

● Paper

## AN ELECTRET PASSIVE ENVIRONMENTAL $^{222}\text{Rn}$ MONITOR BASED ON IONIZATION MEASUREMENT

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**Abstract**—The electret passive environmental  $^{222}\text{Rn}$  monitor\*\* (E-PERM) is an extension of electret dosimeters used for measurement of  $\alpha$  and  $\gamma$  radiation. An E-PERM consists of a small cup or canister, having an electret at the bottom, and a filtered inlet at the top. The  $^{222}\text{Rn}$  gas entering through the filter and the decay products formed inside the cup generate ions which are collected by the electret. The reduction of charge (or surface potential) on the electret is a measure of time integrated  $^{222}\text{Rn}$  exposure. An E-PERM of 220-mL volume with an electret of 0.23 cm thickness gave a surface potential drop of 2.5 V for  $37 \text{ Bq m}^{-3} \text{ d}$  ( $1 \text{ pCi L}^{-1} \text{ d}$ ). The electret voltage was measured with a specially built surface potential voltmeter. This sensitivity was found adequate for a 1-wk measurement of  $^{222}\text{Rn}$  in homes. For longer term measurements, an E-PERM of 40-mL volume and an electret of 51- $\mu\text{m}$  thickness was developed which gave a surface potential drop of 2.6 V for  $37 \text{ Bq m}^{-3} \text{ y}$  ( $1 \text{ pCi L}^{-1} \text{ y}$ ). Other combinations of chamber volume and electret thicknesses gave responses between these two values. The surface potential of electrets made from Teflon® FEP† were shown to stay stable even under extreme conditions of relative humidity. The ion collection process in E-PERMs was also shown to be independent of humidity down to an electret surface potential of 100 V.

### 1. INTRODUCTION

AN ELECTRET (Se80) is a piece of dielectric material exhibiting a quasi-permanent electrical charge. The charge of the electret produces a strong electrostatic field capable of collecting ions of opposite sign. Until recently, electrets have been regarded as curious analogues of magnets, worthy only of academic interest. However, with the development of high dielectric fluorocarbon polymers such as Teflon, electrets have become reliable electronic components capable of maintaining constant electrostatic fields even under high temperature and humidity conditions (Tu75).

Marvin (Ma55) was the first to suggest that the reduction of charge on the electret was due to the collection of ions of opposite sign from the surrounding gas, and he proposed the use of an electret in a closed chamber as a  $\gamma$  dosimeter. His idea was not practical at that time because, as Wolfson (Wo61) soon showed, the charge was not stable in carnauba wax which was the best electret material available at the time. Recently, however, Bauser and Range (Ba78) used a pair of thin Teflon electrets of opposite charges to collect and measure the ions produced

inside an ionization chamber. They showed that the radiation dose calculated from this measurement, agreed well with the actual dose received by the chamber. They also demonstrated that the performance was insensitive to variations in humidities and temperatures in the range normally encountered in the environment. The dose information on their electrets was retained without loss over a period of more than 1 y. This study laid a sound scientific basis for the further development of electret dosimeters.

The next innovation in electret ion chamber development was a single electret dosimeter, reported by Kotrappa et al. (Ko82b). These workers showed that the drop in surface potential of their single electret dosimeter also behaved according to established ion chamber theory, and they went on to demonstrate its use as a personal dosimeter (Gu85). Similar work was carried out later by Pretzsch (Pr83a). The theoretical aspects of electrostatic fields in such ionization chambers were worked out by Fallone (Fa83).

Kotrappa (Ko84) also used this technique to measure the potential  $\alpha$  energy concentration of  $^{222}\text{Rn}$  decay products. Pretzsch (Pr86) recently adapted the method for measurement of  $^3\text{H}$  concentration in a flow through chamber. Kotrappa et al. (Ko81) found a rough correlation between the reduction of the surface voltage on a polycarbonate covered electret and the cumulative  $^{222}\text{Rn}$  exposure in a passive chamber arrangement. They also observed that this charge reduction did not appear to be sensitive to humidity change.

\* Currently with Rad-Elec, Inc., P.O. Box 310, Germantown, MD, 20874.

\*\* Patent pending.

† Teflon® FEP fluorocarbon, manufactured by E. I. du Pont de Nemours and Co. (Inc.), Wilmington, DE 19898.

The main object of the present investigation was to demonstrate the technical feasibility of using electret dosimetry for the measurement of  $^{222}\text{Rn}$  concentrations in homes. The devices developed are called electret passive environmental  $^{222}\text{Rn}$  monitors or E-PERMs.

It is important to note that the new method presented here is distinctly different from the well known method (Ko82a) wherein Rn decay products are collected on a charged surface, and subsequently measured by  $\alpha$  counting or by thermoluminescent dosimetry or by solid-state nuclear track detectors. Instead the present method measures the ionization produced inside the PERM chamber by the  $^{222}\text{Rn}$  and its decay products.

