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# The Extent of Radioactive Equilibrium Between Radon and Its Short-Lived Daughter Products in the Atmosphere

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A set of experimental conditions has been derived which optimizes the accuracy with which the radon content of the atmosphere and its apparent residence time there can be determined from measurement of the filterable gross $\beta$ activity during two separate 10-minute periods following the end of a 20-minute collection period.

The 20-minute collection is made on a filter of essentially 100% retentivity (glass fiber filter) and counted for $\beta$ activity through a 10-mil (70. mg/cm$^2$) aluminum absorber on equipment of known efficiency for the $\beta$ particles emitted by RaB and RaC. The ratio of measured counts during the 61-through-71-minute decay period to that during the 1-through-11-minute period is employed to obtain the atom ratio of RaC to RaB ($\rho$) in the air sampled, the apparent age ($\tau$) of the conglomerate of radon and its daughters, and the total counts to be expected from any given radon concentration in the air.

Extensive examples of atmospheric measurements are given which suggest that under most conditions in the free atmosphere radon is essentially at secular equilibrium with its daughter products. Other collections made following addition of radon to a restricted volume show the expected increase in $\rho$ with time, which confirms the basic validity of the procedure.

## INTRODUCTION

In a previous report (1) it was shown that the radon concentration of the atmosphere could be deduced from measurement of its short-lived decay products by their collection on a filter for a fixed period of time followed by $\beta$-activity measurements during two subsequent periods. In addition to the usual errors associated with air flow measurements and counter calibrations, two sources of error either could not be controlled or were unresolved: the large statistical error inherent in any counting process when a limited number of random events occur and the uncertainty in evaluating the counting efficiency for the conversion electrons emitted by RaB ($Pb^{214}$) and RaC ($Bi^{214}$). The radon present in the air sample, moreover, was assumed to have resulted from an instantaneous emission of radon gas from the soil; this was, of course, an obvious oversimplification.

This report considers means of optimizing the accuracy and sensitivity of this method by determining those counting conditions which reduce the effect of the conversion electrons and their uncertain calibration and which also permit the greatest sensitivity in the determination of concentration and age from $\beta$-activity measurements made during two fixed decay periods.

NRL Problem A02-13; Projects RR 004-02-42-5151 and AEC AT 49-7(2435). This is an interim report; work on this problem is continuing. Manuscript submitted November 9, 1965.

## THEORETICAL CONSIDERATIONS

The growth of radon daughter products in the atmosphere from a fresh radon source, their growth and decay on a filter during a subsequent 20-minute period of air filtration, and the radioactivity decay relationships between the solid daughter products collected on the filter were presented in the previous report (1). These data have been revised and extended to permit interpretation of the apparent radon age in terms of its continuous emission from the soil rather than its instantaneous emission. A summary of this extension of information is given in Table 1.

Plots of the RaC/RaB atom ratios ($\rho$) as functions of elapsed time are shown in Fig. 1 for the conditions of instantaneous and continuous addition of radon to the atmosphere. It is evident that the higher $\rho$ values will represent a much longer time of growth of the radon daughters when interpreted in terms of the constant introduction of fresh radon. Similarly, the radon/RaB activity

TABLE 1
Growth of Radon Daughters in a Fixed Volume of Air on Addition of Radon at the Rate of $10^4$ Atoms per Minute

| Elapsed Time (min) | Atoms | | | | Activity (dis/min) | | Atom Ratio RaC/RaB ($\rho$) | Activity Ratio Rn/RaB |
|---|---|---|---|---|---|---|---|---|
| | Rn* | RaA | RaB | RaC | Rn | RaB | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | — | — |
| 10 | 100,000 | 36.0 | 30.8 | 2.2 | 12.66 | 0.71 | 0.071 | 17.9 |
| 20 | 200,000 | 89.7 | 150.5 | 20.5 | 25.33 | 3.70 | 0.136 | 6.85 |
| 30 | 300,000 | 145.0 | 352.3 | 69.3 | 37.99 | 8.82 | 0.197 | 4.31 |
| 40 | 400,000 | 200.4 | 618.7 | 155.3 | 50.66 | 15.58 | 0.251 | 3.25 |
| 50 | 500,000 | 255.7 | 935.2 | 279.9 | 63.32 | 23.71 | 0.299 | 2.67 |
| 60 | 600,000 | 311.1 | 1290.4 | 441.2 | 75.98 | 32.85 | 0.342 | 2.31 |
| 70 | 700,000 | 366.5 | 1675.4 | 635.5 | 88.65 | 42.76 | 0.379 | 2.07 |
| 80 | 800,000 | 421.8 | 2083.5 | 858.8 | 101.31 | 53.28 | 0.412 | 1.901 |
| 90 | 900,000 | 477.2 | 2509.4 | 1106.9 | 113.98 | 64.27 | 0.441 | 1.773 |
| 100 | 1,000,000 | 532.6 | 2949.0 | 1375.9 | 126.64 | 75.62 | 0.467 | 1.675 |
| 110 | 1,100,000 | 588.0 | 3399.3 | 1662.0 | 139.30 | 87.24 | 0.489 | 1.597 |
| 120 | 1,200,000 | 643.3 | 3857.9 | 1962.3 | 151.97 | 99.08 | 0.509 | 1.534 |
| 130 | 1,300,000 | 698.7 | 4322.8 | 2274.1 | 164.63 | 111.09 | 0.526 | 1.482 |
| 140 | 1,400,000 | 754.1 | 4792.5 | 2595.2 | 177.30 | 123.22 | 0.542 | 1.439 |
| 150 | 1,500,000 | 809.5 | 5266.1 | 2923.8 | 189.96 | 135.45 | 0.555 | 1.402 |
| 160 | 1,600,000 | 864.9 | 5742.6 | 3258.3 | 202.62 | 147.77 | 0.567 | 1.371 |
| 170 | 1,700,000 | 920.3 | 6221.3 | 3597.7 | 215.29 | 160.14 | 0.578 | 1.344 |
| 180 | 1,800,000 | 975.7 | 6701.8 | 3940.8 | 227.95 | 172.54 | 0.588 | 1.321 |

*The small amount of radon decay has been neglected.

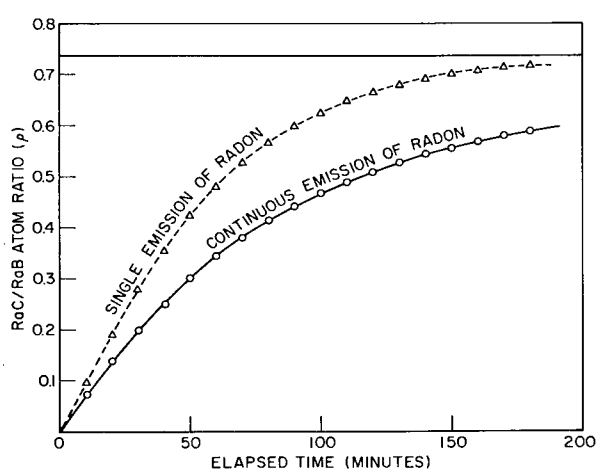


Fig. 1 — Change in the RaC to RaB atom ratio ($\rho$) with the age of the radon conglomerate after exhalation of radon gas from the earth

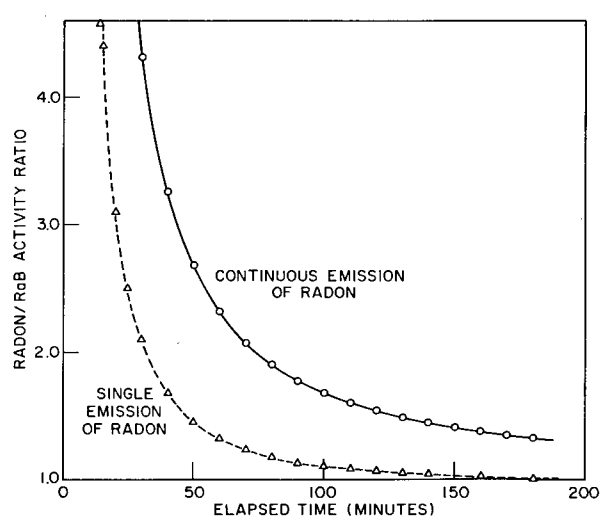


Fig. 2 — Change in the radon to RaB activity ratio with the age of the radon conglomerate

