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RADIOACTIVITY CONDITIONS IN A NON-URANIUM UNDERGROUND MINE DURING MINING OPERATIONS

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ABSTRACT

Radiation and ventilation studies have been carried out at a non-uranium underground mine. This investigation was prompted because of reported radon gas and radon progeny concentrations as high, or higher, than concentration levels measured at conventional underground uranium mines. (A study in the absence of mining operations has been previously conducted and published elsewhere. The present study was carried out during normal mining operations, except when the ventilation system was turned off.) Measurements were conducted under normal operating ventilation conditions and when the ventilation system was turned off. These measurements allowed the radioactivity build-up and clearance times to be calculated. These data are useful because they determine the radiation conditions worst case that would be encountered in the event of a ventilation system failure. Measurements of radon gas concentration in water samples leaves little doubt that the source of radon in the mine is water entering the mine site. It is calculated that the water influx is about 0.08 m^3/s into a mine volume of approximately 1.5 x 10^4 m^3, therefore, leading to very wet underground working conditions.

Key words: Non-uranium mines; Radon gas; Radon progeny; Underground.

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NIVEAUX DE RAYONNEMENT PENDANT L'EXPLOITATION MINIÈRE DANS UNE MINE SOUTERRAINE NE CONTENANT PAS D'URANIUM

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RÉSUMÉ

Des études portant sur la radiation et la ventilation ont été réalisées dans une mine souterraine ne contenant pas d'uranium. L'étude était nécessaire en raison des concentrations de radon et de produits de filiation du radon qui étaient aussi élevées sinon supérieures aux concentrations mesurées dans des mines souterraines classiques d'uranium. (Une étude en l'absence de travaux d'extraction a été menée antérieurement et les résultats ont été publiés ailleurs. L'étude que voici a été réalisée pendant l'exploitation dans des conditions normales de ventilation et quand le système de ventilation était hors service. Elles permettent de calculer l'accroissement de la radioactivité et les vitesses d'élimination. Ces données sont utiles parce qu'elles déterminent les niveaux de rayonnement les plus élevés qui peuvent être atteints dans le cas d'une panne du système de ventilation. La mesure des concentrations de radon dans les échantillons d'eau indique bien que la source de radon est l'eau qui s'infiltre dans la mine. On calcule que la venue d'eau est d'environ 0,08 m^3/s. Cette eau s'ajoute au volume d'eau de la mine qui est d'approximativement 1,5 x $10^4 m^3$. Par conséquent, l'atmosphère de la mine souterraine est très humide et reflète les conditions de travail des mineurs dans ce milieu.

Mots-clé : mines ne contenant pas d'uranium; radon; produits de filiation du radon; environnement souterrain.

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CONTENTS

TABLES

FIGURES

INTRODUCTION

Low concentrations of uranium (^{238}U) and thorium (^{232}Th) minerals are distributed more or less uniformly throughout the crust of the earth. Uranium minerals are found in abundance in uranium mines. To some extent, thorium minerals are also found in relatively high amounts in some uranium mines.

Uranium-238 and ^{232}Th are the parents of two naturally occurring radioactive chains which give rise to radon gas (^{222}Rn) and thoron gas (^{220}Rn), respectively. These two radioactive gases, once formed, migrate through mine walls into mine atmospheres by diffusion and transport mechanisms. Radon and thoron decay in turn into their respective short-lived progenies which when inhaled may pose an occupational health hazard.

Uranium mines are not alone in exhibiting appreciable concentrations of radon and its progeny. To a large extent, all underground mining environments show measurable concentrations of these radioisotopes. However, some non-uranium mines exhibit radon and radon progeny concentrations which are comparable to, if not higher than, uranium mines under average ventilation conditions. This is the case of some 'wet' mines where large amounts of groundwater and surface water enter the mine openings through the mine walls, shafts, drifts and the like. However, these anomalous cases are not restricted only to (non-uranium) wet mines.

The mechanism(s) whereby appreciable concentrations of radon and radon progeny are possible in some wet non-uranium mines is presumed to be as follows:

Water dissolves interstitial ^{222}Rn trapped in the pores of the rock or mineral formations which then enters mine openings. The radioactive gas is produced by the decay of $^{238}U/^{226}Ra$ minerals in the host rock in the ore. Alternatively, radon gas could be formed elsewhere outside the immediate vicinity of the mine. In the latter case, radon gas from these outside locations is dissolved and carried by water into mine openings. The possibility of radium (^{226}Ra) being dissolved and carried by water into mine openings should not be discarded. However, this does not seem to be the most likely explanation for the case investigated here (see below), based on water sample analyses.

This report presents data regarding a comprehensive radiation and ventilation study carried out at a non-uranium underground mine. The access to the mine is by a ramp. A shaft was not required because the ore body was outcropping and steeply dipping. For simplicity, this study has been divided into two main parts, namely, a radiation/ventilation survey conducted in a period during which no mining operations were carried out, and another survey done about two months later when the mine was in full operation. The first phase of this project was aimed at determining build-up and clearance times of radioactive mine atmospheres when the ventilation system of the mine was turned off and on, respectively. The second phase of the project was conducted to assess the effect of mining operations on the radiation level of the mine atmosphere. This underground mine was developed for production to commence in late fall 1988. Hence, the results of this study pertain to the existing auxiliary ventilation system. The third phase of this project will be published when the mine is in full production and a permanent ventilation system is in place. The data in this report pertain to the second phase of this project. Data regarding the first phase of this project have been published elsewhere (1).

EXPERIMENTAL PROCEDURE

Several sampling stations (SS) were chosen for monitoring purposes. These monitoring locations were labelled SS1, SS2, SS3, SS4 and SS5 for identification purposes (see Figure 1). Sampling location SS1 was located on the main ramp so as to monitor the return air exhausting from the mine. The exhaust site of the mine on the main ramp was essentially at ground level and was used by mine personnel, and vehicles, to access the working locations. Sampling station SS1 was situated about 60 m from the mine 'portal', i.e., the mine access and air exhaust site of the mine on the main ramp.

Sampling station SS2 was located on No. 1 level north, approximately 266 m from the portal (and ~206 m from SS1). Sampling station SS3 was situated in front of an electrical station on the main ramp, approximately 180 m from the portal (and ~120 m from SS1). Location SS4 was situated ~210 m from the portal (and ~150 m from SS1). This monitoring location was situated in a development heading branching south from the X-cut No. 1, and about 25 m back from the working face. The area was fed with second pass air from the lower level of the mine via an auxiliary ventilation fan/ventilation tubing system. Location SS5 was located 510 m from the portal (and ~450 m from SS1) in a development heading extending level No. 2 south. The monitoring station was situated 30 m back from the working face. This area was fed with fresh air from surface via the main ventilation system of the mine. The main mining operations conducted at locations SS4 and SS5 were drilling, blasting and mucking in a cyclic fashion.

A variety of radiation and meteorological measurements were carried out at the above locations and elsewhere. These included the following:

1. radon gas concentration, [^{222}Rn], in air;
2. radon progeny concentration in air, i.e., [^{218}Po], [^{214}Pb] and [^{214}Bi];
3. radon progeny Working Level, WL(Rn);
4. thoron progeny Working Level, WL(Tn);
5. radon gas concentration in water samples;
6. barometric pressure (P), air temperature (T), and relative humidity

(RH) in the mine; and

7. ventilation characteristics, i.e., air flow rate, in the mine.

In addition, outdoor meteorological data collected by Environment Canada were used in this project. These data included measurements of P, T, RH, wind direction and wind velocity.

Data corresponding to items 1 to 3 were obtained by continuous monitoring techniques and grab-sampling methods. Items 4 to 7 were obtained by grab-sampling methods only.

Continuous monitoring systems were located at sampling station SS1 for the measurement of [^{222}Rn] and WL(Rn), and at sampling station SS4 for the measurement of WL(Rn). Grab-sampling methods were also used at sampling stations SS1, SS2, SS3, SS4 and SS5 to determine [^{222}Rn] and WL(Rn).

Radon progeny Working Level measurements by continuous monitoring were conducted using Working Level continuous monitors, model α-PRISM, manufactured by alphaNUCLEAR (Toronto, Canada). Radon gas concentration measurements by continuous monitoring were carried out using radon gas continuous monitors, model AB-5/EL, manufactured by Pylon Electronic Development (Ottawa, Canada). Grab-sampling measurements of WL(Rn) were done using α-particle scalers, model TM-372A, manufactured by Tri-Met (Winnipeg, Canada). Radon gas concentration in water samples was determined by the degassing method using a degassing unit, model RDU-200, manufactured by EDA (Toronto, Canada) in conjunction with ZnS(Ag) scintillation cells and a scaler, model RM-1003, manufactured by Pylon. Airborne radon gas concentration by grab-sampling was determined using ZnS(Ag) scintillation cells and a scaler, model RM-1003.

Meteorological variables were measured by grab-sampling using conventional instrumentation. Air flow rate measurements were made by anemometry.

Measurements of [^{222}Rn], radon progeny concentration, and WL(Rn) were carried out during mining operations and during inactive mining periods. Measurements were also conducted under normal ventilation conditions during mining operations and when the ventilation system was partially or totally turned off during periods of no mining activity. The operating conditions of the mine ventilation system are indicated in the graphs by vertical arrows pointing downward to indicate day and time of operation.

The mine ventilation system consisted of a main fan system made up of a large and a smaller fan (hereafter referred to as Fan 1 and Fan 2, respectively), and an auxiliary fan. The location of the fans is shown in Figure 1. The duration of the underground tests was one week (February 1988).

EXPERIMENTAL RESULTS AND DISCUSSION

Experimental data have been summarized in Tables 1 to 13, and Figures 2 to 13. Tables 1 to 7, and Figures 2 to 13 show radon and radon progeny data. Tables 8 and 9 show air flow conditions and meteorological variables in the mine, repectively. Table 10 shows mine geometrical and physical data of interest. Tables 11 and 12 show miscellaneous radiation data. Table 13 shows the result of a ventilation/radiation survey.

Tables 1 to 4 show radon progeny data obtained by grab-sampling techniques using the Thomas-Tsivoglou and Kusnetz methods (2,3). Table 5 shows WL(Rn) obtained by continuous monitoring using radon progeny Working Level monitors, model α-PRISM, manufactured by alphaNUCLEAR (Toronto). The range of values measured for radon and its progeny at the sampling stations selected is shown in Table 11, whereas the ratios of maximum to minimum values are tabulated in Table 12. The radon gas concentration measured at several sampling stations is shown in Table 6. For the benefit of the reader, radiation data tables are given in old and new units, i.e., WL(Rn) and $\mu J/m^3$, respectively. Similarly, radon and radon progeny concentrations, e.g.,

[^{218}Po], are given in SI units (Bq/m^3), and in the more historical units (pCi/L).

Figures 2 to 7 show WL(Rn) data by continuous monitoring, whereas Figures 8, and 9 to 13 show, respectively, WL(Rn), and radon progeny concentrations and radon progeny ratios by grab-sampling. Also shown in Figures 4 to 7 are some radon concentration data by grab-sampling (Figure 4) and WL(Rn) data by grab-sampling (Figures 5 to 7). The ventilation conditions are indicated in Figures 2 to 13 by vertical arrows.

As the above data show, the values for the radiation variables observed in the mine varied markedly depending on airflow conditions and the sampling station. The range of values measured is summarized in Table 11. It should be noted that because of practical constraints a sample frequency had to be chosen compatible with other considerations. In our case, samples were taken at 20 min intervals. Hence, values higher than the maximum values shown in Table 11 are possible. Furthermore, airflow conditions when all the fans were off varied with each location depending on natural ventilation conditions prevailing at the time. These natural ventilation conditions depended partly on outdoor meteorological conditions, particularly at SS1.

The above observations apply to grab-sampling data. The same considerations, however, apply to data obtained by continuous monitoring systems except that in this case additional complicating factors enter into play, namely:

a) Because of the integrating nature of the sampling techniques used in some continuous monitoring systems, there is a time lag between the recording of an event and the actual occurrence of this event. For radon progeny the time delay (lag) is about 1 hour;

b) Under rapid dynamic situations, important radiation information features may be 'missed' by some continuous monitoring systems if the sampling interval chosen is significantly longer than the time interval during which a given event occurs.