## 2. DESIGN AND DEVELOPMENT OF ELECTRET-PERMS

### 2.1 Preparation of electrets, electret holders and electret storage

One of the principle objectives of the present work was to produce electrets which were stable at high humidities. The stability of electrets depends upon (i) the method used in preparing the electrets, (ii) the method of processing the electrets such as annealing at elevated temperatures, (iii) the quality of the electret material, and (iv) the methods used in handling and storing the electrets. Different preparation and processing techniques are discussed by Sessler (Se80). The thick electrets (0.23 cm thick) used in the present investigation were produced by the simultaneous application of heat and electric field to orient the dipoles within the Teflon disks (Pr83b). Then, with the electric field still on, the disks were cooled to "freeze" the dipoles in place. The thin electrets (51 and 127  $\mu\text{m}$  thick) were produced by the electrical breakdown field technique in glass (Se72). All of the electrets were made from Teflon FEP, and all were postannealed to enhance stability.

One side of the thick electret was covered with adhesive Al foil after it was formed. The thin electrets were made from available metal-coated Teflon. The disks were loaded into metal holders.

Figure 1 shows the design of these electret holders made from metal screw caps with 32-mm-diameter holes cut in their centers. The holes serve to expose exactly the same surface area of each electret. The perimeter of the electrets were bonded to the holder with a commercially available hot glue to prevent movement. An additional thin Al sheet was placed immediately behind the electrets in their holders to provide electrical continuity from the electret to the holder. A thick cardboard disk was then force fitted into the holder to hold the electret firmly in place. These electret assemblies were stored in small metal-lined plastic cups which maintain a small (8-mL) air gap in front of the electret.

The holders were also designed to fit snugly into the measurement opening in the electret surface potential voltmeter (electret receptor) to assure reproducible voltage

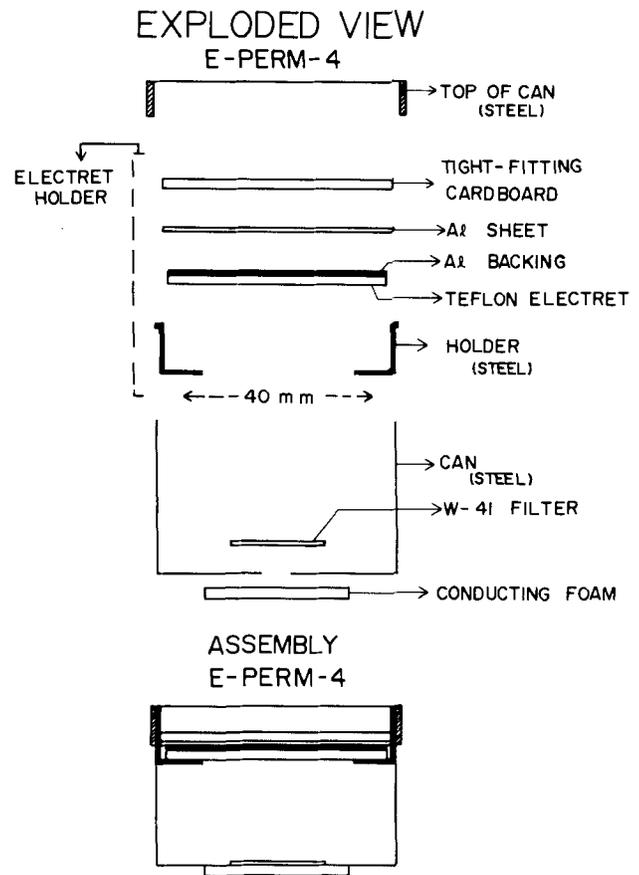


Fig. 1. Design features of E-PERM-4 and the associated electret holders.

measurements. They were hung in place in the E-PERM chambers by inserting them into holes in the chamber lids which were too small in diameter to permit the wider holder rims to pass through. The outside of the chamber lid was then covered with adhesive foil.

### 2.2 Measurement of surface potential of electrets

A method popularly known as the shutter method (also called the capacitive probe method) was used to measure the surface potential of the electret. The method has been described in detail elsewhere (Gu85; Ko82b; Ko84). It was incorporated into a dedicated instrument called an electret surface potential voltmeter (ESPVM) with an LCD digital out-put. An electret receptor on the instrument receives the electret and holds it firmly positioned at a precisely known distance from the voltage sensor. A metallic shutter shields the electrostatic field of the electret from the sensor while the instrument is "zeroed." When the shutter is pulled out, a charge is induced on the sensor which generates a voltage across a capacitor. This voltage is measured by an ultra high impedance circuit in the ESPVM and is read out on the LCD meter. The voltage reading is a unique function of all of the me-

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chanical and electrical parameters of the ESPVM. The parameters are preadjusted so that ESPVM yields a reading of 1 to 2 mV for each volt on the electret. The millivolt reading on the ESPVM is converted into the actual electret surface voltage value by use of an empirically derived calibration factor.

