 1.3×10^5 MeV/L (=1 WL). The same qualitative considerations as for Figure 1, for the normalized WL(Rn), are applicable to Figure 3.

Figure 4 shows the ratio WL(Tn)/WL(Rn) versus the residence time, RT. The graph indicates that this ratio decreases with increasing RT, rapidly

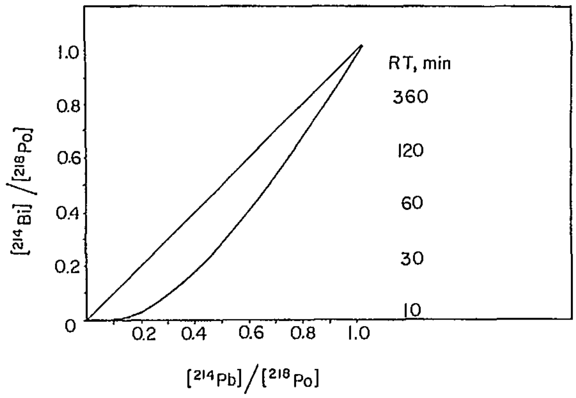

FIGURE 2. $[^{214}Bi]/[^{218}Po]$ versus $[^{214}Pb]/[^{218}Po]$ for different air residence times shown on the right hand side.

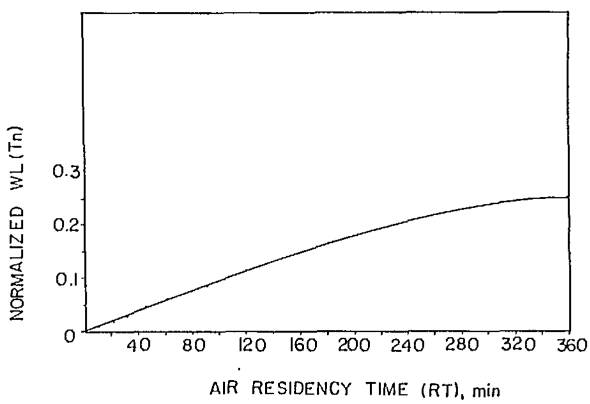

FIGURE 3. Normalized thoron progeny Working Level versus air residence time.

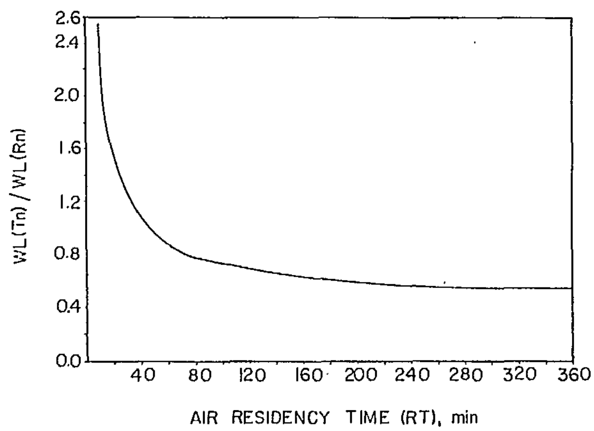

FIGURE 4. Thoron progeny Working Level to radon progeny Working Level ratio versus air residence time

at first for relatively low values of RT, and then more slowly with increasing RT. The ratio WL(Tn)/WL(Rn) is a good indicator of underground airflow conditions. However, the value of this ratio is directly proportional to the relative amounts of ^{238}U and ^{232}Th in the mine walls, or more precisely, to the ^{220}Rn to ^{222}Rn flux ratio across the mine wall/air interface. Figure 4 has been calculated for a ratio $^{238}U/^{232}Th$, in weight, of 1, a figure which has been taken as average for uranium mines in Ontario. For values other than 1, the ratio WL(Tn)/WL(Rn) must be multiplied by the new value.

