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Chapter 1

ELECTRET ION CHAMBERS FOR CHARACTERIZING INDOOR, OUTDOOR, GEOLOGIC AND OTHER SOURCES OF RADON

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ABSTRACT

Electret Ion Chambers (EICs) are portable, passive, accurate integrating ionization chambers that do not require a battery or any external source of power. An EIC consists of an electret, a charged Teflon®[1] disk, enclosed inside an electrically conducting plastic enclosure. The electret serves both as a source of electrostatic field for ion collection and also as a sensor for quantifying the ions collected. The passive EICs, also popularly known as E-PERM®[2] (electret passive environmental radon/radiation monitors) are widely used passive radon detectors in US, Europe, Canada and other countries for the measurement of indoor and outdoor radon concentrations and other applications. Figure 1 illustrates how a radon measuring EIC works. The radon gas passively diffuses into the chamber through small filtered holes into the volume of the chamber, and the alpha particles emitted by the decay process ionize the air molecules inside the chamber. Negative ions produced inside the chamber are collected on the positively charged electret, causing a reduction of its surface charge. The reduction in charge (initial charge minus the final charge of the electret) is a function of the radon concentration, the test duration, and the chamber volume. The charge on the electret surface is measured by using a specially designed portable electret reader. The collected data is analyzed by software using algorithms obtained by appropriate calibrations. The EICs are used not only for indoor and outdoor measurements, but also for characterizing a number of geologically important radon related parameters. Such parameters include, radon in water, radon flux from ground and other surfaces, radon progeny concentration in air, and for geophysical prospecting for uranium.

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[1] Teflon® is the registered trademark for Teflon manufactured by Dupont.
[2] E-PERM® is the registered trademark EIC manufactured by Rad Elec Inc.

This article further provides historic development and standardization of EIC system. The article also provides the theory and practice of measuring geologically important parameters of radon. Bibliography provides a list of publications for those who wish to pursue the technology further.

PART 1. DEVELOPMENT AND STANDADIZATION OF THE ELECTRET ION CHAMBER (EIC) SYSTEMS FOR CHARECERIZING RADON

Introduction

An electret is an important part of the EIC. An electret as defined by Sessler [1] is a piece of dielectric material exhibiting a quasi-permanent electrical charge. The surface charge of the electret produces a strong electrostatic field capable of collecting ions of opposite signs. Until recently, electrets have been regarded as a curious analogue of magnets, worthy of academic interest. However with the development of high dielectric fluorocarbon polymers, such as Teflon, electrets have become reliable electronic components capable of maintaining high constant electrostatic fields even under high temperature and humidity conditions. Properly made electrets can have extraordinary stability with a discharge rate of 1 to 4 % per year when stored in storage cap, as shown by Kotrappa [10]. These are attractive due to the fact that it is possible to get high electrostatic fields without the use of batteries or high voltage units. These have found many applications such as self biased miniature microphones and other useful devices [1, 2]. Marvin [5] was the first to suggest that the reduction of charge on the electret was due to the collection of ions of the opposite sign from the surrounding air. He proposed the use of an electret in a closed chamber as a gamma dosimeter. His idea was not practical at that time because the charge on the electrets made in the early years was not stable because the non availability of materials such as Teflon. However, Bauser and Ranger [4] used a pair of thin Teflon electrets of opposite sign charges to collect and measure 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 showed that the performance was fairly 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 for a period of more than one year. This work established the scientific basis for the performance of the EIC. The next innovation was the development of a single electret dosimeter [38]. In this case one side of the electret was coated with carbon. The electret was located at the bottom of the chamber with the conducting side in contact with the chamber. The electret provided the electric field with respect to the chamber. This combination worked similar to that of Bauser (4). Theoretical aspects of electrostatic fields in such ionization chambers were worked out by Fallone and his coworkers covered many basic aspects and several applications [27-35].

Further, basic development work and a number of applications was done by Pretzsch and his coworkers [14-22, 24]. Some of the earlier work was done by Kotrappa and his coworkers covering some aspects of radon and radon progeny concentrations in air [7, 8, 9].

First systematic study of the electret ion chambers, for use in passive mode was made by Kotrappa [11]. Such device was named an "electret passive environmental radon monitor based on ionization measurement" E-PERM®.

This study recognized that the environmental gamma radiation (terrestrial and cosmic) also contributes to the ionization due to radon during radon measurement. This signal needed to be subtracted during the radon measurement. It also depends upon the material used for the chamber construction. The study included different wall materials so as to determine the materials that provide minimal signal from gamma radiation. A plastic chamber coated with colloidal carbon provided the lowest response to gamma radiation when compared with aluminum or steel. Radon responses were independent of chamber material as long as those are electrically conducting. The radon responses were proportional to the volume of the chambers. Electrets made from thicker Teflon showed a higher response compared to electrets made from thinner Teflon. These observations were further used in building a family of E-PERMs required in the measurement of different concentrations and for different periods. Research in this study also included different methods of making electrets stable and with time, temperature and humidity variation. Further research included the development of the electret reader. This study was the basis for the design of the standardized EIC system shown in Figure 1 described by Kotrappa [12]. Introduction of standardized versions of electret ion chambers and the associated equipment led to rapid expansion of research and development leading to additional research and applications.

The EIC system consists of several components. These include an appropriately characterized and stabilized electret, an electret reader to read the surface charge of the electret in units of volts, the chambers made of electrically conducting polypropylene of different volumes with arrangement to remote closing and opening of electrets, the appropriate calibration factors and analyzing algorithms.

Electrets

It is important to discuss how the electret, being an important component of EIC, is made and how it is characterized. Sessler [1, 2], a pioneer in the field of electrets defines an electret as "a piece of dielectric material exhibiting quasi-permanent electrical charge". The term "quasi permanent" means that the time constants characteristic for the decay of the charge are much longer than the time periods over which studies are performed using the electret. The most practical material used for making electrets is fluorocarbon materials such as Teflon (PTFE or FEP) because of their very high surface and volume resistivity. This property prevents charges on the electrets from recombining, resulting in a long life time. Figure 2 provides schematics of an electret and methods of making an electret. The word "electret" comes from the word "magnet".

A magnet has both north and south poles, and an electret has both positive and negative charges. By grounding the appropriate side it is possible to get either positive or negative electrets. There are a large number of methods of introducing a charge into the Teflon disk [2, 3]. Methods which are relevant to practical electrets for use in an EIC, are "internal polarization by dipole orientation" and surface ion deposition by "breakdown of electrical fields". These are illustrated in items 1 and 2 in Figure 2.

In typical Teflon material there are randomly oriented dipoles. When the material is heated to a high temperature under an applied high electric field, the dipoles get oriented. Temperature needed for dipole orientation is called "glass temperature". At such temperatures the medium is semi fluid without compromising the properties of the material.

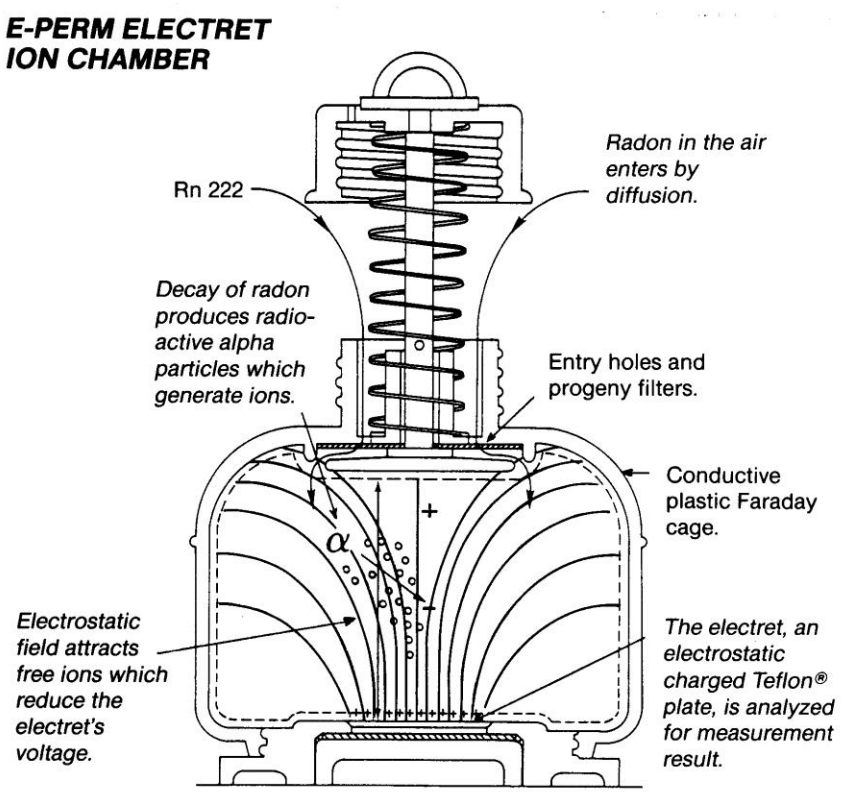


Figure 1. Basic functioning of electret ion chamber for measuring radon in air.

The appropriate temperature is in the range 150 to 200 °C and the applied field is about 10kV cm^{-1}. When the material is slowly cooled still under the electric field, the dipoles are frozen. Such electrets were made and used in an EIC by Kotrappa [11, 12]. The method of making electrets by application of breakdown field is illustrated in item 2 of Figure 2. This method is fully described by Sessler and West [3]. A piece of Teflon is sandwiched between two electrodes separated by low conductivity glass. Typically 2.5 mm soda glass with an electric field of about 40kV cm^{-1} provided electrets with appropriate surface charges for use with an EIC [11, 12]. The exploded view of the different parts of an electret is shown in Figure 4. Usually the negative side of the electret is coated with a thin layer of carbon. Further, these are loaded into a holder made of electrically conducting plastic. The electret holders are designed to be directly loaded into the charging jigs. After charging, it is loaded into a storage cap. Such electrets are further annealed to make them stable against varying temperatures and humidity and other environmental elements. The surface charge is further reduced by exposing the surface of the electret to ions of opposite sign to about 750 volts for electret ion chambers [11, 12]. Figure 4 shows the standardized version of electret assembly with the associated components. By removing the storage cap, the electret assembly can be loaded into the charging jig for charging the electret. Such an electret is shown in the left lower part of Figure 7. Electrets are characterized by their thicknesses, the surface charge density, the area and the dielectric constant of the electret material. Figure 3 illustrates the parameters which characterize the electret and it also illustrates how the surface potential of an electret is measured.

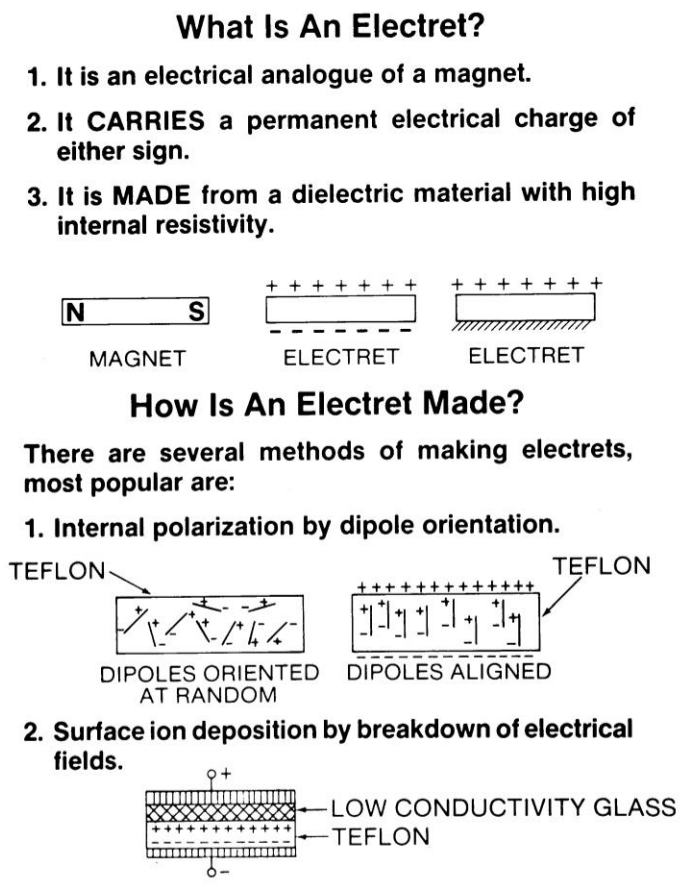


Figure 2. What is an electret and how it is made.

