

The Filtration of Particles of Atomic Dimensions

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13. ABSTRACT <p>Particles of atomic dimensions, as typified by the primary decay products of radon, are readily removed from an air stream by passage through coarse fibrous filters or even through screens, while the radon parent is unaffected. The inverse relationship between the efficiency of removal and the air velocity indicates that diffusion is the mechanism primarily responsible for deposition of these small particles. However, if the particles become attached to aerosols, their collection is governed by aerosol behaviors where collection depends both on filter characteristics and air velocity.</p> <p>These particles are readily collected on aerosol particles and provide a radioactive tag by which aerosol or filter behavior may be studied. Such measurements can be extended to size ranges and concentration levels below those convenient for other techniques.</p>			

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ABSTRACT

Particles of atomic dimensions, as typified by the primary decay products of radon, are readily removed from an air stream by passage through coarse fibrous filters or even through screens, while the radon parent is unaffected. The inverse relationship between the efficiency of removal and the air velocity indicates that diffusion is the mechanism primarily responsible for deposition of these small particles. However, if the particles become attached to aerosols, their collection is governed by aerosol behavior where collection depends both on filter characteristics and air velocity.

These particles are readily collected on aerosol particles and provide a radioactive tag by which aerosol or filter behavior may be studied. Such measurements can be extended to size ranges and concentration levels below those convenient for other techniques.

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This is a final report on this problem. Unless otherwise notified, this problem will be considered closed 30 days after the issuance of this report.

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THE FILTRATION OF PARTICLES OF ATOMIC DIMENSIONS

INTRODUCTION

During the past few years a considerable body of knowledge and experience has been accumulated in regard to the behavior of radioactive particles in the atmosphere stimulated largely by interest in the worldwide dispersal and deposition (fallout) of fission products following nuclear detonations in the atmosphere. Not so coincidentally, this interest has benefitted our knowledge of the natural airborne radioactive species, which, except in close proximity in time and space to a nuclear explosion, are the major contributions to the radioactivity of the atmosphere.

Whereas particles containing fission product radioactivity are produced by condensation or coagulation within the nuclear fireball, the natural radioactive particles are produced in the lower atmosphere as free atoms or ions following radioactive decay of the noble gas precursor (radon or thoron) diffusing from the soil. These decay products, which initially must be atoms or simple oxides or nitrides of lead, bismuth, or polonium, are inherently materials of low volatility and are almost immediately captured irreversibly by the small atmospheric ions or aerosols. Both types of radioactive particles are amenable to collection by filtration and serve as useful tracers for studies of local or global atmospheric mixing processes.

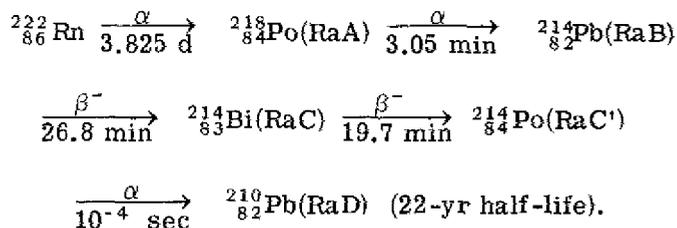
Information developed at NRL on the determination of atmospheric radon concentrations through measurement of its short-lived filterable decay products (1-3) have been employed by Hosler (4, 5) in studies of the air pollution potential and urban-rural climatology in the Washington, D.C., area. Studies such as these require knowledge of the extent of secular equilibrium between radon and its daughters in the atmosphere and the degree of attachment of the daughter products to filterable aerosol particles. Though the atmosphere normally contains sufficient aerosol particles so that effectively all of the decay products of the radon (and thoron) series become attached to particulate matter before appreciable radioactive decay occurs, it has been demonstrated in the laboratory that in an isolated parcel of clean air a significant fraction of the short-lived radioactive atoms of RaA (3-min half-life) can live out their lifetime in a free condition (3). The present report describes the results of some experiments carried out with these primary, unattached particles.

EXPERIMENTAL PROCEDURE

The experimental procedure involved introducing a known quantity of radon gas into a 1.225-m³ chamber containing either clean air or air containing dioctyl phthalate (DOP) aerosol particles of nominal 0.3- μ m diameter. The chamber and ancillary equipment for air purification and sampling have been described previously (3). The aerosol used in these studies was produced by an NRL aerosol generator and filtered through multiple layers of a coarse fibrous filter (IPC 1478) to give an aerosol dispersion which behaved, superficially at least, like 0.3- μ m-dia monodisperse DOP. Known quantities of radon (²²²Rn) were introduced into the chamber by degassing a 10- μ Ci standard radium solution.

Radioactive decay of the radon produces radioactive species of extremely small dimensions ("atomic") which rapidly attach themselves to the chamber walls or to aerosol

surfaces, if such are available; if air turbulence is minimized and no aerosol particles are present, an appreciable quantity of the short-lived RaA (^{218}Po) will exist in the unattached condition. The radioactive decay series involved is



The first three decay products (RaA, RaB, and RaC) are the only ones of importance in this study, since in the analytical procedure measurements are made only of the β radiation emitted by a composite of RaB and RaC.

The atmosphere within the chamber was sampled for particulate radioactivity by withdrawing known quantities of air through a suitable series of filters for 5.00- or 20.00-min periods, after which the collected activity was counted on carefully calibrated counters using a fixed time schedule. From the counting rates of the samples during the 1-through-11-min period and the 61-through-71-min period following the end of collection, determinations could be made of the apparent age of the mixture of decay products (or extent of secular equilibrium with the radon parent) and the quantity of radon from which the collected particulate radioactivity was derived (radon itself was not retained by the filters).

RESULTS AND DISCUSSION

The previous report in this series (3) indicated that a fibrous filter with poor retention characteristics for small aerosol particles showed greatly improved retention of radon decay products in the absence of aerosol, suggesting that diffusion was the mechanism responsible for the collection of these atomic-sized radon decay products. Further experiments confirmed these preliminary findings; they also showed that the radioactive decay of the material collected on the fibrous filter (IPC 1478) differed from that of the particles penetrating the filter. Subsequent studies employing 40-mesh nickel screens in place of the poor fibrous filters showed the same effects, namely, that in the absence of added aerosol particles, screens were good collectors of material having different decay characteristics from the fraction of radioactivity penetrating the screen and collected by an absolute filter. These findings led to the design of more elaborate experiments with the objective of learning more about the behavior of these atomic-sized particles and how they might be utilized in filtration studies.