The ESPVM was calibrated by replacing the electret in its holder with a metallic disk and applying known high voltages to this disk while it was positioned in the electret receptor. The meter exhibits perfect linearity from 10 V to 2000 V when calibrated in this way. This method of measuring the electret surface potential is non-destructive; i.e. the electrets can be measured repeatedly without affecting their surface potential. The cost of the homemade ESPVM was about \$300. The reproducibility of the reading with this instrument was about  $\pm 2$  V over its entire range. The instrument is battery-operated, lightweight (less than 1 kg) and portable.

### 2.3 Parametric variation in electret-PERMS

The surface potential on the non-metalized side of the electret (Se80) is related approximately to the total charge on the electret by the following relationship.

$$QA = (E_o AEV/T), \quad (1)$$

where  $Q$  is the charge density ( $\text{C cm}^{-2}$ ) on the electret,  $A$  is the area of electret ( $\text{cm}^2$ ),  $E_o$  is the permittivity of space ( $8.854 \times 10^{-14}$ ),  $V$  is the surface potential (V),  $E$  is the dielectric constant of Teflon (approximately 2), and  $T$  is the thickness of electret (cm).

It can be seen from this relationship (eqn 1) that the same quantity of charge on a thick and a thin electret will result in different surface potentials. For example, a 0.2-cm-thick electret will exhibit about 10 times the surface potential of a 0.02-cm-thick electret if both have the same total charge. It follows from these considerations that E-

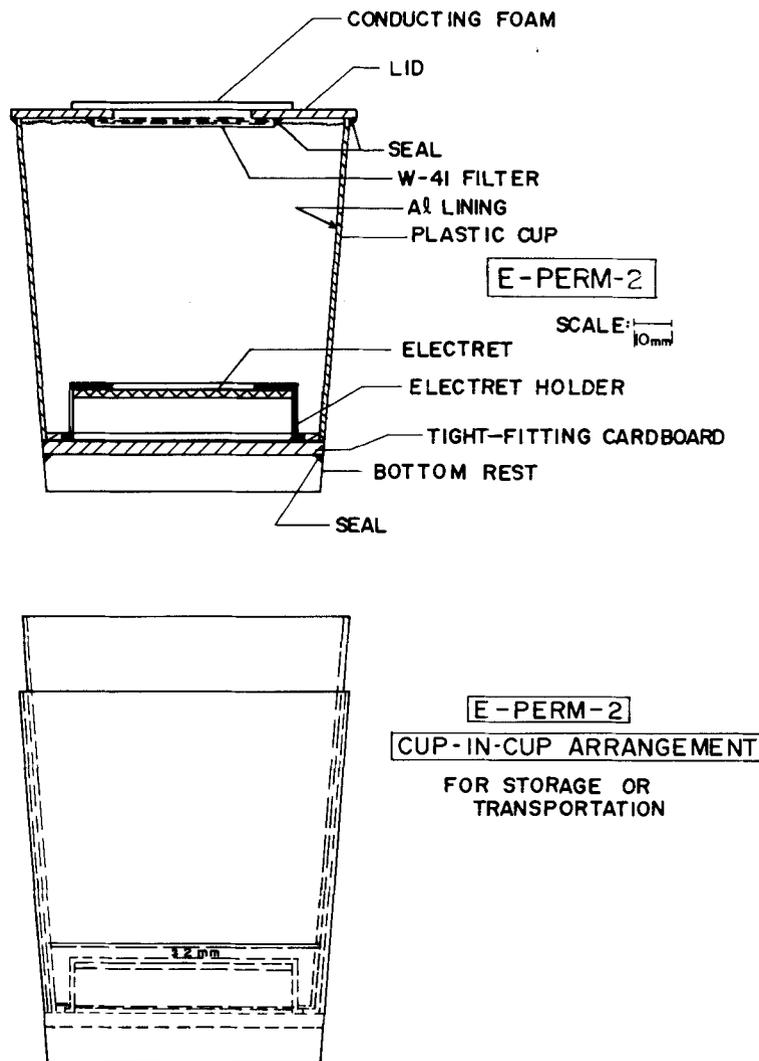


Fig. 2. Design features of E-PERM-2.

PERMs fitted with thick electrets have higher sensitivity and lower range than E-PERMs with thin electret. The sensitivity of an E-PERM also depends upon the chamber volume. Larger volume E-PERMs are more sensitive because they contain relatively more  $^{222}\text{Rn}$  gas. Thus, electret thickness and chamber volume are the principle parameters which can be varied to optimize the sensitivity and range of E-PERMs to accommodate various applications.

#### 2.4 Design of E-PERMs

Figure 2 gives the design features of E-PERM-2. The electret holder is suspended by its outer edge through a circular hole made at the bottom of the polyethylene cup. The holder is held firmly in place by a tightly fitting cardboard disk. The outer perimeter of the disk is sealed with removable silicone rubber sealant. The interior of the cup is lined with a thin Al foil to provide a discharge path to ground. The exterior of the cup is also covered with Al foil to avoid daughter product collection on the charged plastic. Air containing  $^{222}\text{Rn}$  gas enters through a hole in the middle of the lid, which is covered with an electrically conducting foam, a filter (Whitman 41), and a  $^{220}\text{Rn}$  barrier (if needed). The perimeter of the lid is sealed to the cup with conductive adhesive tape to keep it in place.

