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Technical note

Cape Point GAW Station ^{222}Rn detector: factors affecting sensitivity and accuracy

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Abstract

Specific factors of a baseline ^{222}Rn detector installed at Cape Point, South Africa, were studied with the aim of improving its performance. Direct sunlight caused air turbulence within the instrument, resulting in 13.6% variability of the calibration factor. Shading the instrument eliminated this effect. A residual temperature dependence of the calibration factor was reduced to negligible levels with an improved photomultiplier tube. A superior detector head permits field servicing of the instrument, and has reduced one component of the instrumental background by a factor of 2. The other component probably constitutes thoron emissions from the stainless steel walls. The detection limit of the instrument could be reduced from its current 33 to 20 mBq m^{-3} if the thoron were to be eliminated. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: ^{222}Rn (radon); Thoron background; Photomultiplier; Detector; Sensitivity

1. Introduction

In February 1999 the Cape Point Global Atmosphere Watch Station (34°21′S; 18°29′E) installed a ^{222}Rn detector to characterise air masses advected at the site. The Australian Nuclear Scientific & Technology Organisation (ANSTO)[1] supplied the instrument, which is similar to the "new version" described by Whittlestone and Zahorowski (1998).

Fig. 1 shows the main features of the Cape Point ^{222}Rn detector, which was studied intensively to identify site-specific factors affecting its operation. Baseline ^{222}Rn detectors have been installed at only a few locations, and have been subject to frequent design improvements (Collé et al., 1995; Whittlestone and Zahorowski, 1998).

A new detector head (Fig. 2), designed by one of the authors (Whittlestone, while employed at ANSTO), manufactured by AGH Industries[2] and assembled by ANSTO was installed in January 2001 to overcome servicing difficulties and obtain improved performance. Furthermore, the new photomultiplier tube used (Electron Tubes Model 9638B) differed somewhat from the one (Model 9531B) for which the head was originally designed. This note discusses these modifications, and provides a basis for evaluating future improvements.

2. Instrumental background signal

There are potentially three components of the instrumental background: (a) electronic noise plus long-lived contamination of the detector head; (b) alpha activity from the thoron (^{220}Rn) progeny; and (c) alpha activity from the progeny of ^{222}Rn produced by decay of

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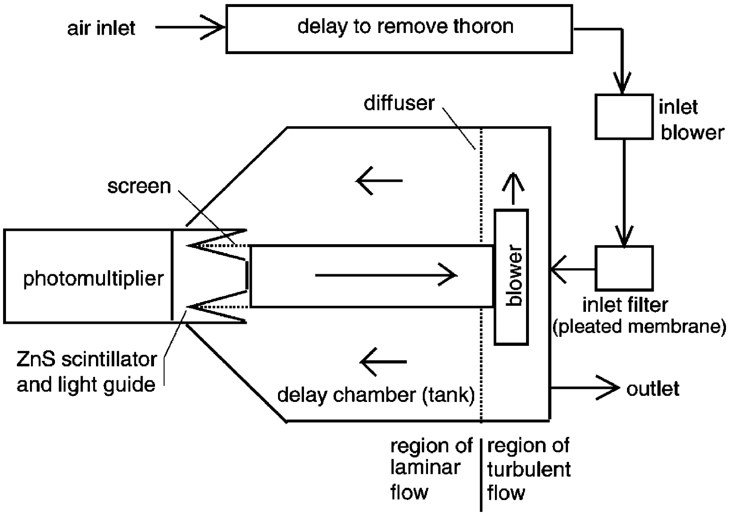

Fig. 1. Schematic diagram of the radon detector (Whittlestone et al., 1994).

