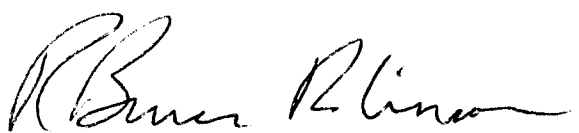


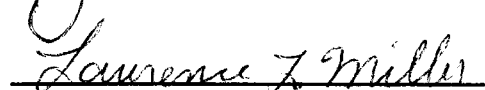
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The Evaluation of Electret Ionization Chambers
as a Field Screening Method for Samples Containing
Natural and Depleted Uranium

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Michael E. Murray

December 1994

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ABSTRACT

Electret ionization chambers have been experimentally evaluated as a field screening method for samples containing natural and depleted uranium. Correlation factors relating the electret's response to uranium standards were experimentally determined and tested. The method was tested on unknown samples in an environment similar to what is expected in radiological characterization studies. Results of the tests indicated this method gives satisfactory results provided sample preparation and ambient environmental conditions are satisfied. The loss of radon from the samples during sample collection and processing was investigated with regard to the decay and regrowth of radioactivity during the period of sample analysis by means of a computer code "EQUIL" developed during this work and by experimental methods. The experimental methods included 1) heating a uranium pitchblende standard and evaluating the changes in the radioactive daughters of radon and 2) agitating a pitchblende standard to simulate the mechanical processing and evaluating the changes in the radioactive daughters of radon. Both the heating and agitation were performed at extremes of normal procedures and for the standards tested no more than 10 percent of the radon was lost from the standards. Standards of 10, 30, 50, and 100 pCi g⁻¹ ²³⁸U were measured on multiple occasions for both natural and depleted uranium. The correlation factor for natural uranium was calculated to be 1.99 V d⁻¹/ pCi g⁻¹ . The correlation factor for depleted uranium was calculated to be 0.18 V d⁻¹/ pCi g⁻¹ . These correlation factors are specific to the type of electret, the sample size (20 g), the sample container and the nuclides studied.

TABLE OF CONTENTS

I. Introduction	1
II. Literature Review	5
Electret History	5
Related Applications	6
Fundamentals	6
Electret Ion Chambers	8
Related Work and Studies	10
Environmental Considerations for Electret Ion Chamber Use	10
Uranium's Physical Properties	13
Uranium's Radioactive Decay Properties	14
Radon	18
Uranium Standards Preparation	19
III. Materials and Equipment	21
The Electret Ion Chamber for Uranium in Soil Analysis	21
Uranium Standards	22
Equipment	26
General	26
Gamma Spectrometer	26
GM "Pancake" Detector	29
ZnS Detector	29
NaI Scintillation	30
Electret Reader	30
Environmental Monitoring Equipment	31
Sample Drying and Grinding Equipment	31
IV. Experimental Procedure and Data	32
Overview	32
Radon Loss Determination	32
Electret Response to Uranium Sources	41
Field Testing	54
Electret Reader Calibration Check	55
Electret Quality Control Check	55
Direct Radiation Measurements Using Portable Radiation Instruments	56
Ambient Environmental Conditions	60
V. Discussion of Results	58
Effects of Radon Loss	58
Interpretation of EQUIL Results	58
Radon Loss by Agitation	60
Radon Loss by Drying	60

Combined Losses	60
Electret's Response to Uranium in Soil	61
Results of Field Testing of the Electret Ionization Chambers	66
Results of Electret Quality Control Checks	70
Electret Reader Response Checks	71
Results of the Portable Radiation Survey Instrument Measurements	72
Lower Limit of Detection	73
Measurement Cost Estimates	74
VI. Conclusions	76
VII. Recommendations	78
List of References	79
APPENDICES	84
APPENDIX 1	85
APPENDIX 2	91
APPENDIX 3	97
APPENDIX 4	100
APPENDIX 5	102
VITA	106

