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REPORT E

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## ABSTRACT

A study is made of the use of wire and nylon screens as the second filter in two filter radon or thoron detectors. It is shown that acceptable detection efficiency is obtained at flow rates comparable to those used in detectors in which other types of filter are used. The main advantage of the screens is their very low flow impedance. Several designs of detector which exploit this feature are discussed. Details are given of the performance of three prototypes: a 32 L radon detector with a limit of detection of 0.7 Bq $m^{-3}$ and power consumption of 1 watt; a 750 L radon detector with a limit of detection of 0.027 Bq $m^{-3}$ and power consumption of 25 watts; and a portable thoron emanometer capable of detecting fluxes as low as 1 mBq $m^{-2}$ $s^{-1}$. The radon detectors are rugged and simple. They can operate with no routine maintenance and are suited to remote locations where only infrequent technical support is available.

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RADON, RADON PROGENY, RADON DAUGHTERS, DIFFUSION, WIRE SCREENS.

## EDITORIAL NOTE

The Australian Nuclear Science and Technology Organisation (ANSTO) replaced the Australian Atomic Energy Commission (AAEC) on 27 April 1987. Reports issued after April 1987 have the prefix ANSTO with no change of the symbol (E, M, S or C) or numbering sequence.

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## 1. INTRODUCTION

Two filter detectors have been used for many years for measuring radon and thoron gas in air. The name is derived from the mode of operation: an air sample is drawn through one filter which removes all radon and thoron decay products ("daughters"), then through a delay chamber (tank) in which some radon decays. Finally the air passes through a second filter which collects the daughters from decay in the delay chamber at a rate proportional to the radon and thoron concentrations.

There are many variations of this basic design. The simplest design has an easily removable second filter. After a prescribed sampling period, the filter is removed and placed in an alpha particle detector, based typically on a zinc sulphide scintillator ( Thomas and LeClare, 1970). Radon and thoron daughters can be determined separately by counting for suitable periods, exploiting the differences in half-lives of the daughters (Table 1). The short lived radon daughters decay to less than 1% of their initial concentration after 3 hours. Pb-212 in the thoron decay chain, has a half-life of 10.64 hours, and so is practically the only species left after about 5 hours.

This simplest form can be automated by addition of a filter changing mechanism. Hutter et al, 1990 have done this for an application where there was effectively no thoron in the air and continuous operation was essential. This detector retains the well-defined time resolution of the simple detector.

Another design for an automated two filter detector (Schery et al., 1980) sacrifices time resolution to gain substantially in sensitivity by installing an alpha particle detector inside the tank so that it counts all the decays during sampling. This is only satisfactory where there is no thoron, because the 10.64 hour half-life of Pb-212 causes a generally unacceptable broadening of the time response. Even for radon, the results are effectively smoothed by a time constant of about an hour.

In order to understand other developments, it is necessary to expand on the simple description of the two filter detector given above. A major challenge in the design of two filter detectors is to prevent the daughters from being plated out on the walls of the tank. Most two filter detectors use a high flow rate to ensure that the air passes from the inlet to outlet filters in a time short compared to the mean plate-out time. In a detector with a volume of one or two cubic metres, the plate-out time is a few minutes even when care is taken to avoid turbulence. Thus flow rates of about a cubic metre per minute are necessary. As a result, the second filter area and the power requirements for the air pump have to be large.

A design by Whittlestone, 1985 is similar to that of Schery and shares its use of continuous counting with its inherent long response time. However, Whittlestone's detector incorporates a particle generator inside the tank. It will subsequently be referred to as the "TF+PG" detector. The daughters become attached to the particles, which have a life time of many hours in a 2 m$^3$ tank. A modest 40 L min$^{-1}$ flow rate is all that is necessary to obtain satisfactory results. This system, as with the other continuous designs described so far, is of limited use when thoron is present. However, compared to detectors using a high flow rate, elimination of thoron is much easier because a delay chamber of a reasonable size can be installed in the inlet line. At 40 L min$^{-1}$ Whittlestone was able to use a 200 L delay chamber to remove thoron. A 2 m$^3$ detector using a flow of 1 m$^3$ min$^{-1}$ to reduce internal plate-out would have to have a 5 m$^3$ delay chamber to achieve comparable reduction of thoron.

Further sophistication was undertaken by Grumm et al., 1990 who used a moving filter system and an alpha spectrometer to count the decays. Their detector was therefore able to detect radon and thoron simultaneously.

None of the previous designs emphasised low power consumption, low tank pressure or minimum maintenance. Three new detector applications have forced consideration of these factors: a portable high sensitivity thoron emanometer (Whittlestone et al, 1994) for measuring thoron flux from recent lava in Hawaii; a high sensitivity radon detector for use on ships or at remote field sites with limited technical support; and a moderately high sensitivity radon detector with very low power consumption for use in remote environmental monitoring.

This report describes detector designs which make use of the high diffusivity of radon or thoron daughters. Inside the tank there are no aerosols, so the daughters remain as either atoms or small clusters of atoms no more than a few nm diameter (Raes et al 1985 ). The high diffusivity of these particles means that a wire or plastic screen is able to remove the daughters with high efficiency and very low flow impedance. Since the major power consumption in these detectors is by the air pump, use of screens makes it possible to dramatically reduce system power requirements. In section 2 the performance of some screens is examined. Then in section 3 some ramifications of the use of screens in two filter detectors are discussed. The application to continuous radon monitors and a high sensitivity thoron emanometer is detailed in section 4.

