

● *Paper*

A PRACTICAL E-PERM™ (ELECTRET PASSIVE ENVIRONMENTAL RADON MONITOR) SYSTEM FOR INDOOR ²²²Rn MEASUREMENT*

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Abstract—The technical and scientific basis for the measurement of indoor ²²²Rn concentration using an E-PERM™ (Electret passive environmental radon monitor) has been described in our earlier work. The purpose of this paper is to describe further development of a practical and convenient system that can be used routinely for indoor ²²²Rn measurement. The ion chamber is now made of electrically conducting plastic to minimize the response from natural γ radiation. A spring-loaded shutter method is used to cover and uncover the electret from outside the chamber. The electret voltage reader has been modified to improve the accuracy and the ease in operation. The calibration, performance, error analysis, and lower limits of detection for these standardized versions of E-PERMs are also described.

INTRODUCTION

THE SCIENTIFIC and technical basis for the measurement of ²²²Rn using an E-PERM™ has already been described in an earlier publication (Kotrappa et al. 1988).

Presently, we would like to describe two standardized versions of E-PERMs which are commercially available to perform short-term and long-term measurements of indoor ²²²Rn. (For further discussion in the paper, Rn means ²²²Rn unless otherwise mentioned.) Both versions have passed a series of tests conducted by the U.S. Environmental Protection Agency. These units differ substantially from the units described in our earlier work.

An electret is a charged Teflon[†] disk carrying a quasi-permanent electric charge. The charge of the electret produces a strong electrostatic field capable of collecting ions of opposite sign. The amount of charge that an electret carries is characterized by its surface potential, diameter, and thickness.

An E-PERM™ consists of a small chamber having an electret at the bottom and a filtered inlet at the top. Radiation from Rn gas entering the chamber and the decay products formed inside the chamber generate ions that are collected by the electret. An E-PERM™ functions as an integrating ionization chamber, wherein the electret serves not only as a source of an electrostatic field but also as a quantitative sensor. The drop in surface voltage of the electret over a known time period is a measure of

time-integrated ionization during that time interval. These data can be converted readily into Rn concentration. The desired sensitivity, dynamic range, and statistical accuracies can be programmed into the design parameters of an electret ion chamber to get an optimum performance for a specific Rn measurement situation.

DESIGN FEATURES OF E-PERM™ CHAMBER

Our earlier study indicated that it is desirable to use a low-Z (atomic number) material for the ion chamber to minimize the response to the natural environmental γ radiation. Accordingly, the present E-PERM™ chambers and the electret holders are made of electrically conducting plastic. It was also indicated in our study that a mechanism must be provided to keep the electret covered in order to eliminate undesired background during storage or transport. The cup-in-cup arrangement described in that work proved to be somewhat complicated for homeowner use. To overcome this deficiency, a novel spring-loaded piston mechanism was adopted to turn the instrument on and off; Fig. 1 shows this feature. When the E-PERM is not in use or when it is in transit, the electret cover is kept down very close to the electret. This effectively cuts off the electret field to the interior of the chamber and shuts off the E-PERM™. The electret cover is attached to a screwcap on top of the E-PERM™ that is tightened to lock the electret cover. When the E-PERM™ is used, the screwcap is unscrewed and a spring lifts the electret cover up and away from the electret and holds it there to turn the E-PERM™ to the "on" position.

The filtered inlet is necessary to allow Rn into the chamber while excluding Rn progeny or environmental

* E-PERM™ is a trademark of the product manufactured by Rad Elec Inc., Frederick, MD 21701.

† Teflon™ is a trademark of the product manufactured by E. I. Du Pont de Nemours and Co., Wilmington, DE 19898.