Figure 5 shows the thoron progeny ratio $[^{212}Bi]/[^{212}Pb]$ versus the residence time of mine air, RT. It is seen that this ratio increases with increasing RT towards a value of 1 at sufficiently high values for the residence time. The maximum theoretical value of the ratio $[^{212}Bi]/[^{212}Pb]$ is unity, a value which indicates a state of thoron progeny radioactive equilibrium. However, as for the case of the radon progeny, radioactive equilibrium is not attained in practice because of selective plate-out on mine walls, and other phenomena. Low values for the ratio $[^{212}Bi]/[^{212}Pb]$ indicate 'young' mine air, i.e., low residence time. Although the radon progeny and thoron progeny ratios indicated above are strongly dependent on airflow conditions, typical approximate values for average ventilation conditions in Canadian underground uranium mines are as follows: $[^{214}Pb]/[^{218}Po]$ ~0.6, $[^{214}Bi]/[^{218}Po]$ ~0.4, $[^{212}Bi]/[^{212}Pb]$ ~0.5.

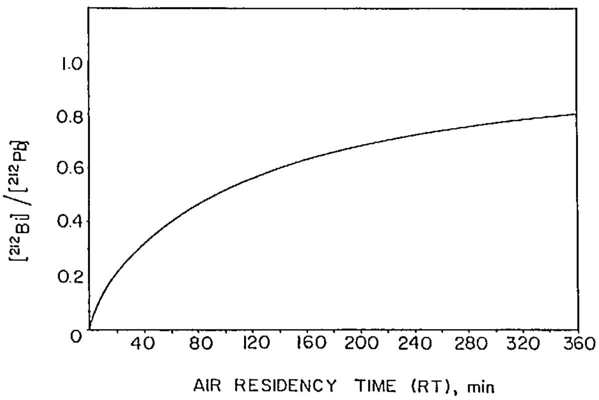

FIGURE 5. Thoron progeny ratio versus air residence time.

The reader should be aware that, as previously indicated, the theoretical data presented in Figures 1 to 5 depend on the mine model used, the presence of discrete radioactive sources, the 'gram ratio' $^{238}U/^{232}Th$, the rock formation, mine environmental conditions, and geological and physico-chemical considerations (Bigu 1985). Hence, without strict experimental validation of the mine model used, and other important considerations, the data presented here are mainly of a qualitative nature.

EXPERIMENTAL PROCEDURES AND RESULTS

The experimental procedures followed and the results obtained in an underground uranium mine and in a wet non-uranium underground mine are presented below. In both cases, residence and/or clearance times of the mine air were determined using naturally occurring radioactive tracers and/or chemical tracer gases such as SF_6. For simplicity, these two cases are dealt with separately and are referred to as Case A and Case B, respectively.

Case A: Underground Uranium Mine

Measurements were carried out in a leaching stope. The uranium leaching procedure has been discussed before. The experimental procedure is described below.

Boreholes were drilled in the wall of the stope, opposite the bulkhead, for monitoring purposes. Two boreholes per leaching block were drilled, i.e., one borehole for each stope of the block. A length of plastic pipe, about 1.5 m in length and approximately 10 cm internal diameter, was driven partially onto a short length of metal pipe fitted to one of the boreholes.

Several sampling ports were located along the plastic pipe to monitor radon gas, ^{222}Rn, radon progeny Working Level, WL(Rn), thoron progeny Working Level, WL(Tn), tracer gas (SF_6) concentration, air flow, and some meteorological variables such as temperature and humidity.

An anemometer was fitted snugly to the end of the pipe. The plastic pipe was terminated by an open-ended wooden box housing a small radon progeny Working Level continuous monitor, model alphaPRISM, manufactured by alphaNUCLEAR (Toronto, Canada), facing the air stream.

A sampling port located in the plastic pipe permitted continuous monitoring of radon gas by means of a radon gas monitor, model AB-5/EL, manufactured by Pylon Electronic Development (Ottawa, Canada). An adjacent sampling port allowed WL(Rn) and WL(Tn) measurements by grab-sampling.

Most of the above radiation and meteorological variables were monitored continuously during the duration of the test: usually, a measurement was taken every 60 minutes or 100 minutes.

The operational procedure was as follows. The stope was aerated for a period of time after which the compressed air supply was turned off for 48 hours to allow the radiation level to build up and reach a near equilibrium state. The compressed air supply was then turned on and maintained constant during the remainder of the tests.

Experiments were conducted shortly after the stope was drained from a previous leaching operation. The tests were of two weeks duration. Radiation levels, air flow, SF_6 concentration levels, and other relevant data were plotted versus time and compared with theoretical models. The data permitted a relatively detailed study of the dynamics of the system. It also allowed estimation of the air residence time by radioactivity, anemometry and tracer gas techniques.

