DEVELOPMENT OF AN ELECTRET PASSIVE ENVIRONMENTAL RADON MONITOR (E-PERM™) - PHASE 2

FINAL REPORT

PREPARED FOR

NEW YORK STATE

ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

PROJECT MANAGER

JOSEPH E. RIZZUTO

PREPARED BY

P. KOTRAPPA
J.C. DEMPSEY

RAD ELEC, INC.
5310 H SPECTRUM DRIVE
270 TECHNOLOGY PARK
FREDERICK, MD 21701

NYSERDA REPORT ___________ AUGUST, 1991

NOTICE

TABLE OF CONTENTS

		Page
	List of Tables	iii
	List of Figures	iv
	Abstract	v
	Acknowledgements	vi
1.0	Project Background and Summary	1
	1.1 Phase 1	1
	1.2 Phase 2	1
	1.3 Current status of E-PERM technology	2
2.0	Description of E-PERM System	4
	2.1 Description of E-PERM	4
	2.2 Design features of E-PERM Chambers	6
	2.3 Design features of Electret Voltage Reader	7
	2.4 Use of the Electret Voltage Reader	8
	2.5 Electret Design	9
	2.6 Electret Response	10
	2.7 Electret Stability	11
	2.8 Reference Electrets	11
3.0	Measuring Radon with E-PERMs	13
	3.1 Calibration of E-PERMs	13
	3.2 Measuring Radon Concentration with E-PERMs	14
4.0	E-PERM Response Characteristics	16
	4.1 Precision of E-PERM Characteristics	16
	4.2 Interchangeability of Long and Short-Term E-PERMs	16
	4.3 Signal Integrating Characteristics	17
	4.4 Elevation Effect	17
	4.5 Temperature Response	17
	4.6 Humidity Response	18
	4.7 Effect of Air Flow over E-PERMs	20
	4.8 Radiation Statistical Error	20
5.0	Error Analysis	22
	5.1 Component Error	22
	5.2 Readout Error	23
	5.3 Gamma Background Error	23
	5.4 Overall maximum Error	24
	5.5 The Lower Limit of Detection	25
6.0	Cost Comparison With Other Types of Passive Monitors	26
	6.1 E-PERM Measurement Costs	26
	6.2 Comparative Costs	27
7.0	Blind Test Evaluation of E-PERMs	29
	7.1 EPA/RMPP Round 6 E-PERM Blind Test E-PERM	29
8.0	Conclusions	35

Page

9.0 References 36

Tables - 37-64

Figures 65-72

10.0 Appendix: Results of E-PERM Evaluations by Others) 73
10.1 Index of Appendix Evaluations and Figures 74
10.2 Initial EPA E-PERM Evaluation 75
10.3 EPA Evaluation of Long-Term E-PERMs vs. Alpha Track 75
10.4 Recent EPA Evaluations of Long and Short-Term E-PERMs 76
10.5 Pennsylvania DOH Double Blind Test 76
10.6 New York State Department of Health Evaluation 77
10.7 Tests of E-PERMs vs. Charcoal Canisters by NYSERDA 77
10.8 Austrian Research Center Short-Term E-PERM Evaluation 78
10.9 University of Iowa Double Blind Test 78
Appendix Figures A1 through A8 80-87
10.10 Appendix References 88

LIST OF TABLES

Table No.		Page
1	Abbreviations and notations used in the tables	37
2	Short-Term Electret Stability Test	38
3	Calibration Data for Short-Term E-PERMs	39
4	Calibration Data for Long-Term E-PERMs	40
5	Performance of Randomly Chosen Short-Term E-PERMs	41
6	Intercomparison of Long-Term and Short-Term E-PERMs	42
7	Effect of 100% RH on Electret Voltage	43
8	Corrections for Background Gamma Radiation by State	44
9	Lower Limit of Detection for Long and Short-Term E-PERMS	45
10	Round 6 EPA/RMPP Short-Term Blind Test Results	46
11	Round 6 EPA/RMPP Short-Term Blind Test Results	53
12	Summary of Round 6 E-PERM Results	64

LIST OF FIGURES

Figure No.		Page
1	Photograph of Prototype E-PERM	65
2	Photograph of Commercial E-PERM	66
3	Sectional Drawing of E-PERM in the Off and On Positions	67
4	Photograph of the SPER-1 Electret Read-Out Instrument	68
5	Photograph of Electret Holder Components	69
6	Photograph of Assembled Electret Holders	70
7	Calibration Line for Short-Term E-PERMs	71
8	Calibration Line for Long-Term E-PERMs	72

ABSTRACT

The development of an electret ion chamber modified for radon measurement is described and characterized. It was given the name E-PERM for electret passive environmental radon monitor. The response characteristics of the two types of electret sensors developed and the E-PERM itself are reported. The results of 518 units blind tested in Round 6 of the EPA RMP Program are presented. Costs per measurement are estimated and compared with other passive monitoring methods. Summary results of E-PERM evaluations presented in eight recent studies by other researchers are presented in an Appendix. The results demonstrate that the new monitor is reliable, accurate and precise.

Key words: Radon, ion chamber, electret, passive.

ACKNOWLEDGEMENTS

The financial support of the New York State Research and Development Authority (NYSERDA) for carrying out this investigation is gratefully acknowledged. The authors wish to acknowledge the help of Mr. A.C. George (DOE, New York) and R. Hopper (EPA Las Vegas) for carrying out several of the E-PERM radon exposures required during the investigation.

Mr. Joseph Rizzuto provided guidance throughout the project as the NYSERDA Project Manager. A volunteer NYSERDA Project Review Committee assembled by Mr. Rizzuto met to evaluate the progress of the project and provide guidance on three occasions. Committee Members were Dr. P. Harrington (NYS Energy Office); Ms. L. Kolhler (EPA); Dr. K. Rinawi (NYS DOH); and Mr. A.C. George (DOE). This guidance was most helpful.

The authors are also grateful to Mrs. Nuala McCarthy for all of the word processing and much editorial assistance and Mr. Robert McCarthy for his help in formulating the charts.

SECTION 1

1.0 PROJECT BACKGROUND AND SUMMARY

The overall goal of this two phase project was to develop, characterize and demonstrate a new type of passive radon monitor which can monitor homes with greater accuracy and lower cost than comparable existing monitors; i.e., charcoal canisters and alpha track devices.

1.1 PHASE 1

Two promising new methods were pursued during Phase 1, one employing a TLD as the sensor and the other an electret ion chamber (EIC). After the initial experiments were completed, it was decided to focus the remainder of Phase 1 work on the EIC approach. That work was successful and a laboratory prototype EIC monitor was developed which was called an E-PERM* for electret passive environmental radon monitor. Several prototypes were fabricated, characterized, demonstrated and a report (1) and technical paper (2) were published to complete Phase I.

1.2 PHASE 2

It was recognized at the outset of Phase 2 that the cup-in-cup E-PERM design that was developed during Phase 1 had several limitations that had to be overcome to make a practical, commercially viable E-PERM. Thus, the principal goals of Phase 2 were to develop a commercially viable E-PERM design and to produce, characterize and field test several prototype units. A satisfactory design was developed and several commercial prototype instruments were fabricated and submitted to the EPA Las Vegas Laboratory for evaluation. The EPA Report was very favorable, concluding that "These results demonstrate that this instrument can measure radon very accurately under varying conditions with very close agreement between replicate samples. The E-PERM performs well when exposed to both low and high radon concentrations."

---

* E-PERM is a trademark assigned to Rad Elec Inc. U.S. Patent No. 4,853,536 was granted for the E-PERM methodology in August 1988 (assigned to Rad Elec Inc.).

As a result of these findings, E-PERMs were accepted by the EPA for entry into the their Radon Monitoring Proficiency (RMP) Program. The RMP program is a voluntary evaluation program which requires participants to submit 5 long-term and 5 short-term E-PERMs to the EPA for a "blind" radon exposure. The concentration values deported to the EPA by each participant must come within ±25% of the known concentration value.

Fifty radon monitoring companies decided to enter E-PERMs in Round 5 of the RMP Program which took place in 1988. Some 500 prototype commercial E-PERMs were fabricated and made available to the fifty participants along with a calibrated read-out instrument. Figure 1 is a photograph of this prototype unit. These units were hand made by coating the inner surfaces of 250 ml. polypropylene jars with a conductive paint. The spring loaded piston mechanism for turning the units on and off (seen at the top of the unit) was inserted through a hole in the top of the chamber and the metal screw top section was glued to the top of the jar. In spite of the relatively poor quality of these prototype E-PERMs, over 90% of them gave concentration values within the acceptable accuracy limit (± 25%) in the blind EPA test and thereby passed Round 5.

Later in 1988, Rad Elec developed the injection molded commercial E-PERM model which is described and characterized in this report. Figure 2 is a photograph of this commercial unit. Some 165 additional radon monitoring companies entered these commercial units in Round 6 of the RMP Program in 1989. (Companies which passed Round 5 were not required to submit monitors again in Round 6) The same ± 25% accuracy limit applied for Round 6, but the method of calculating the results was considerably more stringent than previous rounds (see Section 7.0). The EPA has indicated that 94% of Round 6 E-PERM participants successfully "passed." Some of the results are analyzed and discussed in Section 7.0 of this report. A paper (3) covering all of the results of Phase 2 was published in 1990.

1.3 CURRENT STATUS OF E-PERM TECHNOLOGY

The commercial E-PERM system has been well received by the radon industry. Over 400 companies and agencies are now using them in the U.S. and overseas. Professional radon monitoring companies have been especially receptive of this new technology because, for the first time, it provides a passive type monitor which can be read out in the field, i.e., the portable read-out meter eliminates the need to send the monitors to a central laboratory for analysis as usually required by competitive types of passive monitors. This time saving feature is especially important in measurements made to support real estate transfers.

Several variations in the electret ion chamber technology have been developed and commercialized by Rad Elec Inc. beyond the 200 ml. E-PERM model reported on here. Smaller and larger chambers (75 ml and 500 ml) which accept the same long or short-term electrets have extended the range of this new radon monitoring technology substantially. The incorporation of a calibrated sampling pump and a high efficiency filter element has resulted in the development of an electret RPISU(4) which measures progeny very accurately. E-PERMs are also now being used to make accurate measurements of radon in water by sealing them in jars together with a known volume of the water being tested(5). Their insensitivity to moisture enables this later application.

Recent work has also demonstrated that E-PERMs can be used to measure gamma radiation, even at environmental levels, very accurately. This is accomplished by sealing an E-PERM in a radon-proof bag for a known exposure period(6) None of these extensions of the electret ion chamber technology are covered in this report

2.0 DESCRIPTION OF E-PERM SYSTEM

The general design and operational characteristics of E-PERMs have been described elsewhere;(2, 3) however, they are summarized here again for those who do not have access to these earlier papers.

2.1 DESCRIPTION OF E-PERMS

E-PERMs are ion chambers in which a single electret serves as both the ion collecting high voltage source and the radon sensor. The electret is a permanently charged disk of Teflon (TM Dupont). E-PERMs are passive monitors requiring no power to function, i.e., ambient radon enters into their sensitive volume by diffusion. They are integrating monitors which measure the average radon concentration in the room where they are located during the exposure period.

E-PERMs can be employed for either short-term (2 to 7 days) or long-term (1 to 12 months) measurements by simply attaching a short or long-term electret to the same E-PERM chamber. The charged Teflon disks used for long-term electrets are thinner and thereby less sensitive than short-term electrets (See 2.5 below). The lower sensitivity of long-term E-PERMs makes them suitable for either long-term monitoring of low radon concentrations or short-term monitoring of high concentrations.

The ion chambers of the commercial E-PERMs which are 200 cubic centimeters in volume are made from conductive plastic. The assembled E-PERM has a detachable electret attached on the bottom and filtered holes in the top. The filter permits entry of radon gas into the chamber while preventing ambient dust, progeny and ions from entering. The holes are sized to assure a sufficiently long gaseous diffusion time to minimize the entrance of ^{220}radon (thoron) which decays rapidly (56 sec. half-life). A picture of an E-PERM is shown in Figure 2 and a cross-sectional drawing in Figure 3. Both figures show the E-PERM in both open and closed positions.

As described earlier, the electret collects the ions generated inside the chamber by the radon and radon decay product radiations. The ions formed by the decaying radon radiations (mostly by very energetic alpha emissions) are drawn to the surface of the electret by the electrostatic field which emanates from the electret surface. When the ions contact the surface of the electret, they cause a reduction in its surface voltage and the amount of this voltage reduction is a measure of the time integrated radon concentration during any exposure period. Thus, the electret serves not only as the source of the electrostatic field needed to collect the ions, but also as the quantitative ion sensor.

The same E-PERM with the same electret can usually be used for many separate measurements, e.g., short-term units can make about 20 measurements at the 4 $pCiL^{-1}$ level. Equation 1 below, which was developed in Phase 1, shows the relationship between the electret voltage drop and the average radon concentration during an exposure.

$$RnC = \frac{(V_i - V_f)}{(T)\ (CF)} - B \qquad \text{Equation 1}$$

Where: RnC is the radon concentration in $pCiL^{-1}$

T is the exposure period in days

V_i and V_f are the initial and final electret voltages

CF is the calibration factor in volts per $pCiL^{-1}$

B is the radon concentration equivalent of natural gamma radiation background (BG). B for 1.0 urad h^{-1} was measured to be equivalent to .087 $pCiL^{-1}$. The BG at measurement sites can be measured with a suitable gamma survey meter or it can be taken from an EPA listing of average State BG values (11) (See Sec.5.3).

2.2 DESIGN FEATURES OF THE E-PERM CHAMBER

Phase 1 work showed the importance of using low atomic number materials for E-PERM components in order to minimize interference from natural background gamma radiation (BG). The chamber material must also be electrically conductive so as to prevent the buildup of electrostatic charge on its inner surfaces. Accordingly, the commercial E-PERM chambers and electret holders are made of carbon filled polypropylene. The Phase 1 investigations also established criteria regarding the volume and shape of the ion chamber needed to optimize the E-PERM response to radon and the commercial unit reflects these criteria.

A cover is needed for the electret to prevent it from losing voltage when the chamber is not in use, e.g. during storage or transport. If left uncovered, ions of opposite polarity in the ambient air are attracted to the surface of electrets where they neutralize the charge on the electret. A cup-in-cup cover mechanism was developed during Phase 1 for this purpose. In this configuration, one cup has the electret fixed inside its bottom surface and the bottom of the second cup serves as the electret cover when it is slid bottom-first down over the electret. After homeowner trials, it was decided that this cup-in-cup arrangement was impractical because it required the user to expose the electret directly to ambient air when preparing the unit for a measurement. A novel spring-loaded piston mechanism was developed during Phase 2 for the commercial model which covers and uncovers the electret without exposing it in this way.

As seen in Figure 3, the electret cover is attached to a screwcap on top of the E-PERM which can be screwed down to lock the electret cover down close to the electret. This effectively cuts off the electric field emanating from the electret. Without the electric field, the E-PERM is "off," because no ions are drawn to the electret surface. When the E-PERM is to be used, the screwcap is unscrewed and a compression spring under it lifts and holds the electret cover up against the top of the chamber. This permits the electrostatic field from the electret to emanate into the chamber, thereby turning the E-PERM "on."

As mentioned earlier, the filtered inlet shown in Figure 3 is necessary to allow radon into the chamber while excluding radon progeny, dust and ions from outside. Though not apparent on the drawing, there are six small holes 0.25 cm in diameter in the top of the E-PERM giving a total hole area of 0.3 cm^2. Their recessed position reduces the risk of damage to the filter.

As described the Phase 1 report, the entry hole diameter and the ratio of total hole area to chamber volume control the time it takes radon to diffuse into the E-PERM. The hole parameters sited above were chosen to minimize the E-PERM response to short lived (half-life 56 sec.) ^{220} Rn (thoron). Experiments carried out during Phase 1 showed that E-PERMs with these particular hole parameters have less than 10% response to ^{220}Rn relative to ^{226}Rn. The resulting diffusion rate, which is estimated to be in the order of 10 minutes, still assures suitably fast response to rapid concentration changes in the longer lived (3.824 day half-life) ^{226}Rn.

Phase I work also quantified E-PERM response as a function of chamber volume and electret thickness. It also showed that, in general, their dynamic range is inversely proportional to their sensitivity. Based on this earlier data, design calculations during Phase 2 led to the adoption of the 200 cc E-PERM chamber for the commercial unit. Two electret thicknesses of 0.23cm and 0.0127 cm were chosen for the commercial instrument to serve as short and long-term detectors, respectively. (The thicker electret is roughly 10 times more sensitive than the thin one.) Field experience has confirmed that these design choices accommodate the range of radon concentrations commonly found in homes satisfactorily.

2.3 DESIGN FEATURES OF THE ELECTRET VOLTAGE READER

Figure 4 is a photograph of the SPER-1 instrument developed to read out the surface voltage of electrets (SPER-1 stands for Surface Potential Electret Reader-1). The instrument (1) reads out electret voltages directly in volts on a digital display without making contact with the electret surface; (2) repeats voltage readings from 1 to 1,000 volts to ± 1V; (3) automatically zeroes before every reading; (4) its "on" switch is activated by the movement of the shutter; (5) it holds the voltage reading display for four minutes and then shuts off automatically; (6) it gives a sound signal if the shutter is not closed or opened completely to preclude false readings; (7) it is smaller and more rugged weighing only about 0.5 kg.; and (8) it is powered by a single 9V battery and has a low battery indicator. A cushioned carrying case is now provided with each reader to help protect it from droppage, dust and dirt, etc.

2.4 USE OF THE ELECTRET VOLTAGE READER

The user must carry out the following steps in making each electret voltage measurement. Both the initial and final voltage readings should be carried out as close to the exposure period as possible to assure maximum accuracy. Care must be taken to prevent the electret surface from accumulating dust or lint and from being touched by anything throughout this procedure.

1. Carefully unscrew and remove the electret assembly from the bottom of the E-PERM. (The Teflon disk seen in the inner center of the assembly is the electret.)
2. Place the electret face down into the circular electret receptacle on the voltage reader. Move it a bit to assure that it is well seated and free to move in the receptacle. Care must be taken to assure that no dirt or foreign material is present in the electret receptacle which might keep the electret from seating properly. Revolve the electret assembly until the identification number on its bottom is right side up and parallel with the instrument panel meter.
3. Opening and closing the metal slide with a lever on the side of the voltage reader causes the electret voltage reading to appear on the LCD panel. The slide should be held open for at least 5 seconds to obtain a proper reading and left in the closed position at least for 5 seconds before taking the next reading. When the same voltage value appears twice in a row during this sequence, it reflects the true electret voltage. This takes at least 3 openings because the first value is often spurious.

4. Replace the electret in a storage (covered) mode either in an E-PERM with the pop-up like screwed down or with its shipping cover screwed closed. Make sure there is no dust or lint in the cover or E-PERM shell which can get on the electret surface when it is closed.

2.5 ELECTRET DESIGN

The design production and response characteristics of electrets were also discussed in our earlier work [1, 2, 3].

The commercial electret holder is also injection molded from electrically conductive polypropylene. Figure 5 is a photograph of the various components of the electret holder and Figure 6 shows assembled short-term and long-term electret holders. As seen, the electret holder is designed with male threads which mate with threads on the bottom of the E-PERM chamber. The electret itself (i.e., the Teflon disk) is held firmly in place in the electret holder by an aluminum screen disk which pressed into place with the plug. The assembled electrets are rugged and drop tests show that they are unaffected by most accidental mechanical shocks; e.g., their voltage remains constant.

