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**Assessment of Two-Filter Technique
for Correlating Actinium-227
Concentrations in Soils**

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ASSESSMENT OF TWO-FILTER TECHNIQUE FOR CORRELATING ACTINIUM-227 CONCENTRATIONS IN SOILS

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409

ABSTRACT

Concentrations of actinium-227 in soil samples from waste-disposal sites for uranium processing plants were successfully correlated with radon-219 measurements obtained by the two-filter technique, thus avoiding time-consuming and difficult radiochemical analyses. A flow-through sampling device and procedure were developed which determined actinium levels with a precision of $2 \text{ pCi/g} \pm 50\%$. Theoretical relations for the production of radon from actinium, the decay of radon, and the decay and diffusion of radon daughters in the two-filter apparatus were formulated. Measurements indicated that the emanation fraction for radon-219 was about 15%. Sampling filters collected radon daughters with a 93% efficiency, while radon could be scrubbed from air samples by use of an activated-charcoal canister.

Contents

	<u>Page</u>
1. Summary	1
2. Introduction	1
3. Theoretical Development	2
4. Apparatus and Procedure	4
4.1 Two-Filter Measurements	4
4.2 Determination of Emanation Fraction (f_e)	5
4.3 Determination of Sample Filter Efficiency (f_f)	5
4.4 Determination of Charcoal Filter Efficiency (f_c)	8
5. Results	8
6. Discussion	13
7. Conclusions	15
8. Recommendations	15
9. Acknowledgements	16
10. Appendix	17
10.1 Decay Scheme	17
10.2 Mathematical Development	17
10.3 Description of Proposed Apparatus	25
10.4 Proposed Field Procedure	26
10.5 Summary of Data and Results	26
10.6 Sample Calculations	30
10.7 Nomenclature	38
10.8 Location of Original Data	41
10.9 Literature References	41

1. SUMMARY

The two-filter technique was investigated for determining levels of radon-219 in air and for correlating actinium-227 concentrations in soil. Because emissions from uranium processing wastes containing actinium pose a health hazard, an adequate analytical technique is required to formulate exposure standards. Radon-219 production from soil samples was measured by using the two-filter method; the radon levels were correlated with the previously determined amount of actinium-227 present; and an experimental apparatus and procedure were developed for field measurements. The theoretical relations for formation of radon from actinium, the decay of radon to its daughters, and the diffusion of the daughter products were formulated; the important empirical parameters, such as the emanation factors and filter efficiency, were determined experimentally. A prototype sampler was designed, built, and tested. The device and technique developed could measure actinium-227 activities as low as $2 \text{ pCi/g} \pm 50\%$. Air, pumped through a 300-g soil sample for 30 min, was passed through a 50x2.5-cm-ID decay tube, and the collected decay products were counted for 30 min. Tests indicated that radon-219 had an emanation fraction of 12-20%, while the capture efficiency of the sample filters was 93%. Emanation fractions varied with air and soil humidity. The field apparatus would be similar to the one tested, although soil samples would be dried, and a drying tube would be used in the air inlet to minimize humidity effects and to maintain the desired accuracy. Further testing of the two-filter apparatus is recommended to help calibrate and optimize the field unit and to study the variations in emanation fractions for different soils at ambient conditions.

2. INTRODUCTION

The production of ^{219}Rn from uranium processing wastes is a public health hazard which only recently has been identified (5, 6). Since inhalation of alpha-emitting radon and radon daughters apparently leads to a higher incidence of lung cancer (3), the Nuclear Regulatory Commission and the Environmental Protection Agency are establishing maximum exposure levels for ^{219}Rn in air and for radon parents such as ^{227}Ac and ^{231}Pa in soils. Thus, a rapid and effective method for measuring ^{219}Rn and radon parent levels is desired.

Complete radiochemical analysis of soils for ^{231}Pa and ^{227}Ac is difficult and time-consuming; however, ^{219}Rn can be measured using techniques similar to those used for ^{222}Rn (6). Correlation of ^{219}Rn concentrations with the level of ^{227}Ac in the soil would provide a simplified method for ^{227}Ac analysis. The two-filter method for radon measurement is the procedure studied and evaluated in this work.

The refining of uranium ores involves dissolving the metals in mineral acids and subsequently extracting the uranium in an organic solvent. This process can produce a precipitate containing radium, thorium, and other actinides. In some cases these precipitates were disposed with other tailings,

resulting in surface soils with high concentrations of ^{231}Pa , ^{227}Ac , and ^{223}Ra . These sites were discovered when routine radon measurements indicated high levels of ^{219}Rn , instead of the more common ^{222}Rn isotope (5, 6).

Previous researchers have investigated the two-filter method for ^{222}Rn and ^{220}Rn analysis (10, 11). Procedures for measuring ^{219}Rn as well as ^{222}Rn by alpha spectroscopy have also been developed (6). The literature includes analyses of radon diffusion in soils (9), transport in a two-filter apparatus (8), and the effect of weather on radon emissions (3). The objective of this work was to experimentally assess the two-filter technique for determining ^{219}Rn and ^{227}Ac concentrations.

3. THEORETICAL DEVELOPMENT

The two-filter method determines the concentration of radon in air by passing an air sample through a tube of known dimensions with filters at each end (Fig. 1). Since radon decay daughters are charged, they become attached to aerosol particles and can be captured using small-pore filters. Air entering the tube is cleansed of radon daughters by the first filter, while daughters formed during passage through the tube are collected on the second filter. By measuring the number of daughters on the second filter and accounting for migration to the tube walls, the concentration of radon can be calculated.

Radon-219 decays to beta-emitting actinium-B (AcB) which then decays to alpha-emitting actinium-C (AcC), the species whose decay is counted experimentally (see Appendix 10.1). If the concentration of radon is at steady state and the residence time in the tube is short compared with the half-life of AcB, the concentration of AcB is described by:

$$V_x \frac{\partial C_B}{\partial x} + V_r \frac{\partial C_B}{\partial r} = D \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C_B}{\partial r} \right) + \frac{\partial^2 C_B}{\partial x^2} \right] + P_B \quad (1)$$

where x is the axial coordinate, r is the radial coordinate, V is the velocity, D is the diffusion coefficient, and P_B is the production rate of AcB per unit volume due to the decay of ^{219}Rn . If axial diffusion and the radial velocity component are neglected, the source term becomes:

$$P_B = \lambda_{219} C_{219} e^{-\lambda_{219} \frac{x}{V_x}} \quad (2)$$

and Eq. (1) reduces to:

SOIL: 20-30 MESH
 DRY AND DESICCATED
 SAMPLE SIZE ~300 G

COUNT: SAMPLE FOR 30 MIN
 COUNT FOR 30 MIN

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FIG.
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$$\frac{D}{r} \frac{\partial}{\partial r} r \frac{\partial C_B}{\partial r} - V_x \frac{\partial C_B}{\partial x} + \lambda_{219} C_{219_1} e^{-\lambda_{219} \frac{x}{V_x}} = 0 \quad (3)$$

where λ is $\ln 2$ /half life, C_{219_1} is the initial concentration of ^{219}Rn , and C_B is equal to zero at the tube entrance and walls. This relation can be solved (see Appendices 10.2.1 through 10.2.2) to yield the survival fraction f_s , which is defined as the fraction of AcB produced in the tube which reaches the second filter. Solutions using LaPlace transforms give an f_s value of 0.504. A numerical approximation, using finite elements results reported previously (1, 4, 8), gives similar results.