Radon gas concentration, [^{222}Rn], WL(Rn), and air flow rate, Q, measurements by continuous monitoring methods were conducted (see Figure 6). It should be noted that [^{222}Rn] in Figure 6 are given in counts per hour (cphr). To obtain pCi/L and Bq/m^3 multiply by 2.33 x 10^{-3} pCiL^{-1}/cphr and 0.084 Bqm^{-3}/cphr, respectively.

Figure 6 shows that shortly after injection of air into the stope, WL(Rn) increased rapidly reaching a maximum value of ~70 WL in about 22 h. It then decreased rapidly at first and then more slowly, until eventually a steady-state value was attained after a few days. During the same period of time [^{222}Rn] followed a similar pattern.

The first portion of Figure 6 shows the effect of injecting compressed air into the leaching stope via the air distribution system. The time elapsed between the start of air injection and the time at which maximum values for [^{222}Rn] and WL(Rn) are attained provides a measure of the retention time of airborne radionuclides in the rock heap, i.e., the time taken by the carrier gas (compressed air) to remove radon and its progeny from the interstitial spaces in the heap. The decay portion of the graph is a measure of the residence time. Both retention time and residence time depend on air flow conditions in the leaching stope.

Calculation of retention and air residence times can be done with both radon gas concentration, [^{222}Rn], and WL(Rn), as these two variables are related by the so-called F-factor as indicated above. From experimental data collected, the value for the F-factor in the leaching stope was in the range 0.2 to 0.3.

From Figure 6 and equation 6, the values obtained for the residence time, RT, were in the range 34 to 39 h depending on the variable and time chosen for the measurements.

It should be noted that there is some uncertainty regarding the above values for the residence time as it has been calculated assuming a discrete and non-continuous source of radon gas (Bigu and Schryer 1987).

Figure 7 shows SF_6 gas concentration measured at the exhaust of the stope versus time for a continuous SF_6 tracer gas injection mode. The first portion of the curve shows the build up of gas followed by a steady-state condition characterized by a constant SF_6 concentration. The decay portion of the graph corresponds to the removal of the SF_6 source. The decay portion of the curve permits the residence time of the air in the stope to be determined by reading the time elapsed for the SF_6 concentration to be reduced to 50% of its original maximum value. The value obtained by gas chromatography using SF_6 as a tracer gas and grab-sampling techniques was 33.5 h. Air residence time determined by conventional anemometry gave a value of about 28 h.

Comparison between the values obtained for the air residence time by radioactivity, anemometry, and tracer gas techniques shows that there is fairly good agreement between the radioactivity method (34-39 h) and the tracer gas method (33.5 h), the former being only slightly higher (<17%) than the latter. Anemometry, on the other hand, gave the lowest value (~28 h) for the air residence time in the leaching stope.