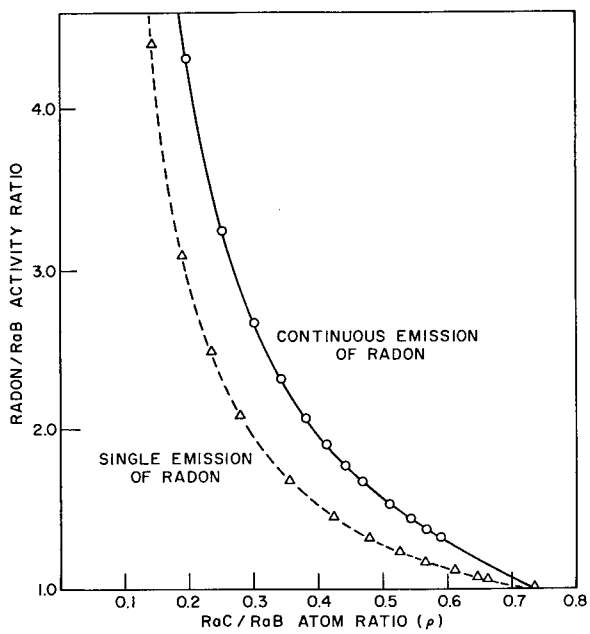


Fig. 3 — Relationship between the radon/RaB activity ratio and the RaC/RaB atom ratio ($\rho$) for the conditions of instantaneous and continuous emission of radon from the soil. These curves are obtained by combining the data of Figs. 1 and 2.

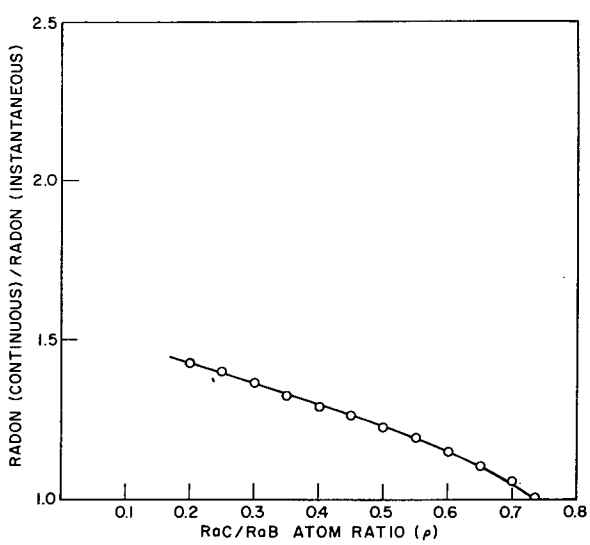


Fig. 4 — Relative radon concentrations in the air under conditions of single and continuous radon influx required to produce identical quantities of radon daughter products. The values plotted are obtained by direct comparison of the curves in Fig. 3.

ratio is quite different for the two conditions, as shown in Fig. 2. The time parameter is removed from consideration in Fig. 3 by comparing directly the radon/RaB activity ratio with the RaC/RaB atom ratio ($\rho$), wherein smooth curves are obtained which intercept the $\rho$ axis at 0.735 for the equilibrium condition corresponding to infinite time.

Interconversion of the single emission and continuous emission conditions can be obtained from the plot in Fig. 4, where the relative radon concentrations in the air required to give the same $\beta$ activity on a filter are shown as a function of the measured $\rho$ value obtainable from the same filter.

## EXPERIMENTAL PROCEDURE

### Air Sampling

Airborne particulate matter and associated radioactivity have been effectively collected on glass fiber filters having an exposed area of about 25 cm$^2$ through use of positive displacement blowers (Roots-Connersville Models AF-24 or AF-315) driven by 1-hp electric motors. Glass fiber filters have essentially 100% retentivity for the radon decay products at the air velocity employed (2) and, moreover, are essentially surface collectors; furthermore, no retention of the gaseous radon by filters has been detected. In this study Gelman Type A filters were employed with the fairly smooth, screen-imprinted back surface used as the collecting surface to reduce the effect of self-absorption of radiation by the filter.

The quantity of dust collected during the 20-minute periods did not measurably affect the air flow (between 0.42 and 0.52 m$^3$/min, depending on the unit), though on occasion a definite imprint of the dust was apparent. The air sampling equipment was calibrated against a rotameter-type flow meter as a function of pressure drop across the filter; flow was determined from pressure readings taken at the start and the end of the run.

After the accurately timed 20-minute collection period, the samples were transferred to other holders and counting was started 60 seconds following termination of the collection.

### Radioactivity Measurements

All radioactivity determinations were made under conditions of standard geometry and

backscattering with lead-shielded, end-window G-M tubes of 5.6-mg/cm² window thickness using conventional $\beta$-counting equipment. Counting was timed and recorded by use of Ametron Count Recorders (Streeter-Amet) which had been modified to operate on a 10-minute cycle.

The equipment was calibrated as described in the previous report (1) by use of standards of $Cs^{137}$, $Pb^{210}$ ($Bi^{210}$), and $UX_2$ prepared to simulate as nearly as possible the filter size and arrangement. Typical calibration data are shown in Fig. 5; counting was done through a series of aluminum absorbers to determine the most appropriate system to use in subsequent measurements of RaB and RaC. The efficiency of the equipment toward these radon daughters is shown in Table 2 for the various absorber arrangements.

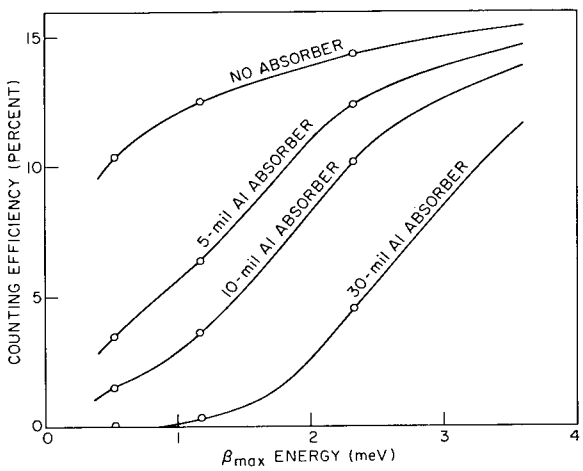


Fig. 5 — Counter calibration curves as a function of $\beta_{max}$ energy and absorber thickness

The accumulated counts to be expected following the filtration of air samples containing 100 picocuries (pCi) of radon per m³ for 20 min at the rate of 1 m³ per min are given in Table 3 for the 10-min periods starting at 1 min and at 61 min following the termination of filtration for different values of $\rho$ and for different absorber thicknesses. The choice of these two time intervals was made on the basis of the sensitivity of the resulting count rate ratio to changes in $\rho$, as described in the previous report (1). The indicated count ratios during the two fixed time periods ($t_{1\text{-}11}$ and $t_{61\text{-}71}$) have been employed to construct curves for translating measured ratios and total counts into $\rho$ values and radon concentrations, as shown in Figs. 6 and 7, respectively. The radon concentration so determined is that which would have resulted from a single, instantaneous emission of radon from the soil; the radon value corresponding to the steady emission of radon can be found by adjusting the above value by a factor obtainable from Fig. 4.

The greatest sensitivity in the determination of $\rho$ is obtained when a 30-mil aluminum absorber is employed, since this effectively stops all radiation except that associated with the RaC component. On the other hand the counting rates are low with resulting increased statistical uncertainty in

TABLE 2

Efficiency of $\beta$ Counting Equipment Toward RaB and RaC Deposited on a Glass Fiber Filter

| Activity | $\beta_{max}$ Energy (MeV) | Counting Efficiency From Fig. 5 and After Estimated Correction for the Effect of Conversion Electrons (%) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No Absorber | | 5-mil Al Absorber | | 10-mil Al Absorber | | 30-mil Al Absorber | |
| | | From Graph | After Corr. | From Graph | After Corr. | From Graph | After Corr. | From Graph | After Corr. |
| RaB ($Pb^{214}$) | 0.65 (100%) (25% low-energy conversion electrons) | 10.90 | 13.63 | 4.10 | 4.51 | 1.82 | 1.87 | 0.0 | 0.0 |
| RaC ($Bi^{214}$) | 3.17 (23%) 1.65 (77%) (5% high-energy conversion electrons) | 13.79 | 14.48 | 10.17 | 10.68 | 7.75 | 8.14 | 3.06 | 3.21 |