The effect of mining operations at the working (sampling) locations SS4 and SS5 was not clear because variations in radiation conditions during a given working shift and/or between different shifts could be ascribed to one or more of the following causes (see Figures 7,8 10 and 11, and Tables 3, 8 and 13):

a) Mine traffic, i.e., passing mining equipment such as trucks and drilling, hauling and mucking equipment;

b) Diesel particulates arising from the operation of mining equipment. Submicron particles provide a substratum to which radon progeny can attach instead of being removed by plate-out mechanisms on mine walls. Hence, an increase in submicron aerosol concentration shows as an increase in WL(Rn) and radon progeny concentrations such as ^{218}Po;

c) Outdoor meteorological conditions which affect SS5 directly. The meteorological conditions for Feb. 11 and 12/88, days for which grab-sampling data are available for SS4 and SS5 (see Tables 2 and 3) were as follows:

<u>Feb. 11/88</u> R.H. : 95% (8:00 h) to 65% (17:00 h)
T : $-4^{o}C$ (8:00 h) to $-9^{o}C$ (17:00 h)
P : 102 kPa (8:00 h) to 102.65 kPa (17:00 h)
Wind velocity (v) : 30-40 km/h (variable)

<u>Feb 12/88</u> R.H. : 90% (8:00 h) to 71% (17:00 h)
T : $-12^{o}C$ (8:00 h) to $-11.6^{o}C$ (17:00 h)
P : 103.3 kPa (8:00 h) to 103.5 kPa (17:00 h)
Wind velocity (v) : 28 km/h (8:00 h) to 10 km/h(17:00h)(steady decline).

It is not clear what effect these varying meteorological conditions had on SS5, a location that was just a few metres away from the fresh air discharge;

d) Influence of conditions at SS5 on other mine locations, in particular SS4 (the other development face where mining operations were carried out) via an auxiliary fan situated in close proximity;

e) Agitation of water ponds and running water in SS5 by passing mine machinery and vehicles. Agitation of water will release radon gas dissolved in it;

f) Fracture and breakage of the rock formation by drilling and blasting operations. Rock fractures and openings allow more ^{222}Rn laden water to enter the working place; and

g) Ventilation changes because of varying conditions, and because of ventilation tubing repairs (see Tables 3, 8 and 13).

Because of items a) to g), the possible effects on the radiation level at SS4 and SS5 by mining operations are most certainly masked, at least partially. One may tentatively assume, unless the contrary is proven conclusively, that mining operations did not greatly affect the radiation level. This is not surprising because as previously shown (1), the major contribution to the radiation level arises from radon gas dissolved in water entering the mine through mine walls. Hence, rock fragmentation (blasting), ore transportation (mucking), drilling, and other mining operations in this non-uranium mine are not expected to play a major role as additional radiation 'sources'.

As expected, a pronounced difference in radiation conditions in the mine air was observed when the ventilation fans were turned off. All radiation variables such as WL(Rn), [^{222}Rn], radon progeny concentrations, e.g., [^{218}Po], and radon progeny disequilibrium ratios increased rapidly (see Figures 4, 5, 7-9, and 11-13). At SS1, however, the situation was more complex because of its close proximity to the portal. Hence, radiation conditions at this location were partly determined by local meteorological factors such as pressure differentials and temperature gradients which greatly influenced local airflow conditions (see Figures 2 and 3).

When the ventilation fans were turned on again, the converse effects of that indicated above were observed, including location SS1. A basic difference between the two cases is worth mentioning, namely, a transient effect (discussed below) which consisted of a rapid increase in the radiation level followed by a continuous decrease until steady-state conditions were attained some time after normal airflow conditions were reestablished (see Figures 2-5, and 7-11).

The ratios of maximum to minimum values for different radiation variables are given in Table 12, whereas the range of values is shown in Table 11. The extreme (high) values observed were obtained during changing airflow conditions, i.e. fan on/off and vice versa. The F-value given in Tables 11 and 12 is defined by the relationship: $F = (WL(Rn)/[^{222}Rn]) \times 10^2$ where $[^{222}Rn]$ is given in pCi/L. The F-factor and the radon progeny disequilibrium ratios $[^{214}Pb]/[^{218}Po]$ and $[^{214}Bi]/[^{218}Po]$ are a measure of ventilation conditions and plate-out of radon progeny on mine walls.

The high values calculated for F(>0.80) and the radon progeny disequilibrium ratios (~0.90) indicate that near equilibrium conditions were reached in the mine between radon gas and its progeny, and between the different members of the progeny series, when the ventilation fans were turned off. The high values for the above variables are indicative of long mine air residence times and low selective plate-out of radon progeny on mine walls, and other large surfaces. (It should be noted that the maximum theoretical value for F and the radon progeny disequilibrium ratios is 1.)

Figures 2 to 5, and 7 and 8 illustrate a feature of great practical interest, namely the build-up and removal of radioactivity in the mine when the ventilation fans are turned off and on, respectively. 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.

A. ZERO AIRFLOW

With only natural ventilation, the radiation level in the mine will increase continuously until a maximum, steady-state value is reached. This value may be modulated by the 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 (4). The maximum value for the radioactivity is a function of the rate of entry and release of radon gas in the mine environment. It should be noted that the term 'rate of release' refers to the case where radon gas is carried into the mine environment by a medium other than air, e.g., water. 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.

A point in case regarding items i) and ii) is shown by comparing Figures 2 and 3 with Figures 4, 5, 7 and 8. The data in these Figures clearly show that the maximum radiation level attained is much larger for sampling stations SS3, SS4 and SS5 than for sampling station SS1. This can be explained easily by noticing the following:

1. Strong natural ventilation conditions prevail at SS1 (60 m from the portal), caused by temperature and pressure differentials between SS1 and outdoors, which are absent in the other sampling stations; and
2. Large radon gas contribution in SS5 from high water influx into this area. (As will be illustrated below, radon gas dissolved in ground and surface water entering the mine is the major and probably only source of radon. Radon gas dissolved in water is released into the mine atmosphere by friction, collision, transport and interphase exchange mechanisms.)

Furthermore, Figures 4 and 5 for Q=0 show that the radioactivity build-up time for SS3 was ~16 h, with some modulation caused by local natural ventilation conditions. For SS1, however, the build-up time was less well defined because of moderate to strong (local) natural ventilation conditions, which changed often and rapidly. For example, no radioactivity build-up was observed for about 6 to 7 h after the ventilation fans were turned off. After that time, irregular radioactivity growth followed for about 9 to 10 h (see Figures 2 and 3). In conclusion, the effect of turning off the ventilation fans was far less pronounced at sampling station SS1 than at sampling station SS3. No conclusions can be drawn for sampling stations SS4 and SS5 because radiation data by continuous monitoring are not available. However, grab-sampling data for these two stations enabled the determination of the mine air clearance time fairly accurately, as discussed below.

B. NON-ZERO AIRFLOW

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.

As pointed out previously, 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 2 and 3).

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 became 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 (see Tables 7, 8 and other data). 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 (portal). Hence a transient (maximum) radiation level should be expected followed by a decay because of air dilution.

The transient effect described above for SS1 is also applicable to the other sampling stations, namely, SS3, SS4, and SS5. However, because these locations are far from the portal where radiation levels are higher than at SS1, radiation concentrations gradients between SS3, SS4 and SS5, and other mine locations further removed from the portal are less than for SS1. Hence, the transient effects discussed above should be significantly reduced for these three locations. This is in fact what is experimentally observed (see Figures 4, 5, 7 and 8). The fastest transient occurs at SS5 which is situated in close proximity to the fresh air ventilation tubing; at SS4 which is supplied directly with (second pass) air from an auxiliary fan a few meters away; and at SS3 from which air is taken to SS4 via the above fan. It is important to notice that the transient time for SS5 is far too fast to be recorded in most cases. This is so because of its proximity to the fresh air ventilation discharge which makes time-synchronization measurements difficult. Under these circumstances, the time chosen for air sampling (5 min) was considerably longer than the transit time of fresh air through SS5 and the transient was 'missed' (see Figure 8).

Chronologically speaking, transient effects appear first at location SS5, followed by SS3 and SS4, and finally SS1. This sequence can be easily understood from the mine ventilation layout (see Figure 1). 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 (see Figures 2 to 5, 7 and 8, and Tables 4 and 6).

The mine air transit time and clearance time calculated from Figures 2 to 5, 7 and 8 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. Naturally, the results should be the same. The difficulty arises from the interpretation of the data. In order to clarify this point, the reader should be aware of the following:

a) As previously indicated, data recorded by continuous monitoring devices of the time integrating type (e.g., alphaPRISM) exhibit a time lag of ~1 hour with respect to the actual occurrence of an event.

b) Continuous radiation monitoring devices tend to smooth out rapidly changing radiation conditions. If the sampling time is of the same order, or longer than the period of the radiation event, the device may show a largely reduced response or miss the event altogether.

c) A sudden and very steep change (decrease) in radiation conditions will cause the continuous monitoring device to respond with a rather long radioactive decay tail. This is due to the decay of the radon progeny in the sampling filter. This situation is analogous to sampling air at a given flow rate and then turning the sampling pump off. The activity in the filter will decay according to well known laws. For radon progeny it will take 3 to 4 h for the activity to decay completely.

d) There is a time lag between the appearance of radon gas and its progeny. This is to be expected, and is well understood on theoretical grounds as ^{218}Po is formed by the decay of ^{222}Rn (half-life ~3.82 d), and so on.

Items a) to c) are responsible for a substantial broadening and time shifting of the radiation response of the instrument with respect to the time profile of the actual radiation event. The Figures in the text clearly show this.

Other differences between profiles by grab-sampling and continuous monitoring can be ascribed partly to the particular sampling frequency chosen.

Examination of the data presented in the Figures shows that the approximate mine air clearance times are: 3-5 h for SS1, 2-3 h for SS3, $\lesssim$2.0 h for SS4, and <2 h for SS5. These figures are subject to some uncertainty because of items a) to d).

C. WATER INFLUX AND RADON GAS IN MINE WATER

Relatively high concentrations of radon gas ($\gtrsim$2.6 x 10^3 Bq/m^3) have been measured in air in this non-uranium underground mine (see Table 6). Because this is a non-uranium mine, the question arises as to where the radon gas comes from?

Because of the usually very wet conditions in the mine and the highly fractured nature of the surface of the mine walls, sensor installation and measurement of radon flux by fluxmeter cans was extremely difficult, and hence, not attempted.

Radon flux measurements at dry locations of the mine using fluxmeter cans would identify the presence of radon gas in interstitial pores in the rock formation. The radon 'trapped' in the pores emanates into open spaces by diffusion (concentration gradients) and convective (transport) processes. Because of the rather limited diffusion length of radon gas in most materials, i.e., $<2-3$ m (5,6), the measurement of an appreciable radon gas flux would indicate the presence of ^{238}U and ^{226}Ra in the immediate vicinity of the mine, i.e., mine walls, ceiling and floor.

Direct radon gas flux measurements failing, the second choice was to determine the presence of ^{222}Rn and its parents (^{238}U and ^{226}Ra) in waste rock and ore by emanation studies. Measurements of this kind are in progress and will be reported elsewhere when completed.

A strong suspicion, confirmed by direct measurement (1), was the presence of radon gas dissolved in water entering the mine. (This is also supported by previous studies by other workers in adjacent mines.) It should be noted that no direct measurements of water quantity, inflow or stagnation, were conducted. The water quantity data used below for calculation purposes were supplied by mine personnel and other officials.

Water samples were taken from a number of locations and degassed by conventional techniques. The gas was collected in scintillation cells and the α-particle activity was measured and followed for a period of time. The observed radioactive half-life of the gas confirmed the presence of radon in water samples. Table 7 summarizes some of the results obtained. Radon gas concentrations in excess of 1.0 x 10^6 Bq/m^3 (~2.7 x 10^4 pCi/L) were obtained. At the surface water discharge point the activity concentration measured (1) was ~3.1 x 10^5 Bq/m^3 (~8.4 x 10^3 pCi/L). A previous calculation (1), assuming a water influx into the mine of about 5 m^3/min (7), a radon gas emanation coefficient in water of 0.5 (50%), and an average [^{222}Rn] in water of 3.8 x 10^5 Bq/m^3 (~1.0 x 10^4 pCi/L), showed that the rate of release of activity into the mine volume (~1.5 x 10^4 m^3) was 9.5 x 10^5 Bq/min (~2.6 x 10^7 pCi/min).

The above calculation is a crude one because of the large uncertainty in the values for the average radon gas concentration in water, the radon gas emanation coefficient, and geometric distribution of water sources with different radon gas concentrations, and other variables not discussed here.

The influence and interplay of the above variables, and the modelling of the mine, assuming water as the major carrier of radon gas into the mine, is beyond the scope of this report. This topic will be discussed at length in a separate forthcoming report.