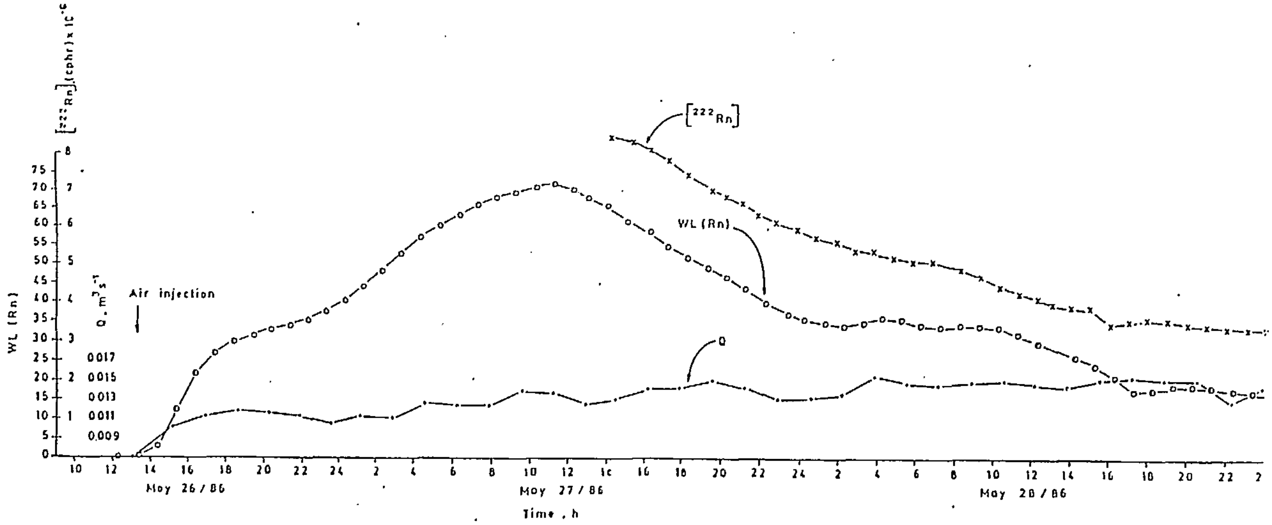

FIGURE 6. Radon progeny Working Level, WL(Rn), radon gas concentration, [^{222}Rn], and airflow, Q, versus time in leaching stope after injection of air.

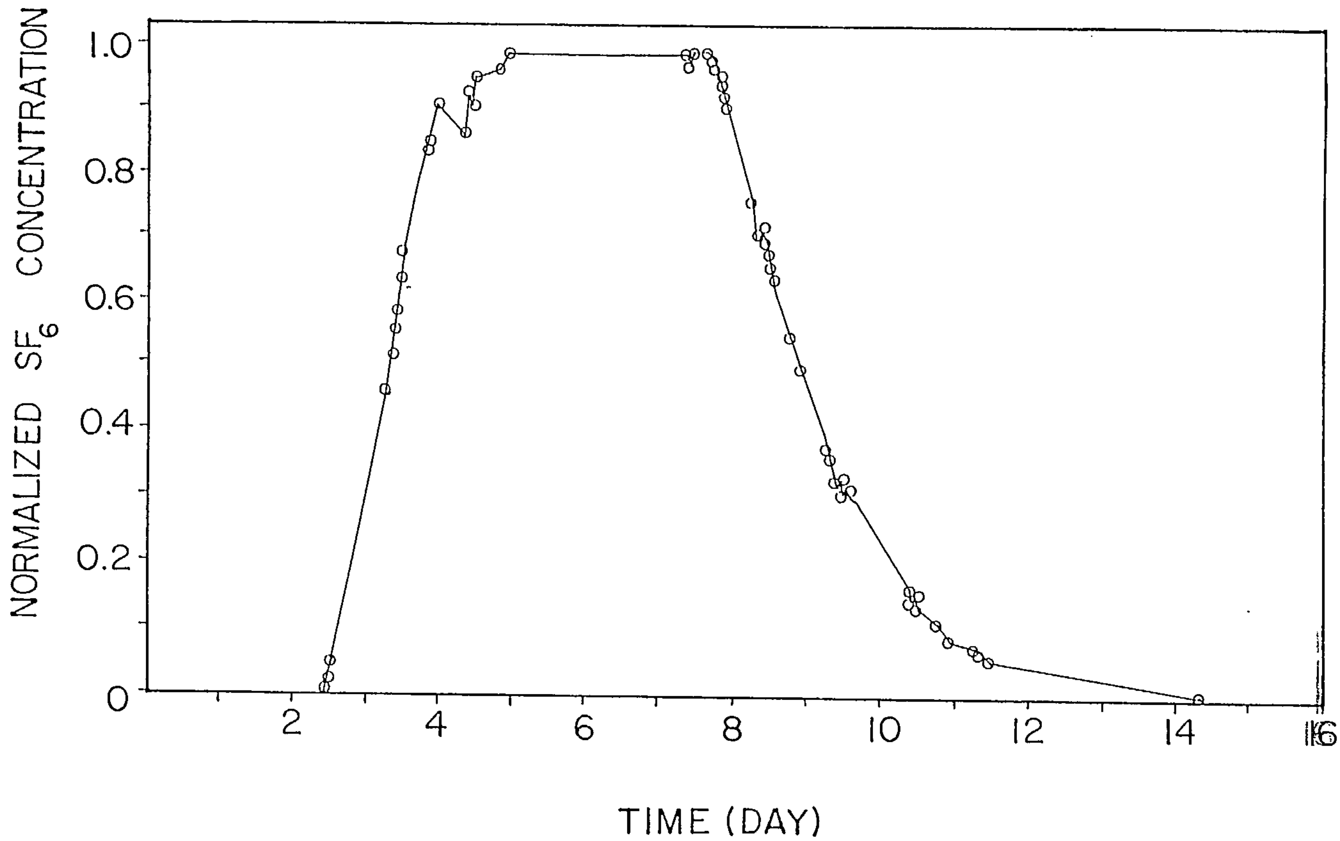

FIGURE 7. Normalized SF_6 concentration versus time.