TABLE 3
Calculated $\beta$ Counts Obtainable From 20-Minute Collections of Radon Daughters on Glass Fiber Filters for a Radon Concentration of 100 pCi/m³ and a Filtration Rate of 1 m³/min

| | Disintegrations During 10-Minute Periods | | Total Counts During 10-Minute Periods | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | No Absorber | | 5-mil Absorber | | 10-mil Absorber | | 30-mil Absorber | |
| | $t_{1\text{-}11}$ | $t_{61\text{-}71}$ | $t_{1\text{-}11}$ | $t_{61\text{-}71}$ | $t_{1\text{-}11}$ | $t_{61\text{-}71}$ | $t_{1\text{-}11}$ | $t_{61\text{-}71}$ | $t_{1\text{-}11}$ | $t_{61\text{-}71}$ |
| $\rho = 0.048$ | | | | | | | | | | |
| RaB | 3798 | 864 | 518 | 118 | 171 | 39 | 71 | 16 | 0 | 0 |
| RaC | 1687 | 1594 | 244 | 231 | 180 | 170 | 137 | 130 | 54 | 51 |
| Total | 5485 | 2458 | 762 | 349 | 351 | 209 | 208 | 146 | 54 | 51 |
| Ratio ($t_{61\text{-}71}/t_{1\text{-}11}$) | 0.448 | | 0.458 | | 0.595 | | 0.702 | | 0.945 | |
| $\rho = 0.190$ | | | | | | | | | | |
| RaB | 13170 | 2879 | 1795 | 392 | 594 | 130 | 246 | 54 | 0 | 0 |
| RaC | 8233 | 5640 | 1192 | 817 | 879 | 602 | 670 | 459 | 264 | 181 |
| Total | 21403 | 8519 | 2987 | 1209 | 1473 | 732 | 916 | 513 | 264 | 181 |
| Ratio ($t_{61\text{-}71}/t_{1\text{-}11}$) | 0.398 | | 0.405 | | 0.497 | | 0.560 | | 0.685 | |
| $\rho = 0.390$ | | | | | | | | | | |
| RaB | 22700 | 4903 | 3094 | 668 | 1024 | 221 | 424 | 92 | 0 | 0 |
| RaC | 19562 | 10279 | 2833 | 1488 | 2089 | 1098 | 1592 | 837 | 628 | 330 |
| Total | 42262 | 15182 | 5927 | 2156 | 3113 | 1319 | 2016 | 929 | 628 | 330 |
| Ratio ($t_{61\text{-}71}/t_{1\text{-}11}$) | 0.359 | | 0.364 | | 0.424 | | 0.461 | | 0.525 | |
| $\rho = 0.564$ | | | | | | | | | | |
| RaB | 28946 | 6227 | 3945 | 849 | 1305 | 281 | 541 | 116 | 0 | 0 |
| RaC | 30758 | 13775 | 4454 | 1995 | 3285 | 1471 | 2504 | 1121 | 987 | 442 |
| Total | 59704 | 20002 | 8399 | 2844 | 4590 | 1752 | 3045 | 1237 | 987 | 442 |
| Ratio ($t_{61\text{-}71}/t_{1\text{-}11}$) | 0.335 | | 0.339 | | 0.382 | | 0.406 | | 0.448 | |
| $\rho = 0.735$ | | | | | | | | | | |
| RaB | 33221 | 7136 | 4528 | 973 | 1498 | 322 | 621 | 133 | 0 | 0 |
| RaC | 41689 | 16562 | 6037 | 2398 | 4452 | 1769 | 3393 | 1348 | 1338 | 532 |
| Total | 74910 | 23698 | 10565 | 3371 | 5950 | 2091 | 4014 | 1481 | 1338 | 532 |
| Ratio ($t_{61\text{-}71}/t_{1\text{-}11}$) | 0.316 | | 0.319 | | 0.351 | | 0.369 | | 0.397 | |

the true values. With no absorption except for that inherent in the counting tube window, maximum count rates are obtained but also decreased sensitivity results because both RaB and RaC are counted simultaneously; moreover, the effect of the large quantity of low-energy conversion electrons associated with RaB cannot be accurately assessed. Since a 10-mil aluminum absorber will remove nearly all response to the conversion electrons from the RaB and also reduce to a considerable extent the counter response to the RaB itself, use of an absorber of this 10-mil thickness is considered to be a practical compromise.

Estimations of the overall errors (standard deviations) based on the counting statistics to be expected from use of this procedure to determine the radon concentration have been made for the conditions of an air flow of 0.5 m³/min, a background of 30 counts/min, and a 5% contribution

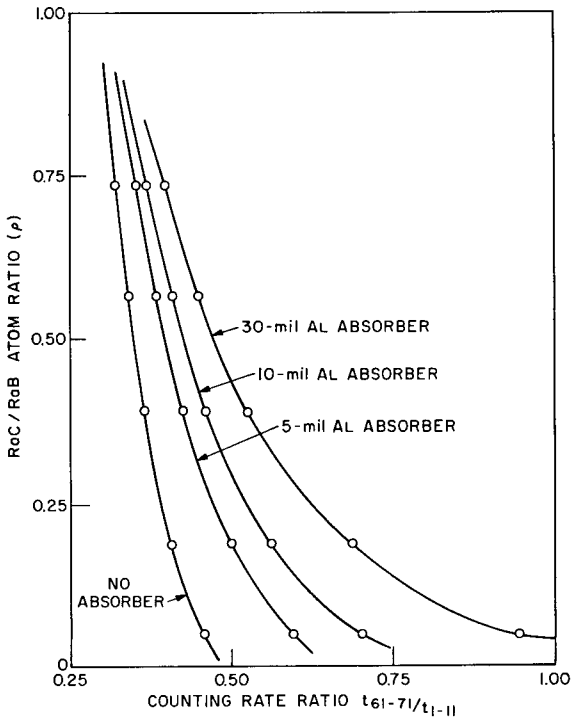


Fig. 6 — Effect of absorber thickness on the relationship between the ratio of the counting rates at $t_{1\text{-}11}$ and $t_{61\text{-}71}$ and the RaB/RaC atom ratio $\rho$

of longer lived activity (ThB+C and fission products) to the initial count, which conditions approximate those actually encountered. The statistical errors ($\sigma$) corresponding to radon concentrations of 100 to 4000 pCi/m³ and $\rho$ values of 0.735, 0.564, and 0.390 are presented in Fig. 8 for filter samples counted through 10-mil aluminum absorbers. It seems reasonable to expect this method to permit radon concentrations to be determined with a standard error of 5% or less for most conditions where relatively high atmospheric concentrations (> 1000 pCi/m³) of radon may develop.

### Atmospheric Sampling

Samples of atmospheric radioactivity were collected as described above on a roof 20 feet above the ground. The sampling equipment was contained in a box having louvered sides all around to permit unimpeded access of air; the exhaust was directed upward and away from the sampling site.

In addition to the radioactivity measurements described above, supplementary determinations were made at 5 to 6 hours and 17 to 18 hours following collection to enable corrections to be made for the small quantity of thoron daughter products and fission products retained by the filters.

### Chamber Studies

The effect of the residence time of radon in the atmosphere on its experimentally determined concentration and on the measured $\rho$ values was studied by the described technique following release of a known quantity of radon gas (0.20 $\mu$Ci) into closed volumes of 35 m³ and 0.31 m³. Continuous mixing was provided by low-speed fans. Sampling was done at rates of 0.212 m³/min and 0.00196 m³/min in the two cases, resulting in the withdrawal of 11.5% and 11.8%, respectively, of the particulate matter with each sample taken. The filtered air was returned to the chamber. Cigarette smoke was introduced into the larger chamber to supply a quantity of aerosol particles to serve as nuclei for attachment of the short-lived radon daughters; a controlled quantity of 0.3$\mu$ (dia) dioctyl phthalate aerosol (DOP) was used for this purpose in the second (glove-box) experiment. The results of these two experiments are discussed later in the next section.