## 2. PERFORMANCE OF SCREENS AS SECOND FILTER

### 2.1 Wire mesh

Woven wire mesh has been used widely for detection of unattached radon daughters (for example George, 1972, Strong, 1988 or Soloman and Ren, 1992), and the penetration and retention characteristics of the screens can be estimated using the theory of Cheng and Yeh, 1980. Measurements of penetration through 400 mesh stainless steel wire screens (wire thickness 25 μm, spacing 64 μm) were performed with a

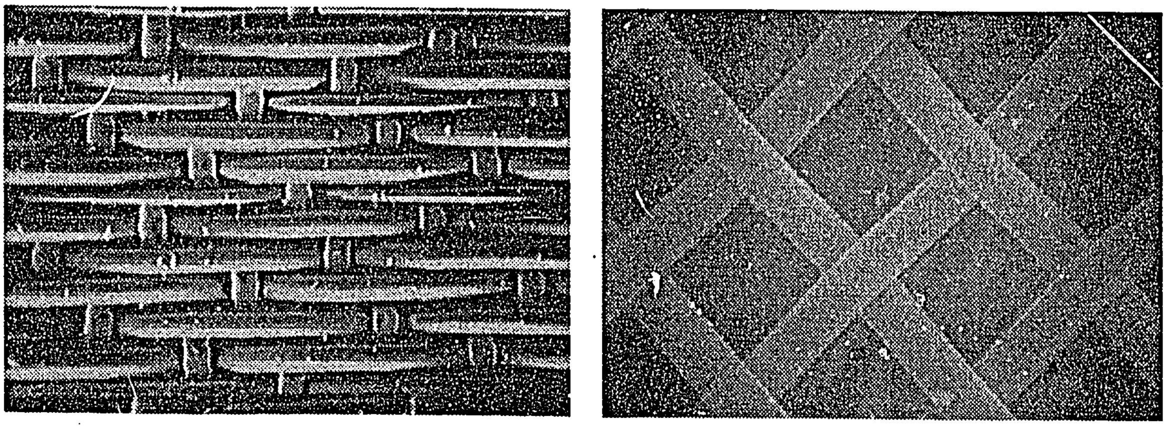
36L two filter detector in order to find the approximate size of daughters at the exit filter of the detector. The resulting penetration with a face velocity (flow rate divided by filter area) of 60 cm $s^{-1}$ was 10 ± 2.4 per cent. This was compared with calculations based on the theory of Cheng and Yeh, 1980 which yielded penetrations of 20% for 1 nm and 8% for 0.7 nm particles. The close agreement of the experimental penetration with the value calculated for 0.7 nm particles demonstrate that the size of the daughter ion clusters was closer to 0.7 than to 1 nm.

To give some idea of the implications of this result for practical detectors, we set an arbitrary upper limit of 30% for the penetration by daughter ion clusters through the screen collector. From Cheng and Yeh's theory, the face velocity would be 180 cm $s^{-1}$ for 400 mesh wire screens. Thus a screen of diameter 25 mm could take a flow rate of about 50 L $min^{-1}$.

## 2.2 Nylon mesh

Nylon mesh was investigated because it offered the possibility of being inexpensive and easy to handle. In an intensive experiment for studying thoron, it would be feasible to use a screen just once, and avoid build-up of Pb-212 which occurs with re-used screens.

It is not possible to use nylon mesh for sizing particles, because the mesh pores do not have consistent sizes. This is illustrated in Figure 1 by photomicrographs of wire and nylon screens. However, the requirement of a second filter for a detector is only that the screen retains a high proportion of unattached radon daughters.



a. Nylon mesh

b. Wire mesh

Figure 1. Photomicrographs of nylon and wire screens.

Nylon mesh made by Spectrum (1100 Rankin Rd Houston Texas, USA) had approximately 10 μm openings and 45 μm thickness, which was similar to 400 mesh wire screen. The front and total (front plus back) retentions were studied for a wide range of face velocities, again using a 36 L two filter detector. For each determination, a pair of measurements was made: first a filter (Gelman type AE glass fibre) alone, then the filter with a screen placed in front. Two alpha particle detectors were used, one for the filter and one for either the front or back face of the screen. Having a large diameter of 100mm and less than 1mm filter to scintillator spacing, the detector had very close to 2 π counting geometry. Per cent penetration is 100 times the ratio of the filter counts when the screen was present to the count with no screen. Total retention is simply 100 - penetration. Front face retention is defined here as the total retention multiplied by the ratio of the count from the front face of the screen to the sum of the counts on the back and the front. Because of losses caused by alpha particles striking the screen, the sum of the counts from the front and back of the screen plus the count from the filter is less than the count from a filter without a screen.

The results are given in Figure 2. Calculations of penetration of a 400 mesh wire screen by 0.7 nm particles (Cheng and Yeh, 1980) are included to demonstrate that the nylon mesh behaves in a similar way to wire mesh. It is reasonable to use the theoretical curve as a basis for interpolation of the experimental data to other face velocities. However, application of the theory to other nylon mesh sizes or particle size distributions is not recommended without empirical confirmation

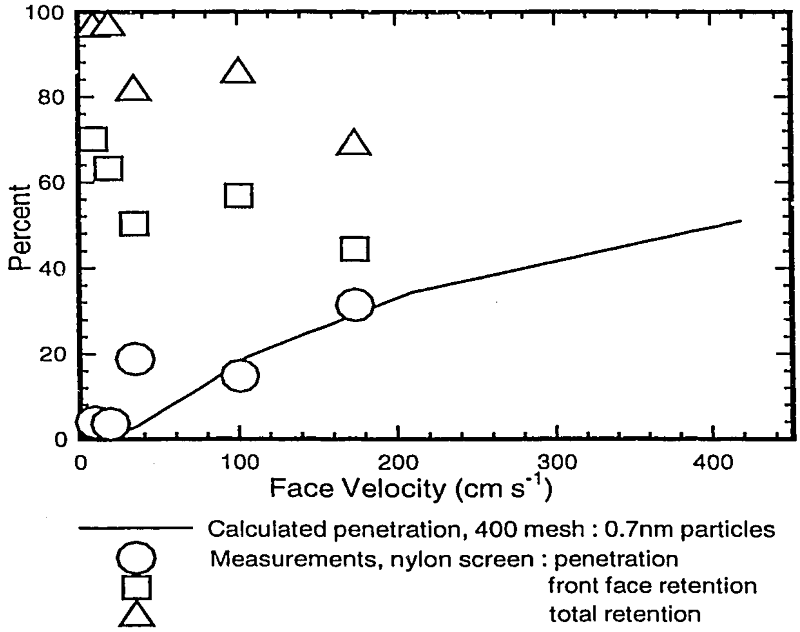


Figure 2. Nylon mesh penetrations, and front face and total screen retentions. The line is the calculated penetration for 400 mesh wire screen from Cheng and Yeh, 1980.