Case B: Wet Non-Uranium Underground Mine

Radiation measurements were conducted in a wet, non-uranium underground mine at three locations labelled SS1, SS2, and SS3, located, respectively, 60 m, 266 m and 180 m from the mine entrance. This mine was characterized by discrete ^{222}Rn sources dissolved in ground and surface water entering the mine at several entry points. The mine was ventilated by means of two fresh air intake fans and an auxiliary fan. Measurements were carried out with the fans on and off in order to characterize radiation conditions in the mine. The build-up of radon progeny activity versus time was investigated by turning the ventilation fans off for a period of time. Mine air clearance and residence times were determined by turning the ventilation fans on until steady-state conditions were re-established. The same type of instrumentation and measurements as for the previous case, i.e., leaching stope, were used. The results of this study are summarized in Figures 8 and 9. The operation of the fans is indicated in Table 1.

The build-up and removal of radioactivity by ventilation can be divided into two parts, namely:

a) zero airflow by forced (mechanical) ventilation, i.e., Q=0. The only airflow is by natural ventilation; and
b) non-zero airflow, i.e., Q>0.

Table 1 - Operation of the mine ventilation system.

Date Dec/87	Time	Fan 1	Fan 2	Aux. Fan	Symbol
1	13:30	OFF	ON	ON	A*
1	21:52	OFF	OFF	ON	B
2	10:00	ON	ON	ON	C
2	17:32	OFF	OFF	OFF	D
3	09:06	ON	ON	ON	E

* Prior to Dec. 1/87 at 13:30, fans 1 and 2, and the auxiliary fan were on at all times.

For the Q=0 case, the radiation level in the mine will increase continuously until a maximum, steady-state value is reached. This value may be modulated by natural ventilation conditions which, in turn, are affected by external meteorological conditions.

The rate of growth (build-up) of radioactivity in the mine, and the time taken for this radioactivity to reach an equilibrium (steady-state) condition depends on the half-life of the radioisotope under consideration. The maximum value for the radioactivity is a function of the rate of entry and release of radon gas in the mine environment. The differences observed in the maximum value attained by the radiation level and the time taken to reach this maximum at different locations in the mine are attributed to:

i) local natural ventilation conditions; and
ii) non-uniform distribution and strength of the radon gas sources at different locations of the mine.

Figures 8 and 9 for Q=0 show that the build-up time for SS2 was ~12 h (B > C) and >15 h (D > E). For SS1, however, the build-up time was less defined because of moderate to strong (local) natural ventilation conditions, which changed often and rapidly. For example, the build-up time was ~6 h for the period A > B (not shown), but was far less defined for B > C (Figures 8 and 9), and undefined for D > E. In conclusion, the effect of turning off the ventilation fans was far less pronounced at sampling station SS1 than at sampling stations SS2 and SS3.

The dynamic situation for the case Q>0 (i.e., forced mechanical ventilation) is somewhat more complex than the case investigated above, i.e., Q=0. The radiation levels (WL(Rn) and [^{222}Rn]) at SS1 increased markedly at first, shortly after turning the ventilation fan(s) on, until a maximum value was attained to be followed by a rapid decrease until a constant, steady-state value was reached (see Figures 8 and 9).

This behaviour cannot be explained by assuming uniform mine air mixing, and hence a constant radiation level throughout the volume of the mine. If this were the case, an increase in airflow from Q=0 would certainly not affect the radiation levels observed at SS1 for some time; only after a period of time would the radiation levels decrease as air dilution mechanisms become important. Hence, no maximum (peak) would be observed, only a continuous decrease to a minimum value.

The observed effect could be explained, however, by the presence of [^{222}Rn] and WL(Rn) negative gradients between SS1 and other locations in the mine, particularly locations with large water influx rates (and hence high [^{222}Rn]) and poor natural ventilation conditions. Locations that meet these requirements are abundant in the mine. Assuming plug flow, for the sake of simplicity, it is not difficult to visualize that when the ventilation fans are turned on, mine air is displaced from the volume of the mine close to the fresh ventilation air discharge and travels along the mine volume to the exhaust site. Hence, a transient (maximum) radiation level should be expected followed by a decay because of air dilution.