## RESULTS AND DISCUSSION

Radon concentration measurements in atmospheric samples made by the described technique are summarized in Table 4 for the assumed conditions of continuous and of instantaneous emission of radon from the soil and for secular equilibrium in the atmosphere. The $\rho$ values, also included in Table 4, when compared with the secular equilibrium value of 0.735 given by Fig. 3 suggest that the radon/radon daughter relationship is certainly near secular equilibrium under the conditions prevailing at the sampling site. This reasonably close approach to equilibrium diminishes in importance the assumption made as to the mode of introduction of radon into the sample volume. The agreement between pairs of $\rho$ values or radon concentrations obtained from essentially duplicate determinations falls within the range expected for measurements

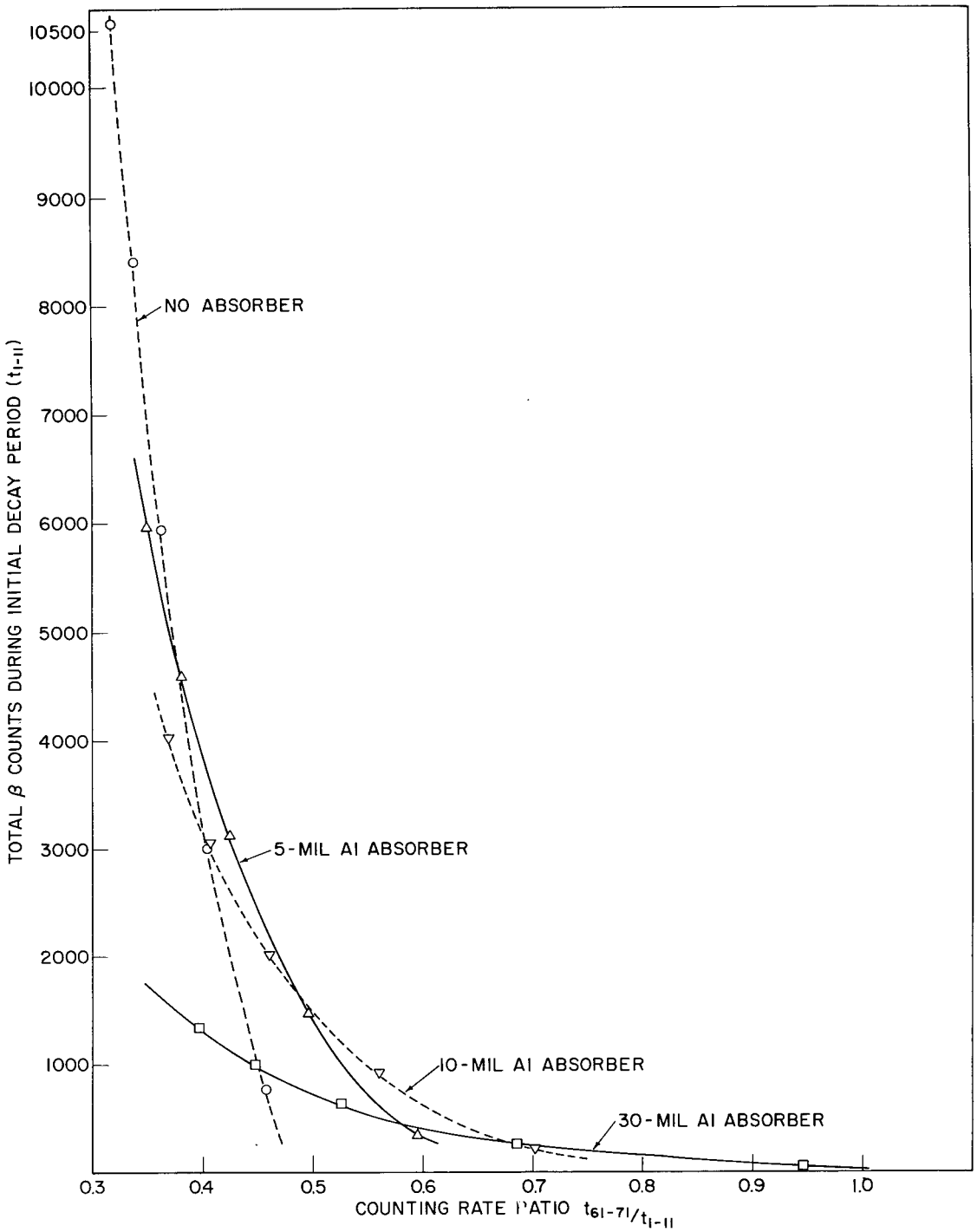


Fig. 7 — Effect of absorber thickness on the relationship between the total counts during the initial period ($t_{1-11}$) and the ratio of the counting rates at $t_{61-71}$ and $t_{1-11}$, and for a radon concentration of 100 pCi/m³ and a filtration rate of 1 m³/min for 20 min.

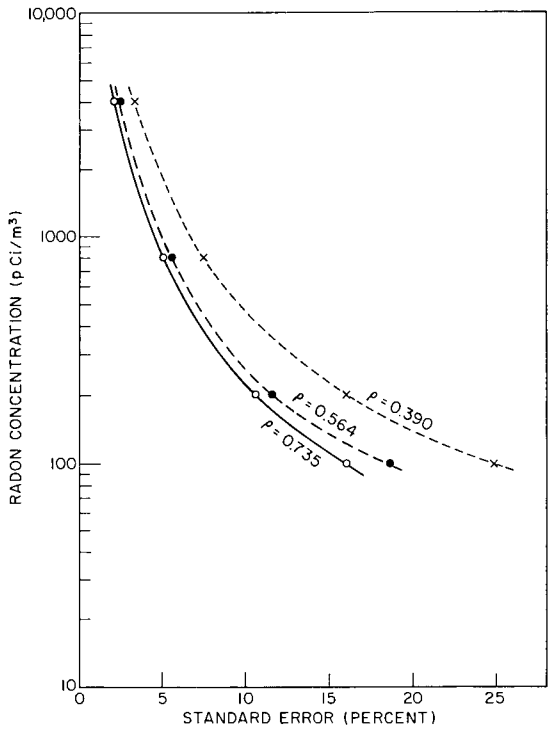


Fig. 8 — Estimations of the statistical error inherent in the determination of radon concentrations using filter samples counted through 10-mil aluminum absorbers assuming a 20-min sampling period at the rate of 0.5 m³/min, a background of 30 counts/min, and a 5% contribution of ThB+C and fission products.

having the rather large, random errors associated with low counting rates.

For values of $\rho$ in excess of 0.735 to occur in the free atmosphere, as is suggested by a few of the measurements, some mechanism must exist there for removing the gaseous radon from its solid daughters or for fractionating the daughter products relative to one another. Wilkening (3) has demonstrated one such fractionation process in which RaA is preferentially removed by the strong electrostatic charge developed in the atmosphere during thunderstorms. This loss of RaA would interrupt the radon decay chain with the result that the RaC/RaB atom ratio ($\rho$) would increase above the equilibrium value. There was no indication that such a mechanism was in operation during any of our sample collections; however, no electric field measurements were made.

If the assumption is made that the observed departures of $\rho$ from the equilibrium value of 0.735 are artifacts due to the low accuracy in determing $\rho$ (primarily a function of the total count during the 61-71 minute decay period) and that secular equilibrium did exist, the initial count during the 1-11 minute decay period can be employed to calculate the radon concentration. Such calculations have been made for the extended series of collections made on January 5 and January 7, 1965; the results of both types of measurement are compared in Figs. 9 and 10. The horizontal axis of the diamond-shaped pattern surrounding the points indicates the collection time, while the vertical axis indicates the standard error ($\sigma$) in the determination of the radon concentration based on the uncertainty in the measured activity ratio. The statistical errors associated with each of the measurements in the series which assumes equilibrium conditions to exist are not shown but are considerably smaller since the determination is based on a single measurement made during the period of highest activity.

From Figs. 9 and 10 it may be concluded that no advantage ensues from use of the more complicated procedure, at least under the sampling conditions existing here. Indeed, it permits one to place more reliance on the results of the many determinations of radon activity made by numerous investigators who have invariably assumed secular equilibrium to exist in the free atmosphere. It would appear that, in general, this approach is valid. On the other hand, during the developing stages of a strong temperature inversion in the atmosphere, or immediately following ventilation of a mine, tunnel, or similar closed space, departures from equilibrium would be expected and the simple approach could seriously underestimate the radon concentration.

