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# LABORATORY AND FIELD EVALUATION OF A NEW RADON PROGENY WORKING LEVEL MONITOR USING LOW-POWER CMOS ELECTRONICS

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by

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ABSTRACT

A miniaturized radon progeny Working Level monitor using low-power CMOS electronics has been evaluated in a Radon/Thoron Test Facility (RTTF), and in an underground uranium mine. The instrument was tested under rapidly changing environmental conditions and under steady-state conditions. The instrument was found to respond adequately to dynamic radiation conditions. The sensitivity of the instrument was ~3.7 cphr/mWL as tested in the RTTF. This value increased significantly with the amount of thoron progeny present in the underground uranium mine.

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Key words: Radon progeny; Working Level; CMOS electronics; Dosimeter.

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# ÉVALUATION EN LABORATOIRE ET SUR LE TERRAIN D'UN NOUVEAU MONITEUR DE RAYONNEMENT DOTÉ DU SYSTÈME ÉLECTRONIQUE CMOS À FAIBLE PUISSANCE POUR LE CONTRÔLE DU NIVEAU D'ACTIVITÉ DES PRODUITS DE FILIATION DU RADON

par

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## RÉSUMÉ

Le modèle réduit d'un moniteur doté du système électronique CMOS à faible puissance a été évalué dans une mine d'uranium souterraine ainsi qu'à l'installation expérimentale de contrôle des émanations de radon et de thoron (IERT). L'appareil a été évalué dans des conditions environnementales stables et dans des conditions environnementales changeant rapidement. Le moniteur fonctionnait adéquatement dans des conditions de rayonnement dynamiques. D'après les résultats des essais à l'installation expérimentale, la sensibilité de l'appareil était de ~3,7 cphr/mWL. Cette valeur augmentait considérablement selon la quantité de produits de filiation du thoron présents dans la mine d'uranium souterraine.

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Mots clé : Produit de filiation du radon; niveau d'activité; système électronique CMOS; dosimètre.

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# INTRODUCTION

Miniaturized personal dosimetry instrumentation for the measurement of $\alpha$-particles from radon decay products found in uranium mines and mills, and in certain building materials, is of great practical value for monitoring radiation levels to which radiation workers and general public alike are exposed. The measurement of radon progeny is particularly difficult because of the requirement for a portable unit with a high sensitivity capable of measuring radon progeny concentrations of the order of a few $pCiL^{-1}$. Standard techniques such as track-etch and TLD are used extensively but suffer from the problem of complicated, post-facto reading procedures. The search for direct-reading, electronic $\alpha$-detection methods has resulted in the recent development of portable systems using silicon-barrier, and large-area diffused junction semiconductor diodes as detectors. The semiconductor diode detector is a well-established device with known advantages and limitations, and represents, therefore, a good initial approach to the problem of monitor miniaturization. The search for improvements in $\alpha$-detection systems continues, however, in the interest of more effective health protection procedures.

One approach to developing an electronic means of detecting any radiation is to find a physical effect which causes an electronic device or circuit function degradation and exploit it. This has been successful in the development of MOSFET gamma-sensors and dosimeters based on these sensors (1,2). MOSFET sensors are, however, not sensitive enough to detect $\alpha$-particles from sources below a few 10's of $\mu$Ci. On the other hand, $\alpha$-particles have been found to be the source of circuit malfunctions in the application of high density semiconductor memories and extensive efforts have been made to remove all sources of alphas and shield the silicon chips from them. Dynamic Random Access Memories (DRAMS) are the most sensitive in the currently used memory family. It has been proven that even the semiconductor device packaging material emitting a few alphas $cm^{-2}$ $h^{-1}$ had sufficient activity to cause high 'soft' error rates (3). An error is a discrepancy between the data written into a memory and the data subsequently read from it. A 'soft' error is one which occurs in a transient fashion in the memory whereas a 'hard' error is a permanent one usually associated with the permanent failure of one memory element. It should be noted that when this problem first arose a few years ago the memories were not very dense and the source of the problem was not known. The $\alpha$-particle theory was largely proven by measuring memory soft error rates while exposing memories to known $\alpha$-sources and then backtracking to find the sources of activity in packaging materials (3).

This paper describes a dosimeter prototype of the active type that operates using a DRAM chip as an $\alpha$-particle detector. The instrument is commercially known as the Radon Sniffer WL meter, or Radon Sniffer, for short.

## DESCRIPTION AND OPERATION OF THE DOSIMETER

The dosimeter consists of a sampling 'head' and an electronic reader all in one unit.

The sampling head consists of a DRAM chip, as detector, and its associated electronic circuitry, a small sampling pump, a battery power pack, and a sample holder where an absolute filter (0.8 $\mu$m Millipore, 25 mm diameter) is located. During air sampling, radon progeny are deposited on the filter where they decay. Alpha-particles from the decay of radon progeny strike the detector and produce 'errors'.

The digital detector serves both to detect $\alpha$-particles and to give an output of standard digital pulses whose number is proportional to the number of $\alpha$-particles absorbed by the detector. The detector is insensitive to $\beta$-

and $\gamma$-radiation. The number of pulses is stored in a register which is read by the reader. The detector is biased using a standard voltage supply used for the rest of the electronics.

A useful feature of the instrument is that the sampling pump can be switched off if so desired. This allows the decay of radioisotopes to be followed in detail.

The reader uses a liquid crystal display (LCD) which indicates total accumulated $\alpha$-count in real time.

Figure 1 shows a simplified diagram of the sampling head/reader system. Figure 2 shows a view of the instrument. Some of the operating characteristics of the instrument are given below.

Operating Voltage : 6 V dc

Power Consumption : 985 mW

Air Flow Rate: : 1 L/min (adjustable from 0.5 L/min to 3/5 L/min)

Battery Capacity : 15 h (6 V battery, 2.5 A-H sealed lead acid)

Detector Efficiency: ~15%

Sampling Head Current Consumption: 50 mA

Reader Current Consumption : 2 mA

Pump Current Consumption : 112 mA

Total Current Consumption : 164 mA.