As with the 400 mesh wire screen, the nylon mesh can provide 70% retention of unattached radon daughters in a two filter detector for face velocities of 180 cm $s^{-1}$. This information has been applied to the design of a high sensitivity thoron detector in section 4. The instrument had a 100 mm diameter screen and a flow rate of 400 L $min^{-1}$, implying a face velocity of 85 cm $s^{-1}$. A front face retention of 60% would be expected on the basis of the data in Figure 2.

## 3. OPTIMISATION OF DESIGN OF TWO FILTER RADON/THORON DETECTORS

Having adopted a screen as the second filter, many aspects of the design of the detector change. Most obvious is the effect on design of reduced tank pressure, which will be discussed first (3.1). Another consequence of using a screen is reduced power consumption. In fact, parts of the detector other than the second filter become the major flow impedances. Careful design of these parts can result in further lowering of power consumption. The approach used here is to split the flow into internal and external flow loops (3.2). This also facilitates removal of thoron from the inlet to a radon-only detector. Finally the effects of the flow rates in each flow loop on detector time resolution and efficiency are discussed (3.3)

### 3.1 Tank pressure.

It is important to ensure that no daughters can enter the tank from outside. There can be up to two orders of magnitude higher daughter concentration outside compared to inside the tank. Even a very small leak into the tank can therefore cause serious errors. If a positive pressure is maintained in the tank, no daughters from outside the detector can enter, even through large leaks. In practice, the method used to create the over-pressure is to push air into the inlet rather than draw it from the outlet.This means that the tank has to withstand the full pressure drop across the filter, typically 10 to 20 kPa, with consequent constructional cost penalties. With use of the screen instead of a filter, the pressure drop is about three orders of magnitude less, and is insignificant compared to other restrictions in the flow path.

Another benefit of the screen in this context is that it makes the detector less sensitive to daughters which may enter the instrument from outside as a result of an ineffective filter. This is because filter defects are more likely to permit the entry of attached daughters. Unattached daughters are retained on even a very poor filter by diffusion. Once inside the detector, the same principle applies to retention of the daughters on the screen. Attached daughters from outside will pass through the screen, and not contribute to the count. Maintaining a strong positive over-pressure is therefore less necessary in a system using a screen.

## 3.2 Optimisation of air flow paths.

In most two filter detectors a flow rate high enough to achieve a tank transit time of about a minute is needed to prevent plate-out. As a result the air exchange in the tank is much faster than is necessary in detectors whose time resolution is limited by other factors to 30 minutes or more. Whittlestone, 1985 was able to reduce the flow rate needed to prevent plate-out by injecting sub-micron particles into the tank. The daughters became attached to the particles which had a plate-out time of a few hours.

A low inlet flow rate has the advantages of reduced pumping power, smaller air lines and filters, and most importantly reduction of the size of the inlet delay chamber needed to remove thoron. The optimised detector using a screen achieves this by using two flow loops.

As shown in Figure 3, a low flow loop takes ambient air through a relatively small diameter tube to the blower, then through a small delay chamber to remove thoron if so desired, and a modest capacity first filter into the tank. An adjustable vent on the outlet of the tank maintains sufficient over-pressure to prevent daughters from outside from entering the tank. In a prototype 750 L detector an adequate flow rate of 90 L min$^{-1}$ and over-pressure of 100 Pa were achieved using a small centrifugal blower consuming 3.4 watts of electricity.

The second flow loop is contained completely within the tank (Figure 3), which optimises several aspects of detector design. Firstly, the flow loop is made as short as possible, reducing flow impedance. Secondly, plate-out is optimised for systems using a photomultiplier, because the area of internal fixtures close to the screen is minimised, compared to the reverse configuration with the photomultiplier inside. Thirdly, this arrangement permits the part of the system most likely to need servicing, the alpha particle detector, to be readily accessible. Finally, the mechanical construction is as light and simple as possible, with a minimum of penetrations of the tank.

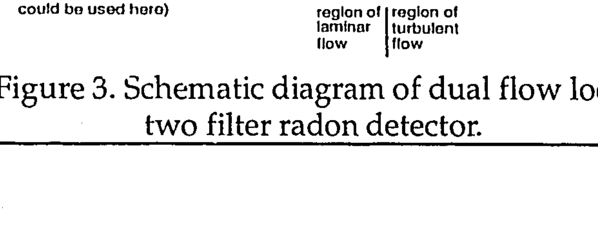


Figure 3. Schematic diagram of dual flow loop two filter radon detector.

The most complex part of the inner flow loop is the detector-screen assembly. Here the need for simplicity, ruggedness, light weight and low power for one component conflicts most strongly with the need for the same criteria applied to other components. The detector, whether solid state or scintillator, should be as small as possible, and the screen to detector distance should be minimised to obtain optimum efficiency and energy resolution. These requirements are antithetical to the need for a large enough screen to achieve high daughter collection and as large an area as possible to permit the air to pass with a minimum of resistance.

Figure 4 illustrates the compromise reached for the 750L photomultiplier/zinc sulphide based prototype referred to above. An air flow aperture just 20% smaller than the one in Figure 4 was unable to achieve an adequate flow with the blower available. Yet a larger flow area could be achieved only by increasing either the screen to scintillator spacing or the diameter of the scintillator. Already 7mm, the screen to scintillator spacing could not be increased without considerable loss of efficiency. An increase in diameter while retaining a 50 mm diameter photomultiplier would result in a reduction of light collection through the light guide. To achieve the diameter shown, the light guide attenuation was an average of a factor of two. Although a higher attenuation may be acceptable, there is a law of diminishing returns applying to this procedure: a factor of two in flow area without increasing the screen to scintillator spacing requires a doubling of the screen diameter with a consequent quadrupling of the area from which the light guide must collect light. While some small improvement may be possible, the design shown achieved a satisfactory 800 L/min for a power consumption of 22 watts. The predominant flow impedance was the screen to scintillator aperture, which leaves little room for improvement.

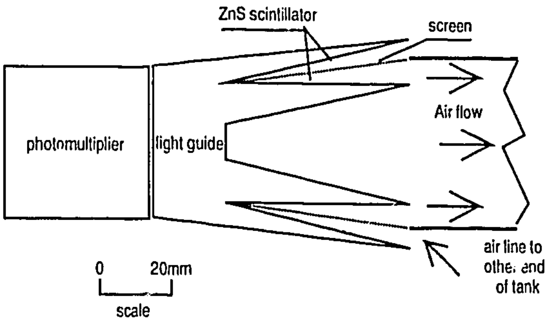


Figure 4. Light guide and screen assembly.