It should be noted that if radon gas dissolved in water is the main source of radon entering the mine at different locations, the source of radon could be, in principle, far removed from the mine site. This contention, however, cannot be verified without further experimentation and hydrological information.

D. RADIUM (^{226}Ra) IN WATER SAMPLES

It has been assumed above that the radon gas measured in water was actually radon gas dissolved in the samples. However, the possibility of radium (^{226}Ra) dissolved in water as the origin of radon gas has also been considered. In order to verify this, water samples were completely degassed, and stored in leak-free glass containers. After one month, water samples were degassed again and the gas collected in scintillation cells was measured. The result of these tests indicated almost negligible amounts of ^{226}Ra in water. Hence, it may be concluded that the radon gas measured in water was indeed radon gas dissolved in the water samples.

E. OBSERVATIONS REGARDING THE VENTILATION SYSTEM

The observations that follow are identical to the observations reported in a previous report (1). They will be repeated here for the benefit of the reader.

Careful inspection of the ventilation tubing showed numerous holes, tears and large openings (splits) with substantial loss of ventilation air. Furthermore, ventilation tubing of a smaller diameter than desirable was used in a side branch, thereby contributing to energy losses by friction.

Another important observation made was that water dripping from the mine ceiling collected in relatively large quantities in the ventilation tubing. Several locations where this occurred were identified. The weight of the water caused deformation and bending of tubing leading to the formation of water 'ponds' at the bottom of the ventilation tubing. Because radon gas is dissolved in water and the surface of the water ponds in the tubing was subjected to large airflows and air linear velocities, degassing of radon was greatly encouraged under these conditions. This would explain the higher than expected WL(Rn) (see Table 3 for SS5) in mine areas near the fresh ventilation air discharge where, in principle, negligible radiation levels should have been observed.

From the above discussion, it is recommended that for optimum operating conditions the ventilation tubing should be inspected on a daily basis and repairs made when leakages are identified. This practice will in turn improve airflow in needed areas, reduce radiation levels and minimize ventilation costs.

CONCLUSIONS AND RECOMMENDATIONS

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

1. The effect, if any, of mining operations on the radiation levels at SS4 and SS5 (the two development faces in the mine) was not clear because variations in radiation conditions during a given working shift and/or between shifts could be ascribed to the following causes: a) traffic (i.e., passing mining equipment); b) diesel particulates arising from the operation of mining equipment; c) outdoor meteorological conditions which affected SS5 directly; d) influence of conditions in SS5 on conditions in SS4 via the auxiliary fan; e) agitation of water ponds in SS5 during the course of mining operations; f) breakage and fracture of rock formations during drilling and blasting allowing more ^{222}Rn laden water to enter the working face; and g) ventilation changes because of ventilation tubing repairs and other causes (see Tables 3, 8 and 13).
2. Elevated radon gas and radon progeny concentrations were measured in this wet non-uranium mine. The radiation levels observed under normal ventilation conditions were as high or higher than those measured in conventional underground uranium mines.
3. Radiation levels when the mine ventilation system was turned off were considerably higher than radiation levels under normal ventilation conditions. In some cases, radiation levels increased by more than two orders of magnitude over their usual level.
4. The source of radiation in this non-uranium mine has been traced to water entering the mine site through walls and other large mine surfaces. Radon

gas concentrations in water samples in excess of 1 x 10^6 Bq/m^3 (~2.7 x 10^4 pCi/L) were measured. Taking into account that the water influx in the mine is about 5 m^3/min, and the high radon gas concentration levels in water indicated above, it is possible to calculate (theoretically) the radiation level in the mine from ventilation conditions and water source distribution conditions.

5. No appreciable radium (^{226}Ra) was found in water samples.
6. When the ventilation fans were turned off, near equilibrium conditions in the mine were attained given by the high values of the F-factor, and the radon progeny disequilibrium ratios. These high values are also indicative of very long mine air residence times, as expected.
7. Radioactivity build-up time and clearance time depended on the heading or work mine location, and natural and forced ventilation conditions. These data are important to assess radioactivity dose exposure in the event of a failure in the operation of the ventilation system.

This study shows that any further reduction in ventilation (fresh air quantity) will increase radiation levels significantly. Conversely, good air management principles will reduce existing radiation levels. The ventilation tubing should be inspected on a regular basis and repaired if necessary in order to improve ventilation conditions in the mine. Accumulation of water in the ventilation tubing should be avoided because this is a source of radon.

Further investigation will be necessary to control radiation levels, by regulating water quantity, i.e., optimum requirements.

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Table 1 - Radon progeny data at location SS3. Data obtained by the Thomas-Tsivoglou and Kusnetz methods.

Date	Time	[^{218}Po] pCi/L	[^{218}Po] (Bq/m^3)	[^{214}Pb] pCi/L	[^{214}Pb] (Bq/m^3)	[^{214}Bi] pCi/L	[^{214}Bi] (Bq/m^3)	WL(Rn)	PAEC (μJ/m^3)	[^{214}Pb]/[^{218}Po]	[^{214}Bi]/[^{218}Po]
Feb 11/88	9:45	66.7	(2468)	37.5	(1388)	25.5	(944)	0.354	7.36	0.56	0.38
"	11:25	48.9	(1809)	16.5	(611)	7.9	(292)	0.164	3.41	0.34	0.16
"	14:21	-	-	-	-	-	-	0.128	2.66	-	-
"	15:00	-	-	-	-	-	-	0.198	4.12	-	-
"	15:30	-	-	-	-	-	-	0.166	3.45	-	-
"	16:10	-	-	-	-	-	-	0.130	2.70	-	-
Feb 12/88	9:00	-	-	-	-	-	-	0.117	2.43	-	-
"	9:30	-	-	-	-	-	-	0.123	2.56	-	-
"	10:00	-	-	-	-	-	-	0.125	2.60	-	-
"	10:30	-	-	-	-	-	-	0.155	3.22	-	-
"	11:00	-	-	-	-	-	-	0.130	2.70	-	-
"	11:30	-	-	-	-	-	-	0.140	2.91	-	-

Table 2 - Radon progeny data at location SS4. Data obtained by the Thomas-Tsivoglou method. Also shown are the mining operations at the development face.

Date	Time	$[^{218}Po]$ pCi/L	(Bq/m^3)	$[^{214}Pb]$ pCi/L	(Bq/m^3)	$[^{214}Bi]$ pCi/L	(Bq/m^3)	WL(Rn)	PAEC $(\mu J/m^3)$	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	Mining Operations
Feb 11/88	9:00	48.0	(1776)	26.1	(966)	16.8	(622)	0.245	5.10	0.54	0.35	-
"	10:41	78.0	(2886)	34.5	(1277)	13.9	(514)	0.307	6.39	0.44	0.18	10:41 to 12:00 scoop mucking (pile hosed down at 11:45)
"	11:55	74.2	(2745)	39.8	(1473)	22.4	(829)	0.362	7.53	0.54	0.30	-
"	14:15	99.0	(3663)	46.6	(1724)	22.9	(847)	0.424	8.82	0.47	0.23	14:00 to 14:35 roof bolting
"	15:00	71.7	(2653)	38.4	(1421)	16.8	(622)	0.331	6.88	0.54	0.23	-
Feb 12/88	8:48	70.1	(2594)	26.7	(988)	9.8	(363)	0.244	5.08	0.38	0.14	8:30 to 10:15 mucking
"	9:30	71.4	(2642)	27.2	(1006)	11.8	(437)	0.255	5.30	0.38	0.17	-
"	10:00	-	-	-	-	-	-	0.272	5.66			-
"	10:30	64.1	(2372)	32.3	(1195)	19.2	(710)	0.301	6.26	0.50	0.30	10:25 to 12:00 roof bolting
"	11:15	59.3	(2194)	26.2	(969)	11.1	(411)	0.236	4.91	0.44	0.19	-
"	11:55	70.3	(2601)	34.7	(1284)	20.4	(755)	0.325	6.76	0.49	0.29	12:30 to 15:20 jumbo drilling
"	14:00	43.0	(1591)	20.4	(755)	12.0	(444)	0.192	3.99	0.47	0.28	-
"	14:30	51.2	(1894)	23.8	(881)	11.4	(422)	0.216	4.49	0.46	0.31	-

Table 3 - Radon progeny data at location SS5. Data obtained by the Thomas-Tsivoglou method. Also shown are the mining operations at the development face.

Date	Time	$[^{218}Po]$ pCi/L (Bq/m^3)	$[^{214}Pb]$ pCi/L (Bq/m^3)	$[^{214}Bi]$ pCi/L (Bq/m^3)	WL(Rn)	PAEC (μJ/m^3)	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	Mining Operations
Feb 11/88	9:00	18.9 (699)	8.4 (311)	4.1 (152)	0.078	1.62	0.44	0.22	8:00 to 9:30 roof bolting and timbering
"	9:45	37.8 (1399)	13.1 (485)	4.9 (181)	0.124	2.57	0.35	0.13	9:40 to 10:15 mucking
"	10:30	29.3 (1084)	9.5 (351)	6.0 (222)	0.101	2.10	0.32	0.20	10:25 to 14:50 jumbo drilling
"	11:00	31.3 (1158)	8.8 (326)	3.7 (137)	0.090	1.87	0.28	0.12	Repairs to ventilation tubing
"	11:30	15.1 (559)	6.1 (226)	5.0 (185)	0.065	1.35	0.40	0.33	-
"	14:15	17.4 (643)	6.1 (226)	4.4 (163)	0.065	1.35	0.35	0.25	-
"	15:00	20.9 (773)	6.8 (252)	6.1 (226)	0.079	1.64	0.33	0.29	15:00 to 16:00 loading
"	16:10	22.8 (843)	7.2 (266)	3.1 (115)	0.072	1.49	0.32	0.15	-
Feb 12/88	9:52	11.0 (407)	3.7 (137)	2.6 (96)	0.040	0.832	0.34	0.24	10:00 to ? drilling
"	10:30	11.6 (429)	4.5 (167)	3.2 (118)	0.047	0.978	0.39	0.28	-
"	11:15	10.9 (403)	4.6 (170)	3.7 (137)	0.048	0.998	0.42	0.34	-
"	11:45	15.1 (559)	5.2 (192)	4.3 (159)	0.058	1.206	0.34	0.28	-
"	14:30	16.4 (607)	6.2 (229)	3.3 (122)	0.061	1.269	0.38	0.20	14:03 to ? loading
"	15:09	19.2 (701)	7.1 (263)	0.8 (29.6)	0.059	1.227	0.37	0.04	-

Table 4 - Radon progeny data at several underground mine locations (Feb 14/88). Data obtained by the Thomas-Tsivoglou and Kusnetz methods. Fans turned off on Feb 13/88 at 17:35 h, and turned on at ∿10:00 h on Feb 14/88.

Location	Time	$[^{218}Po]$ pCi/L (Bq/m^3)	$[^{214}Pb]$ pCi/L (Bq/m^3)	$[^{214}Bi]$ pCi/L (Bq/m^3)	WL(Rn)	PAEC (μJ/m^3)	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$
SS3	9:38	696.8 (25782)	420.5 (15559)	183.3 (6782)	3.54	73.6	0.60	0.26
"	10:20	1469.1 (54357)	1287.1 (47623)	1179.2 (43630)	12.45	259.0	0.88	0.80
"	11:05	331.7 (12273)	188.8 (6986)	125.9 (4658)	1.77	36.8	0.57	0.38
"	11:45	211.0 (7807)	87.0 (3219)	59.0 (2183)	0.88	18.3	0.41	0.28
"	12:20	115.0 (4255)	57.4 (2124)	32.9 (1217)	0.53	11.0	0.50	0.29
SS4	9:35	558.9 (20679)	440.3 (16291)	350.9 (12983)	4.12	85.7	0.79	0.63
"	10:05	491.3 (18178)	438.9 (16239)	384.8 (14238)	4.17	86.7	0.89	0.78
"	10:16	– –	– –	– –	4.32	89.9	–	–
"	10:30	– –	– –	– –	11.45	238.2	–	–
"	10:45	– –	– –	– –	5.08	105.7	–	–
"	11:00	– –	– –	– –	2.96	61.6	–	–
"	11:15	– –	– –	– –	1.95	40.6	–	–
"	11:30	– –	– –	– –	1.36	28.3	–	–
"	11:45	– –	– –	– –	1.14	23.7	–	–
"	12:00	– –	– –	– –	0.94	19.6	–	–
"	12:15	– –	– –	– –	0.77	16.0	–	–
"	12:30	74.4 (2753)	55.9 (2068)	55.4 (2050)	0.59	12.3	0.75	0.74
SS5	9:30	2432.5 (90003)	1990.7 (73656)	1764.2 (65275)	19.20	399.4	0.82	0.73
"	10:15	– –	– –	– –	11.60	241.3	–	–
"	10:25	– –	– –	– –	3.48	72.4	–	–
"	10:35	– –	– –	– –	2.74	58.0	–	–
"	10:45	– –	– –	– –	1.79	37.2	–	–
"	11:00	– –	– –	– –	1.01	21.0	–	–
"	11:30	– –	– –	– –	0.51	10.6	–	–
"	12:00	– –	– –	– –	0.22	4.6	–	–
"	12:29	38.3 (1417)	23.6 (873)	17.6 (651)	0.23	4.8	0.62	0.46

Table 5 - Radon progeny Working Level averaged over sampling time for several underground mine locations.