The relationship in Figure 3 gives the relationship of these parameters with surface potential V_S. The surface potential V_S is measured by a method known as "capacitive probe method", fully described by Sessler [1], and is illustrated in the lower part Figure 3. When a movable shutter is moved out of the electret, the charge is induced on the probe, which in turn charges the capacitor C and the voltage on the capacitor is measured in a digital panel meter through an ultra high impedance operational amplifier. When the shutter is pushed back, the capacitor is discharged. When the shutter is pulled again the measurement is repeated. This electret surface voltmeter is available for measuring the surface voltage of commercially available electrets used in the EIC. Figure 7 shows a commercially available electret reader that works on this principle. For routine measurement, the electret is introduced into the receptacle. The lever is drawn to read the electret and when the lever is released the shutter goes back and is ready for another measurement. Being a non contact method, measurements can be repeated without affecting the surface voltage on the electret. The instrument is usually calibrated with a simulated electret with a known applied voltage. The manufacturer provides all the necessary information on the appropriate use of the electret voltage reader. Two types of electrets are manufactured and supplied by the manufacturer for use with commercially used EICs. The 1.588 mm thick electret (called thick or ST electret) is made from PTFE Teflon and the 0.127 mm thick electret (called thin or LT electret) is made from FEP Teflon.

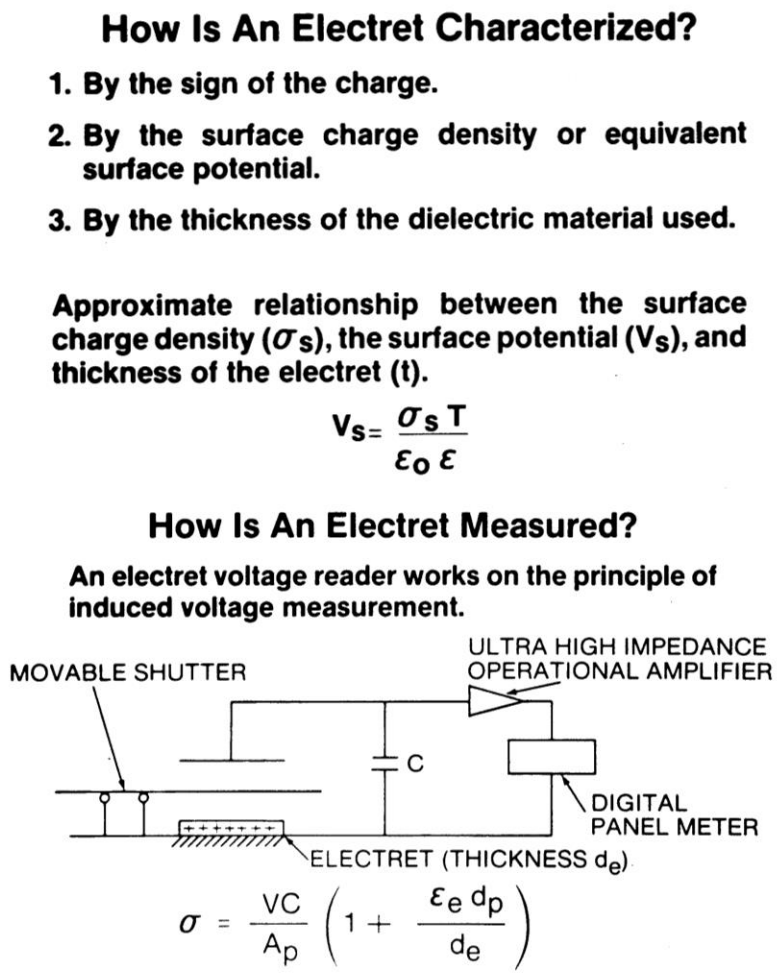


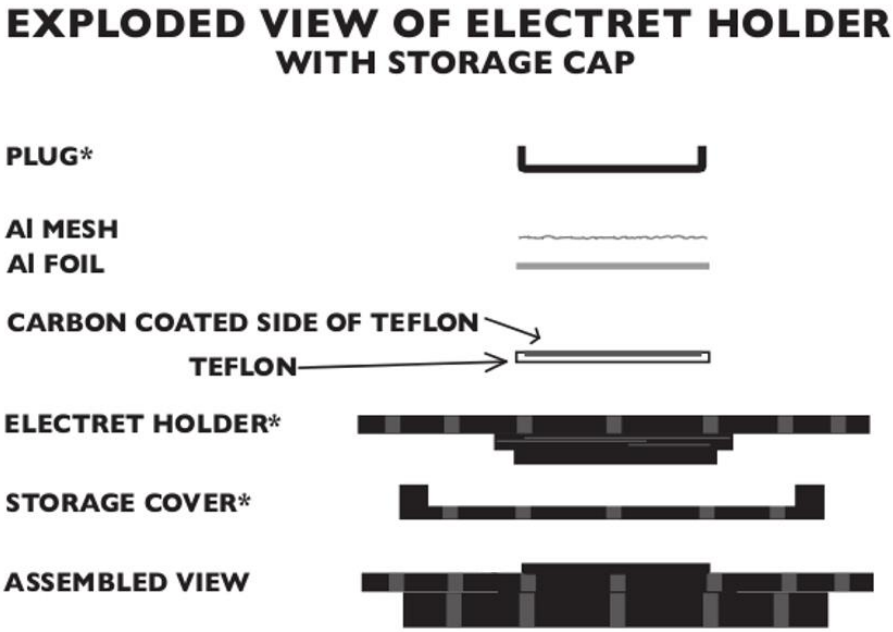
Figure 3. How is electret characterized and how is it measured.

These both have an electret surface area of 8.43 cm^2. Figure 5 illustrates a simple EIC used for characterizing alpha and beta radiations. Alpha or beta radiation ionizes air inside the chamber that also houses an electret. The electret, usually carrying positive charge, collects the negative ions. After a desired exposure period, the source is removed, electret is taken out and the surface potential is measured. The initial reading, final reading, and the exposure period are all used in calibration algorithms to calculate the desired characteristics of the source. Figure 5 illustrates the principle of electret ion chambers.

Conversion of the Electret Discharge in Volts to Collected Charge in Coulombs

Equation (1) gives the relationshipbetween various parameters.

$$\frac{Q}{V_S} = \frac{E\,E_0\,A}{d} \tag{1}$$



*Made of electrically conducting polypropylene.

Figure 4. Exploded view of components of electrets.

Using equation (1) it is possible to calculate the relationship between the surface voltage and the surface charge. Such a relationship is useful in the theoretical calculation of the responses of EICs.

Q is the total charge on the electret
E is the dielectric constant of the electret = 2 for Teflon
E_0 is the permittivity of space = 8.854×10^{-14} $C.V^{-1}$ cm^{-1}
A is the area of the electret = 8.43 cm^2
d is the thickness of the electret
Vs is the surface voltage of the electret in volts
For d (thickness of electret) = 0.1588 cm

$$Q/Vs = 9.40 \times 10^{-12}\ CV^{-1} \tag{2}$$

1 volt change on electret corresponds to a collection of 9.40×10^{-12} coulombs
For d (thickness of electret) of 0.0.0127 cm

$$Q/Vs = 1.18 \times 10^{-10}\ CV^{-1}$$

1 volt change on electret corresponds to a collection of 1.18×10^{-10} coulombs

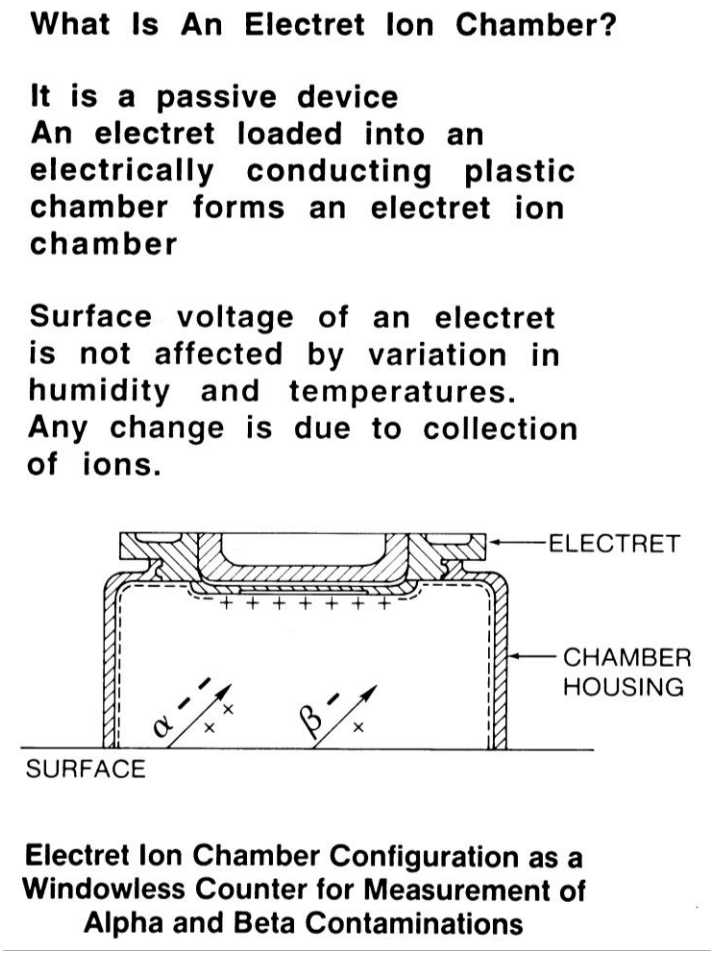


Figure 5. What is an electret ion chamber and how alpha and beta radiation measured with EIC.

Example of Calculating the Response Factor for an EIC Gamma Monitors

The Bragg Gray equation for uniformly irradiated (by X and/or gamma radiation) air cavity the conversion rate (CR) is calculated and is given by equation (3).

$$CR = 33.97 \times 10^{-14}\ C.mrad^{-1}.ml^{-1} \quad (3)$$

Dividing equation (3) by equation (2) gives the response in V $mrad^{-1}$ ml^{-1}, multiplying by 58 (the volume of the chamber) gives the response factor in V $mrad^{-1}$.

The result is about 2.0 volt per mrad. This is very close to the experimental response factor [42].

Such methods are used for calculating theoretical responses of EICs for different radiations.

Practical EIC units are used with electrets in the range of 100 to 750 volts. This is also the range for operating conventional ionization chambers. The final voltage becomes the initial voltage for the next measurement.