The above characteristics were determined under laboratory and field conditions. The detector efficiency was determined using a $^{241}$Am source, and filters loaded with $^{222}$Rn progeny from a Pylon Rn-190 calibration source.

## EXPERIMENTAL PROCEDURE

The instrument was tested and calibrated under laboratory-controlled conditions in a large Radon/Thoron Test Facility (RTTF) of the walk-in type, and under field conditions in an underground uranium mine (4). The field tests were conducted in conjunction with the evaluation of a fan/filter assembly system in a production stope. Hence, some of the tabulated data may contain information regarding the operating conditions of the fan/filter system.

Two units were evaluated in the RTTF, namely, Sniffer #1 and #2, over a period of two weeks. Only Sniffer #2 was evaluated underground, for one week.

The two units were tested in the RTTF under low radiation level conditions and low to moderate aerosol concentration levels in order to investigate plate-out effects.

The unit evaluated underground was tested in an area where thoron progeny is also present in addition to radon progeny. Relatively high concentrations of thoron and its decay products are a common occurrence in uranium mines in Ontario.

Data obtained with the Radon Sniffer were compared with grab-sampling data by the Thomas-Tsivoglou and Kusnetz methods (5,6), and by continuous monitoring. Thoron progeny Working Levels, WL(Tn), were estimated by the Rock method (7). The following radon progeny measurements were made: [$^{218}$Po], [$^{214}$Pb] and [$^{214}$Bi] where the square brackets stand for airborne activity concentration. In addition, the radon progeny Working Level, WL(Rn), was measured.

## EXPERIMENTAL RESULTS AND DISCUSSION

The experimental data obtained are presented under two experimental conditions, i.e., laboratory-controlled conditions in the Radon/Thoron Test Facility (RTTF), and under field conditions in the underground uranium mine.

### A. LABORATORY-CONTROLLED CONDITIONS (RTTF)

Table 1 shows the radioactivity and aerosol concentration (N) conditions in the RTTF. Except for the first day, when no aerosol concentration measurements were made, N varied from $<3x10^3$ $cm^{-3}$ to $\sim 2.5x10^4$. The aerosol concentration was varied by changing the amount of an NaCl aqueous solution injected into the RTTF according to standard procedures and techniques.

The radon progeny Working Level, WL(Rn), was adjusted to vary in the range of 0.01 to 0.06 by varying the aerosol concentration, N, in the RTTF while maintaining the radon gas concentration, [$^{222}$Rn], at about 15 $pCiL^{-1}$.

The ratios [$^{214}$Pb]/[$^{218}$Po] and [$^{214}$Bi]/[$^{218}$Po] varied with N, increasing with increasing N, as predicted by theory. The low values for these two ratios at low aerosol concentration indicates that substantial plate-out of radon progeny takes place on the RTTF walls.

No thoron was injected into the RTTF so that a radon/radon progeny atmosphere only was present for accurate radon progeny calibration of the instruments.

The purpose of injecting aerosol into the RTTF was twofold:

a) to vary WL(Rn), as indicated above, in order to estimate the sensitivity of the instruments within a given WL(Rn) range; and

b) to investigate plate-out effects, i.e., loss of radioactive aerosols in the instruments sampling heads.

Calibration of the Sniffer was preferentially conducted at low values for WL(Rn) to estimate their sensitivity for low radiation level applications such as radiation surveys of residential areas and dwellings.

Table 2 shows the results of the calibration of the two instruments in the RTTF. The table shows the instruments average $\alpha$-particle count rates, $\overline{CR(\alpha)}$, and the average WL(Rn), $\overline{WL(Rn)}$, measured in the RTTF. It should be noted that the Sniffer provides total $\alpha$-particle count in real time. Count rates are estimated by subtracting the total $\alpha$-particle counts at two different times, and dividing this quantity by the time interval. The values here are given in counts per hour (cphr).

Table 2 shows the following points of interest:

a) The $\alpha$-particle count rate $\overline{CR(\alpha)}$ increases with increasing WL(Rn) as would be expected, except at the beginning of sampling or if saturation effects take place.

b) The two instruments differ in sensitivity, $CR(\alpha)/WL(Rn)$, by about 37%. As the two instruments operated at a flow rate of 1 L $min^{-1}$, the above difference is partly attributed to differences in $\alpha$-particle detector and electronics sensitivity.

c) Except for the first day, when no measurements of N were taken, the sensitivity of the instruments increased with increasing aerosol concentration indicating that losses of radon progeny at low radiation levels take place in the sampling head. At low aerosol concentrations the presumed losses were in the approximate range of 17% to 30%.

## B. FIELD CONDITIONS (UNDERGROUND TESTS)

Field conditions for the underground tests are shown in Table 3. Radon progeny activity concentrations and WL(Rn) were much higher than those corresponding to laboratory conditions (see Table 1). Furthermore, thoron progeny was also present in significant amounts, as evidenced by the values of the ratio WL(Tn)/WL(Rn). Aerosol concentration, although not measured directly in terms of particle count, was most probably quite high ($>1.0\times10^5$ $cm^{-3}$) as inferred from measurements of diesel particulate mass by nylon cyclones and cascade impactors (4,8).

Field conditions were varied substantially during the underground tests by changing the operating conditions of the fan/filter system evaluated concurrently with the Sniffer (see Table 3). Field conditions also changed during the working shift because of mining operations upstream of the location where the tests were conducted.

Varying underground field conditions provided an excellent opportunity to thoroughly evaluate the instrument under dynamic conditions. Table 4 shows the results of the evaluation.

Table 4 shows gross $\alpha$-count, $N_\alpha$, as a function of time as measured by the Sniffer and the calculated $\alpha$-particle count-rate, $(CR)_\alpha$ in counts per min, cpm. The sensitivity of the instrument, $(CR)_\alpha/WL(Rn)$ is given, as before, in cphr/mWL. Also shown in the table is the average sensitivity of the Sniffer calculated over the daily working shift.