Date	Time	T_s (h)	Location	$\overline{WL(Rn)}$	PAEC ($\mu J/m^3$)	Remarks
Feb 10/Feb 10	0:40/13:40	13.0	SS1	0.226±0.030	4.70	α-PRISM No. 61
Feb 10/Feb 11	0:40/7:40	31.0	"	0.258±0.03	5.36	α-PRISM No. 40
Feb 11/Feb 12	11:52/8:33	20.6	"	0.272±0.03	5.65	"
Feb 12/Feb 13	10:45/9:46	23.0	"	0.262±0.03	5.45	"
Feb 14/Feb 15	16:04/8:44	16.6	SS3	0.180±0.06	3.74	α-PRISM No. 61
Feb 10/Feb 10	14:20/22:00	7.6	SS4	0.240±0.02	4.99	"
Feb 11/Feb 12	13:22/4:23	15.0	"	0.205±0.04	4.26	"
Feb 12/Feb 13	22:08/10:08	12.0	"	0.187±0.04	3.89	"

Notes: T_s stands for sampling time. The abbreviation PAEC indicates potential alpha energy concentration. The horizontal bar over WL(Rn) is used to indicate average value. The symbols α-PRISM No. indicate the α-particle personal dosimeter used.

Table 6 - Radon gas concentration in air at several underground mine locations. Data obtained by grab-sampling.

Date	Time	Location	[^{222}Rn] Bq/m^3 (pCi/L)	Remarks
Feb 11/88	14:33	SS1	2102 (56.8)	
	14:35	SS1	2760 (74.6)	
	11:39	SS3	2028 (54.8)	
	11:41	SS3	2164 (58.5)	
	11:26	SS4	2694 (72.8)	
	11:29	SS4	2486 (67.2)	
	11:49	SS5	141 (3.8)	Leak?
	11:52	SS5	914 (24.7)	
Feb 14/88	10:00	SS3	16132 (436)	Fans turned on at 10:14:30
	10:15	SS3	35039 (947)	
	10:30	SS3	36704 (992)	
	10:45	SS3	18537 (501)	
	11:00	SS3	11433 (309)	
	11:20	SS3	6882 (186)	
	11:40	SS3	4773 (129)	
	12:00	SS3	4625 (125)	
	12:30	SS3	3922 (106)	

Table 7 - Radon gas concentration measured in water samples taken at several underground mine locations (see Figure 1).

Date	Location	$[^{222}Rn]$ Bq/m^3 (pCi/L)	Remarks
Feb 13/88	SS2	1,183,371 (31983)	From roof
	SS5	800,125 (21625)	From wall
	SS5	1,058,496 (28608)	Upstream
	SP3	1,153,179 (31167)	From pipe
	SP3	1,018,092 (27516)	From pond
	SP4	583,379 (15767)	From pond
	Subramp/ X-cut 2B	453,879 (12267)	From pond

Notes: The values for the radon gas concentration, $[^{222}Rn]$, in water samples given above represent lower limit estimates based on water samples degassed twice independently. Measurements show, however that appreciable amounts of ^{222}Rn still remain in water samples after degassing the samples twice as recommended by the manufacturer of the instrumentation used in these measurements. It is concluded that the data of the above table underestimate the true values of $[^{222}Rn]$ by $\gtrsim$10%.

SP stands for sump pump.

Table 8 - Airflow rate conditions at sampling stations SS1, SS2, SS3, SS4, SS5, and other underground mine locations.

Date	Location	Cross-Section (m^2)	Q (m^3/s)	Remarks
Feb 11/88	SS1	17.5	15.8	
	SS2	21.4	5.7	
	SS3	20.5	15.0	
	SS4	13.5	1.2	
	SS5	15.2	2.7	
	V4	16.5	4.6	
	V5	6.8	1.4	
	V16	14.0	0.5	
	Cross-cut #1	18.3	2.7	Below subramp
Feb 12/88	SS1		18.0	
	SS2		1.6-1.9	
	SS3		18.0	
	SS4		1.9	
	SS5		-	
	V4		2.3	
	V5		4.5	
Feb 13/88	SS1		1.9	
	SS2		-	
	SS3		?	
	SS4		2.9	
	SS5		3.2	
	V4		2.7	
Feb 13/88	SS1	19.0	24.3	
	SS2	23.0	0.9	
	SS3	19.7	12.6	
	SS4	17.3	1.1	
	SS5	18.3	4.1	
	V2	17.4	5.1	Level 2 North, 20 m from Y
	V3	14.7	0.8	X-cut 2B, 20 m from Y
	V4	16.1	4.8	Subramp 10 m down from X-cut 2A
	V5	15.8	5.3	X-cut 2A, 10 m from subramp
	V6	20.2	9.5	10 m uphill from X-cut 2A on subramp
	V9	17.8	6.8	12 m downhill from Level 1 south by-pass on X-cut #1
	V11	18.6	16.2	15 m downhill from SP1
	V13	0.6	4.6	End of ventilation tube (Level 2 south)
	V14	0.14	0.4	End of ventilation tube (Level 1 north)
	V15	0.28	3.5	End of ventilation tube (Level 1 south)

Table 9 - Underground meteorological data (temperature (T), relative humidity (RH) and barometric pressure (P))

Date	Location	Time	T (^{o}C)	RH (%)	P (kPa)	Remarks
Feb 11/88	SS1	10:30	8	78	99.6	
"	SS1	14:29	6	89	99.9	
"	SS3	10:55	6.5	85	100.1	
"	SS4	9:04	12.6	-	-	
"	SS4	10:35	~13	74	99.9	
"	SS5	9:30	~10	69	100.1	
"	SS5	12:00	7	75	100.3	
"	Portal	14:42	3-4	90-93	99.7	
	Surface	-	20	20-29	99.8	Offices
Feb 12/88	SS1	9:40	7	77	100.9	
"	SS3	10:00	5-6	88	101.4	
"	SS4	9:59	10	84	101.2	
"	SS5	10:12	6	86	101.6	
"	Surface	9:45	0	79	100.8	Outdoors

Table 10 - Geometric (physical) data and other miscellaneous data for the underground mine.

Location From	To	Distance (m)
SS1	Portal	60
SS2	SS1	206
SS2	Portal	266
SS3	SS1	120
SS3	Portal	180
SS4	SS1	150
SS4	Portal	210
SS5	SS1	450
SS5	Portal	510
End of level 1 north	Portal	476
End of X-cut 2A	Junction main ramp	275
End of X-cut 2B	X-cut 2A/subramp	190
End of main drift	Portal	950

The following cross-sections (X-sections) were measured:

X-section for SS1 : 19.0 m^2

X-section for SS2 : 23.3 m^2

X-section for SS3 : 19.7 m^2

X-section for SS4 : 17.3 m^2

X-section for SS5 : 18.3 m^2

Average X-section for the mine : ~16.0 m^2

Volume of the mine : ~1.52×10^4 m^3

Maximum ventilation rate observed with all fans operating: ≥ 18 m^3/s

Note: Several operators were involved (independently) in the X-section measurements. Hence the values for these cross-sections may differ depending on the exact location of the measurement by a given operator.

Table 11 - Range of values for radon and radon progeny data measured by grab-sampling at several mine locations.

Location	$[^{218}Po]$ (Bq/m^3)	$[^{214}Pb]$ (Bq/m^3)	$[^{214}Bi]$ (Bq/m^3)	$\frac{[^{214}Pb]}{[^{218}Po]}$	$\frac{[^{214}Bi]}{[^{218}Po]}$	WL(Rn)	$[^{222}Rn]$ (Bq/m^3)	F-Value
SS1	-	-	-	-	-	0.1-3.25[1]	2102-2760	0.18[1]
SS2	-	-	-	-	-	-	-	-
SS3	1809-54357	611-47623	292-43630	0.34-0.88	0.16-0.80	0.12-12.45	2028-36704*	0.22-(~1.25)[+]
SS4	1776-20679	755-16239	363-14238	0.38-0.89	0.14-0.78	0.19-11.45	2486-2694	0.28
SS5	403-90003	137-73656	30-65275	0.28-0.82	0.04-0.73	0.04-19.20	? -914	-

Notes: * Upper value represents the maximum obtained shortly after a period during which the mine ventilation was turned off. No $[^{222}Rn]$ measurements were conducted during this period in the other underground locations. Because of this, upper values for F are not given for other locations.

\+ The value $F > 1.0$ occurs because the maximum values taken for WL(Rn) and $[^{222}Rn]$ do not coincide in time. To convert Bq/m^3 to pCi/L divide above values by 37. To convert WL(Rn) to $\mu J/m^3$ (PAEC) multiply by 20.8.

1 Values obtained by continuous monitoring. The minimum values for WL(Rn) and $[^{222}Rn]$ have been taken to calculate the F-value for the reasons given above for item (+).

Table 12 - Ratios of maximum to minimum values measured for different radiation variables. Maximum and minimum values were obtained with fans off and on, respectively.

Location	[^{218}Po] (Bq/m^3)	[^{214}Pb] (Bq/m^3)	[^{214}Bi] (Bq/m^3)	[^{214}Pb]/[^{218}Po]	[^{214}Bi]/[^{218}Po]	WL(Rn)	[^{222}Rn] (Bq/m^3)	F-Value
SS1	-	-	-	-	-	32.5	1.31	-
SS2	-	-	-	-	-		-	-
SS3	30.05	77.94	149.42	2.59	5.00	103.75	18.10	∿5.00
SS4	11.64	21.51	39.22	2.34	5.57	60.26	1.08	-
SS5	223.33	537.63	2175.83	2.93	18.25	480.00	-	-

Notes: The F-value is defined as (WL(Rn)/[^{222}Rn]) x 10^2 where [^{222}Rn] is given in pCi/L.
To convert Bq/m^3 to pCi/L divide above values by 37.
To convert WL(Rn) to μJ/m^3 multiply by 20.8.
The data in this table have been calculated based on data given in Table 11.

Table 13 - Airflow rate and radon progeny Working Level data for several underground locations (survey conducted from 11:20 to 13:15 on Feb 13/88)

Location	Q (m^3/s)	WL(Rn)	Remarks
K1	4.1	0.14	Location SS5
K2	~4.8	0.53	
K3	4.8	0.41	
K4	5.3	0.38	
K5	9.5	0.29	
K6	~12.6	0.33	
K7	12.6	0.33	Location SS3
K8	-	0.58	
K9	-	0.46	
K10	1.1*	0.41	Location SS4
K11	~6.8	0.84	
K12	0.4**	0.69	
K13	-	1.07	
K14	0.9	1.29	Location SS2
K15	~16.2	0.46	
K16	24.3	0.44	Location SS1

Notes: * Q at end of ventilation tubing: 3.5 m^3/s.

** Measured at end of ventilation tubing.

WL(Rn) measurements by Kusnetz method.

K-locations are shown in Figure 1.