LIST OF TABLES

<u>Table</u>	<u>Page No.</u>
1 The Uranium-238 decay series. Only the principal nuclides are given with averages given for particle energies.	15
2 Depleted uranium standards	23
3 Uranium standards from pitchblende.	24
4 Results of independent analysis of depleted uranium standards.	25
5 Results of independent analysis of uranium pitchblende standards.	25
6 Radioactive sources used.	25
7 Statistics for electret ionization chambers response to background radiation. . . .	44
8 Statistics for electret ionization chambers response to background radiation from soil.	45
9 Statistics for electret ionization chambers response to radiation from soil with 10 pCi/g of depleted uranium.	46
10 Statistics for electret ionization chambers response to radiation from soil with 30 pCi/g of depleted uranium.	47
11 Statistics for electret ionization chambers response to radiation from soil with 50 pCi/g of depleted uranium.	48
12 Statistics for electret ionization chambers response to radiation from soil with 100 pCi/g of depleted uranium.	49
13 Statistics for electret ionization chambers response to radiation from soil with 10 pCi/g of ^{238}U and all decay products.	50
14 Statistics for electret ionization chambers response to radiation from soil with 30 pCi/g of ^{238}U and all decay products.	51
15 Statistics for electret ionization chambers response to radiation from soil with 50 pCi/g of ^{238}U and all decay products.	52

TablePage No.

16	Statistics for electret ionization chambers response to radiation from soil with 100 pCi/g of ^{238}U and all decay products.	53
17	Results of the direct radiation measurements of the prepared uranium soil standards.	57
18	Summary of data used to correlate electret response to depleted uranium and uranium pitchblende standards.	64
19	Summary of the field screening results and comparison to laboratory gamma spectroscopy analysis.	68

LIST OF FIGURES

<u>Figure</u>	<u>Page No.</u>
1 Schematic of the electret materials and electrometer interface..	6
2 Electret ionization chamber.	21
3 Gamma ray spectrum of ^{238}U (depleted uranium) using a high purity germanium detector.	27
4 Gamma ray spectrum of the ^{238}U series using a high purity germanium detector.	28
5 Relative activities of radon and daughter products after a total loss of radon.	35
6 Relative activities of radon and daughter products after a 75% loss of radon.	36
7 Relative activities of radon and daughter products after a 25% loss of radon.	37
8 Total relative alpha activity vs. time for different retention percentages of radon in soil after an instantaneous release.	38
9 Measured ^{214}Pb radioactivity data following sample agitation and predicted ^{214}Pb radioactivity as a function of radon retention fractions.	40
10 Measured ^{214}Pb radioactivity data following sample drying and predicted ^{214}Pb radioactivity as a function of radon retention fractions.	42
11 Electret ionization chamber response to normal background radiation, no soil standard in place.	44
12 Electret ionization chamber response to normal background radiation from soil, no ^{238}U standard.	45
13 Electret ionization chamber response to soil with 10 pCi/g depleted uranium.	46
14 Electret ionization chamber response to soil with 30 pCi/g depleted uranium.	47

<u>Figure</u>	<u>Page No.</u>
15 Electret ionization chamber response to soil with 50 pCi/g depleted uranium.	48
16 Electret ionization chamber response to soil with 100 pCi/g depleted uranium.	49
17 Electret ionization chamber response to soil with 10 pCi/g uranium and all decay daughters.	50
18 Electret ionization chamber response to soil with 30 pCi/g uranium and all decay daughters.	51
19 Electret ionization chamber response to soil with 50 pCi/g uranium and all decay daughters.	52
20 Electret ionization chamber response to soil with 100 pCi/g uranium and all decay daughters.	53

I. Introduction

Beginning with the Manhattan Project and continuing through the Cold War, the United States mined and processed vast amounts of uranium. While many of the facilities were government owned, many were private industries and institutions that were contracted for their expertise. Uranium in the form of ore was liberally provided to research institutions for the development of more efficient methods of mechanically and chemically extracting the uranium. As a byproduct of the process to enrich ^{235}U , depleted uranium (material all most entirely ^{238}U , being depleted in ^{234}U and ^{235}U) became plentiful. The uranium metal was provided to many small machining and milling companies to shape the uranium metal into various components to support the United States' atomic energy programs (DOE 1980).

Even though security measures were stringent and health precautions were taken, residual uranium contamination still exists in and around some of these facilities. Much of the private contract work occurred in the 1940s and 1950s and many of the facilities have changed ownership or are being used for entirely different purposes. In 1974 the United States Congress instructed the Atomic Energy Commission (AEC) to locate the privately owned facilities and to determine if remedial action was required. In 1977 the Department of Energy (DOE) was established and assumed the responsibilities for the above mentioned actions.