Uncovered electrets collect ions from the ambient air which causes them to lose voltage. The electret manufacturer provides a protective cap with all electrets which screws onto the top of the electret holder in order to keep the electret covered during shipping, storage, etc. Thus, electrets can be kept covered either with the on/off cover when mounted in E-PERMs or with their protective caps.

The electret holder (with the protective cap off) is sized to fit snugly into the cylindrical measuring receptacle in the electret reader. A protective lip around the periphery of the electret surface (part of the electret holder) rests on a metal rim around the bottom of this receptacle while the voltage is being read to assure a precise reproducible distance always exists between the surface of each electret measured and the voltage sensor in the reader.

2.6 ELECTRET RESPONSE

The electrets used in the commercial E-PERMs are made and processed in the same manner described in our Phase 1 report [(1)]. Polytetrafluoroetheylene (PTFE) disks, 0.152 cm thick by 3.8 cm diameter are used for short term electrets and tetrafluoroethylene (FEP) Teflon disks 0.0127 x 3.8 cm are used for long term electrets. As mentioned earlier, these two particular electret thicknesses were chosen to provide E-PERMs optionally responsive to the most common home radon concentrations during the exposure periods recommended in EPA measurement protocols. The same 200 ml. chamber is used for both short-term and long-term E-PERMs; the only difference being the sensitivity (thickness) of the electret attached to it during the measurement. In general, short-term E-PERMs are intended for 2 to 7 day exposures and long-term E-PERMs for 1-12 month exposures. However, there is no inherent reason why a long-term electret cannot be used for short exposures, as long as the electret voltage drop realized during an exposure is adequate to assure the reader error (± 1V) does not contribute an unacceptably to the overall error in the radon concentration measurement (see 5.2) Short-term E-PERMs can also be used for exposures longer than 7 days in low radon levels, as long as the electret voltage does not fall below about 200 volts. Tests described in this report (see Section 3.2 below) verify this interchangeability of electrets within their range limits. In fact, long-term electrets are often used for short-term measurement in homes that are known to contain a high radon concentration.

The surface voltage of all new electrets is controlled to about 750 volts. The calibration curve becomes a bit non-linear for E-PERMs with electrets above this voltage probably because of ion multiplication. The curve also becomes less linear below about 200 volts, so electrets should not be used much above 750 volts or below 200 volts. The 550 volt range (between 200V to 750V) corresponds to a dynamic radon monitoring range of 240 and 2800 $pCiL^{-1}$ - days for short and long-term E-PERMs respectively.

2.7 ELECTRET STABILITY

The electrical stability of the electrets is very important to assure accurate E-PERM measurements. The first report [1] on the E-PERM includes a discussion of some of the treatments used to stabilize the voltage of electrets. They also included a list of electret voltages taken repeatedly on the same electrets over several months to demonstrate their electrical stability.

A similar stability test was carried out again in the present investigation because the design of the current commercial electrets and readout instrument are quite different than the prototype units used in the earlier stability evaluations. Table 2 shows the results of a four month test of the electrical stability of 30 typical commercial short-term electrets carried out by the EPA in their Las Vegas Laboratory.[6] The electrets were stored with their covers on in the laboratory throughout the test period. Considering the fact that the voltage reader is only accurate to within ± 1 volt for both the initial and final readings, it can be seen that none of the electrets listed underwent a measurable voltage loss over the 4 month test period.

2.8 REFERENCE ELECTRETS

Reference electrets are essentially long-term electrets which have undergone special processing and quality assurance to verify their voltage stability. The routine use of these referenced electrets, which are available from Rad Elec Inc., is recommended to assure that any drift or malfunction of the readout meter is detected. Their initial voltage is carefully measured and certified with reference to a simulated (metal disk) electret connected to a special electronic high voltage supply which, in turn, is measured with a voltmeter with certified NIST traceable calibration.

Rad Elec recommends that E-PERM system users measure and record the voltages of two such reference electrets at least once a week as a routine part of their SPER-1 QA procedure. If the voltage of both of these electrets vary by more than three volts from the prior week measurement values, a meter drift or malfunction is indicated and corrective action is recommended. The second reference electret is necessary in case the first one is accidently touched, i.e., if only one reference electret were available, and it gave a low reading, the user might not know whether the meter or the electret were at fault.

3.0 MEASURING RADON WITH E-PERMs

3.1 CALIBRATION OF E-PERMS

The Phase 1 report indicated that a constant calibration factor was applicable over the total operating range of electret voltage from 200 to 750 volts. However, careful measurements carried out during Phase 2 show that calibration factors for the commercial E-PERMs vary by about 15% over this voltage range for both short and long-term monitors. Accordingly, a range of calibration factors (CF) has been determined based on the midpoint electret voltage of each particular measurement. The midpoint voltage is the average of the initial and final electret voltage for a particular radon measurement. The procedure used to derive this calibration data is discussed below. (The calibration factors currently recommended for use by E-PERM user are derived by averaging a series of such results obtained in several calibrated chambers and they are updated routinely.*)

Generally, twenty-five E-PERMs of the same type are exposed to the same known average concentration in a calibrated radon chamber. The procedure used in the first calibration test carried out in Phase 2 was as follows: Five short-term E-PERMs having nearly the same initial electret voltages were grouped into a subset. Five such subsets, each having slightly lower (about 100 V lower) initial voltages formed the total set of 25 E-PERMs used in the experiment. The total set was exposed in the chamber simultaneously. The radon chamber remained at a fairly constant concentration throughout the test period and that concentration was measured and recorded hourly with a continuous monitor. This procedure was repeated several times for both short-term and long-term E-PERMs to obtain statistically sound data. Table 5, 3 and 4 give the data obtained from these calibration experiments for short-term and long-term E-PERMs, respectively. This data was then used to calculate the calibration factors for both E-PERM types using Equation 1 above. The

* Current calibration factors and back-up data are available from Rad Elec Inc., 5310H Spectrum Drive, Frederick, MD 21701.

average of the standard deviations of the calibration factors for each 5 E-PERM subset is less than 3% for both sets of data. Equations 2 and 3 below, derived by linear regression, are the CF equations defined by these data for short and long-term E-PERMs, respectively.

$$CF\ (ST) = 1.5692 + 001251 \times \frac{(V_i + V_f)}{2} \qquad \text{Equation 2}$$

$$CF\ (LT) = 0.178 + 000062 \times \frac{(V_i + V_f)}{2} \qquad \text{Equation 3}$$

Where:

CF (ST) and CF (LT) are the calibration factors for short-term and long-term E-PERMs in $pCiL^{-1}$ -d.

Figures 7 and 8 give the graphical representation of these results.

3.2 MEASURING RADON CONCENTRATION WITH E-PERMS

Following are the steps required to measure radon with E-PERMs:

(1) Measure the initial electret voltage (V_i) using the electret voltage reader. (See Section 2.4)

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

(3) Turn the E-PERM unit to its "on" position (i.e., unscrew the top lid) and record the date and time it was turned on.

(4) Deploy the E-PERM at the location to be monitored in accordance with EPA protocol.

(5) After a known exposure time (2 to 7 days for short-term or 1 to 12 months for long-term E-PERMs), turn the E-PERM to its "off" position. Record the date and time it was shut off.

(6) Remove the electret and measure its final voltage (V_f).

(7) Determine the correction (B) to be applied for gamma background at the site. (See Section 5.3)

(8) Calculate the radon concentration using Equations 1 and 2 or 1 and 3 above .

With suitable written instructions, E-PERMs can be deployed by home owners as well as radon measurement professionals. Experience has shown that they can be mailed for deployment and return by homeowners with good results. However, they should be analyzed (read-out) only by technicians who have been trained to handle the electrets and use the SPER-1 instrument properly.

4.0 E-PERM RESPONSE CHARACTERISTICS

4.1 PRECISION OF E-PERM RESULTS

Table 5 gives the result of a study conducted to determine the repeatability and precision of measurements made with randomly chosen E-PERMs. Subsets of two short-term electrets each were randomly chosen from fifteen (15) different production batches for testing (electrets are produced in batches of about 250 units). All were loaded into randomly chosen E-PERM chambers and exposed simultaneously in a radon chamber for the same period. The radon concentration value was again calculated for each E-PERM using equation 1. The percentage coefficient of variation was then calculated for each 2-E-PERM subset using the standard procedure applicable to a sample size of 2. A further correction of 1.253 was applied to each result as recommended by Dixon and Massey [7] to compensate for small sample bias (N=2) to arrive at the unbiased estimations of the population standard deviations listed in Table 3. As seen, the mean standard deviation for all 15 subsets tested was 4.8%.

4.2 INTERCHANGEABILITY OF LONG AND SHORT-TERM E-PERMS

Long and short-term E-PERMs should give the same concentration values when exposed together to a time-integrated radon level within the overlapping region of their dynamic ranges. To verify this limited interchangeability of long and short-term units, several E-PERMs of both types were placed simultaneously into a radon chamber and exposed for the same period of time. The concentration in the chamber was known, so a time-integrated radon exposure value was chosen which was close to the upper range limit of the short-term E-PERMs and to the lower range of the long-term E-PERMs. As seen in Table 6, the concentration values obtained with the two types of instruments were essentially the same. This data demonstrates that long-term E-PERMs do, indeed, give accurate results when used for short exposures in higher radon concentrations, and visa-versa.

4.3 SIGNAL INTEGRATING CHARACTERISTICS

The excellent signal integration and retention characteristics of E-PERMs were demonstrated and reported in the Phase 1 report for the cup-in-cup type instruments. A test of the integration capability of the commercial model E-PERMs was conducted during Phase 2 at the Department of Energy's Environmental Measurement Laboratory (EML). E-PERMs were exposed for 16 h in the EML radon chamber to a known 40 $pCiL^{-1}$ then left out of the chamber for 8 h in a known concentration of 0.5 $pCiL^{-1}$. This cycle was repeated 4 times giving a total of 106.7 $pCiL^{-1}$ - days of chamber exposure and 0.7 $pCiL^{-1}$ - days of office exposure. The total time integrated radon concentration as measured by the E-PERMs was within 5% of the combined integrated exposure of 107.4 $pCiL^{-1}$ - days.

4.4 ELEVATION EFFECT

Kotrappa and Stieff [9] recently showed that elevation has a slight effect on the response of the 200 ml E-PERM above 4,000 feet elevations. Radon concentrations measured at 4,000 and 5,000 feet elevations must be increased by 3% and 9%, respectively. No correction is necessary elevations less than 3000 feet. Corrections for other elevations can be interpolated on a linear basis. This correction is quite small and it can be applied by E-PERM users in mountainous areas of the country using only a rough estimate of the elevation at measurement sites.

4.5 TEMPERATURE RESPONSE

Calculations based on the elevation effect experiment referred to in 4.4 above indicate that the air density changes up to 11% have no effect on E-PERM response. This air density change corresponds to a temperature change of approximately 36°F or 20°C (303° K / 273° K = 1.104 or 10.4%). Accordingly, it was reasoned that temperature changes in the range of 20° C (36° F) should also have a negligible effect on the E-PERM response. This was verified in an experiment wherein four E-PERMs were located in a warm air stream for 3.8 days at an average temperature of 43°C. Three other electrets were located upstream from the heat source where the average temperature for the same exposure period was 24°C. The experiment was carried out in a large basement and a small fan was run constantly to facilitate equal radon concentrations in the vicinity of all of the monitors. The average concentration, as determined by the 3 units in the warm air stream was 8.9 ± 0.4 $pCiL^{-1}$ and that determined by the cool units was 9.7 ± 0.5 $pCiL^{-1}$. The difference between the two average values (0.8 $pCiL^{-1}$) is considered to be statistically insignificant because it is within the error bars of the two measurements. Thus, the experiment verified that E-PERMs are, indeed, temperature insensitive over a temperature range of at least 20°C (36°F). Calculations based on the elevation effect data in 4.4 above indicated that the slight effect expected at extremes of environmental temperature will be indistinguishable within the overall E-PERM error. Another temperature effect has been observed, however. Experiments carried out in Phase 2 show that electret voltages tend to rise and fall slightly as their temperature goes up or down (about 1V per 10°F) but only if their voltage is measured while they are still hot or cold, When their temperature returns to room temperature, their voltages return to exactly the same starting voltage. The voltage response of the voltage readers was also found to increase about 0.5V per 10°F increase. As a result of these experiments, E-PERM users have been instructed to be sure that the temperature of the electret and SPER-1 are approximately the same(i.e., within ±5° F) during the initial and final voltage reading.

4.6 HUMIDITY RESPONSE

It was also shown in our earlier experimental work [(1)] using a laboratory model E-PERM that changes in relative humidity from 12% to 98% have no appreciable effect on E-PERM response. The U.S. Environmental Protection Agency [(A1)] also evaluated the humidity response of several prototype E-PERMs and concluded that they showed no measurable response up to 65% RH (the maximum RH tested).

During Phase 2 the DOE chamber at their EML Facility in New York was modified to enable humidity control. A. C. George, the manager of that facility, exposed and read out a number of short-term and long-term electrets in the chamber at various relative humidities and reported the following results (8) to the authors.

Six short-term E-PERMs were exposed to an average concentration of 49.1 $pCiL^{-1}$ (as measured by EML) for 104 hours at a constant RH of 87%. The average E-PERM concentration was 45.8 ± 2.2 $pCiL^{-1}$.

Eight long-term E-PERMs were exposed to an average concentration of 39.2 $pCiL^{-1}$ for 456.75 hours with RH varying as follows: 4 days at 87%, 1 day at 95%, and 14 days at 50% (the RH was varied to accommodate other experiments being carried out simultaneously). The average E-PERM concentration of the eight units as reported by George was 36.7 ± 0.5 $pCiL^{-1}$. George concluded from these two experiments that "The intercomparison results indicate that both the short and long-term detectors (E-PERMs) agree very well with the true value (difference of 6.7%)."

Table 7 shows voltage measurements of 12 long-term and 12 short-term electrets after one and two weeks of continuous exposure to 100% RH. The electrets represented were chosen randomly from routine production lots and sealed in air-tight containers with wet sponges. They were all stored at room temperature (about 75°F) with their covers on during the two week period. The electret covers all have small filtered holes in them so the moisture quickly equilibrates at the electret surface. As seen in Table 7, only a few of the test electrets (e.g., ST No. 5) showed appreciable voltage change. (One volt changes are not significant because the readout meter is only accurate to ± 1 volt.) Careful inspection of the surface of those electrets which show measurable voltage loss on such tests indicate that the loss may be due to dirt (particles and fibers) on the surface. It was concluded from these tests that Rad Elec Inc. electrets show no appreciable effect in radon response even at 100% RH. Of course, it is very unlikely that electrets will ever be exposed to 100% RH continuously over such an extended period in home testing. However, RH can reach 100% for short periods in home basements especially at certain times of the year.

It should be pointed out that the simple 100% RH test exposure procedure described above has proven to be an excellent QA tool for assuring electret stability. The procedure is now applied routinely by Rad Elec Inc. to a representative number of electrets from every production batch. Electrets which change more than 5 volts per week over a two week period are deemed unacceptable.

4.7 EFFECT OF AIR FLOW OVER E-PERMS

It is well known that even slow movement of air over most types of charcoal canisters effects their radon response substantially. Mindful of this phenomena, a brief experiment was carried out to evaluate the effect of air flow over E-PERMs.

The louver covering the return air duct in a home was removed and four short-term E-PERMs were placed directly in the duct. The furnace fan control was set to run continuously for the four days exposure. A rough measurement of the air velocity in the duct indicated a flow of 70 to 100 feet per minute. Four other short-term E-PERMs were placed on a table about four feet below the air duct entrance. After four days, all eight E-PERMs were analyzed. The average radon concentration recorded by the four units in the moving air stream was 3.8 ± 0.2 $pCiL^{-1}$ and that by the still air units was 3.7 ± 0.2 $pCiL^{-1}$. Accordingly, it was concluded that air flows up to about 100 feet per minute do not effect E-PERM response to radon.

4.8 RADIATION STATISTICAL ERROR

The radiation statistical (Poison) error in E-PERM results is practically negligible because of the very large number of alpha disintegrations that are integrated by the detector during the exposure period. On first consideration, it would appear that the Poison statistical error analysis method may not apply to E-PERM measurements because electrets do not detect alpha particles as discrete events. However, the electret does collect ions in discreet pulses as the alpha emissions occur in the E-PERM chamber. In order to get a perspective on the magnitude of this Poison error, it is useful to calculate the number of alpha disintegrations which occur in the E-PERM to assess the equivalent Poison error associated with a hypothetical radon measurement.

Let us consider a three day measurement in a chamber held at 1 $pCiL^{-1}$. By definition, 1 $pCiL^{-1}$ is 2.2 disintegrations per minute (dpm) per liter of air or 3168 disintegrations per day (dpd). Thus, 1 $pCiL^{-1}$ of radon in the 200 ml E-PERM chamber yields 3168 x 0.2 = 634 dpd. However, two of the four radon progeny which quickly form and decay in the chamber are also alpha emitters. The two short lived beta emitting progeny (there are four progeny in all) probably do not contribute much to the signal because of the relatively low interaction of betas with air. Both of these alpha emitting progeny are usually (about 95% of the time) positively charged when formed. The electrostatic field from the electret is positive, so the charge progeny affix themselves to the inner chamber wall soon after they are formed. When they decay, their alphas are only emitted into the chamber volume 50% of the time (the alphas go into the chamber wall the rest of the time). In net effect then, each radon gas disintegration gives rise to one other alpha particle.

Accordingly, instead of 634 dpd, 1 $pCiL^{-1}$ of radon really gives rise to 634 x 2 = 1268 dpd. Thus, in a 3 day radon measurement of 1 $pCiL^{-1}$, for example, the electret must collect ions from 1268 x 3 = 3804 alpha events. Therefore, the Poison error for such a measurement is

$$\pm \sqrt{3804} \;/\; 3804 \times 100 = 1.4\%$$

Obviously, this radiation statistical error will usually be even or less for measurements of more than 1 $pCiL^{-1}$ or of longer durations.

5.0 ERROR ANALYSIS

The previous section discussed the effect of many variable environmental parameters on the radon response of E-PERMs. It showed, in general, that they do not affect the response appreciable or that the small error which they might introduce can be corrected for readily. Parameters which can introduce appreciable error are discussed and quantified in this Section.

The overall error of the E-PERM system is made up of three components:

1. The E-PERM component error (E1) associated with the chamber volume, electret thicknesses and other chamber parameters. 2. The readout error (E2) associated with the reading of the electrets. 3. The background error (E3) associated with the uncertainty of the natural gamma radiation background.