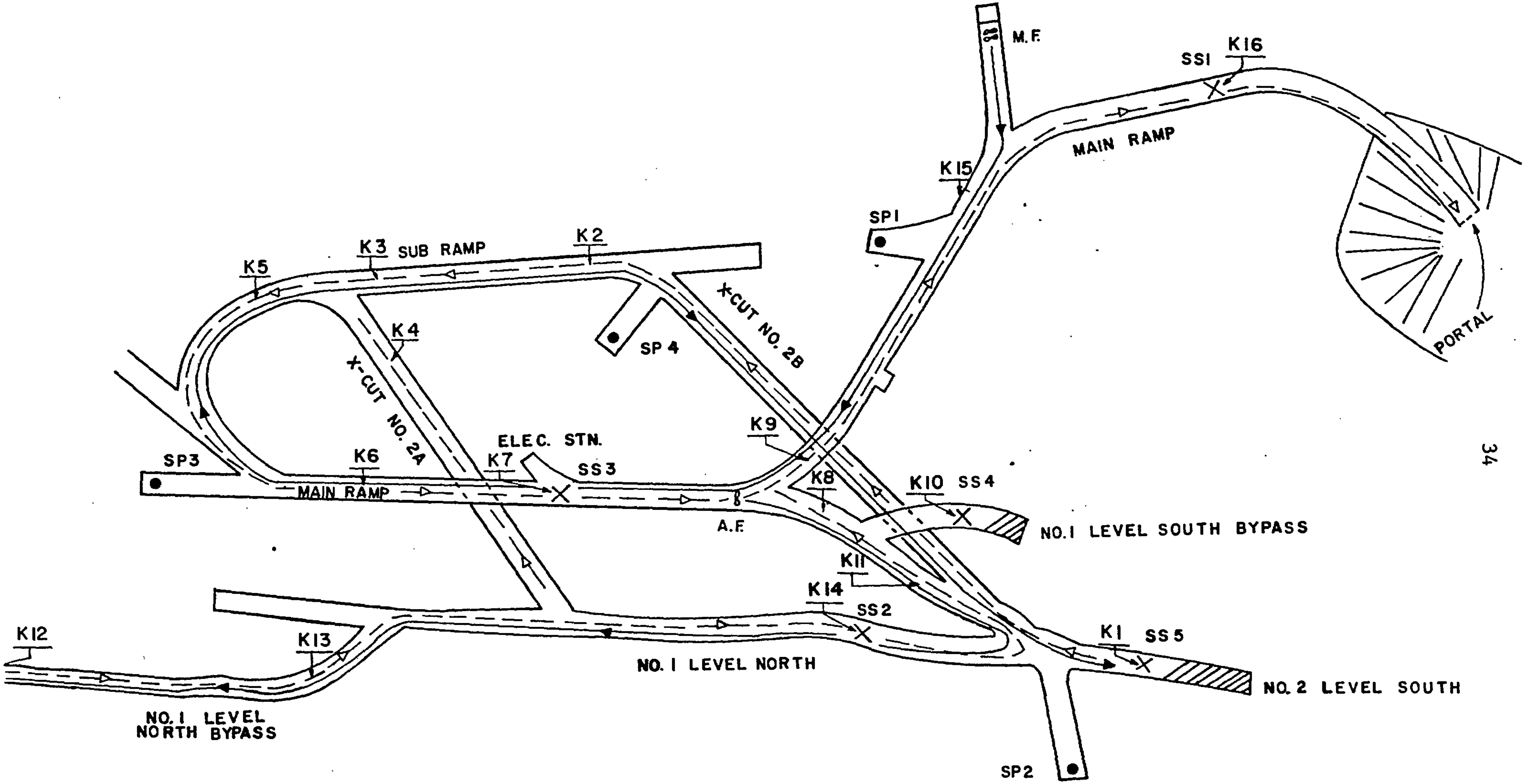

Fig. 1 - Layout of underground sites where measurements were carried out. The symbols SP, MF, and AF stand for sump pump, main fan, and auxiliary fan, respectively. The K's indicate locations where ventilation and/or radiation measurements were carried out. The symbol SS stands for sampling station.

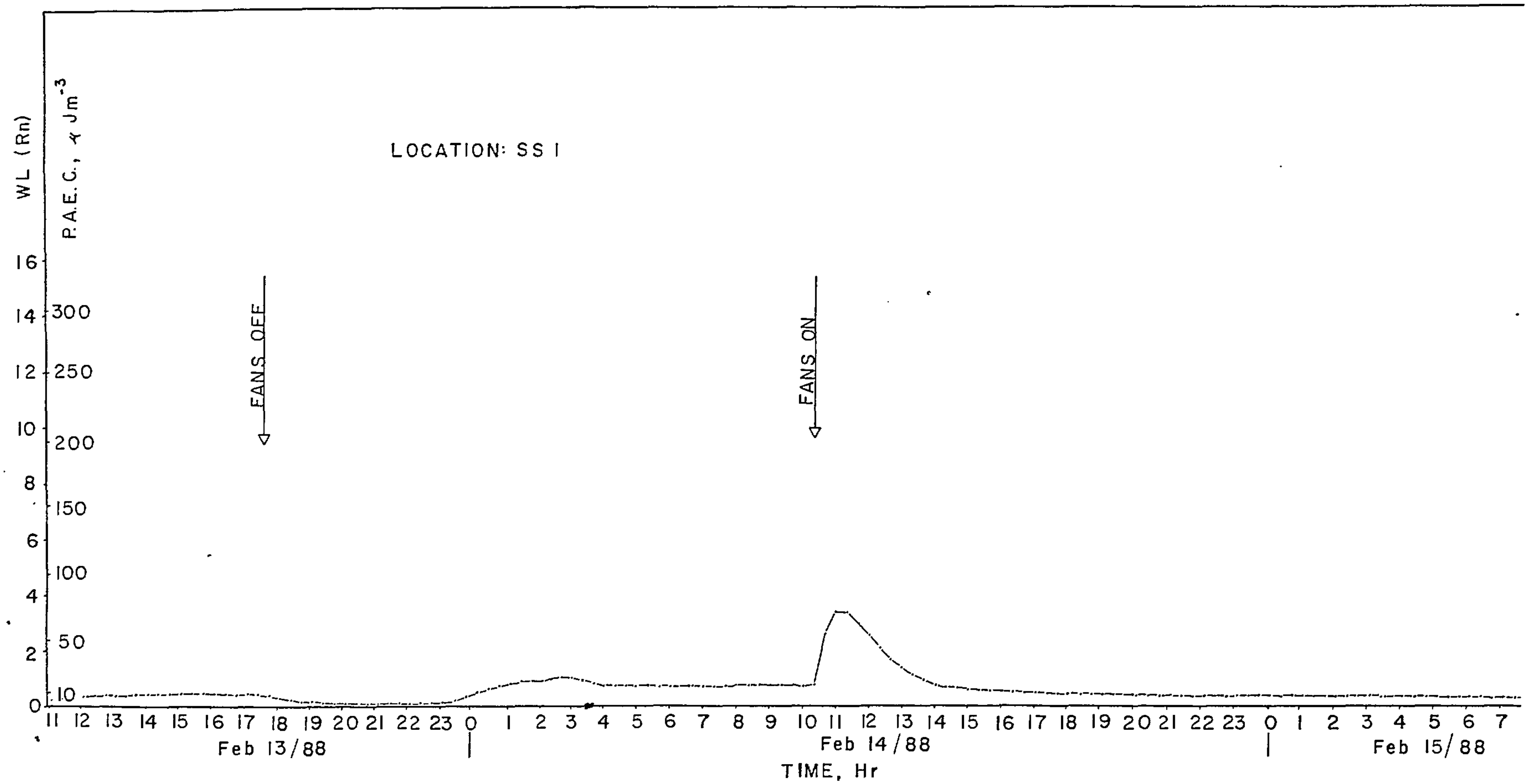

Fig. 2 - WL(Rn) versus time at location SS1.

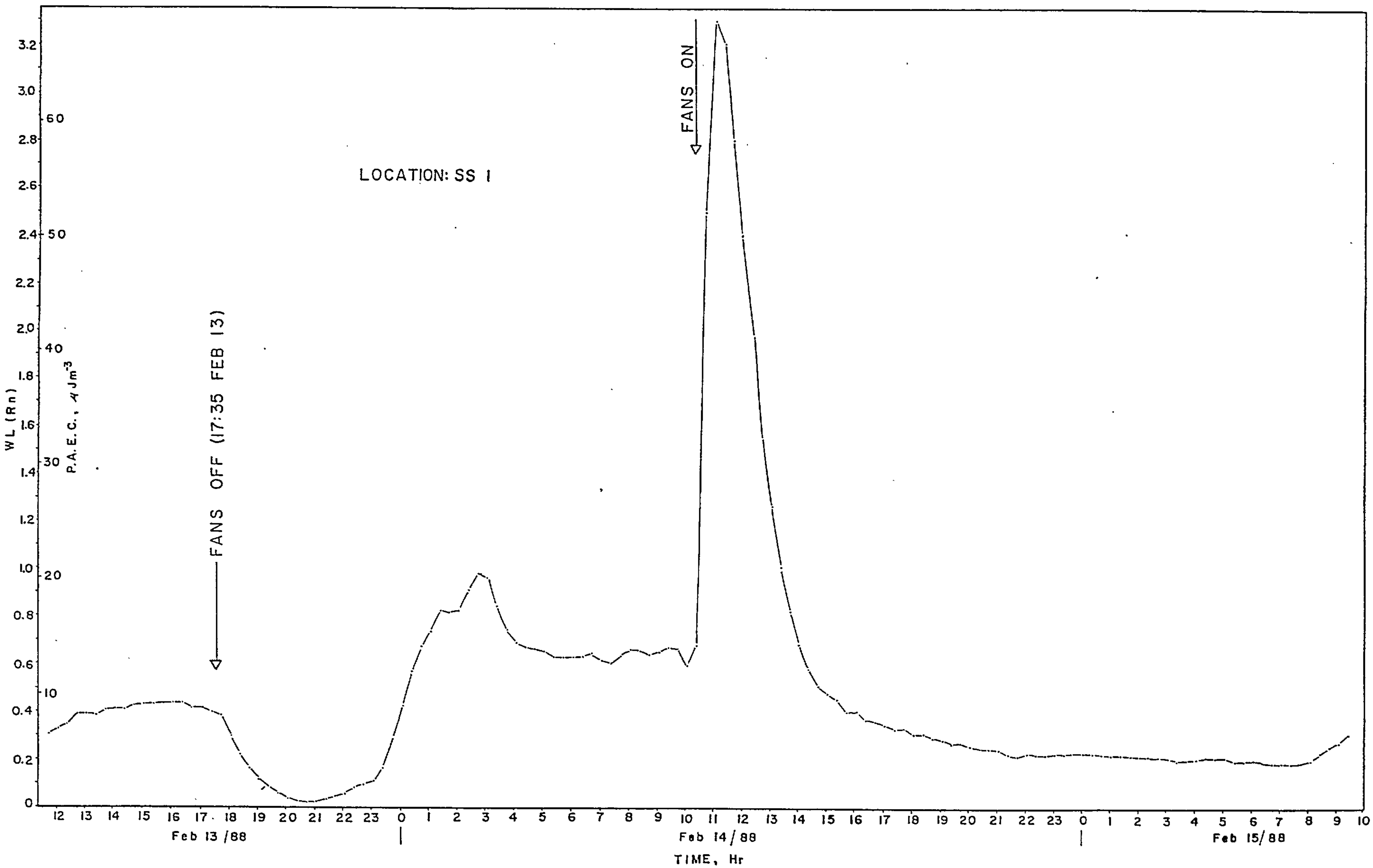

Fig. 3 - WL(Rn) versus time at location SS1 (expanded version of Fig. 2).