Effect of Aerosol Concentration on the Retention of Radon Decay Products by Metal Screens

A number of runs were made to determine the effect of aerosol concentration on the filterability of radon decay products by screens. Typical results with 40-mesh nickel screens are given in Table 1; a few experiments with coarser metal screens and with plastic screens gave results in qualitative agreement with those presented.

Diocetyl phthalate (either polydisperse or monodisperse 0.3- μm -dia DOP) aerosol was added to the chamber, and then a measured quantity of radon was introduced. Fans were operated briefly to ensure mixing and then turned off for the duration of the run.

Table 1
 Typical Examples of the Effect of Aerosol Concentration on the
 Collection of Radon Decay Products by 40-mesh Nickel Screens
 (5-min collections at 3.17 l/min (3.94 cm/sec))

Elapsed Time (min)	Smoke Conc.* (%)	Collector†	Measured Counts‡		Count Ratio§	Radon Equivalent (10 ⁵ pCi/m ³)		Fraction Collected†† (%)	Screen Efficiency‡‡ (%)	
			C ₁₋₁₁	C ₆₁₋₇₁		Collected¶	Added**			
Run 1: Radon added to 1,225-m ³ chamber containing polydisperse DOP aerosol (approx equivalent to 0.3-μ dia)										
132	0.56	Screen	472	332	0.703	0.75	52.9	1.4	1.70 (0.36)	
		Filter	131430	53917	0.415	43.2		81.7		
1077	0.25	Screen	562	492	0.875	1.58	45.8	3.4	4.33 (0.49)	
		Filter	115254	45830	0.397	34.9		76.2		
1570	0.17	Screen	745	712	0.960	2.93	40.9	7.2	8.46 (0.71)	
		Filter	103122	41381	0.401	31.7		77.5		
2552	0.063	Screen	1062	1132	1.066	6.70	36.0	18.6	22.9 (1.29)	
		Filter	76836	30159	0.393	22.6		62.8		
2917	0.045	Screen	1382	1482	1.072	8.72	33.0	26.4	30.7 (2.06)	
		Filter	65715	25995	0.396	19.7		59.7		
3982	0.015	Screen	1592	1512	0.950	6.28	28.4	22.1	37.6 (4.56)	
		Filter	33293	13397	0.402	10.4		36.6		
4355	0.008	Screen	2121	1971	0.929	7.43	26.4	28.1	46.6 (6.73)	
		Filter	29370	11456	0.390	8.50		32.2		
5492	0.003	Screen	2141	1991	0.930	7.50	22.3	33.6	65.2 (14.4)	
		Filter	12750	5147	0.404	4.00		17.9		
7192	6 × 10 ⁻⁴	Screen	2274	1874	0.824	5.31	16.9	31.4	75.4 (29.1)	
		Filter	5549	2233	0.402	1.73		10.2		
9727	7 × 10 ⁻⁵	Screen	1184	1034	0.873	3.24	12.2	26.6	85.9 (38.3)	
		Filter	1910	727	0.381	0.53		4.3		
11292	2 × 10 ⁻⁵	Screen	1512	1162	0.769	2.93	8.64	33.9	86.4 (53.7)	
		Filter	1304	556	0.426	0.46		5.3		
14175			Polydisperse DOP added							
14370	0.65	Screen	35	0	—	—	3.72	—	(0.47)	
		Filter	7279	3033	0.417	2.47		66.4		
15516	0.23	Screen	15	15	1.00	0.07	3.07	2.3	3.0 (0.24)	
		Filter	6005	2598	0.433	2.26		73.6		
Run 2: Radon added to 1,225 m ³ chamber containing 0.3-μ dia DOP aerosol										
182	0.76	Screen	425	265	0.624	0.45	73.6	0.6	0.65 (0.22)	
		Filter	188582	80830	0.429	69.2		94.0		
1287	0.025	Screen	1815	1955	1.077	11.9	61.0	19.5	27.9 (1.62)	
		Filter	110199	42130	0.382	30.8		50.5		
1435	0.017	Screen	2225	2215	0.996	10.0	57.7	17.3	25.1 (2.03)	
		Filter	107166	40930	0.382	29.9		51.8		
1630	1.8 × 10 ⁻³	Screen	5525	4865	0.884	16.1	55.6	29.0	71.5 (20.1)	
		Filter	21969	8583	0.391	6.42		11.5		
2722	6.8 × 10 ⁻⁵	Screen	5370	4850	0.903	16.9	47.2	35.8	93.5 (80.1)	
		Filter	1334	778	0.583	1.17		2.5		
3073	5 × 10 ⁻⁶	Screen	5510	4910	0.891	16.6	42.9	38.7	90.9 (84.2)	
		Filter	1031	738	0.716	1.67		3.9		
4157	2 × 10 ⁻⁷	Screen	3730	3210	0.860	9.92	36.4	27.3	92.5 (89.4)	
		Filter	442	331	0.749	0.80		2.2		
4492	1 × 10 ⁻⁸	Screen	6430	4630	0.720	10.6	33.3	31.8	93.1 (85.7)	
		Filter	1069	593	0.555	0.79		2.4		

*100% on the smoke meter = 5.7 × 10⁶ particles/cm³ of 0.3-μ DOP; values below 0.008% are based on extrapolation of the measured rate of aerosol loss to walls (Run 1) or controlled removal of aerosol by filtration (Run 2).

†40-mesh nickel screen in series with a Gelman A glass-fiber backup filter.

‡Counts on standardized counter as described in Ref. 3.

§Ratio of 61-71-min count to 1-11-min count following the end of the collection.

**Based on the radon equivalent necessary to give the measured count and count ratio.

††Corrected for radon loss through decay and sampling.

‡‡Difference between this total and 100% represents the loss of radon daughters to the walls of the chamber.

¶¶Based on the radon equivalent; the values in parentheses are based on comparison of the initial count rates of the screen and the filter.

Radioactivity collections were made by drawing a measured amount of air sequentially through a 40-mesh metal screen superimposed on a glass-fiber filter of essentially 100% retentivity; aerosol concentrations were measured before and after each filter collection. Sufficient time was allowed between collections for secular equilibrium between radon and its decay products to become re-established in the chamber. The duration of the collections was accurately timed (either 5.00 or 20.00 min); radioactivity measurements were made simultaneously on the screen and filter using intercalibrated and standardized counters as described previously (3).