Designing for a solid state detector would face different constraints. Whereas screen area was not a factor with the scintillator, this area would be critical for the solid state detector. Above a certain screen face velocity the daughter collection efficiency becomes unacceptable. This is an insurmountable obstacle to increasing flow rate, and imposes an upper limit on the size of a system using a solid state detector.

## 3.3 Time resolution and efficiency.

Moving filter detectors incorporating a dual flow loop system will have the same efficiency as the single loop version, but a broadened time response. There are two effects. Firstly, it clearly takes longer to change the air sample if the inlet flow rate is reduced. Secondly, the nearly laminar flow in the tank no longer helps to achieve efficient sample changing. In a well designed single loop system a complete change of sample occurs in the time it takes one tank volume of air to pass through. With the dual loop system, however, the fast inner loop flow ensures that newly entering air is well mixed with air already there. As a result, the time response of the radon concentration, C, will be characterised by an equation of the form:

$$C = C_{\infty}\left(1 - e^{-\frac{qt}{v}}\right) \qquad 1)$$

where q is the inlet flow rate and v the tank volume. Radon decay is so much less than the air exchange rate that it can be ignored. Equation 1 represents a smooth broadening of the time response which should be considered when selecting inlet flow rate.

The time response and efficiency of fixed filter radon detectors are more complex because these detectors are able to count the short-lived Po-218, with its half-life of 3.05 minutes. In a system bigger than about 20 L, the mean plate-out time may be many minutes, longer than the Po-218 half life. Thus the latter may limit efficiency and time response for a given flow rate. A computer code has been written to simulate the response of a fixed filter, two filter detector. Laminar flow is assumed, so that daughters build up in air as it passes from the first filter for a time designated the transit time (tt), which is equal to the tank volume divided by the flow rate. Plate-out is parameterised by a mean time (pt) before deposition on the walls. The subroutine which performs the calculation is given in the Appendix.

Figure 5 illustrates the major effects of different plate-out and tank transit times. The alpha activity on the second filter, assumed 100% efficient, is calculated as a function of time after the quantity of radon in the tank is increased stepwise from zero to 1 Bq. In a 1 $m^3$ tank, this would correspond to a concentration of 1 Bq $m^{-3}$. With no plate-out and a very short transit time, the filter activity would reach 2 Bq. The upper curve shows the response on nearly ideal conditions. There is an initial rapid rise as the Po-218 reaches equilibrium, then a slower rise to an asymptotic value close to 2 Bq. The other dashed curves show that as transit time increases, less Po-218 reaches the filter, resulting in a slower response time and lower efficiency. As plate-out time decreases, (solid curves) the efficiency decreases, but there is some improvement in time response, because the short plate-out time results in a shorter effective transit time.

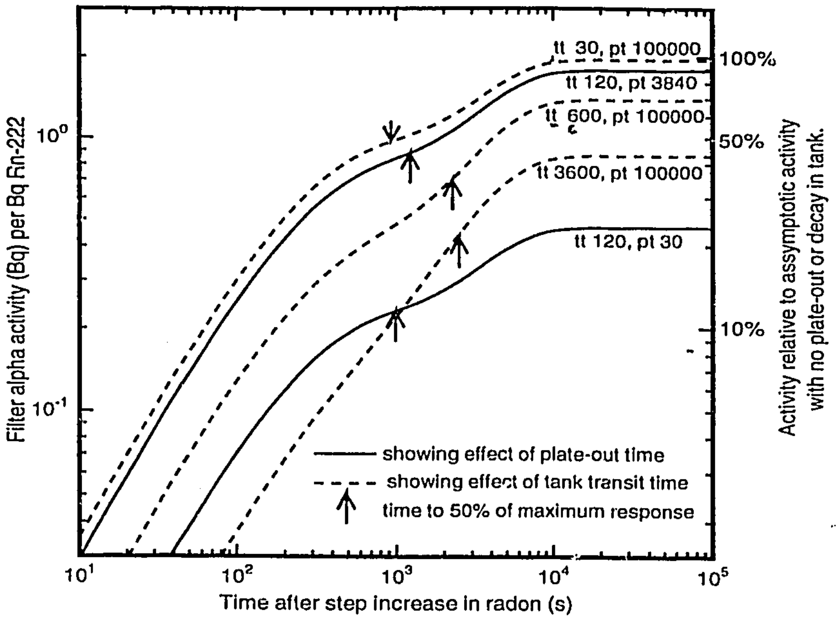


Figure 5. Simulated response of a fixed filter detector to a step increase in the amount of radon in the tank from 0 to 1 Bq. Plate-out times (pt) and tank transit times (tt) are in seconds.

A fast transit time clearly improves the response of the fixed filter detector, which gives high flow rate systems an advantage over low flow rate systems in detecting sudden increases in radon concentration. But how do they respond to a step decrease? The decrease to 50% of maximum is certainly improved, but the time for the count rate to decrease to less than 10% of maximum is also important. A change of wind sector can decrease radon concentrations by a factor of ten in less than an hour (Whittlestone et al. 1990). Calculations show that there is very little difference in decay times to 10% of maximum for different transit times, and that this decay time is close to two hours.

## 4. DUAL FLOW LOOP DETECTORS WITH WIRE SCREENS

Table 2 lists the design parameters and performance of several detectors, including a 32 L prototype which was used to verify the design principles of the dual flow loop detector presented schematically in Figure 3. All calibrations were performed by passing air through a dry radon source (Pylon Electronics Corp. Canada) and calculating the radon concentration from the stated radon output of the source and the flow, which was measured by a commercial gas meter (Toyo Co. Japan model ML-2500).