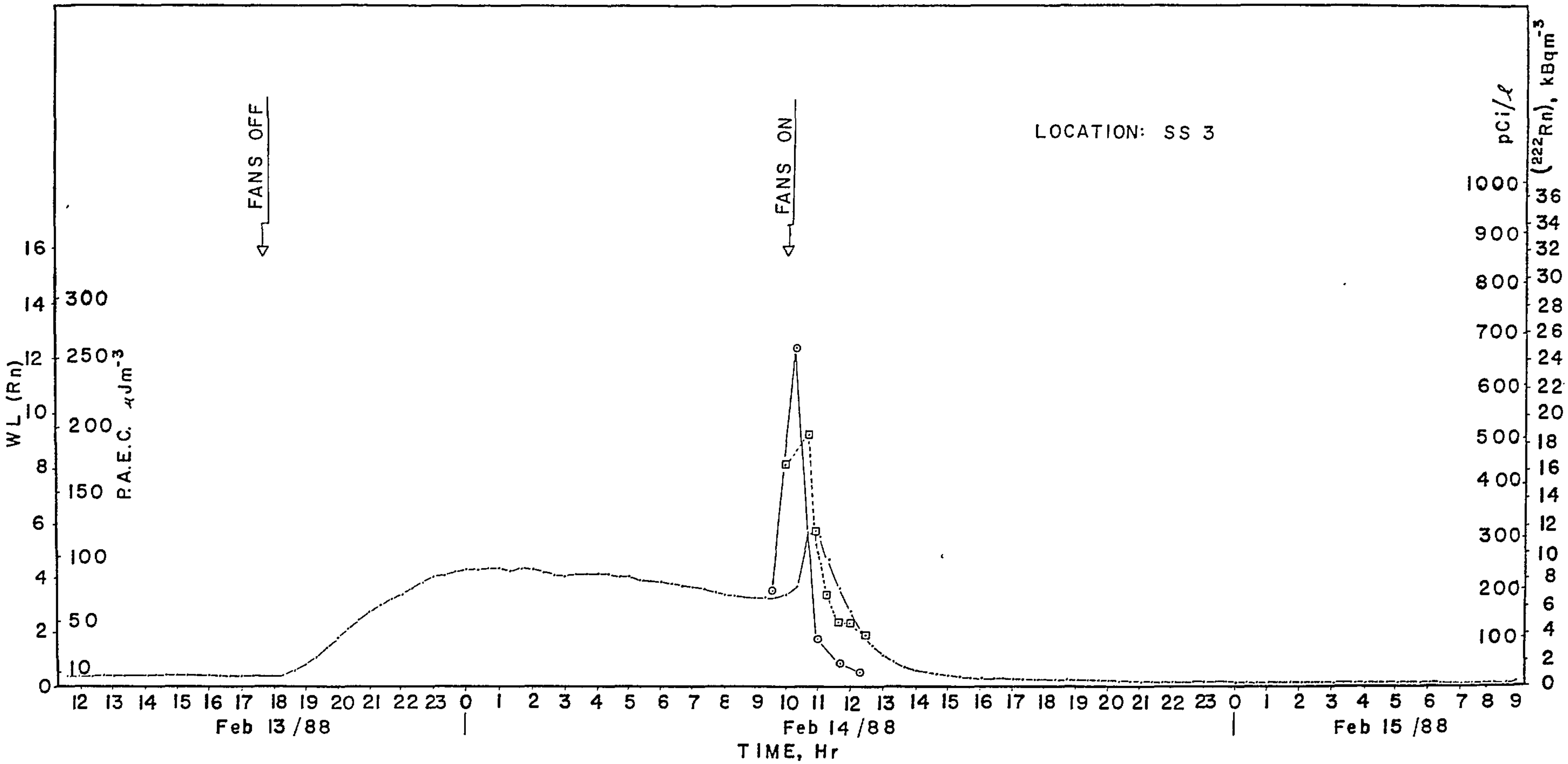

Fig. 4 – [^{222}Rn] by grab-sampling (⊡), WL(Rn) by grab-sampling (⊙), and WL(Rn) by continuous monitoring (–·–) versus time at location SS3.

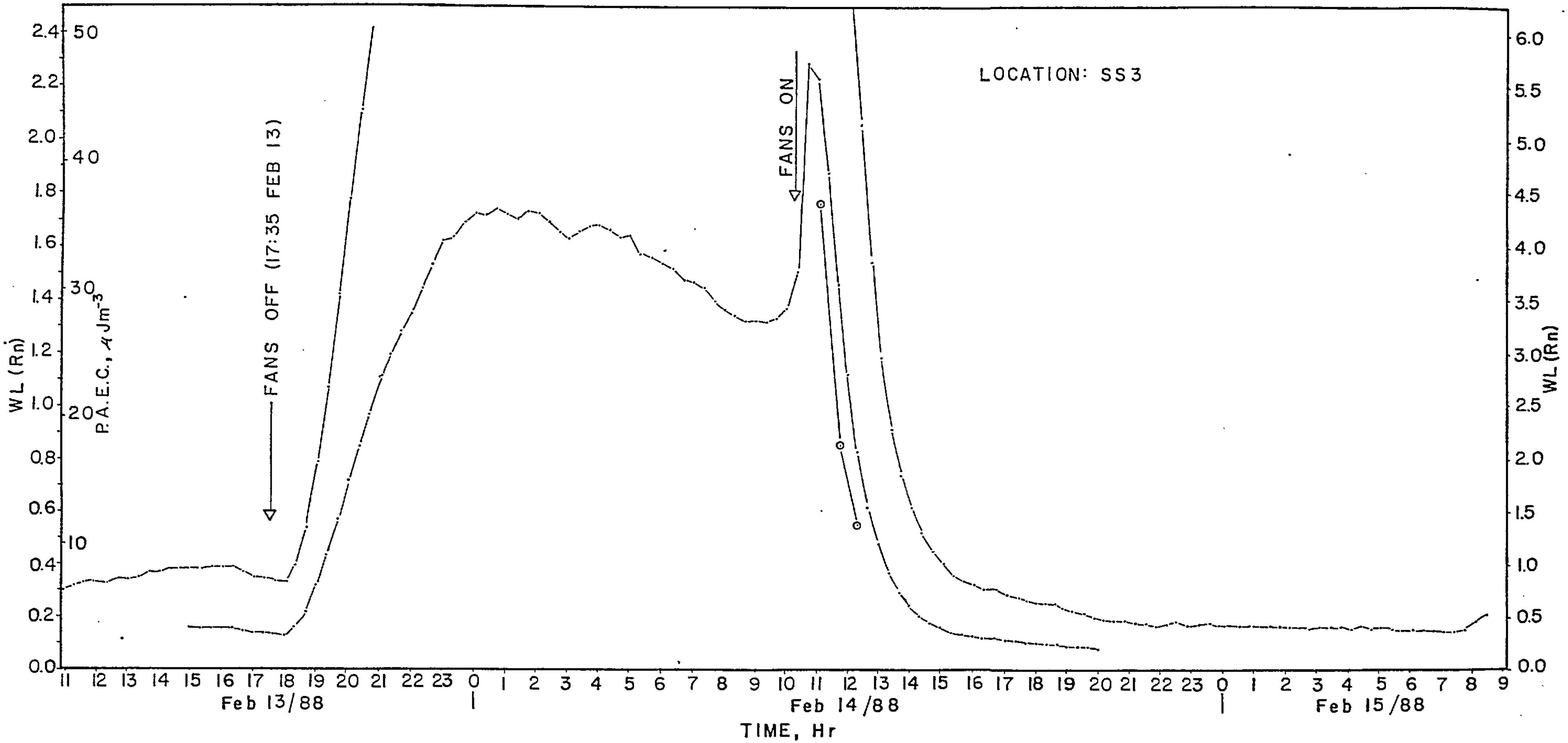

Fig. 5 - WL(Rn) by continuous monitoring (-·-) and by grab-sampling (⊙) versus time at location SS3. Values for the lower (-·-) graph and the (⊙) graph should be read on the right hand side scale. Values for the upper (-·-) graph should be read on the left hand side scale. The lower continuous graph is a compressed version of the upper graph, and both represent an expanded version of Fig. 4.

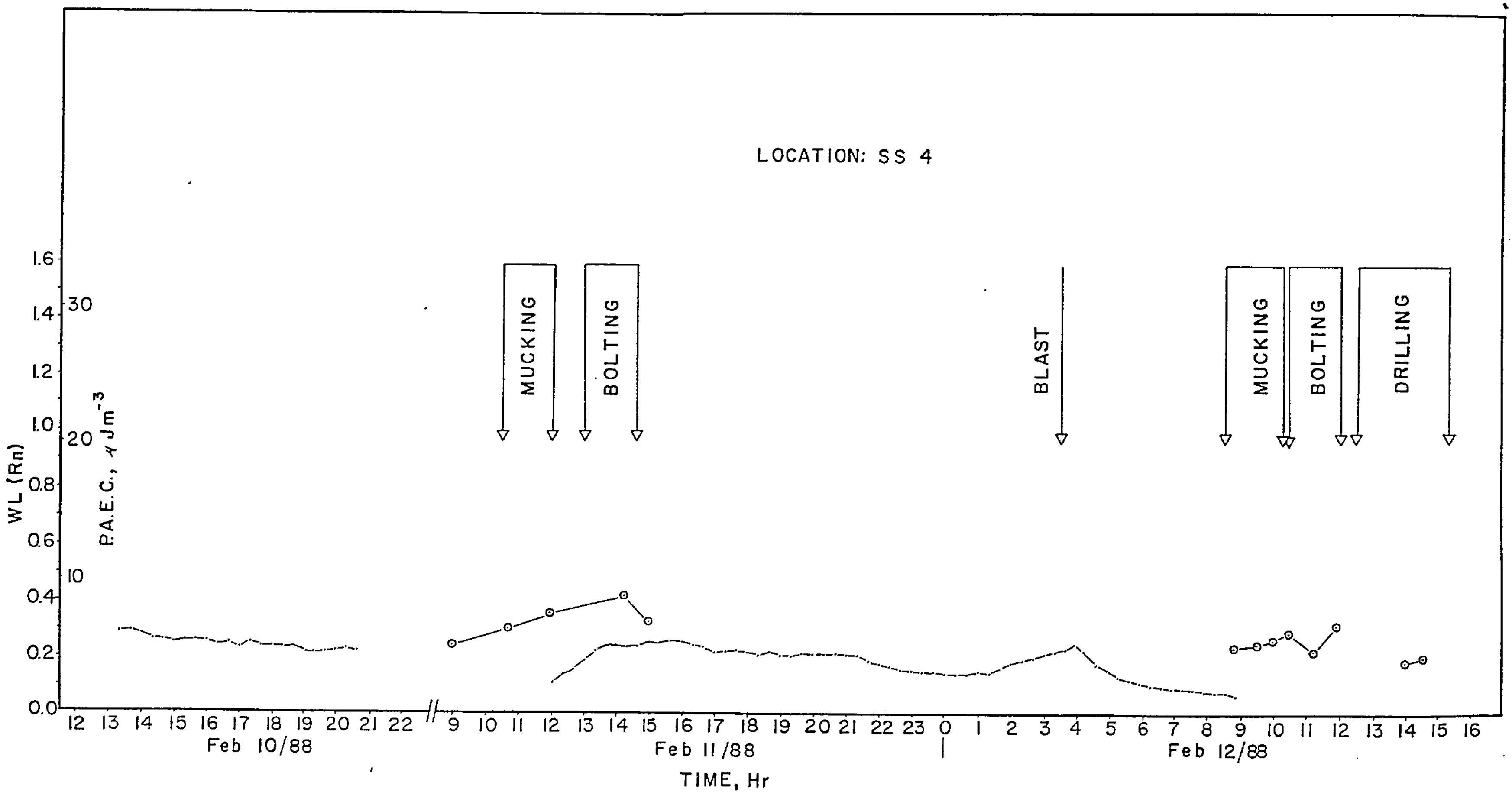

Fig. 6 - WL(Rn) versus time at location SS4. Grab-sampling data are indicated by ⊙. Graphs labelled (-·-) represent data by continuous monitoring.

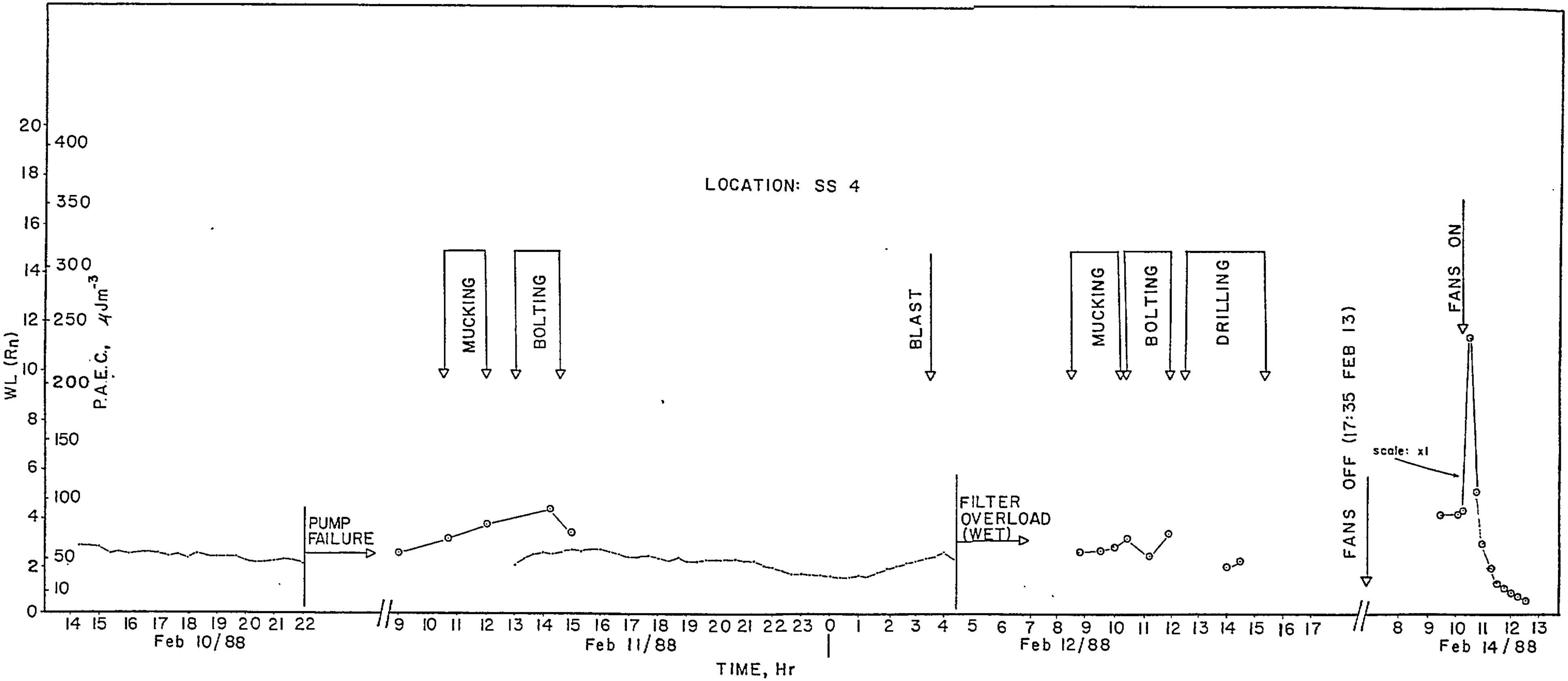

Fig. 7 - WL(Rn) versus time at location SS4. Grab-sampling data are indicated by ⊙. Graphs labelled (-·-) represent data by continuous monitoring.