Several points can be readily noted from the data in Table 1: (a) the fraction of the total radioactivity collected by the screen increased as the aerosol concentration decreased; i.e., the screen was a more efficient collector at low aerosol concentrations; (b) the count ratio (ratio of the 61-through-71-min count to the 1-through-11-min count) was higher on the screen, indicating deposition of a RaA-rich component there; and (c) the count ratio of the activity deposited on the backup filter was essentially that expected of an equilibrium mixture of radon decay products. The relationship between the age of the mixture and the count ratio, and the effect of excess RaA on the count ratio of an equilibrium mixture of radon decay products is discussed in the Appendix.

From theoretically derived calibration curves (3) it is possible to relate the quantity of radioactivity and its count ratio during decay to the quantities of radon from which the screen and filter radioactivities are derived. Since the total amount of radon in the chamber at any time is known (radon added less that removed by decay and during sampling), it is possible to calculate the relative amounts of radon giving rise to "free" RaA (from the screen), to an equilibrium mixture of decay products (from the filter), and to deposition on the walls (total radon less the above two fractions). From the Fraction Collected column of Table 1 it is apparent that collection by the walls becomes increasingly important as the aerosol content is reduced. The limiting value obtained (near 70% deposition of RaA on the walls in the absence of aerosol) is a function both of the surface-to-volume ratio of the chamber and the extent of convective mixing within the chamber. The effect of aerosol concentration on the distribution of radioactive decay products from radon within the 1.225-m³ chamber is shown graphically in Fig. 1.

Collection Efficiency of 40-Mesh Nickel Screens for Unattached RaA

The previous series of experiments gave some information about the collection efficiency of nickel screens toward unattached RaA, but only at a fixed linear velocity of air flow (3.94 cm/sec). A new series of studies was undertaken to determine the effect of air velocity on retentivity, as this would shed some light on the mechanism of collection (the relative importance of diffusion, interception, and impaction processes). Also, to simplify the interpretation of the radioactivity data two new steps were added to the process.

Prior to each run the chamber atmosphere was recycled through an absolute filter sufficiently to remove in excess of 90% of the particulate matter (including both attached and unattached RaA, RaB, and RaC atoms) and then allowed to stand 10 min for convective air motions to cease and for RaA to approach equilibrium with radon in the chamber. A second identical screen was used behind the first, so that the air sample passed in sequence through two identical screens before passing through the glass-fiber filter. This ensured that comparable radioactivity was collected by the two screen collectors (i.e., unattached RaA), while any radioactivity associated with larger particulates passed through. Hence, it was possible to calculate the retention efficiency of the screen for RaA by treating the radioactivity collected on the two screens as the first two terms in a geometric progression: $s = a/(1 - r)$, where s is the sum of n terms ($n = \infty$), r is the common ratio (less than unity), and a is the first term. Thus $a/s = 1 - r$, and retention

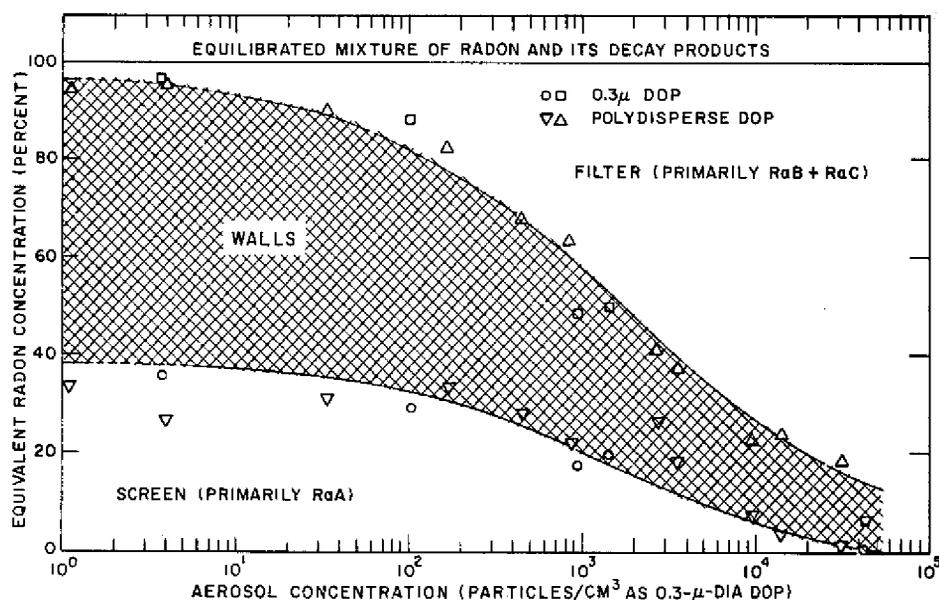


Fig. 1 - Competition of aerosol and wall surfaces for attachment of short-lived radon decay products

efficiency R in percent is $R(\%) = 100(1 - r)$. The common ratio r is that obtained by dividing the count on the second screen by that on the first.

Experimental results obtained under three different sampling conditions are listed in Table 2. In the first case the two screens were separated by a thin gasket, and in the other cases separation was maintained at 2.5 and 5.0 cm. In the latter two cases removable sleeves of aluminum foil were put in the connecting sections of tubing of the same effective diameter as the filters and counted simultaneously with the filter and screens. Corrections, usually of minor importance, were made for deposition on this surface. In all cases the radioactivity collected by each pair of screens was essentially identical in decay characteristics and corresponded to a mixture in excess of 95% RaA; the corresponding final filter was measurably leaner in RaA, particularly at the low flow rates, at which RaA deposition on the screens was nearly complete.

The results of the three different experimental runs were essentially identical, as indicated in Fig. 2, where a rectilinear relationship was obtained between $\log R$ (retention) and the square root of linear velocity over the range of 4 to 140 cm/sec. (An equivalent straight line was obtained in plots of the log of penetration vs the reciprocal of the velocity.) The inverse relationship between retention and flow velocity indicates a diffusion-controlled process. Before calculations of diffusion constants can be made, it will be necessary for these experiments to be repeated with a less complicated aerodynamic system. This could be done by using a parallel array of wires in place of the crossed mesh of a screen.

Retention Efficiency of Filters

The retention efficiency of several filter materials toward unattached RaA is listed in Table 3 for different flow velocities. The experiment was carried out as described in the previous section by comparing the radioactivity collected on two identical filters in series; an absolute filter was used to collect the material penetrating the first two filters.