Because stations SS2 and SS3 are far from the mine entrance where radiation levels are higher than at SS1, radiation concentration gradients between SS2 and SS3 and other mine locations further removed from the mine entrance are less than for SS1. Hence, the transient effects discussed above should be significantly reduced for these two locations. This is in fact what is experimentally observed (see for instance Figure 9).

Chronologically speaking, transient effects appear first at location SS3, then at SS2, and

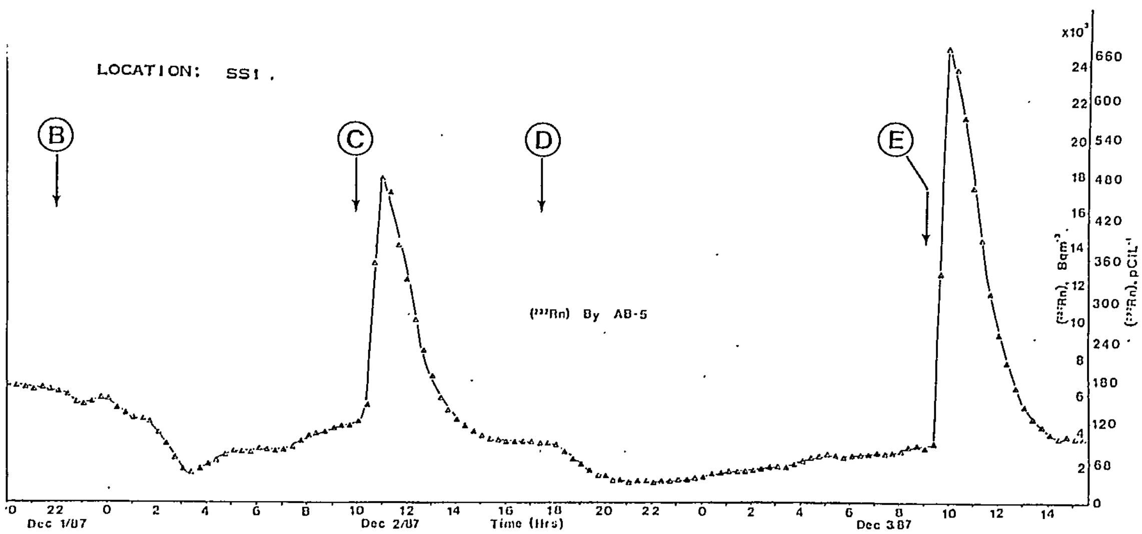

FIGURE 8. Radon gas concentration versus time at location SS1. (See Table 1 for the meaning of the symbols A, C, D, and E.)