The validity of this approach for determining radon concentrations from measurements of its filterable decay products was tested by the chamber studies in which a measured quantity of radon was released into closed spaces of known volume as described earlier. The data accumulated in two experiments are summarized in Tables 5 and 6. In both instances the expected progressive increases in $\rho$ with time were found. The experimental values of $\rho$ obtained through use of the described procedure are compared in Figs. 11 and 12 with calculated results which duplicate as nearly as possible the actual conditions

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TABLE 4

Summary of Radon Concentrations Deduced from Count Ratios Under the Assumptions of One Instantaneous Emission of Radon From the Soil at Some Past Time, of Continuous Emission of Radon From the Soil at a Uniform Rate Beginning at Some Past Time, and of Secular Equilibrium of Radon and Its Daughters in the Atmosphere

| Collection Date | Time (EST) | Air Flow Rate ($m^3$/min) | RaB+C Count ($t_{1\text{-}11}$) | Count Ratio $t_{61\text{-}71}/t_{1\text{-}11}$ | Absorber Thickness (mils Al) | $\rho$ | Radon Concentration ($pCi/m^3$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Instantaneous Emission | Continuous* Emission | Secular Equilibrium |
| 1964 | | | | | | | | | |
| Oct. 29 | 0730-0750 | 0.501 | 1475 | 0.398 | 30 | 0.73 ± 0.09 | 223 ± 30 | 224 | 220 ± 6 |
| | 0732-0752 | 0.430 | 10896 | 0.322 | 0 | 0.71 ± 0.06 | 249 ± 18 | 256 | 240 ± 3 |
| Nov. 9 | 0940-1000 | 0.428 | 7117 | 0.331 | 5 | 0.86 ± 0.06 | 303 ± 20 | — | 279 ± 4 |
| | 0942-1002 | 0.501 | 2234 | 0.369 | 30 | 0.85 ± 0.08 | 286 ± 28 | — | 333 ± 8 |
| Nov. 10 | 0810-0830 | 0.518 | 12006 | 0.388 | 10 | 0.64 ± 0.03 | 670 ± 35 | 744 | 579 ± 6 |
| | 0812-0832 | 0.436 | 9829 | 0.378 | 10 | 0.69 ± 0.04 | 602 ± 37 | 635 | 562 ± 6 |
| Nov. 12 | 0800-0820 | 0.513 | 9640 | 0.391 | 10 | 0.63 ± 0.04 | 556 ± 30 | 623 | 470 ± 5 |
| | 0802-0822 | 0.436 | 2832 | 0.384 | 30 | 0.78 ± 0.06 | 452 ± 39 | — | 485 ± 10 |
| Nov. 13 | 0805-0825 | 0.515 | 764 | 0.402 | 30 | 0.72 ± 0.13 | 115 ± 23 | 117 | 111 ± 5 |
| | 0807-0827 | 0.436 | 1871 | 0.382 | 10 | 0.68 ± 0.09 | 118 ± 16 | 126 | 107 ± 3 |
| Nov. 16 | 0945-1005 | 0.515 | 1870 | 0.412 | 30 | 0.68 ± 0.07 | 299 ± 34 | 318 | 271 ± 7 |
| | 0947-1007 | 0.433 | 4214 | 0.386 | 10 | 0.65 ± 0.06 | 277 ± 24 | 305 | 243 ± 4 |
| Nov. 23 | 0835-0855 | 0.521 | 2468 | 0.377 | 10 | 0.70 ± 0.08 | 126 ± 17 | 131 | 118 ± 3 |
| | 0837-0857 | 0.442 | 1882 | 0.369 | 10 | 0.74 ± 0.10 | 106 ± 18 | 106 | 106 ± 3 |
| Nov. 24 | 0815-0835 | 0.521 | 5956 | 0.388 | 10 | 0.65 ± 0.05 | 331 ± 26 | 364 | 286 ± 4 |
| | 0817-0837 | 0.439 | 4799 | 0.382 | 10 | 0.67 ± 0.06 | 302 ± 27 | 326 | 273 ± 4 |
| Nov. 25 | 0814-0834 | 0.515 | 2042 | 0.389 | 10 | 0.64 ± 0.10 | 115 ± 17 | 128 | 99 ± 3 |
| | 0816-0836 | 0.433 | 1600 | 0.364 | 10 | 0.76 ± 0.11 | 88 ± 16 | — | 92 ± 3 |
| Nov. 27 | 0850-0910 | 0.515 | 4874 | 0.381 | 10 | 0.68 ± 0.06 | 259 ± 23 | 276 | 237 ± 4 |
| | 0852-0912 | 0.439 | 4052 | 0.371 | 10 | 0.73 ± 0.06 | 233 ± 24 | 234 | 231 ± 4 |
| Nov. 30 | 0810-0830 | 0.513 | 3834 | 0.372 | 10 | 0.72 ± 0.07 | 190 ± 20 | 194 | 187 ± 3 |
| Dec. 7 | 0935-0955 | 0.521 | 1296 | 0.362 | 10 | 0.78 ± 0.12 | 58 ± 12 | — | 62 ± 2 |
| Dec. 9 | 0830-0850 | 0.521 | 4331 | 0.393 | 10 | 0.62 ± 0.06 | 250 ± 23 | 283 | 208 ± 4 |
| | 0832-0852 | 0.442 | 3310 | 0.405 | 10 | 0.58 ± 0.05 | 246 ± 27 | 286 | 187 ± 4 |
| Dec. 14 | 0808-0828 | 0.521 | 2623 | 0.361 | 10 | 0.78 ± 0.09 | 117 ± 16 | — | 126 ± 3 |
| | 0810-0830 | 0.430 | 2154 | 0.337 | 10 | 0.90 ± 0.15 | 94 ± 12 | — | 125 ± 3 |
| 1965 | | | | | | | | | |
| Jan. 5 | 0710-0730 | 0.541 | 4589 | 0.384 | 10 | 0.66 ± 0.07 | 238 ± 21 | 259 | 212 ± 4 |
| | 0755-0815 | 0.541 | 4918 | 0.393 | 10 | 0.62 ± 0.05 | 272 ± 24 | 307 | 227 ± 4 |
| | 0840-0900 | 0.541 | 5302 | 0.365 | 10 | 0.76 ± 0.06 | 236 ± 22 | — | 245 ± 4 |
| | 0925-0945 | 0.541 | 3637 | 0.358 | 10 | 0.80 ± 0.07 | 152 ± 17 | — | 168 ± 3 |
| | 1010-1030 | 0.541 | 4564 | 0.368 | 10 | 0.75 ± 0.06 | 208 ± 20 | — | 211 ± 4 |
| | 1055-1115 | 0.541 | 3489 | 0.365 | 10 | 0.76 ± 0.07 | 155 ± 19 | — | 161 ± 3 |
| | 1310-1330 | 0.541 | 2711 | 0.392 | 10 | 0.62 ± 0.07 | 149 ± 18 | 168 | 125 ± 3 |
| | 1520-1540 | 0.541 | 2342 | 0.351 | 10 | 0.84 ± 0.10 | 91 ± 13 | — | 108 ± 3 |
| Jan. 7 | 0820-0840 | 0.541 | 6315 | 0.369 | 10 | 0.74 ± 0.05 | 292 ± 24 | 292 | 292 ± 4 |
| | 0905-0925 | 0.541 | 6534 | 0.370 | 10 | 0.74 ± 0.05 | 304 ± 24 | 304 | 302 ± 4 |
| | 1015-1035 | 0.541 | 4761 | 0.375 | 10 | 0.71 ± 0.06 | 229 ± 21 | 236 | 220 ± 4 |
| | 1530-1550 | 0.541 | 2235 | 0.361 | 10 | 0.79 ± 0.09 | 96 ± 14 | — | 103 ± 3 |

*No conversion factors derivable for conditions where $\rho > 0.735$.