Table 2
Collection Efficiency of 40-Mesh Nickel Screens for Unattached RaA (^{218}Po)

Air Vel.* (cm/sec)	Smoke Conc.† (particles per cc)	Collector‡	Activity§ (counts/10 min)		Count Ratio¶ (C_{61-71}/C_{1-11})	Retention by First Screen** , †† (%)
			C_{1-11}	C_{61-71}		
Superimposed screens (separation ca. 1.5 mm)						
1.93	0	Screen 1	4440	4040	0.910	96.5
		Screen 2	155	106	(0.684)	
		Filter	1356	496	0.366	
3.94	0	Screen 1	8720	7840	0.899	92.0
		Screen 2	696	590	0.848	
		Filter	627	304	0.485	
4.0	0	Screen 1	2500	2130	0.852	89.0
		Screen 2	274	274	(1.00)	
		Filter	77	48	(0.62)	
5.66	0	Screen 1	9720	7920	0.815	86.6
		Screen 2	1305	996	0.763	
		Filter	1154	597	0.517	
8.05	0	Screen 1	12040	9480	0.787	77.7
		Screen 2	2684	2167	0.807	
		Filter	1953	1346	0.689	
8.2	0	Screen 1	2300	2120	0.922	73.5
		Screen 2	609	619	1.02	
		Filter	324	253	(0.78)	
10.95	0	Screen 1	13520	11840	0.876	69.3
		Screen 2	4148	3472	0.837	
		Filter	4341	3168	0.730	
13.4	0	Screen 1	15240	12920	0.848	63.8
		Screen 2	5522	4680	0.848	
		Filter	5384	4099	0.761	
13.75	0	Screen 1	2530	2350	0.929	66.6
		Screen 2	846	796	0.941	
		Filter	668	555	0.831	
15.6	0	Screen 1	18874	15714	0.833	52.2
		Screen 2	9022	7514	0.833	
		Filter	14747	10213	0.693	
19.9	0	Screen 1	17634	—	—	50.0
		Screen 2	8820	8326	0.944	
		Filter	12763	10982	0.860	

(Table continues)

Table 2 (Continued)

Air Vel.* (cm/sec)	Smoke Conc.† (particles per cc)	Collector‡	Activity§ (counts/10 min)		Count Ratio¶ (C ₆₁₋₇₁ /C ₁₋₁₁)	Retention by First Screen**,†† (%)
			C ₁₋₁₁	C ₆₁₋₇₁		
20.25	0	Screen 1	2800	2760	0.986	58.6
		Screen 2	1160	1151	0.992	
		Filter	1498	1245	0.831	
29.1	0	Screen 1	20874	19334	0.926	41.7
		Screen 2	12160	11033	0.907	
		Filter	27943	23693	0.848	
37.5	0	Screen 1	5594	4874	0.871	33.4
		Screen 2	3723	3249	0.873	
		Filter	7056	5517	0.782	
41.0	0	Screen 1	26074	22314	0.856	34.1
		Screen 2	17183	15017	0.874	
		Filter	50329	40310	0.801	
60.0	0	Screen 1	12830	—	—	26.1
		Screen 2	9486	—	—	
		Filter	24726	—	—	
70.0	0	Screen 1	6994	6314	0.903	29.1
		Screen 2	4961	4535	0.914	
		Filter	15233	12601	0.827	
85.0	0	Screen 1	7074	5834	0.825	18.2
		Screen 2	5783	4612	0.798	
		Filter	32518	20879	0.642	
102.5	0	Screen 1	8794	7514	0.854	18.1 20.6§§
		Screen 2	7204	6005	0.834	
		Filter	26688	20576	0.771	
110.	0	Screen 1	3524	2994	0.850	14.0 12.4§§
		Screen 2	3030	2586	0.853	
		Filter	21876	13861	0.634	
127.5	0	Screen 1	3974	3704	0.932	10.4 18.3§§
		Screen 2	3562	3262	0.916	
		Filter	14140	12035	0.851	
140.	0	Screen 1	4174	3734	0.907	9.1 15.3§§
		Screen 2	3795	3350	0.883	
		Filter	19326	15076	0.780	

(Table continues)

Table 2 (Continued)

Air Vel.* (cm/sec)	Smoke Conc.† (particles per cc)	Collector‡	Activity§ (counts/10 min)		Count Ratio¶ (C ₆₁₋₇₁ /C ₁₋₁₁)	Retention by First Screen**,†† (%)
			C ₁₋₁₁	C ₆₁₋₇₁		
Screens separated by 2.5 cm††						
3.4	0	Screen 1	2630	2340	0.890	93.8
		Screen 2	164	135	0.823	
		Filter	81	10	—	
5.7	0	Screen 1	8304	7094	0.854	86.1 (85.5)
		Screen 2	1157	896	0.774	
		Filter	493	301	(0.610)	
		Liner	58	—	—	
10.9	0	Screen 1	8114	7634	0.941	67.6 (65.1)
		Screen 2	2630	2301	0.875	
		Filter	1596	1211	0.759	
		Liner	313	—	—	
11.1	0	Screen 1	1604	1444	0.900	73.6 (70.4)
		Screen 2	423	319	0.754	
		Filter	128	78	(0.61)	
		Liner	72	—	—	
18.1	0	Screen 1	12034	11514	0.956	57.4 (54.9)
		Screen 2	5125	4555	0.889	
		Filter	5138	4480	0.872	
		Liner	553	—	—	
21.2	0	Screen 1	4160	3820	0.918	59.1 (56.4)
		Screen 2	1702	1547	0.909	
		Filter	1791	1457	0.813	
		Liner	202	—	—	
24.2	0	Screen 1	10954	9794	0.894	51.2 (45.1)
		Screen 2	5348	4806	0.898	
		Filter	9075	7334	0.808	
		Liner	1500	—	—	
39.4	0	Screen 1	7480	6680	0.893	38.6 (38.1)
		Screen 2	4593	4129	0.899	
		Filter	9641	8427	0.874	
		Liner	100	—	—	
43.9	0	Screen 1	5514	4834	0.877	35.3 (34.4)
		Screen 2	3568	3123	0.875	
		Filter	7415	5553	0.749	
		Liner	143	—	—	

(Table continues)

Table 2 (Continued)