### 4.1 32 L radon detector

Three features of the 32 L detector were optimised: firstly, the apex angle of the cone guiding air to the screen was made less than 90° to prevent the formation of stagnant air pockets; secondly, air flow in the tank was made close to laminar by use of diffuser of a closely woven cloth (denim) fitted across the tank at the outlet of the internal blower (see Figure 3); thirdly, the blower was selected to have not only the right flow range for this detector, but to act as a flow meter as well. The latter was the most important feature favouring the small DC centrifugal blower over axial blowers, although its lower power consumption would be important in some applications. Figure 6 gives the current as a function of air flow for selected operating voltages. Some variation of these characteristics was observed for different blowers, but once calibrated, the flow could be determined within 10% in the range of interest.

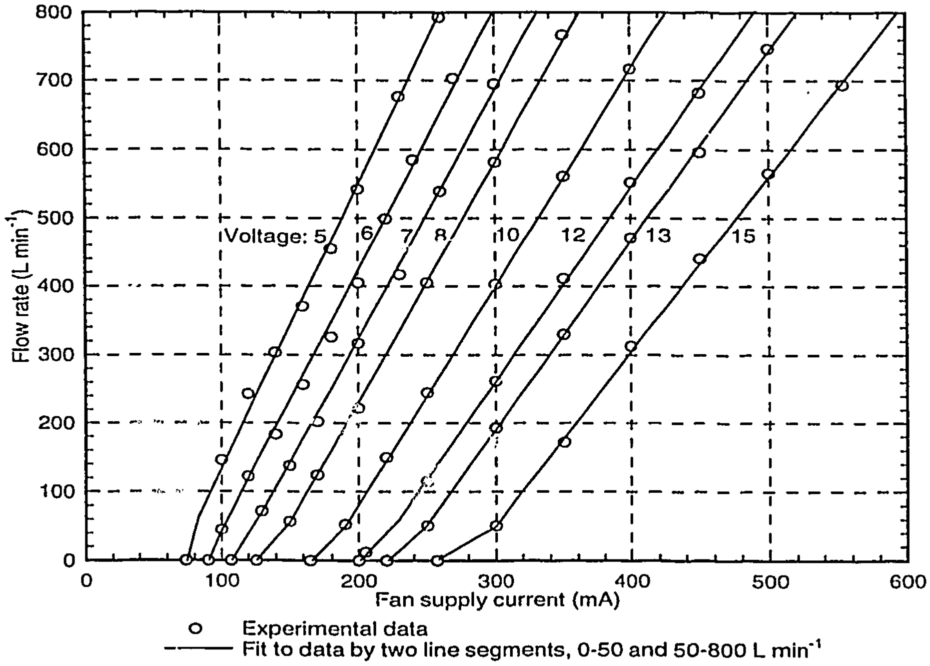


Figure 6. Small centrifugal blower flow vs current for a range of supply volts

Plate-out was the major unknown in the design. It was evaluated by operating the inner loop at different flow rates. The efficiency of the collection of daughters on the screen was calculated using the code in the Appendix. Losses from penetration of the screen were evaluated from the solid curve in Figure 2. Figure 7 shows the calculated efficiency for the case when there was no plate-out and for a mean plate-out time which yielded the best match with the experiment. It is the variation of the efficiency with transit time rather than its absolute value, which was important in determining the plate-out constant, so a scale factor has been applied to the experimental data to force agreement at 29 s transit time. The resulting mean plate-out time is 150 s ±5s, the small error reflecting the strong change in slope of the calculated line with variation of the mean plate-out time.

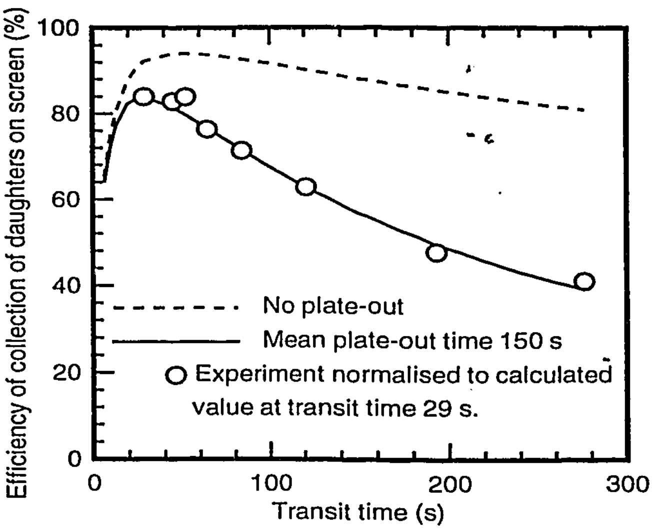


Figure 7. Calculated and experimental daughter collection efficiencies as a function of air transit time through the tank. Both calculated curves allow for loss from decay in the tank and penetration of the screen assuming 0.7 nm particles. The size of the circles represents the experimental error.

The calculated collection efficiency in the absence of plate-out (Figure 7), exhibits a maximum at a transit time of 30 s. This is close to optimum. Longer times will lead to losses by decay and plate-out, shorter times to loss by screen penetration.

It can be seen in Table 2 that the time response of the detector (40 minutes to 50%) is markedly longer than the calculation in Figure 5, which is close to 1000 s or 17 minutes. In part this is due to the time needed for the radon to increase in the tank after a step change in the feed air. But the mean air residence time in the tank was only 6 minutes, so some other factor would appear to be involved. This discrepancy was not investigated. Even so, the response was markedly faster than the detector "TF+PG" listed in Table 2, with its 90 minute response time.

Environmental factors affecting this type of detector are temperature, humidity and pressure. These factors will affect the retention of the daughters on the screen by changing their diffusion characteristics. Provided the retention is high, this effect will be small for changes in conditions expected at any given site. Evidence for this is provided in Figure 2, which shows that a factor of 2 in face velocity results in only a 10% change in retention of daughters on a 400 mesh screen. A similar argument applies to changes in the plateout rate brought about by environmental changes. Provided the plateout loss is small, variation of plateout will not be important. Temperature changes will not make large changes in plateout for a given flow regime. However, if a temperature gradient is applied, turbulence may increase and markedly change plateout. An experiment was performed to check whether the 32 L detector was adversely affected by temperature gradients. With the detector axis horizontal, a 1 kW