E-PERM™

Electret-Passive Environmental Radon Monitor (Schematic)

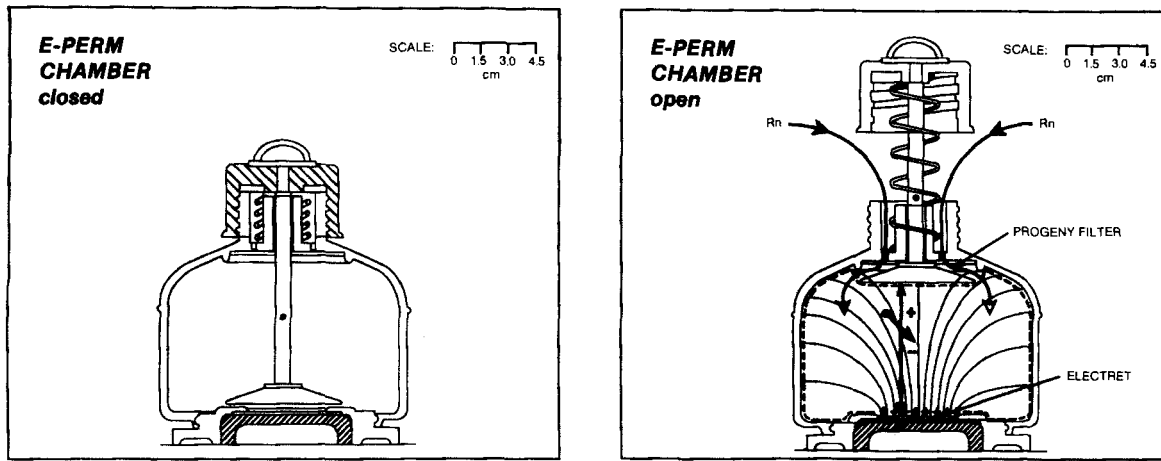


Fig. 1. Electret passive environmental ^{222}Rn monitor in electret-covered and electret-exposed conditions. E-PERM™ chamber closed condition is for storage, shipment, or handling prior to deployment. The E-PERM™ chamber open condition is for the actual measurement of ^{222}Rn .

ions. An annular filter over six small holes recessed in the top of the E-PERM™ serves this purpose (see Fig. 1). The recessed position reduces the chance of damage to the filter. The ratio of the area (0.3 cm^2) of the holes to the total volume (210 mL) of the chamber is chosen to give a sufficient diffusion delay time (Kotrappa et al. 1987). This ensures that the E-PERM™ has less than 10% response to ^{220}Rn and relatively quick response to ^{222}Rn .

The air volume in the commercial E-PERM™ is 210 mL, and it is shaped to optimize ion collection by the electret.

DESIGN FEATURES OF ELECTRET VOLTAGE READER

The electret surface potential voltmeter (sometimes called the electret voltage reader) has already been described (Kotrappa et al. 1988). A new version of this device is commercially available. The new instrument incorporates several improvements: 1) it reads out the electret voltage digitally in volts; 2) it automatically zeroes before every reading; 3) it holds the reading for up to 4 min; 4) it has an auto shut-off after 4 min; 5) its "on" switch is activated by the movement of the shutter; 6) it is small and portable, weighing about 0.5 kg; 7) it is powered by a single 9-V battery; and 8) it repeats voltage readings from 1 to 1999 V to $\pm 1 \text{ V}$.

DESIGN OF ELECTRET HOLDER

The electret holder is also made of electrically conductive plastic and is designed so that it screws directly into the bottom of the E-PERM™ chamber. When removed from the chamber, the electret can be kept covered with a cap that uses the same threads. A protective lip

around the electret fits the measuring receptacle in the reader with close reproducible tolerances. The electret is held firmly in place in the electret assembly, and both the assembly and the E-PERM™ are rugged and not affected by mechanical shocks.

ELECTRETS

Electrets are made and processed the same way as described in our earlier work. Polytetrafluoroethylene (PTFE) Teflon™ disks, 0.152 cm thick, are used for making electrets for short-term measurements (2 to 7 d) and electret disks made of Tetrafluoroethylene (FEP) Teflon™ disks 0.0127 cm thick are used for making electrets for long-term measurements (1 to 12 mo). These two electret types are referred to as short-term and long-term electrets, and when these are loaded into an E-PERM™ chamber, they are referred to as short-term E-PERMs and long-term E-PERMs, respectively. The sensitivity of the E-PERMs is inversely proportional to the thickness of the electret used. The sensitivities and dynamic ranges offered by these particular electret thicknesses have been selected to provide optimum performance for most indoor Rn measurements.