Air Vel.* (cm/sec)	Smoke Conc.† (particles per cc)	Collector‡	Activity§ (counts/10 min)		Count Ratio¶ (C ₆₁₋₇₁ /C ₁₋₁₁)	Retention by First Screen**,†† (%)
			C ₁₋₁₁	C ₆₁₋₇₁		
67.1	0	Screen 1	6874	6114	0.889	25.6 27.0§§
		Screen 2	5115	4226	0.826	
		Filter	13446	10532	0.783	
		Liner	—	—	—	
96.0	0	Screen 1	5634	4874	0.865	19.5 (15.8)
		Screen 2	4535	3868	0.853	
		Filter	16887	13648	0.808	
		Liner	1340	—	—	
118.	0	Screen 1	6004	5154	0.858	18.7 (16.6)
		Screen 2	4883	4206	0.861	
		Filter	19761	15713	0.795	
		Liner	775	—	—	
125.	0	Screen 1	4280	3820	0.892	20.3 (17.5)
		Screen 2	3413	2901	0.850	
		Filter	14377	11584	0.806	
		Liner	669	—	—	
Screens separated by 5.0 cm‡‡						
3.1	0	Screen 1	3168	2868	0.905	95.7
		Screen 2	135	155	—	
		Filter	245	113	—	
		Liner	—	—	—	
5.1	0	Screen 1	5229	4909	0.939	89.6
		Screen 2	544	477	0.877	
		Filter	346	204	(0.590)	
		Liner	—	—	—	
7.5	0	Screen 1	5070	4750	0.937	81.7 (81.0)
		Screen 2	928	822	0.886	
		Filter	554	372	0.671	
		Liner	40	—	—	
10.3	0	Screen 1	6230	6150	0.987	76.7
		Screen 2	1450	1383	0.954	
		Filter	1030	757	0.735	
		Liner	—	—	—	
13.8	0	Screen 1	5960	5590	0.938	64.8
		Screen 2	2098	1915	0.913	
		Filter	1243	858	0.690	
		Liner	—	—	—	

(Table continues)

Table 2 (Continued)

Air Vel.* (cm/sec)	Smoke Conc.† (particles per cc)	Collector ‡	Activity§ (counts/10 min)		Count Ratio¶ (C ₆₁₋₇₁ /C ₁₋₁₁)	Retention by First Screen**,†† (%)
			C ₁₋₁₁	C ₆₁₋₇₁		
17.1	0	Screen 1	6436	5706	0.886	57.1 (55.4)
		Screen 2	2761	2374	0.860	
		Filter	3854	2822	0.732	
		Liner	200	—	—	
24.1	0	Screen 1	5314	5014	0.944	47.0
		Screen 2	2817	2585	0.918	
		Filter	4384	3544	0.808	
		Liner	—	—	—	
30.9	0	Screen 1	3519	3189	0.906	42.5
		Screen 2	2024	1782	0.880	
		Filter	3787	3099	0.818	
		Liner	45	—	—	
33.6	0	Screen 1	2760	2420	0.877	42.5 (42.0)
		Screen 2	1586	1334	0.841	
		Filter	2287	1760	0.769	
		Liner	37	—	—	
44.8	0	Screen 1	3200	2740	0.856	33.2 36.6§§
		Screen 2	2137	1847	0.864	
		Filter	3404	2787	0.819	
		Liner	—	—	—	
79.5	0	Screen 1	3070	2560	0.834	21.2 28.5§§
		Screen 2	2420	2147	0.887	
		Filter	8060	6187	0.768	
		Liner	—	—	—	
100	0	Screen 1	1230	1100	0.894	13.5 20.4§§
		Screen 2	1064	967	0.909	
		Filter	3728	2848	0.764	
		Liner	—	—	—	
123	0	Screen 1	1090	940	0.862	12.2 18.1§§
		Screen 2	957	841	0.878	
		Filter	3981	3091	0.776	
		Liner	—	—	—	
DOP smoke added to above						
8.4	1 × 10 ⁶	Screen 1	27	10	—	— 0.23§§
		Screen 2	29	19	—	
		Filter	11588	4909	0.424	
		Liner	—	—	—	

(Table continues)

Table 2 (Continued)

Air Vel.* (cm/sec)	Smoke Conc.† (particles per cc)	Collector‡	Activity§ (counts/10 min)		Count Ratio¶ (C ₆₁₋₇₁ /C ₁₋₁₁)	Retention by First Screen**,†† (%)
			C ₁₋₁₁	C ₆₁₋₇₁		
27.9	6 × 10 ³	Screen 1	68	—	—	— 0.20§§
		Screen 2	97	—	—	
		Filter	30735	12681	0.413	
		Liner	0	—	—	

*Velocity was adjusted by changing the air flow rate and the filter area.

†Chamber atmosphere was cleaned of particles before the start of the experiment, and the air was recycled through an absolute filter prior to each run.

‡Two 40-mesh nickel screens were followed by a Gelman A glass-fiber filter.

§Counted on a calibrated counter at fixed time intervals following a 5-min collection period.

¶Values in parentheses are not statistically significant due to low count rates.

**Retention is based on the relation $R(\%) = 100(1 - A_2/A_1)$, where A_1 and A_2 are the measured activities of the first and second screens, respectively.

††Values in parentheses have been corrected for deposition of activity on the wall surface between the screens.

‡‡Radioactivity deposited on the detachable aluminum liner covering the wall surface between the collecting screens.

§§These values are based on the fraction of the total recovered activity deposited on screen 1.

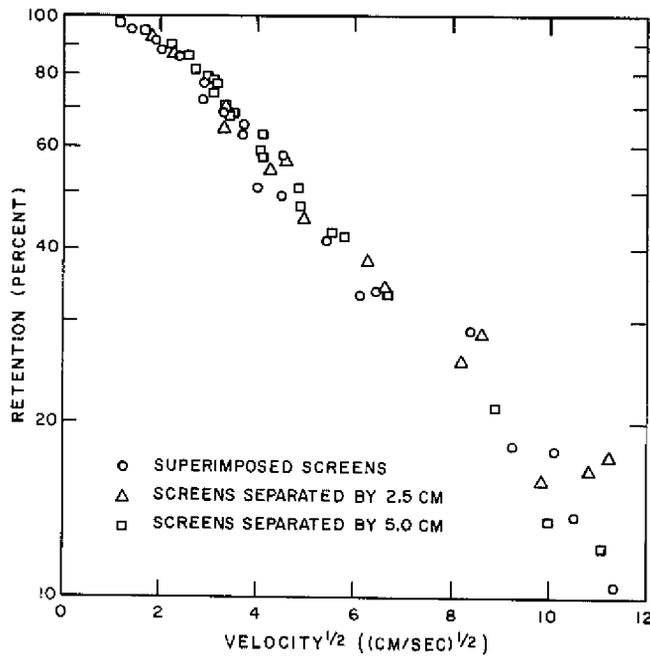


Fig. 2 - Collection efficiency of 40-mesh nickel screens for unattached RaA (²¹⁸Po) as a function of air velocity: (a) Superimposed screens; (b) Screens separated by 2.5 cm; (c) Screens separated by 5.0 cm