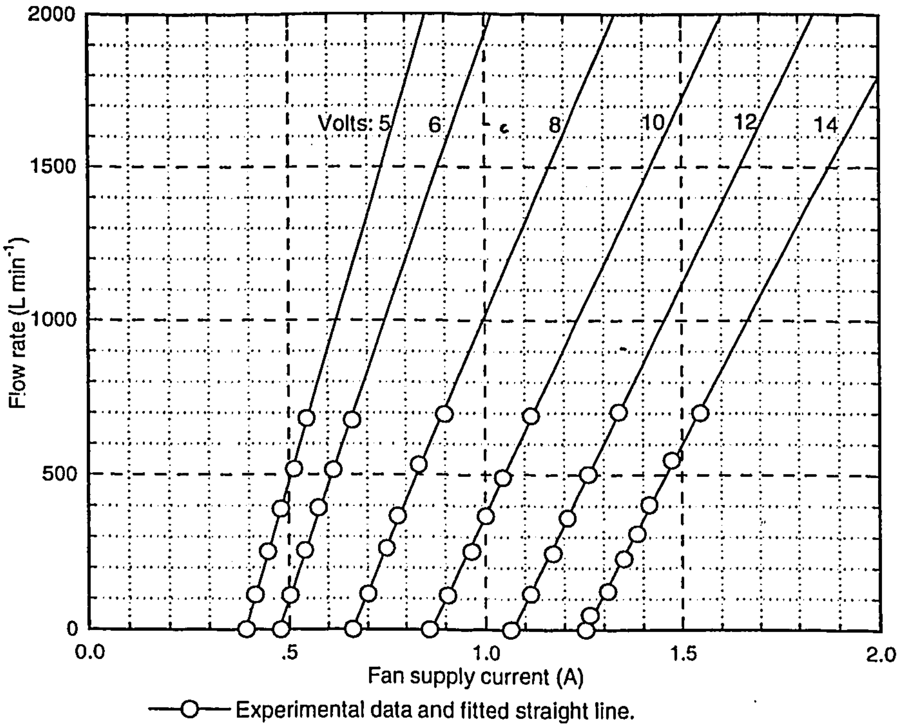


Figure 8. Big centrifugal blower flow vs current for a range of supply volts.

radiant heating element was placed with its axis parallel to the air flow, and displaced horizontally 0.3 m from the detector side. A reduction of count rate of 10% was observed. Under more normal conditions, temperature gradients are unlikely to significantly affect the performance of this detector.

### 4.2 750 L radon detector.

A 750 L prototype detector was built to the specifications shown in Table 2. Its internal blower was larger than the one in the 32 L detector, but it was similar in that the flow rate could be determined from the current drawn through it. Some flow vs current curves are given in Figure 8.

This instrument has operated for several months out doors at the Cape Grim Baseline Air Pollution Station in Tasmania. The sensitivity per unit volume of detector was comparable to the other two filter detectors listed in Table 2, with approximately 0.17 counts $s^{-1}$ per Bq radon in the detector. An improvement of about 25% could be made in this sensitivity by increasing the inner loop flow rate and using a 635 mesh screen (see Table 2).

Experience during the field trial showed that the external loop blower was not powerful enough to guarantee a positive pressure in the tank during periods of high winds. One solution to this problem would be, as suggested in Table 2, to use the larger blower. If power consumption were a factor, an alternative solution would be to take the exhaust air from the detector to a point close to the inlet where the pressure difference would be very small.

## 4.3 Discussion

Table 2 shows how the design parameters interact in accordance with the general principles presented in section 3. Plate-out loss is a significant factor in practice, which can be reduced by a decrease in transit time. In the case of the prototype and revised design for the 750 L detector, a reduction from 20% to 9% was achieved by an inner flow increase from 500 to 800 L/min. The consequent increase in face velocity would have lead to a decrease in screen retention from 85% to 76%, cancelling the gain. To offset this loss, the revised design calls for use of a 635 mesh screen.

Comparison of the different basic designs show that loss from decay in the tank is low for all the dual flow loop designs, a major virtues of this design over the "TF+PG" design. This gain is balanced by two properties of screens. Firstly, they do not retain all the daughters, especially when high flow rates are used. Secondly, they do not permit as high a proportion of the alpha particles decaying on the screen to reach the scintillator, which means that the counting efficiency is lower. In the designs presented, the result is that a given volume of detector has a similar efficiency for each design. The best performance of dual flow loop detectors with screens is the design for a 750 L detector, which should be 40% more efficient than the "TF+PG" design, and close to the best that can be achieved with this type of detector.

Given that the 1500 L detector design is approaching the limits of face velocity practicable, is there a reasonable upper limit to the size of the detector? A 130mm photomultiplier is probably the largest reasonably robust and readily available. Scaling the screen design in Figure 4 would give an increase in screen area by a factor of 6.7. Applying this factor to the tank volume yields 10 $m^3$. The limit of detection would be 2 mBq $m^{-3}$.

In terms of efficiency per unit volume, the scintillation cell is clearly better than the others. But bigger scintillation cells do not work well because a higher proportion of the alpha particles are absorbed by air in the cell. The authors suggest that two filter detectors should be preferred for volumes greater than about 10 L. Below this, the simplicity and better time response of the scintillation cell would make it the preferred option.

In all respects other than efficiency, which is potentially only 40% better, the new design of two filter detector is markedly superior to the "TF+PG" design. The response time is a factor of two better, all routine maintenance has been eliminated and the power consumption reduced by an order of magnitude.

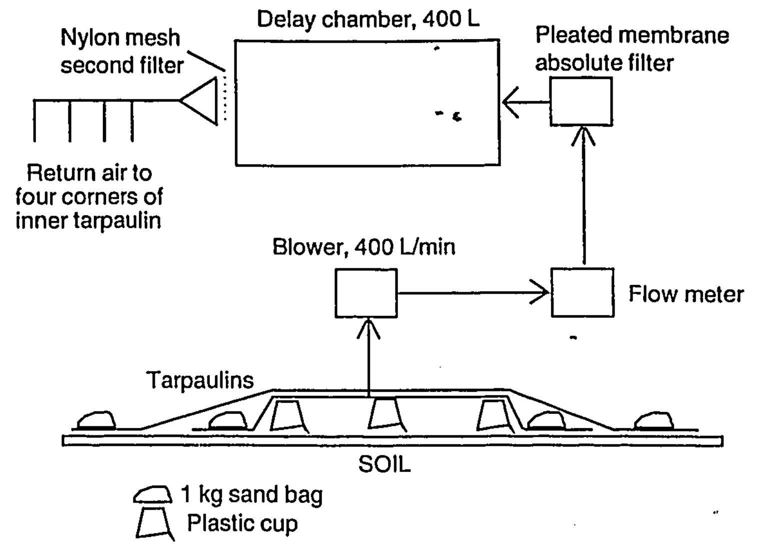


Figure 9. High sensitivity thoron emanometer.