The amount of AcB collected depends on the amount of ^{219}Rn reaching the two-filter tube, the residence time in the tube f_s , and the capture efficiency of the sample filter f_f . If the known half-lives of AcB and AcC and the elapsed time of sampling and counting are used, the number of counts expected can be computed (see Appendix 10.2.3). A soil sample of weight W with an actinium activity ($\text{s}^{-1}\text{g}^{-1}$) of C_{227} produces $C_{227}W$ radon atoms per second. However, the number of atoms escaping from the soil is given by $f_e C_{227}W$, where f_e , the emanation fraction, is an experimentally measured parameter which relates the amount of radon emanating from the soil to the amount produced in the soil. The amount of radon entering the decay tube from the sample is thus (Fig. 1):

$$N_{219_1} = (C_{227}W)f_e T e^{-\lambda_{219} T_d} \quad (4)$$

where T is the sampling time and T_d is the residence time between the sample and the decay tube. Since f_f is less than unity, some AcB produced upstream of the decay tube also enters and must be accounted for in the calculations (Appendix 10.2.3).

By measuring f_e and f_f , and by calculating f_s , T , and T_d , we can relate the measured AcB level on the sample filter to the concentration of ^{219}Rn in the air and ^{227}Ac in the soil. We also wish to measure f_c , the capture efficiency of the charcoal filter (Fig. 1) for undecayed ^{219}Rn to determine whether the air exiting the device can be recycled through the sample and if it poses a safety hazard.

4. APPRATUS AND PROCEDURE

4.1 Two-Filter Measurements

Measured amounts of dry, 30-mesh soil samples obtained from the radiological waste disposal site in Blaresville, Pa., were individually placed between two 10-cm Whatman #41 filters inside a 12.7-cm-diam by 6.35-cm-high sample chamber (Fig. 1). The soil sample was previously assayed for actinium-227 by gamma spectroscopic analysis.

The sample holder was suspended between two one-liter funnels. Gelman 25-mm Metrical DM-450 filters (0.45 μ m pore diameter) were inserted in both ends of the 50x2.5-cm-ID decay tube. Components were connected with 1.25-cm-ID rubber tubing. Air was drawn into the system at about 6 l/min and passed through an anhydrous calcium sulfate Drierite Laboratory Gas Drying Unit, which reduced the relative humidity to less than 1%. Air was passed downward through the sample chamber, carrying the emanated ^{219}Rn to the decay tube. Most radon daughters formed upstream of the decay tube were removed by the first Gelman filter, while the remaining ^{219}Rn passed through the two-filter tube. Daughter products formed in the tube were collected on the second filter, which was subsequently removed and counted for AcC on an alpha spectrometer after a 10- to 30-min sampling period. The air flow continued through a standard gas-mask charcoal filter to strip the residual ^{219}Rn , and the cleaned air was vented to the atmosphere or recycled through the system.

4.2 Determination of Emanation Fraction (f_e)

A measured soil sample, previously assayed for ^{227}Ac , was enclosed in a 17-liter sample drum (Fig. 2) and allowed to equilibrate with ambient air for several hours, which permitted the concentrations of AcB and AcC to grow to measurable levels (Appendix 10.6.1). Air was then pumped out of the sample drum at 10-11 l/min and through a Gelman filter which captured the decay products. A pumping time of two minutes was chosen to approximate a complete replacement of air in the drum and was minimized to ensure negligible production of ^{219}Rn . Alpha emissions from the captured AcC were used to calculate the concentration of ^{219}Rn in the air. Comparison of the measured level of ^{219}Rn with the total production of ^{219}Rn in the soil yielded the emanation fraction (see Appendix 10.6.1). Samples BV01 and BV02, containing 23,701 and 7567 pCi/g of ^{227}Ac , respectively, were tested in this manner.

The emanation fraction was also measured using the two-filter apparatus. Alpha emissions from the downstream filter were used to calculate f_e (Appendix 10.6.1). Samples BV02 and VCC17A containing 7567 and 10.8 pCi/g ^{227}Ac , respectively, were assayed by this procedure.

4.3 Determination of Sample Filter Efficiency (f_f)

Air containing ^{219}Rn was passed through three Gelman filters in series (Fig. 3). The first and second filter were 20 cm apart, while the last two filters were closely spaced (~ 1 mm) to prevent appreciable ^{219}Rn decay. Daughter products formed between the first and second filters were captured in the two downstream filters which were counted simultaneously for alpha emissions. The filter efficiency f_f was calculated from the ratio of these measurements (Appendix 10.6.2).

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EMANATION FRACTION DETERMINATION

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FIG.
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FILTER EFFICIENCY APPARATUS

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4.4 Determination of Charcoal Filter Efficiency (f_c)

A charcoal filter was installed in the filter test apparatus (Fig. 3), and air containing ^{219}Rn was passed through the system. The 0.45- μm pre-filter removed any daughter products while the charcoal filter absorbed a portion of the ^{219}Rn . Daughters produced by the remaining ^{219}Rn were collected and counted on the downstream sample filter. Comparison of results with and without the charcoal filter in place yielded f_c (Appendix 10.6.3).

5. RESULTS

The data obtained and the calculated results are tabulated in Appendix 10.5. The emanation fractions measured in the first group of experiments were highly erratic. For sample BV01, f_e ranged from 0.017 to 0.186 (Fig. 4) and averaged 0.082. For BV02, f_e varied from 0.027 to 0.425 with a mean of 0.202. The values appeared to be higher for runs conducted later in the day (Fig. 5). The amount of time during which the air had been held in the sample drum also seemed important (Fig. 6); samples held overnight produced f_e values much lower than average. Initial observations suggested that local weather conditions, especially temperature and humidity, had an important effect on f_e , with f_e decreasing as humidity increased. In addition, increased equilibration time tended to decrease the calculated value of f_e due to the depletion of atmospheric aerosols which migrated to the walls of the drum.

Emanation fractions obtained from the two-filter test were more stable. With sample BV02, f_e values averaged 0.134 with a range of 0.119 to 0.153. Tests on sample VCC-17A yielded a mean f_e value of 0.176 with results varying from 0.146 to 0.202. Because the humidity was controlled during these runs and because the f_e values were not obtained by assuming a steady-state aerosol concentration in the drum, the results produced were more reliable.

The collection efficiency of the sample filters was calculated to be 93%, while the charcoal filter capture efficiency was 99%. These results include a correction for the background radiation level, which was about 0.4 counts/min.

Tests on the two-filter apparatus with a flow-through sample chamber produced about 100 times as many counts as similar tests using the larger sample container. The counts obtained in the flow-through apparatus also tended to be less variable than with the larger container, although fluctuations were still present. Addition of the drying tube and use of dry samples reduced these fluctuations to less than 10% of the mean value, thus giving greater precisions than the desired result of $\pm 50\%$.