It should be noted that because of rapidly changing field conditions caused, for instance, by the operation of the fan, only data representative of steady-state conditions have been included in the calculation of the sensitivity of the instrument. The data and periods used for the calculation are indicated by brackets. Brackets have also been used to indicate the operating conditions of the fan/filter system.

Figure 3 shows WL(Rn), as determined by two continuous monitoring systems (and by grab-sampling), and the gross $\alpha$-count, $N_\alpha$, as measured by the Sniffer, versus time.

The data from Tables 3 and 4, and Figure 3 indicate the following:

1. The sensitivity, $(CR)_\alpha/WL(Rn)$, of the instrument was significantly higher underground ($4.17 \pm 0.32$ to $5.99 \pm 0.70$ cphr/mWL) than that measured under laboratory-controlled conditions in the RTTF ($3.63 \pm 0.28$ cphr/mWL). The higher value for the sensitivity is attributed to the contribution to the $\alpha$-particle count, $N_\alpha$, from the thoron progeny. On average, the sensitivity of the instrument increased with increasing values of the ratio WL(Tn)/WL(Rn).
2. The underground calibration of the instrument was substantially less

accurate than that corresponding to the calibration in the RTTF where environmental conditions were maintained fairly constant on a daily basis. Another contributing factor was flow rate drift of the instrument sampling pump. It was found that the flow rate decreased significantly with increasing exposure of the instrument to diesel particulates. Under sustained sampling (2 to 3 days) under moderate diesel particulate loading conditions, the flow rate decreased to about 50% of its initial value, i.e., from 1 L $min^{-1}$ to approximately 0.5 L $min^{-1}$. This effect is not unusual as the pump used in the instrument was not of the servo-controlled type;

3. The $\alpha$-particle count rate recorded by the instrument followed the underground WL(Rn) profile quite closely (see Figure 3) indicating that the Sniffer responded satisfactorily to dynamic radon progeny conditions. Time lag effects relative to grab-sampling data are well known because of the time-integrating nature of the technique used in the instrument.
4. The instrument $\alpha$-particle detector was sensitive to direct exposure to moderately strong sources of light as evidenced (see Table 4, June 9) by the considerable increase in $\alpha$-particle count following the change of the sampling filter during which direct light from the miners cap-lamp was accidentally shone onto the detector.

## CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are offered:

1. The instrument responded adequately to dynamic radiation conditions;
2. The sensitivity of the instrument depended on the ratio WL(Tn)/WL(Rn), as expected. For radon/radon progeny mixtures only, the sensitivity of the instrument was ~3.7 cphr/mWL.
3. The nuclear detector used is sensitive to light and should be protected

against accidental light exposures.

4. For precise measurements under moderate dust concentrations the use of a servo-controlled sampling pump is strongly recommended.

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Table 1 - Radon progeny in Radon/Thoron Test Facility (RTTF) (partial recirculation mode).

| Date | Time | [$^{218}$Po] (pCiL$^{-1}$) | [$^{214}$Pb] (pCiL$^{-1}$) | [$^{214}$Bi] (pCiL$^{-1}$) | [$^{214}$Pb]/[$^{218}$Po] | [$^{214}$Bi]/[$^{218}$Po] | WL(Rn) | N cm$^{-3}$ |
|---|---|---|---|---|---|---|---|---|
| June 2/87 | 9:45 | 5.28 | 1.41 | 0.30 | 0.27 | 0.06 | 0.014 | |
| | 10:45 | 5.22 | 1.28 | 0.71 | 0.24 | 0.14 | 0.014 | No aerosol injected |
| | 11:40 | 4.24 | 0.93 | 1.16 | 0.22 | 0.27 | 0.013 | |
| | 13:02 | 5.51 | 1.68 | 0.58 | 0.30 | 0.10 | 0.016 | |
| | 13:45 | 6.68 | 1.69 | 0.32 | 0.25 | 0.05 | 0.017 | (no measurement of N) |
| | 14:45 | 5.00 | 1.06 | 1.09 | 0.21 | 0.22 | 0.015 | |
| | 15:45 | 5.12 | 1.74 | 0.81 | 0.34 | 0.16 | 0.017 | |
| June 3/87 | 7:50 | 4.44 | 0.96 | 0.64 | 0.22 | 0.14 | 0.012 | |
| | 8:45 | 4.23 | 0.86 | 0.46 | 0.20 | 0.11 | 0.010 | |
| | 9:45 | 3.58 | 0.72 | 0.68 | 0.20 | 0.19 | ≤0.010 | |
| | 10:45 | 4.33 | 0.95 | 0.37 | 0.22 | 0.08 | 0.010 | <3x10$^{3}$ |
| | 11:35 | 4.74 | 0.82 | 0.37 | 0.17 | 0.08 | 0.010 | |
| | 13:05 | 5.92 | 0.73 | 0.09 | 0.12 | 0.01 | 0.010 | |
| | 13:45 | 4.43 | 0.66 | 0.29 | 0.15 | 0.06 | ≤0.010 | |
| | 14:45 | 5.26 | 1.09 | -0.24 | 0.21 | - | 0.010 | |
| | 15:45 | 4.88 | 0.53 | 0.42 | 0.11 | 0.09 | ≤0.010 | |
| June 4/87 | 8:00 | 3.62 | 0.44 | 0.13 | 0.12 | 0.04 | 6.4x10$^{-3}$ | $\lesssim$3x10$^{3}$ |
| | 8:45 | 10.70 | 3.19 | 1.22 | 0.30 | 0.11 | 0.032 | |
| | 9:40 | 11.66 | 4.21 | 2.10 | 0.36 | 0.18 | 0.041 | |
| | 10:45 | 8.84 | 5.01 | 2.36 | 0.57 | 0.27 | 0.043 | |
| | 11:40 | 6.70 | 3.13 | 3.97 | 0.47 | 0.59 | 0.038 | |
| | 13:05 | 7.72 | 3.85 | 3.23 | 0.50 | 0.42 | 0.040 | 5x10$^{3}$ - 6x10$^{3}$ |
| | 13:55 | 9.58 | 4.35 | 3.41 | 0.45 | 0.35 | 0.045 | |
| | 14:45 | 14.11 | 5.92 | 2.04 | 0.42 | 0.14 | 0.052 | |
| | 15:40 | 11.50 | 5.82 | 3.38 | 0.51 | 0.29 | 0.054 | |
| June 5/87 | 8:00 | 3.88 | 0.81 | 0.42 | 0.21 | 0.11 | ∼0.010 | $\lesssim$3x10$^{3}$ |
| | 9:15 | 7.90 | 2.99 | 2.20 | 0.38 | 0.28 | 0.031 | |
| | 10:25 | 10.77 | 4.85 | 3.67 | 0.45 | 0.34 | 0.049 | |
| | 11:00 | 8.88 | 5.63 | 3.94 | 0.63 | 0.44 | 0.052 | |
| | 11:35 | 11.21 | 6.43 | 3.25 | 0.57 | 0.29 | 0.056 | |
| | 13:00 | 12.25 | 6.30 | 4.01 | 0.51 | 0.33 | 0.060 | |
| | 13:45 | 14.88 | 7.63 | 2.55 | 0.51 | 0.17 | 0.064 | ∼2.5x10$^{4}$ |
| | 14:45 | 12.68 | 6.71 | 3.39 | 0.53 | 0.27 | 0.060 | |
| | 15:45 | 9.43 | 5.22 | 3.55 | 0.55 | 0.38 | 0.050 | |