## 5 THORON EMANOMETER WITH A NYLON SCREEN

The thoron flux measurement program carried out by Whittlestone et al., 1994 needed an emanometer with sufficient sensitivity to determine the flux from barren recent lava, or at least be able to set an upper limit on such a flux of about 1 mBq $m^{-2}$ $s^{-1}$. Additional design constraints were that the system should be rugged, portable, reasonably fast, inexpensive and function on rough terrain in windy conditions. This section describes the design of the emanometer shown in Figure 9.

As a starting point in the design, methods were examined for transferring as many thoron atoms as possible from the ground surface into the detector. This implied a combination of a large area and a high enough flow rate to avoid loss of thoron by decay before it reached the detector. Since the 0.3 $m^2$ area of the radon/ thoron emanometer described by Zahorowski and Whittlestone, 1994, yielded a sensitivity to thoron of 60 mBq $m^{-2}s^{-1}$, an initial estimate of the area which should be sampled was 18 $m^2$. Such an area could not be covered by a rigid structure, so a tarpaulin was used. Practicalities limited the area covered to 6 $m^2$. A 2.7 x 3.6 m tarpaulin was used as shown in Figure 9: the inner 6 $m^2$ was spaced 0.09 m above the ground by plastic cups and the outer border was pressed to the ground by plastic bags filled with about 1 kg of sand to act as a seal. An additional seal was provided in the form of a second tarpaulin covering the first. The efficacy of this sealing system is discussed in detail by Whittlestone et al., 1994.

The concentration of thoron in the volume under the tarpaulin is inversely proportional to the height of the spacers. It is therefore possible to improve the sensitivity of the measurement by lowering the spacing as far as possible. On the other hand, the accuracy of the measurement is dependent on how well the volume is defined. On rough ground, a height greater than the roughness is needed. Also, in a thoron emanometer, it is necessary to flush air from the sample area to the detector in a time comparable to or less than the half-life of thoron (54 s). Too low a height would make it difficult to ensure efficient flushing. The compromise reached was a height of 0.09 m with the spacers 0.3 m apart. Thus roughness over distances of the order of a metre was accommodated by allowing the tarpaulin to follow the surface. Problems were encountered in estimating the volume only when the roughness was more than about 0.05 m in 0.3 m.

Edge effects were minimised by drawing the air sample from the centre of the tarpaulin. To appreciate the factors involved in selecting a suitable flow rate, consider a slightly simplified model in which the tarpaulin is circular with radius r, at a height of h (m) above the ground. For a flow rate of Q ($m^3\ s^{-1}$) the concentration N (atoms $m^{-3}$) of thoron at the centre will be:

$$N = \frac{E}{h\lambda}\left(1 - e^{-\frac{\pi r^2 h\lambda}{Q}}\right) \qquad 2)$$

where λ is the thoron decay constant (s) and E the thoron flux (atoms $m^{-2}\ s^{-1}$)

Equation 2 shows that the concentration of thoron increases as flow decreases. At 400 L/min, for the present system, N is 66% of the maximum. Halving the flow rate would give only another 20%. Doubling the flow on the other hand would reduce N by a factor of 0.6. From these considerations, the flow should be no more than 400 L/min.

A large two filter detector was considered to be the only type feasible for this system. The largest volume of tank which could be transported conveniently was 400 L. At 400 L/min, plate-out losses were estimated to be 10%. (The detector had a similar flow rate and cross section to the 750 L detector listed in Table 2. Since the plate-out loss for the latter was 20%, the loss for a detector half the length should be 10%). Since a lower flow would increase the plate-out and a higher flow would reduce the thoron concentration from the tarpaulin, 400 L $min^{-1}$ was optimum.

As indicated in Figure 9, the detector had a single flow loop, and the flow through the screen was 400 L $min^{-1}$. A screen rather than a filter was desirable because it reduced the air flow impedance, and thus reduced both pumping power and the pressure within the tank. Since the filter diameter was 90 mm, the face velocity was 105 cm $s^{-1}$. Hence the front face collection efficiency for nylon screens was 58% (Figure 1). The use of nylon screens was favoured in this application because they were inexpensive and easy to handle. It was economic to prepare a large number to use just once during the experiment.

The sequence of operations in making a flux measurement was:
1) Set up the detector as shown in Figure 9;
2) Operate for 2 hours. Longer periods would have improved sensitivity, but reduced the number of samples which could be taken;
3) Wait for at least 5 hours for all radon daughters to decay;
4) Count alpha particle emission from the screen for at least 2 hours, and up to 16 hours for the sites with the lowest fluxes.

Calibration of this instrument was performed by making side-by-side measurements with the radon/thoron emanometer described by Zahorowski and Whittlestone, 1994. A site was selected which was flat and with uniform low grass. Parameters such as flow paths under the tarpaulin and the effect of the plastic cups were considered to give bigger uncertainties than the problems of intercomparing two different instruments. Therefore theoretical calibration was rejected in favour of comparison with the other instrument.

The calibration factor for a 1 hour sampling period, a 5 hour wait and a 1 hour count was 2446 ± 164 counts per Bq $m^{-2}$ $s^{-1}$. The error quoted is for counting statistics only. In addition to this there is a calibration uncertainty of the small emanometer of 7%, and an estimated uncertainty in the uniformity of the soil over which the intercomparison took place of 20%.

With the protocol used for the calibration and the background count rate of 12 per hour, the limit of detection (the flux at which the counting error was 30%) was 7.5 mBq $m^{-2}$ $s^{-1}$. For a two hour sample time and a 16 hour count, the limit of detection was 1.1 mBq $m^{-2}$ $s^{-1}$.