5.1 COMPONENT ERROR

This error factor includes E-PERM response variations due to the small dimensional variations expected from unit to unit; e.g., in chamber volume and electret (Teflon) thickness. The experiments described in 3.1 above using Table 3 data gave a standard error (E1) of 4.8%. The E-PERM and electrets used in these experiments were chosen at random, so the variations seen in the results are representative of all commercial unit. Thus, E1 can be taken as ± 5% and the error in radon concentration then due to E1 can be expressed as:

$$E1 = \pm 0.05 \quad (RnC)$$

Where: RnC = measured radon concentration

5.2 READOUT ERROR

The electret voltage reader displays voltages to an accuracy of ± 1 volt over its entire voltage range. This is the readout error (E2). Since two readings are required to determine the radon concentration, the fractional readout error associated with making a radon measurement is:

$$\pm \frac{\sqrt{1^2 + 1^2}}{(V_i - V_f)}$$

The percent error in radon concentration (E2) which can result from this fractional error in the voltage reading is:

$$E2 = \pm \frac{\sqrt{2} \times 100}{(V_i - V_f)} = \frac{140}{V_i - V_f}$$

5.3 GAMMA BACKGROUND ERROR

The gamma background radiation (BG) at the measurement site is a positive interference in E-PERM radon measurements. (See Equation 1) If the exact BG value is known at any measurement site (e.g., in uR/hr) it can be converted to equivalent $pCiL^{-1}$ and subtracted from apparent radon concentrations measured at that site.

Careful measurements have shown that 1 ur/hr of gamma radiation generates the same number of ions in an E-PERM as 0.087 $pCiL^{-1}$ - day of radon. This latter number can be used as a factor to convert any measured BG level to its equivalent radon concentration (B) to apply in Equation 1. Thus, if the BG at a radon measurement site is accurately measured or otherwise known accurately, it can be converted and subtracted from the apparent radon concentration. For all practical purposes, this approach eliminates it (BG) entirely as an error source. The BG can be measured with a suitable survey meter or by exposing E-PERM sealed in a radon-proof bag(10) at the site for a known time.

Rather than requiring E-PERM users to measure the BG at every site, it is more practical instead to use the statewide average BG levels published by the EPA [11] as a basis for calculating the value of B. Of course, the BG varies substantially across any state, but variations as high as $\pm$ 20% will introduce no more than 0.2 pCiL^{-1} error in any radon measurement. Table 8 lists the average BG level in every state and the equivalent radon concentration levels for each which must be subtracted from apparent radon concentration values. As seen, BG values are listed for both higher and lower elevations in some states which further minimizes the potential error. (Rad Elec provides this state BG list to all E-PERM users.)

Since the highest and lowest B (background equivalent) values in Table 5 are 1.2 and 0.6 pCiL^{-1} respectively (e.g., for Colorado and Florida), it can be seen the maximum error due to BG (E3) would only be 0.3 pCiL^{-1} even if an average B value of 0.9 pCiL^{-1} (i.e., average between 1.2 and 0.6 pCiL^{-1}) were subtracted from every apparent radon concentration without regard to the true BG value at any site. Thus, by correcting results with state average B values as described above, the error in any radon measurement made in that state should be no more than 0.1 pCi/L. It is on this basis that it can be said that, even at concentrations as low as 1 pCiL^{-1}, the BG error in E-PERM results will be no more than $\pm$ 20%.

Based on this assumption, the percent concentration error (E3) which can result of BG uncertainty is:

$$E3 = (0.20 \times BG \times D)$$

where D is the factor to convert BG values to equivalent radon concentration (0.087 pCiL^{-1} per μR hr^{-1}).

5.4 OVERALL MAXIMUM ERROR

Combining all three errors defined above by the method of quadrature, the overall maximum error (EO) is given by the following equation

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

$$= \sqrt{5^2 + \left(\frac{140}{Vi - Vf}\right)^2 + (10 \times BG \times D)^2} \quad \text{Equation 4}$$

The EO calculated with Equation 4 is the overall statistical error.. Hand held scientific calculators can be programmed with Equation 4 so that the maximum error in any E-PERM radon concentration measurement value can be specified. This is not possible with either of the competitive passive monitoring methods (charcoal canisters or alpha track) because of the many more variables involved.

5.5 THE LOWER LIMIT OF DETECTION

For the purposes of this section, the definition used by Thomas (12) is used for the lower limit of detection (LLD) viz, that radon concentration that can be measured to an accuracy of 50%. For E-PERMs, this LLD depends upon the period of exposure, the electret voltage region and the type of E-PERM (i.e., short or long-term E-PERM) used in a particular measurement. The LLD can be calculated for various exposure periods by substituting various voltage differentials into the equation for total error (Equation 4) above. For example, a two day measurement with a short-term E-PERM with a voltage change from 707V to 700V gives a concentration of 0.5 $pCiL^{-1}$ within an overall error (EO) of 51%. Thus 0.5 $pCiL^{-1}$ is the LLD for this measurement. (Calculating the exact LLD, i.e. at an EO of exactly 50% would result in fractional voltages which are not measurable with the SPER-1.) As Equation 4 indicates, the LLD also varies somewhat with electret voltage. Table 9 shows the range of LLD's expected for various exposure periods.

It should be noted that LLD values usually given for charcoal and alpha track based devices are based on a radiation statistical calculation method which is not applicable to E-PERMs. E-PERM LLD values determined by the above methodology cannot be compared directly with LLD values for the charcoal and alpha track devices.

6.0 COST COMPARISON WITH OTHER TYPES OF PASSIVE MONITORS

6.1 E-PERM MEASUREMENT COSTS

As mentioned earlier, one of the goals of this development effort was to develop a passive monitor which would reduce the cost of radon measurement for homeowners. Accordingly, a rough comparison of the cost of E-PERM measurements with measurements made with the two other types of passive radon monitors, (i.e., charcoal canisters and alpha track devices) is presented in this section. It must be pointed out, however, that unit costs and other cost factors involved in the use of passive monitors vary widely, so the comparisons made here are only approximate.

The present cost of an electret voltage reader when bought in single units varies from $900 to $1800* depending on the number of units purchased. Because of the insignificant time needed to make a measurement, a single SPER-1 reader can service a very large number of E-PERMS (e.g., hundreds per day). Reusable E-PERM chambers presently cost about $50* per unit and the consumable electrets about $25*.

A single short-term electret can be used to make at least 15 measurements when used for making three day measurements of concentrations in the range of 4 $pCiL^{-1}$. The maximum number of measurements available with an electret will, of course, depend on the radon concentrations it is exposed to and the cumulative duration of the exposures, i.e., an electret gives fewer measurements at higher concentrations. However, most homes have radon levels less than 4 $pCiL^{-1}$ so electrets do, on average, last for at least 15 measurements. Assuming that the meter and chamber amortization costs are $1 per measurement, the cost per E-PERM measurement is roughly about $2.70, i.e., $1.70 electret use cost and $1.00 for equipment amortization. Readers and

* Substantial quantity discounts are available on all E-PERM system components. The only manufacturer at the present time is Rad Elec Inc.

chambers can be used for many years without service or replacement so their amortization costs for short-term measurements is very low.

Likewise, a long-term electret, which also costs about $25, can give about 6 three month measurement in concentrations in the 4 pCi/L^{-1} range. On this basis, the electret cost in making a long-term E-PERM measurement is about $4.20. However, since the $50 E-PERM chamber is used for a considerably longer period here, some chamber amortization cost should probably be added to the measurement cost. Assuming a $5 amortization cost per reading for the E-PERM chamber, the total long-term measurement cost would be $9.20.

A smaller E-PERM chamber is now available for long term measurements which cost only about $20 including the electret. The comparable amortization cost per reading for this device which can be used for about 8 one year measurements with the same long-term electret, would be about $2.00, so its unit measurement cost is about $5.10.

6.2 COMPARATIVE COSTS

Unit measurement costs using charcoal canisters or alpha-track devices vary widely However, the $2.70 per measurement E-PERM cost estimated for short-term measurement indicated above can be compared roughly to the current $4-15 price for charcoal canister measurements. The $9.20 and $5.10 long-term E-PERM measurement cost estimates can be compared with the current market cost of $10-20 per alpha track measurement. Even though these comparisons are very rough, it is apparent that the E-PERM system does, indeed, afford an economical alternative radon measurement method. Recent field experience verifies this conclusion.

Through not quantified here, it is obvious that the substantially lower cost of the E-PERM read-out instrument (about $1800) relative to charcoal or alpha-track read-out instruments, reduces the relative cost of E-PERM measurements over time. The fact that a single read-out instrument suffices for both long and short-term measurements also translates to a considerable economic advantage for E-PERM users who make both types of measurements.

7.0 BLIND-TEST EVALUATION OF E-PERMS

The final task in Phase 2 was to demonstrate the electret ion chamber technology in the field and determine its advantages and disadvantages, especially with respect to accuracy and precision, relative to other available passive devices. Initially, it was planned to carry out this task using the prototype E-PERMs developed in Phase 2. However, the new technology became commercially viable so quickly that the field demonstrations were carried out with the molded commercial E-PERM units.

The completion of the project coincided with the initiation of Round 6 of the USEPA Radon Measurement Proficiency Program (RMPP) so it was decided to utilize the results of the blind radon chamber tests required of participants in that program as the principle E-PERM evaluation mechanism for the project. To this end, the authors asked all E-PERM participants to provide their results to them for analysis. Only 45% of the E-PERM participants did so, but they provided results for 518 units, which is sufficient for a meaningful evaluation.

7.1 EPA/RMPP ROUND 6 E-PERM BLIND TEST RESULTS

As part of their Radon Monitoring Proficiency Program (RMPP), the USEPA requires all companies who wish to be listed by them as proficient Primary Radon Measurement Laboratories to participate in a blind test of their ability to measure radon accurately. The proficiency listing earned by a participating company applies only to those types of monitoring instruments which that company enters into a particular round of tests. In past test rounds (Rounds 1 through 6), companies which entered with passive type monitors were required to send five duplicate units to EPA's designated Radon Coordinator for the blind test. The five devices were exposed to known radon concentrations (i.e., known to EPA, but not to participants) for known time periods. The monitors were then returned to the participant together with a notification of the exact length of time they were exposed. The participant was required to analyze them and notify the Coordinator of the average radon concentration to which each was exposed. If the results fell within a designated range (see below) of the EPA target value, the participant "passed" the blind test and was listed by the EPA as a proficient Primary Radon Measurement Laboratory.

Long and short-term E-PERMs are regarded by the EPA as different types of instruments, so participants who wished to be listed as proficient users of both types were required to submit both 5 long-term and 5 short-term units. About 160 companies entered a total of 1465 E-PERMs in Round 6. In order to pass Round 6, participants had to attain a Mean Absolute Value of the Relative Errors (MARE) of 0.250 or less based on their five measured concentration values. In practice, only four of the results obtained with the five E-PERMs submitted by each participant were averaged because the fifth unit was used as an unexposed control in every instance (though participants were not told which unit was used as the control). The Absolute Value of Relative Error (ARE) for each measurement was defined by EPA as:

ARE =(Mi - Ti) / Ti

where: Mi = the participant measured concentration value

Ti = the target (EPA measured) concentration value

The MARE value was the mean or average of the four ARE values.

Following is an example of the format used by the EPA to notify a short-term E-PERM participants of their MARE results in Round 6:

• • •

Company Method Code: ZJMHS
Device Brand: RAD ELEC INC
Type/Model: E PERM ST

Method: ES

ANNOUNCED (Single Blind) TEST RESULTS

Company Method Code	RTI Detector Number	Measured Value Mi	Target Value Ti	Absolute Value of Relative Error (Mi-Ti)/Ti
ZJMHS ES				
	603005	05.200	05.518	0.058
	603006	05.700	05.518	0.033
	603007	11.700	12.735	0.081
	603008	00.000	Control	Control
	603009	11.400	12.735	0.105
			Mean	0.069

The calculated mean of the absolute relative errors (MARE) *successfully meets* the 0.250 limit of performance.

• • •

As indicated at the bottom of the notification letter, this participant "passed" the blind test with a MARE value of 0.069 which is well within the EPA established limit of 0.250.

Though the EPA has not published the complete Round 6 data to date, an Agency official has reported the percentages of the various types of passive monitor which "passed" Round 6 were as follows:

Electret Ion Chambers (E-PERM)	94% passed (278 out of 293 participants*)
Activated Charcoal	69% passed (104 out of 136 participants*)
Alpha Track Detectors	67% passed (16 out of 21 participants*)

* The number of participants in each category were calculated from other data released by the USEPA.

It is apparent from these comparative results that the accuracy of both long and short-term E-PERMs were superior to the other two types of passive monitors which were entered into the Round 6 RMP test program.

Tables 10 and 11 are compilations of Round 6 results for short-term and long-term E-PERMs, respectively. They were provided in response to direct requests from the authors by 78 short-term and 54 long-term Round 6 E-PERM participants. Including the control units, which are not listed, the two Tables represent results for 390 short-term and 270 long-term E-PERMs for a total of 660 units. It is understood that a total of 293 sets of five or 1465 E-PERMs were entered in Round 6. Thus the results listed in the Tables represent 45% of the total number of E-PERMs entered in Round 6 which is a representative sample of total entries. The other 55% of the E-PERM participants did not respond to the authors' request for voluntary submission of their results.

The EPA reported all target concentration values to three decimals. These are also listed in the Tables. They also gave the exact dates and times during which they were exposed (not in the Tables) so it was a simple matter to identify E-PERM groups which were exposed together, i.e., E-PERMs which were in the chamber at the same time and for the same exposure period. Those which were found to have been exposed together in this way are grouped together in Tables 10 and 11. The several horizontal lines which appear throughout the Tables serve to delineate the E-PERMs which were exposed together. In looking over common E-PERM exposure groupings , several useful characteristics of the results are immediately apparent. It was also obvious, for example, that about half of the E-PERMs had been exposed to very low concentrations of about 2 to 5 $pCiL^{-1}$ and half to about 12-17 $pCiL^{-1}$. Column headings in both Tables make this distinction.

Asterisks have been placed after the overall MARE values in the last column listed of both Tables to designate participants that exceeded the EPA's 0.25 MARE criteria. As seen, only five of the short-term and two of the long-term E-PERM participants represented in the list failed the blind test. It can also be seen that three of the five participants whose short-term E-PERMs failed are all in one particular exposure grouping viz., those exposed to 15.073 $pCiL^{-1}$. Set numbers 13.4.8, 13.5.8, and 13.6.8 in Table 10 show the data for these units which failed. Each of these three failures was caused by an accuracy error of at least +50% or more. The results of all of the other E-PERMs exposed in this 15.073 $pCiL^{-1}$ concentration group (i.e., even those which passed the test) also exhibit very high and all of them are positive errors. The average error for the 16 units exposed together in this grouping was +39.8%, whereas the combined average error for all of the other short-term E-PERMs tested was only 8.5%. This anomalously high error in this one particular group (15.073 $pCiL^{-1}$) suggests that the EPA's target concentration for this group was erroneous. Accordingly, the 16 E-PERM results in this particular grouping have not been included in the overall average MARE values shown in Table 12 which is a summary analysis of the Round 6 results that are listed in Tables 10 and 11.

As seen, in Table 12, the mean MARE values for all of the short-term and long-term E-PERM results received are 0.118 and 0.104, respectively, and the overall average MARE is 0.112.

Though these average results are well within the EPA's 0.250 Round 6 "passing" limit, the error in some of the individual results listed is considerably higher than has ever been observed in the many other calibrated chamber tests carried out by the authors.

A simple mechanical failure was found to be the cause of some of the false-positive outlyers. This was caused by a few participants not turning their E-PERMs completely off before sending them to the EPA for the blind exposure. Ions can reach the electret when this mechanism is not completely off (i.e., when the electret cover is not screwed all the way down on top of the electret). This causes a false positive result. The EPA retained all E-PERMs submitted for at least a month before exposing them. Even a small flow of ions to the electret could reduce the electret voltage several volts over that long a period. Table 8 also shows that the short -term E-PERMs exposed in the 12 to 17 $pCiL^{-1}$ range gave more accurate results (average MARE of 0.067) than those exposed in the 2 to 5 $pCiL^{-1}$ range (average MARE of 0.169). The same is true of the long-term E-PERM results, though the spread between the low and high concentration units was not as wide (0.085 vs 0.132, respectively).

It is apparent that most of the errors in the individual E-PERM results were negative; i.e., the reported concentration values were lower than the EPA target values. This suggests that the most likely cause of the discrepancy was a slightly erroneous calibration factor. The calibration factor has since been modified to correct for this discrepancy.

8.0 CONCLUSIONS

The principle advantage of this new E-PERM radon measurement method is its ability to give immediate results, even in the field. This capability circumvents the delays usually involved in sending other passive devices (e.g., charcoal canisters of alpha-track monitors) to a central laboratory for analysis. E-PERM also usually have a cost advantage over other passive type devices, especially where their ability to make many successive measurements with the same electret utilized. All of the R&D goals of the NYSERDA Agreement were accomplished. Indeed, the development of the electret ion chamber technology involved has progressed well beyond the project goals and has become commercially viable. It is now widely accepted and used throughout the world.

9.0 REFERENCES

1. Kotrappa, P.; Dempsey, J.C.; Hickey, J.R.; Development of an Electret Passive Environmental Radon Monitor. New York State Energy Research Development Authority: Report No. 86-13; 1987.

2. Kotrappa, P.; Dempsey, J.C.; Hickey, J.R.; Stieff, L.R.; An Electret Passive Environmental ^{222}Rn Monitor Based on Ionization Measurement. Health Phys. 54:47-56; 1988.

3. Kotrappa, P.; Dempsey, J.C.; Ramsey, R.W.; Stieff, L.R.; A Practical E-PERM™ (Electret Passive Environmental Radon Monitor) System for Indoor ^{222}Rn Measurement. Health Phys. 58:461-467; 1990.

4. Kotrappa, P.; Dempsey, J.C.; Stieff, L.R.; Development of Electret Technology to Measure Indoor Radon - Daughter Concentration. UNC/GJ-TMC-5, UC-511; May 1989.

5. Kotrappa, P.; Jester, W.A.; The Measurement of Dissolved radon-222 in Water Using E-PERM Radon Monitors and Comparison with a Standard Liquid Scintillation Procedure.

6. Private Communication. R. Hopper; USEPA Office of Radiation Protection, Las Vegas, NV Facility (1990).

7. Dixon, W.J.; Massey, F.J.; Introduction to Statistical Analysis. McGraw Hill Books, 1957.

8. Private Communication, A.C. George, Radiation Physics Division, EML, DOE. New York. Jan. 1990.

9. Kotrappa, P.; Stieff, L.R.; Elevation Correction Factors for E-PERM Radon Monitors. Accepted for Publication in Health Physics; 1991.

10. Kotrappa, P.; Hobbs, T.G.; Calibration and Performance Evaluation of Electret Ion Chamber System for Environmental Gamma Radiation Levels Around Nuclear Installations. Presented at Health Physics Society Meeting: Anaheim, CA, June 1990 (available from authors).

11. Bogen, K.T.; Goldin, A.S.; Population Exposure to External Natural Radiation Background in the United States. USEPA. Technical Note ORP, SEPD-80-12.