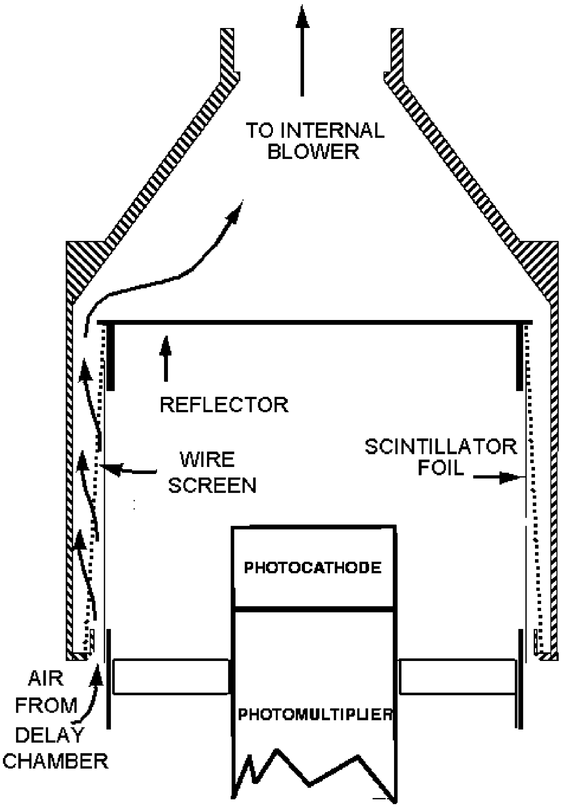

Fig. 2. Schematic diagram of ^{222}Rn detector head assembly.

any ^{226}Ra within the instrument. Hutter et al. (1995) discuss ^{220}Rn background for a different version of the dual filter detector. At Cape Point, the measured ^{222}Rn is sometimes zero after the background counts from the first two sources have been subtracted. From this it is deduced that the count from ^{222}Rn progeny is less than the error in determining the other two and will not be considered further. Electronic noise plus long-lived contamination was measured by turning the blowers off and waiting for about two days for the decay of ^{212}Pb, the 10.4 h half-life progeny of thoron.

Modelling the decay of ^{212}Pb from standard theory of radioactivity yields

$$M_i = L_2/(L_2 - L_1)(\exp(-L_1 T_i) - L_1/L_2 \exp(-L_2 T_i)), \tag{1}$$

where M_i is the ^{222}Rn concentration that would yield the same count rate as the modelled ^{212}Pb in the ith 30-min count period after the blowers were turned off, with M_0 set to 1. L_1 is the decay constant of ^{212}Pb, 0.0652 h^{-1}. L_2 is the decay constant of ^{212}Po, 0.686 h^{-1}.

Two time periods were selected, one between 5 and 27 h after switch-off, and the other from 34 h until the end of the test. Waiting 5 h allowed the progeny of ambient ^{222}Rn to decay to $<0.1\%$ of their initial concentration, and after 27 h only about 12% of the ^{212}Pb was left. The first period encompassed most of the ^{212}Pb, and virtually no counts from ^{222}Rn. The second period had only a small contribution from ^{212}Pb, and the counts were almost entirely from the steady background. This permitted the experimental counts to be related to the background and ^{212}Pb contribution:

$$C_1 = j_1\,{}^{212}R + k_1 R_{\mathrm{bg}} \tag{2}$$

and

$$C_2 = j_2\,{}^{212}R + k_2 R_{\mathrm{bg}}, \tag{3}$$

where C_1 and C_2 are the integrated experimental counts from periods 1 and 2, whilst j_1, k_1, j_2 and k_2 are evaluated from the model and correspond to 10.33, 24.3, 0.838 and 9.19, respectively.

${}^{212}R$ is the "equivalent ^{222}Rn concentration", which is the concentration of ^{222}Rn that would result in the same count rate as the ^{212}Pb. R_{bg} is the concentration of ^{222}Rn which would result in the same count rate as the steady background.

${}^{212}R$ and R_{bg} were evaluated by solving Eqs. (2) and (3) for each test. To check the validity of the model, the average variance between the model and the experiment was determined over the period 5 h after the blowers were turned off till the end of the test. In all cases the variance was close to 1, which proves that the model was consistent with the experimental data. The errors on ${}^{212}R$ and R_{bg} were derived from the counting errors on C_1 and C_2.