Theoretical curves of counts expected on the second filter of the studied apparatus as a function of soil activity can be generated for different emanation fractions (Appendix 10.2.3). Such curves are presented in Fig. 7 for the average and extreme values of f_e , where the data points generally correspond to an average value of 0.15 (Appendix 10.6.4). Note

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EMANATION FRACTION VS TIME AND DAY

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FIG.
4

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EMANATION FRACTION VS HOUR OF DAY

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FIG.
5

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EMANATION FRACTION VS EQUILIBRATION TIME

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COMPARISON OF OBSERVED AND PREDICTED
COUNT ON SECOND FILTER VERSUS
CONCENTRATION OF ^{227}Ac

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FIG.
7

that the deviation in soil activities inferred from this graph for a given filter count are within the desired $\pm 50\%$ precision. Measurements on a 1123 pCi soil sample, with 30-min sampling and counting periods, resulted in approximately 60 counts, or five times the level of background radiation. Thus, it would be possible to measure a 2 pCi/g sample using a soil mass of 250 to 400 g, assuming a minimum activity of twice the background level.

6. DISCUSSION

The major problem found in using the two-filter method for ^{219}Rn and ^{227}Ac measurements was the lack of reproducible data. This resulted in large variations of f_e values calculated from known samples and would result in a low precision when measuring unknown soil concentrations. Actual variations of the emanation fraction with time of day, weather conditions, equilibration time, and type and age of the soil sample would also render the technique unreliable. It is difficult to separate such effects, since a low value of f_e could correspond to an early morning sample or to a sample with high ambient humidity and long equilibration time. The reliability of the experimental apparatus is also questionable, because leaks, variations in flow, and changes in sensitivity could have affected the results.

We feel that a major source of irreproducibility is the variation in air and soil humidity. Previous researchers found that radon emissions and diffusion are strong functions of humidity (3, 7). Diurnal fluctuations in soil moisture and air humidity would explain the reduced f_e value observed in the early morning under damp conditions and the high f_e value seen for warmer, drier conditions. This problem can be reduced by maintaining the soil sample and test system at a constant humidity, and preferably a low humidity for increased sensitivity. Because soil samples are routinely ground and dried, storing them in a desiccator and passing all air entering the system through a drying tube should prevent these variations.

Use of flow-through apparatus substantially increases sensitivity over conventional techniques. The addition of a drying tube to reduce air humidity further improves the results to give measurements which are reproducible to within 10%, especially when a fresh, dry soil sample is tested. The desired sensitivity and precision of 2 pCi/g $\pm 50\%$ of ^{227}Ac is attainable with our crude apparatus, and it appears that greater precision would be possible with better equipment and a standard procedure.

Measurements with the flow-through unit indicated that f_e for ^{219}Rn was about 0.13 - 0.18. Further studies are necessary to determine the accuracy and variation with different soils. Tests run with a more refined apparatus (Fig. 8) under controlled conditions could help determine the effects of humidity on f_e and aid in the optimization of the field sampler and test procedure.

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The results of the filter tests confirm that the small-pore filter efficiently captures ^{219}Rn daughters, but the fraction that escapes must be accounted for in the calculations of f_e and ^{227}Ac levels. Use of multiple filters could eliminate this problem. Because the charcoal filter essentially removed ^{219}Rn from the air stream, air leaving the tube could be recycled through the sample. If no recycle were employed, the filter could also clean fresh inlet air or could strip discharged air of ^{219}Rn .

Our basic experimental apparatus (Fig. 1) and procedure are workable for field studies. Better equipment, with quick-release gas connections for easy handling, a standardized technique for soil grinding, drying, and handling, and maintenance of low humidity in the system with a drying tube should all contribute to more reliable and accurate results. Measurements could be made by implementing our calculational techniques or by using a standard sampling procedure and calibrating the unit in the laboratory.

7. CONCLUSIONS

1. The two-filter method can measure ^{219}Rn levels and ^{227}Ac concentration in the soils to $2 \text{ } \mu\text{Ci/g} \pm 50\%$ (95% confidence).
2. To obtain accurate results for measurements of ^{227}Ac levels and the emanation fraction f_e , the soil sample must be uniform and dry, and the system must be kept dry.
3. The sampling device and procedure tested are usable for field measurements.
4. The emanation fraction for ^{219}Rn averages 15%, with a range of 12 to 20%.
5. The emanation fraction and the measured activity of samples are highly dependent on humidity, soil conditions, and quality of the apparatus.

8. RECOMMENDATIONS

1. The proposed field sampler would parallel our test apparatus (Fig. 1). The decay tube would be approximately 50-cm long and 3.25-cm-ID. Air would pass over a desiccant before entering the system; sample flow would be $\sim 6 \text{ l/min}$. A soil container 20 to 25 cm in diameter and about 5 cm high would hold the sample suspended between two large-pore filters. The unit would have a minimal dead volume and use quick-release junctions for easy access (Appendix 10.3.2).
2. Sampling requires about 300-g soil samples which are ground to about 30 mesh, dried, and maintained dry using a desiccator and drying tube. The soil should be counted for 30 min, and, after a 2-min delay, the filter would be counted for 30 min. Samples should be run three to six times for reliable results, and the soil activity should be calculated using the method presented in this study or by using calibration curves (Appendix 10.4).

3. A laboratory apparatus with the same dimensions as the field unit should be tested (Fig. 8). The unit should include two decay tubes, an air humidifier and dryer, a charcoal filter for air cleanup, and provisions for variation in flow and setup. Quick-release junctions and improved equipment should be used where possible. The device should be set up in a properly vented laboratory where ambient conditions can be controlled (Appendix 10.3.1).

4. Further experimental work should include: a study of the emanation fraction for different soils to determine the expected variation and to obtain more accurate values for field use; calibration of the field device with known samples; study of the effect of changing the flow direction of air through the soil sample; continued study of the effects of humidity, temperature, pressure, and soil conditions on the measurements; and optimization of the field device and procedure.

9. ACKNOWLEDGEMENTS

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10. APPENDIX

10.1 Decay Scheme

The complete decay chain of ^{227}Ac to AcD (^{207}Pb) is shown in Fig. 9. Because the radionuclides between actinium and ^{219}Rn have short half-lives compared to that of actinium, it is reasonable to assume they have equilibrated with ^{227}Ac during the roughly 30-year period since disposal.

The model for determining ^{219}Rn activity from alpha-counting of AcC uses the following simplifications:

1. The small amount of ^{215}Po (AcA) decaying to astatine ($2.3 \times 10^{-4} \%$) may be ignored.
2. The presence of AcA in the decay scheme may be neglected due to a relatively short half-life ($1.78 \times 10^{-3} \text{ s}$).
3. The small proportion of AcC decaying by beta emission (0.28%) may be ignored.

With these assumptions the decay chain from ^{219}Rn to ^{207}Pb becomes:

with effective exponential decay constants for ^{219}Rn , ^{211}Pb , and ^{211}Bi of 10.5, 0.0192, and 0.3224 min^{-1} , respectively.