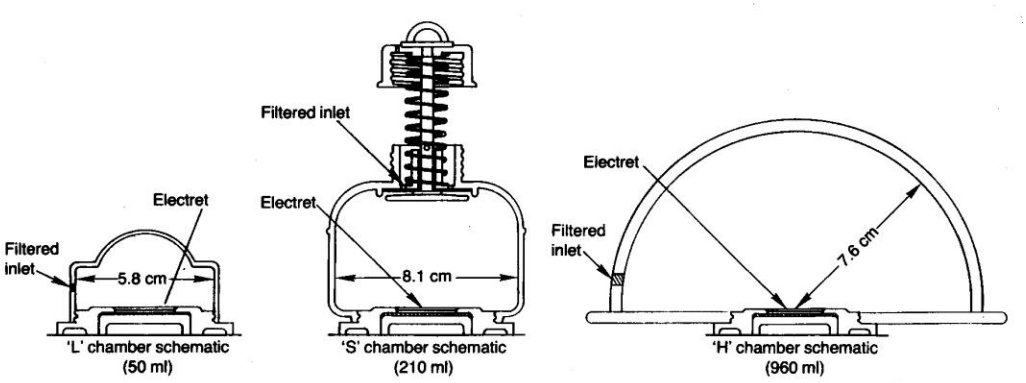


Figure 6A. Cross section ns of different EIC chambers used for radon measurement.

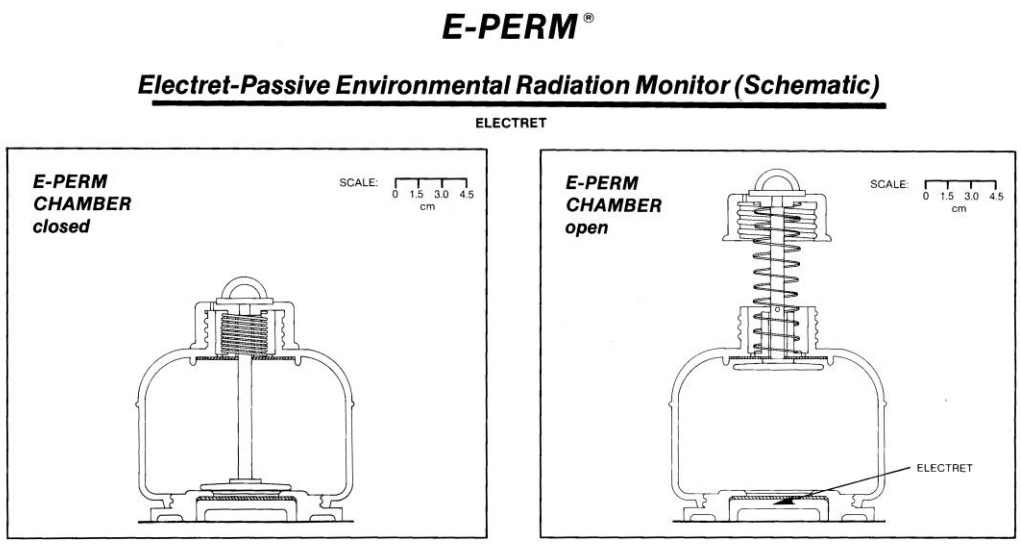


Figure 6B. Principle of operating EIC in on/off mode. Left is off and right is on.

Each electret gives a large number of measurements, adding to the economy of the technology. The response factor, also called as calibration factors (CF) that converts the data to the quantity that is being measured These are discussed later while discussing the use of EIC for different applications.

Comparison between Electret Ion Chambers and Conventional Ionization Chambers

The electret ion chamber (EIC) is a unique form of conventional of ionization chambers used for measuring ionizing radiations. In a typical ionization chamber, electric field is maintained between the two plates using a high voltage source. When ionizing radiation such as gamma radiation passes through the chamber volume, a measurable current is established in proportion to the intensity of radiation.

This current gives a measure of the ionizing radiation. In EIC, we have two readings, one is the initial volt on electret and the other is final volt on the electret.

In case of EIC, electret provides not only the high voltage needed for ionization chamber to function, but also serves as a sensor. The difference between the two readings is the sensor signal. The average reading of the electret, often called as mid-point voltage defines the average electric field. The rate of discharge of the electret defines the current, similar to the current in conventional ionization chambers. Since EIC can be used for extended periods (from days to months), the measurable current can be very small, and hence it is possible to measure very low levels ionization, not practical in conventional ionization chambers. Further, EIC performs well with highly humid atmospheres making it a very practical tool to measure ionizing gases, such as radon and thoron, tritium and other ionizing noble gases, in air in homes or in an atmosphere where humidity can be varying.

Scientific Basis for Electret Ion Chambers

Bauser and Range [4] were the first to use a pair of thin Teflon electrets of opposite charges to collect and measure 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 showed that the performance was fairly 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 for a period of more than one year.

Figure 7. Components of EIC for radon measurements; top left: radon EIC, top right: electret voltage reader, bottom left: electret in open mode.

This study laid a solid scientific basis for electret ion chambers (EIC) technology. These are also called as electret dosimeters.

Providing two electrets of opposite polarity served the purpose of demonstration of technology, but this was not practical. Next attempt was to build an EIC with one electret located at the bottom of a conducting chamber. If the electret carries positive charge, the entire conducting chamber is at negative potential (ground). Electret can be taken out and measured. Only one electret need to be measured, simplifying the operations.

This innovation of using single electret in EIC technology reported by Pretzsch and his coworkers [14 to 24] and later by Kotrappa and his coworkers [7, 8, 9]. 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 personal dosimeters, and possible uses for radon measurement. The theoretical aspects of electrostatic fields in such ionization chamber were worked out by Fallone and his coworkers [27 to 35]. Kotrappa [7, 8, 9] and his coworkers were the first to report a rough correlation between the reductions of surface voltage and cumulative ^{222}Rn exposure in a passive chamber arrangement and further observed that this change in reduction did not appear to be sensitive to humidity change. This became a foundation for further development of practical EICs for measuring. ^{222}Rn (also called as radon).

R and D Leading to a Practical EIC for Indoor Radon Measurements

In the early 80s, there was a sudden large interest in measuring indoor radon concentration because of the discovery of homes with very high radon levels. This led to a systematic research and development of EIC aimed at for measuring radon concentrations in homes. Kotrappa and his coworkers [11] described in detail the conceptual design and performance of EIC for measuring radon concentration and various parameters that determine the performance. The study included the chambers of different volumes, ranging from 40 ml to 1250 ml and electrets of different thicknesses, ranging from 51 µm to 2.3 mm. The study concluded that the response was directly proportional to the volume of the chamber and proportional to the thickness of the electret. The study recognized the importance of response to gamma radiation level when measuring low concentrations of radon usually found in home, and further recognized the importance of the wall material in reducing the background due to gamma radiation. The gamma response successively decreased with the steel, Al and Aluminum lined plastic, respectively. It was also shown that electret produced and used in this study have high stability for practical use from a period of 2 days to one year, even at relatively high humidity. This study also provided the parameters needed to design an EIC required in meeting any requirement. This paper also provided the basic design parameters of an electret voltage reader suitable for routine use.

Standardization of EIC for Indoor Radon Measurement

It was important to move the R and D results to practical device. Next landmark work was to design a practical radon monitoring system using the parametric studies published earlier [11].

This led Kotrappa and associates [12] to standardization of practical electret passive environmental radon monitoring system abbreviated as E-PERM. The system consists of electrets, chambers and electret voltage readers and calculation procedures. The chamber and the electret holders were made of electrically conducting plastic to minimize the response of the gamma background to the radon measurement. The components were made by injection molding for high reproducibility. A spring loaded shutter mechanism is introduced to cover and uncover the electret from outside to serve as on-off mechanism. The optimized system components were: an electret voltage reader that is simple to use and accurate to ±1 volt of surface potential, chamber volume is 210 ml and electret thicknesses are 0.1.524 mm and 0.127 mm. These E-PERMS were designed for making radon measurements in 2 to 7 days with 1.52 mm thick electret and one month to 12 months using 0.127 mm thick electret. The paper [12] describes fully the calibration, performance, error analysis, and the lower limits of detection. The entire system was commercially produced so that it can be easily used. The system was evaluated by USEPA and was introduced as an approved method for measuring indoor radon concentration in air. This system became very popular and is used in many countries by radon and radiation specialists. The system has been evaluated by several investigators in many countries [25, 26, 46, 51, 74] and shown to meet the specifications [12] for measuring radon in air. Standardized version of EIC is often called as E-PERM, as such the words EIC and E-PERM means the same.

Description of Radon Measuring EIC and Related Components

Figure 1 shows the schematic of typical radon measuring EIC. Radon gas diffuses into the chamber through filtered openings. Radon decays inside the chamber leading to other radioactive decay products (^{214}Po and ^{218}Po). The decay products being particles diffuse to the interior surfaces of the chamber. Ionizing radiations emitted by the decay of radon and the decay products ionize air in the chamber. The negative ions are drawn to the surface of the positively charged electret located at the bottom of the chamber. The surface charge of the electret gets depleted due to the collection of ions. The depleted charge of the electret over a time period is equivalent to the time integrated charge produced by radon and the associated decay products. This in turn is proportional to the integrated radon concentration over that period. The technical basis for the measurement of indoor radon using the EIC has been fully described in three papers by Kotrappa and associates [11, 12, 13].

Components of EIC

The major components of EIC are: electret, chamber, mechanical system to cover the electret when EIC is not in use, the electret reader and the analysis tools to calculate radon concentration.

The Electret

The electret used in the EIC is a disk of Teflon® (Du Pont) which has been electrically charged and processed by special procedures so that the charge on the electret remains stable

even at high humidity or low/high temperatures. The production and processing of electrets is fully described elsewhere [11, 12, 13].

The Electret Reader

A method popularly known as shutter method or capacitative probe (Figure 3) method is adopted as the basis for the design of a dedicated electret reader to measure the surface voltage of the electrets. An electret is firmly positioned the electret receptacle and is positioned at a precise distance from the sensing plate. A metallic shutter separates electret from the sensor. When the shutter is pulled out, a charge is induced on sensor plate and generates a voltage across the capacitor. This voltage is measured by an ultra high impedance circuit to read out on the LCD meter. The meter is calibrated using a dummy electret with precise surface voltages. The electret reader reads out the electret volts correct to 1 volt.

It initializes to zero reading before registering a new reading. It has auto off set to 2 minutes of non-operation. The reader measures 1 to 1999 volts. It reads both positive and negative voltages. Figure 7 shows a photograph of the electret voltage reader.

The relationship between the surface volts to surface charge depends upon the thickness of the electret. Conversion factors can be used to convert reading in volts to charge on the electret in coulombs. For 1.542 cm thick electrets, the relationship between the surface charge and the surface potential is: Coulombs $volt^{-1} = 9.69 \times 10^{-12}$.

For 0.0127 cm thick electret, the relationship between the surface charge and the surface potential is: Coulombs $volt^{-1} = 1.175 \times 10^{-10}$. Open area is 8.43 cm^2. One side of the electret is electrically conducting and is held firmly in a holder that is also made of electrically conducting plastic. Electrets are produced and processed in the holder and are covered with a screw cap. When cap is unscrewed, electret can be lowered into the well of the electret reader to read the surface potential in volts, or can be screwed into the EIC chamber.

EIC Chambers

These are made of electrically conducting polypropylene, made by injection molding to maintain the required precision and reproducibility. This further helps minimize the response from gamma radiation [11]. Chambers of 3 different volumes are available to get different sensitivities. The volumes are 58 ml, 210 ml and 960 ml.

Figure 6A gives schematics each one of these chambers and the location of electrets. Figure 6B illustrates the method of switching the EIC on and off. In the off position electret is closed and EIC can be transported or stored without picking up any additional signal. Such on/off design of different design is also incorporated in 50 ml chamber [66].

Basic Electret Ion Chamber System for Measuring Radon Gas

Electret ion chambers (EICs) are portable, passive, accurately integrating ionization chambers that do not require a battery or any external source of power. Figure 1 shows the schematic of typical EIC used for measuring radon gas.