Table 2 - Radon Sniffer sensitivity ($\overline{CR(\alpha)}/\overline{WL(Rn)}$) and other data. Measurements were carried out in the Radon/Thoron Test Facility (RTTF).

| Date | Instrument Sniffer (#) | $\overline{CR(\alpha)}$ (cphr) | $\overline{WL(Rn)}$ (mWL) | $\overline{CR(\alpha)}/\overline{WL(Rn)}$ (cphr/mWL) | N $cm^{-3}$ |
|---|---|---|---|---|---|
| June 2/87 | 1 | 76.46 | 15.6±1.6 | 4.90 | No aerosol injected (no measurement of N) |
| " 3/87 | 1 | 43.71 | 10.2±0.8 | 4.29 | $<3x10^3$ |
| " 4/87 | 1 | 223.80 | 44.6±6.3 | 5.02 | $5.0x10^3 - 6.0x10^3$ |
| " 5/87 | 1 | 329.40 | 58.3±4.2 | 5.65 | $\sim 2.5x10^4$ |
| | | | Average*: | 4.97±0.56(4.95±0.69) | |
| June 2/87 | 2 | 60.00 | 15.6±1.6 | 3.85 | No aerosol injected (no measurement of N) |
| " 3/87 | 2 | 32.80 | 10.2±0.8 | 3.22 | $<3x10^3$ |
| " 4/87 | 2 | 163.20 | 44.6±6.3 | 3.66 | $5.0x10^3 - 6.0x10^3$ |
| " 5/87 | 2 | 220.40 | 58.3±4.2 | 3.78 | $\sim 2.5x10^4$ |
| | | | Average*: | 3.63±0.28(3.70±0.19) | |

Note: a) $\overline{CR(\alpha)}$ stands for daily average α-particle count rate (in counts per hour, cphr).

b) $\overline{WL(Rn)}$ stands for daily average radon progeny Working Level (in milliWorking Levels, mWL).

c) N represents the aerosol concentration in the RTTF (particles per $cm^3$, $cm^{-3}$).

* The average values given for the instrument sensitivity represent the average of the four days, taken independently, and the sensitivity calculated over the four-day period (figures in round brackets).

Table 3 - Radon and thoron progeny grab-sampling data taken at the Sniffer location.