10.2 Mathematical Development

10.2.1 Analytical Solution for Survival Fraction f_s

The daughter products formed by alpha decay of ^{219}Rn are charged and can diffuse to the walls of the two-filter tube where they attach. As a result, only a fraction of the generated daughter products reach the sample filter. This survival fraction must be known to calculate ^{219}Rn and ^{227}Ac concentrations from the measured levels of AcB .

The differential equation describing the steady-state concentration of AcB in the tube is:

$$V_x \frac{\partial C_B}{\partial x} + V_r \frac{\partial C_B}{\partial r} = D \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C_B}{\partial r} \right) + \frac{\partial^2 C_B}{\partial x^2} \right] + P_B \quad (1)$$

	<u>Species</u>	<u>Half-Life</u>
$^{231}_{91}\text{Pa}$ $\downarrow$ $^{227}_{89}\text{Ac}$ $\swarrow$ 58.6% $^{227}_{90}\text{Th}$ $\searrow$ 1.4% $^{223}_{87}\text{Fr}$	Protactinium	5.25×10^4 y
	Actinium	21.6 y
	Radioactinium	18.2 d
	Actinium K	22 m
$^{223}_{88}\text{Ra}$ $\downarrow$ $^{219}_{86}\text{Rn}$ $\downarrow$ $^{215}_{84}\text{Po}$ $\swarrow$ ~100% $^{211}_{82}\text{Pb}$ $\searrow$ 0.00023% $^{215}_{85}\text{At}$	Actinium X	11.43 d
	Actinon (An)	3.96 s
	Actinium A	1.78 ms
	Actinium B	36.1 m
	Astatine	~0.1 ms
$^{211}_{83}\text{Bi}$ $\swarrow$ 0.28% $^{211}_{84}\text{Po}$ $\searrow$ 99.7% $^{207}_{81}\text{Tl}$	Actinium C	2.15 m
	Actinium C'	0.52 s
	Actinium C''	4.79 m
$^{207}_{82}\text{Pb}$	Actinium D	Stable

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COMPLETE DECAY SCHEME
 OF PROTACTINIUM-231

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with

$$\left. \frac{\partial C_B}{\partial r} \right|_{(0,x)} = 0, \quad C_B(R, x) = C_B(r, 0) = 0$$

and appropriate boundary conditions at the end of the tube. Axial dispersion and radial velocity can be neglected for high Schmidt numbers and low Reynolds numbers, respectively. The velocity profile was assumed to be uniform since there was insufficient time to develop a parabolic profile under the conditions considered. Eq. (1) then reduces to

$$v_x \frac{\partial C_B}{\partial x} = D \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C_B}{\partial r} \right) \right] + p_B \quad (5)$$

The production term varies exponentially with time in the tube according to:

$$p_B = \lambda_{219} C_{219_1} e^{-\lambda_{219} \frac{x}{v_x}} \quad (2)$$

By introducing the dimensionless groups,

$$\psi = \frac{DC_B}{\lambda_{219} C_{219_1} R^2} \quad (6)$$

$$\eta = \frac{r}{R} \quad (7)$$

$$\mu = \frac{Dx}{v_x R^2} \quad (8)$$

Equation (5) reduces to:

$$\frac{1}{\eta} \frac{\partial}{\partial \eta} \left(\eta \frac{\partial \psi}{\partial \eta} \right) - \frac{\partial \psi}{\partial \mu} + e^{-\kappa \mu} = 0 \quad (9)$$

where

$$\kappa = \frac{\lambda_{219} R^2}{D} \quad (10)$$

and

$$\psi(1, \mu) = 0, \quad \psi(0, \eta) = 0, \quad \left. \frac{\partial \psi}{\partial \eta} \right|_{\eta=0} = 0$$

Taking the LaPlace transform with respect to μ gives:

$$\frac{1}{\eta} \frac{d}{d\eta} \eta \frac{d\psi}{d\eta} - s\psi + \frac{1}{s + \kappa} = 0 \quad (11)$$

The particular solution is:

$$\psi_p = \frac{1}{s(s + \kappa)} \quad (12)$$

and the solution to the homogeneous equation is:

$$\psi_h = k' I_0(\sqrt{s} \eta) + k'' K_0(\sqrt{s} \eta) \quad (13)$$

To satisfy $\psi(0) = \text{finite}$, k'' must be zero; to satisfy $\psi(1) = 0$,

$$k' = \frac{-1}{s(s + \kappa) I_0(\sqrt{s})} \quad (14)$$

So the complete solution to Eq. (11) is:

$$\psi = \frac{1}{s(s + \kappa)} \left[1 - \frac{I_0(\sqrt{s} \eta)}{I_0(\sqrt{s})} \right] \quad (15)$$

By expanding 0th order Bessel functions into a power series and neglecting terms of higher than order one,

$$\psi \approx \frac{1}{s(s + \kappa)} \left[1 - \frac{1 + \frac{s\eta^2}{4}}{1 + \frac{s}{4}} \right] \quad (16)$$

The inverse LaPlace transform is considerably simplified and a Heaviside expansion of ψ yields a parabolic profile:

$$\psi = \frac{1 - \eta^2}{\kappa - 4} (e^{-4\mu} - e^{-\kappa\mu}) \quad (17)$$

If we include the quadratic terms in the Bessel functions:

$$\psi = \frac{1}{s(s + \kappa)} \left[1 - \frac{1 + \frac{s\eta^2}{4} + \frac{s^2\eta^2}{64}}{1 + \frac{s}{4} + \frac{s^2}{64}} \right] \quad (18)$$

a Heaviside expansion yields:

$$\psi = k_1 \frac{1 - \eta^4}{\kappa} - 16k_2(\eta^2 - \eta^4) - 64k_3(\eta^4 - 2\eta^2 + 1) \quad (19)$$

where:

$$k_1 = 1 - e^{-\kappa\mu} \quad (20)$$

$$k_2 = \frac{1}{8\kappa} + \frac{e^{-\kappa\mu}}{(\kappa^2 - 8\kappa)} + \frac{e^{-8\mu}}{(64 - 8\kappa)} \quad (21)$$

$$k_3 = \frac{1}{64\kappa} - \frac{e^{-\kappa\mu}}{\kappa(8-\kappa)^2} + \left[\frac{\mu}{64-8\kappa} + \frac{16-\kappa}{64(\kappa-8)^2} \right] e^{-8\mu} \quad (22)$$

The survival fraction f_s is obtained by dividing the total flux by the total production:

$$f_s = \frac{\int_0^{r_0} V_x C_B 2\pi r dr}{\int_0^x \pi R^2 P_B dx} = \frac{2 \int_0^1 \psi \eta d\eta}{\int_0^\mu e^{-\kappa\mu} d\mu} \quad (23)$$

Substitution and integration gives:

$$f_s = \frac{(e^{-4\mu} - e^{-\kappa\mu})\kappa}{2(\kappa-4)(1-e^{-\kappa\mu})} \quad (24)$$

and

$$f_s = \frac{\frac{2}{3\kappa} k_1 - \frac{8}{3} k_2 - \frac{256}{3} k_3}{\frac{1}{\kappa}(1 - e^{-\kappa\mu})} \quad (25)$$

for the first- and second-order approximations, respectively.