Calibration of E-PERMs

Equation (1) is used for calculating the Rn concentration from the measured parameters:

$$\text{RnC} = \frac{(V_i - V_f)}{(T)(CF)} - BG \quad (1)$$

where

RnC is the Rn concentration in Bq m^{-3} ;
T is the exposure period in days;

V_i and V_f are the measured initial and final electret voltages, respectively;

CF is the calibration factor in units of V per Bq m^{-3} d; and

BG is the Rn concentration equivalent of natural γ radiation background. A BG of $0.1 \mu\text{Gy h}^{-1}$ ($10 \mu\text{rad h}^{-1}$) was measured to be equivalent to 32Bq m^{-3} . A linear correction can be made to accommodate other BG values.

In our earlier work, we reported that a constant calibration factor can be used over an operating range of electret voltage from 200 V to 700 V. However, it was later observed that the calibration factor varied somewhat over this voltage range. This is probably due to the non-uniformity of the electrical field in the E-PERMTM chamber. Different calibration factors are now used with the commercial E-PERMs depending on the midpoint electret voltage, defined as the average of the initial and final electret voltage in any particular measurement. The procedure used to derive these values is discussed below.

Calibration procedures and results

A series of experiments were conducted with known Rn concentration wherein E-PERMS were exposed for

known time periods, and the changes in their electret voltages were measured.

Table 1 gives the data obtained during a calibration run for short-term E-PERMs. Five E-PERMs having nearly the same initial readings were grouped into a subset. Five such sets formed a total set. These were exposed simultaneously in a Rn chamber for the same time duration. The calibration factor (CF) was calculated for each measurement using eqn (1). An average of the standard deviations of the calibration factors was calculated and was less than 3% in each subset. Table 2 gives similar data for long-term E-PERMs. Equations (2) and (3) give linear regression equations for short- and long-term E-PERMs, respectively:

$$CF(ST) = 0.04241 + 0.0000338 \times \frac{(V_i + V_f)}{2} \quad (2)$$

$$CF(LT) = 0.00481 + 0.0000168 \times \frac{(V_i + V_f)}{2} \quad (3)$$

where

$CF(ST)$ and $CF(LT)$ are the calibration factors for short-term and long-term E-PERMs, respectively, in units of V per Bq m^{-3} d; and

Table 1. Calibration data for short-term E-PERMs. Exposure period was 2 d and 22 h. The ^{222}Rn chamber concentration was 1184Bq m^{-3} (32pCi L^{-1}).

No.	Initial volts (V)	Final volts (V)	Voltage drop (V)	Midpoint voltage (V)	Calibration factor (CF)	Average and SD of midpoint voltage	Average calibration factor and SD
1	300	132	168	216	0.04746		
2	297	128	169	213	0.04773		
3	286	97	189	238	0.05338		
4	296	130	166	213	0.04692		
5	303	136	167	210	0.04716	218 ± 10	0.04852 ± 0.0024
6	403	216	187	310	0.05283		
7	407	215	192	311	0.05424		
8	395	202	193	299	0.05451		
9	408	217	191	313	0.05395		
10	389	196	193	293	0.05600	305 ± 8	0.05431 ± 0.0010
11	506	317	189	412	0.05338		
12	493	292	201	393	0.05678		
13	504	305	199	404	0.05622		
14	502	300	202	401	0.05711		
15	497	304	193	401	0.05600	402 ± 6	0.05589 ± 0.0013
16	598	380	218	489	0.06157		
17	604	400	204	502	0.05762		
18	600	396	204	498	0.05762		
19	594	381	213	488	0.06016		
20	601	392	209	497	0.05903	495 ± 5	0.05919 ± 0.0015
21	747	525	222	636	0.06270		
22	749	525	224	637	0.06327		
23	742	518	224	630	0.06327		
24	742	500	242	621	0.06835		
25	751	534	217	643	0.06130	643 ± 7	0.06378 ± 0.0024

Linear regression equation between average of midpoint voltage (MPV) and average calibration factor (CF): $CF = 4.241 \times 10^{-2} + 3.3759 \times 10^{-5} \times \text{MPV}$.

Units of CF are in volts per Bq m^{-3} d. To obtain the corresponding equation for volts per pCi L^{-1} d, multiply coefficients on right side by 37. Correlation Coefficient: 0.994.