12. Thomas, J.W., Thoron determination by a two filter method. USAEC Health and Safety Report HASL-TM-71-1; 1971.

TABLE 1 ABBREVIATIONS AND NOTATIONS

#	Electret number
ACF	The average calibration factor of the subgroup
AMPV	The average MPV of the subgroup
ARC	Average radon concentration in pCi L^{-1}
CF	Calibration factor
D	The date of manufacture
DV	The difference between IV and FV in volts
FV	Final voltage of the electret in volts
IV	Initial voltage of the electret in volts
LT	Long-term
MPV	The average of IV and FV in volts
PCV	The coefficient of variation in percent
RC	Radon concentration in pCi L^{-1}
SD	The standard deviation of the corresponding subgroup
ST	Short-term

TABLE 2 SHORT-TERM ELECTRET STABILITY TEST*

Electret Number	Volts on 1/17/90	Volts on 5/10/90	Electret Number	Volts on 1/17/90	Volts on 5/10/90
9101	471	471	8726	414	414
8597	515	516	8360	466	468
7853	460	460	8612	410	409
8701	435	435	7632	480	477
8361	551	551	8808	482	482
8636	468	468	4377	424	423
8708	525	524	8720	499	499
8705	569	569	8830	415	415
8353	393	393	8775	469	468
8588	536	537	8767	531	532
8048	482	480	8375	377	375
8653	430	429	8479	550	551
7122	452	450	8596	493	493
8342	523	523	8389	507	505
8615	479	478	8495	483	483

*Performed by R. Hopper [6] at the EPA Los Almos Laboratory.

TABLE 3 CALIBRATION DATA FOR SHORT-TERM E-PERMS

E-PERM No.	Initial Voltage (V)	Final Voltage (V)	Voltage Drop (V)	Mid-Point voltage (V)	Calibration factor ($v/pCiL^{-1}$ d)	Average Calibration factor and (SD)
1	300	132	168	216	1.7560	
2	297	128	169	213	1.7660	
3	286	97	189	238	1.9751	
4	296	130	166	213	1.7360	
5	303	136	167	210	1.7449	1.7952
			Mean	218		(0.0888)
			SD	± 10		
6	403	216	187	310	1.9547	
7	407	215	192	311	2.0069	
8	395	202	193	299	2.0169	
9	408	217	191	313	1.9961	
10	389	196	193	293	2.0720	2.0095
			Mean	305		(0.0370)
			SD	± 8		
11	506	317	189	412	1.9751	
12	493	292	201	393	2.1009	
13	504	305	199	404	2.0801	
14	502	300	202	401	2.1131	
15	497	304	193	401	2.0720	2.0679
			Mean	402		(0.0481
			SD	± 6		
16	598	380	218	489	2.2781	
17	604	400	204	502	2.1319	
18	600	396	204	498	2.1319	
19	594	381	213	488	2.2259	
20	601	392	209	497	2.1841	2.1900
			Mean	485		(0.0555)
			SD	± 5		
21	747	525	222	636	2.3199	
22	749	525	224	637	2.3410	
23	742	518	224	630	2.3410	
24	742	500	242	621	2.5289	
25	751	534	217	643	2.2681	2.3599
			Mean	643		(0.0888)
			SD	± 7		

Linear Regression Equation between average of mid-point voltage (MPV) and average calibration factor (CF)
CF = 1.5692 + 0.00125 x MPV (Correlation Coefficient = 0.994)

TABLE 4 CALIBRATION DATA FOR LONG-TERM E-PERMS*

E-PERM No.	Initial Voltage (V)	Final Voltage (V)	Voltage Drop (V)	Mid-Point voltage (V)	Calibration factor ($v/pCiL^{-1}$ d)	Average Calibration factor and (SD)
1	749	651	98	700	0.22030	
2	748	652	96	700	0.21578	
3	744	645	99	695	0.22252	
			Mean	698		0.21952
			SD	± 2		(0.0281)
4	642	557	96	605	0.21360	
5	650	554	96	602	0.21578	
6	652	557	95	605	0.21360	
			Mean	604		0.21434
			SD	± 2		(0.0104)
7	506	317	189	412	0.20679	
8	493	292	201	393	0.21360	
9	504	305	199	404	0.21360	0.21131
			Mean	505		(0.00322)
			SD	± 2		
10	452	359	93	406	0.20909	
11	450	361	89	406	0.2001	
12	449	358	91	404	0.20561	0.20757
			Mean	405		(0.074)
			SD	± 1		
13	352	262	90	307	0.20231	
14	348	255	93	302	0.20909	
15	350	264	86	307	0.19329	0.20561
			Mean	305		(0.00363)
			SD	± 2		
16	251	172	79	212	0.1776	
17	251	166	85	209	0.1911	
18	252	168	84	210	0.1887	0.18581
			Mean	210		(0.00592)
			SD	± 1		

Linear Regression Equation between average of mid-point voltage (MPV) and average calibration factor (CF)
CF = 0.1780 + .0000621 x MPV (Correlation Coefficient = 0.957)

TABLE 5 PERFORMANCE OF RANDOMLY CHOSEN SHORT-TERM E-PERMS

Date of Manufacture	Initial voltage (V)	Final Voltage (V)	Voltage Diff. (V)	Coef. of Variation (%)
9 Nov	752	593	159	
9 Nov	752	598	154	2.9
10 Nov	753	597	156	
10 Nov	760	599	161	2.8
8 Dec	759	598	161	
8 Dec	756	584	172	5.9
12 Dec	756	590	166	
12 Dec	751	572	179	6.6
3 Dec	753	582	171	
3 Dec	751	574	165	3.0
5 Nov	758	584	174	
5 Nov	753	588	165	4.8
6 Dec	753	598	155	
6 Dec	755	584	171	8.7
4 Nov	758	584	174	
4 Nov	753	585	168	3.1
1 Dec	753	589	164	
1 Dec	757	594	163	0.5
13 Dec	751	569	182	
13 Dec	752	589	163	9.8
5 Dec	754	593	161	
5 Dec	758	596	162	0.5
28 Nov	752	574	178	
28 Nov	752	584	168	5.1
9 Dec	757	583	174	
9 Dec	753	598	161	6.9
2 Dec	757	580	177	
2 Dec	762	580	182	2.5
10 Dec	753	574	179	
10 Dec	758	587	171	4.0
		Mean Values	168.3	4.5
			SD ± 8.1 (4.8%)	

TABLE 6 INTERCOMPARISON OF LONG-TERM AND SHORT-TERM E-PERMS*

Test No.	Electret Type	Initial Voltage	Final Voltage	Radon Conc.	Ave. Conc. (SD)
1	ST	626	314	85.5**	
2	ST	680	365	84.7	86.6
3	ST	684	365	84.7	3.1%
4	ST	638	305	91.3	
5	LT	651	621	81.8	
6	LT	652	622	81.8	
7	LT	645	613	87.5	
8	LT	557	527	84.1	
9	LT	551	519	89.9	
10	LT	557	527	84.1	
11	LT	460	431	83.6	85.0
12	LT	455	425	86.6	2.9%
13	LT	458	428	86.6	
14	LT	359	330	86.2	
15	LT	361	332	86.1	
16	LT	358	330	83.2	
17	LT	262	234	85.7	
18	LT	255	227	85.9	
19	LT	264	238	83.2	

*All E-PERMs introduced simultaneously into the radon chamber for a period of 1 day and 16 hours.

**The average chamber concentration were 86 pCi L^{-1}.

TABLE 7 EFFECT OF 100% RH ON ELECTRET VOLTAGE

Electret No.	Initial Voltage	After 7 days* (volts)	After 14 days (volts)	Electret No.	Initial Voltage	After 7 days (volts)	After 14 days (volts)
LT1	713	709	711	ST1	708	704	704
LT2	747	746	747	ST2	704	704	706
LT3	753	753	757	ST3	725	723	725
LT4	723	714	714	ST4	717	711	711
LT5	741	739	743	ST5	740	727	729
LT6	749	750	754	ST6	728	729	730
LT7	744	734	737	ST7	714	714	709
LT8	747	744	742	ST8	706	702	702
LT9	738	738	742	ST9	719	715	717
LT10	743	742	745	ST10	714	711	710
LT11	716	713	714	ST11	713	711	712
LT12	742	742	746	ST12	707	706	708

* days of exposure to 100% RH at room temperature

TABLE 8 - CORRECTIONS FOR BACKGROUND GAMMA RADIATION BY STATE

This table lists the average background gamma radiation (BG) by state* for "S" E-PERM chambers and the corresponding BG Correction in equivalent (EQ.) pCiL. These BG Corrections must be subtracted from the apparent radon concentration values when calculating E-PERM radon concentrations. Lower elevation (LE) and higher elevation (HE) BG values are listed for some states.

State	BG (uR/h)	BG Correction (Eq. pCiL)	State	BG (uR/H)	BG Correction (Eq. pCiL)
AL (LE)	6.86	0.6	MT	11.31	1.0
AL (HE	10.04	0.9	NE	10.40	0.9
AK	9.85	0.9	NV	12.10	1.1
AZ	11.20	1.0	NH	10.00	0.9
AR (LE)	6.85	0.6	NJ (LE)	6.90	0.6
AR (HE)	10.36	0.9	NJ (HE)	9.87	0.9
CA	10.06	0.9	NM	12.73	1.1
CO	13.05	1.1	NY	9.94	0.9
CT	9.88	0.9	NC (LE)	6.82	0.6
DE	6.81	0.6	NC (HE)	10.18	0.9
DC	8.49	0.7	ND	10.36	0.9
FL	6.82	0.6	OH	10.04	0.9
GA (LE)	6.86	0.6	OK (LE)	6.93	0.6
GA (HE)	10.10	0.9	OK (HE)	10.30	0.9
HI	9.81	0.9	OR	10.13	0.9
ID	11.40	1.0	PA	7.02	0.6
			PA**	9.94	0.9
IL	10.07	0.9	RI	9.84	0.9
IN	11.39	1.0	SC (LE)	6.82	0.6
IA	10.14	0.9	SC (HE)	10.00	0.9
KS	10.31	0.9	SD	10.48	0.9
KY (LE)	6.86	0.6	TN (LE)	6.87	0.6
KY (HE)	10.08	0.9	TN (HE)	10.12	0.9
LA	6.82	0.6	TX (LE)	6.86	0.6
ME	9.97	0.9	TX (HE)	10.68	0.9
MD (LE)	6.82	0.6	UT	12.52	1.1
MD (HE)	9.96	0.9	VY	9.96	0.9
MA	9.93	0.9	VA (LE)	6.82	0.6
MI	10.10	0.9	VA (HE)	10.18	0.9
MN	10.25	0.9	WA	9.96	0.9
MS	6.87	0.6	WV	10.26	0.9
MO (LE)	6.90	0.6	WI	10.09	0.9
MO (HE)	10.06	0.9	WY	13.33	1.2

* Taken from Table A-1 in "Population Exposure to External Natural Radiation Background in the USA" by T. Bogen and S. Goldin. EPA technical Note-OP/SPED-80-12, April, 1981.

**Urban average value (preferred value for PA).

TABLE 9 LOWER LIMIT OF DETECTION FOR LONG AND SHORT-TERM E-PERMS

E-PERM Type	Exposure Period (days)	LLD Range* ($pCiL^{-1}$)	LLD Range ($pCiL^{-1}$-days)
ST	2	0.5 to 0.8	1 to 1.6
ST	7	0.3	2.1
ST	60	0.2	12
LT	30	0.5 to 0.7	15 to 21
LT	90	0.3	27
LT	365	0.2	73

*See Section 5.5 for the definition of LLD used here

TABLE 10 - EPA/RMPP ROUND 6 LONG-TERM BLIND TEST RESULTS

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 2 - 17	MARE* MEAN
1.1.1	978025	10.600	12.523		0.154	
JLLJW	978026	11.000	12.523		0.122	
	978027	12.800	12.617		0.015	
	978028	12.100	12.617		0.041	0.083
2.1.2	266560	03.300	03.512	0.060		
HMJTM	266561	03.300	03.512	0.060		
	266563	17.000	14.283		0.190	
	266564	15.900	14.283		0.113	
						0.106
2.2.2	319300	02.700	03.512	0.231		
HVVSV	319301	02.900	03.512	0.174		
	319303	17.300	14.283		0.211	
	319304	17.300	14.283		0.211	
						0.207
3.1.2	784435	13.600	14.006		0.029	
BHJTJ	784436	13.300	14.006		0.050	
	784437	13.500	14.307		0.056	
	784438	13.200	14.307		0.077	
						0.053
3.2.2	358620	13.700	14.006		0.022	
BLWBT	358621	13.000	14.006		0.072	
	358623	14.400	14.307		0.007	
	358624	14.600	14.307		0.021	
						0.030
4.1.3	757505	07.600	05.161	0.473		
SLDHZ	757506	05.400	05.161	0.046		
	757507	13.600	14.351		0.052	
	757508	11.300	14.351		0.213	
						0.196
4.2.3	496870	04.700	05.161	0.089		
STSHM	496871	06.800	05.161	0.318		
	496872	14.200	14.351		0.011	
	496873	13.800	14.351		0.038	
						0.114

*Failure Value (i.e., > 0.250)

TABLE 10 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) (pCiL-1)	Target Conc. (Tc) (pCiL-1)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
4.3.3	567190	05.000	05.161	0.031		
VHSFD	567191	04.500	05.161	0.128		
	567191	14.700	14.351		0.024	
	567193	15.200	14.351		0.059	
						0.061
5.1.4	515800	06.000	05.106	0.175		
FVZWT	515801	07.400	05.106	0.449		
	515802	17.400	14.380		0.210	
	515803	16.800	14.380		0.168	
						0.251*
5.2.4	934155	05.100	05.106	0.001		
LHWWD	934156	05.000	05.106	0.021		
	934157	14.600	14.380		0.015	
	934159	14.900	14.380		0.036	
						0.018
5.3.4	215335	05.100	05.106	0.001		
MBBVT	215336	05.900	05.106	0.155		
	215338	14.600	14.380		0.015	
	215339	14.400	14.380		0.001	
						0.043
5.4.4	304260	05.100	05.106	0.001		
ZMDMW	304261	04.700	05.106	0.080		
	304262	14.500	14.380		0.008	
	304264	15.400	14.380		0.071	
						0.040
6.1.7	637030	04.700	05.048	0.069		
BFJVJ	637031	04.600	05.048	0.089		
	637032	18.100	14.398		0.257	
	637033	14.800	14.398		0.028	
						0.111
6.2.7	694605	05.200	05.048	0.030		
HFVWV	694606	00.000	Damaged	Damaged		
	694607	17.200	14.398		0.195	
	694608	14.700	14.398		0.021	
						0.082
6.3.7	884175	05.000	05.048	0.010		
HWZHV	884176	05.200	05.048	0.030		
	884178	14.700	14.398		0.021	
	884179	14.500	14.398		0.007	
						0.017

*Failure Value (i.e., > 0.250)

TABLE 10 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
6.4.7	401705	03.700	05.048	0.267		
JHWSJ	401706	04.100	05.048	0.188		
	401707	12.800	14.398		0.111	
	401708	12.800	14.398		0.111	
						0.169
6.5.7	993160	04.400	05.048	0.128		
SHSLM	993161	04.600	05.048	0.089		
	993162	14.500	14.398		0.007	
	993163	14.100	14.398		0.021	
						0.061
6.6.7	471665	04.700	05.048	0.069		
ZFJFM	471666	04.700	05.048	0.069		
	471668	14.300	14.398		0.007	
	471669	14.400	14.398		0.000	
						0.036
6.7.7	527230	04.700	05.048	0.069		
SJFBB	527231	05.200	05.048	0.030		
	527233	14.400	14.398		0.000	
	527234	15.300	14.398		0.063	
						0.040
7.1.8	502100	04.600	04.423	0.040		
HBFHJ	502101	04.300	04.423	0.028		
	502102	14.200	14.510		0.021	
	502104	14.900	14.510		0.027	
						0.029
7.2.8	103485	05.600	04.423	0.266		
LFWMV	103486	04.500	04.423	0.017		
	103487	15.200	14.510		0.048	
	103488	14.700	14.510		0.013	
						0.086
7.3.8	534390	03.800	04.423	0.141		
LZBMV	534391	04.100	04.423	0.073		
	534392	15.000	14.510		0.034	
	534394	14.100	14.510		0.028	
						0.069
7.4.8	570120	04.700	04.423	0.063		
MFTTW	570121	05.200	04.423	0.176		
	570123	13.700	14.510		0.056	
	570124	16.600	14.510		0.144	
						0.110

*Failure Value (i.e., > 0.250)

TABLE 10 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
7.5.8	994020	04.800	04.423	0.085		
ZFMHV	994021	04.100	04.423	0.073		
	994023	04.900	14.510		0.027	
	994024	20.900	14.510		0.440	
						0.156
7.6.8	746445	02.800	04.423	0.367		
MWMHJ	746446	03.900	04.423	0.118		
	746448	13.900	14.510		0.042	
	746449	12.900	14.510		0.042	
						0.160
7.7.8	333935	12.800	04.423	1.894		
WLDSW	333936	06.300	04.423	0.424		
	333937	15.100	14.510		0.041	
	333938	14.300	14.510		0.014	
						0.593*
7.8.8	189720	04.700	04.423	0.063		
VFBJV	189721	05.200	04.423	0.176		
	189722	14.700	14.510		0.013	
	189723	15.700	14.510		0.082	
						0.083
8.1.1	919015	04.300	04.385	0.019		
TWHMZ	919016	04.000	04.385	0.088		
	919017	14.600	14.692		0.006	
	919018	16.200	14.692		0.103	
						0.054
9.1.6	672485	04.200	04.187	0.003		
DZFMZ	672486	04.600	04.187	0.099		
	672488	14.800	14.873		0.005	
	672489	14.500	14.873		0.025	
						0.033
9.2.6	879255	04.100	04.187	0.021		
FFBFD	879256	04.000	04.187	0.045		
	879257	13.900	14.873		0.065	
	879259	14.200	14.873		0.045	
						0.044
9.3.6	938820	04.000	04.187	0.045		
MHMTJ	938821	04.000	04.187	0.045		
	938823	14.400	14.873		0.032	
	938824	14.500	14.873		0.025	
						0.037

*Failure Value (i.e., > 0.250)

TABLE 10 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
9.4.6	730920	04.200	04.187	0.003		
WFDLZ	730921	04.400	04.187	0.051		
	730922	21.100	14.873		0.419	
	730923	14.800	14.873		0.005	
						0.119
9.5.6	532835	03.400	04.187	0.188		
TFJDV	532836	03.300	04.187	0.212		
	532838	13.500	14.873		0.092	
	532839	14.100	14.873		0.052	
						0.136
9.6.6	512970	04.000	04.187	0.045		
FJFLH	512971	04.300	04.187	0.027		
	512972	14.200	14.873		0.045	
	512973	14.400	14.873		0.032	
						0.037
10.1.1	140115	04.300	04.162	0.033		
WZDZM	140116	04.200	04.162	0.009		
	140117	17.300	14.899		0.161	
	140118	19.300	14.899		0.295	
						0.125
11.1.5	774380	04.400	04.555	0.034		
DSZZV	774381	04.500	04.555	0.012		
	774382	15.000	14.929		0.005	
	774384	14.200	14.929		0.049	
						0.025
11.2.5	648685	04.300	04.555	0.056		
HZZBS	648686	04.400	04.555	0.034		
	648688	13.600	14.929		0.089	
	648689	13.200	14.929		0.116	
						0.074
11.3.5	811400	04.400	04.555	0.034		
JJVWM	811401	04.300	04.555	0.056		
	811403	16.100	14.929		0.078	
	811404	14.300	14.929		0.042	
						0.053
11.4.5	679555	03.900	04.555	0.144		
JWZTV	670556	04.100	04.555	0.100		
	670558	14.500	14.929		0.029	
	670559	15.600	14.929		0.045	
						0.079

*Failure Value (i.e., > 0.250)