For a 2.5-cm-diam, 50-cm-length tube, a flow rate of 6 l/min and decay of ^{219}Rn ,

$$\kappa = 5.47$$

$$\mu = 0.0785$$

and f_s values are 0.42 and 0.504 for the first- and second-order approximations, respectively.

10.2.2 Numerical Approximation

The solution to Eq. (3) can be approximated numerically by using Tan's solution (8) for a constant P_B and the Gormley-Kennedy (1) equation [Eq. (30)]. The method divides the tube into short sections for which the constant production assumption is valid and uses the Gormley-Kennedy equation to estimate the fraction of atoms produced in each segment which reaches the end of the tube. A weighted summation of the fractions yields f_s , which was calculated by D.J. Crawford to be 54%.

10.2.3 Calculation of ^{227}Ac Levels

To calculate the concentration of ^{227}Ac in the soil, an algorithm must be developed which relates the measured counts from the decay products on the second filter to the soil activity. The activity of the soil,

$$A_{227} = C_{227}W \quad (26)$$

is equal to the rate of ^{227}Ac disintegration or the rate of ^{219}Rn formation. The number of ^{219}Rn atoms escaping from the soil during the sampling period is:

$$N_{219_0} = A_{227}T f_e (3 \times 10^{-7} \text{ s}^{-1}/\text{pCi}) \quad (27)$$

where T is the sampling time and f_e is the fraction of ^{219}Rn emanating from the soil. Decay will occur during the delay time T_d before the air sample reaches the first filter, so the number of ^{219}Rn atoms entering the tube is reduced to:

$$N_{219_1} = N_{219_0} e^{-\lambda_{219}T_d} \quad (28)$$

The amount of AcB collected on the second filter is determined by the fraction of AcB which passes through the first filter ($1-f_f$), the fraction of AcB entering the tube which reaches the second filter (f'_s), the residence time in the decay tube (τ), and the fraction of AcB generated which traverses the entire tube (f_s).

From the theory of Gormley and Kennedy (1, 4), for the diffusion of particles in laminar flow in straight tubes, the deposition fraction w is given by:

$$w = 1 - 0.8191e^{-7.314h} - 0.0975e^{-44.6h} - 0.0325e^{-144h} \quad (29)$$

So,

$$f'_s = 1 - w = 0.819e^{-7.314h} + 0.0975e^{-44.6h} + 0.0325e^{-144h} \quad (30)$$

for

$$h > 0.0156, \quad h = \frac{\pi d^2}{2Q}$$

The resulting expression for the total number of AcB atoms collected on the second filter is:

$$N_{BT} = f_f \left[N_{219_1} (1 - e^{-\lambda_{219}\tau}) f_s + N_{219_0} (1 - e^{-\lambda_{219}T_d}) (1 - f_f) f'_s \right] \quad (31)$$

where f_f is the filter efficiency and f_s is the survival fraction calculated in Appendix 10.2.1.

Although the short residence time prevents the decay of AcB in the two-filter tube, AcC will form on the second filter during the sampling period. The decay of N_B and N_C is given by:

$$\frac{dN_B}{dt} = P_{ave} - \lambda_B N_B, \quad N_B(0) = 0 \quad (32)$$

and

$$\frac{dN_C}{dt} = \lambda_B N_B - \lambda_C N_C, \quad N_C(0) = 0 \quad (33)$$

where P_{ave} is the average collection rate of AcB on the filter:

$$P_{ave} = \frac{N_{BT}}{T} \quad (34)$$

Thus, the number of daughter atoms on the filter at the end of sampling, N_B^o and N_C^o , are given by:

$$N_B^o = \frac{P_{ave}}{\lambda_B} (1 - e^{-\lambda_B T}) \quad (35)$$

and

$$N_C^o = \frac{P_{ave}}{\lambda_C} (1 - e^{-\lambda_C T}) + \frac{P_{ave}}{\lambda_C - \lambda_B} (e^{-\lambda_C T} - e^{-\lambda_B T}) \quad (36)$$

The amount of daughter products on the filter is determined by measuring the decay of AcC on the alpha spectrometer. The number of counts observed X_C should be given by:

$$X_C = \int_{T_0}^{T_C} \lambda_C N_C(T) dt \quad (37)$$

where $N_C(T)$ is determined by Eq. (33) with $N_B = N_B^o e^{-\lambda_B T}$ and $N_C(0) = N_C^o$. We find

$$N_C(T) = \frac{\lambda_B N_B^0}{\lambda_C - \lambda_B} (e^{-\lambda_B T} - e^{-\lambda_C T}) + N_C^0 e^{-\lambda_C T} \quad (38)$$

Substituting into Eq. (37) and solving, we get:

$$X_C = \frac{N_B^0 \lambda_C \lambda_B}{\lambda_C - \lambda_B} \left[\left(\frac{e^{-\lambda_B T_0} - e^{-\lambda_B T_C}}{\lambda_B} \right) - \left(\frac{e^{-\lambda_C T_0} - e^{-\lambda_C T_C}}{\lambda_C} \right) \right] + N_C^0 (e^{-\lambda_C T_0} - e^{-\lambda_C T_C}) \quad (39)$$

or

$$X_C = a_1 N_B^0 + a_2 N_C^0 \quad (40)$$

For a given counting procedure, a_1 and a_2 are constants. The total counts actually measured will be:

$$X' = \epsilon (a_1 N_B^0 + a_2 N_C^0) \quad (41)$$

where ϵ is the efficiency of the alpha counter. For a specified sample weight, sampling time, counting times, and emanation fraction, we can compute the concentration of ^{227}Ac if the number of counts and the counting efficiency are known.

10.3 Description of Proposed Apparatus

10.3.1 Laboratory

A block flow diagram of the proposed laboratory design is shown in Fig. 8. The pump does not have to be of any particular style, but the flow rate of the air must be variable. The flow should also be in a control loop to maintain constant flow rate.

The air flows through a humidifier and dryer in parallel. Control values on both devices allow the humidity to be varied. A bubbler would be an adequate humidifier, while the dryer must be able to reduce the humidity to below 1%. The Laboratory Gas Drying Unit containing 1.25 lb of 8-mesh Drierite (anhydrous CaSO_4) was adequate in the experiments.

The conditioned air passed through the sample chamber in nonfluidizing flow. The sample chamber needs to be about 25 cm in diameter and about 5-cm high to hold a 1-kg soil sample. The bed depth is about 1.25 cm for this unusually large sample. The soil should be held in

place by large diameter filter paper. The gas stream then flows through a short tube (approximately 15-cm-long and 1-cm-ID) to reduce dead volume.

The two-filter tube should be 50-cm long with a 3.25-cm ID and a flow rate of 6000 cm³/min. The expected residence time is about 4 s or one half-life of ²¹⁹Rn. The Reynolds number of the gas is approximately 600, so the flow is laminar.