Table 2. Calibration data for long-term E-PERMs. Exposure period was 5 d and 3 h. The ^{222}Rn chamber concentration was 3182 Bq m^{-3} (86 pCi L^{-1}).

No.	Initial volts (V)	Final volts (V)	Voltage drop (V)	Midpoint voltage (V)	Calibration factor (CF)	Average and SD of midpoint voltage	Average calibration factor and SD
1	749	651	98	700	0.005954		
2	748	652	96	700	0.005832		
3	744	645	99	695	0.006014	698 ± 2	0.005933 ± 0.000076
4	652	557	96	605	0.005773		
5	650	554	96	602	0.005832		
6	652	557	95	605	0.005773	604 ± 2	0.005793 ± 0.000028
7	552	460	92	506	0.005589		
8	550	455	95	503	0.005773		
9	553	458	95	506	0.005773	505 ± 2	0.005711 ± 0.000087
10	452	359	93	406	0.005651		
11	450	361	89	406	0.005408		
12	449	358	91	404	0.00553	405 ± 1	0.005610 ± 0.002
13	352	262	90	307	0.005468		
14	348	255	93	302	0.005651		
15	350	264	86	307	0.005224	305 ± 2	0.005530 ± 0.000099
16	251	172	79	212	0.0048		
17	251	166	85	209	0.005165		
18	252	168	84	210	0.00510	210 ± 1	0.005022 ± 0.00016

Linear regression equation between average of midpoint voltage (MPV) and average calibration factor (CF): $CF = 4.881 \times 10^{-3} + 1.5810 \times 10^{-6} \times \text{MPV}$.

Units of CF are in volts per $\text{Bq m}^{-3} \text{ d}$. To obtain the corresponding equation for volts per $\text{pCi L}^{-1} \text{ d}$, multiply the coefficients by 37.

Correlation Coefficient: 0.920.

V_i and V_f are the initial and final voltages of the electret, respectively.

Figures 2 and 3 give the graphical representation of these results. The error bands (corresponding to one standard deviation) are listed in Tables 1 and 2. They appear large in Fig. 1 because of the sensitive scale chosen and are only in the range of 2 to 4%.

Table 3 gives the result of a study conducted on a large number of short-term E-PERMs. Two electrets were randomly chosen from each production batch to form a subset, and 15 subsets covered a total of 15 batches. These were loaded into randomly chosen E-PERMTM chambers. A percentage coefficient of variation was calculated for each subset using standard procedures applicable to a sample size of two. Further correction of 1.253 for small sample bias ($N = 2$) was applied (Dixon and Massey 1957) to arrive at an unbiased estimation of population standard deviation.

Another experiment was done by introducing both short-term and long-term E-PERMs simultaneously into a Rn chamber for the same period of time. These results are given in Table 4.

METHOD OF MEASURING ^{222}Rn CONCENTRATION WITH E-PERMs

The following are steps required in measuring Rn with E-PERMs.