| Date | Time | Location | $[^{218}Po]$ $pCiL^{-1}$ | $[^{214}Pb]$ $pCiL^{-1}$ | $[^{214}Bi]$ $pCiL^{-1}$ | $\frac{[^{214}Pb]}{[^{218}Po]}$ | $\frac{[^{214}Bi]}{[^{218}Po]}$ | WL(Rn) | WL(Tn) | $\frac{WL(Tn)}{WL(Rn)}$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| June 15/87 | 9:37 | Exhaust | 90.6 | 60.6 | 50.9 | 0.669 | 0.562 | 0.591 | 0.090 | 0.153 | |
| | 10:20 | " | 43.0 | 28.8 | 28.8 | 0.669 | 0.669 | 0.308 | 0.070 | 0.230 | |
| | 11:00 | " | 56.1 | 34.5 | 27.1 | 0.615 | 0.483 | 0.334 | 0.068 | 0.203 | |
| | 11:40 | " | 48.7 | 29.8 | 25.4 | 0.612 | 0.522 | 0.297 | 0.063 | 0.213 | Fan on, no filters |
| | 12:20 | " | 61.6 | 35.5 | 13.2 | 0.576 | 0.214 | 0.308 | 0.066 | 0.221 | |
| | 13:00 | " | 35.9 | 21.0 | 15.1 | 0.585 | 0.420 | 0.200 | 0.065 | 0.322 | |
| | 13:40 | " | 26.2 | 18.4 | 15.6 | 0.702 | 0.595 | 0.180 | 0.070 | 0.389 | |
| June 16/87 | 9:02 | Exhaust | 41.8 | 24.6 | 16.1 | 0.588 | 0.385 | 0.228 | 0.082 | 0.357 | Fan on, no filters |
| | 10:00 | " | 46.0 | 33.6 | 24.2 | 0.730 | 0.526 | 0.309 | 0.085 | 0.276 | |
| | 10:40 | " | 44.5 | 37.2 | 33.3 | 0.836 | 0.748 | 0.359 | 0.082 | 0.229 | |
| | 11:20 | " | 59.6 | 41.1 | 29.1 | 0.689 | 0.488 | 0.379 | 0.086 | 0.227 | Fan off, no filters |
| | 12:00 | " | 61.5 | 46.9 | 33.2 | 0.762 | 0.540 | 0.426 | 0.089 | 0.210 | |
| | 12:40 | " | 50.3 | 41.0 | 35.0 | 0.815 | 0.696 | 0.391 | 0.096 | 0.246 | |
| | 13:20 | " | 54.2 | 36.7 | 24.8 | 0.677 | 0.458 | 0.335 | 0.069 | 0.207 | |
| June 17/87 | 9:00 | Exhaust | 79.2 | 56.1 | 44.9 | 0.708 | 0.567 | 0.534 | 0.087 | 0.163 | Fan off, filters in place |
| | 10:00 | " | 30.4 | 13.9 | 9.41 | 0.457 | 0.309 | 0.137 | 0.069 | 0.501 | |
| | 10:40 | " | 25.7 | 11.29 | 9.18 | 0.439 | 0.357 | 0.118 | 0.059 | 0.502 | |
| | 11:20 | " | 22.2 | 12.5 | 9.43 | 0.563 | 0.425 | 0.122 | 0.053 | 0.433 | Fan on, filters in place |
| | 12:00 | " | 27.0 | 11.8 | 6.57 | 0.437 | 0.243 | 0.112 | 0.049 | 0.436 | |
| | 12:40 | " | 23.7 | 13.96 | 8.45 | 0.589 | 0.356 | 0.127 | 0.053 | 0.417 | |
| | 13:20 | " | 30.4 | 14.6 | 7.35 | 0.480 | 0.242 | 0.133 | 0.052 | 0.389 | |
| June 18/87 | 9:20 | Exhaust | 36.7 | 22.8 | 18.3 | 0.621 | 0.499 | 0.222 | 0.081 | 0.365 | |
| | 10:00 | " | 30.8 | 20.1 | 14.5 | 0.652 | 0.471 | 0.188 | 0.063 | 0.335 | |
| | 10:40 | " | 23.6 | 12.0 | 10.0 | 0.508 | 0.423 | 0.123 | 0.054 | 0.441 | |
| | 11:20 | " | 23.5 | 12.1 | 7.8 | 0.515 | 0.332 | 0.115 | 0.060 | 0.518 | |
| | 12:00 | " | 24.1 | 12.72 | 8.2 | 0.528 | 0.340 | 0.120 | 0.052 | 0.434 | Fan on, filters in place |
| | 12:40 | " | 27.4 | 11.7 | 8.1 | 0.427 | 0.296 | 0.118 | 0.048 | 0.410 | |
| | 13:20 | " | 27.2 | 13.3 | 7.59 | 0.489 | 0.279 | 0.124 | 0.048 | 0.385 | |
| June 19/87 | 9:26 | Exhaust | 47.5 | 37.3 | 27.9 | 0.816 | 0.611 | 0.350 | 0.074 | 0.211 | |
| | 10:05 | " | 41.1 | 27.9 | 19.4 | 0.679 | 0.472 | 0.260 | 0.087 | 0.335 | Fan off, filters in place |
| | 10:42 | " | 27.7 | 16.9 | 11.2 | 0.610 | 0.404 | 0.160 | 0.075 | 0.469 | |
| | 11:26 | " | 23.6 | 11.9 | 7.5 | 0.504 | 0.318 | 0.120 | 0.061 | 0.508 | |
| | 12:01 | " | 25.5 | 9.6 | 8.5 | 0.376 | 0.333 | 0.110 | 0.061 | 0.554 | |
| | 12:40 | " | 27.6 | 13.7 | 5.3 | 0.496 | 0.192 | 0.120 | 0.049 | 0.408 | Fan on filters in place |
| | 13:20 | " | 25.5 | 12.2 | 6.9 | 0.478 | 0.271 | 0.120 | 0.074 | 0.617 | |

Table 4 - Sniffers radiation data, and radon and thoron progeny at the underground test location.