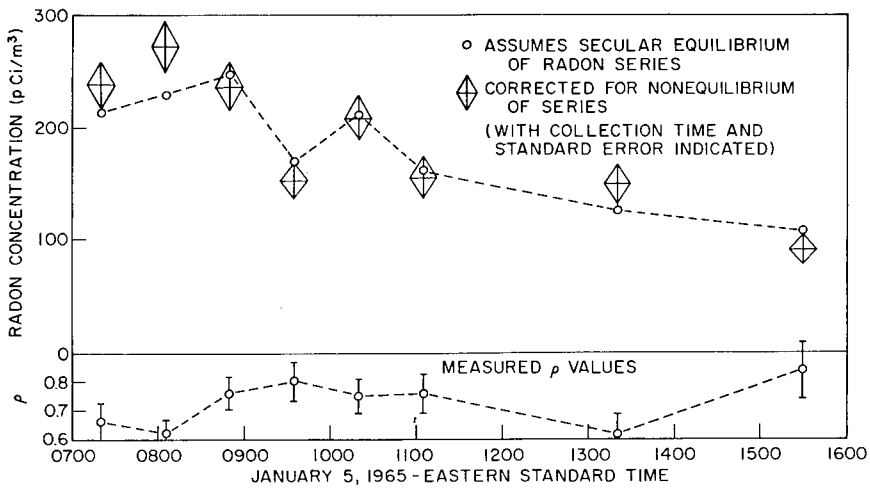


Fig. 9 — Atmospheric radon concentrations on January 5, 1965

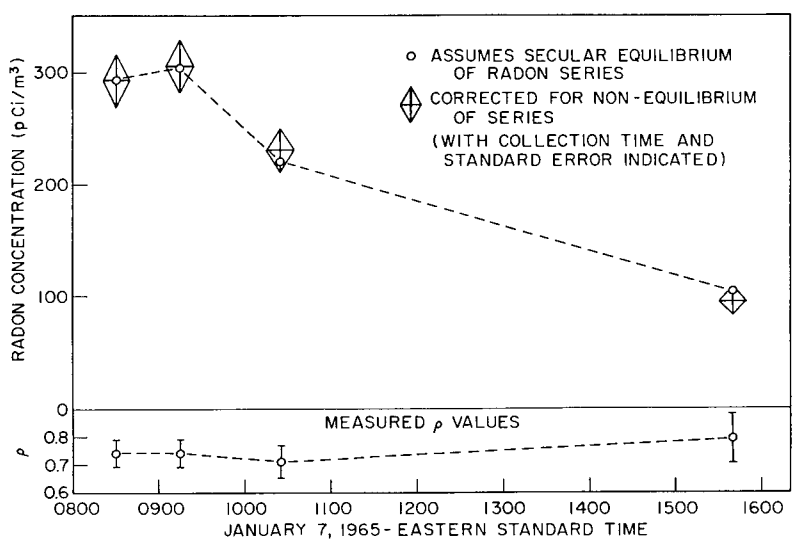


Fig. 10 — Atmospheric radon concentrations on January 7, 1965

encountered during the experiment. Account has been taken of the changes in $\rho$ with time during the collections as described in the Appendix (this was ignored in the general solution of the experimental procedure), the changing composition caused by withdrawal of samples, and the background of other airborne radioactivity. The agreement is entirely satisfactory in view of the difficulty in setting an exact zero time for introduction of the radon, which was degassed from a radium solution, and the impossibility of evaluating the affect of the chamber walls both in removing aerosols and in removing radioactive atoms or ions. This wall effect could result in the lower $\rho$ values observed and in the lack of closer approachment to the 0.735 equilibrium value.

The lack of quantitative agreement between the measured radon concentrations and the added quantity of radon was rather disturbing. Studies currently underway, however, show that there is a decided wall effect and that the chamber surfaces are in competition with the aerosol for attachment of the radioactive atoms or ions of the radon decay products and that, in the absence

TABLE 5

Experimental Evaluation of 0.20 $\mu$Ci Radon Released into a Chamber (Room) of 35 m³ Volume and Sampled at the Rate of 0.212 m³/min*

| Sample | Elapsed Time (min) | Counter Unit | Count $t_{1\text{-}11}$ | | | | Count $t_{61\text{-}71}$ | | | | Ratio $t_{61\text{-}71}/t_{1\text{-}11}$ | Count Correction Factors | | Corrected Count $t_{1\text{-}11}$ | Expected Count $t_{1\text{-}11}$ From 100 pCi/m³ Radon | Calculated Radon Conc. (pCi/m³) | | $\rho$§ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Gross | Background | ThB+C; Fission Products | Net | Gross | Background | ThB+C; Fission Products | Net | | Flow† | Filter Efficiency | | | Corr. for $\rho$ | Equilibrium Assumed‡ | |
| 1 | 0-20 | D | 8840 | −313 | −122 | 8405 | 4740 | −313 | −114 | 4313 | 0.513 | 4.72 | 1.00 | 39670 | 1395 | 2844 | 961 | 0.29 |
| 2 | 30-50 | D | 16900 | −313 | −122 | 16465 | 7700 | −313 | −114 | 7273 | 0.442 | 4.72 | 1.00 | 77715 | 2370 | 3279 | 1882 | 0.45 |
| 3 | 60-80 | M | 18500 | −270 | −122 | 18108 | 7800 | −270 | −114 | 7416 | 0.410 | 4.72 | 1.00 | 85470 | 2895 | 2952 | 2183 | 0.56 |
| 4 | 90-110 | M | 17700 | −270 | −122 | 17308 | 7390 | −270 | −114 | 7006 | 0.405 | 4.72 | 1.00 | 81694 | 2950 | 2769 | 2086 | 0.58 |
| 5 | 120-140 | D | 17400 | −313 | −122 | 16965 | 7205 | −313 | −114 | 6778 | 0.400 | 4.72 | 1.00 | 80075 | 3270 | 2449 | 1939 | 0.60 |
| 6 | 150-170 | D | 15400 | −313 | −122 | 14965 | 6310 | −313 | −114 | 5883 | 0.393 | 4.72 | 1.00 | 70635 | 3455 | 2044 | 1711 | 0.63 |
| 7 | 285-305 | M | 16500 | −270 | −122 | 16108 | 6600 | −270 | −114 | 6216 | 0.386 | 4.72 | 1.00 | 76030 | 3460 | 2197 | 1942 | 0.66 |
| 8 | 310-330 | D | 16000 | −313 | −122 | 15565 | 6700 | −313 | −114 | 6273 | 0.403 | 4.72 | 1.00 | 73467 | 3205 | 2292 | 1779 | 0.59 |

*Radon was added during the first 3 min (approx.) of the experiment; cigarette smoke was added 10 min before and 170 min and 305 min after the start of the run. The background of old radon in the room was approximately 500 pCi/m³.

†Reciprocal of 0.212 m³/min.

‡The expected counts from 100 pCi/m³ of radon in equilibrium with its daughters are 4130 for counter unit D and 3915 for counter unit M.

§Determined from $t_{61\text{-}71}/t_{1\text{-}11}$ using the 10-mil-absorber curve shown in Fig. 6.

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TABLE 6
Experimental Evaluation of 0.20 $\mu$Ci Radon Released into a Chamber of 0.31 $m^3$ Volume and Sampled at the Rate of 0.00196 $m^3$/min*

| Sample | Elapsed Time (min) | Count† $t_{1\text{-}11}$ | Count† $t_{61\text{-}71}$ | Ratio $t_{61\text{-}71}/t_{1\text{-}11}$ | Count Correction Factors | | Corrected Count $t_{1\text{-}11}$ | Expected Count $t_{1\text{-}11}$ From 100 pCi/$m^3$ Radon | Calculated Radon Conc. (pCi/$m^3$) | | $\rho$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Flow‡ | Filter Efficiency | | | Corrected for $\rho$ | Equilibrium Assumed§ | |
| 1 | 0-20 | 2390 | 1660 | 0.695 | 510 | 1.00 | $1.22 \times 10^6$ | 225 | $5.42 \times 10^5$ | $0.30 \times 10^5$ | 0.052 |
| 2 | 30-50 | 10400 | 5360 | 0.515 | 510 | 1.00 | $5.30 \times 10^6$ | 1370 | $3.87 \times 10^5$ | $1.28 \times 10^5$ | 0.27 |
| 3 | 60-80 | 16100 | 7000 | 0.435 | 510 | 1.00 | $8.21 \times 10^6$ | 2500 | $3.28 \times 10^5$ | $1.99 \times 10^5$ | 0.46 |
| 4 | 90-110 | 16900 | 7100 | 0.420 | 510 | 1.00 | $8.62 \times 10^6$ | 2810 | $3.07 \times 10^5$ | $2.09 \times 10^5$ | 0.51 |
| 5 | 120-140 | 20200 | 8120 | 0.402 | 510 | 1.00 | $10.31 \times 10^6$ | 3230 | $3.19 \times 10^5$ | $2.50 \times 10^5$ | 0.58 |
| 6 | 150-170 | 19920 | 7920 | 0.398 | 510 | 1.00 | $10.16 \times 10^6$ | 3320 | $3.06 \times 10^5$ | $2.46 \times 10^5$ | 0.60 |
| 7 | 180-200 | 20380 | 7980 | 0.392 | 510 | 1.00 | $10.39 \times 10^6$ | 3480 | $2.99 \times 10^5$ | $2.52 \times 10^5$ | 0.62 |
| 8 | 260-280 | 21480 | 8220 | 0.383 | 510 | 1.00 | $10.95 \times 10^6$ | 3730 | $2.94 \times 10^5$ | $2.65 \times 10^5$ | 0.67 |
| 9 | 285-305 | 16940 | 6600 | 0.390 | 510 | 1.00 | $8.64 \times 10^6$ | 3530 | $2.45 \times 10^5$ | $2.09 \times 10^5$ | 0.63 |

*An 0.3$\mu$ (dia.) DOP aerosol was added 10 min before the start of the experiment to a concentration of $10^4$ particles/cc; the radon addition was made during the initial 3 min of the experiment.