1. Measure the initial electret voltage (V_i) using the electret voltage meter.

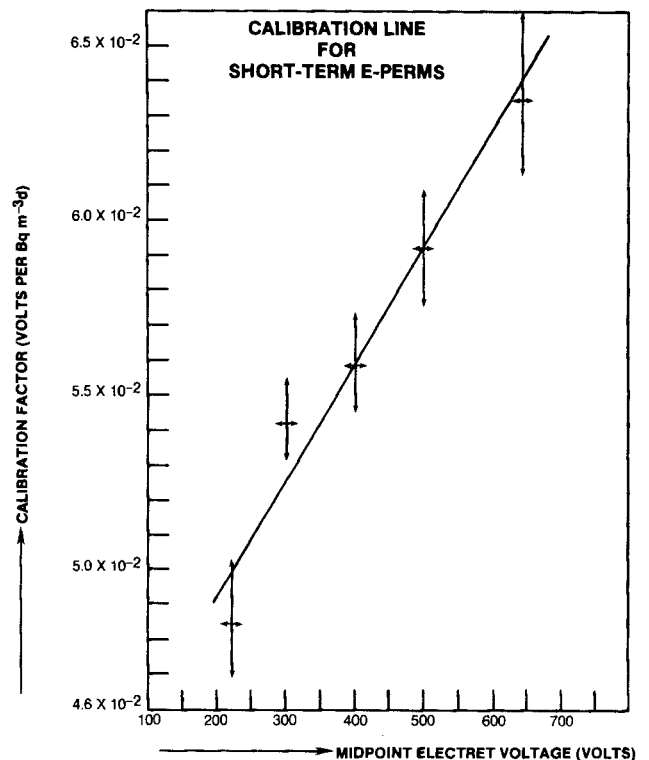


Fig. 2. Linear regression correlation of calibration factor and the midpoint electret voltage for short-term electrets. The midpoint voltage is defined as the average of initial and final voltages.

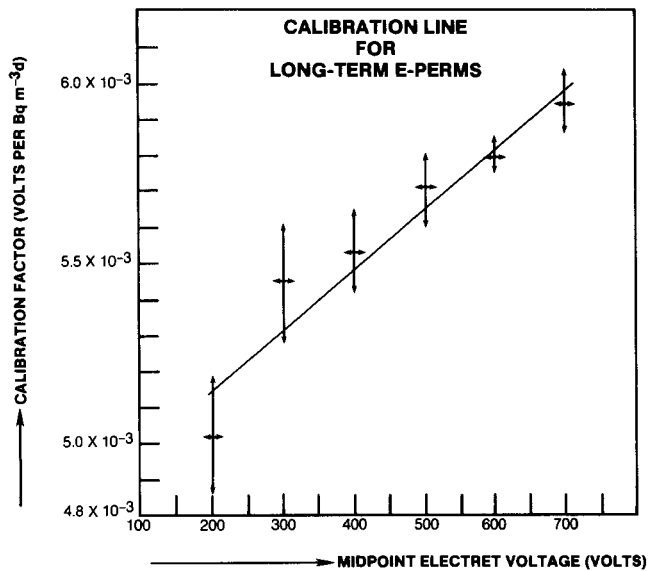


Fig. 3. Linear regression correlation of calibration factor and the midpoint electret voltage for long-term electrets. The midpoint voltage is defined as the average of initial and final voltages.

Table 3. Performance of randomly chosen short-term E-PERMs.

Date of manufacturing	Serial no.	Initial volts (V)	Final volts (V)	Diff. volts (DV)	Coeff. variation (PVC) (%)
9 Nov	222	752	593	159	
9 Nov	15	752	598	154	2.9
10 Nov	42	753	597	156	
10 Nov	207	760	599	161	2.8
8 Dec	2240	759	598	161	
8 Dec	2167	756	584	172	5.9
12 Dec	3380	756	590	166	
12 Dec	3288	751	572	179	6.6
3 Dec	1191	753	582	171	
3 Dec	1189	751	574	165	3.0
5 Nov	213	758	584	174	
5 Nov	2	753	588	165	4.8
6 Dec	1771	753	598	155	
6 Dec	1754	755	584	171	8.7
4 Nov	68	758	584	174	
4 Nov	194	753	585	168	3.1
1 Dec	544	753	589	164	
1 Dec	638	757	594	163	0.5
13 Dec	3604	751	569	182	
13 Dec	3684	752	589	163	9.8
5 Dec	1453	754	593	161	
5 Dec	1392	758	596	162	0.5
28 Nov	3002	752	574	178	
28 Nov	2991	752	584	168	5.1
9 Dec	2410	757	583	174	
9 Dec	2528	753	598	161	6.9
2 Dec	753	757	580	177	
2 Dec	732	762	580	182	2.5
10 Dec	2912	753	574	179	
10 Dec	2667	758	587	171	4.0
		Mean of DV		168.3	
		SD of DV		± 8.1 (4.8%)	

Average and range of PVC: 4.5% and 0.5% to 9.8%, respectively.

Table 4. Results of long-term and short-term E-PERMs introduced simultaneously into the ^{222}Rn chamber for a period of 1 d and 16 h. Chamber concentration was 3182 Bq m^{-3} (86 pCi L^{-1}).