As part of the decision to restore a site, the facility and surrounding area must be radiologically characterized as to the presence, nature, and extent of any uranium

contamination. The characterization process includes many direct measurements of emanating radiation and the collection, processing, and analysis of soil samples which is time consuming and expensive (Nuhfer 1992). The goal of this work is to develop and test a simple and inexpensive method for conducting field screening measurements of uranium contamination in soil samples. The method developed will meet the requirements set forth by DOE for analytical procedures (DOE 1992b).

The method developed by this work is based on using an electret configured to form an ionization chamber into which a sample is placed. The electret's electrostatic charge, indirectly measured in volts, is dissipated as radioactive decay particles ionize the air in the electret chamber and the electret collects the ions. Therefore, the change in the electret's static charge is proportional to the radioactive material present in the sample. While the electret ionization chamber responds to all ionizing radiation, the correlations developed by this work are specific to uranium and cannot be applied to any other radioactive materials.

The advantages to field screening methods are primarily related to the rapid information gained while the characterization work is in progress. The need to develop a new field screening method arises because the portable radiation survey instruments (i.e., geiger-muller, ZnS and NaI detectors) currently in use cannot quantify low concentrations of uranium in soil (in a timely manner) at the guideline levels established by the DOE (DOE 1992a). While the actual guideline for uranium contamination in soil is site specific (DOE 1992a), a typical value for ^{238}U is 30 pCi/g above the natural background (Rodriguez et al. 1992). As a result, soil samples are collected, transported

to a laboratory, processed, and analyzed. Subsequently, the samples are archived and/or disposed of as radioactive waste. Each of these steps are time consuming and expensive. While the characterization process depends on defensible analytical data, the quantity of samples may be reduced by employing an effective field screening method. Another advantage to the field engineer leading the characterization is to use field screening data to alter the sampling plan to collect additional samples when uranium concentrations are high or especially if uranium concentrations are near the cleanup guidelines. Much of the cost associated with characterization is the cost of mobilizing the sampling personnel and equipment (Roelant et al. 1993, Marchant 1993). The use of field screening in many instances may justify itself by negating multiple visits to remote sites. For these reasons, the EPA and DOE are encouraging field screening methods (Luftig 1993, Koglin 1993).

This work is directed toward correlating the electret's response to two common forms of uranium contamination encountered by the author and fellow investigators. A common form of uranium encountered is depleted uranium, that is ^{238}U and its first two daughters (all three with the same disintegrations per second per unit mass) and ^{235}U and ^{234}U (be present only in trace quantities). The other form of uranium encountered is that of uranium ore or ore bearing materials. In this case the entire ^{238}U decay series (to be discussed later), the ^{235}U decay series, and possibly (to a lesser degree) the thorium series, may be present as contaminants.

The essence of this thesis is to understand how uranium in soil effects the electret under specific conditions in order to correlate the electret's response to concentrations of ^{238}U in soil based on a fundamental understanding of the electret and the basic nuclear

decay properties of ^{238}U and its daughters. To accomplish this task, uranium standards in a soil matrix were prepared to cover the range of concentrations of interest and multiple measurements were taken using electret ionization chambers. Using the same uranium standards, measurements were also made with instruments typically used in the field during environmental characterization work.

II. Literature Review

Electret History

An electret is a dielectric material that can retain an electrical charge almost indefinitely. In 1885, Oliver Heaviside published a study of the possibility of producing permanently electrized bodies analogous to permanently magnetized bodies. In this theoretical exercise he suggested calling such bodies "electrets," a word that sounded like a proper electric counterpart of "magnets," (Jefimenko 1974). It was not until sometime between 1919 and 1925 that the Japanese scientist Mototaro Eguchi actually made the first electrets (Jefimenko 1974). Feynman (1977) described creating a simple electret by melting wax and putting a strong electric field on it while as a liquid. The dipole moments get partially aligned and remain that way when the liquid solidified. The solid material had a permanent polarization which remains when the field is removed. Eguchi's electrets were made very similar to that described by Feynman above. With the development of high dielectric fluorocarbon polymers such as TeflonTM ¹, electrets have become reliable and are capable of maintaining a constant electrostatic field even under high temperature and humidity conditions (Surette et al. 1993).

¹ Teflon is a registered trademark of E. I. DuPont de Nemours & Company Inc., Wilmington, DE 19898.