Table 3
Determination of the Retention Efficiency of Some Filter Papers Toward
Unattached RaA (^{218}Po) from Radon Decay*

Filter	Air Velocity (cm/sec)	Measured Counts†			Count Ratio on Initial Filter‡	Collection Efficiency of Initial Filter	
		Filter 1	Filter 2	Final Filter		Pct§	Fraction¶
IPC 1478	1.2	1930	0	48	—	100.0	97.6
	4.0	9990	0	0	—	100.0	100.0
	5.6	14470	44	696	0.770	99.7	95.1
	13.1	40300	15	87	0.983	99.96	99.7
	50	11510	0	30	0.805	100.0	99.7
	51	42401	125	251	—	99.7	99.1
	100	8230	253	19	0.859	96.9	96.8
Type 5G	4.0	9750	24	29	—	99.8	99.5
	50	10830	0	20	0.859	100.0	99.8
	85	9110	10	19	0.872	99.9	99.7
	100	8197	10	—	0.876	99.9	—
Whatman 41	4.0	9510	8	0	0.777	99.9	99.9
	50	7950	20	0	0.839	99.7	99.7
Microsorban	4.0	5990	65	0	0.780	98.9	98.9
HV-70	50	2470	10	0	0.927	99.6	99.6
Polypore AM-1	50	4690	40	10	0.904	99.1	98.9
Whatman GF/A	4.0	4950	5	0	0.814	99.9	99.9
	50	6630	0	0	0.879	100.0	100.0
Gelman A	4.0	9990	0	Not used	—	100.0	—
	50	4088	0	Not used	0.893	100.0	—

*Chamber was cleaned of particles by filtration prior to each determination.

†Initial and second filters were the materials being tested; the final filter was a Gelman A glass-fiber filter.

‡Ratio of counts at 61-71 min to counts at 1-11 min following a 5-min collection of activity on the filter pack.

§Calculated from the expression Retention (%) = $100(1 - \text{filter 2 count}/\text{filter 1 count})$.

¶Fraction of the total radioactivity collected by the first filter in the pack

Within experimental error, even the poorest of these filters was found to be 100% effective toward these atomic-sized particles. In a few cases involving the poorer filter media, the radioactivity on the final filter exceeded that on the second filter; this was apparently due to the presence of aerosol particles to which RaA atoms become attached and were transported through the filter without collection. Penetration of particulate radioactivity through these poorer filters is readily accomplished via aerosol particles in the 0.3- μm size range, since diffusion of aerosols in this size range is orders of magnitude slower than for atomic-sized particles.

These results indicate that filters having low retention for submicron aerosols can be good collectors for gaseous molecules or dispersions of atomic-sized particles, provided that such materials become irreversibly attached to the filter on contact. This condition is normally attained with vapors of high boiling materials (metals, salts, metal oxides, etc.) and can be obtained for other volatile materials by proper surface treatment of the individual fibers which comprise the filter matrix.

In a second series of experiments (Table 4), polydisperse DOP aerosol (nominally $0.3 \mu\text{m}$ in diameter) was tagged with radon decay products in near secular equilibrium with the radon parent, and the collection efficiency of the filters was redetermined as a function of linear velocity. Though decay measurements indicated the presence of some excess of the first members of the decay series, there was no evidence of fractionation of radioactivity among the filters of a given collection (i.e., the decay rates were similar). Comparison of the fraction of the collected radioactivity accumulated by the two filters, however, did suggest that aerosol fractionation was occurring as the particles passed through the series of filters, with the second filter being exposed to an aerosol of somewhat smaller average size. In these experiments it was not possible to rely on the ratio of activity on the two test filters to give a measure of collection efficiency because of this fractionation; with screens the aerosol collection efficiency was so low that no measurable fractionation occurred.

Penetration of the IPC 1478 filter was greatest at the lower velocities (retention increased with increasing air velocity) as would be expected for an impaction process. This was opposite from the result obtained for screens in the absence of aerosol, where diffusion was the controlling process. The measured collection efficiency of this and the other filters was in accord with efficiency determinations based on smoke concentration measurements or on radioactivity collection of atmospheric aerosols (6).

CONCLUSIONS

Particles of atomic dimensions which become irreversibly attached to surfaces on contact are readily removed from an air stream by passage through coarse fibrous filters or through screens, whereas submicron aerosols readily penetrate such media. The inverse relationship between the efficiency of removal and the air velocity indicates that diffusion is the mechanism primarily responsible for deposition of these small particles. The great diffusivity of the atomic-sized primary radon decay products and their ready attachment to any available surfaces permits them to be used to tag aerosol dispersions and serve as a radioactive tracer for such materials, and also to be used in the absence of aerosol to study the diffusion process.

The data presented in this report have indicated how the short-lived radon decay products may be employed in evaluating the efficiency of filter media. Such measurements can be extended to size ranges and to concentration levels below those which can be conveniently made by other techniques.

These results also prove that atomic- or molecular sized particles (gaseous or vapor molecules) can be very simply removed from an air stream by filtration, provided that they have a large attachment coefficient for the collecting medium; however, if they become attached to aerosols, such as the normal atmospheric aerosols, much more rigorous filtration is required to prevent their penetration into a protected air space.