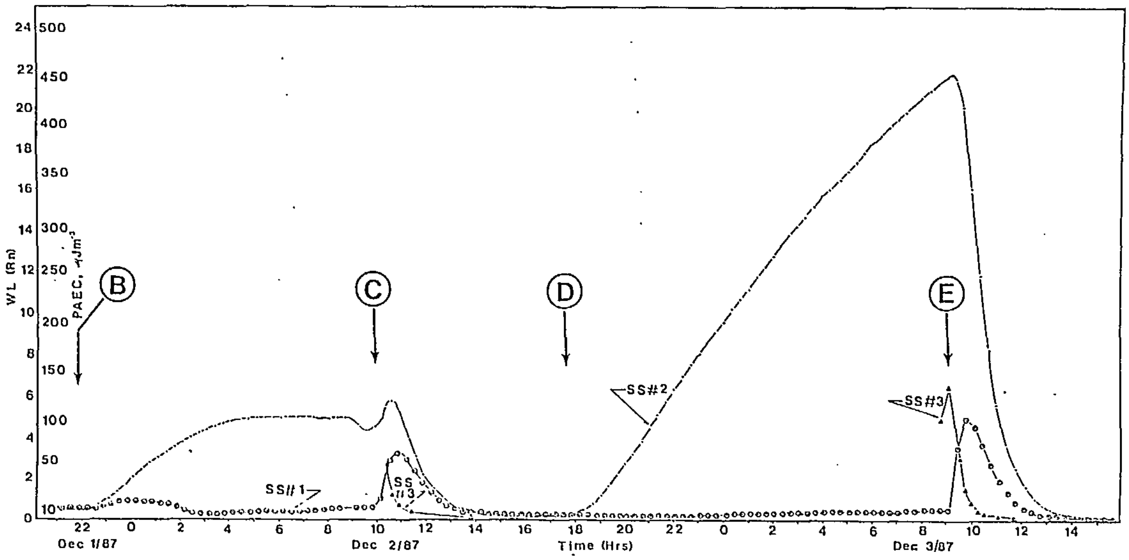

FIGURE 9. Radon progeny Working Level, WL(Rn), versus time for several locations. (See Table 1 for the meaning of the symbols, B, C, D and E.)

finally at SS1. The time elapsed between turning on the fans and the occurrence of a transient (e.g., maximum) at a given location is a measure of the mine air transit time, or air residence time. The time until the steady-state constant value is reached is a measure of the mine air clearance time. These times will, of course, vary with the location of the sampling station.

The mine air transit time and clearance time calculated from Figures 8 and 9 may give different results depending on whether use is made of continuous monitoring data or grab-sampling data. However, this difference is more apparent than real (Bigu et al. 1988).

Examination of the data presented in Figures 8 and 9 shows that the approximate mine air clearance times are, 2.25 h for SS1, 2.5 h for SS2 and 2.7 h for SS3, i.e., in excess of 2 h in each case.

CONCLUSIONS

The main conclusions that can be derived from this paper are as follows:

1. Naturally occurring airborne radioisotopes found in many underground mines can be used to determine airflow parameters of practical interest such as mine air clearance and residence times;

2. Experimental procedures can be designed and implemented to determine variables of interest such as radioactivity build-up, radioactive source strength characterization, and air recirculation conditions; and

3. Good agreement has been found between the use of anemometry, chemical tracer gases (SF_6), and naturally occurring radioactive tracers (radon, thoron, and their respective progeny) to characterize airflow conditions in underground mines.

REFERENCES

Beckman, R.T. and Holub, R.F., 1979, "Radon Daughter Growth with Continuous Radon Influx and Various Ventilation Rates," MSHA Investigation Report IR 1099, U.S. Department of Labour, Washington D.C., U.S.A.

Bigu, J., 1985, "Theoretical Models for Determining ^{222}Rn and ^{220}Rn Progeny Levels in Canadian Underground Uranium Mines - A Comparison with Experimental Data," Health Physics, vol. 48, No. 4, pp. 371-399.

Bigu, J. and Schryer, D., 1987, "Radioactivity Emissions from Bacterially-Assisted Leaching of Uranium Stopes," Division Report MRL 87-174(TR), Mining Research Laboratories, CANMET (EMR), Ottawa, Canada.

Bigu, J., 1988a, "Considerations Regarding the Occurrence of Radon, Thoron, and Their Decay Products in Non-Uranium Mines," Special Report SP 89- , Mining Research Laboratories, CANMET (EMR), Ottawa, Canada.

Bigu, J., 1988b, "Measurements of Radioactive Air from Bacterial Leaching of Uranium Stopes," Division Report MRL 88-42(TR), Mining Research Laboratories, CANMET (EMR), Ottawa, Canada.

Bigu, J., Frattini, A., and Edwardson, E., 1988c, "Radioactivity Conditions in a Non-Uranium Underground Mine in the Absence of Mining Operations," Division Report MRL 88-67(TR), Mining Research Laboratories, CANMET (EMR), Ottawa, Canada.

Hardcastle, S.G. and Butler, K., 1986, "Evaluation of the Climate and Airflow in a Flood Leaching Stope," Division Report MRL 87-68(TR), Mining Research Laboratories, CANMET (EMR), Ottawa, Canada.

Rolle, R., 1972, "Radon Daughters and Age of Ventilation Air," Health Physics, vol. 23, p. 118.

Schroeder, G.L., and Evans, R.D., 1969, "Some Basic Concepts in Uranium Mine Ventilation." Trans. SME-AIME, vol. 244, p. 301.

Thomas, J.W., and Epps, J.W., 1970, "Radium A, B, and C Concentrations and Working Levels from Radon Emanation in a Mine Tunnel," Report HASL-TM 70-4 (Available from U.S. Dept. of Energy Technical Information Center, Oak Ridge, TN).