The sample filters (0.45- μ m pores) are to be placed at both ends of the tube, and must be easily and quickly removable to avoid errors in the counting procedure. Two two-filter tubes have been included so that gas can be circulated through one of them and switched to the other when a measurement is desired. The exiting gas passes through a standard gas-mask charcoal canister to absorb the remaining ²¹⁹Rn before being either vented or recirculated back to the pump. The type of tubing connecting the device is not important, but Swagelok or similar fittings are desired for ease of construction and modification.

10.3.2 Field

The proposed field apparatus is considerably simpler than the laboratory apparatus (see Fig. 1). The pump, drum, dryer, venting, valving, and two-filter tubes should remain unaltered, while the humidifier and one two-filter tube should be eliminated. The entire apparatus should be constructed on a mobile frame to permit sampling in the field.

10.4 Proposed Field Procedure

Soil samples from the site of interest, weighing approximately 400 g, will be taken, dried overnight in a 110°C oven, ground to less than 30 mesh, and stored in a desiccator. Three hundred grams of the prepared soil will be put in the drum between two large-pore filter papers (Whatman #41 ashless or equivalent). Pumping time will be 30 min at 5 to 6 l/min; air entering the sample chamber will be at less than 1% relative humidity. The two-filter tube will be fitted on either end with Gelman Metrical DM-450 filters. The standard 30-min counting procedure outlined elsewhere will be used.

10.5 Summary of Data and Results

10.5.1 Emanation Fractions

Emanation fractions were calculated for two different apparatuses for different soil samples. For the drum apparatus (Fig. 2) the emanation fractions appear in Table 1.

Table 1. Emanation Fractions for Drum Apparatus

<u>Soil Sample</u>	<u>Counts</u>	<u>ϵ</u>	<u>Date</u>	<u>Time</u>	<u>Equili- bration Time (min)</u>	<u>Emanation Fraction</u>
BV01.1	60,621	0.24	9/11	1:43 pm	113	0.101
.2	67,028	0.27	9/11	3:01 pm	78	0.114
.3	34,374	0.27	9/12	9:34 am	~1000	0.045
.4	133,767	0.27	9/12	2:08 pm	158	0.186
.5	57,134	0.27	9/12	3:38 pm	98	0.091
.6	18,003	0.27	9/13	1:40 pm	578	0.024
.7	12,786	0.27	9/14	9:27 am	~1000	0.017
						$\bar{f}_e = 0.082$
						$\sigma_n = 0.055$
BV02.1	58,718	0.27	9/14	2:32 pm	202	0.425
.2	13,574	0.27	9/15	11:28 am	1200	0.097
.3	26,372	0.27	9/15	1:30 pm	122	0.215
.4	27,812	0.27	9/15	3:01 pm	91	0.246
.5	3,750	0.27	9/17	10:24 am	2600	0.027
						$\bar{f}_e = 0.262$
						$\sigma_n = 0.137$

For the flow-through apparatus, the emanation fractions are given in Table 2. The size of the soil samples and their concentrations are presented in Table 3.

Table 3. Activity of Soil Samples

<u>Soil Sample</u>	<u>Weight (g)</u>	<u>C₂₂₇ (pCi/g)</u>
BV01	91.9	23,701
BV02	52.6	7,567
VCC17A	104.0	10.8

10.5.2 Charcoal Filter Tests

The data used to calculate the charcoal-filter efficiency (f_c) are presented in Table 4.

Table 4. Test Results With and Without Charcoal Filter

<u>Without Filter</u>			
<u>Charcoal Test</u>	<u>Counts Measured on Sample Filter</u>	<u>ϵ</u>	<u>Corrected Count*</u>
1	487	0.27	482
2	263	0.27	258
3	485	0.27	480
6	702	0.27	697
7	249	0.27	244
8	372	0.27	367
			$\bar{x} = 422$
			$\sigma_n = 155$
<u>With Filter</u>			
1	8	0.27	3
2	5	0.27	0
			$\bar{x} = 2$
			$\sigma_n = 1.5$

*The corrected counts are the counts measured minus the background of ~5 counts/10-min period.

Table 2. Emanation Fractions for Flow-Through Apparatus

Soil Sample	Run Number	Atoms Entering Tube	h	f'_s	AcB Atoms Collected	Amount on Filter at End of Sampling Run		f_e
			Eq. (30)	Eq. (30)		NB	Nc	
BV01	Long Flow 1	1.14×10^7	0.034	0.337	3.53×10^6	2.68×10^6	1.45×10^5	0.153
	2	1.12×10^7	0.034	0.341	3.48×10^6	2.65×10^6	1.44×10^5	0.119
	3	1.08×10^7	0.037	0.356	3.41×10^6	2.59×10^6	1.41×10^5	0.130
								$\bar{f}_e = 0.134$
								$\sigma_n = 0.01$
VCC17A	Weak Dryer 4	2.53×10^4	0.043	0.389	7.28×10^3	5.95×10^3	3.23×10^2	0.202
	5	2.56×10^4	0.043	0.386	7.34×10^3	5.58×10^3	3.03×10^2	0.147
	6	2.41×10^4	0.045	0.399	6.96×10^3	5.29×10^3	2.87×10^2	0.202
	7	2.51×10^4	0.044	0.390	7.22×10^3	5.49×10^3	3.20×10^2	0.155
								$\bar{f}_e = 0.176$
								$\sigma_n = 0.026$

The efficiency of the charcoal filter is:

$$f_c = \frac{\text{counts without filter} - \text{counts with filter}}{\text{counts without filter}} = \frac{422 - 2}{422} = 99.6\%$$

10.5.3 Sample Filter Tests

The data for the determination of the sample filter efficiency are presented in Table 5.

Table 5. Sample Filter Data

Three Filter Test	Counts Upstream Sample Filter	Counts Downstream Sample Filter	Adjusted Counts (Upstream) [*]	Adjusted Counts (Downstream)	f_f (%)
1 (600-s count)	157	17	564	53	90.6
2 (600-s count)	64	14	219	41	
(1750-s count)	173	20	589	32	94.6
3 (600-s count)	79	8	275	16	
(1680-s count)	200	22	692	42	<u>93.9</u>
					$\bar{x} = 93$
					$\sigma_n = 2$

* Adjusted count = $\frac{\text{measured counts} - \text{background}}{\epsilon}$ where ϵ is 0.27 and 0.24 for the measurements on the upstream and downstream filters, respectively.

10.6 Sample Calculations

10.6.1 Emanation-Fraction Determination (f_e)

For fraction test 1, using the 17-liter drum and soil sample BV01, we can calculate the activity A of ^{227}Ac and ^{219}Rn .

$$A_{219} = 23,701 \text{ pCi/g} \times 91.9 \text{ g} = 2.178 \times 10^6 \text{ pCi}$$

The expected concentration of ^{219}Rn is

$$C_{219} = f_e \frac{A}{V_c} = f_e \frac{2.178 \times 10^6 \text{ pCi}}{17 \text{ l}} = (1.28 \times 10^5 \text{ pCi/l}) f_e$$

However, the airborne concentrations of AcB and AcC may not have reached equilibrium. From Fig. 10 and the known equilibration time of 113 min, we see AcC and AcB concentrations have reached 82% of the ^{219}Rn activity:

$$C_B = C_C = (1.28 \times 10^5 \text{ pCi/l}) f_e (0.82) = (1.05 \times 10^5 \text{ pCi/l}) f_e$$

Since these daughters tend to migrate to the walls of the drum, a correction factor of the form $\lambda/(\lambda + \lambda_d)$, where λ_d is the half-life of depletion due to diffusion, must be introduced. The expression for λ_d , obtained from Jacobi (2) is:

$$\lambda_d = \frac{F}{V_c} [U_d^f P_f + U_d^a P_a]$$

where F/V_c is the surface-to-volume ratio of the drum, U_d is the deposition velocity of daughter products, and P is the percent of daughter products either attached to aerosols (P_a) or free (P_f).