No.	Short-term (ST) or Long-term (LT)	Initial volts (V)	Final volts (V)	^{222}Rn conc. (Bq m^{-3})	Mean ^{222}Rn conc. (Bq m^{-3})
1	ST	626	314	3180	
2	ST	680	365	3115	3210 ± 109
3	ST	684	365	3152	
4	ST	638	305	3394	
5	LT	651	621	3031	
6	LT	652	622	3030	
7	LT	645	613	3241	
8	LT	557	527	3115	
9	LT	551	519	3332	
10	LT	557	527	3115	
11	LT	460	431	3099	3146 ± 94
12	LT	455	425	3212	
13	LT	458	428	3209	
14	LT	359	330	3198	
15	LT	361	332	3196	
16	LT	358	330	3087	
17	LT	262	234	3183	
18	LT	255	227	3190	
19	LT	264	238	2950	

Calculation of ^{222}Rn concentration was done by using the regression equations obtained in the calibration runs.

Radon concentration units are in Bq m^{-3} . To obtain the corresponding concentrations in pCi L^{-1} , divide the results by 37.

2. Screw the electret into the bottom of the E-PERM chamber.

3. Turn the E-PERM unit to its "on" position.

4. Deploy it at the location being monitored in accordance with standard procedures.

5. After a known period of exposure time (T) (2 to 7 d for short-term and 1 to 12 mo for long-term E-PERMs), turn the E-PERMTM to the "off" position, and measure the final electret voltage (V_f).

6. Employ eqns (1) and (2) or (1) and (3) above to calculate the Rn concentration.

The E-PERMTM can be either deployed by Rn measurement professionals or sent by mail for deployment and returned by homeowners.

Dynamic range, system sensitivity, and error analysis

Electrets are recommended for use between the voltages of about 750 V down to 200 V giving a useful range of about 550 V. The calibration curve is no longer linear below 200 V. This range corresponds to a dynamic monitoring range of 9000 to $100,000 \text{ Bq m}^{-3} \text{ d}$ (240 to $2800 \text{ pCi L}^{-1} \text{ d}$) for short- and long-term E-PERMs, respectively.

Overall random error of the E-PERMTM system consists of three parts: 1) Error (E1) associated with the chamber volume, electret thicknesses, and other chamber parameters; 2) Error (E2) associated with the reading of the electrets; 3) Error (E3) associated with the uncertainty of the natural γ radiation background.

The error 1 was found to be less than 5% (Tables 3 and 4) and can be taken as ± 0.05 .

Error in concentration calculation E1 is:

$$E1 = \pm 0.05 \frac{(V_i - V_f)}{(CF \times T)}$$

The electret voltage reader displays voltages to an accuracy of no more than 1 V over the range of measurement. A difference between the two readings is required to calculate the Rn concentration. The fractional error associated with the difference of two readings is:

$$\pm \frac{\sqrt{2}}{(V_i - V_f)}$$

Therefore, the concentration error (E2) as a result of the fractional error in the voltage reading is:

$$E2 = \pm \frac{\sqrt{2}}{(V_i - V_f)} \frac{(V_i - V_f)}{CF \times T}$$

It is reasonable to assume that the natural γ radiation background is known with an uncertainty of 10%. The concentration error (E3) as a result of this uncertainty is:

$$E3 = \pm (0.10 \times BG \times D),$$

where D is the conversion factor to an equivalent Rn concentration in units of Bq m^{-3} per $\mu\text{Gy h}^{-1}$, and BG is the natural radiation background in $\mu\text{Gy h}^{-1}$.

Combining all the errors by the method of quadrature, the overall error (EO) is given by:

$$EO = \sqrt{E1^2 + E2^2 + E3^2}$$

$$= \sqrt{\left(\frac{V_i - V_f}{CF \times T}\right)^2 \left(0.0025 + \frac{2}{(V_i - V_f)^2}\right) + (0.10 \times BG \times D)^2}$$

The lower limit of detection (LLD) is defined as the Rn concentration that can be measured with an error of 50% (Thomas 1971). The LLD depends upon the period of exposure, the voltage region, and whether it is a short- or long-term E-PERMTM. The LLD can now be calculated for various exposure periods by substituting various voltage differentials in the equation for EO. Taking an example of 2-d measurement with a voltage change from 707 V to 700 V, the overall error (EO) is 56%. (Note that the calculation for 50% is not made because this will result in fractional voltages that cannot be measured.) This works out to be approximately 20 Bq m^{-3} . The LLD in the lower most region of voltages (206 to 200 V) for the same period leads to a slightly higher value of 28 Bq m^{-3} . Table 5 gives the range of lower limits of detection for various measurement periods.