Related Applications

The first practical utilization of electrets occurred in the late 1940s and is attributed to the Japanese engineers who built condenser-type microphones. Electret microphones are commercially available and are noted for their exceptionally excellent electroacoustical characteristics. Until the late 1960s, a serious hinderance to the practical application of electrets was the lack of rigorous theory describing the fundamental phenomena responsible for the electret effect. There was, therefore, a certain reluctance on the part of both physicists and engineers to accept or to incorporate electrets as *bona fide* components for instruments and devices (Jefimenko 1974).

In the last 20 years, as the fundamental physics became more understood, a number of other electret devices have been developed. Among them are radiation detectors, dosimeters, memory storage units, humidity meters, air cleaners, vibration detectors, pressure gauges, electrostatic relays, current generators, voltage generators and electron beam deflectors (Jefimenko 1974). It is the ability to indirectly detect radiation that makes electrets useful in this study.

Fundamentals

While a detailed theoretical understanding of the electrostatic properties of electrets is not required for this work, a basic understanding is necessary in order to maximize the electret's capabilities. Sessler (1987) derived Equation 1 which predicts simple electret behavior. Figure 1 provides a schematic drawing of an electret indicating the parameters used in Equation 1.

$$V = \frac{\sigma}{\epsilon_0 (\epsilon_1/s_1 + \epsilon/s)} \quad \text{Equation 1}$$

Where:

- V = Potential voltage across an air gap of distance s_1 .
- s = Electret thickness. A value of 0.1 cm was used.
- σ = Surface charge distribution density.
- ϵ = Dielectric constant of the electret material. A value of 2.1 was used.
- ϵ_0 = Dielectric constant physical of space equal to 8.85×10^{-14} farad/cm.
- ϵ_1 = Dielectric constant of the air gap. A value of 1.0 was used.
- s_1 = Distance (1 cm) from the capacitance probe to the electret surface.

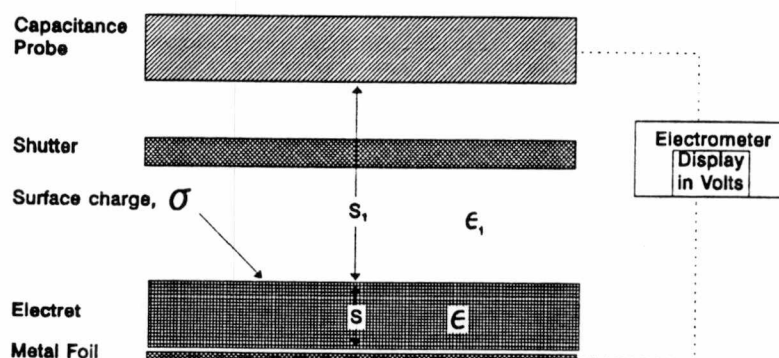


Figure 1 Schematic of the electret materials and electrometer interface. (Sessler and West 1971).

While these characteristics are important in designing and understanding the physics of the electret, the potential voltage (the quantity to be measured in this work) can be accurately determined at a specific location relative to the electret. For a thorough mathematical approach to electrets, the reader is referenced to Fallone and Podgorsak (1983) who used the theory of linear systems to derive the potential and electric fields in a spacial relationship in a cylindrical electret chamber. Though beyond the intended scope of this thesis, the work of Fallone and Podgorsak allows one to predict the electrostatic potential three dimensionally for an electret configuration and thus may prevent the electret user from operating on the fringes of the electret's stable electrostatic field. Basic to this work is understanding the operational characteristics and limitations of the electret ionization chambers selected for this work.

Electret Ion Chambers

Ion chambers have long been in use to measure radiation fields. The typical ion chamber utilizes a high voltage source applied across parallel plates. When ionizing radiation enters the chamber, ion pairs are produced and collected at the appropriate electrode. The resulting electrical current that occurs during ion collection can be amplified and recorded electronically with an electrometer (Turner 1986). The average energy to produce an ion pair is denoted as the W value. The W values for alpha and beta particles in air are 36 and 34 eV/ip, respectively. If the energies and number of the particles being emitted from a sample are known, then the number of electrons being produced can be determined.