Detailed Method of Deriving Calibration Equations for a Radon EIC [12, 13]

The E-PERM® Electret Ion Chambers (EICs) have been widely used for research in indoor and outdoor radon measurements. Calibration factors are fitted to an equation that relates the calibration factors to the initial and final voltages. The calibration equations currently in use restrict the use of electrets to the initial readings of 750-250 volts. Recent research indicated that it is possible to derive the calibration equations applicable for wider ranges. A detailed procedure is described for calibrating SST EICs and deriving an appropriate equation, applicable over the range of 750 volts to 70 volts. Furthermore, the newly derived equation fits the experimental data with better precision, compared to the currently used equations.

Calibration Procedure

Because of the continuously decreasing nature of the electret voltages during a measurement, the calibration factors are not constants and depend upon the initial and final voltages of electrets. Calibration factor is related to midpoint voltage (MPV), the average between the initial and final voltages. Calibration factors are fitted to an equation that relates the calibration factors to the MPV). Equation (4) is used for calculating the radon concentration.

$$RnC = \frac{(IV - FV)}{(T) \times (CF)} - BG \tag{4}$$

where: RnC is the radon concentration in the radon test chamber (pCi/L or Bq/m3). T is the exposure period in days. IV and FV are the initial and final voltages respectively. CF is the calibration factor in volts per (pCi L^{-1}-days) or in volts per (Bqm^{-3}-days). BG is the radon equivalent per unit gamma radiation. The constant 0.087 is the radon concentration (pCi L^{-1}) equivalent for 1 µRh^{-1}. Similar unit can be used in SI units.

A set of EICs with staggered initial voltages (from 100 volts to 750 volts) are exposed in a standard radon test chamber for a known radon concentration for a known time period.

Using equation (4), CF is calculated for the respective MPV.

Fitting an Appropriate Equation to the Experimental Data

The data can be fitted to a linear regression equation (5) or equation (6)

CF=A+ B x MPV ----- (5)

CF=C +D Ln(MPV) ---- (6)

A, B, C and D are constants.

In the earlier work[9] equation (5) was used. Linear regression equation was fitted between CF and MPV. Such equation was found to fit good only between the MPV of 700 volts and 200 volts only.

In recent work[10} the data was fitted between CF and natural logarithm of MPV. Such equation was found to fit good between the MPV of 700 volts and 100 volts.

The constants A and B; C and D are provided by the manufacturer for several combinations of chambers and two standard thicknesses of electret.

Table 2 gives experimental CF and the calculated CF using the fitted equation (6). Experimental data when fitted to natural logarithm of MPV appears to fit perfectly leading to an error of less than 2%.

When initial and final voltages are determined, equation (6) is used to calculate CF. Then equation (4) is used to calculate radon concentration.

The Performances of EIC for Measuring Radon

EICs are not affected by varying temperature and humidity found in the normal environment

EICs are not affected by the external electric field

EICs are not affected by the air draft

EICs are not affected by the presence of thoron in air

EICs are not affected by the ions generated by external ion sources

EICs are not affected by the external dust load

EICs are not affected by the magnetic fields or any radiofrequency sources

*The performance is affected by the presence of X or gamma radiation and elevations. Manufacturers recommendations are avaialble for the users. *Standard corrections are applicable for sampling at different elevations.

*Standard corrections are applicable for different gamma backgrounds.

Table 2. Percent deviation of CF relative to measured CF using equation

MPV	Measured CF	Fitted CF	% Dev(relative to measured)
731.7	2.0075	2.0484	2.0
697.5	2.0734	2.0345	1.9
649	2.0033	2.0136	0.5
549.8	1.9456	1.9654	1.0
450.5	1.9662	1.9075	3.0
354.9	1.8178	1.8382	1.1
259.2	1.7395	1.7468	0.4
163.6	1.6159	1.6131	0.2
70.1	1.3644	1.3668	0.2

Analysis procedures for sensitivity, error analysis and derivation of detectable limits at different concentrations is published and is provided by the manufacturer.

Inter-comparison of the performances compared to reference levels have been studied at national and international standard test chambers and in blind test.

The results have shown acceptable performances [25, 26, 46, 51, 74]. In none of these exercises there has been any adverse remarks and confirm the observation made in discussions on the performances. In many of these inter-comparison exercises, EIC is used as reference detector to assess other devises.

Advanced Researches on EIC

Most of the basic research on EIC is done by three groups: Kotrappa and associates in India and US, Pretzsch and associates in Germany and Fallone and associates in Canada. Relevant references are cited in the section on references. Some [2] researches of significance are mentioned in the following paragraphs.

Uncertainty Evaluation

Uncertainty evaluation is provided in detail [12]. This includes sensitivity analysis and the calculation of errors for each radon measurement. Further procedures are discussed (Manufacturers Manual) for calculating the lower method detection for different combinations of chambers and electrets in the (Manufacturers Manual).

Caresana and his associates [26] studied several commercially available EICs and evaluated the uncertainties associated with the measurement of radon and gamma radiation. In this work, attention is focused upon the electret ion chambers (EIC), widely used in radon concentration measurements. Measurements of gamma radiation sensitivity are performed in a secondary standard calibration laboratory and measurement of radon concentration sensitivity is performed in a radon chamber 0.8 m^3 in volume.

Raw data are analyzed to evaluate the calibration factors and the combined uncertainties are determined. The aim of the study is more rigorous than the study reported earlier by Kotrappa [12]. This study conforms to international standards (ISO 95) and some of this information is in draft ISO/ WD/ 766 (2007).

Basically results agree well with the simplified version given by Kotrappa [12].

Simplified version has an advantage for easy calculations without compromising the accuracy.

Advanced Method of Deriving Equation for Calibration Factors [12, 13]

EICs are designed to be used over the entire useful range (750 to 70 volts. Further these need two readings, initial and final volts for computation of results. This requires a calibration factors for any pair of readings characterized by mid- point voltage (MPV).

Because of continuously decreasing nature of electric field during the use of an EIC, from 750 volts down to 70 volts, calibration factor (CF) also varies depending upon the MPV.

These features are very different compared to other passive radon detectors such as alpha track detectors whose calibration factors remains the same for the entire range of use. These features of EIC make the calibration of the devices more complicated.

Detailed method of calibration is already described. The most recent research of fitting the CF with natural logarithm of MPV improved the fit and make it applicable over wider range of electret voltages compared to earlier practice [12].

The study also proved that CF decreases exponentially with MPV because of the increasing recombination of ions at the decreasing electric field.

Significant Observations in Advanced Researches Relating to Radon EIC

Reference [14] gives a novel method of the concept of reusable electrets. This is applicable to the measurement of X-rays using EIC not usable for radon. Reference [15] gives theoretical model for calculating the responses for radon EIC. This is of significance for radon EIC. The methods provide a theoretical basis for calculating approximate responses, finally trusting on the experimental results. Reference [16] is a very useful to calculate the response for different dimensions of the chambers.

It also analyzes the commercially available EIC chambers [12] in comparison with the optimized models. This concludes that commercially produced models are close to the optimized dimensions and can be marginally improved. Reference [15, 16] continues to analyze the optimized models for the effect of relative humidity and pressures. Experimentally determined effects for commercially produced EIC [37] are similar in most cases. Reference [19, 20, 21, 24] applies the theoretical models for designing EICs for photons and neutrons, not applicable for radon EIC.

Reference [22, 23] analyzes the surface charges on the electrets, both before the use and after the use of commercially produced electrets. The study concludes that surface charges tend to become more uniform after the usage of EIC. Recent experimental study [13] shows that the equation for calibration factor applies equally well down to the electret voltages of 70 volts, discounting any effect on surface charges of electrets.

Reference [27, 28, 29, 30, 31, 33, 34, 35] reports further studies on the charge distribution on electrets and electro static fields inside the EIC and possible applications for characterizing radioactive sources used in medical applications. These studies are fundamental in nature and are useful in further researches. Reference [38] discusses the feasibility of the use of EIC for radon measurement.

One particular work [32] is of some interest in further developments. This deals with the radiation induced conductivity (RIC) of Teflon in electret ion chambers. This is of a particular interest while using EIC for characterizing X-rays. In such EIC unit, electret not only collects the ions produced inside the EIC chambers, but also directly irradiated by X-rays.

Such direct irradiation may cause some recombination of charges on the surface of electret causing additional electret discharges.

Such effect is also found to be dose rate dependent. Such effect may be of interest in characterizing alpha and beta sources. Further if one uses an EIC of very small volume for exposure to X rays, the possible measurement of radiation induced discharge of electret itself can be used for measuring high levels of X and gamma radiations.

Experimental Elevation Correction Factors for Commercially Available EIC

Radon monitors are usually calibrated in a standard radon test chamber at sea level. When such detectors are used at elevations other than the sea level, the results need a correction. The geometries of EIC radon monitors are complex and theoretical calculation of the correction factors is difficult, though attempted. The correction factors are determined using a radon source inside an experimental chamber that can be maintained at different pressures over extended time periods. The correction factors are determined [37] for three different models of commercially available EIC (E-PERM) for elevations up to 3000 meters. Theoretical results do agree in general trend, but not agree very well with the results in these experimental studies. This is because of limitations of several assumptions made in theoretical modeling. Manufacturer of the commercially available EIC recommend using the experimentally determined factors.

Techniques for Measuring Short Duration High Radon Concentration [85]

EICs are normally standardized for measuring relatively low radon concentrations usually found in homes and outdoor environment. However, there are situations when very high levels need to be measured. Examples of such situations are: unventilated uranium mines, radon therapy caves, waste storage silos and acute inhalation experiments. Concentrations of 50,000 and 100,000 pCi/L (2 to 4 MBq/m3) are not uncommon as found in radon in underground soil and in radon therapy caves. At such high levels exposure periods have to be small to avoid full discharge of electrets. Such situations do does not allow equilibrium to reach between radon and the associated decay products inside the chamber.

For this reason, the standard calibration factors will not give correct results. The suggested [85] correct procedure is to expose the detector to radon for desired exposure period, then move the detector to low radon area. Measure the final voltage of electret after a period of at least 3 hours. The deficiency in the ramp up time is compensated during the ramp down time. This procedure has been tested and found to give good results. This method is also suggested by Kunzamann [17].

Use of EIC As Personal Dosimeters for Radon Workers

Radon professionals who perform indoor radon measurement or radon mitigation require to keep a record of the personal radon exposure during their occupational work. For such a purpose it is desirable to use a personal radon dosimeter. Ideal such dosimeter should be an accurate integrator capable of rapidly responding to the varying radon concentrations, sensitive enough for a practical use and small to wear for the workers. A 50 ml EIC (LST) and a standard AT detector meet these specifications. Houle [84] devised an experiment to compare these two devices for their performances.

In this study triplicate EICs and ATs from five different manufacturers were exposed repeatedly to 60 minutes and then low radon air for 120 minutes in a specially designed radon chamber. Radon was provided by a Pylon radium source with a measured air flow through the source. Length of exposure was carefully recorded.

Grab samples of the test chamber were taken to confirm the radon concentration of the chamber. A second run was made exposing detectors to 15 minutes for radon and 120 minutes for low radon air. Results are expected to show the effectiveness of the devices as a personal dosimeter. Radon concentration of air used as radon air was about 230 pCi/L (8500 Bq/m3) and the room air was used as low radon air. Most of the AT detectors showed a higher response by about 50%. These can be used as personal dosimeters keeping in mind the possible positive bias. Author was unable to ascertain the possible reasons for this high positive bias. Only EIC detectors responded with in 3% of the expected integrated concentrations. These can be used as personal dosimeters with confidence.