| Date | Time | Nα (α-count) | (CR)α (cpm) | WL(Rn) | WL(Tn) | (CR)α/WL(Rn) (cphr/mWL) | Ave. Sensitivity (cphr/mWL) | Remarks |
|---|---|---|---|---|---|---|---|---|
| June 15/87 | 10:00 | 0 | - | 0.59 | 0.09 | - | | |
| | 10:23 | 246 | 10.7 | 0.30 | 0.07 | 2.15 | | |
| | 10:40 | 505 | 15.2 | - | - | 3.06 | | |
| | 11:00 | 897 | 19.6 | 0.33 | 0.07 | 3.52 | | |
| | 11:20 | 1369 | 23.6 | - | - | 4.25 | | |
| | 11:40 | 1820 | 22.6 | 0.30 | 0.06 | 4.57 | | Fan on, no filters |
| | 12:00 | 2263 | 22.2 | - | - | 4.49 | | |
| | 12:20 | 2705 | 22.1 | 0.30 | 0.06 | 4.44 | | |
| | 12:40 | 3152 | 22.4 | - | - | 4.50 | | |
| | 13:00 | 3525 | 18.7 | 0.20 | 0.06 | 5.60 | | |
| | 13:20 | 3910 | 19.3 | - | - | 5.78 | | |
| | 13:40 | 4290 | 19.0 | 0.18 | 0.07 | 6.37 | 4.84±0.89 | |
| June 16/87 | 8:40 | 21730 | 15.3 | - | - | 4.02 | | |
| | 9:00 | 22049 | 15.9 | 0.23 | 0.08 | 4.18 | | Fan on, no filters |
| | 9:20 | 22365 | 15.8 | - | - | 4.15 | | |
| | 9:40 | 22760 | 19.8 | - | - | 3.84 | | |
| | 10:00 | 23160 | 20.0 | 0.31 | 0.08 | 3.89 | | |
| | 10:20 | 23553 | 19.7 | - | - | 3.83 | | |
| | 10:40 | 24028 | 24.8 | 0.36 | 0.08 | 4.14 | | |
| | 11:00 | 24524 | 24.8 | - | - | 4.14 | | |
| | 11:20 | 25029 | 27.7 | 0.38 | 0.09 | 4.38 | | Fan off, no filters |
| | 11:40 | 25549 | 26.0 | - | - | 4.12 | | |
| | 12:00 | 26098 | 27.5 | 0.43 | 0.09 | 3.88 | | |
| | 12:20 | 26647 | 27.5 | - | - | 3.88 | | |
| | 12:40 | 27224 | 28.9 | 0.39 | 0.10 | 4.43 | | |
| | 13:00 | 27777 | 27.7 | - | - | 4.25 | | |
| | 13:20 | 28343 | 28.3 | 0.33 | 0.07 | 5.07 | | Fan off, no filters |
| | 13:40 | 28850 | 25.4 | - | - | 4.55 | 4.17±0.32 | |
| June 17/87 | 8:40 | 65293 | 32.0 | - | - | 3.59 | | Fan off, filters in place |
| | 9:33 | 67890 | 49.0 | 0.53 | 0.09 | 5.50 | | |
| | 9:50 | 68495 | 35.6 | - | - | 4.00 | | |
| | 10:10 | 69047 | 27.6 | 0.14 | 0.07 | 12.10 | | |
| | 10:30 | 69500 | 22.6 | - | - | 9.90 | | |
| | 10:50 | 69874 | 18.7 | 0.12 | 0.06 | 9.50 | | |
| | 11:10 | 70225 | 17.6 | - | - | 8.95 | | Fan on, filters in place |
| | 11:30 | 70496 | 13.6 | 0.12 | 0.05 | 6.70 | | |
| | 11:50 | 70777 | 14.1 | - | - | 6.95 | | |
| | 12:10 | 71008 | 11.6 | 0.11 | 0.05 | 6.19 | | |
| | 12:30 | 71240 | 11.6 | - | - | 6.19 | | |
| | 12:50 | 71461 | 11.1 | 0.13 | 0.05 | 5.25 | | |
| | 13:10 | 71689 | 11.4 | - | - | 5.39 | | |
| | 13:30 | 71923 | 11.7 | 0.13 | 0.05 | 5.27 | | |
| | 13:33 | New filter | | - | - | - | | |
| | 13:39 | 71961 | - | - | - | - | 5.99±0.70 | |

Cont. overleaf

Table 4 - cont.

| Date | Time | Nα (α-count) | (CR)α (cpm) | WL(Rn) | WL(Tn) | (CR)α/WL(Rn) (cphr/mWL) | Ave. Sensitivity (cphr/mWL) | Remarks |
|---|---|---|---|---|---|---|---|---|
| June 18/87 | 8:53 | 85845 | 12.03 | - | - | 3.25 | | |
| | 9:22 | 86144 | 10.3 | 0.22 | 0.08 | 2.78 | | |
| | 9:50 | 86525 | 13.6 | - | - | 3.67 | | |
| | 10:10 | 86740 | 10.7 | 0.19 | 0.06 | 3.41 | | |
| | 10:30 | 86970 | 11.5 | - | - | 3.67 | | |
| | 10:50 | 87202 | 11.6 | 0.12 | 0.05 | 5.67 | | |
| | 11:10 | 87437 | 11.8 | - | - | 5.77 | | |
| | 11:30 | 87635 | 9.9 | 0.11 | 0.06 | 5.16 | | |
| | 11:50 | 87845 | 10.5 | - | - | 5.47 | | Fan on |
| | 12:10 | 88043 | 9.9 | 0.12 | 0.05 | 4.94 | | filters in place |
| | 12:30 | 88239 | 9.8 | - | - | 4.89 | | |
| | 12:50 | 88429 | 9.5 | 0.12 | 0.048 | 4.83 | | |
| | 13:10 | 88615 | 9.3 | - | - | 4.72 | | |
| | 13:30 | 88809 | 9.7 | 0.12 | 0.048 | 4.68 | 4.49±0.96 | |
| June 19/87 | 8.32 | 112290 | 20.6 | - | - | 3.53 | | |
| | 9.32 | 113296 | 16.8 | 0.35 | 0.07 | 2.88 | | |
| | 9.35 | New filter | - | - | - | - | | Fan off, |
| | 9.36 | 704595 | - | - | - | - | | filters in place |
| | 9:50 | 704687 | 6.6 | - | - | - | | |
| | 10:10 | 704867 | 9.0 | 0.26 | 0.09 | 2.08 | | |
| | 10:30 | 705068 | 10.1 | - | - | 2.33 | | |
| | 10:50 | 705304 | 11.8 | 0.16 | 0.07 | 4.43 | | |
| | 11:10 | 705541 | 11.9 | - | - | 4.46 | | |
| | 11:30 | 705775 | 11.7 | 0.12 | 0.06 | 5.85 | | |
| | 11:50 | 705972 | 9.9 | - | - | 4.95 | | Fan on, |
| | 12:10 | 706195 | 11.2 | 0.11 | 0.06 | 6.11 | | filters in place |
| | 12:30 | 706362 | 8.4 | - | - | 4.58 | | |
| | 12:50 | 706535 | 8.7 | 0.12 | 0.05 | 4.35 | | |
| | 13:10 | 706702 | 8.4 | - | - | 4.20 | | |
| | 13:30 | 706852 | 7.5 | 0.12 | 0.07 | 3.75 | 4.74±0.77 | |