In the case of an electret ionization chamber, where the high voltage source is a physical characteristic, rather than measuring the current, the decrease in the electret's electrostatic charge due to the collection of positive ions is measured. Since the number of particles emitted from a source is related to the source's radioactivity, it is possible to correlate the decreased electrostatic charge (measured indirectly in volts) per unit time to the radioactivity in a sample by use of Equation 2.

$$\frac{dV}{dT} \propto A \quad \text{Equation 2}$$

Where:

dV = Change in electrostatic potential (volts)

dT = Time differential for dV

A = Radioactivity in the sample

For a given set of circumstances, sample size, ion chamber dimensions, temperature, nuclides present, etc., a proportionality constant k may be determined experimentally and Equation 2 may be modified to give Equation 3. This work experimentally determines the k values for two common forms of uranium contaminating soil in the environment associated with present and past DOE operations.

$$\frac{dV}{dT} = kA \quad \text{Equation 3}$$

Related Work and Studies

Electrets have been used to create ion chambers for a about two decades. The literature was reviewed to find similar work and studies which would provide a foundation for this work and to take advantage of previous knowledge in designing this experimental work. The majority of the literature found dealt with using the electret ion chamber to measure the concentration of radon and thoron in air (Kotrappa et al. 1981 and 1982a, Sheets 1993, Soman 1982, EPA 1990). The electret ion chamber also provides a convenient tool to measure the radiation dose rate from x-rays and gamma radiation (Bauser and Ronge 1978, Pretzsch and Köstel 1984, Kotrappa et al. 1982b). The electret ion chamber has also been shown to be useful in quantifying radioactive surface contamination (Uda et al. 1985 and 1986, Gammage et al. 1993). Surette and Wood (1993) used a modified electret radon chamber to specifically measure tritium concentrations in air. While a significant amount of other work has been conducted with electret ion chambers, only these contained information relevant to this work.

Environmental Considerations for Electret Ion Chamber Use

As with any instrument or measurement technique, environmental factors must be considered during laboratory and field testing. For electrets, the ambient temperature, barometric pressure, humidity, and background radiation all have potential to alter the electret's response under specific circumstances. Each of these factors and their possible influence is discussed below.

Surette and Wood (1993) reported that Teflon™ electrets are reliable and capable of maintaining a constant electrostatic field even under high temperatures. Bauser and Ronge (1978) demonstrated electrostatic stability at temperatures up to 55°C. Another possible effect temperature may have is to change the molar density of the air in the chamber. According to Charles' law for ideal gasses, the molar density of a gas space at constant pressure is inversely proportional to the absolute temperature. For example increasing the temperature from 25°C (298°K) to 35°C (308°K) decreases the molar density by 3 percent. By decreasing the molar density, the probability of an alpha or beta particle causing ionization in the chamber is decreased. Therefore, while the electret is capable of collecting ions produced over a wide range of temperatures and because the number of ions produced varies with temperature, operational temperature bounds must be established according to the accuracy desired from the measurement procedure.

Barometric pressure also affects the molar density of the air within the ion chamber. Boyle's ideal gas law states that at constant temperature, molar density varies proportionally with the pressure of the gas. For example, if the pressure increases from 29 to 30 inches of Hg, the molar density increases by 3.4 percent. As with temperature, the changes in molar density must be eliminated or determined and compensated.

The effect of air moisture content (i.e., humidity) on the performance have been studied with mixed conclusions. Surette and Wood (1993) observed (using the same type electrets as in this work) no humidity effects as long as the relative humidity was not condensing and no adverse effects were observed after the electret ion chambers were exposed to 95 percent relative humidity for about four hours. Bauser and Ronge (1978)

came to a similar conclusion using a different type of chamber. To the contrary, Kotrappa et al. (1981) in a study to measure air concentrations of radon, reported the electret's ion collection efficiency decreased from 68 to 38 percent when the relative humidity increased from 15 to 75 percent. Soman (1982) drew similar conclusions in his radon work as Kotrappa.

The electret ion chamber is also affected by the presence of normal background (cosmic and terrestrial) gamma and x-ray radiation. The electret ion chamber has been studied by Pretzsch and Köstel (1984) for use in personnel dosimetry for gamma and x-ray radiation. They stated one of the advantages of electret ion chambers over the pocket chamber is that the electret ion chamber has a very flat energy response to gamma's of energies greater than 100 keV. This flat energy response is important to this work in that the complex gamma energy spectra of the uranium decay series does not have to be evaluated in order to determine background corrections. Rad Elec Inc.², has determined that for the specific electret and chamber used in this work, the electret decreases 1 volt per day for a gamma level of 10 $\mu\text{R/h}$ (Rad Elec Inc. 1992). Surette and Wood (1993) using the Rad Elec 50 cm³ chamber also determined 10 $\mu\text{R/h}$ resulted in a 1 volt per day loss in the electret's electrostatic charge. Kotrappa et al. (1982a) suggested that background levels of 50 - 100 $\mu\text{R/h}$ does not pose any special problems in determining radon concentrations in air. Typical background radiation in the United States ranges from 8 - 12 $\mu\text{R/h}$ (Berven et al. 1981, NCRP 1975). The work of Uda et al. (1986)