†Corrected for counter background; a negligible background of airborne radioactivity was present. All results were normalized to the D counter as calibrated August 2, 1965.

‡Reciprocal of 0.00196 $m^3$/min.

§Expected counts were obtained from Fig. 7; for the equilibrium condition this value was 4130 counts.

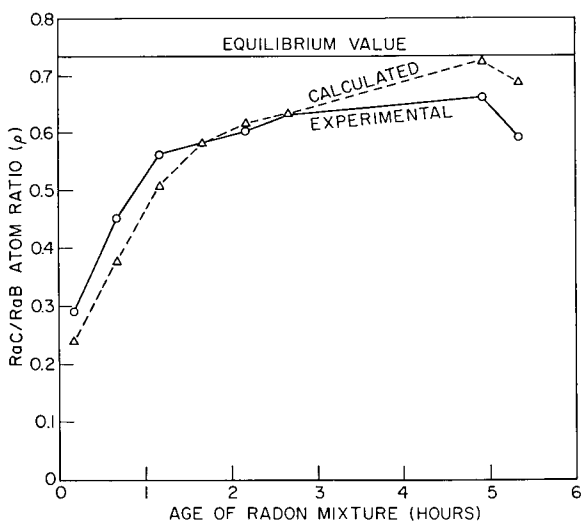


Fig. 11 — Temporal changes in the RaC/RaB atom ratio ($\rho$) following release of 0.20 $\mu$Ci of radon into a chamber (room) of 35 $m^3$ volume. The samples were taken at 0.212 $m^3$/min for 20 min. The background of old radon was approximately 500 pCi/$m^3$.

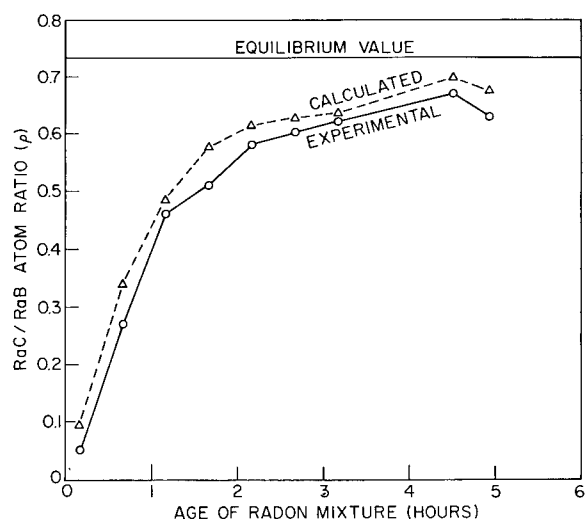


Fig. 12 — Temporal changes in the RaC/RaB atom ratio ($\rho$) following release of 0.20 $\mu$Ci of radon into a chamber of 0.31 $m^3$ volume. The samples were taken at 0.00196 $m^3$/min for 20 min. The background of other airborne radioactivity was negligible.

of aerosol, little of the radon daughter activity remains airborne. The progressive decrease in observed radon with time is in accord with the loss of aerosol through coagulation and deposition, during which time the relative surface area of the wall increases. The wall effect is greatest in the large chamber, which contains so much permanently mounted equipment that it has a large surface-to-volume ratio. The apparent increase in radon concentration with introduction of additional smoke, as noted in Table 5, is to be expected if the relative surface areas of aerosol and wall are of significance.

The application of correction factors based on the $\rho$ values does give a rather high degree of internal consistency to the measured radon concentrations, except for the first few measurements involving extreme degrees of nonequilibrium. Even these fall reasonably well into agreement when corrections are applied for the rapid changes in $\rho$ occurring during the early collections (see Appendix). In any case the corrected values are more realistic than those derived from the assumption of secular equilibrium between radon and its daughters. The discrepancy between the experimental and the true radon concentration should not be encountered in measurements made of the radon concentration in the free atmosphere, since in that environment interaction with the ground surface would be much more restricted. On the other hand, use of this technique to measure radon concentrations in mines, tunnels, or other closed spaces might be expected to show a wall effect whose magnitude would depend on the configuration of the restraining walls and the rate of mixing within the volume.

## CONCLUSIONS

Reasonably accurate estimations can be made of the radon concentrations in the free atmosphere by collection on efficient filters of the short-lived descendants of radon and measurement of their $\beta$ activity during two fixed periods following collection. The measurement of the extent of secular equilibrium of radon and its daughter products may be conveniently determined by 10-min counts starting 1.0 min and 61.0 min after a collection of 20.0 min duration; counting on calibrated equipment with a 10-mil aluminum absorber inserted between the sample and counting tube gives a good compromise between sensitivity and the uncertainties introduced by the complex group of conversion electrons emitted and by counting statistics.

This method will detect any gross departures of radon in the atmosphere from secular equilibrium with its daughter products and permits a determination of the apparent age of the mixture.

In the free atmosphere radon is apparently near secular equilibrium with its daughters at most times; however, during initial stages of inversions and in recently ventilated spaces equilibrium departures can be expected. Chamber studies using artificial aerosols indicate a loss of radon daughter products to the walls or other surfaces and suggest that underestimation of radon by this method may result when the surface-to-volume ratio is high or when mixing promotes intimate contact between the air and a surface.

## ACKNOWLEDGMENT

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# Appendix

## CHANGES IN $\rho$ DURING NONEQUILIBRIUM CONDITIONS

The rapid changes in the RaC/RaB atom ratio ($\rho$) encountered in the chamber studies immediately after the addition of radon necessitated the development of new tables relating the growth and decay of radon daughter activity collected during 20-min filtration periods to the radon concentration in the air. Such an approach was not required for determinations of atmospheric radon, since in that case it was assumed that the atmosphere could be considered to be in or near a state of dynamic equilibrium during periods of 20-min duration.

Calculations of the collection and growth of RaA, RaB, and RaC on a filter during a 20-min collection were made taking into account the changes in RaA, RaB, and RaC occurring in the air prior to and during filtration. These changes are a function of the time during which the radon daughter products have been growing into equilibrium. The decay of these activities on the filter following termination of collection and taking into account the successive decay of members of the series is shown in Table A1 for collections made during periods of growth of the radon mixture corresponding to ages of 0-20 min, 40-60 min, 80-100 min, and infinite age (secular equilibrium established). The data used to construct working curves for determination of $\rho$ and the radon concentration are contained in Table A2.

Application of the information contained in Tables A1 and A2 to the results of the chamber studies does increase the accuracy of radon determinations during early states of growth of the radon daughters; however, its affect on the determination of $\rho$ is not of great significance. A comparison of the results of the small chamber run based both on the standard procedure and on this more realistic procedure is shown in Table A3. Only during periods of low $\rho$ values are any substantial differences noted in the derived radon concentrations. In addition to the comparison of the experimental values of $\rho$ and radon concentration for the two procedures, the expected values are also indicated; the experimental values of $\rho$ (by either procedure) and the expected values are in good agreement, while the measured radon concentrations are about 50% low. This latter result is attributed to a "wall effect" due to the large surface-to-volume ratio and to the mechanical mixing within the chamber making the walls more accessible to impingement of diffusing ions and unattached atoms. The sampling process itself removes 11.8% of the aerosol and radon daughters with each collection, which results in effectively 6% of the radon being in a daughter-free, unmeasurable conditon during any collection.