Substituting the appropriate values (obtained from D.J. Crawford) gives:

$$\begin{aligned} \lambda_d &= \frac{3662 \text{ cm}^2}{17,000 \text{ cm}^3} [(1 \text{ cm/s})(0.01) + (10^{-2} \text{ cm/s})(0.99)] \\ &= 0.0043 \text{ s}^{-1} = 0.26 \text{ min}^{-1} \end{aligned}$$

Hence,

$$C_B = f_e (1.05 \times 10^5 \text{ pCi/l}) \left(\frac{0.0192 \text{ min}^{-1}}{0.0192 + 0.26 \text{ min}^{-1}} \right) = 7220 f_e \text{ pCi/l}$$

$$\begin{aligned} C_C &= f_e C_B \left(\frac{\lambda_C}{\lambda_C + \lambda_d} \right) = f_e (7220 \text{ pCi/l}) \left(\frac{0.3254 \text{ min}^{-1}}{0.3254 + 0.26 \text{ min}^{-1}} \right) \\ &= 4013 f_e \text{ pCi/l} \end{aligned}$$

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GROWTH OF ^{219}Rn DECAY PRODUCTS

DATE 9-26-79	DRAWN BY BAR	FILE NO. CEPS-X-299	FIG. 10
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Since $N_i = \frac{C_i V_i}{\lambda_i}$,

$$N_B = \frac{(7220 \text{ f}_e \text{ pCi/l})(17 \text{ l})(3.7 \times 10^{-2} \text{ s}^{-1}/\text{pCi})}{0.0192 \text{ min}^{-1})(\frac{1}{60} \text{ min/s})} = 1.419 \times 10^7 \text{ f}_e$$

Similarly,

$$N_C = 4.654 \times 10^5 \text{ f}_e$$

The number of counts measured will be:

$$X = \epsilon[a_1 N_B + a_2 N_C]$$

where X is the number of counts = 60,621, ϵ is the efficiency of alpha spectrometer, and a_1 and a_2 are derived in Appendix 10.2.3. f_e is solved:

$$\begin{aligned} \text{f}_e &= \frac{X}{\epsilon(a_1 N_B + a_2 N_C)} = \frac{60,621}{(0.24)[(0.147)(1.419 \times 10^7) + (0.501)(4.654 \times 10^5)]} \\ &= 0.109 \end{aligned}$$

The emanation fraction can also be calculated from the two-filter tube tests on sample BV02:

$$A_{219} = 7567 \text{ pCi/g (52.6 g)} = 3.98 \times 10^5 \text{ pCi}$$

The total production of ^{219}Rn during the sampling time T is:

$$\begin{aligned} N_{219} &= A_{219} T(3.7 \times 10^{-2} \text{ s}^{-1}/\text{pCi}) \\ &= (3.98 \times 10^5)(1800 \text{ s})(3.7 \times 10^{-2} \text{ s}^{-1}/\text{pCi}) \\ &= 2.651 \times 10^7 \end{aligned}$$

A fraction f_e of this is actually emitted to the surrounding gas stream, and the radon decays before reaching the two-filter tube. The amount of ^{219}Rn entering the tube is:

$$N_{219_1} = f_e N_{219} e^{-\lambda_{219} T_d}$$

where T_d is the delay time before the decay tube:

$$T_d = \frac{V_d}{Q} = \frac{(562 \text{ cm}^3)(60 \text{ s/min})}{7100 \text{ cm}^3/\text{min}} = 4.75 \text{ s}$$

Thus:

$$N_{219_1} = f_e (2.651 \times 10^7) [\exp^{-(0.175 \text{ s}^{-1})(4.75 \text{ s})}] = 1.155 \times 10^7 f_e$$

As this radon transits the tube, some of it decays and the daughter products diffuse to the walls. The daughter products reaching the second filter as a result are:

$$N_{B1} = N_{219_1} (1 - e^{-\lambda_{219} \tau}) f_s$$

where τ is the residence time in the decay tube and f_s is the survival fraction of the decay products, 0.50 (Appendices 10.2.1 - 10.2.2). Since the first filter does not remove all the daughter products produced upstream, the amount traversing the tube is:

$$N_{B2} = f_e N_{219} (1 - e^{-\lambda_{219} T_d}) f'_s (1 - f_f)$$

where $f_f = 0.93$ and $f'_s = 0.6316$, as given by Eq. (30). Thus the total number of daughter atoms reaching the filter N_{Bf} is

$$\begin{aligned} N_{Bf} &= N_{B1} + N_{B2} = f_e (1.155 \times 10^7) (1 - e^{-(0.175 \text{ s}^{-1})(3.96 \text{ s})}) (0.504) \\ &\quad + f_e (2.651 \times 10^7) (1 - e^{-(0.175 \text{ s}^{-1})(4.75 \text{ s})}) (0.6316) (0.07) \\ &= 3.572 \times 10^6 f_e \end{aligned}$$

Ninety-three percent of this value is collected on the sample filter, so

$$N_{BT} = 3.322 \times 10^6 f_e$$

From Appendix 10.2.3 we can calculate N_B^o and N_C^o :

$$\begin{aligned} N_B^o &= \frac{N_{BT}}{T\lambda_B} (1 - e^{-\lambda_B T}) = \frac{3.322 \times 10^6 f_e}{30 \text{ min}(0.0192 \text{ min}^{-1})} \\ &\quad \times [1 - e^{-(0.0192 \text{ min}^{-1})(30 \text{ min})}] \\ &= 2.525 \times 10^6 f_e \\ N_C^o &= \frac{N_{BT}}{T} \left[\frac{1 - e^{-\lambda_C T}}{\lambda_C} + \frac{e^{-\lambda_C T} - e^{-\lambda_B T}}{\lambda_C - \lambda_B} \right] = \frac{3.322 \times 10^6 f_e}{30 \text{ min}} \text{ times} \\ &\quad \left[\frac{[1 - e^{-(0.3254 \text{ min}^{-1})(30 \text{ min})}]}{0.3254 \text{ min}^{-1}} + \right. \\ &\quad \left. \frac{[e^{-(0.3254 \text{ min}^{-1})(30 \text{ min})} - e^{-(0.0192 \text{ min}^{-1})(30 \text{ min})}]}{0.3254 \text{ min}^{-1} - 0.0192 \text{ min}^{-1}} \right] \\ &= 1.370 \times 10^5 f_e \end{aligned}$$

From Appendix 10.2.3 the total number of counts, X , is:

$$X = (a_1 N_B^o + a_2 N_C^o) \epsilon$$

or

$$28,816 = 0.24[(0.4151)(2.52 \times 10^6 f_e) + (0.5216)(1.37 \times 10^5 f_e)]$$

Solving for f_e gives $f_e = 0.108$.