To minimize the sensitive volume during storage or transportation, the lid is removed and another cup inserted inside. The false bottom of the inserted cup, which is also coated with a conductive layer of Al foil, straddles the electret without touching it. This cup-in-cup arrangement leaves only a small volume of air for ionization so the E-PERM is effectively "off" during transportation and storage. To expose E-PERM-2 for  $^{222}\text{Rn}$  measurement, the inside cup is removed and the top lid containing the filter is fitted on the outside cup to form E-PERM-2. This cup-in-cup configuration is shown in lower part of Fig. 2.

Figure 1 shows the design of an E-PERM with smaller volume (E-PERM-4). This is made of a commercially available 60-mL steel ointment can. The bottom of the can has a hole and filter assembly for  $^{222}\text{Rn}$  entry. The electret holder is suspended from the top of the can. The lid, which fits over the holder, is then sealed with adhesive tape. The sensitive volume is about 40 mL. E-PERM-1 (not shown) is simply a 1250-mL "cookie" can with provisions for fixing the electret holder in center of its bottom and a filtered inlet in the lid.

### 3. EVALUATION OF ELECTRET PERMS

#### 3.1 Electret stability

The covered electret assemblies were stored in metal cookie cans which contained filtered openings so that the electrets were exposed to the ambient conditions of humidity and temperature. Table 1 lists successive surface potential readings taken on several electrets during two summer months when the relative humidity was greater than 95%, at least half of the time. The data shows that the electrets were stable even under these adverse conditions. The observed small surface potential drop was as

expected because of the ions formed in the small air volume (8 mL) in the electret storage holders.

#### 3.2 Calibration of E-PERMs

Routine E-PERM calibration work was carried out in a small (8-L) homemade Rn test chamber with an air flow rate of about  $8 \text{ L min}^{-1}$ . The  $^{222}\text{Rn}$  concentration in this chamber was intercalibrated with that in the chamber at the US Department of Energy's Environmental Measurement Laboratory (EML), New York, NY. The  $^{222}\text{Rn}$  concentration held constant to within  $\pm 5\%$  at  $1295 \text{ Bq m}^{-3}$  ( $35 \text{ pCi L}^{-1}$ ) throughout the investigation.

The general procedure used for E-PERM evaluation was to introduce the devices to be tested into the chamber after recording their electret surface potentials. They were taken out after a known exposure time and the surface potential of electret read again. Figure 3 shows the results of a calibration run with an E-PERM-1 using the same electret all the way from 866 V down to 15 V. A near perfect linear relationship is seen to exist between  $^{222}\text{Rn}$  dose and the electret response in E-PERM-1. The data shows that a single calibration factor can be used for these E-PERMs in the surface potential range from 850 V to 100 V. Figure 3 also shows the data from a similar experiment run under high humidity conditions (95% RH). The high humidity was obtained by placing a sponge ( $5 \text{ cm}^2$ ) moistened with water inside the E-PERM during the experiment. It is apparent that high humidity has no appreciable effect on the calibration factor (slope of the line) until the electret surface potential falls below 100 V.

Figure 4 gives the results of a similar experiment with an E-PERM-2. It can be seen that the response of E-PERM-2 is also linear with integrated  $^{222}\text{Rn}$  exposure. Similar experiments carried out for smaller E-PERMs (E-PERMs 4 to 6) showed no humidity effects down to a surface potential of 50 V. The 850-V upper limit was chosen in every case to avoid ion multiplication which occurs at higher voltages.

Several E-PERMs-2 were sent to EML by mail and received by mail after a known exposure to  $^{222}\text{Rn}$  in the range of  $1850$  to  $3700 \text{ Bq m}^{-3} \text{ d}$  ( $50$  to  $100 \text{ pCi L}^{-1} \text{ d}$ ). The average calibration factor is shown in Table 2. The signal contribution due to  $\gamma$  background in the calibration chamber was not taken into account because it was known to be insignificant compared to that from  $^{222}\text{Rn}$ . E-PERM-5 and E-PERM-6 were sent to the Bureau of Mines Rn test chamber at Denver, CO. for exposure to known  $^{222}\text{Rn}$  doses in the range of  $74,000$  to  $148,000 \text{ Bq m}^{-3} \text{ d}$  ( $2000$  to  $4000 \text{ pCi L}^{-1} \text{ d}$ ). The average calibration factor for these E-PERMs are shown in Table 2. Data on other E-PERM models obtained in the 8-L laboratory test chamber is also presented in Table 2.

It is useful to consider the characteristics of E-PERMs which cause their humidity independent performance. The freshly formed decay products of  $^{222}\text{Rn}$  are known to carry positive charge. It is also known that some of these charged decay products lose their charge more rapidly in humid air than in dry air. Monitors which depend on daughter product collection exhibit humidity sensi-

Table 1. Typical stability data of electrets of various thicknesses stored in holders. The temperature varied from 21°C to 26°C and relative humidity from 80% to 95%.