Table 4
Determination of the Efficiency of Some Filter Papers Toward
DOP Aerosol Tagged with Radon Decay Products*

Filter	Air Velocity (cm/sec)	DOP Conc. (%)†	Measured Counts‡			Calculated Collection Efficiency (%)		
			Filter 1	Filter 2	Final Filter	Filter 1§	Filter 2¶	From Retention Ratio**
IPC 1478	5.5	19	5710	5161	24533	16.1	17.4	9.6
	8.1	18	2150	1578	7514	19.1	17.4	26.6
	11.7	15	12830	9452	54452	16.7	14.8	26.3
	12.5	12	4800	4584	19156	16.8	19.2	4.5
	12.5	7	3300	2661	19641	12.9	11.9	19.4
	21.2	8	5630	4635	25210	15.9	15.5	17.7
	23.5	1.5	4270	3501	23720	13.6	12.9	18.0
	36.5	11	10790	7843	44967	17.0	14.9	27.3
	60	0.9	2750	1801	11304	17.3	13.7	34.5
	64	7	12830	8359	46910	18.8	15.1	34.8
	65.2	10	27710	12771	62671	26.9	16.9	53.9
	105	5	29030	10220	56000	30.5	15.4	64.8
	110	14	31190	23903	66152	25.7	26.5	23.4
	117	11	19230	7307	41784	28.1	14.9	62.0
Type 5G	4.0	6	13350	759	116	93.8	(86.7)	94.3
	8.1	14	10430	405	58	95.7	(87.5)	96.1
	21.2	7	18270	1437	464	90.6	75.6	92.1
	64.5	7	55210	1892	435	96.0	81.3	96.6
	75	9	35270	2064	484	93.3	81.0	94.1
	97.5	6	39310	2500	561	92.8	81.7	93.6
	112.5	1.5	36510	2317	590	92.6	79.7	93.7
	150	0.5	24710	779	19	96.9	(97.6)	96.9
Whatman 41	62.5	0.5	9670	33	48	99.2	—	99.7
Microsorban	62.5	0.5	9830	20	0	99.8	—	99.8
HV-70	8.1	8	10610	0	0	100.0	—	100.0
	55	1.3	14910	14	48	99.6	—	99.9
Polypore Am-1	65	0.9	23150	38	0	99.8	—	99.8
Whatman GF/A	62.5	0.6	12710	0	39	99.7	—	99.7
Type 6	62.5	0.8	13470	Not used	20	99.9	—	—
Gelman A	8.1	9	10590	Not used	0	100.0	—	100.0
	57.5	1.1	15605	Not used	19	99.9	—	99.9

*5-min collections of radon decay products in near equilibrium with radon in the chamber containing polydisperse DOP ("effective" dia near 0.3 μ).

†100% corresponds to 5.7×10^6 0.3- μ -dia DOP particles per cm³.

‡First two filters in sequence were of the material being tested; the final filter was a Gelman A glassfiber filter. Filters were counted on a calibrated β -counter for 10 min starting 1 min after the end of the collection. The counter background was approximately 30 counts/min.

§Fraction of total activity retained by the first filter in the pack.

¶Fraction of activity passing through the first filter and retained by the second filter. Values in parentheses are of low reliability due to low counts.

**Retention calculated from relation $R(\%) = 100(1 - A_2/A_1)$ where A_1 and A_2 refer to counts on filters 1 and 2.

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Appendix

β ACTIVITY OF DECAY PRODUCTS FROM RaA COLLECTIONS

Radon gas (^{222}Rn) diffusing from the soil is initially free of short-lived decay products, but immediate in-growth of RaA (^{218}Po , 3.05-min half-life) takes place, followed in turn by growth of RaB (^{214}Pb , 26.8-min half-life) and RaC (^{214}Bi , 19.7-min half-life). After several hours, secular equilibrium between the radon and its short-lived descendants is effectively established.

The effect on the distribution of decay products of the continuous addition of radon to a fixed volume of air has been considered previously.* Here the condition is considered in which a portion of the RaA and all of the longer lived descendants of radon are missing from the air mass. This condition can be obtained when the average lifetime of the decay products in the air before attachment to wall surfaces is comparable to the half-life of RaA for radioactive decay and shorter than the half-lives of RaB and RaC. Thus, for a residence half-time of 3 min for these unattached atomic-sized "solid" particles, airborne RaA should be reduced to near 50% of its equilibrium value, and RaB and RaC should be reduced to near zero values.

The accumulation of radon decay products on a filter during the selective filtration of RaA from air containing RaA in secular equilibrium with radon gas is presented in Table A1. The status of the α -emitting RaA and its β -emitting descendants RaB and RaC at 1-min intervals is given assuming an initial condition of 100 pCi/m³ of radon in an infinite air mass and filtration at a flow rate of 1 m³/min through a filter of 100% effectiveness for RaA. RaB and RaC are produced on the filter as a result of radioactive decay of the collected RaA; the gaseous parent radon is not collected by the filter. This situation would exist in the atmosphere for that portion of the radon whose RaB and RaC descendants had been removed by deposition.

In Table A2 calculated results of the radioactive decay of the collected RaA and the in-growing RaB and RaC accumulated during 5- and 20-min filtration periods are presented for seven consecutive 10-min periods after an initial 1-min delay at the end of filtration to allow for sample manipulation.

In Table A3 equipment calibration data are used to convert calculated disintegration rates to β -activity rates for two time periods (1-11 min and 61-71 min) following termination of 5- and 20-min sampling times. Counting is done through a window of 91 mg/cm² to eliminate counting α particles and to accentuate the effect of the higher energy RaC β -component in the mixture of decay products. The derived β -activity ratios during the two time periods are characteristic of the in-growth and decay of descendants of RaA collected under the specified conditions. The calibration points (activity ratios) corresponding to a fresh radon input to the atmosphere (age of the airborne mixture equals zero) are combined in Fig. A1 with those for older airborne mixtures (from NRL Report 6229) to give plots of activity ratios vs residence time of the radon in the atmosphere.

*L.B. Lockhart, Jr., and R.L. Patterson, Jr., "The Extent of Radioactive Equilibrium Between Radon and Its Short-Lived Daughter Products in the Atmosphere," NRL Report 6374, Apr. 1966.