TABLE 10 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) (pCiL^{-1})	Target Conc. (Tc) (pCiL^{-1})	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
11.5.5	379195	03.000	04.555	0.341		
MMTMZ	379196	02.500	04.555	0.451		
	379197	16.000	14.929		0.072	
	379199	15.100	14.929		0.011	
						0.219
12.1.6	882360	04.100	04.353	0.058		
MHWBT	882361	04.300	04.353	0.012		
	882362	00.000	Damaged			
	882363	17.800	15.050		0.183	
						0.084
12.2.6	324985	04.000	04.353	0.081		
MMMTS	324986	03.700	04.353	0.150		
	324987	16.100	15.050		0.070	
	324989	15.000	15.050		0.003	
						0.076
12.3.6	142560	05.600	04.353	0.286		
SBLZF	142561	05.600	04.353	0.286		
	142562	17.300	15.050		0.149	
	142563	16.400	15.050		0.090	
						0.203
12.4.6	848915	03.700	04.353	0.150		
TSMHM	848916	04.100	04.353	0.058		
	848918	18.200	15.050		0.209	
	848919	17.400	15.050		0.156	
						0.143
12.5.6	631745	03.70	04.453	0.150		
	631746	03.50	04.353	0.196		
	631748	17.70	15.050		.176	
						0.174
12.6.6	968190	04.000	04.353	0.081		
	968191	04.300	04.353	0.012		
	968192	18.700	15.050		0.243	
	968194	18.600	15.050		0.236	
						0.143
13.1.6	513695	15.300	15.273		0.002	
BHVWF	513696	14.800	15.273		0.031	
	513697	14.000	15.086		0.072	
	513698	14.200	15.086		0.059	
						0.041

*Failure Value (i.e., > 0.250)

TABLE 10 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
13.2.6	794645	14.700	15.273		0.038	
BTDMJ	794646	15.800	15.273		0.034	
	794648	15.000	15.086		0.006	
	794649	14.700	15.086		0.026	
						0.026
13.3.6	431540	14.300	15.273		0.064	
BVDLB	431541	14.400	15.273		0.057	
	431543	13.400	15.086		0.112	
	431544	13.700	15.086		0.092	
						0.081
13.4.6	620610	15.000	15.273		0.018	
THHTJ	620611	12.000	15.273		0.214	
	620613	13.000	15.086		0.138	
	620614	14.000	15.086		0.072	
						0.111
13.5.6	950085	14.900	15.273		0.024	
TFBMW	950086	15.100	15.273		0.011	
	950087	13.800	15.086		0.085	
	950088	14.200	15.086		0.059	
						0.045
13.6.6	838065	14.800	15.273		0.031	
TMZZZ	838066	14.800	15.273		0.031	
	838068	14.900	15.086		0.012	
	838069	14.000	15.086		0.072	
						0.037
14.1.1	275540	05.100	05.394	0.054		
HSMJS	275541	05.100	05.394	0.054		
	275542	15.000	15.839		0.053	
	275544	14.600	15.839		0.078	
						0.060
15.1.1	277280	15.100	15.588		0.031	
HMZJT	277281	15.100	15.588		0.031	
	277282	16.100	15.671		0.027	
	277283	15.200	15.671		0.030	
						0.030

*Failure Value (i.e., > 0.250)

TABLE 11 - EPA/RMPP ROUND 6 SHORT-TERM BLIND TEST RESULTS

SET NO. CODE	Detector Number	Measured Conc. (Mc) (pCiL^{-1})	Target Conc. (Tc) (pCiL^{-1})	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
1.1.1	787290	11.200	11.397		0.017	
SMBHL	787291	10.400	11.397		0.087	
	787292	10.500	11.829		0.112	
	787293	11.700	11.829		0.011	
						0.057
2.1.4	779330	05.200	05.518	0.058		
DFTHT	779331	04.500	05.518	0.185		
	779333	11.000	12.735		0.136	
	779334	10.700	12.735		0.160	
						0.135
2.2.4	150990	05.200	05.518	0.058		
FVDHW	150991	04.600	05.518	0.166		
	150992	11.900	12.735		0.066	
	150993	10.900	12.735		0.144	
						0.108
2.3.4	270715	07.800	05.518	0.414		
SBFBT	270716	07.800	05.518	0.414		
	270717	13.000	12.735		0.021	
	270719	13.400	12.735		0.052	
						0.255*
2.4.4	603005	05.200	05.518	0.058		
ZJMHS	603006	05.700	05.518	0.033		
	603007	11.700	12.735		0.081	
	603009	11.400	12.735		0.105	
						0.069
3.1.1	179085	19.200	13.124		0.463	
JWMVS	179086	23.500	13.124		0.791	
	202230	06.600	05.394	0.224		
	202231	04.100	05.394	0.240		
						0.429*
4.1.2	862590	04.500	04.802	0.063		
ZDSTB	862591	03.800	04.802	0.029		
	862593	13.500	14.095		0.042	
	862594	12.700	14.095		0.099	
						0.103

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
5.1.3	716570	05.200	05.200	0.000		
JJHBL	716571	04.500	05.202	0.135		
	716572	16.400	14.136		0.060	
	716574	14.300	14.136		0.012	
						0.077
5.2.3	416995	04.000	05.202	0.231		
TTLLW	416696	04.300	05.202	0.173		
	416698	13.000	14.136		0.080	
	416699	13.200	14.136		0.066	
						0.138
5.3.3	391415	04.600	05.202	0.116		
	391416	04.600	05.202	0.116		
	391417	13.800	14.136		0.024	
	391419	13.800	14.136		0.024	
						0.076
6.1.8	682675	02.600	02.602	0.001		
FTZTB	682676	02.500	02.602	0.039		
	682678	12.400	14.149		0.124	
	682679	12.100	14.149		0.145	
						0.077
6.2.8	809470	02.400	02.602	0.078		
FZLBL	809471	02.900	02.602	0.115		
	809473	14.200	14.149		0.004	
	809474	14.700	14.149		0.039	
						0.059
6.3.8	299660	03.700	02.602	0.422		
LVBWB	299661	02.100	02.602	0.193		
	299662	13.700	14.149		0.032	
	299663	13.500	14.149		0.046	
						0.173
6.4.8	791155	02.000	02.602	0.231		
SFZLV	7991156	02.400	02.602	0.078		
	791157	11.900	14.149		0.159	
	791159	12.900	14.149		0.088	
						0.139
6.5.8	887200	02.000	02.602	0.231		
TDHJZ	887201	02.000	02.602	0.231		
	887202	13.100	14.149		0.074	
	887204	13.100	14.149		0.074	
						0.153

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) (pCiL^{-1})	Target Conc. (Tc) (pCiL^{-1})	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
6.6.8	172820	02.300	02.602	0.116		
WFZVF	172821	02.400	02.602	0.078		
	172822	13.300	14.149		0.060	
	172824	13.900	14.149		0.018	
						0.068
6.7.8	594780	03.300	02.602	0.268		
WLMTJ	594781	02.300	02.602	0.116		
	594782	11.800	14.149		0.166	
	594783	13.900	14.149		0.018	
						0.129
6.8.8	760765	02.800	02.602	0.076		
HSWFS	760766	02.100	02.602	0.193		
	760767	13.500	14.149		0.046	
	760768	13.500	14.149		0.046	
						0.090
7.1.11	330110	02.900	03.512	0.174		
FFVDZ	330111	02.900	03.512	0.174		
	330112	17.500	14.283		0.225	
	330113	15.700	14.283		0.099	
						0.168
7.2.11	338420	05.700	03.512	0.623		
HLVZZ	388421	03.000	03.512	0.146		
	388423	15.300	14.283		0.071	
	388424	16.900	14.283		0.183	
						0.256*
7.3.11	445460	04.400	03.512	0.253		
SDMWH	445461	03.200	03.512	0.089		
	445462	16.400	14.283		0.148	
	445464	16.300	14.283		0.141	
						0.158
7.4.11	581950	02.500	03.512	0.288		
THLZJ	581951	02.400	03.512	0.317		
	581952	16.000	14.283		0.120	
	581953	16.411	14.283		0.127	
						0.213
7.5.11	955745	03.000	03.512	0.146		
TSVTB	955746	03.000	03.512	0.146		
	955747	13.300	14.283		0.069	
	955748	14.000	14.283		0.020	
						0.095

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
7.6.11	259300	04.500	03.512	0.281		
VLDSZ	259301	03.500	03.512	0.003		
	259302	15.000	14.283		0.050	
	259304	15.000	14.283		0.050	
						0.096
7.7.11	830825	02.400	03.512	0.317		
WJJZB	830826	02.500	03.512	0.288		
	830827	15.000	14.283		0.050	
	830829	15.000	14.023		0.050	
						0.176
7.8.11	178715	02.900	03.512	0.174		
ZHMWB	178716	02.800	03.512	0.203		
	178718	14.600	14.283		0.022	
	178719	15.500	14.283		0.085	
						0.121
7.9.11	129755	02.800	03.512	0.203		
WWTSD	129756	02.800	03.512	0.203		
	129758	17.800	14.283		0.246	
	129759	17.000	14.283		0.190	
						0.211
7.10.11	231525	03.000	03.512	0.146		
TVDJZ	231526	02.900	03.512	0.174		
	231527	17.500	14.283		0.225	
	231528	18.100	14.283		0.267	
						0.203
7.11.11	873180	02.900	03.512	0.174		
TLSMW	873181	04.400	03.512	0.253		
	873183	15.700	14.283		0.099	
	873184	17.400	14.283		0.218	
						0.186
8.1.3	765170	02.300	02.775	0.171		
BBMLF	765171	02.200	02.775	0.207		
	765173	12.900	14.347		0.101	
	765174	14.500	14.347		0.011	
						0.122
8.2.3	778150	03.200	02.775	0.153		
BVLBM	778151	02.200	02.775	0.207		
	778153	13.900	14.347		0.031	
	778154	14.800	14.347		0.032	
						0.106

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
8.3.3	279330	02.400	02.775	0.135		
WBBWM	279331	02.300	02.775	0.171		
	279332	13.800	14.347		0.038	
	279334	13.500	14.347		0.059	
						0.101
9.1.5	172900	06.900	06.304	0.095		
FVBBB	172901	06.100	06.304	0.032		
	172903	14.300	14.562		0.018	
	172904	13.800	14.562		0.052	
						0.049
9.2.5	980975	06.100	06.304	0.032		
JLSVJ	980976	04.900	06.304	0.223		
	980977	14.500	14.562		0.004	
	980979	13.400	14.562		0.080	
						0.085
9.3.5	686575	05.300	06.304	0.159		
LZMDM	686576	05.200	06.304	0.175		
	686577	15.400	14.562		0.058	
	686578	13.800	14.562		0.052	
						0.111
9.4.5	179885	05.800	06.304	0.080		
WMDFF	179856	05.100	06.304	0.191		
	179857	13.600	14.562		0.066	
	179879	12.900	14.562		0.114	
						0.113
9.5.5	818095	05.800	06.304	0.080		
ZSMHM	818096	05.200	06.304	0.175		
	818097	12.600	14.562		0.135	
	818098	15.400	14.562		0.058	
						0.112
10.1.1	402415	04.400	04.385	0.003		
WMMDT	402416	04.400	04.385	0.003		
	402417	14.200	14.672		0.033	
	402419	14.200	14.692		0.033	
						0.018

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
11.1.1	787015	07.400	04.555	0.625		
MDFSD	787016	05.000	04.555	0.098		
	787017	14.200	14.929		0.049	
	787018	14.900	14.929		0.002	
						0.193
12.1.14	354315	02.700	03.019	0.106		
FFBLL	354316	02.400	03.019	0.205		
	354317	14.400	15.064		0.044	
	354319	13.500	15.064		0.104	
						0.115
12.2.14	485475	01.800	03.019	0.404		
DLBZM	485476	02.300	03.019	0.238		
	485477	14.600	15.064		0.031	
	485479	15.500	15.064		0.029	
						0.175
12.3.14	193930	02.900	03.019	0.040		
DMJDL	193931	02.900	03.019	0.040		
	193932	14.000	15.064		0.071	
	193933	15.300	15.064		0.016	
						0.041
12.4.14	464230	03.400	03.019	0.126		
HBHDB	464231	02.700	03.019	0.106		
	464233	14.200	15.064		0.057	
	464234	14.300	15.064		0.051	
						0.085
12.5.14	395110	02.100	03.019	0.304		
LHMVW	395111	02.600	03.019	0.139		
	395112	15.000	15.064		0.004	
	395114	15.200	15.064		0.009	
						0.114
12.6.14	832350	02.600	03.019	0.139		
LSWDW	832351	02.500	03.019	0.139		
	832353	14.500	15.064		0.037	
	832354	14.200	15.064		0.057	
						0.101
12.7.14	215305	02.600	03.019	0.139		
SZTVV	215306	02.200	03.019	0.271		
	215308	14.900	15.064		0.011	
	215309	14.700	15.064		0.024	
						0.111

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
12.8.14	163305	02.500	03.019	0.172		
TBJHZ	163306	02.300	03.109	0.238		
	163308	15.900	15.064		0.055	
	163309	15.000	15.064		0.004	
						0.117
12.9.14	149180	02.500	03.019	0.172		
TWBFB	149181	02.400	03.019	0.205		
	149182	16.000	15.064		0.062	
	149183	15.500	15.064		0.029	
						0.117
12.10.14	648295	02.400	03.019	0.205		
TWFHW	648296	02.300	03.019	0.238		
	648297	15.600	15.064		0.036	
	648298	15.000	15.064		0.004	
						0.121
12.11.14	731885	02.300	03.019	0.238		
VZHJD	731886	02.300	03.019	0.238		
	731888	14.000	15.064		0.071	
	731889	14.800	15.064		0.018	
						0.141
12.12.14	203865	02.300	03.019	0.238		
WMBVV	203866	02.000	03.019	0.338		
	203867	15.300	15.064		0.016	
	203868	15.000	15.064		0.004	
						0.149
12.13.14	353705	03.300	03.109	0.093		
ZDFLT	353706	03.100	03.019	0.027		
	353707	14.000	15.064		0.071	
	353708	14.500	15.064		0.037	
						0.057
12.14.14	199910	02.300	03.019	0.238		
ZSLDZ	199911	02.100	03.019	0.304		
	199913	13.600	15.064		0.097	
	199914	14.100	15.064		0.064	
						0.176
13.1.8	219870	05.400	04.547	0.188		
HBHHL	219871	05.000	04.547	0.100		
	219876	19.700	15.073		0.307	
	219874	20.800	15.073		0.380	
						0.244

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
13.2.8	597660	04.000	04.547	0.120		
HTTBD	597661	04.500	04.547	0.010		
	597662	19.200	15.073		0.274	
	597663	20.900	15.073		0.387	
						0.198
13.3.8	515985	03.800	05.547	0.164		
JTLDS	515986	04.100	04.547	0.098		
	515987	17.500	15.073		0.161	
	515989	19.300	15.073		0.280	
						0.176
13.4.8	922215	00.000	Damaged	Damaged		
MBZDL	922216	03.800	04.547	0.164		
	922217	25.300	15.073		0.670	
	922218	22.500	15.073		0.493	
						0.445*
13.5.8	655510	03.100	04.418	0.298		
VDJBZ	655511	03.100	04.418	0.298		
	655513	22.700	15.073		0.506	
	655514	25.200	15.073		0.672	
						0.444*
13.6.8	149105	03.300	04.547	0.274		
VVHWJ	149106	03.200	04.547	0.296		
	149107	23.800	15.073		0.579	
	149109	24.800	15.073		0.645	
						0.449*
13.7.8	729895	03.400	04.547	0.252		
ZDBVT	729896	03.400	04.547	0.252		
	729898	17.700	15.073		0.174	
	729899	17.600	15.073		0.168	
						0.212
13.8.8.	866605	04.000	04.547	0.120		
ZJWJW	866606	04.600	04.547	0.012		
	866607	20.500	15.073		0.360	
	866608	19.700	15.073		0.307	
						0.200
14.1.1	843975	14.700	15.273		0.038	
BDMTF	843976	14.700	15.273		0.038	
	843978	14.100	15.086		0.065	
	843979	15.900	15.086		0.054	
						0.049

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
15.1.4	548175	01.900	02.949	0.356		
MHHZM	548176	02.000	02.949	0.322		
	548177	14.000	15.191		0.078	
	548178	15.000	15.191		0.013	
						0.192
15.2.4	497745	02.200	02.949	0.254		
WFBJM	497746	02.100	02.949	0.288		
	497747	14.400	15.191		0.052	
	497749	14.300	15.191		0.059	
						0.163
15.3.4	664085	02.500	02.949	0.152		
WMZLT	664086	02.300	02.949	0.220		
	664087	12.900	15.191		0.151	
	664088	14.900	15.191		0.019	
						0.136
15.4.4	523815	02.500	02.949	0.152		
BDZSS	523816	02.300	02.949	0.220		
	523817	15.000	15.191		0.013	
	523818	14.500	15.191		0.045	
						0.108
16.1.7	679595	04.300	04.418	0.027		
BSMWD	679596	03.900	04.418	0.117		
	679597	14.000	15.573		0.101	
	679599	15.000	15.573		0.037	
						0.070
16.2.7	871000	03.800	04.418	0.140		
HJTWT	871001	03.600	04.418	0.185		
	871002	15.100	15.573		0.030	
	871004	15.600	15.573		0.002	
						0.089
16.3.7	268970	03.600	04.418	0.185		
SZJHZ	268971	03.800	04.418	0.140		
	268972	14.500	15.573		0.069	
	268973	14.300	15.573		0.082	
						0.119
16.4.7	636350	04.200	04.418	0.049		
THTHF	636351	03.400	04.418	0.230		
	636353	15.400	15.573		0.011	
	636354	15.700	15.573		0.008	
						0.075

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
16.5.7	690170	03.900	04.418	0.117		
TVDLT	690171	03.600	04.418	0.185		
	690173	15.400	15.573		0.011	
	690174	16.000	15.573		0.027	
						0.085
16.6.7		03.600	4.418	0.185		
		09.000	4.418	0.095		
		16.800	15.573		.079	
		15.100	15.573		.030	
						.097
16.7.7	676545	03.500	04.418	0.208		
LLDHB	676546	03.700	04.418	0.163		
	676547	15.900	15.573		0.021	
	676548	16.200	15.573		0.040	
						0.108
17.1.2	768075	04.000	04.774	0.162		
LZFJF	768076	04.200	04.774	0.120		
	768077	14.300	15.783		0.094	
	768078	15.100	15.783		0.043	
						0.105
17.2.2	206310	06.100	04.774	0.278		
ZLMBZ	206311	05.200	04.774	0.089		
	206312	16.000	15.783		0.014	
	206313	14.500	15.783		0.081	
						0.116
18.1.4	742035	04.700	05.394	0.129		
HBDDL	742036	04.900	05.394	0.092		
	742037	14.800	15.839		0.066	
	742038	14.600	15.839		0.078	
						0.091
18.2.4	553440	04.400	05.394	0.184		
JMHHV	553441	04.600	05.394	0.147		
	553442	16.300	15.839		0.029	
	553443	14.900	15.839		0.059	
						0.105
18.3.4	761880	04.800	05.394	0.110		
LTJJZ	761881	04.600	05.394	0.147		
	761882	14.600	15.839		0.078	
	761884	14.400	15.839		0.091	
						0.107

*Failure value (i.e., > 0.250)

TABLE 11 (continued)

SET NO. CODE	Detector Number	Measured Conc. (Mc) ($pCiL^{-1}$)	Target Conc. (Tc) ($pCiL^{-1}$)	MARE For Tc's 2 - 5	MARE For TL's 12 - 17	MARE* MEAN
18.4.4	132825	04.500	05.394	0.166		
ZFMDD	132836	04.700	05.394	0.129		
	132827	14.700	15.839		0.072	
	132829	14.100	15.839		0.110	
						0.119

*Failure value (i.e., > 0.250)

TABLE 12 SUMMARY OF ROUND 6 E-PERM RESULTS*

TARGET RANGE (pCiL)	No. of E-PERMs Tested		Average E-PERM MARE	Overall E-PERM MARE
		SHORT-TERM		
2 to 5	157		0.169	0.118
12 to 15	158		0.067	
		LONG-TERM		
2 to 5	87		0.132	.104
12 to 15	126		0.085	
	518		OVERALL AVERAGE	0.112

*Only includes results voluntarily submitted by Rad Elec customers (45% of total E-PERMS tested in Round 6.