ELECTRET NUMBER	SURFACE POTENTIALS of 0.23 cm electrets (V) on stated dates			SURFACE POTENTIALS of 127 $\mu\text{m}$ electrets (V) on stated dates			SURFACE POTENTIALS of 51 $\mu\text{m}$ electrets (V) on stated dates		
	AUG. 12	SEPT. 24	OCT. 20	AUG. 12	SEPT. 24	OCT. 20	AUG. 12	SEPT. 24	OCT. 20
1	979	972	967	365	365	363	416	415	413
2	671	668	666	580	581	580	481	481	481
3	591	585	581	660	660	651	255	255	255
4	449	449	447	530	530	526	304	306	306
5	433	435	433	561	561	558	238	238	237
6	339	330	326	470	470	468	238	238	238
7	488	482	480	642	640	636	286	286	284
8	686	680	678	383	385	383	266	266	264
9	429	422	419	618	616	613	176	178	178
10	438	440	436	429	431	422	273	272	270
11	440	437	435	451	453	451	299	299	297
12	607	605	601	460	462	453	345	347	345
13	715	713	712	400	402	402	358	359	359
14	352	352	350	490	490	488	436	438	436
15	347	345	343	567	565	560	354	356	354
16	956	943	937	436	438	436	290	290	288
17	433	427	423	475	475	475	314	315	314
18	510	510	507	589	591	589	354	356	354
19	624	623	621	470	470	467	315	314	312
20	475	473	471	585	583	576	275	275	275

NOTE: 1) Resolution or least count of electret surface potential voltmeter is 2 volts  
2) Repeatability  $\pm 2$  volts

tivity because of this effect. However, E-PERM response derives from ions produced in air rather than daughter product collection. The process of collection of these ions in strong electric fields is essentially independent of humidity. The positively charged electrets used in the E-PERMs in this investigation repel charged decay products to the surface of walls. A small fraction of the decay products that become neutral under humid condition also go to walls eventually by the process of diffusion. Therefore, the disposition of decay products in the chamber does not depend upon the humidity. Hence, the ionization generation and collection remain independent of humidity.

### 3.3 Response of E-PERMs to $\gamma$ radiation

Several E-PERMs were exposed to radiation from a  $^{137}\text{Cs}$  source and the surface potential of their electrets were measured before and after exposure. The results are given in Table 3. It can be seen that the response for a 1-d exposure at  $0.10 \mu\text{Gy h}^{-1}$  ( $10 \mu\text{rad hr}^{-1}$ ) is approximately

equivalent to a  $^{222}\text{Rn}$  exposure of 22.2 to  $66.6 \text{ Bq m}^{-3}$  ( $0.6$  to  $1.8 \text{ pCi L}^{-1}$ ) for a day.

The different responses observed among the various E-PERMs are due to several factors. For example, more of the  $\alpha$  radiation is dissipated in the air rather than in the walls in larger volume chambers because more of the  $\alpha$  particles can traverse their entire range before impinging on a wall. Therefore, larger volume chambers give higher response per unit volume compared to smaller volume chambers. This effect can be seen in column 4 of Table 2. The E-PERM response to  $\gamma$  radiation, on the other hand, is not affected by the size of the chamber so long as the saturation collection of ions takes place (see column 2 of Table 3). However, it is well known that the material of construction of ion chambers has some effect on their  $\gamma$  response. Chambers fabricated from high atomic number material such as steel give a higher response relative to lower atomic number chamber materials such as Al or plastic. As a result of the combination of these effects, the