## 6. CONCLUSIONS

Wire and nylon mesh screens have been shown to be effective as the second filter in "two filter" radon or thoron detectors. In a conventional 2 $\pi$ counting geometry, the counting efficiency is only about 60% of that of a membrane filter. However, with careful design so that both the back and front of the screen are counted, it is possible to obtain an efficiency of more than 90%. Use of a screen in place of a filter is indicated when cost and weight of the detector are important. In one of the systems discussed, it was possible to use a blower weighing one kg to replace one of about 10 kg. At the same time there was a capital cost saving of a few hundred dollars and a reduction of annual electricity consumption of almost $300. Reduced pressure drop across the screen also reduces the pressure which the tank of a two filter detector has to withstand, resulting in reduced construction costs. Thus in many applications, such as the thoron emanometer, the disadvantages of the screen were strongly outweighed by the advantages.

Full benefit of the screens in two filter detectors is realised only when the flow through the first filter is separated from the flow through the screen. By matching the blower to the flow impedance in each flow path, it is possible to build a detector with very low power consumption. An added advantage of using a low flow through the sampling line for a radon detector is the reduction in size of the delay needed to remove thoron.

The dual flow loop radon detectors with screens have the virtues of low cost, simplicity, low power consumption and freedom from routine maintenance. They can be built easily with detection limits as low as 2mBq $m^{-3}$. This technology extends the range of sites at which baseline radon measurements can be made to remote areas with little regular technical backup and a harsh environment.

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Appendix. Subroutine used to calculate two-filter detector response.

This derivation closely follows the derivation given by R.D.Evans [1959], with allowance for the special conditions applicable here.

The calculation is in two parts, the first to obtain the concentration of radon daughters in air passing through the screen, and the second to obtain the concentration on the screen itself. The first part is different from that of Evans, and will be explained in detail.

Laminar flow is assumed, so a slice of air passes down the chamber, taking a transit time equal to the internal loop flow rate divided by the chamber volume. At any time the rate of change of the daughter concentration is, in close analogy to Evans' equation 15:

$$dN_A/dt = N_{Rn}\lambda_{Rn} - N_A(\lambda_A + \lambda_P) \qquad \text{A1}$$

$$dN_B/dt = N_A\lambda_A - N_B(\lambda_B + \lambda_P) \qquad \text{A2}$$

$$dN_C/dt = N_B\lambda_B - N_C(\lambda_C + \lambda_P) \qquad \text{A3}$$

The solutions to these are the same as Evans', with $\lambda_A$ replaced by $\lambda_A + \lambda_P$ etc. The difference is the plate-out time constant, which is assumed to be the same for each daughter. When short transit times are used, this assumption will not cause significant errors.

The subroutine listed below calculates the daughter concentrations at the transit time, tt, and the the filter activities at selected times assuming no change in radon concentration, and zero activity at the start.

Definitions used in main program:

```
'Calculate count rate from two filter detector after step change of radon in
tank from 0 to 1 Bq m^-3.
'Assumptions: laminar flow, all daughters have same plate-out rate
   DEFSTR C : DEFINT I,J,M,N
   DIM f(200),tf(200),fa(200),fb(200),fc(200)
'*** arrays for storing filter activities fx(n) at times tf(n).
   DATA 500,1000,120,120,600,10,2.104E-6,.003797,.0004318,.0005868
   READ ql,vl,tt,p,r,inc,lr,la,lb,lc
'*** data are: inner loop flow rate (L/min), tank volume (L), transit time (s),
'*** mean plate-out time (s), time range of calculation (s), number
'*** of time steps, decay constants (s^-1) of radon and daughters.
   q=ql/60000 : v=vl/1000  :lp=1/p '**convert L/min to m^3/s. L to m^3
```

```
   SUB calc
   SHARED q,v,tt,lr,la,lb,lc,p,lp,r,inc,f(),tf(),fa(),fb(),fc()
   SHARED ninc,a,b,ac,rn,pa,pb,pc,pp,af,bf,fcf,ff
'*** first calculate concentration of Po-218, a, Pb-214, b, and  Bi-214, ac, at screen
   rn=tt          '*** radon atoms/m^3 decaying in "tt" from air with activity 1 Bq m^-3
   ka=1/(lp+la)
   a=ka*(1-EXP(-(lp+la)*tt))
   k1=ka*la/(lp+lb)
   k2=ka*la/(la-lb)
   k3=-k1-k2
   b=k1+k2*EXP(-(lp+la)*tt)+k3*EXP(-(lp+lb)*tt)
   l1=k1*lb/(lc+lp)
   l2=k2*lb/(lc-la)
   l3=k3*lb/(lc-lb)
   l4=-l1-l2-l3
   ac=l1+l2*EXP(-(lp+la)*tt)+l3*EXP(-(lp+lb)*tt)+l4*EXP(-(lp+lc)*tt)
   pa=100*a/rn : pb=100*b/rn : pc=100*ac/rn : pp=100-pa-pb-pc
'*** calculate activity on filter from 1 to R seconds in inc steps
   x=(r/10.0)^(1.0/inc) : y=10    '*****time at which filter activity is calculated is
                                  '**** multiplied by x each loop below
   ka1=q*a/la : ka2=-ka1
   kb1=(ka1*la+q*b)/lb  : kb2=ka2*la/(lb-la) : kb3=-kb1-kb2
   kc1=(kb1*lb+q*ac)/lc : kc2=kb2*lb/(lc-la) : kc3=kb3*lb/(lc-lb)
   kc4=-kc1-kc2-kc3
   af=la*ka1 : bf=lb*kb1 : fcf=lc*kc1 : ff=af+fcf  '**activities at long times
   FOR i=0 TO inc
   tf(i)=y
   y=y*x
   fa(i)=la*(ka1+ka2*EXP(-la*tf(i)))
   fb(i)=lb*(kb1+kb2*EXP(-la*tf(i))+kb3*EXP(-lb*tf(i)))
   fc(i)=lc*(kc1+kc2*EXP(-la*tf(i))+kc3*EXP(-lb*tf(i))+kc4*EXP(-lc*tf(i)))
   f(i)=fa(i)+fc(i)
   NEXT i
   i=inc+1 : tf(i)=99999
   fa(i)=af : fb(i)=bf : fc(i)=fcf : f(i)=ff '** t=infinity values
   END SUB
```