Performance of EIC in Magnetic Field

EIC are used for measuring radon and other ionizing radiations caused by alpha, beta, gamma and neutrons. EIC is an ionization chamber that uses the electrostatic field provided by the electret. EICs do not have any electronic components and can be introduced into the area where high magnetic fields are present such as in accelerator areas. A systematic study [93] is conducted in the laboratories of National Institute of Standards and Technology. Relative responses are measured with and without the magnetic fields. Magnetic fields are varied from 100 to 9000 gauss. No significant effect is noticed while measuring alpha and gamma radiations, However a significant effect is found while measuring beta radiation from ^{90}Sr-Y. Depending upon the magnetic field orientation, the relative responses increased from1.0 to 2.7 in vertical orientation. Responses decreased from 1 to 0.6 in the magnetic fields in horizontal position. This is due to the setting up of a circular motion for the electron by the magnetic field, which may increase or decrease the path lengths of electrons. It is concluded that EIC can be used for measuring alpha (and hence radon) and x and gamma radiation in the range of magnetic field studied. However caution must be exercised while measuring beta radiation.

Inherent Discharge of Electrets

Stability of electrets used in EIC are well studied [10]. In spite of their high stability, electrets show some finite rate of discharge even when not exposed to ionizing radiations. This is called as inherent discharge of electrets. For example ST electrets show a discharge rate of 1 to 2 volts month. This is very small compared to the discharges that occur while measuring indoor radon. When encountered special cases such as measuring very low radon concentration using small volume (50 ml) EIC, the inherent discharge may contribute significantly for the final results. Manufacturer recommends a correction for such discharges. Analysis algorithms provided by the manufacturer such corrections are already built in.

Radon Metrology Using NIST ^{222}Rn Emission Standards

Development of radon emission standards has been an important contribution to the field of radon metrology.

For the first time these standards are usable for calibrating radon monitors in our own laboratory with traceabile to national standard. These are hermetically sealed polyethylene capsules filled with ^{226}Ra solution. These are available in four strengths: 5,50,500, and 5000 Bq of ^{226}Ra. The standards are specified both in terms of strength of radium and the emanation coefficients Volkovitsky [95]. These two parameters are sufficient to calculate the expected rate of radon emanation rate. These can be used in two modes: accumulator mode and steady state mode. Equation (7) gives the expected radon concentration at delay of T days when enclosed in an enclosed container, termed as accumulator.

Use of NIST Standard Used in an Accumulator Mode (Figure 11 in Part 1)

This is fully described by Kotrappa [56]

Equation (7) gives the radon concentration at any accumulation time T days.

$$RnC = \frac{f\ Ra\ (1 - \exp\ (-k \times T)}{(V)} \tag{7}$$

where RnC is the radon concentration in Bq m^3, in an accumulator of volume V (m^3)

Ra radium content in Bq

k is the decay constant of radon in day^{-1} units

T is the accumulation or elapsed time in days

f is the emanation coefficient characteristic of the source as provided by NIST.

If a CRM (continuous radon monitor) is enclosed in an accumulator, it should read the radon concentration as given by equation (7) for an accumulation time of T days

If a passive devices such as an EIC or AT device need to be calibrated, equation (7) need to be integrated from 0 to T days to provide the average concentration of radon after an accumulation time of T days. This is given by equation (8)

$$RnC = \frac{f\ Ra}{V}(1 - \frac{(1 - \exp(-k\ T)}{(k\ T)}) \tag{8}$$

Kotrappa [56] used this method to calibrate the EICs and a CRMs for radon.

Use of NIST Standard Used in a Steady Flow Mode

This is fully described by Kotrappa [57]

When air flows over the source at a known steady rate, it is possible to calculate the radon concentration in air. Equation (9) gives the radon emanation rate.

$$RnC = [f\ .\ Ra\ .\ k] / F \quad \text{---} \tag{9}$$

where *RnC* is the radon concentration in air Bq m^{-3} . *f* is the emanation fraction. *F* is the air flow rate in m^3 s^{-1}. *Ra* is the radium activity in Bq. *k* is the decay constant of radon in s^{-1}.

A practical one meter cube radon test chamber is designed and operated bases on the use of NIST standard used in a steady flow mode [94].

Another example is the calibration of radon flux monitor using NIST emanation standard [68].

EIC for Radon in and around Volcanoes

Because of their unique features, these have found use in and around active and passive volcanoes. The studies by Heiligmann [48, 49] published in Journal of Volcanology and Geothermal Research is of special interest.

Manufacturers Manuals

Standardized version of electret ion chambers, also called as E-PERM$^{(R)}$ are manufactured by Rad Elec Inc. Most of the applications are also developed by Rad Elec Inc. in association with several Institutions and Universities. Currently Rad Elec Inc is the only organization manufacturing and supplying the standardized EIC system. Rad Elec Inc. has the responsibility to supply operating manuals. The web site www.radelec.com provides the basic information needed including several basic applications and some downloadable publications.

PART 2. USEFUL APPLICATIONS OF RADON EIC

1 EIC for measuring American national ambient radon concentration
2 EIC for the measurement of thoron and the use of passive radon thoron discriminative monitors
3 EIC for measuring radon decay products in air using E-RPISU (electret -radon progeny integrating sampling unit)
4 EIC based radon flux monitor for *in situ* measurement of radon flux from ground, granite, concrete surfaces and for uranium exploration
5 EIC for uranium prospecting for accurate time-efficient surveys using EIC based radon gas monitors
6 EIC for uranium prospecting for accurate time-efficient surveys using EIC based radon flux monitors
7 EIC for characterizing soil and building materials
8 EIC for the measurement of dissolved radon in water

1. EIC for Measuring American National Ambient Radon Concentration

This is an important study [89, 41] carried out by US EPA (United States Environmental Protection Agency). This is of national as well as geological importance. This study covers the quarterly measurement of radon in all 50 US States for a two year period. The second phase covered 50 locations in one state (Nevada) covering various geologies. The detectors were located in well ventilated shelters located approximately two meters above the ground.

The gamma background needed for subtracting its ionization component was measured using co-located TLDs for identical sampling periods. To minimize the statistical error, a set of three detectors were used for each measurement. This study concluded that field measurements using SST E-PERM EICs have been made with acceptable errors and the devices have exhibited sufficient sensitivity for measuring ambient levels of radon concentrations. Coefficient of variations for the mean estimates were well below the 50% required for reproducibility, except for New Mexico (88%) because of its low mean value (0.16 pCi/L or about 6 Bqm^{-3}).

For those who need more details, please refer to the original publications.

The SST type of E-PERM EIC was chosen because of the following reasons:

1 The performance is not affected by varying temperatures and humidity found in all the locations in the US.
2 A study comparing the outdoor radon concentration measured by EIC and a calibrated RGM (radon gas monitor) agreed within 5 % of each other, over extended periods.
3 A study comparing the radon concentration measured by EIC and RGM in a radon test chamber agreed similarly.
4 USEPA confirmed that the Manufacturer is likely to be in business over the next decade, to assure supply of equipment, if the study needed to be repeated.
5 Limit of detection of radon, as determined independently by USEPA, is 2 Bq m^{-3}

The following observations are noted based on these studies:

Results ranged from 2.2 to 41.1 Bqm^{-3} for individual results with a median value of 14.4 Bq m^{-3}. This level is now officially considered to be the national ambient average radon concentration in the US. The annual mean ranged from a low of 5.9 to a high of 20.7 Bqm^{-3}.

The second study [41] has several interesting observations attempting to correlate outdoor radon concentration with local geology:

The mean outdoor radon in Nevada is comparable (15 Bqm^{-3}) to that observed in Nevada in a national study. However, the range is considerable (2.6 to 52 Bqm^{-3}). There appears to be some correlation with the radon soil gas data and the outdoor radon concentration. The towns with more than 20% of indoor radon concentration above the EPA action limit of 48 Bqm^{-3}, appear to correlate with higher outdoor radon concentrations.

The protocols used in this study have become a model for similar measurements.

2. EIC for the Measurement of Thoron and the Use of Passive Radon Thoron Discriminative Monitors

There are two major isotopes of radon gas, one is ^{222}Rn (usually called radon) that is released from uranium and the other is ^{220}Rn (usually called thoron) released from thorium. In view of the presence of both uranium and thorium in the earth crust, both radon and thoron are found in nature and in homes. Radon has a half life of 3.8 days, whereas thoron has a shorter half life of 55 seconds. In homes, radon is found in much higher concentrations than thoron because of the differences in half life. This may not be so in some regions, thorium is much more abundant than uranium in the ground [91].

There are some special situations where there can be high airborne thoron such as locations where thorium is processed or stored.

The radon measuring EIC is designed with a small diffusion inlet area leading to the diffusion time much longer (more than 5 minutes) than the half life of thoron. This minimizes the entry of thoron. Normally radon EIC has about 3% response to thoron and is considered insignificant, therefore the EIC is considered as a pure radon detector. This was confirmed in Japan [25], and was designated as R EIC. Thoron measuring EIC [45, 86] is designed with larger diffusion inlet areas (Figure 8) leading to the diffusion time much shorter than the half life of thoron to allow thoron to get into the sensitive volume. Such thoron EICs also register radon and some thoron. This is termed as R-T (radon-thoron). A pair of detectors (R and R-T) are needed to make a thoron measurement. The differential signal between R and RT units is used for calculating thoron concentration. Such a pair is called as "discriminative set used to discriminate and measure both radon and thoron".

Once calibrated properly, it is possible to calculate both radon and thoron concentration, when a mixture of these gases are present in the sampling atmosphere. Calibration is done using either a standard thoron test chamber [86] or a test chamber monitored by standard thoron measuring continuous monitors such as Rad 7 [45]. Different sets are now available in different volumes, 58 ml, 210 ml and 960 ml. Such availability extended the range and sensitivity for monitoring from a few days to one year. Vargas [51] found that the 210 ml set gave satisfactory results in one of the inter-comparison studies.

Equation (10) is used for the calculation.

$$Tn = \frac{(I - J)}{CF(I, J) \times D} - \frac{(K - L)}{CF(K, L) \times D} \tag{10}$$

where I and J are the initial and final electret voltages of RT monitor. K and L are the initial and final electret voltages of R monitor. D is the exposure period in days. Tn is the thoron concentration in units of $kBq\ m^{-3}$. CF is the calibration factor in units of volt drop per ($kBq\ m^{-3}$ *days*) for the corresponding pair of data.

Equations connecting the CF with MPV are available for all the three EIC sets of discriminative monitors. The detailed procedures of using these EIC sets to measure both radon and thoron concentrations are fully described [45, 86].

The EICs come in different volumes, providing different sensitivities. The thoron calibration factors for 58 ml, 210 ml and 960 ml volume R and RT pairs are respectively 2.8, 18.7 and 89 volts drop per ($kBq\ m^{-3}$-*days*) respectively.

These provide much wider sensitivities and ranges compared to alpha track based passive radon-thoron discriminative monitors.

Attenuation of Thoron in Membranes

In many cases both radon and thoron are present in the environment to be sampled. These two gases not only have different half lives, but also have different biological properties, with different action limits. While measuring indoor radon, thoron is an interference and should be stopped from entering the sensitive volume of true radon monitors. The methods used for stopping thoron usually take advantage of the differences in half lives of radon and thoron. Any such method should not stop radon, only thoron.

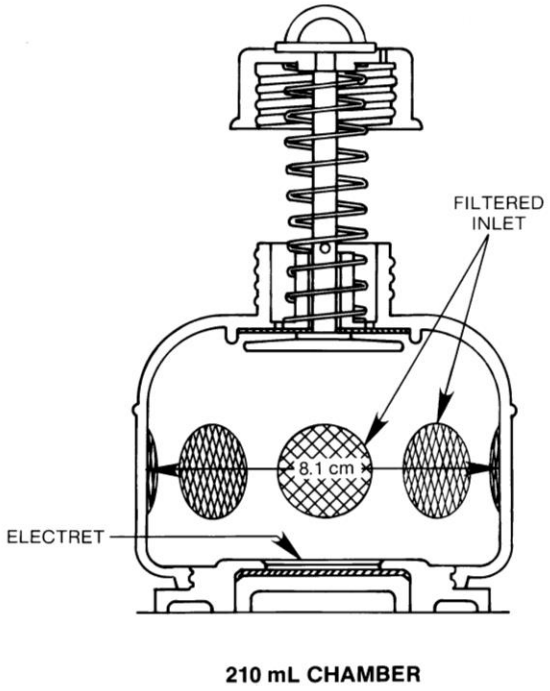


Figure 8. Schematic of 210 ml thoron (R-T) measuring EIC.