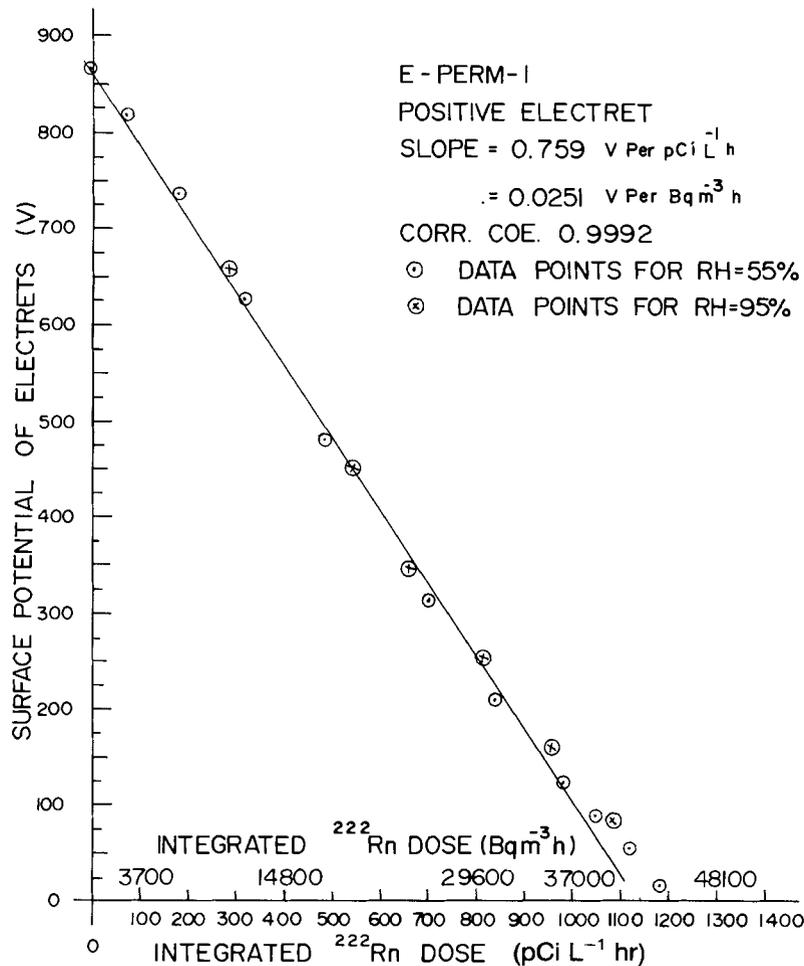


Fig. 3. Dose response relationship for E-PERM-1.

small steel E-PERMs give relatively (relative to  $^{222}\text{Rn}$  response) higher response to  $\gamma$  radiation compared to the larger chambers (see column 4 of Table 3). Obviously, it is desirable to use larger volume chambers made of low atomic number materials in order to minimize the relative response to  $\gamma$  radiation.

### 3.4 Practical limits, dynamic range and applications of E-PERMs

Using the data presented in Table 2 and Table 3, it is possible to calculate the practical limits and dynamic range of each of the E-PERM. The useful voltage range of the electrets used in E-PERM-1 to E-PERM-3 is 700 V and, for E-PERM-4 to E-PERM-6, it is 750 V.

Under the currently available electret surface potential voltmeter, the surface potentials of electrets can be measured with an accuracy and reproducibility of  $\pm 2$  V. If a sealed E-PERM is used to measure background  $\gamma$  radiation, its voltage differential must be subtracted from that of the measurement E-PERM in order to obtain the net response for  $^{222}\text{Rn}$  exposure only. When each measurement has an uncertainty of  $\pm 2$  V, the difference will have the uncertainty of  $\pm 2.83$  V.

The E-PERM-1 is designed to monitor homes in 1 d. This E-PERM will give a voltage drop of 29 V in a home that has a  $^{222}\text{Rn}$  concentration of  $37 \text{ Bq m}^{-3}$  ( $1 \text{ pCi L}^{-1}$ ) and a  $\gamma$  radiation background of  $0.1 \mu\text{Gy h}^{-1}$  ( $10 \mu\text{rad hr}^{-1}$ ). However, the net voltage drop due to  $^{222}\text{Rn}$  only is  $18 \pm 2.83$  V after the background voltage subtraction. This level can be measured with an uncertainty of about 16%. The dynamic range of E-PERM-1 is about  $890 \text{ Bq m}^{-3} \text{ d}$  ( $24 \text{ pCi L}^{-1} \text{ d}$ ). This means that the final electret voltage of E-PERM-1 would be too low to use if exposed to a  $^{222}\text{Rn}$  concentration in excess of  $890 \text{ Bq m}^{-3}$  ( $24 \text{ pCi L}^{-1}$ ) for longer than 1 d. Obviously, one would monitor for less time or use a different E-PERM type in such a high Rn home. Similarly E-PERM-2, which is designed for 7-d exposure, will go out of range if exposed to concentrations in excess of  $740 \text{ Bq m}^{-3}$  ( $20 \text{ pCi L}^{-1}$ ) for the entire 7 d. In such circumstances, a second shorter term measurement would be required. Table 4 gives the parameters needed to calculate the range of other E-PERM types.

From the above discussions, it is clear that a single E-PERM cannot be designed to provide both high sensitivity and a wide enough dynamic range to monitor the