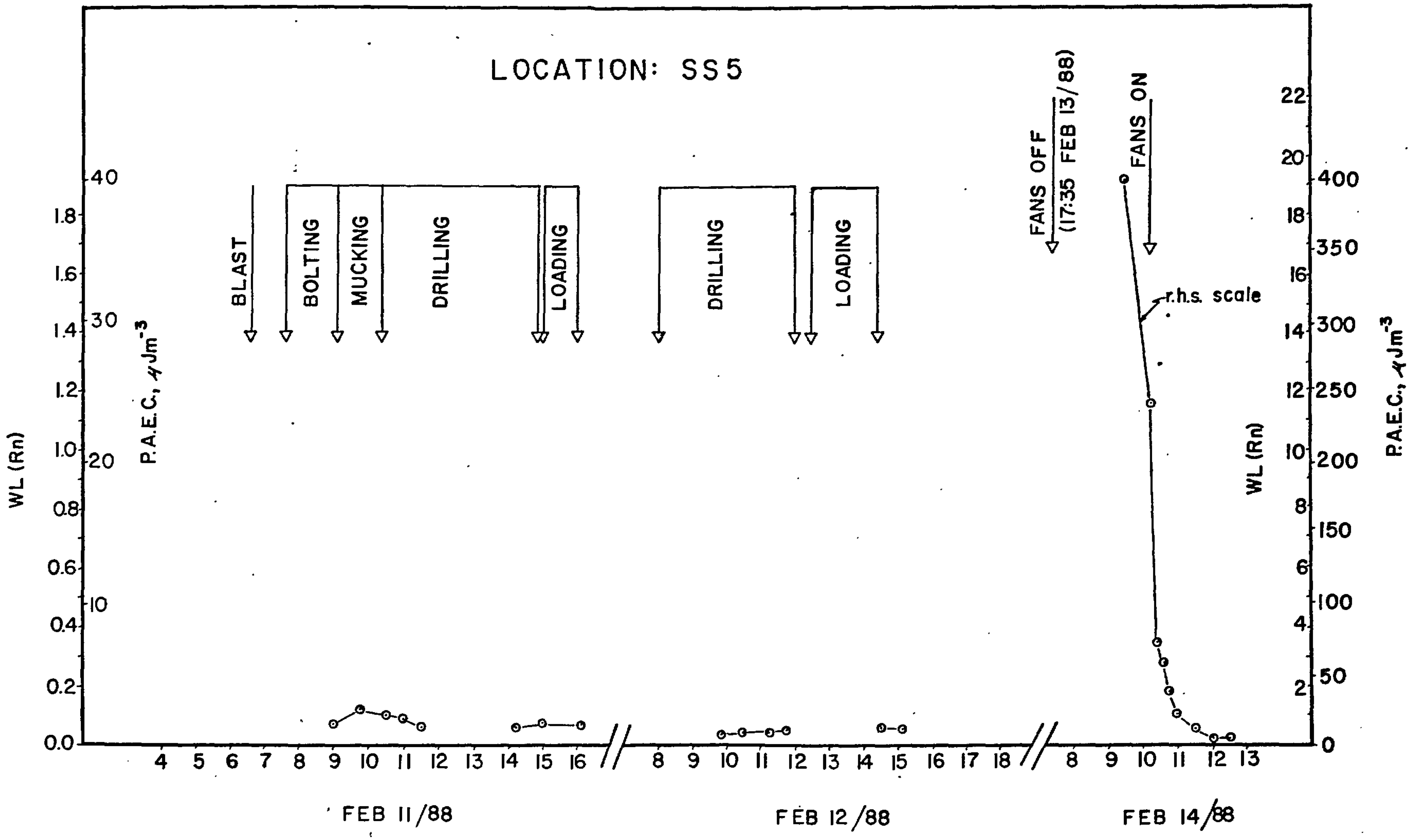

Fig. 8 - WL(Rn) by grab-sampling versus time at location SS5.

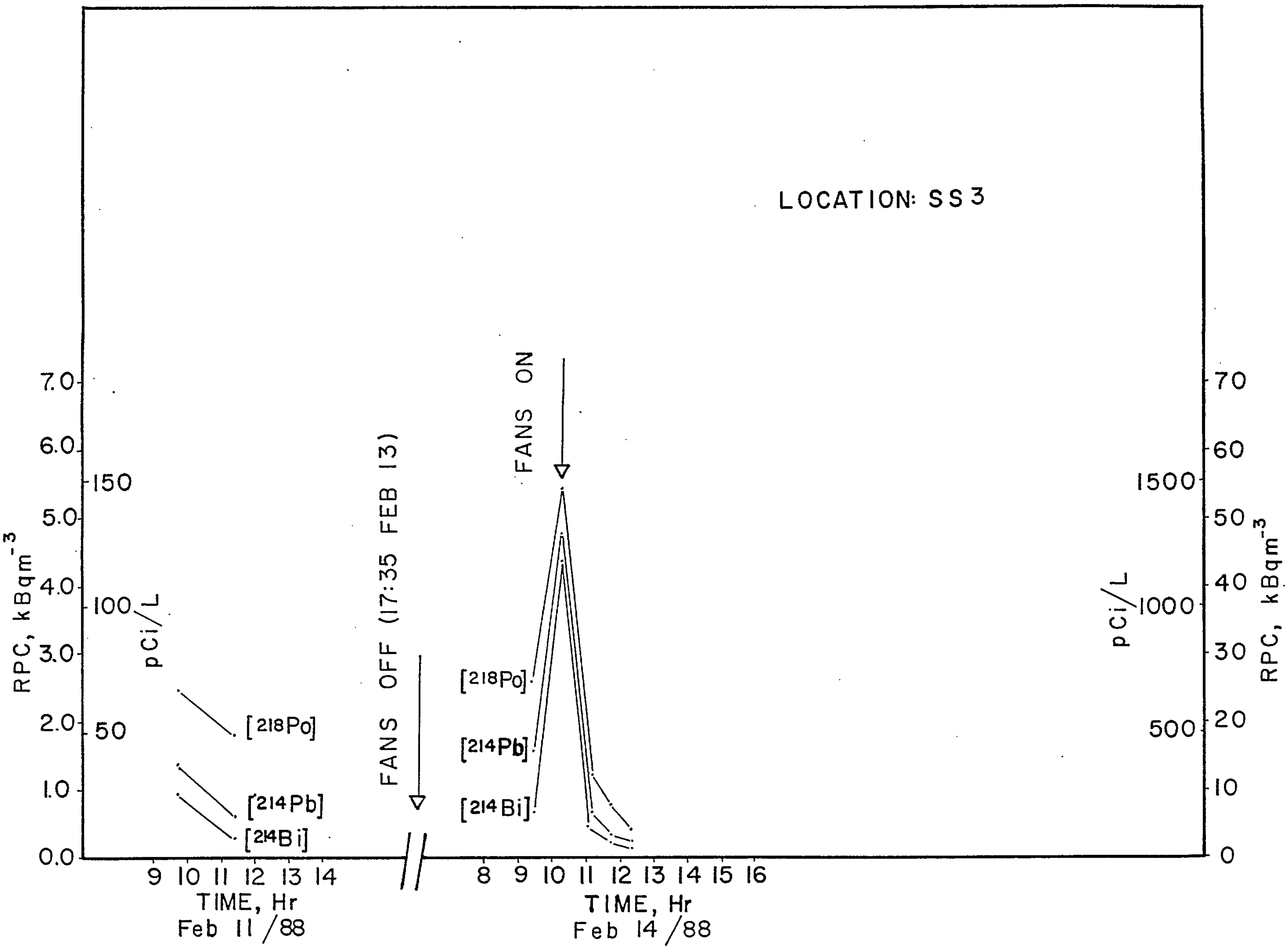

Fig. 9 - Radon progeny concentration (RPC) versus time at location SS3.
Data for Feb 14/88 should be read on the right hand side scale.

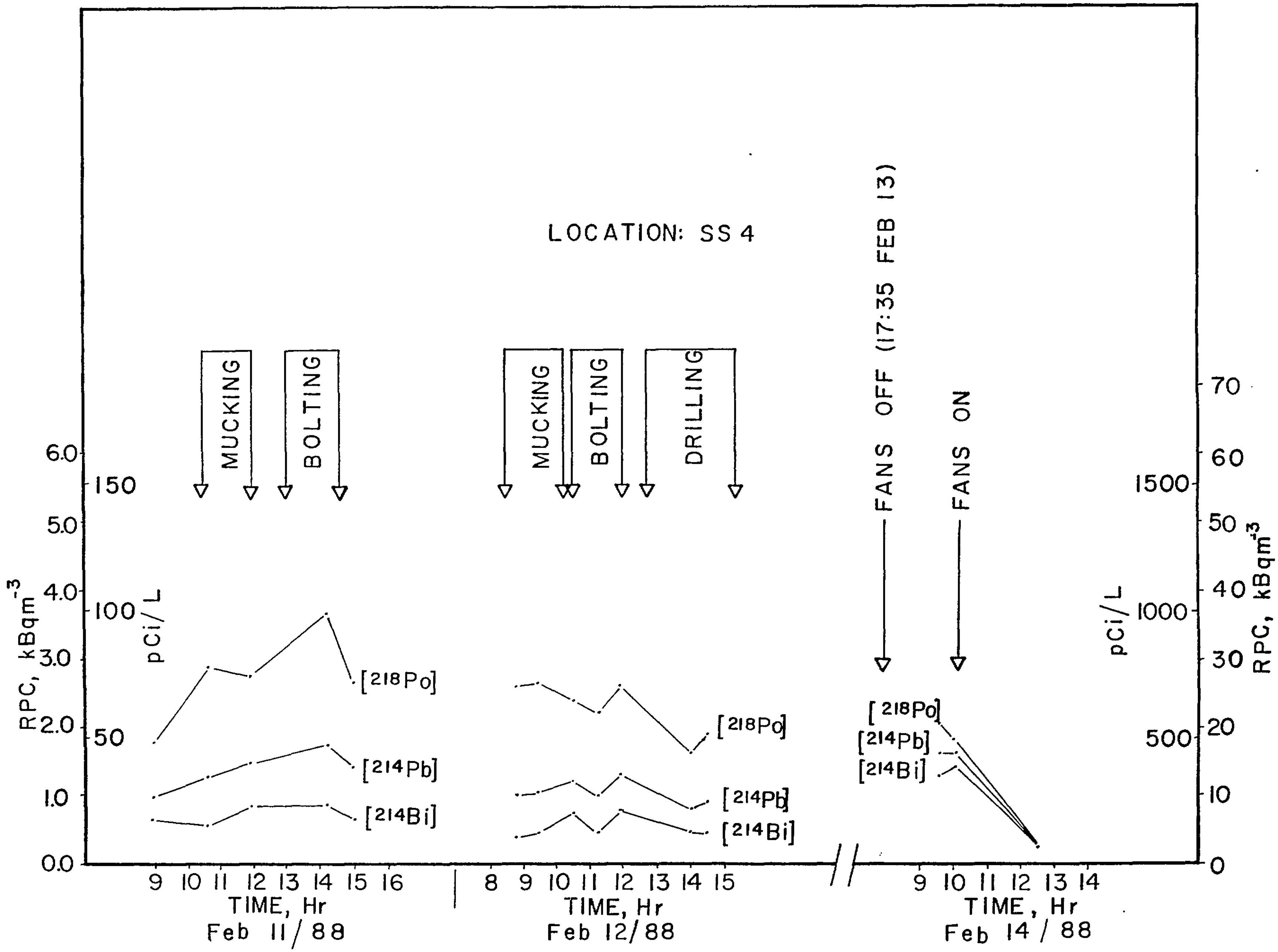

Fig. 10 - Radon progeny concentration (RPC) versus time for location SS4. Data for Feb 14/88 should be read on the right hand side scale.