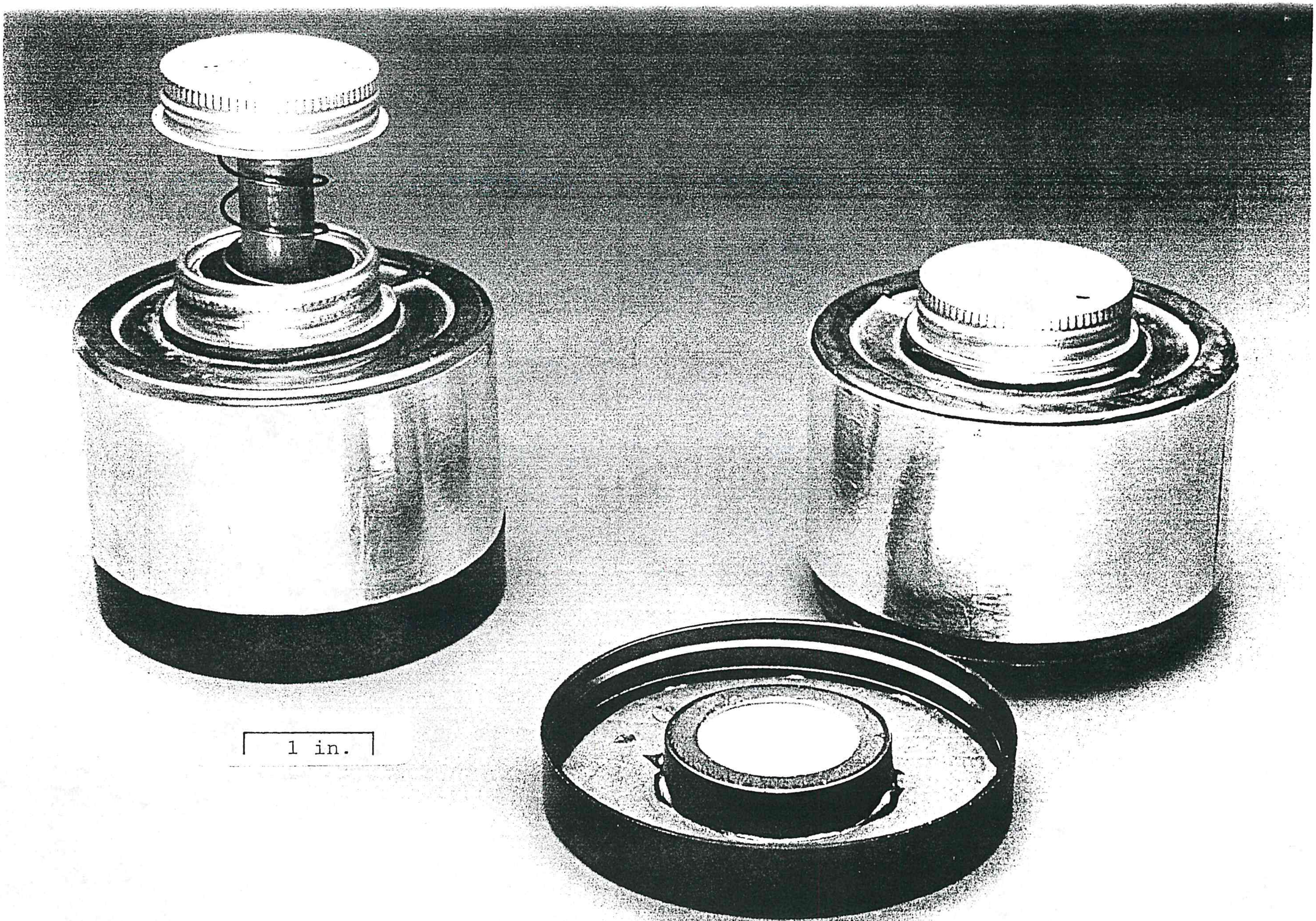


FIGURE 1 PHOTOGRAPH OF PROTOTYPE E-PERM

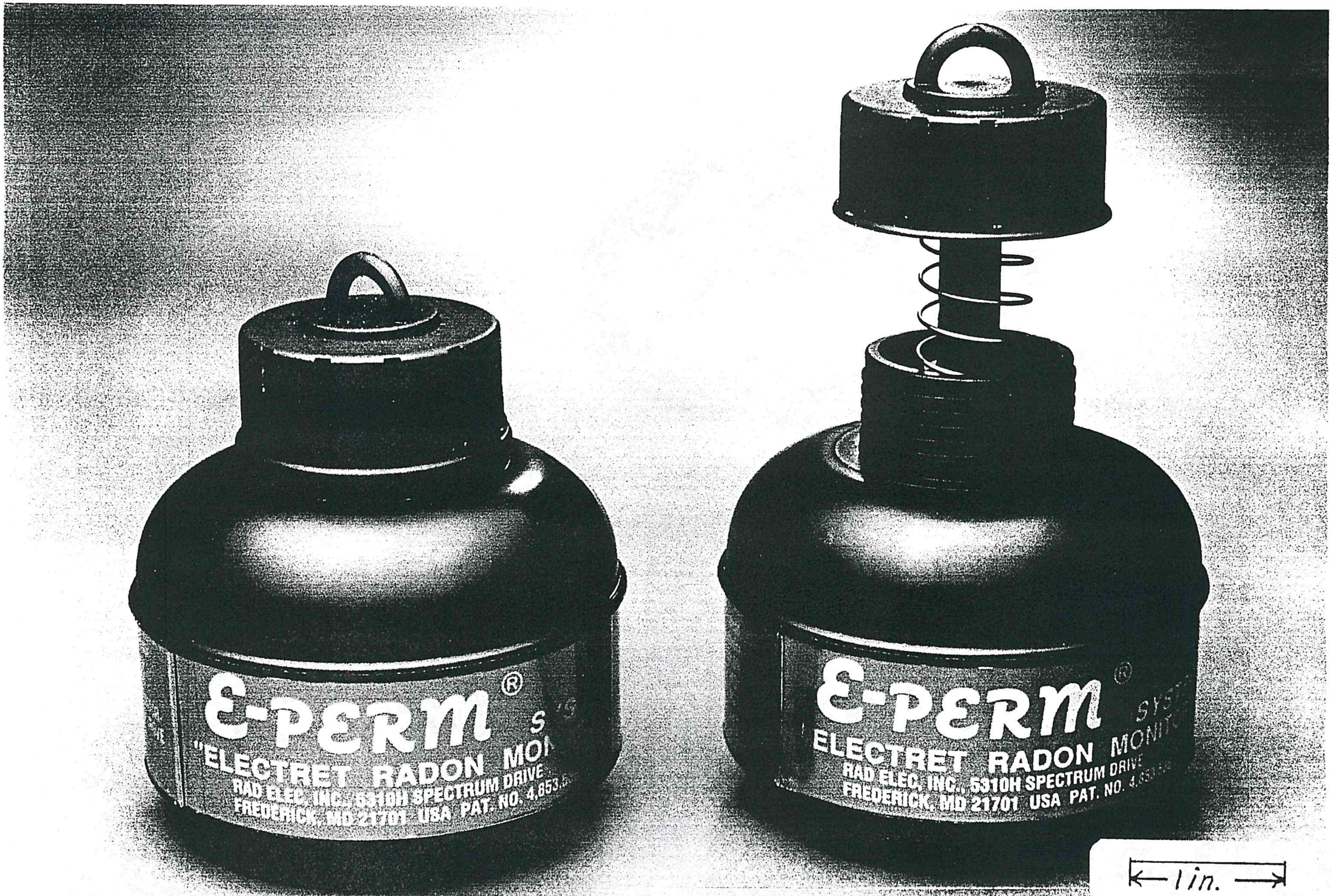


FIGURE 2 PHOTOGRAPH OF COMMERCIAL E-PERM

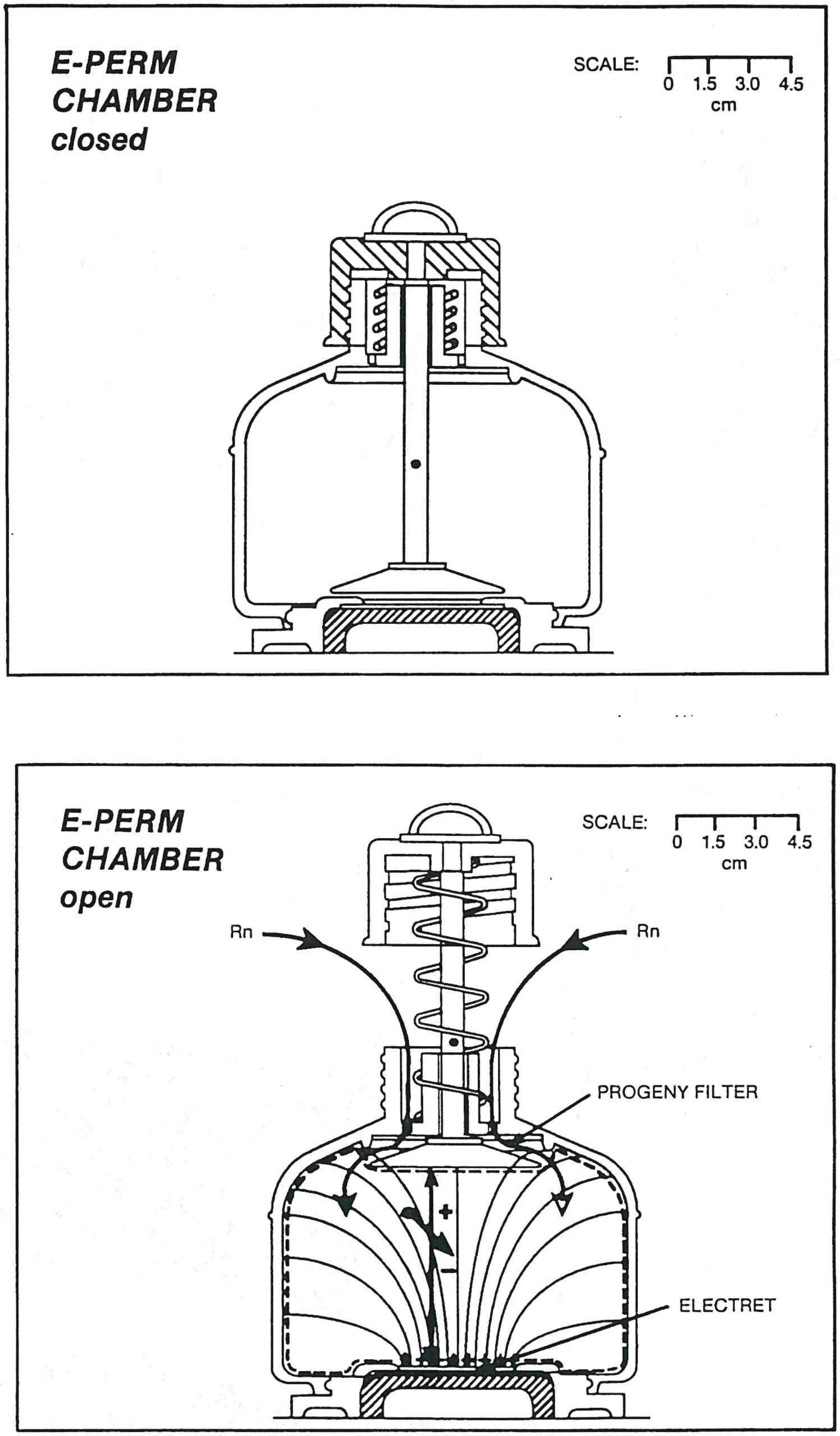


FIGURE 3 - SECTIONAL DRAWING OF E-PERM
IN THE OFF (TOP) AND ON (BOTTOM) POSITIONS

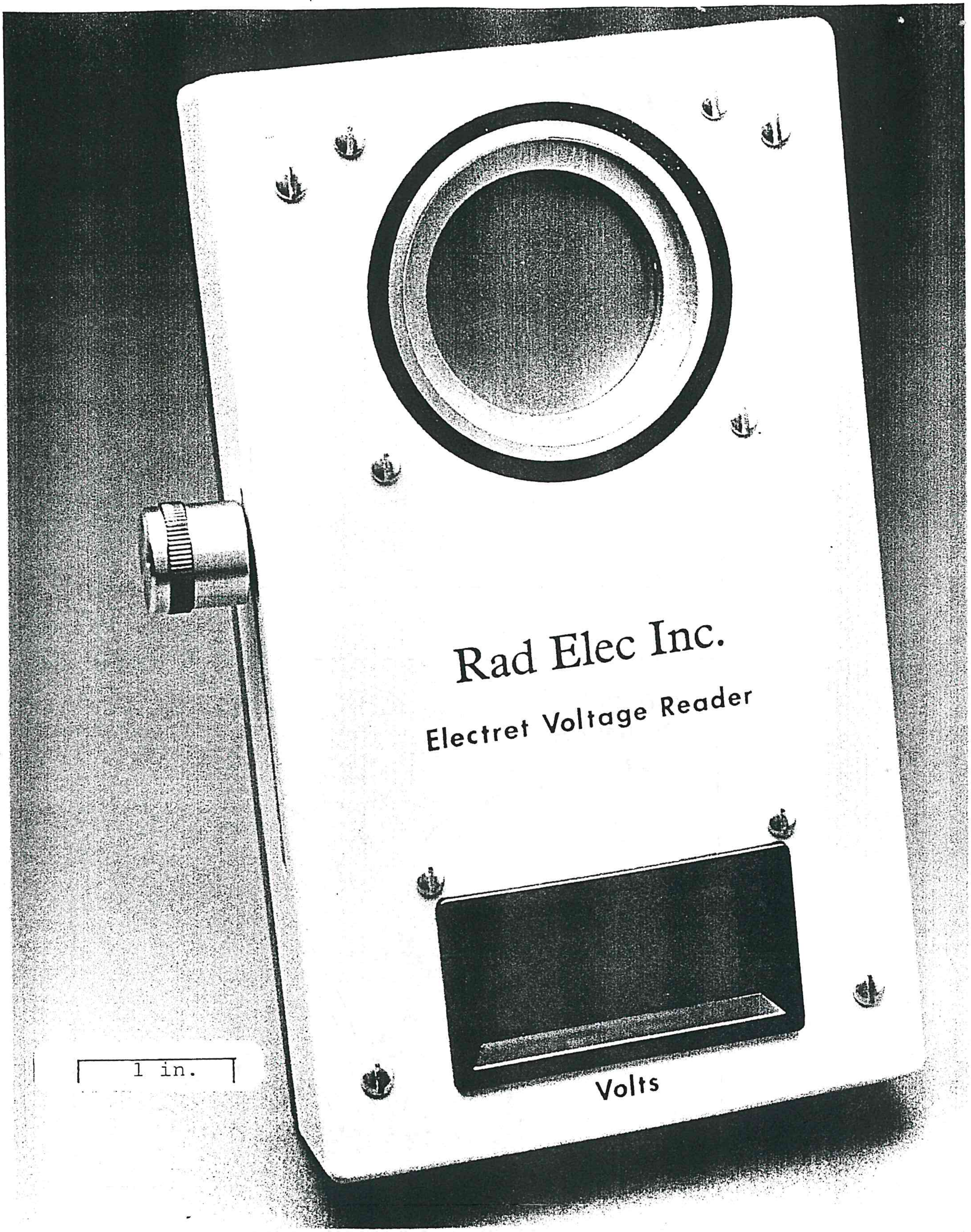


FIGURE 4 - PHOTOGRAPH OF THE SPER-1 ELECTRET READ-OUT INSTRUMENT

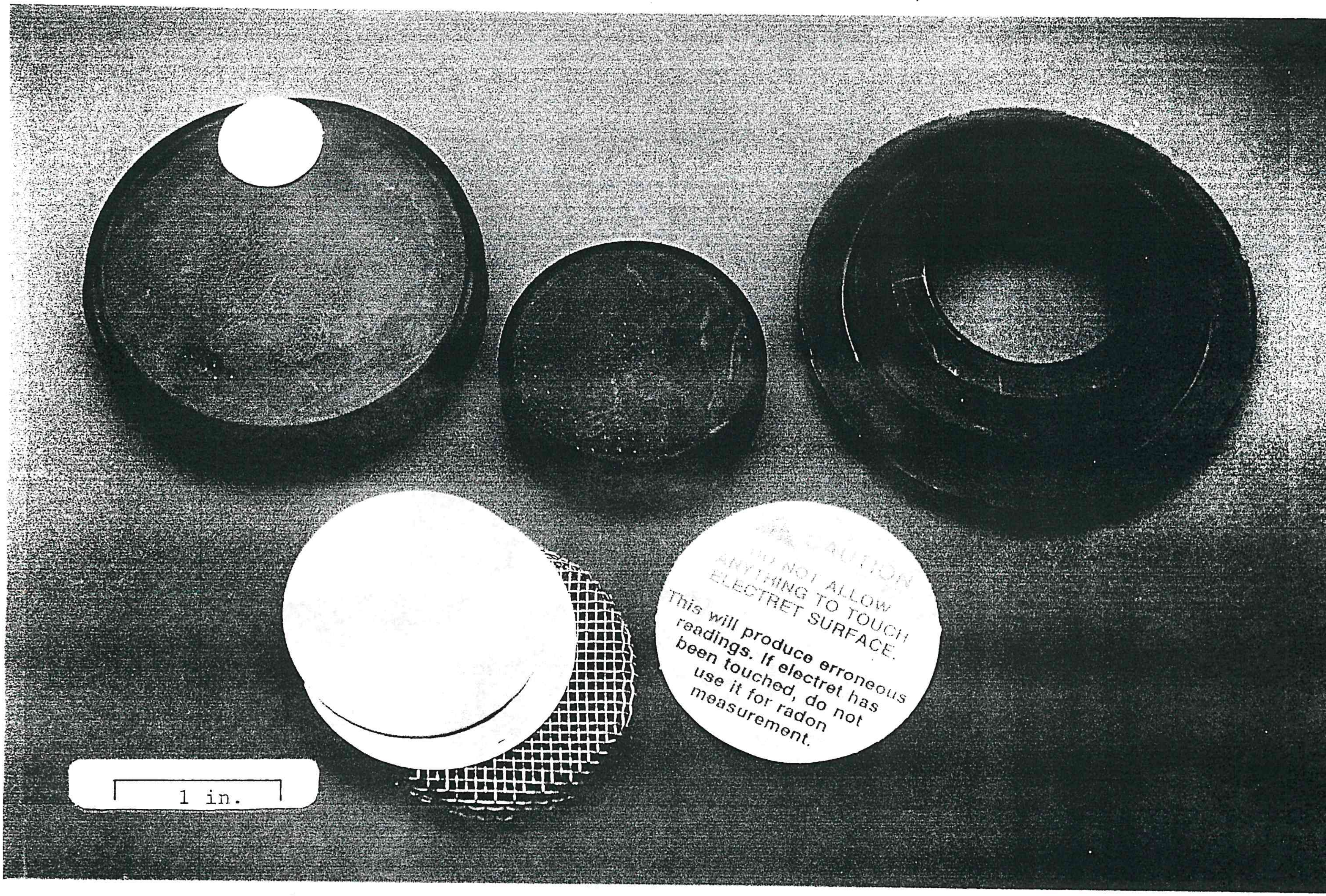


FIGURE 5 PHOTOGRAPH OF ELECTRET HOLDER COMPONENTS
(White Disk at lower left is the Electret)