DISCUSSION

Advantages and disadvantages of the E-PERMTM methodology have been fully discussed in our earlier work

Table 5. Lower limits of detection for E-PERMs.

Period of measurement (d)	Long-term (LT) or Short-term (ST)	Range of LLD (Bq m^{-3})
2	ST	20 to 28
7	ST	11 to 12
60	ST	8 to 9
30	LT	18 to 26
90	LT	10 to 11
365	LT	8 to 9

Lower limit of detection (LLD) is defined as the level that can be measured with 50% uncertainty. To obtain the corresponding concentrations in pCi L^{-1} , divide the values in column three by 37.

(Kotrappa et al. 1988). Some of the deficiencies of the earlier versions have been remedied in the present design, and these are already discussed in the paper.

It may be appropriate to discuss the cost of the system in comparison with other passive methods of measuring Rn. The present cost of the electret voltage reader when bought in single units is \$1500. Because of the small time needed to make a measurement, a single unit can service a very large number of E-PERMs (100 to 1000). Reusable E-PERMTM chambers cost \$38 per unit when bought in quantities of 10. Consumable electrets cost \$18 per electret when bought in quantities of 10. However, there are substantial discounts when bought in larger quantities.

It is easy to see that a short-term electret can give more than 15 measurements when used for making 3-d measurements at a concentration of about 150 Bq m^{-3} (4 pCi L^{-1}), leading to about a dollar per measurement. The number of measurements for each electret will be larger at lower concentrations and smaller at higher concentrations.

It can be seen further that a long-term electret can give five to six 3-mo measurements at a concentration of 150 Bq m^{-3} (4 pCi L^{-1}). These are not economically efficient for making 1-y measurements. A less expensive small volume chamber (not discussed in this paper) is available in which a long-term electret can give as many as seven to eight 1-y measurements at a concentration of 150 Bq m^{-3} (4 pCi L^{-1}).

The above discussions are given to make a comparison of the cost of making an E-PERMTM measurement compared to the charcoal and α -track methods. It can be seen that these devices give an economically viable alternative to the presently used systems.

It should be noted that the same reader and same methodology are usable whether one wishes to make a long-term or short-term measurement, thereby providing a unified approach when compared to two totally different methodologies used for charcoal and α -track methods.

The E-PERMs are true integrators and are technically comparable with an α -track detector with a filtered inlet. A test was conducted at the Department of Energy Environmental Measurement Laboratory (EML) in New York to test the integrating capability of E-PERMs. E-PERMs were exposed for 16 h in the Rn chamber (1500 Bq m^{-3}) and for 8 h in the office (20 Bq m^{-3}). This cycle was repeated four times, giving a total of 64 h of chamber exposure and 32 h of office exposure. The average Rn concentration measured by E-PERMs was close to the real average within the expected errors. This demonstrated their integrating capability even when subjected to these extreme step variations.

In our earlier work, it was shown that electrets stay stable relative to environmental conditions with temperatures ranging from 21 to 28°C and humidity up to 95%. Further experiments indicated that the electrets stay stable over a much wider range of temperatures and humidities covering almost all conditions encountered in the environment. It has also been shown in our earlier work that relative humidity has no effect on the performance of the E-PERMTM. In fact, E-PERMs have been successfully used in 100% relative humidity for making measurements

of Rn in water.[‡] The U.S. Environmental Protection Agency has also come to the same conclusion based on their own evaluation (Hopper 1987). This important aspect of the E-PERMTM makes it a superior method compared to the methods that use charcoal for measurement of Rn.

Because of conflicting claims about the performance of charcoal and α -track detectors (Matuszek et al. 1988), direct performance comparisons of E-PERMs with these devices are not attempted in this paper.

Note: The calibration equations for the commercially supplied units may have slightly different calibration equations compared to those presented in this paper. Users of E-PERMs are cautioned to use the equations supplied by the manufacturer and not the ones given in this paper. However, the discussions and conclusions remain essentially the same.

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