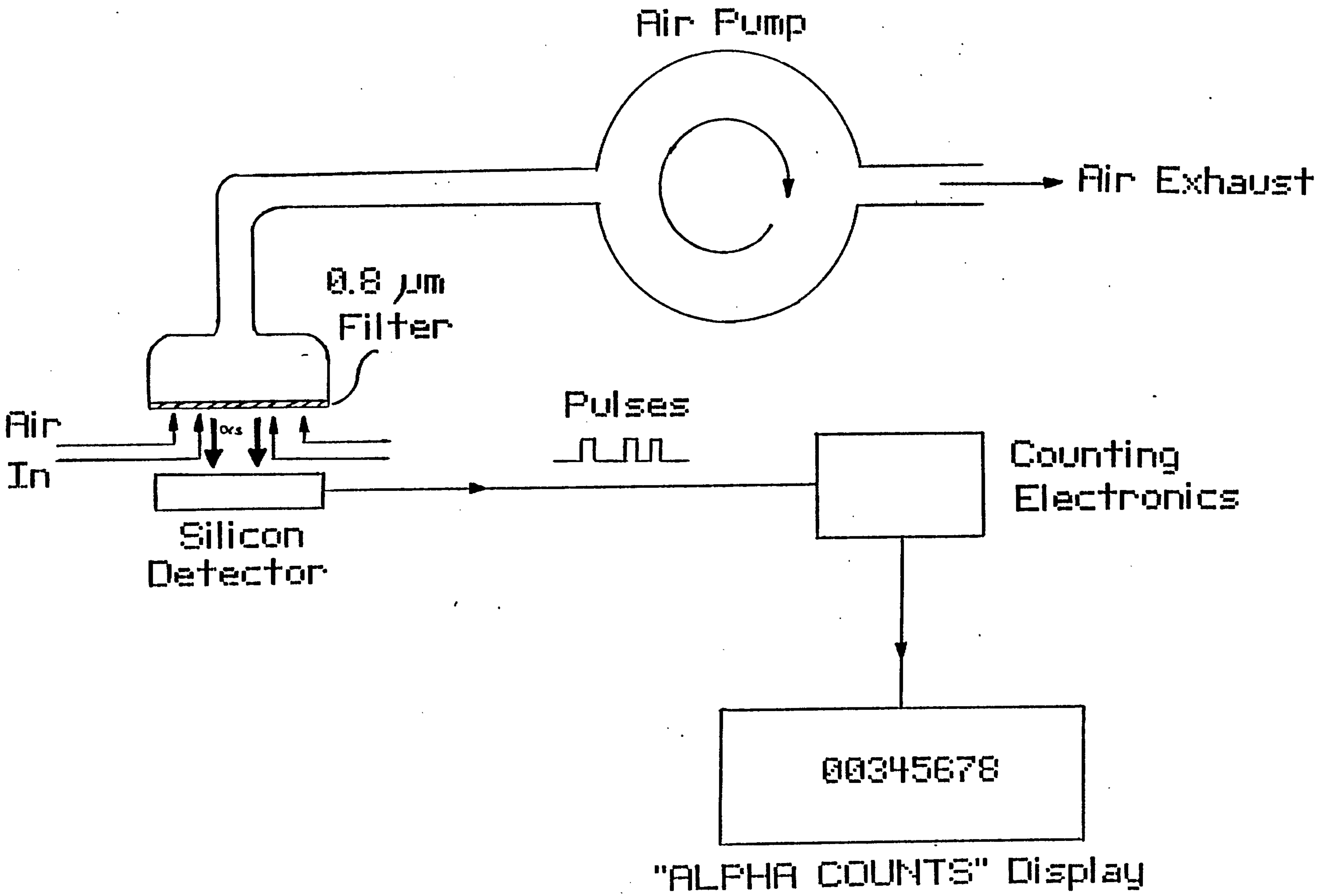


Fig. 1 - Simplified diagram of the operating principle of the monitor.