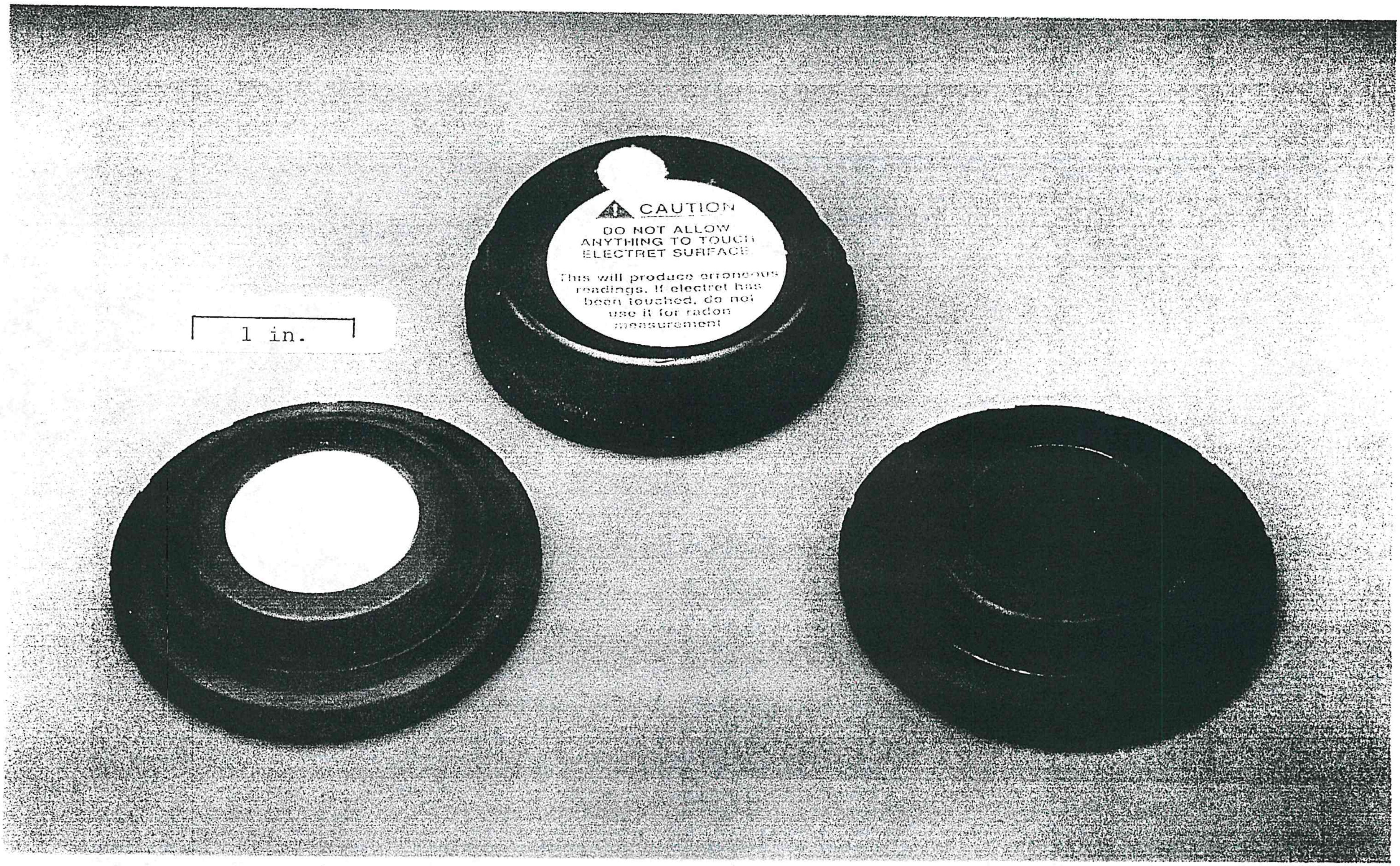


FIGURE 6 PHOTOGRAPH OF ASSEMBLED ELECTRET HOLDERS

FIGURE 7, CALIBRATION LINE FOR SHORT-TERM E–PERMS

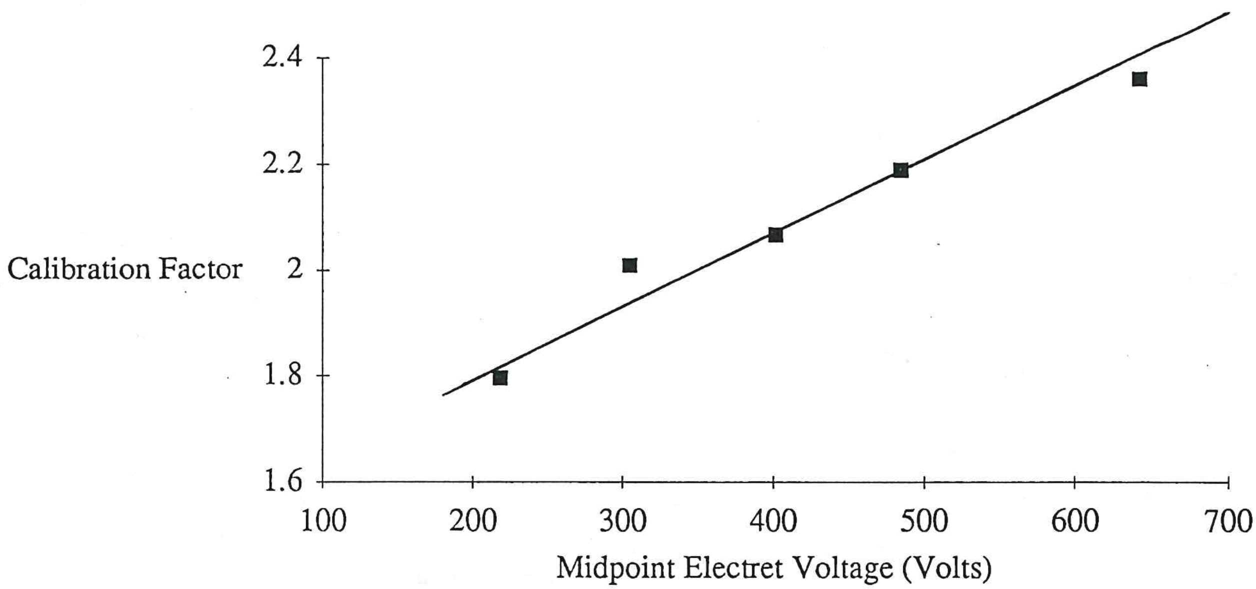
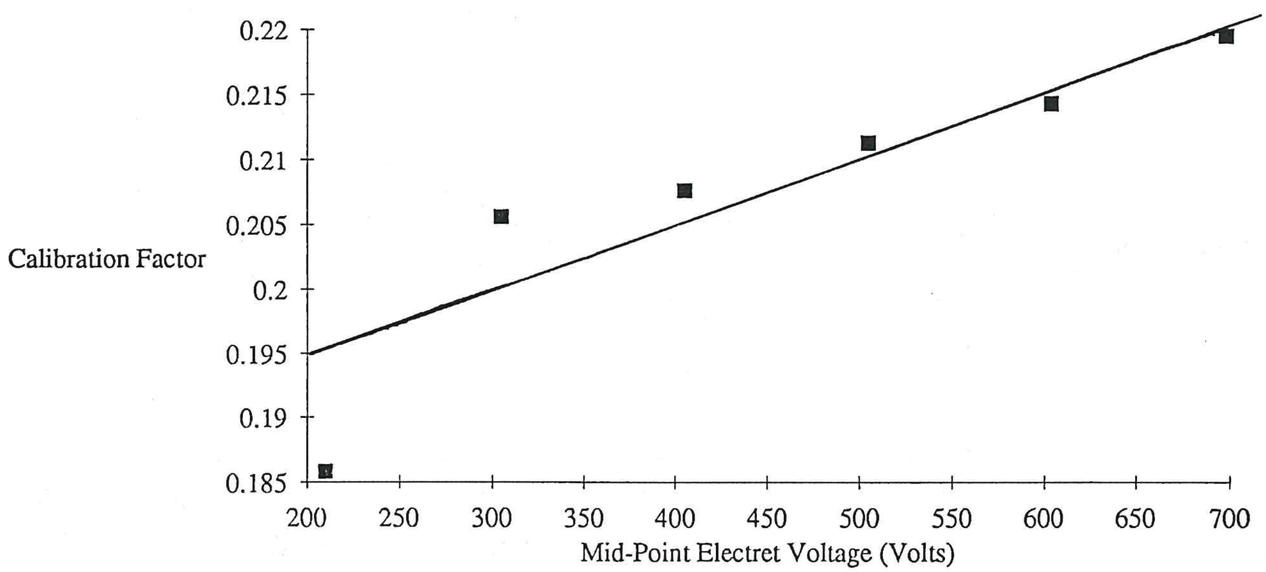


FIGURE 8, CALIBRATION LINE FOR LONG-TERM E–PERMS



SECTION 10

10.0 APPENDIX 1

Results of E-PERM Evaluations by Other

Several researchers in other laboratories have carried out extensive evaluations of E-PERMs and some have published. This Appendix presents, in summary form, the principle findings of eight of these evaluations. The Appendix is self-contained with respect to references and figures, and all are prefixed with the letter 'A' to avoid confusion with those in the main body of the report.

10.1 INDEX OF APPENDIX EVALUATIONS AND FIGURES

Section		Page Summary	Page Figure
10.1	Index	74	
10.2	Initial EPA E-PERM Evaluation	75	80
10.3	EPA Test of Long-Term E-PERMs vs. Alpha-Track Devices	75	81
10.4	Recent EPA Evaluation of Long and Short-Term E-PERMs	76	82
10.5	Pennsylvania DOH Double Blind Test Results	76	83
10.6	NY State DOH E-PERM Evaluation	77	84
10.7	Tests of E-PERMs vs. Charcoal Canister Tests by New York State Energy Authority	77	85
10.8	Results of Austrian Research Center E-PERM Evaluation	78	86
10.9	University of Iowa Double Blind Tests	78	87
10.10	Appendix References	87	

10.2 INITIAL EPA E-PERM EVALUATION

The initial EPA evaluation of the E-PERM system was conducted by R. Hopper (A 1) at the Las Vegas Facility in 1987. The E-PERMs evaluated were prototype units, the only type available at the time. They were fabricated from steel canisters. The units were tested over a wide range of radon concentrations, temperatures and humidities. The evaluation was carried out via mail, i.e., the E-PERMs were exposed by the EPA in Nevada and returned to Rad Elec in Maryland for read out. As seen in Figure A1, the results of the evaluation were very good and Hopper concluded that "These results demonstrate that this instrument can measure radon very accurately under varying conditions with very close agreement between replicate samples. The E-PERM performs well when exposed to both low and high radon concentrations." As a result of these tests, the EPA approved the entry of E-PERMs by any company into their RMP Program.

10.3 EPA EVALUATION OF LONG-TERM VS. ALPHA TRACK

A recent paper by R.J. Lyon, et al. (A2) of the USEPA compares three different makes of alpha track detectors and long-term E-PERMs in a double blind test. Three sets of exposure conditions were used to evaluate the effect of high concentrations (200 $pCiL^{-1}$ in a radon chamber) for short exposure periods (7 days) and low concentrations (7.6 and 6.2 $pCiL^{-1}$ of "naturally occurring" radon) for longer exposures (3 to 6 months). The results are shown in Figure A2. At least thirty of each type detector were exposed to each of the three sets of exposure conditions to arrive at the average concentration values shown.

The seven day exposures at the 200 pCiL-1 level were carried out to determine "whether a brief, high radon concentration will produce the same results as an extended exposure to a low radon concentration." The wide swings which occurred in the concentration of the "naturally occurring" radon (0.4 to 60 $pCiL^{-1}$) during the 180 day exposure period provided a good test of the signal integrating capability of both types of detectors tested. As seen, the E-PERMs responded more accurately than alpha-track devices to both sets of extreme exposure conditions. The EPA authors concluded that "The EIC (E-

PERMs) showed superior precision and accuracy as the exposure duration increased. In this study, device D (the E-PERM) was the most precise and accurate radon measuring device for long-term exposure conditions."

10.4 RECENT EPA EVALUATIONS OF LONG AND SHORT-TERM E-PERMS

Figure A3 presents the results of their evaluation of the Rad Elec calibration curves for short and long-term E-PERMs carried out by the EPA Las Vegas Laboratory.[(A3)] Six ranges of electret voltages were used with mid-point voltages (MPV) from 218 V through 719 V. As seen, the average error with respect to the EPA target concentration was -7.7% and the overall standard deviation was only 5.4%.

10.5 PENNSYLVANIA DOH DOUBLE BLIND TEST RESULTS

In late 1989, the Pennsylvania Department of Environmental Resources (DER) carried out a double-blind test of several radon monitoring companies and devices offered to the public in that state[(A4)]. The test included several types of short-term passive methods including open faced charcoal canisters, diffusion barrier charcoal method; alpha track detectors; short-term. E-PERM, long-term E-PERM, and short-term alpha track detectors. Figure A4 summarizes the results of these tests graphically by showing the high, low and median MARE values obtained with each. As seen, the median MARE values of 0.10 and 0.11 obtained for the long and short-term E-PERMs, respectively, were lower than those obtained with the other tested and the precision of the E-PERMs was substantially better. As a result of these and similar follow-up tests, the Pennsylvania DER ordered the manufacturers of some of the charcoal and alpha track devices tested to stop selling them in Pennsylvania and to report their inaccuracy to previous users.

10.6 NEW YORK STATE DEPARTMENT OF HEALTH E-PERM EVALUATION

J.M. Matuszek of the New York State Department of Health recently carried out an evaluation[(A5)] of both long and short-term E-PERMs. The study also evaluated some types of charcoal and alpha track devices. All of the devices were exposed to know concentrations in the DOE chamber at the Environmental Measurement Laboratory in New York City. The E-PERM results are shown in Figure A5. The overall average MARE values of 0.047 and 0.022 which were obtained for short and long-term E-PERMs, respectively show, excellent E-PERM accuracy (*MARE values up to 0.25 is considered "passing" in the EPA/RMP program).

The average MARE values shown in Figure A5 for the E-PERMs which were exposed for only one day are somewhat higher than the others. E-PERMs do not generate sufficient signal (electret voltage drop) in such a short exposure period to assure good accuracy. Also, it takes a few hours for the progeny to reach equilibrium in the E-PERM chamber which can cause a low reading in a one day exposure. For these reasons, current Rad Elec and EPA protocols expressly limit the minimum exposure time for short and long-term E-PERMs to 2 days and one month, respectively.

The author concludes that: "Electret detectors appear to provide a convenient, accurate and precise system for the measurement of radon concentration." The accuracy and precision of the results of the charcoal and alpha track monitors exposed simultaneously during the study were substantially less than for the E-PERMs and the author discusses the reasons for these shortcomings.

10.7 TESTS OF E-PERMS VS. CHARCOAL CANISTERS BY NEW YORK STATE ENERGY AUTHORITY

A complete E-PERM system with 40 E-PERMs was delivered to the New York State Research and Development Authority (NYSERDA) at the end of Phase 2 as part of the Agreement for this project. NYSERDA made the system available to the New York State Energy Authority and W.J. Condon, et al [(A6)] of that group carried out extensive field testing of the E-PERM vs.

open faced charcoal canisters The E-PERMs and canisters were sent by mail to several homeowners for simultaneous exposure side by side. Some of the homes were tested for two days and some for five days.

Figure A6 shows the results of these side by side exposures of charcoal canisters and E-PERMs. The wide divergence of some of the readings is typical of such comparison testing. Though there is no way to determine which values are correct, the canister readings are more suspect because of the many factors which affect the absorption of radon on charcoal. Variations in radon concentration, temperature, humidity, and air velocity during exposure all affect canister readings. None of these factors affect the response of E-PERMs. According to Matuszek [A5], charcoal canister results are heavily weighted toward the radon concentrations the charcoal "sees" toward the end of an exposure period. Different types and even different batches of charcoal must also be calibrated separately for their interdependent radon and moisture absorption characteristics.

10.8 AUSTRIAN RESEARCH CENTER SHORT-TERM E-PERM EVALUATION

H. Staatmann of the Austrian Research Centre at Seibersdorf, Austria recently carried out an independent evaluation of both short and long-term E-PERMs[A7]. Statmann exposed several E-PERMs to four different target concentrations ranging from 4.0 to 181.5 pCiL^{-1} and for four exposure periods ranging from 2.81 to 10.06 days. His results are presented in Figure A7. As seen, the average overall error was only –3.9% and the average statistical deviation was only 3.1%. A large ion chamber was used as the reference monitor for these tests.

10.9 UNIVERSITY OF IOWA DOUBLE BLIND TESTS

Figure A8 shows the results of a double blind test of four types of short-term passive monitors carried out by R.W. Field and B.C. Kross[A8] of the University of Iowa in the basement of a home. The various types of monitors evaluated in this study are shown. The E-PERMs used in this investigation were all sent to Iowa through the mail, exposed, and returned to Rad Elec in

Maryland for analysis. All of the other passive monitors tested (except the EPA canisters) were obtained by the investigators in local stores and returned to the manufacturer for analysis. Three different exposure periods (2, 5 and 7 days) were used to accommodate the instructions included with the various monitor types. A Fempto Tech continuous monitoring instrument which employs a passive ion chamber as the radon sensor was used as the reference monitor. The researchers estimated the accuracy of this instrument to be ± 10%.

The five short-term E-PERMs which were exposed in each of the three exposure periods all gave very good results, i.e., the average MARE values for the 2, 5, and 7 day E-PERM exposure groups were 0.045, 0.091 and 0.052, respectively, and the average standard deviations were 0.4%, 1.1% and 0.4%, respectively. The overall average E-PERM MARE was only 0.063 and the average E-PERM standard deviation was 7.3%. As seen, the E-PERM accuracies are much higher (better) than those for all but one of the seven other groups of monitors tested. It is interesting to note that the average MARE for the 15 EPA open faced canisters was only 0.264, which is higher than the maximum value (0.250) required to pass the EPA RMPP blind test.