Table A1
 Collection of RaA in Equilibrium with 100 pCi/m³ of Radon
 (no RaB or RaC present; filtered at 1 m³/min with 100% retentivity)

Elapsed Time (min)	Atoms			Activity (dis/min)		
	RaA	RaB	RaC	RaA	RaB	RaC
1	879	98	1	99	1	0.02
2	1580	369	7	277	6	0.15
3	2139	774	21	420	15	0.50
4	2584	1281	47	533	27	1.20
5	2939	1863	85	623	41	2.32
6	3222	2502	137	695	56	3.91
7	3446	3181	205	753	73	6.02
8	3626	3888	287	798	91	8.66
9	3769	4613	385	835	110	11.84
10	3884	5349	498	864	129	15.55
11	3975	6088	626	887	148	19.79
12	4047	6827	768	906	167	24.55
13	4105	7562	924	920	186	29.80
14	4151	8289	1093	932	205	35.52
15	4188	9008	1275	942	223	41.70
16	4216	9715	1468	949	242	48.30
17	4240	10410	1673	955	260	55.31
18	4258	11091	1888	959	278	62.69
19	4273	11759	2113	963	295	70.43
20	4285	12413	2346	966	312	78.50

Table A2
Radioactive Decay of RaA and Its Descendants Following
Collection of RaA on a Filter of 100% Retentivity
(from 100 pCi/m³ radon sampled at 1 m³/min)

Time Interval (min)	Radioactive Decays					
	RaA	RaB	RaC	RaA	RaB	RaC
0-1	5.00-min collection			20.00-min collection		
	Sample removed from blower and placed in counter					
1-11	2099	878	172	3062	3432	1311
11-21	217	859	389	316	2915	1872
21-31	23	682	501	33	2280	2079
31-41	2	529	530	3	1764	2055
41-51	0	409	510	0	1362	1903
51-61	0	316	465	0	1052	1692
61-71	0	244	409	0	813	1463

Table A3
Calculated Activity Ratios at t = 1-11 and t = 61-71 min
from 5- and 20-min Collections of Pure RaA*

Decay Product	Activity for 1-11-min decay period		Activity for 61-71-min decay period	
	Dis/min	Counts/min†	Dis/min	Counts/min†
	5.00-minute collection			
RaB	877.5	15.80	243.9	4.39
RaC	171.7	13.50	408.7	32.12
Total β		29.30		36.51
	Ratio $\frac{C_{61-71}}{C_{1-11}} = 1.246$			
	20.00-minute collection			
RaB	3432.1	61.78	812.5	14.63
RaC	1310.8	103.03	1462.5	114.95
Total β		164.81		129.58
	Ratio $\frac{C_{61-71}}{C_{1-11}} = 0.786$			

*Radon concentration 100 pCi/m³; sampled at the rate 1 m³/min.

†Counting efficiency was 1.80% for RaB and 7.86% for RaC on standardized counter.

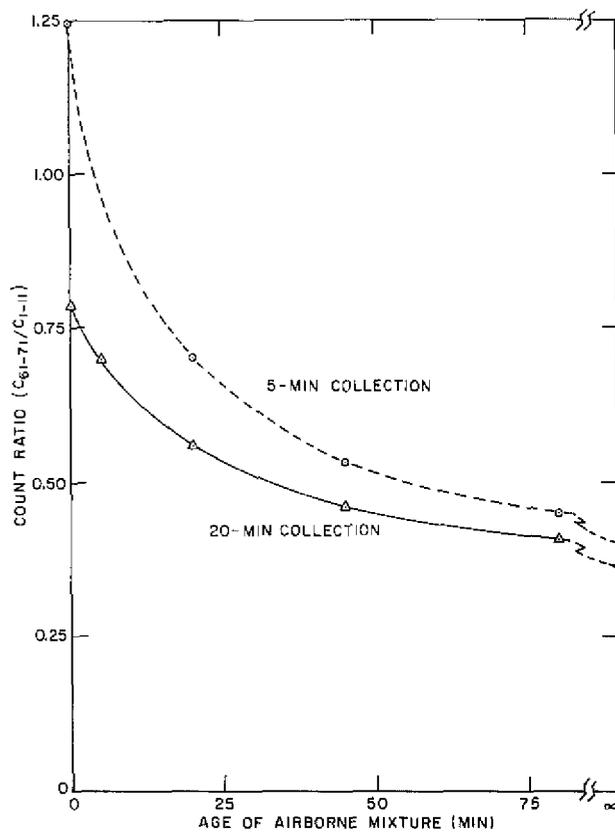


Fig. A1 - Relationship between the age of the radon series and the ratio of counts obtained at $t = 61-71$ to those at $t = 1-11$ minutes after collection and counting by standard procedure

Finally Fig. A2 presents the calculated count ratios expected for mixtures of radon decay products expressed in percentages of two terms: radon in equilibrium with RaA alone, and radon in secular equilibrium with RaA, RaB, and RaC. The first condition is approximately that corresponding to the unattached RaA component of the atmosphere ("free" RaA atoms or simple RaA-containing molecules), and the latter condition corresponds to RaA that has been attached to filterable airborne particles sufficiently long for its decay products RaB and RaC to have reached secular equilibrium with a portion of the radon. The graph of count ratio vs percentage radon giving unattached RaA shows that the count ratio is rather insensitive to the unattached RaA component until a large percentage of the RaA exists in the unattached condition.

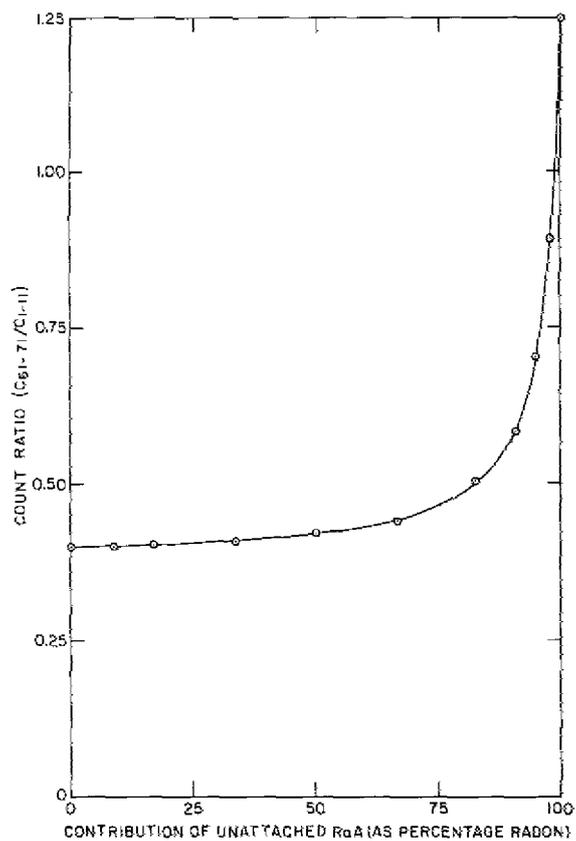


Fig. A2 - Effect of unattached RaA on the measured counting rate ratio (C_{61-71}/C_{1-11}) of an equilibrium mixture of short-lived radon decay products