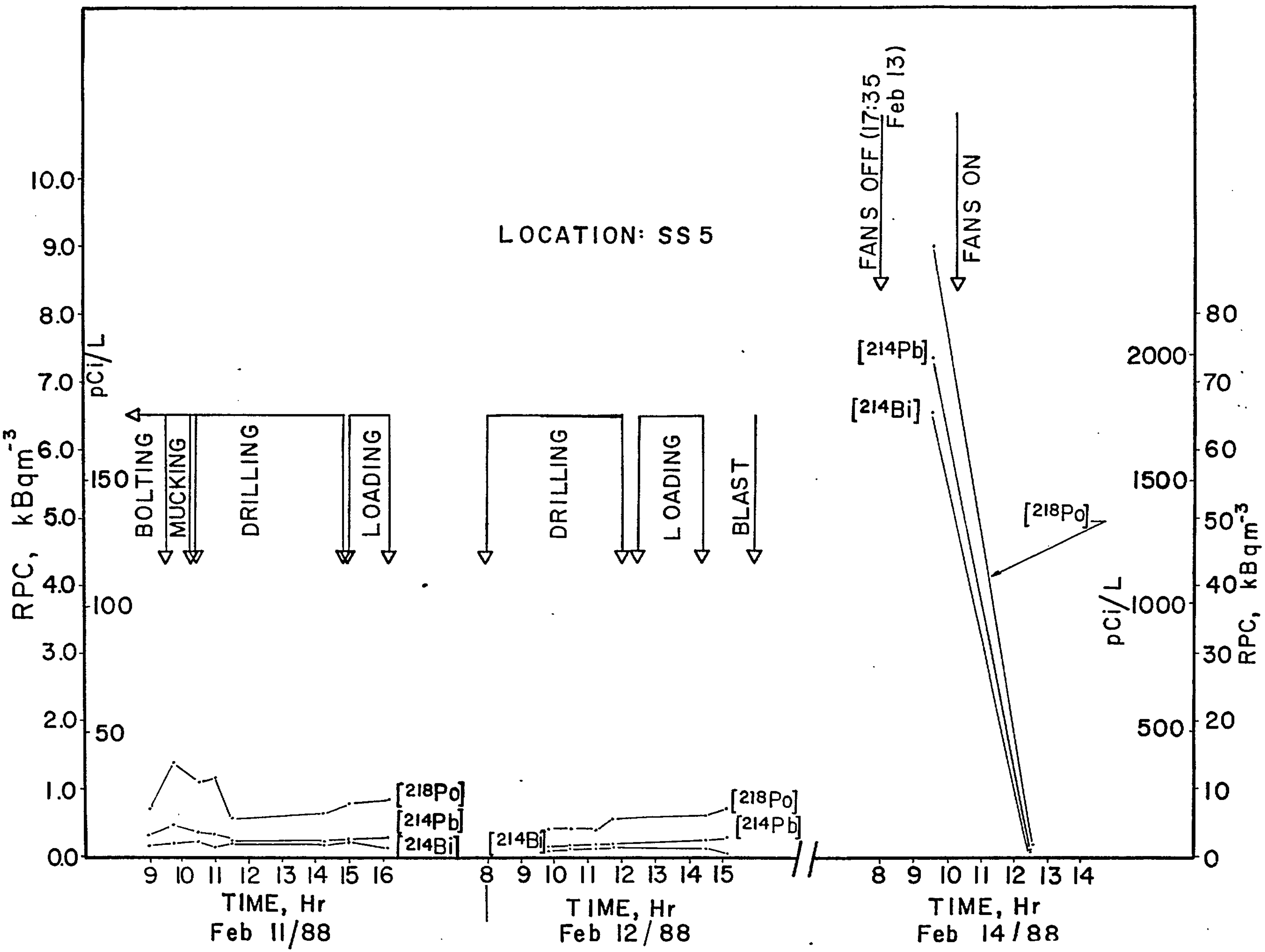

Fig. 11 - Radon progeny concentration (RPC) versus time for location SS5. Data for Feb 14/88 should be read on the right hand side scale.

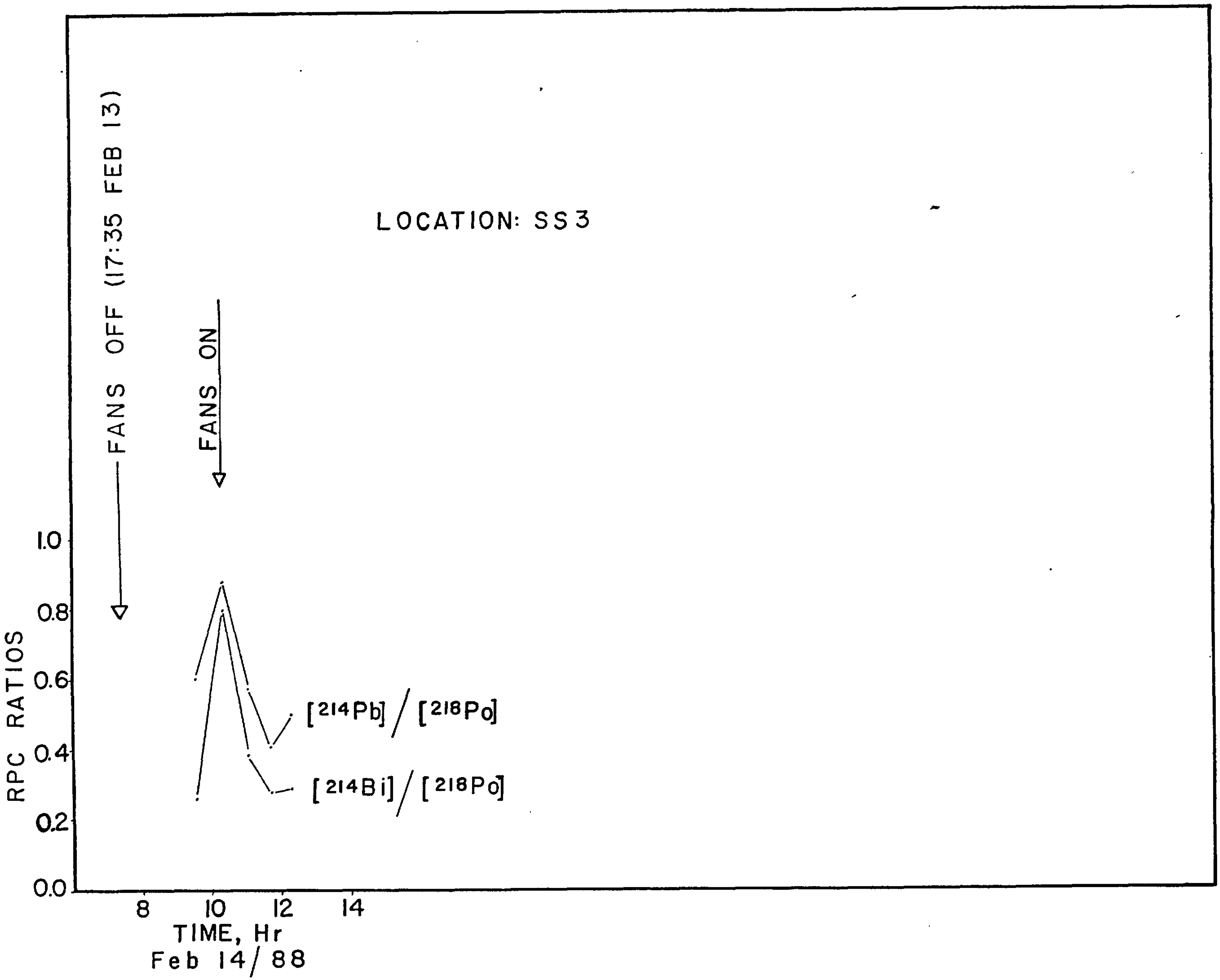

Fig. 12 - Radon progeny concentration (RPC) ratios versus time at location SS3.

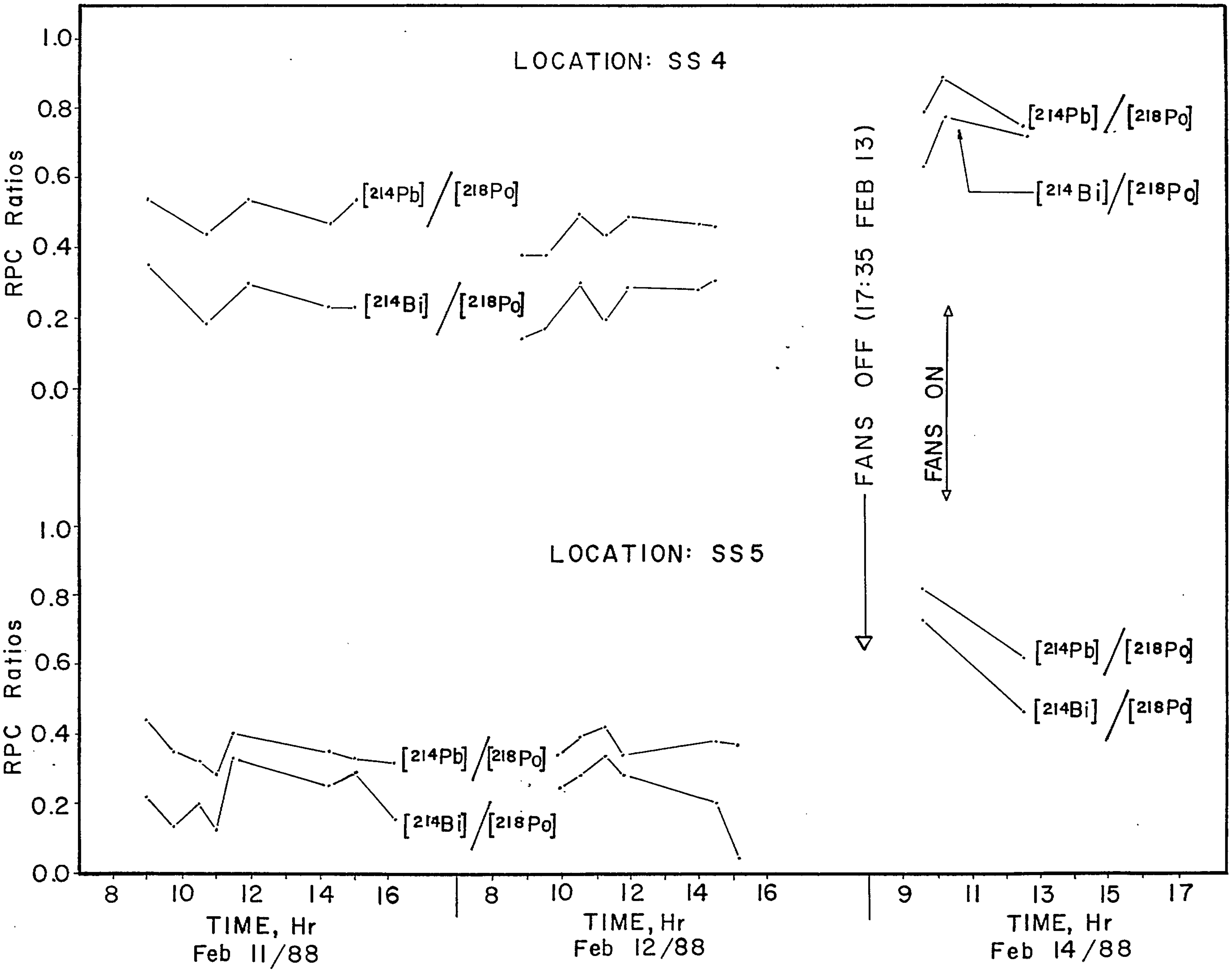

Fig. 13 - Radon progeny concentration (RPC) ratios versus time at locations SS4 and SS5.