Recently a study (Leung, 2007) used a thin layer (5 to 6 μm) of polyethylene (PE) in front of the passive entry of gas into the sensitive volume of the passive radon monitors. This stopped 92% of thoron, but allowed more than 98% of radon to go through to the sensitive volume. This is considered adequate for most passive radon monitors. It is easy to explain the performance of PE, based on the differences in the half lives between radon and thoron. The time taken to diffuse through PE is the same for both radon and thoron, but that diffusion time is very small relative to the half life of radon leading to insignificant decay of radon during the passage, whereas it is significant relative to the half life of thoron leading to the significant decay of thoron. Smaller or larger thicknesses of PE will not function satisfactorily. Leung optimized and demonstrated that 5 to 6 μm thick PE works satisfactorily. There are other methods of achieving the same results. In electret ion chambers (Kotrappa, [12] radon enters through a small opening. By controlling the ratio of the diffusion area to the sensitive volume, it is possible to control the diffusion entry time, thus stopping or minimizing thoron interference. The EIC for radon responds only to 3% of thoron while fully responding to radon. Another method used in flow-through radon monitors is to have a long loop of tube to allow the decay of thoron before entry into the sensitive volume. Even though PE works, it has some practical limitations. The membrane is very thin and electrostatic. It is difficult to position this on the inlet of the radon progeny filter in a stretched condition, and sealing the edges with an adhesive can be quite challenging. This may introduce uncertainty in the performance. In recent work [65] Tyvek membranes are studied for the attenuation of thoron. These have several advantages. Tyvek membranes of standard thicknesses, well defined properties and complete transparency to radon, are available commercially. These are antistatic and have relatively larger thicknesses for handling and sealing.

In this work [65], different layers of Tyvek membranes are introduced between the thoron source and the thoron detector, and thoron attenuation is measured, leading to attenuation of thoron for different thicknesses of Tyvek. The results can be used to control the thoron attenuation factors. 960 ml and RT pairs are used to measure thoron attenuation in different thicknesses of Tyvek membranes. A stack of 7 membranes (1 mm thick) reduces thoron by 50%, and a stack of 31 membranes (4 mm thick) reduces thoron by 95%. There is virtually no decay of radon for the Tyvek membranes even with 31 membranes (4 mm thick) whereas a stack of 31 membranes reduced the thoron concentration by 95%.

Applications Attenuators

A stack of Tyvek membranes can easily be built to be used as a thoron attenuator without attenuating radon. Such a stack can be inserted at the passive entry of any passive radon monitors such as AT monitors or other similar radon monitors. One of the important applications is in uranium exploration projects. 960 ml electret ion chambers are widely used in uranium exploration projects in Canada, (Charlton [96] and elsewhere. The procedure results in mapping of radon concentrations on the ground to indentify radon anomalies (ups and down) to locate where to look for uranium. It is also important to make sure that such anomalies are not caused by thoron. Using EIC radon monitors with a thoron attenuating stack of Tyvek in parallel with a regular radon monitor will prove whether the signal is due to thoron or not. Any uncertainty in uranium exploration work is solved.

3. EIC for Measuring Radon Decay Products in Air Using E-RPISU

Health effects of radon are attributed to the inhalation and deposition of the airborne decay products. Usually the concentration is referred to as potential; alpha energy concentration and is expressed in the units of working levels. Please see Figure 1 for the schematic views of the monitoring head. An air-sampling pump (0.5 to 2 liters per minute) is used to collect the radon progeny for a known sampling time on a 3.5 cm^2 filter sampler mounted on the side of an electret ion chamber. The flow rate can be adjusted for a desired flow rate. Recommended flow rate is 0.5 to 1 liter per minute. Sampling duration is usually between 1 to 7 days. The filter paper is mounted such that the progeny collected emit their radiation into the interior of the chamber. The alpha radiation emitted by the progeny collected on the filter ionizes air in the electret ion chamber. The ions are continuously collected by the electret, providing integrated alpha activity collected on the filter paper. The standard electrets and the readers used in the standard radon EIC System can be with this unit. The initial and final readings of the electret, the flow rates and the duration sampling (as recorded by the time totalizer) are used in a software to calculate progeny concentration in WL units. Software is provided for data analysis by the manufacturer.

These monitors have sufficient sensitivity to provide results with better than 10% precision at 0.01 WL for a 2 day measurement when used with LT electrets. These provide better than 10% precision at 0.001 WL, when used with ST Electrets. The sampling heads are designed to minimize the deposition losses during sampling.

First part of Figure 9 shows the schematic of the EIC radon progeny integrating sampling unit (E-RPISU) in off position for storage or shipping. The second part shows the schematic of the E-RPISU in the sampling mode.

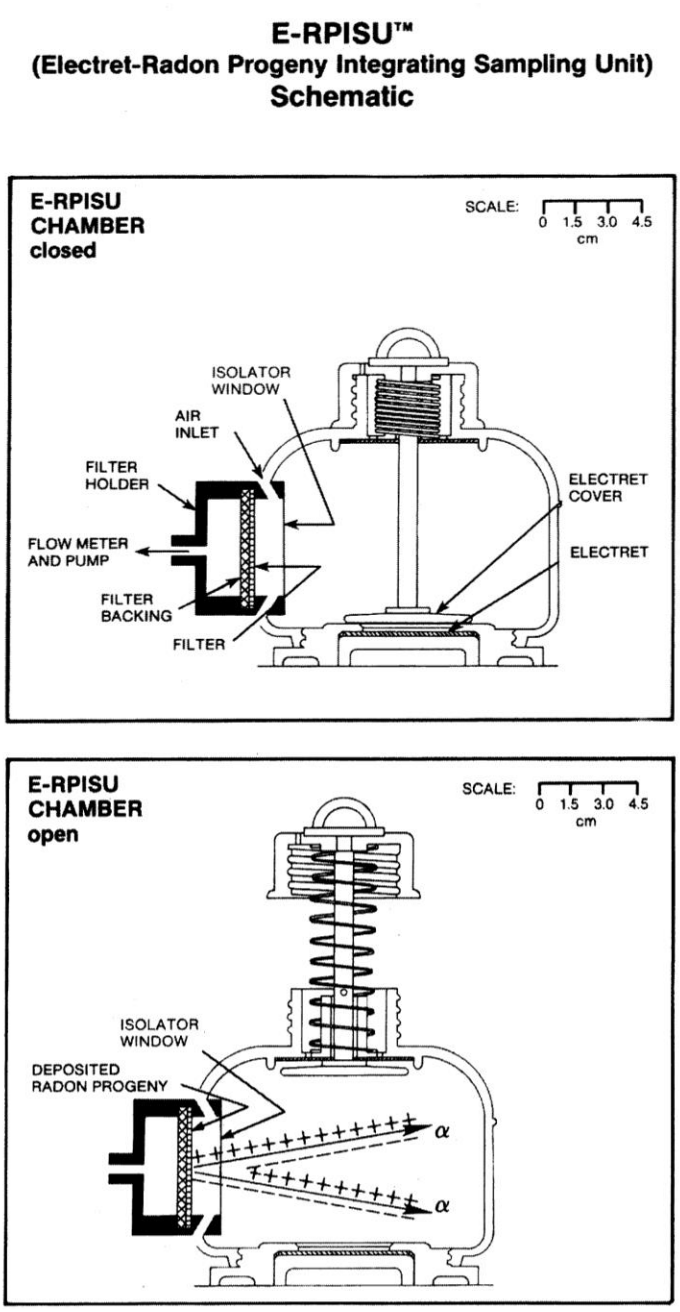


Figure 9. Schematic of EIC radon progeny monitor in air (E-RPISU).

A commercial unit that combines E-PERM and E-RPISUTeflon® is available (Rad Elec Inc.) for simultaneous measurement of radon, radon progeny, unattached radon progeny concentrations and equilibrium factors over extended periods. This also provides an accurate measurement of radon for determining equilibrium factors.

Development of this device was called "Radon Progeny Integrating-Sampling Unit" (E-RPISU®) was partially supported by US Department of Energy at Grand Junction, CO.

A scientific paper was published [97] The E-RPISU® Unit was evaluated by the USEPA, listed for use, and was used in several Radon Monitoring Proficiency Programs. Following is an extract from the USEPA Evaluation Report "During the evaluation, the E-RPISU® evolved as a viable and reliable instrument that may be used to measure radon decay products in units of WL with accuracy comparable with other decay product monitors when using the USEPA protocol. The unit did not show sensitivity to relative humidity or differing equilibrium conditions used in the Test Chamber. The E-RPISU® was well within 25% variation maximum allowed by USEPA when compared to calibrated WL Monitors, never more than 12%" Units were also entered into DOE-EML Inter-comparison project (EML-527, 1990) and showed results within 15 % of the target value.

The E-RPISU® is basically composed of an air sampling pump, a flow meter and an electret ion chamber with an appropriate filter holder and an electret. The protocols applicable to other progeny monitors are applicable to this unit also. Operating user manual is available from the manufacturer. The entire system needs to be operated simultaneously for the identical duration. This also provides an accurate measurement of radon for determining equilibrium factors. The software does such analysis. One of the methods of measuring unattached decay products of radon is to sample air through a wire mesh. Two E-RPISU units can be run together, one with the filter and the other with the mesh. Calculate radon progeny concentration on both using the same procedure. The ratio of the result with mesh to that of filter gives the unattached fraction.

4. EIC Based Radon Flux Monitor for *In Situ* Measurement of Ground, Granite, Concrete Surfaces and for Uranium Exploration

Recent interest in radon (^{222}Rn) emanation from building materials like granite and concrete has sparked the development of a measurement device that is suitable for field or home measurements. Based on tests with discrete component flux monitors, a large volume (960 ml) hemispherical electret ion chamber (EIC) was modified to work both as the accumulator and detector in a single device. Usually the flux monitors have two components, one component is an accumulator and the other component is a radon detector. The device entrance is covered by a carbon coated Tyvek sheet to allow radon from the surfaces to be characterized into the EIC chamber. An optional 4 mm thick Tyvek membrane can be introduced to minimize the response to thoron in the EIC. This device is calibrated with a NIST radon emanation standard whose radon emanation rate is precisely known. Side-by-side measurements with other emanation techniques on various granite surfaces in lab and field environments produce comparable emanation results. For low emitting building materials like concrete, a flux of 110 Bq m^{-2} d^{-1} (11 pCi ft^{-2} h^{-1}) can be measured with 10% precision using an ST electret for 8 hours. Sensitivities, ranges and applicable errors are discussed.

These can be used with a collar, if required as in the case of uranium exploration, or without a collar for measuring radon flux from ground or from concrete and granite surfaces. Manufacturer provides detailed user manual for different applications. A schematic figure illustrates different parts of the EIC flux monitors.

There has been an increased interest in the radon emanation from granite used for countertops and tiles in homes. Radon originates from naturally occurring uranium present in granites and other building materials made from stone.

The radon emanation rate of granite, along with the home's volume and ventilation rate determines its contribution to room radon. The radon emanation rate is also called the radon flux and is defined as radon activity released per unit area per unit time. While the appropriate scientific flux unit would be Bq m^{-2} s^{-1}, units like Bq m^{-2} d^{-1} and pCi ft^{-2} h^{-1} are easier to use in practice. Results are provided in these units with some conversion factors for other units in the text.