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TABLE A1

Radioactive Decay of Radon Descendants on a Filter Following a 20-min Collection During Which the Radon Conglomerate Progressively Increased in Age*

| Counting Interval (min) | Radioactive Decays | | | Counting Interval (min) | Radioactive Decays | | |
|---|---|---|---|---|---|---|---|
| | RaA | RaB | RaC | | RaA | RaB | RaC |
| Age 0-20 min; $\rho = 0.0$ to 0.190 | | | | Age 80-100 min; $\rho = 0.564$ to 0.623 | | | |
| 0-1 | Sample Manipulation | | | 0-1 | Sample Manipulation | | |
| 1-6 | 2226 | 4112 | 1709 | 1-6 | 2316 | 15867 | 16655 |
| 6-11 | 715 | 3775 | 2069 | 6-11 | 745 | 14109 | 16380 |
| 11-16 | 230 | 3370 | 2311 | 11-16 | 239 | 12454 | 15874 |
| 16-21 | 74 | 2977 | 2450 | 16-21 | 77 | 10962 | 15196 |
| 21-26 | 24 | 2622 | 2504 | 21-26 | 25 | 9640 | 14223 |
| 26-31 | 7 | 2307 | 2498 | 26-31 | 7 | 8474 | 13533 |
| 31-36 | 3 | 2027 | 2443 | 31-36 | 3 | 7431 | 12630 |
| 36-41 | 1 | 1782 | 2353 | 36-41 | 1 | 6544 | 11717 |
| 41-46 | 0 | 1566 | 2244 | 41-46 | 0 | 5753 | 10814 |
| 46-51 | 0 | 1375 | 2119 | 46-51 | 0 | 5057 | 9938 |
| 51-56 | 0 | 1209 | 1983 | 51-56 | 0 | 4443 | 9101 |
| 56-61 | 0 | 1063 | 1847 | 56-61 | 0 | 3904 | 8301 |
| 61-66 | 0 | 934 | 1707 | 61-66 | 0 | 3432 | 7552 |
| 66-71 | 0 | 821 | 1576 | 66-71 | 0 | 3017 | 6851 |
| Age 40-60 min; $\rho = 0.355$ to 0.478 | | | | Age ∞ (secular equilibrium); $\rho = 0.735$ | | | |
| 0-1 | Sample Manipulation | | | 0-1 | Sample Manipulation | | |
| 1-6 | 2316 | 12780 | 10802 | 1-6 | 2316 | 17594 | 21219 |
| 6-11 | 745 | 11397 | 11006 | 6-11 | 745 | 15627 | 20470 |
| 11-16 | 239 | 10069 | 10960 | 11-16 | 239 | 13788 | 19533 |
| 16-21 | 77 | 8866 | 10715 | 16-21 | 77 | 12134 | 18467 |
| 21-26 | 25 | 7798 | 10325 | 21-26 | 25 | 10670 | 17320 |
| 26-31 | 7 | 6855 | 9839 | 26-31 | 7 | 9379 | 16136 |
| 31-36 | 3 | 6025 | 9285 | 31-36 | 3 | 8245 | 14950 |
| 36-41 | 1 | 5295 | 8699 | 36-41 | 1 | 7245 | 13782 |
| 41-46 | 0 | 4654 | 8094 | 41-46 | 0 | 6367 | 12654 |
| 46-51 | 0 | 4090 | 7491 | 46-51 | 0 | 5594 | 11572 |
| 51-56 | 0 | 3594 | 6900 | 51-56 | 0 | 4916 | 10551 |
| 56-61 | 0 | 3158 | 6329 | 56-61 | 0 | 4321 | 9589 |
| 61-66 | 0 | 2776 | 5785 | 61-66 | 0 | 3798 | 8696 |
| 66-71 | 0 | 2440 | 5272 | 66-71 | 0 | 3338 | 7866 |

*Based on sampling of 100 pCi of radon per unit volume in various stages of equilibrium with its descendants.

TABLE A2
Calculated $\beta$ Activity from 100 pCi of Radon per $m^3$ of Air Sampled at the Rate of 1 $m^3$/min for 20 min

| Radon Age* (min) | | Initial Activity ($t_{1\text{-}11}$) | | Final Activity ($t_{61\text{-}71}$) | | Activity Ratio Final/Initial | |
|---|---|---|---|---|---|---|---|
| | | Disintegrations | Counts† | Disintegrations | Counts† | Disintegrations | Counts† |
| 0-20 | RaB | 7887 | 153.8 | 1755 | 34.2 | | |
| ($\rho$ = 0 to 0.190) | RaC | 3778 | 315.5 | 3282 | 274.0 | | |
| | Total | 11665 | 469.3 | 5037 | 308.2 | 0.432 | 0.657 |
| 40-60 | RaB | 24177 | 471.5 | 5216 | 101.7 | | |
| ($\rho$ = 0.355 to 0.478) | RaC | 21808 | 1821.0 | 11057 | 923.3 | | |
| | Total | 45985 | 2292.5 | 16273 | 1025.0 | 0.354 | 0.447 |
| 80-100 | RaB | 29976 | 584.5 | 6449 | 125.8 | | |
| ($\rho$ = 0.564 to 0.623) | RaC | 33035 | 2758.4 | 14403 | 1202.7 | | |
| | Total | 63011 | 3342.9 | 20852 | 1328.5 | 0.331 | 0.397 |
| $\infty$ | RaB | 33221 | 647.8 | 7136 | 139.2 | | |
| ($\rho$ = 0.735) | RaC | 41689 | 3481.0 | 16562 | 1382.9 | | |
| | Total | 74910 | 4128.8 | 23698 | 1522.1 | 0.316 | 0.369 |

*Continuously changing age during the 20-min filtration period.
†Collected on glass fiber filter of 100% retentivity; counted through 10-mil aluminum absorber.

TABLE A3
Comparison of Derived $\rho$ Values and Radon Concentrations in the Small Chamber Run (Radon = $6.41 \times 10^5$ pCi/$m^3$) Based on a Fixed and a Variable Age of the Radon/Radon Daughter Mixture

| Elapsed Time (min) | RaC/RaB Atom Ratio ($\rho$) | | | Radon Concentration (pCi/$m^3$) | | |
|---|---|---|---|---|---|---|
| | Standard Procedure* | Modified Procedure† | Expected Value‡ | Standard Procedure* | Modified Procedure† | Expected Value‡ |
| 0-20 | 0.052 | 0.070 | 0.095 | $5.42 \times 10^5$ | $3.93 \times 10^5$ | $6.03 \times 10^5$ |
| 30-50 | 0.27 | 0.27 | 0.34 | $3.87 \times 10^5$ | $3.66 \times 10^5$ | $6.04 \times 10^5$ |
| 60-80 | 0.46 | 0.45 | 0.49 | $3.28 \times 10^5$ | $3.28 \times 10^5$ | $5.93 \times 10^5$ |
| 90-110 | 0.51 | 0.50 | 0.58 | $3.07 \times 10^5$ | $3.09 \times 10^5$ | $5.90 \times 10^5$ |
| 120-140 | 0.58 | 0.57 | 0.61 | $3.19 \times 10^5$ | $3.22 \times 10^5$ | $5.89 \times 10^5$ |
| 150-170 | 0.60 | 0.59 | 0.63 | $3.06 \times 10^5$ | $3.09 \times 10^5$ | $5.85 \times 10^5$ |
| 180-200 | 0.62 | 0.61 | 0.64 | $2.99 \times 10^5$ | $3.02 \times 10^5$ | $5.84 \times 10^5$ |
| 260-280 | 0.67 | 0.66 | 0.70 | $2.94 \times 10^5$ | $2.96 \times 10^5$ | $6.01 \times 10^5$ |
| 285-305 | 0.63 | 0.62 | 0.67 | $2.45 \times 10^5$ | $2.48 \times 10^5$ | $5.81 \times 10^5$ |

*The value of $\rho$ is assumed to be constant during the sampling period.
†The value of $\rho$ is assumed to increase with the age of the radon conglomerate during collection.
‡Calculations based on modified procedure and taking in account changes produced by removal of 11.8% of the aerosol with each sample.

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13. ABSTRACT

A set of experimental conditions has been derived which optimizes the accuracy with which the radon content of the atmosphere and its apparent residence time there can be determined from measurement of the filterable gross $\beta$ activity during two separate 10-minute periods following the end of a 20-minute collection period.

The 20-minute collection is made on a filter of essentially 100% retentivity (glass fiber filter) and counted for $\beta$ activity through a 10-mil (70. mg/cm$^2$) aluminum absorber on equipment of known efficiency for the $\beta$ particles emitted by RaB and RaC. The ratio of measured counts during the 61-through-71-minute decay period to that during the 1-through-11-minute period is employed to obtain the atom ratio of RaC to RaB ($\rho$) in the air sampled, the apparent age ($\tau$) of the conglomerate of radon and its daughters, and the total counts to be expected from any given radon concentration in the air.

Extensive examples of atmospheric measurements are given which suggest that under most conditions in the free atmosphere radon is essentially at secular equilibrium with its daughter products. Other collections made following addition of radon to a restricted volume show the expected increase in $\rho$ with time, which confirms the basic validity of the procedure.

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| Atmosphere | | | | | | |
| Measurement | | | | | | |
| Radon | | | | | | |
| Radioactive decay | | | | | | |
| Filter collections | | | | | | |
| Radon decay products | | | | | | |
| Secular equilibrium | | | | | | |

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