Fig. 3 shows the time series of equivalent ^{222}Rn concentration with a fitted curve during a typical background measurement. Calibrations and background evaluations (as "equivalent ^{222}Rn concentration") over two years are summarised in Table 1. All the quantities except thoron will change as electronics are adjusted to accept different pulse height amplitudes from the scintillator. An electronic threshold of 50 mV at the preamplifier has been set to be as low as practicable, while avoiding purely electronic noise. The parameter used to adjust the scintillator pulse height threshold was the high voltage (HV), which was decided upon after a compromise was reached between a high HV to maximise sensitivity, and a low HV to minimise the background. The HV used for each period was that which yielded the lowest minimum level of detection, defined as that ambient ^{222}Rn concentration for which the counting error in a 1-h count was 30%.

Tests between February 1999 and April 2000 indicated that the thoron originated from within the tank. A clean 200-l plastic drum, which would reduce any thoron upstream of the inlet filter by a factor of 8, was placed between the latter and the tank inlet. However, neither the drum nor rigorous cleaning of the tank with mild abrasives had any effect. In May a third of the tank was lined with aluminium foil, to investigate whether the thoron was being emitted from the stainless steel sheet. This yielded an apparent reduction of 30% in thoron (Table 1). However, when the tank was fully lined, the thoron level did not decrease any further, for yet unknown reasons. For comparison, the total background of 56 mBq m^{-3} from February 2001 is close to the 67 mBq m^{-3} measured by Hutter et al. (1995) after they had taken remedial measures.

3. Variability and temperature dependence of sensitivity

At Cape Point the sensitivity of the instrument is dependent on the absolute temperature of the electronic components and on the intensity of direct sun on the instrument, independent of the component temperature. This latter effect is caused by convection currents induced inside the instrument, causing the highly diffusive ^{222}Rn progeny to plate-out on the walls (George et al., 1983; Bigu and Grenier, 1984). Analysis before and after installation of shade cloth, and by allowing for solar heating at the time of measurement,

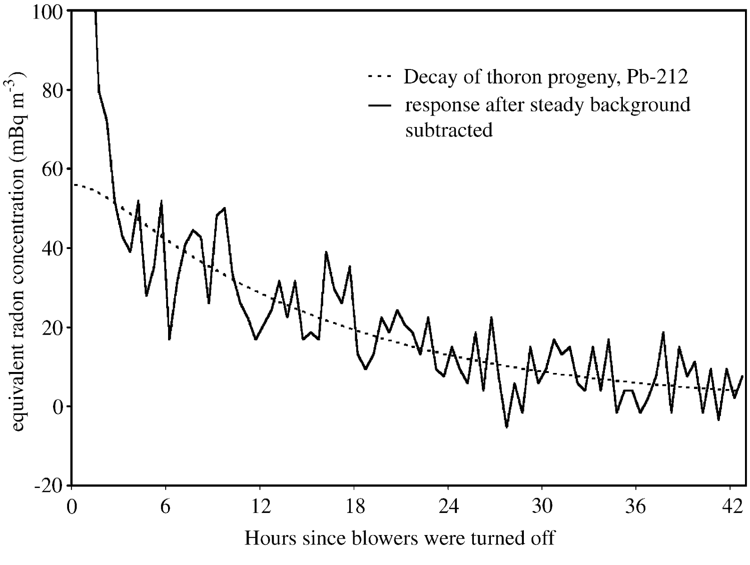

Fig. 3. Response of the ^{222}Rn detector after turning off the blowers. The steady component of the background has been subtracted from the experimental data.

Table 1
Summary of thoron and background measurements at Cape Point

Period	Sensitivity[a]		Lower level of detection, $\mathrm{mBq\,m^{-3}}$	Background		Comment
	Value (counts $\mathrm{s^{-1}}$ $(\mathrm{Bq\,m^{-3}})^{-1}$)	Gradient ($\%\ \mathrm{V^{-1}}$)		Long-lived activity ($\mathrm{mBq\,m^{-3}}$)	Thoron ($\mathrm{mBq\,m^{-3}}$)	
Feb 1999–Apr 2000	0.263	1.4	42	36	69	Thoron unaffected by remedial measures
May 2000–Jan 2001	0.263	1.4	37	36	44	Thoron reduced by lining 30% of tank
From Feb 2001	0.301	0.21	33	20	56	New head and 100% lining. Improved sensitivity and background but thoron worse
Potential	0.301	0.21	20	20	0	New head if thoron is zero

[a] The sensitivity gradient is the % change in sensitivity per volt change in the high voltage supply to the photomultiplier.