This monitor uses a well known "accumulation theory" of determining the radon flux from the objects (Kotrappa, 2009). The entire volume of the chamber serves as an accumulator and the electret ion chamber (EIC) part serves as a radon monitor. Equation (11) relates the average radon measured by the EIC and the radon flux F when the accumulator has no radon losses other than radioactive decay.

$$C(Rn)Av = \frac{(F \times A)}{V \times 0.1814}\left[1 - \left(\frac{1 - e^{-0.1814T}}{0.1814T}\right)\right] \tag{11}$$

Notation:
F is the radon flux in Bq m^{-2} d^{-1}
A is the area of the granite measured in m^2
A is also the area of the radon flux monitor window in m^2
(F × A) is the exhalation rate in Bq d^{-1}
0.1814 is the decay constant of radon in d^{-1}
C(Rn) Av measured by EIC, is the integrated average radon concentration in Bq m^{-3}
T is the accumulation time in days
V is the air volume of the accumulator in m^3
The radon flux F calculated using equation (11) leads to a flux in units of Bq m^{-2} d^{-1}.
Manufacturer provides spreadsheet for the analysis.

These have been used widely by radon measurement professionals and have shown acceptable results. These were used in an IAEA Inter-Comparison exercises by Vargas [46] published under the title: "Inter-comparison of different direct and indirect methods to determine radon flux from soil".

The study shows that the EIC worked properly and are in good agreement with other direct methods, both integrated and continuous. Due to condensation problems in certain environmental conditions, it is recommended that the EIC should not be used in such environments. The study carried out during solar hours provided better results. For this study, the EIC without collars were more appropriate. It can be concluded that EIC flux monitors are appropriate in field campaigns due to their performance, mobility and price. The flux monitors with collars are most appropriate during uranium exploration projects, which are done during 6 to 8 hours during day hours.

Inter-comparison study done by Kotrappa and Steck [67, 68] gave acceptable results when used on granites. These were the EIC flux monitors without collars and without thoron filters. Appropriate user manuals are available from the manufacture for different applications of the EIC radon flux monitors.

Several users have used these flux monitors for their studies [54, 55, 59, 60, 67, 68, 70, 71, 75, 78, 82].

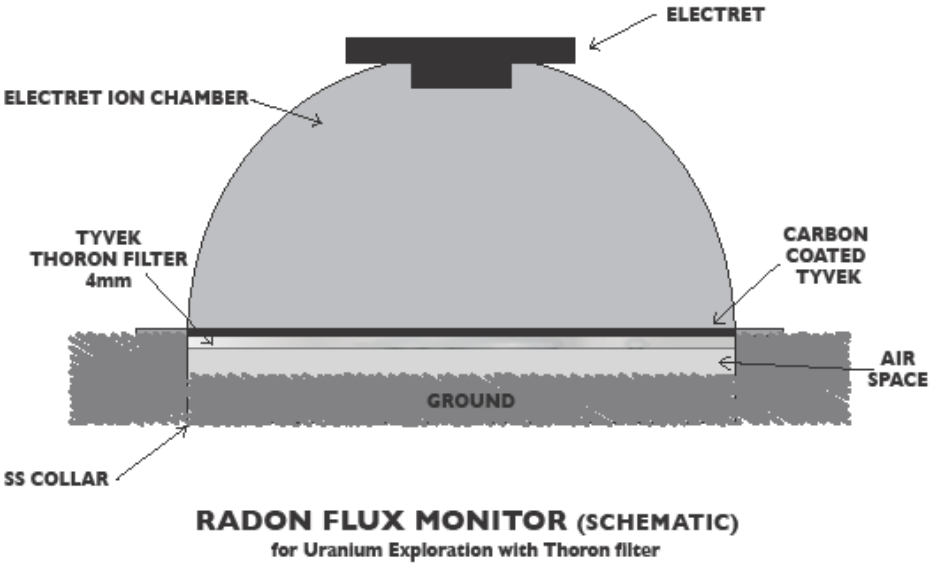


Figure 10. EIC based radon flux monitor.

Some investigators have used passive flux monitors in their work. These are similar to the currently used flux monitors (Figure 3), but are vented (four filtered holes). These were calibrated on uranium tailing beds [54] producing known radon flux. Note that accumulator type (figure 3) do not require calibration. Some workers found that the radon flux measured from ground does not agree with the measurements done with calibrated passive devices. Where relative values are needed the passive types have some advantages.

5. EIC for Uranium Prospecting for Accurate Time-Efficient Surveys Using EIC Based Radon Gas Monitors

Measurement of radon gas above the ground is one of the standard practice for uranium prospecting. Until now only passive detectors that can be used for such surveys is to use alpha track detectors which need several months for the results. When radon survey was done more than 20 years back, the techniques (AT techniques) were not that sophisticated and lots of data had to be rejected to draw some general conclusions [96]. With the availability of large volume EIC it is possible to measure radon concentrations in about three days and the results are arrived in the field, with good sensitivity, better than 0.5 pCi/L (about 20 Bq/m3). Recently a large scale survey was made in Canada [96] and concluded that it is possible to perform uranium prospecting for accurate time-efficient surveys of radon emissions in air is possible. This study was aimed at previously surveyed area to compare results with a comparison to earlier radon and He surveys using EIC radon monitors. The present efforts were aimed at getting large number of results in exploration setting in 3 to 4 days with an acceptable accuracy. Large volume (960 ml) Electret Ion Chambers (EIC) was chosen. Exposure duration was chosen to be about 3 days. Same staff members responsible for

deployment and retrieval were able to do the analysis and complete the report within one week. This has sufficient sensitivity to measure 0.5 pCi/L (about 20 Bq/m3) in 3 days.

In addition, the EIC technology was also available for measuring dissolved radon in water in streams. Rad Elec's standard method is also usable for measuring radon in water samples collected from streams. Such measurements were also a part of prospecting.

Protocol

Large volume (960 ml) EIC (HST EIC) is enclosed in a Tyvek Bag. It is lowered into a small pit 2 feet x 2 feet x 6 inches. The pit is covered with another Tyvek sheet and edges were tied down with soil and pebbles in that area. The latter step prevents the cover to fly out. Tyvek, being transparent to radon, the EIC sees the radon in the surrounding areas. Analysis was done using standard spread sheet to calculate the results in any required format and units. Assuming the gamma level of 10 µR/h, the radon calculations were done. This is not exact because gamma background can be higher at certain locations due to the presence of uranium. Since gamma signal over and above normal background of 10 µR/h is a positive signal for the presence of uranium; combined signals are better suited for the purposes of uranium prospecting. Following is the summary of the report:

> "Ur-Energy Inc. is focusing its exploration efforts on discovery of an Athabasca-style unconformity-associated uranium deposit in the Thelon Basin, NWT, and Canada. This work describes the exploration methodology and results to date of electret ion chamber (EIC) radon surveys employed in the summer of 2005 in the search for a deeply buried, high grade uranium deposit at Ur-Energy's Screech Lake Property. The survey has demonstrated that accurate radon gas measurements covering sizeable surface areas can be obtained within three days under variable summer field conditions. A total of 433 ground-EIC measurements were completed over a grid measuring 3 km by 1.5 km and centered on Screech Lake. In addition, 26 water samples from streams and lakes in the area were measured for radon content. Current work has confirmed, extended, and refined historic results obtained in past explorations that included radon and radiogenic helium surveys. The work was done using commercially available 960 ml HST EIC radon monitors. Additionally new radon anomalies have been discovered. This work has rekindled interest in using practical, short duration radon surveys for uranium exploration". (Ref) This study not only confirmed the earlier studies, but identified other locations due to better resolutions.

6. EIC for Uranium Prospecting for Accurate Time-Efficient Surveys Using EIC Based Radon Flux Monitors

Even though the methods described in previous section (5) was perfectly suitable for large scale surveys, manufacturers of EIC came up with another device for measuring radon flux from the ground. Radon flux is a better and faster index of radon emanation from the ground. Further such measurements can be done in 6 to 8 hours on the same day.

This method has all of the advantages of radon gas surveys, but is a more efficient, better quantifier of radon emanation from the ground. This has become the standard method used in recent uranium prospecting work.

Figure 10 illustrates the way a radon flux monitor with stainless steel collar can be deployed for uranium prospecting.

Protocols

Radon flux monitors with collars are fitted into the ground and sides are covered with the soil (Figure 3). Several hundreds of these can be anchored in 1 to 2 hours. At the end of the day these are taken out and assessed in the night. Such surveys saved several days compared to the 4A method. These are more sensitive because the detectors are right on the ground to be measured, where as in method 4A the radon measurement is the area.

Following extract is from the web site of RadonEX (Canadian uranium exploration company):

EIC based radon flux monitors in conjunction with radon in water provided revolutionary assessment of the uranium exploration results.

A program using EIC technologies, on the ice of Patterson Lake led directly to the drilling discovery of Patterson Lake South (PLS) uranium deposit - the biggest mineral discovery of 2013 in the world.

Conclusions: EIC radon based is a powerful technology that can revolutionize the uranium prospecting technology. The current technique has advanced the methodology for uranium prospecting from several months to 8 hours.

7. EIC for Characterizing Soil and Building Materials

A four liter glass jar with rubber seals has been successfully used as a convenient sealable accumulator for characterizing radon EICs using NIST radon emanation standards [56]. This is simply done by enclosing a NIST radon emanation source and the radon EIC unit inside the jar and sealing the jar. Using the characteristics of the NIST source (radioactivity of Ra in Bq and the emanation factor of the source) it is possible to calculate the expected radon concentration at the end of a known accumulation period. Comparison of the calculated radon concentration from calibrated radon EIC and the expected theoretical radon concentration, leads to the verification of calibration factors for the enclosed radon EIC.

Calibration constants of radon EIC can be corrected based on the results. Equation (12) gives the relationship between various parameters.

$$C(Rn)Av = \frac{(Ra \times f)}{V \times 0.1814}\left[1 - \left(\frac{1 - e^{-0.1814T}}{0.1814T}\right)\right] \tag{12}$$

Notation:

F is the radon flux in Bq m^{-2} d^{-1}

(Ra × f) is the exhalation rate in Bq d^{-1}

0.1814 is the decay constant of radon in d^{-1}

Ra is the radioactivity of radium in Bq

f is the radon emanation factor

(Rn) Av is the integrated average radon concentration in Bq m^{-3}

T is the accumulation time in days

V is the air volume of the accumulator in m^3

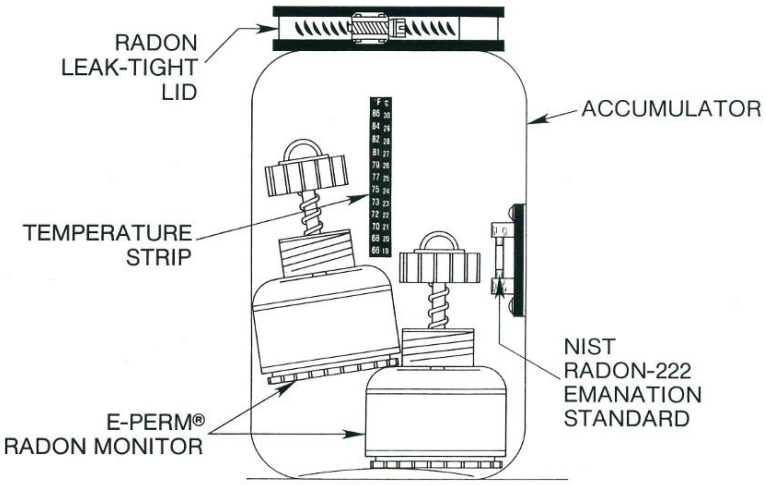


Figure 11. The accumulator system for calibrating EIC with NIST emanation standard.