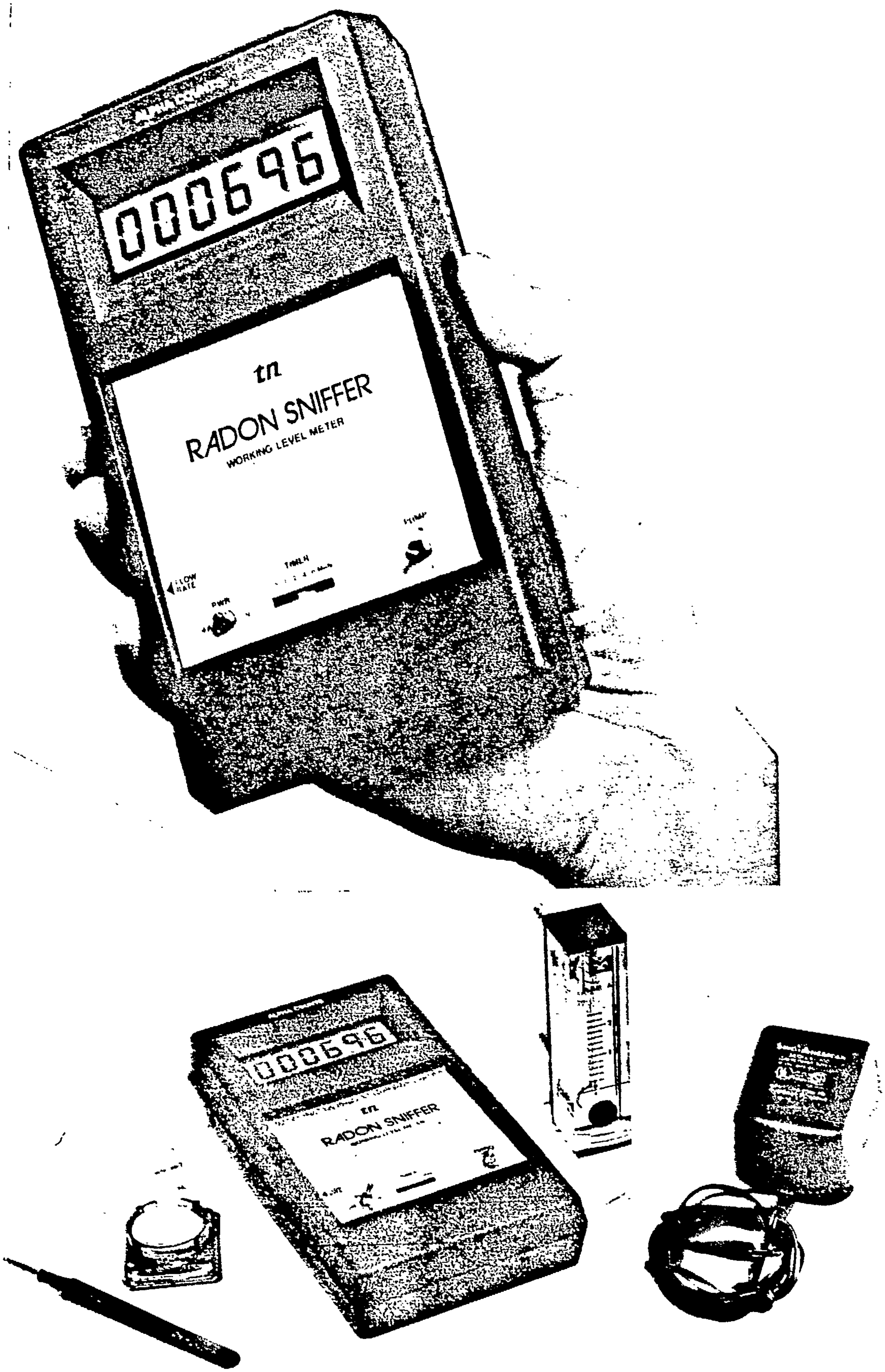


Fig. 2 - View of the instrument.

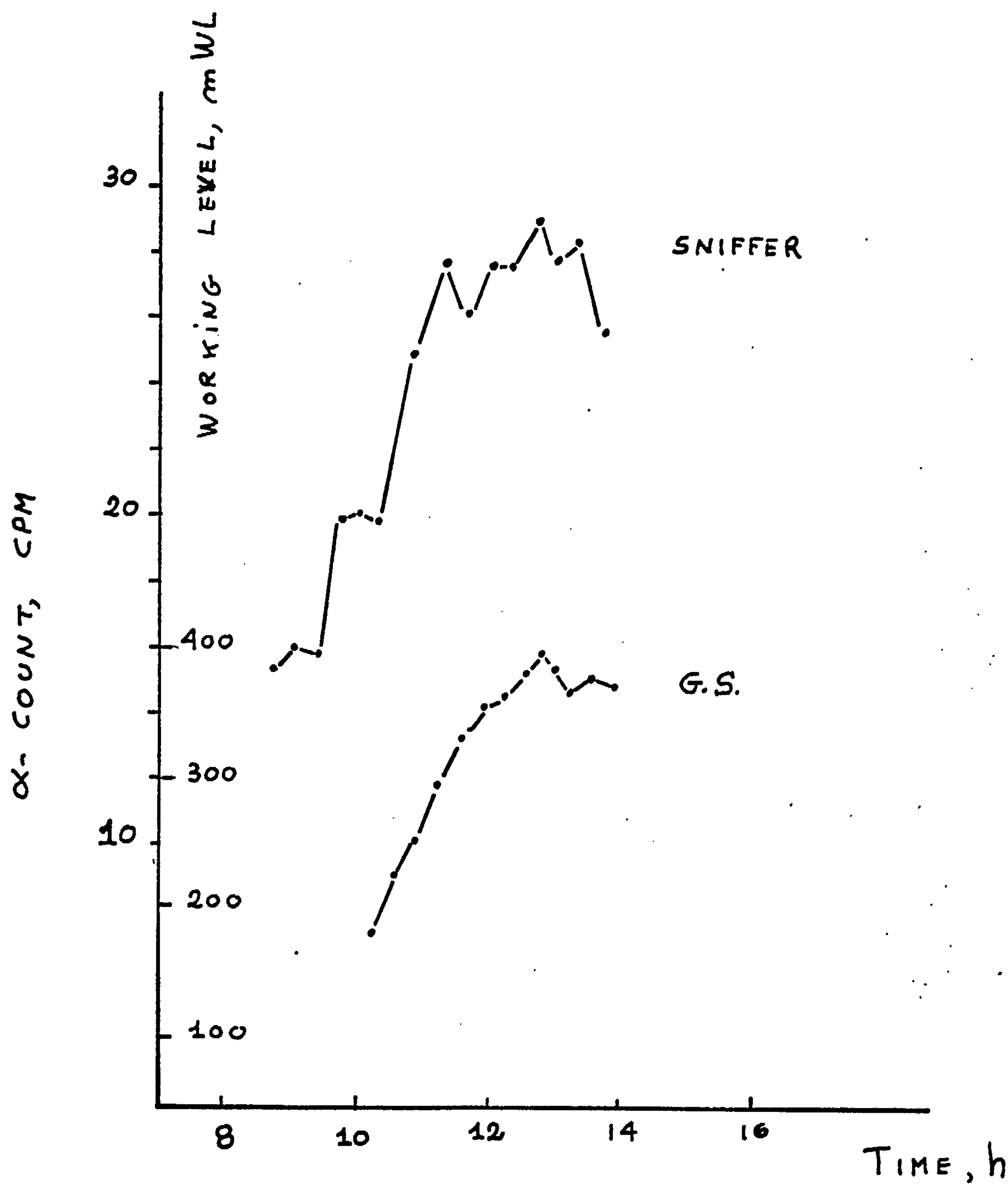


Fig. 3 - Sniffer α-count rate (counts per minute, cpm), and grab-sampling (G.S.) Working Level versus time.