10.6.2 Filter Efficiency

The number of counts on a filter is proportional to

$$X_1 = (C_CQT)f_f$$

where Q is volumetric flow rate and T is sample time. The number of counts from an adjacent downstream filter would be

$$X_2 = (1 - f_f)(C_CQT)f_f$$

So,

$$\frac{X_1 + X_2}{X_1} = \frac{[C_CQT]f_f + f_f(1 - f_f)[C_CQT]}{(C_CQT)f_f} = 1 + (1 - f_f) = 2 - f_f$$

For three-filter test No. 1,

$$f_f = 2 - \frac{564 + 53}{564} = 90.6\%$$

10.6.3 Charcoal Filter

The efficiency of the charcoal filter is given by:

$$f_c = \left(\frac{\text{unfiltered counts} - \text{filtered counts}}{\text{unfiltered counts}} \right) (100)$$

Calculating the average efficiency gives:

$$f_c = \left(\frac{422}{422 + 2} \right) (100) = 99.5\%$$

10.6.4 Theoretical Counts vs Soil Concentration

From an assumed value of 15% for the emanation fraction, the concentration of ^{227}Ac in soil can be calculated.

$$\text{counts} = X' = \epsilon[a_1 N_B^0 + a_2 N_C^0]$$

$$N_B^0 = N_{BT}(0.76017)$$

$$N_C^0 = N_{BT}(0.04124)$$

$$N_{BT} = f_f[N_{2191}(1 - e^{-\lambda_{219}\tau})f_s + N_{2190}(1 - e^{-\lambda_{219}T_d})(1 - f_f)f'_s]$$

$$N_{2191} = N_{219}^0(e^{-\lambda_{219}T_d})$$

$$N_{219}^0 = A_{227}f_e T(3.7 \times 10^{-2} \text{ s}^{-1})$$

$$A_{227} = C_{227} W$$

where:

$$\epsilon = 0.24$$

$$a_1 = 0.41507$$

$$a_2 = 0.52157$$

$$f_f = 0.93$$

$$\lambda_{219} = 0.175 \text{ s}^{-1} = 0.0192 \text{ min}^{-1}$$

$$\tau = 3.96 \text{ s}$$

$$f_s = 0.504$$

$$T_d = 4.75 \text{ s}$$

$$f'_s = 0.6316$$

$$f_e = 0.15$$

$$T = 30 \text{ min} = 1800 \text{ s}$$

$$C_{227} = \text{activity of soil, pCi/g}$$

W = soil sample weight, g

So,

$$\begin{aligned}\frac{X'}{W} &= \frac{\text{counts}}{g} = 0.0809 \frac{N_{BT}}{W} = 0.0379 N_{219_1} + 0.00187 N_{219_0} \\ &= 0.0184 N_{219_0} = (1.223)f_e C_{227}\end{aligned}$$

So for f_e of 0.15,

$$\frac{X'}{W}(g^{-1}) = 0.1838 C_{227}$$

where C_{227} is in pCi/g.

10.7 Nomenclature

A_i	activity of species i , pCi
a_1	constant defined in Eqs. (39) and (40)
a_2	constant defined in Eqs. (39) and (40)
C_i	concentration of species i , pCi/l or pCi/g
C_{219}	concentration of radon, pCi/l or pCi/g
D	diffusivity of ^{219}Rn
F	surface area of drum, cm^2
f_c	efficiency of charcoal filter
f_e	emanation fraction of ^{219}Rn from soil
f_f	efficiency of sample filter for capture of ^{219}Rn daughters
f_s	survival fraction, fraction of daughter products produced in decay tube arriving at second filter
f'_s	modified survival fraction, fraction of daughters passing through first filter which arrive at second filter
h	dimensionless parameter in Gormley-Kennedy equation [Eq. (29)]

I_0, K_0	Bessel functions
k', k''	constants appearing in Eq. (13)
k_1, k_2, k_3	see Eqs. (20) through (22)
z	length of two-filter tube, cm
N_B	number of AcB atoms
N_C	number of AcC atoms
N_{Bf}	number of daughter atoms reaching second filter
N_{BT}	number of daughter atoms collected on second filter
N_{219}	number of ^{219}Rn atoms produced in soil sample
N_{219_0}	number of ^{219}Rn atoms escaping from soil sample
N_{219_1}	number of ^{219}Rn atoms entering two-filter tube
N_B^0	number of AcB atoms on sample filter at end of sampling period
N_C^0	number of AcC atoms on sample filter at end of sampling period
$P_{a,f}$	percentage of particles attached to aerosols or free
P_B	production rate of AcB in two-filter tube, $\text{s}^{-1}\text{cm}^{-3}$
P_{ave}	average collection rate of AcB, s^{-1}
Q	volumetric flow rate in tube, cm^3/s
r	radial coordinate, cm
R	radius of two-filter tube, cm
s	Laplace transform variable with respect to μ
T	length of sampling time, min
T	time, s
T_0	time between end of sampling and beginning of counting, s or min
T_c	time between end of sampling and end of counting, s or min
T_d	residence time between sample chamber and two-filter tube, s or min
U_d^a	deposition velocity of daughter products which are attached to aerosol particles, cm/s

U_d^f	deposition velocity of daughter products which are unattached, cm/s
V	linear velocity in tube, cm/s
V_C	volume of drum in emanation fraction studies, cm^3
V_d	dead volume downstream of soil sample, cm^3
v_r	radial velocity, cm/s
v_x	axial velocity, cm/s
W	weight of soil sample, g
w	Gormley-Kennedy deposition fraction [Eq. (29)]
x	axial coordinate, cm
X	measured counts on alpha spectrometer for emanation fraction test
X'	measured counts on alpha spectrometer for second filter test
X_C	counts due to disintegration of AcC
X_j	counts on j^{th} filter

Greek Symbols

ϵ	efficiency of alpha spectrometer
η	dimensionless radial coordinate
κ	$\lambda_{219} R^2/D$, dimensionless
λ_d	rate constant for deposition of daughter products, s^{-1}
λ_i	exponential decay constant of species i , s^{-1}
μ	dimensionless axial coordinate, $DX/(V_x R^2)$
σ_n	standard deviation
τ	residence time in two-filter tube, s
ψ	dimensionless concentration, $DC_B/(\lambda_{219} C_{219_0} R^2)$
ψ	dimensionless transformed concentration

Subscripts

219 radon-219

227	actinium-227
0	drum
1	entrance of first filter
B	actinium-B
C	actinium-C
h	homogeneous solutions to second-order ordinary differential equations
p	particular solutions to second-order ordinary differential equations

10.8 Location of Original Data

The data are located in ORNL Databook A-8259-G, pp. 66-69, on file at the MIT School of Chemical Engineering Practice, Bldg. 1505, ORNL.

10.9 Literature References

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