Table 2
Variation of sensitivity, S (counts $\mathrm{s^{-1}}\,(\mathrm{Bq\,m^{-3}})^{-1}$), with data logger temperature, $T_{\log}$ (°C), before and after installing shade cloth

	Unshaded	Shaded
Average sensitivity, S	0.227	0.255
Slope of S vs. $T_{\log}$	–0.00357	−0.00175
Change in S per °C (%)	1.6	0.69
Average T_{amb}	16	16
T_{amb} range	11	9
($T_{\log} - T_{\mathrm{amb}}$) range	19	7
Correlation with $T_{\log}$	0.9	0.63
Variability of distribution of S (std. dev. (%))	13.6	4.4

permitted a more accurate calibration factor to be derived.

The data logger (Campbell Scientific; model CR510) incorporates a temperature sensor, which represents the temperature of other components in the electronics enclosure. The average sensitivity was greater and the variability substantially less when the instrument was shaded (Table 2). Since the average ambient temperature (T_{amb}) was the same for both sets of measurements, this showed that reduction of direct solar heating was the major factor improving sensitivity and variability.

The greater slope of the unshaded sensitivity temperature dependence proved that direct sunlight caused more sensitivity reduction than could be accounted for by the temperature of the electronic components, supporting the idea of turbulence causing loss of ^{222}Rn progeny by plate-out. The relative amount of direct solar heating (ambient temperature minus data logger temperature) also provided added support for this, assuming a similar temperature dependence of the electronics in both groups of measurements. All the sensitivities were adjusted to the value they would have when the temperature data logger was 20°C, $S(20)$, using the slope of the shaded sensitivity vs. temperature (Table 2) in the formula:

$$S(20) = S(T_{\log}) + 0.00175(T_{\log} - 20).$$

Table 3 shows that the sensitivity of the shaded instrument is practically independent of the direct sunlight indicator ($r = -0.2$). Furthermore, the variability of the sensitivity is slightly reduced from 4.4% (Table 1) to 3.9%, by taking the data logger temperature into account. However, the sensitivity of the unshaded instrument was almost as sensitive to the sunlight indicator as it was to the data logger temperature ($r = 0.7$).

Calibration adjustments based on the data logger temperature for the "unshaded sensitivity" reduced the variability from 13.6% to 10.7%. The strong correlation with the sunlight index suggested that further improvement is still possible. A linear correction was made to the unshaded sensitivities to estimate the value the sensitivity would have when the tank was 16°C warmer than ambient, using the formula

$$S(20,16) = S(20) + 0.00324(T_{\log} - T_{\mathrm{amb}} - 16). \tag{4}$$

As shown in Table 3, this correction virtually eliminated the systematic difference between the calibration factors for the shaded and unshaded groups, and reduced the variability of the unshaded sensitivity estimates to 8.6%. A more accurate sensitivity can be derived at any given time by taking the sensitivity at 20°C with $T_{\log} - T_{\mathrm{amb}} = 16$°C, and applying a correction according to the actual temperature and temperature difference. The corrections are

$$S(T_{\log}) = 0.282 - 0.00175(T_{\log} - 20) \tag{5}$$

Table 3
Variation of sensitivity, S (counts s^{-1} $(\mathrm{Bq\,m^{-3}})^{-1}$), with sunlight indicator, $T_{\log} - T_{\mathrm{amb}}$ (°C), before and after installing shade cloth

	Unshaded	Shaded
Average sensitivity at $T_{\log} = 20°\mathrm{C}$	0.256	0.282
Correlation, S to $T_{\log}-T_{\mathrm{amb}}$	0.7	−0.2
Slope of S vs. $T_{\log}-T_{\mathrm{amb}}$	–0.00324	NA
Std. dev. (%)	10.7	3.9
Average $S(20, 16)$ (unshaded $S(20)$ corrected to $T_{\log}-T_{\mathrm{amb}} = 16°\mathrm{C}$)	0.281	
Std. dev. (%)	8.6	

with a standard deviation of 3.9% when the instrument was shaded, and

$$S(T_{\log}, T_{\log} - T_{\mathrm{amb}}) = 0.281 - 0.00175(T_{\log} - 20) - 0.00324(T_{\log} - T_{\mathrm{amb}} - 16) \quad (6)$$

with a standard deviation of 8.6% when the instrument was unshaded.