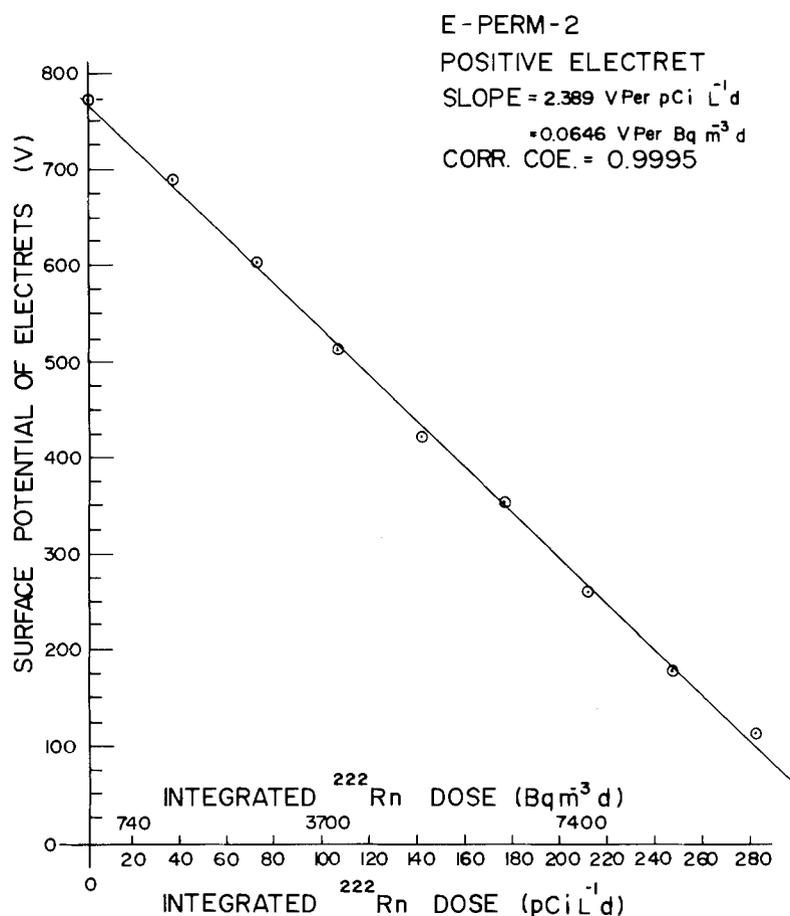


Fig. 4. Dose response relationship for E-PERM-2.

homes over the widest extremes of  $^{222}\text{Rn}$  concentrations which have been found in homes. It is practicable to repeat the measurement using larger range E-PERMs in the few homes which exceed the limit of a particular E-PERM used in the first measurement.

It should be noted that the combinations of electret thicknesses and canister volumes used in making E-PERMs need not be confined to those studied here. Several new combinations can be fabricated and used based on field requirements since the electret material is available in a variety of thicknesses and canisters are available in various volumes. Any electret/canister combination can be easily calibrated and used.

### 3.5 Discussion of random uncertainties in E-PERM system

Following are the possible sources of uncertainties in the E-PERM system for measuring Rn concentrations.

(i) Response is almost linearly dependent upon the thickness of the electret. The manufacturer's catalog lists percentage variation of thicknesses of Teflon as  $\pm 7\%$ . It is possible, of course, to reduce this uncertainty by measuring and rejecting disks which are beyond certain limits.

However, for purposes of the present investigation uncertainty due to thickness variation can be taken as  $\pm 7\%$ .

(ii) Response is almost linearly dependent upon the area of the electret exposed to ions. The area defining in the electret container hole is fabricated on a precision lathe with an accuracy of  $\pm 0.015$  cm. However, the cutting is not smooth in all cases, and the burrs must be removed. The linear uncertainty can be taken as  $\pm 0.030$  cm which works out to be about a  $\pm 2\%$  uncertainty in area.

(iii) The response is linearly dependent upon the volume of the chamber. The chambers are chosen from the manufacturers who make them in very great numbers with good quality control. This uncertainty is about  $\pm 2\%$ .

(iv) Calibration uncertainty can be about  $\pm 5\%$ .

(v) The statistical (counting) uncertainty is negligible for E-PERMs due to the very great number of  $\alpha$  emissions which the electrets integrate over the normal exposure period. For example, a total of nearly 14,800  $\alpha$  disintegrations take place in the 220-mL E-PERM-2 due to  $^{222}\text{Rn}$  and decay products, when exposed to a  $^{222}\text{Rn}$  concentration of  $37 \text{ Bq m}^{-3}$  ( $1 \text{ pCi L}^{-1}$ ) for 7 d. Assuming half of these (7400) expend their total energy in the sensitive volume, the statistical uncertainty at this level is only about  $\pm 1\%$ .

Table 2. Characteristics of various E-PERM models and their calibration factors.

Model Name	Volume Chamber (cm <sup>3</sup> )	Thickness of Electret	Average Calibration Factor* (V) Per unit integrated <sup>222</sup> Rn dose		No. of E-PERMs tested
			V for 1 Bq m <sup>-3</sup> d	V for 1 pCi L <sup>-1</sup> d	
E-PERM-1	1250	0.23 cm	0.486	18.0	5
E-PERM-2	220	0.23 cm	0.0681	2.52	10
E-PERM-3	220	127 μm	0.00535	0.198	5
E-PERM-3'	220	51 μm	0.00214	0.079	5
E-PERM-4	40	0.23 cm	0.00946	0.350	10
E-PERM-5	40	127 μm	0.000514	0.019	25
E-PERM-6	40	51 μm	0.000195	0.0072	25

\*Standard deviation varied from 8% to 13%.

Table 3. Response of E-PERMs for gamma radiation from <sup>137</sup>Cs source.