FIGURE A1 INITIAL EPA E–PERM EVALUATION (1987)

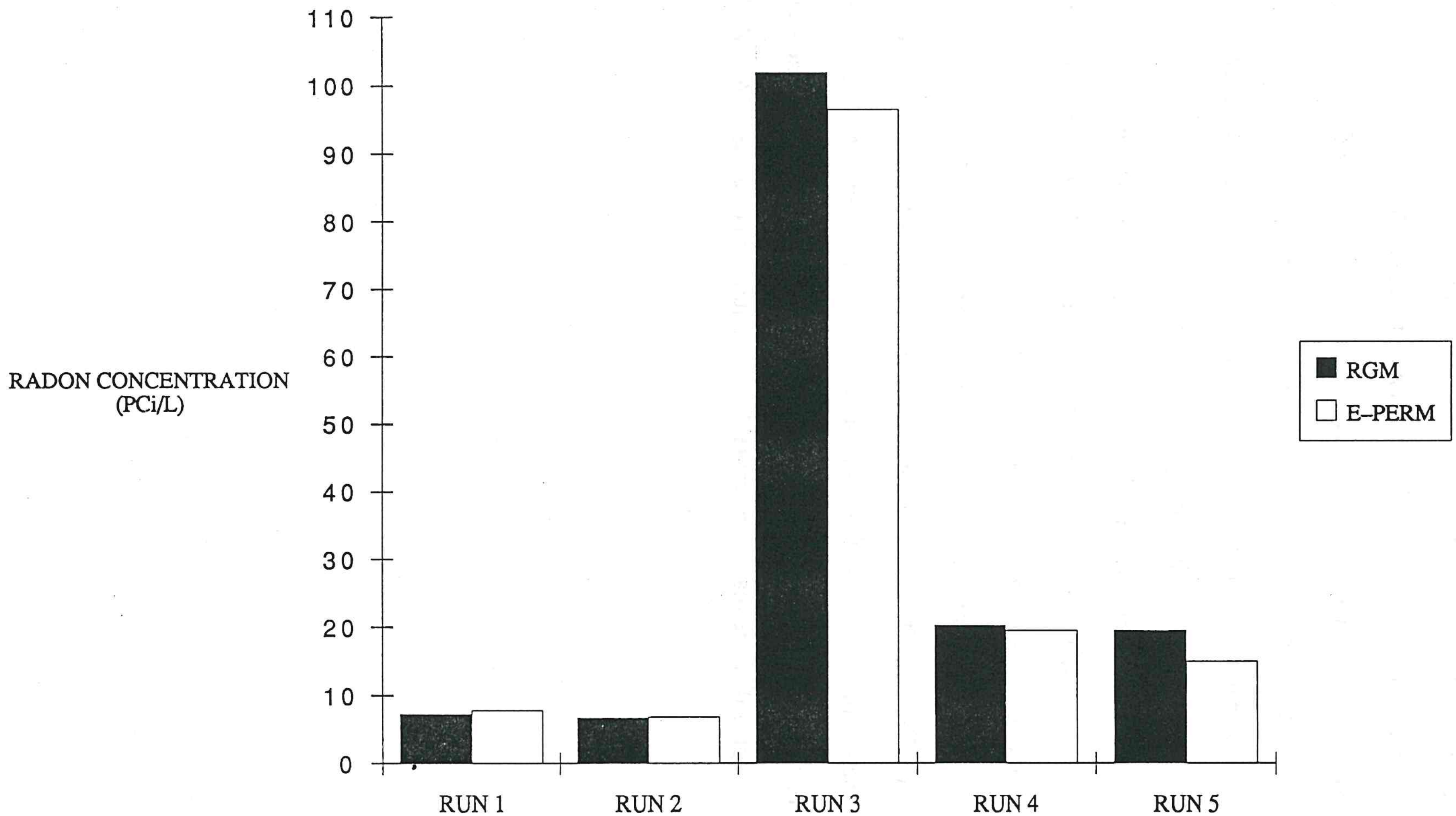


FIGURE A2 EPA TEST OF LONG-TERM E-PERMS VS. ALPHA TRACK DEVICES*

Exposure Period (days)	Target Conc. ($pCiL^{-1}$)	Min. Conc. ($pCiL^{-1}$)	Max. Conc. ($pCiL^{-1}$)	Mean Conc. ($pCiL^{-1}$)	SD (%)	Results with > 25% error (%)
			Alpha Track Device A			
7	200.0	84.0	1418.0	400.0	96	35
98	7.6	3.0	14.4	10.0	33	79
180	6.2	0.5	6.8	5.1	2.7	33
				Averages	43.9	49
			Alpha Track Device B			
7	200.0	78.0	282.0	164.0	30	65
98	7.6	2.3	10.0	6.1	30	46
180	6.2	3.8	9.2	6.8	20	36
				Averages	26.7	49
			Alpha Track Device C			
7	200.0	170.0	218.0	196.0	6	0
98	7.6	5.6	7.1	6.4	6	7
180	6.2	3.0	5.8	4.9	14	30
				Averages	8.7	12.3
			Long-Term E-PERM			
7	200.0	186.0	244.0	196.0	8	0
98	7.6	7.1	11.1	7.6	9	3
180	6.2	5.4	8.2	6.0	8	3
				Averages	8.3	2

* Carried out by R.J. Lyon ; et al.(A2) at the EPA Las Vegas Laboratory

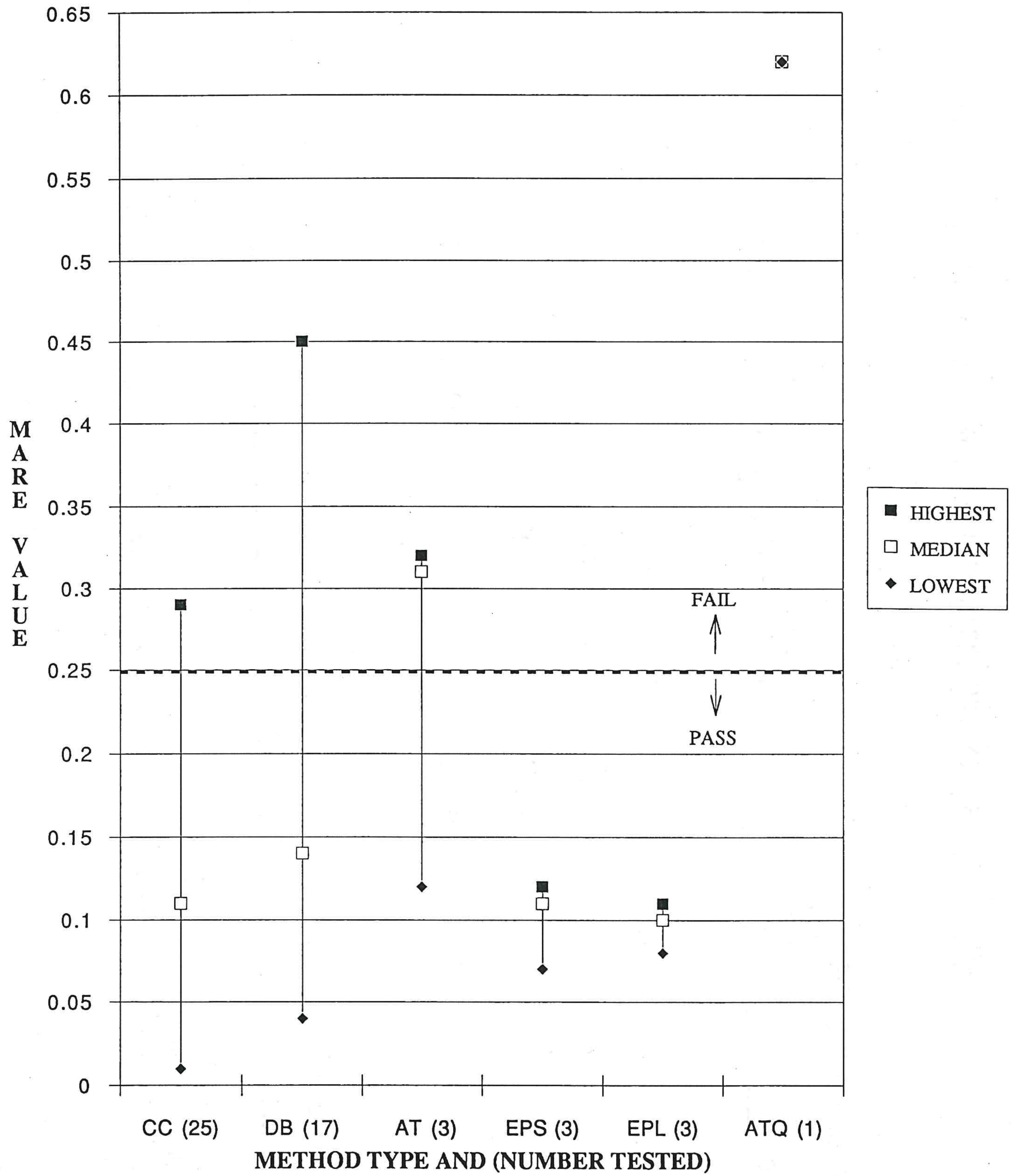
FIGURE A3 EPA EVALUATION OF LONG AND SHORT-TERM E-PERMS*

E-PERMS IN BATCH (NO.)	MPV* (Volts)	TARGET CONC. ($pCiL^{-1}$)	MEASURED CONC. ($pCiL^{-1}$)	AVG. MARE VALUE	SD (%)
		Short-Term E-PERMs			
4	693	15.8	15.6	.013	6.2
4	682	7.0	7.4	.057	1.9
5	596	41.5	36.2	.128	5.7
6	495	10.0	10.6	.060	7.5
6	397	22.1	22.3	.009	4.9
8	361	42.6	41.9	.016	6.0
5	315	16.0	17.1	.069	7.6
6	253	35.8	33.5	.064	4.2
6	183	34.9	32.7	.040	6.1
50		Averages		.034	5.6
		Long-Term E-PERMs			
3	719	11.4	13.2	.158	5.1
3	615	12.1	13.2	.091	4.4
3	513	12.7	13.2	.039	9.1
3	416	12.3	13.2	.073	5.3
3	316	12.8	13.2	.031	2.1
3	218	12.3	13.2	.073	4.2
18	Averages	12.3	13.2	.077	5.4

*Carried out at the USEPA Las Vegas Laboratory(A)

**Mid-point voltages of electrets

Figure A4 PENNSYLVANIA DOUBLE BLIND TEST



CC: open faced charcoal
DB: diffusion barrier charcoal
AT: alpha track

EPS: E–PERM short-term
EPL: E–PERM long-term
ATQ: short-term alpha track

FIGURE A5 NY STATE DOH E-PERM EVALUATION [a]

Exposure time (days)	E-PERMs Exposed (No.)	Reference value (pCi/l)	Short-term E-PERMs (pCi/l ± SD)	MARE[b] Value (ST Ave.)	Long-term E-PERMs (pCi/l ± SD	MARE[b] Value (LT Ave.)
1	3	41.1	35.6 ± 2.0	0.134[c]	30.3 ± 7.5	0.263[c]
3	2	42.5	39.7 ± 3.8	0.066	42.8 ± 1.2	0.007
4	3	42.0	40.3 ± 0.9	0.040	41.0 ± 2.3	0.024
5	3	44.4	43.6 ± 3.3	0.018	42.1 ± 2.1	0.052
7	3	43.6	42.6 ± 0.9	0.023	41.9 ± 0.6	0.039
Average MARE Values				0.037		0.031

a Performed by J. Matuszek (1)
b Added by Rad Elec
c Omitted from average MARE values because EPA E-PERM protocol requires more than 1 day exposure (see text)

Figure A6 NEW YORK STATE ENERGY AUTHORITY E-PERM VS. CHARCOAL EVALUATION

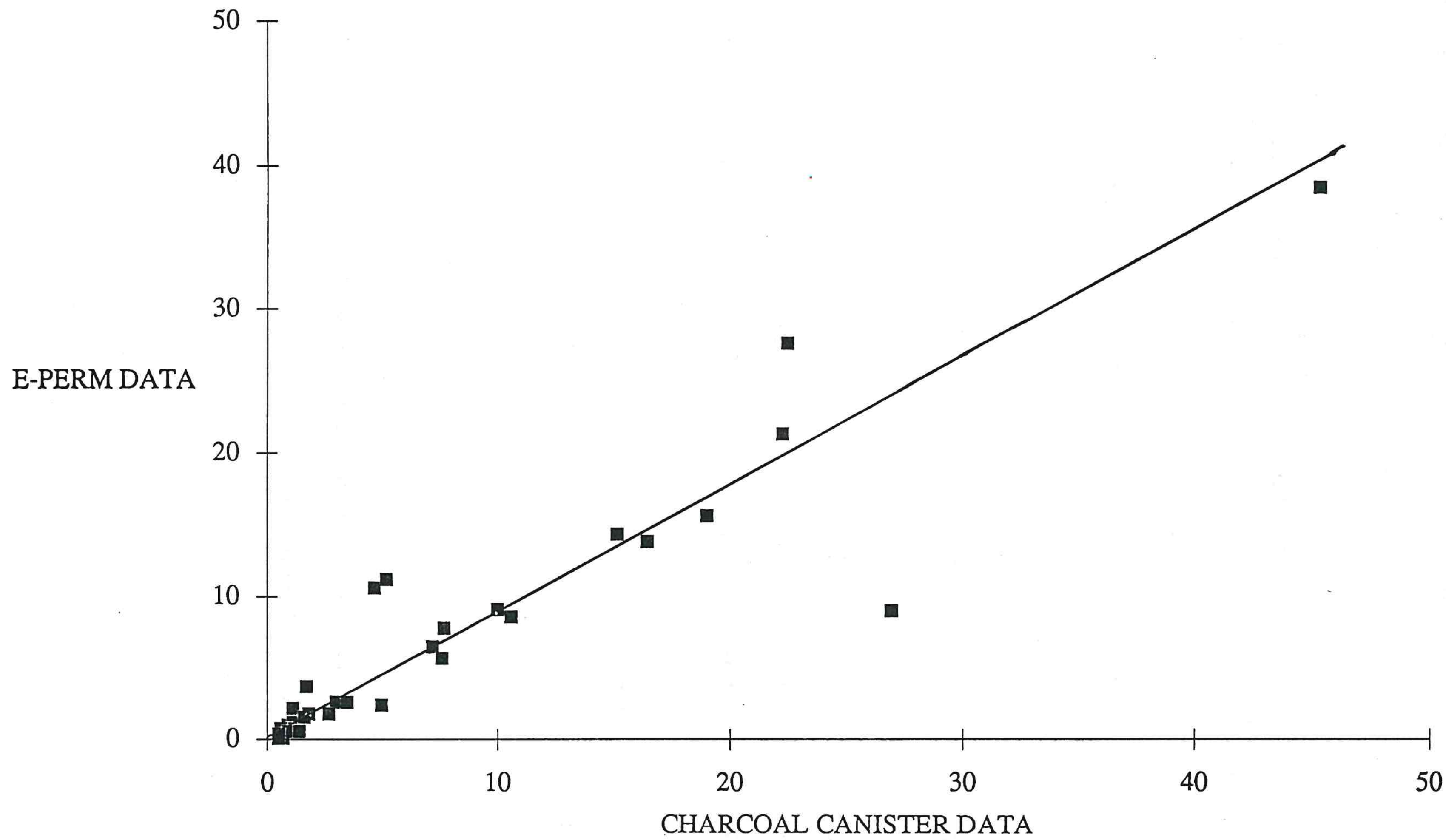


FIGURE A7 RESULTS OF AUSTRIAN RESEARCH CENTER E-PERM EVALUATION*

Electret Type**	Exposure (Days)	Target Concentration ($pCiL^{-1}$)	E-PERM Concentration ($pCiL^{-1}$)	Average Concentration ($pCiL^{-1}$)	SD (%)	Average Error (%)
LT	2.81	181.5	177.9			
LT	2.81	181.5	172.6	176.1	1.7	– 3.4
LT	4.93	75.1	72.8			
LT	4.93	75.1	73.0	72.9	0.2	– 2.8
ST	4.05	11.7	11.5			
ST	4.05	11.7	10.4			
ST	4.05	11.7	11.0	11.0	5.0	– 5.8
ST	10.06	4.0	4.0			
ST	10.06	4.0	3.6			
ST	10.06	4.0	3.9	3.8	5.5	– 3.5
				Averages	3.1	– 3.9

* Carried out by H. Statmann (A7) at Seibersdorf, Austria

**LT = long-term; ST = short-term

FIGURE A8 UNIVERSITY OF IOWA DOUBLE BLIND COMPARISONS*

Supplier	Detectors No. & (type*)	Exposure Period (days)	Target Radon Conc. ($pCiL^{-1}$)	Measured Radon Conc. $pCiL^{-1} \pm SD$	MARE Value
RAD ELEC, INC.	5 (EPS)	7	10.6	10.2 ± 0.4	0.045
AMER. RADON SERVICES	15 (DB)	7	10.6	10.8 ± 0.8	0.057
AIR CHECK INC.	15 (DB)	7	10.6	11.4 ± 1.1	0.098
THE RADON PROJECT	15 (DB)	7	10.6	10.5 ± 2.7	0.169
RAD ELEC, INC	5 (EPS)	5	10.6	10.1 ± 1.2	0.091
TERRADEX	15 (ATQ)	5	10.6	3.4 ± 1.7	0.679
RAD ELEC, INC.	5 (EPS)	2	9.2	9.6 ± 0.5	0.052
RYAN NUC. LABS	15 (CC)	2	9.2	11.0 ± 0.8	0.198
KEY TECH.	15 (CC)	2	9.2	10.3 ± 0.8	0.136
EPA	15 (CC)	2	9.2	11.6 ± 0.5	0.264

*Carried out by R.W. Field and B.C. Kross (A8)

**Open face charcoal canisters (CC); diffusion barrier charcoal canisters (DB); short-term alpha track detectors (ATQ), short-term E-PERMs (EPS)

10.10 APPENDIX REFERENCES

A1 Hopper, R.D.; Operational Evaluation of Electret Passive Environmental Radon Monitor (E-PERM). USEPA Report, Office of Radiation Programs, Las Vegas, NV, Sept. 1987.

A2 Lyon, R.J.; Hopper R.D.; Parks, B.S.; Dickson, M.; and Boyd, M; Accuracy and Precision of Passive Long-Term Radon Detectors as a Function of Concentration and Exposure Time. The 1990 International Symposium on Radon and Radon Reduction Technology; Atlanta, GA; Feb. 1990.

A3 Standard Operating Procedure for the E-PERM; Calibration and Performance Evaluation of Short-Term and Long-Term E-PERMs. SOP Rn/POS3; USEPA Office of Radiation Programs, Las Vegas, NV Facility; 1989.

A4 Gerusky, T.M.; Letter to all Pennsylvania DER certified radon measurement laboratories; Nov. 1989.

A5 Matuszek, J.M.; Hutchinson, J.A.; Lance, B.H.; Virgil, M.G. and Mahoney, R.J.; Standardization of radon measurements. Environmental International 14:371-378; 1988.

A6 Condon, W.J., Huang, J. and Rimawi, K.; Survey of Indoor Radon Levels in New York State and Evaluation of U.S. EPA Screening Protocols. New York Energy Authority Report 90-9, June 1990.

A7 Staatmann, H; Private Communication. Austrian Research Center, Seibersdorf, Austria. (Available from authors).

A8 Field, R.W. and Kross, B.C.; Field Comparison of Several Commercially Available Radon Detectors. AJPH Vol. 80, No. 9 , Sept. 1990.