Since shading the tank, no long-term drifts in photomultiplier and amplifier gain have been observed. However, to ensure that such variation does not affect the calibration accuracy, calibration is performed monthly, and the most recent value used. As more calibration data become available, further analysis will be carried out to determine whether several calibration values can be combined to yield a more accurate estimate of the detector efficiency at any given time.

4. Serviceability

A major feature of the new head is the relative simplicity of its construction and the ease with which components such as scintillator foil, wire screen and photomultiplier can be replaced. Air enriched in ^{222}Rn causes a build up of its long-lived progeny, ^{210}Pb. After 21 years, the background count from ^{210}Pb will equal half the average ^{222}Rn concentration. It is therefore necessary to replace the wire screen every few years. The photomultiplier will normally last for decades, but is fragile and subject to damage if exposed accidentally to daylight while the HV is connected.

5. Discussion

The instrumental background of the ^{222}Rn detector has been improved with the introduction of a new detector head, in which the scintillator views only one side of the wire screen (Fig. 2). The improved air flow path has led to an improvement of 14% in collection efficiency for the ^{222}Rn progeny, which has more than compensated for loss of counts obtained from the back of the screen in the original design (Fig. 1). Furthermore, the use of a single scintillator foil has reduced the total scintillator area. The combined effect of these improvements including the 50 mm extended cathode photomultiplier tube (type 9638B) has been a reduction in the equivalent ^{222}Rn concentration from electronic noise and long-lived activity on the scintillator by a factor of 1.8.

Initially, the variability of the sensitivity was high (standard deviation = 13.6%), due to the effect of direct sunlight on the instrument. Installation of shade cloth reduced the variability to 4.4%. A residual dependence on absolute temperature of 0.69% $°\mathrm{C}^{-1}$ with the old detector head has been attributed to changes in the pulse height threshold of the electronic counter. For this detector head correction formulae have been derived (Eqs. (5) and (6)), which can correct the calibration factor to be applied at any time for temperature effects.

Although not enough calibrations have been done at different temperatures to assess the temperature sensitivity of the instrument with the new head and photomultiplier, it is reasonable to assume that the effect of temperature is caused by a shift in the gain of the system, resulting in a shift of the pulse height discriminator threshold. Table 1 shows that the sensitivity of the instrument to changes in the photomultiplier HV was reduced by a factor of 6.6 with the new head. It is likely therefore that the change in sensitivity caused by temperature changes has been reduced from 0.69% $°\mathrm{C}^{-1}$ to 0.105% $°\mathrm{C}^{-1}$, which is low enough to be ignored.

6. Conclusions

The major factor in the variability of the ^{222}Rn detector sensitivity has been identified as the effect of direct sunlight in creating turbulence inside the instrument, resulting in plate-out of ^{222}Rn progeny. Shading the instrument completely eliminated this effect. Residual temperature dependence has been reduced by a factor of 7 to negligible levels by use of a photomultiplier with improved characteristics. Long-lived activity and electronic noise have been reduced by a factor of almost 2, to an equivalent ^{222}Rn concentration of 20 $\mathrm{mBq\,m^{-3}}$ by use of an improved detector head. However, the other major source of background counts, thoron gas, has not been fully identified. The source has been isolated to either the stainless steel walls of the tank or other internal components, but remedial action has only reduced this by about 20%, resulting in a lower detection limit (33 $\mathrm{mBq\,m^{-3}}$) for the instrument, compared to a potential limit of 20 $\mathrm{mBq\,m^{-3}}$, if the thoron were absent.

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