Model Name Chamber	Response (V) for 2.4 μGy (240 μrad)	Equivalent integrated <sup>222</sup> Rn Dose		Material of Chamber
		(Bq m <sup>-3</sup> d)	(pCi L <sup>-1</sup> d)	
E-PERM-1	10.8	22.2	0.60	Steel with Al lining
E-PERM-2	2.00	29.2	0.79	Plastic with Al lining
E-PERM-3	0.15	29.6	0.80	- same -
E-PERM-3'	0.06	29.6	0.80	- same -
E-PERM-4	0.50	22.9	1.43	Steel
E-PERM-5	0.034	66.6	1.80	Steel
E-PERM-6	0.013	63.3	1.71	Steel

Table 4. Dynamic range and other useful parameters for various E-PERM models.

Model Name	Dynamic Range		Net drop in surface potential (V) at a $^{222}\text{Rn}$ concentration of 37 Bq m <sup>-3</sup> d (1 pCi L <sup>-1</sup> d) for stated number of days		Dynamic range in days when $^{222}\text{Rn}$ concentration is 740 Bq m <sup>-3</sup> d (20 pCi L <sup>-1</sup> d)
	Integrated $^{222}\text{Rn}$ concentration (Bq m <sup>-3</sup> d)	(pCi L <sup>-1</sup> d)	No. of days	(V)	
E-PERM-1	888	24	1	18 ± 2.8	1.2
E-PERM-2	5 735	155	7	17.6 ± 2.8	7.7
E-PERM-3	74 444	2012	90	17.8 ± 2.8	101
E-PERM-3'	186 332	5036	225	17.8 ± 2.8	252
E-PERM-4	32 634	882	50	17.5 ± 2.8	44
E-PERM-5	523 624	14152	900	17.1 ± 2.8	708
E-PERM-6	1373 773	37129	2375	17.1 ± 2.8	1856

Totaling the above uncertainties, the overall uncertainty as calculated by addition in quadrature is about ±9%.

### 3.6 Stability of exposure signal

As mentioned earlier, Bauser and Range (Ba78) have shown that the dose information stored on their electrets was retained without loss over a period of more than 1 y even at high humidities. A few experiments were conducted in our laboratory to verify this electret "memory." The surface potential of electrets were brought down by giving appropriate ion doses (using an  $\alpha$  source). The charge stability of these electrets was followed for several months without measurable fading of surface potential.

### 3.7 Advantages and disadvantages of E-PERMs

#### Advantages

(1) E-PERM performance is independent of humidity over the range normally encountered in the environment.

(2) It only takes a few seconds to readout the E-PERM electrets. Readout is non-destructive, and it can be done repeatedly without affecting the signal on the electret. The instrument for reading them is relatively inexpensive (about \$300).

(3) The electrets can be used repeatedly as long as their surface potential is within the useful voltage range

(100 to 800 V). When they fall below this range, they can be recharged and reused.

(4) The design parameters of electrets and E-PERM can be chosen to cover a wide variety of sensitivity and range requirement to accommodate many applications.

(5) E-PERMs are passive devices requiring no moving parts.

(6) The methodology for preparation of electrets is well known and is adaptable to mass production.

(7) The change in electret voltages is essentially a linear function of  $^{222}\text{Rn}$  exposure so that a single calibration factor can be used to calculate the concentration.

(8) The statistical (radioactivity) uncertainty is negligible (see section 3.5).

(9) E-PERMs appear to be economically competitive with other types of passive monitors now available.

#### Disadvantages

(1) A single E-PERM cannot cover the lowest to highest range of  $^{222}\text{Rn}$  exposures found in homes for the same exposure period without sacrificing sensitivity.

(2) Electrets must be handled and stored with special but simple precautions; e.g. touching the electrets will significantly alter their voltage.

(3) E-PERMs are sensitive to normal background radiation. A 0.1  $\mu\text{Gy h}^{-1}$  (10  $\mu\text{rad hr}^{-1}$ ) adds a signal contribution equivalent to about 1 pCi L<sup>-1</sup> of  $^{222}\text{Rn}$  in 1 d. This correction must be made to measurements taken in homes which have low  $^{222}\text{Rn}$  concentrations.

#### 4. DISCUSSIONS AND CONCLUSIONS

Only limited field studies have been conducted to date. More extensive studies are underway.

The present studies indicated that E-PERMs do not suffer from humidity effects. The E-PERMs can be designed to perform both short-term (1 d to 1 wk), and long-term (3–12 mo) by the proper choice of chamber volumes and electret thicknesses. The linear response over the entire dynamic range simplifies the computational methods for calculating and interpreting  $^{222}\text{Rn}$  dose. Because of the inexpensive nature of the methodology, E-PERMs are practical for large-scale home surveys.

The small response of E-PERMs to background  $\gamma$  radiation, if not corrected for, can result in significant error in monitoring low  $^{222}\text{Rn}$  homes. This background radiation does not vary widely from place to place and a constant correction may be adequate. However, a second sealed E-PERM can be exposed simultaneously to mea-

sure the background so that it can be accurately deducted from the  $^{222}\text{Rn}$  concentration value. This latter approach has the added advantage of giving the homeowner an accurate reading of the background radiation in his home. Because of the humidity insensitivity of E-PERMs and the great range and sensitivity they afford, they lend themselves to several additional applications.

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