Radon Emanating Radium Content for Soil Samples

In the place of NIST source, use the soil sample to be characterized. Measure the average radon concentration of radon after a known period of accumulation using a radon EIC. Knowing all the parameters in equation (12), solve for *(Ra × f)*. This does not give radium content of the sample but it can be called as radon emanating radium content. If *f* is known then real radium content can be determined. In practice, 10 to 30 grams of soil is taken, then dried and ground to fine powder. The sample is then wetted with 20% water. Such a soil sample has an approximate *f* value of 0.2. Further divide *(Ra × f)* by *f* and the weight of the sample to calculate radium concentration of the soil sample in units of Bq/gram. This method is simple with no chemistry or radiochemical analysis involved. This was used by Heiligmann [48, 49] in his study on "distal degassing of radon and carbon dioxide on Galreras volcano, Columbia". Because of similarities of soil samples they just reported radon emanating radium concentration (Bq kg^{-1}) in soil samples of interest.

8. EIC for Characterizing Soil and Building Materials

Radon Exhalation Rates from Building Materials [40, 69]

Methods similar to methods used in section on Radon emanating radium content from soil, are usable for building materials such as samples of granite or granites. These are characterized in terms of radon flux from their surfaces. Equation (13) gives the relationship between different parameters when used for granites, enclosed in a 4 liter sealable glass jar.

$$C(Rn)Av = \frac{(F \times A)}{V \times 0.1814}\left[1-\left(\frac{1-e^{-0.1814T}}{0.1814T}\right)\right] \qquad (13)$$

Notation:
F is the radon flux in Bq m^{-2} d^{-1}
A is the area of the granite measured in m^2
(F × A) is the exhalation rate in Bq d^{-1}
0.1814 is the decay constant of radon in d^{-1}
C(Rn) Av measured by EIC, is the integrated average radon concentration in Bqm^{-3}
T is the accumulation time in days
V is the air volume of the accumulator in m^3
The radon flux F is calculated using equation (13) that leads to a flux in units of Bq m^{-2} d^{-1}.

Enclose the sample and a radon EIC inside the sealable 4 liter jar. After the desired accumulation period analyze the radon RIC to determine the radon concentration. Calculate *(F × A)* from equation (13). Knowing the total surface area *A*, the radon flux *F* can be calculated in appropriate units. Kotrappa [40] has analyzed three samples for two different periods of accumulation (3 days and 5, 9 days). The results obtained were in the range of 20-30 Bq m^{-2} d^{-1} generally agreeing with the results reported in the literature. Methodology provides error analysis and lower methods of detection (LLD). For a two day accumulation period, LLD works out to be 7 Bq m^{-2} d^{-1}.

9. EIC for the Measurement of Radon in Water

EIC for the Measurement of Dissolved Radon in Water

Measurement of radon in water is important because of several reasons. Quite a large population use well water for drinking and other daily uses.

When water goes through geological rocks containing sources of radon such as uranium, it picks up radon that remains as dissolved radon in water in the wells.

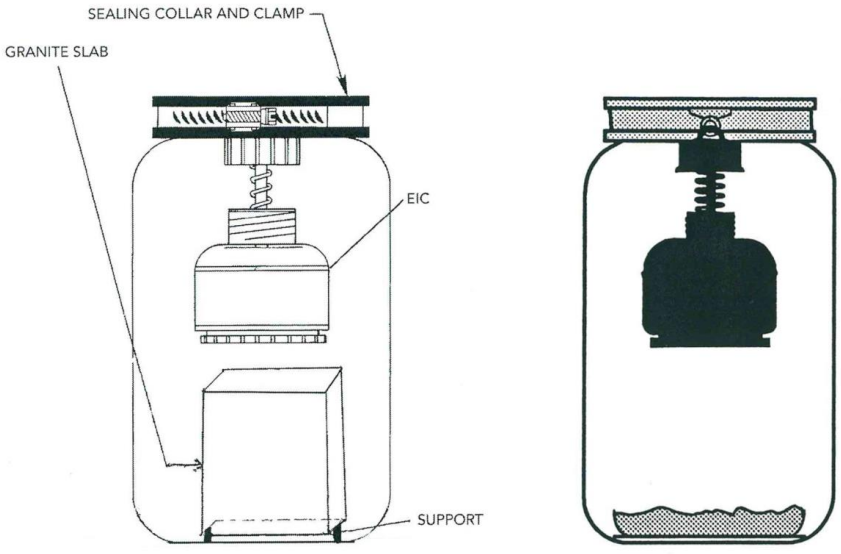


Figure 12. Left: EIC: for characterizing building materials Right: for charactering soil samples.

Just like radon in air in homes can vary from home to home, concentration of dissolved radon in water can vary home to home depending upon the geology of the location. Such water when used for showering, laundering, and other purposes, contributes to the radon in air. The USEPA has estimated that the dissolved radon concentration of 10,000 pCi/L leads about 1 pCi/l in air. Further, drinking such water can also have some biological effects on people. Normally, the concentration of dissolved radon in well water can vary from 1000 to several million pCi/L. While doing geophysical exploration for uranium, radon water steams have led to the discovery of uranium sources. Dissolved radon in water has been used as a tracer for many interesting research studies. The EIC method belongs to the general class of "de-emanation method" of the bottom of a glass measurement measuring radon in water. A small water sample of a known volume is placed in jar of a known volume. A radon EIC is suspended in the air phase above the water. The lid of the measurement jar is closed and sealed to make it radon-tight. Radon reaches equilibrium between the water and air phase. At the end of the desired exposure period, the measurement jar is opened and the EIC is removed. The average radon concentration in the air phase is calculated using the standard EIC procedure. A calculation using this air concentration in conjunction with the other parameters gives the radon concentration of the water. EIC methods are widely used as indoor radon monitors and are not affected by 100% relative humidity, and because of this property, it is possible to do in situ measurement of radon in water.

Kotrappa and Jester [43] have described the theory and practice of measuring the radon concentration in water using the EIC method.

Equation (14) is used for the calculation of dissolved radon concentration in water.

$$C(Rn)W = \frac{(Av\,C(Rn)A \times k\,T \times (\frac{VA}{VW} + 0.26)}{\exp(-k\,D) \times (1 - \exp(-k\,T)} \tag{14}$$

Notation:

C(Rn)W Radon concentration of water sample, Bq L^{-1}

AvC(Rn) A Average radon concentration in air as measured by radon EIC, Bq L^{-1}

D delay time between time of collection to start of analysis in days

T Analysis time between start of analysis to the end of analysis

k Decay constant of radon in day $^{-1}$

VA Volume of air in liters

VW Volume of water sample in liters

0.26 is the Oswald Coefficient (ratio of the radon concentration in the liquid phase to the radon concentration in air phase), normally neglected for small volume samples (50 to 200 ml samples).

The only parameter that needs to be measured is *AvC(Rn) A* the radon concentration in air inside the measuring jar.

The method is schematically shown in Figure X. Water sample in glass bottle is held at the bottom of the jar in a clip. Radon EIC is inserted into the jar. Jar is sealed and analysis bottle is lifted up.

Water spills and releases radon into the jar. Radon EIC measures the average radon concentration in air inside the jar. Kotrappa and Jester [43] provides detailed analysis of errors and minimum methods of detection.

Additional Researches on This Topic

Dua and others [47, 87] adapted the method to make continuous measurement of dissolved radon in water. The USEPA [52] did a detailed evaluation of the EIC method in comparison with the standard liquid scintillation (LS) method for measurement of different concentrations. They found that the EIC method consistently gave 15% higher results compared to the LS method and recommended to apply this correction to be in agreement with the LS method. International users [61, 63, 64] have used the EIC method successfully in their projects.

The method was used for studying dissolved radon in water in different seasons [92] from the same well. Kitto [72] did an assessment of the EIC method in comparison with other methods. Kotrappa [80] also reviewed and compared different methods of measuring radon in water. References has listed several intersting uses for radon in water.

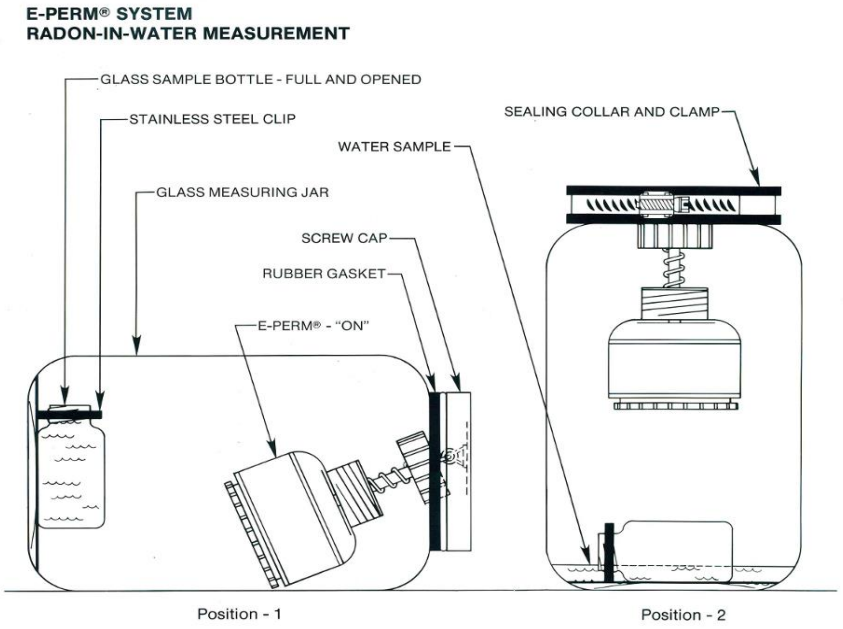


Figure 13. Schematic of EIC for measuring radon in water (change from position 1 to 2 to start the analysis).

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thankful to my wife and associate Chandra Kotrappa not only in preparing this document but also for her contribution in researches leading to technologies needed for making electrets. My grateful thanks are due to Dr. Dan Steck and Andreas C. George, well known scientists in the field of radon and radon metrology, for reviewing this document and providing several useful comments to improve the document. Further they were kind enough to agree with me to include their summary report in the document.

Summary Comments from the Reviewers: Quotes

Comments by: Andreas C. George

Electret ion chamber technology has become an alternative and useful method for characterizing radon gas originating from various sources. The principle of detection of Electret Ion Chambers (EIC), has been investigated thoroughly in the past thirty years by several investigators and was found appropriate and useful for measuring environmental radon concentrations. The group headed by Dr. P Kotrappa researched and applied the EIC technology successfully to measure the concentration of radon indoors, outdoors and in the characterization of soil geology and building materials. The EIC technology has been proven to be very useful and practical in measuring the emanation of radon from soil surfaces. This particular use and those of other applications when used properly offer an alternate, less tedious and cost-effective method by providing results directly from reading the electret in the field. There is no need for sample transfer making the method direct and practical.

Here is my summary review: from Dan Steck Ph.D

This manuscript provides a thorough review of the electret ion chamber (EIC) technique and its practical applications. The description is detailed enough to be useful to radiation measurements specialists and basic enough to be useful to exploration geologists. Part 1 provides an excellent understanding of the underlying principle of radiation detection using EICs. Particular attention and detail are given for its use in airborne radon detection. Part 2 is a comprehensive description of the wide-ranging applications for radon and thoron measurements of concentration and flux from a variety of source material. Examples and documentation of performance are given for sophisticated laboratory uses as well as challenging field measurements. Part 3 provides almost 100 references for support and additional details. Overall, readers engaged in radon and thoron work will find this a useful work.

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