² Rad Elect Inc., 5330J Spectrum Drive, Frederick, MD 21701.

demonstrated that the efficiency for gamma radiation is four orders of magnitude less than that of alpha particles, which is the primary radiation generating ions in this work.

Uranium's Physical Properties

Uranium is the last of the naturally occurring elements in the periodic table with an atomic number of 92 and the greatest atomic weight (238). It has a density of 19.05 g/cm³ which makes it useful as a projectile and for counter weights (CRC 1972). Uranium has strong affinity for oxygen and is not found in nature in its metallic state, but rather most commonly combined with oxygen to form oxides, phosphates, sulfates, carbonates, and silicates. Uranium is widely distributed throughout the earth's crust with minute amounts present in nearly every type of rock. Its estimated average concentration in the earth's crust (as a whole) is about 0.0004 percent (Nininger 1956). As found in nature uranium consists of three isotopes of mass numbers 238, 235, and 234 with relative abundances 99.28, 0.71, and 0.006 percent, respectively. The isotope ²³⁸U is the parent of the natural 4n + 2 radioactive series which includes radium (²²⁶Ra) and radon (²²²Rn) and eventually decays to stable lead (²⁰⁶Pb). Uranium metal is white, ductile, malleable, and capable of taking a high polish, but tarnishes readily on exposure to the atmosphere. Finely divided uranium burns on exposure to air, and the compact metal burns when heated in air at 170°C (VNSE 1976). Much of the uranium soil contamination in and around machining facilities is from deposition resulting from uranium fires ignited during machining (DOE 1980).

Uranium has four oxidation states (III), (IV), (V), and (VI); of which (IV) and (VI) are the most important because these are responsible for the formation of the oxides

UO₂ and UO₃ (VNSE 1976). Under environmental conditions these compounds are quite stable and tend to be transported only by mechanical means and not as much by being dissolved in water and transported in solution (Lange 1974).

Uranium's Radioactive Decay Properties

The nuclide of prime interest is ²³⁸U because, 1) it is the parent of the uranium series, 2) it is the most abundant uranium isotope, and 3) it is in the main contaminant at many DOE sites. The half-life of ²³⁸U is 4.91×10^8 years and has a specific activity of 0.33 $\mu\text{Ci/g}$ (Turner 1986). ²³⁸U decays by alpha emission with an average energy of 4.19 million electron volts (MeV) per alpha particle (Kocker 1981). The uranium decay series begins with ²³⁸U and goes to stable ²⁰⁶Pb as detailed in Table 1. In the process, 8 alpha particles and 6 beta particles are emitted.

The decay rate of ²³⁸U in a sample is described by its activity, i.e., the number of atoms that disintegrate per minute. The activity A at any given time t can be determined by Equation 4.

$$A = A_0 e^{-\lambda t} \quad \text{Equation 4}$$

Table 1 The Uranium-238 decay series. Only the principal nuclides are given with averages given for particle energies. (Kocker 1981)

Nuclide	Half-life	Decay Mode	Particle Energy, MeV	Gamma Energies (Intensity), keV
²³⁸ U	4.5×10 ⁹ y	α	4.19	none
²³⁴ Th	24.1 d	β	0.0435	63(4) 92(3)
²³⁴ Pa	1.2 m	β	0.2236	95(16) 98(25) 131(20) 569(11)
²³⁴ U	25,000 y	α	4.75	none
²³⁰ Th	80,000 y	α	4.60	none
²²⁶ Ra	1600 y	α	4.77	186(3)
²²² Rn	3.82 d	α	6.49	324(3)
²¹⁸ Po	3.04 m	α	6.0	none
²¹⁴ Pb	26.8 m	β	0.220	295(19) 351(37)
²¹⁴ Bi	19.7 m	β	0.632	609(46) 1120(15)
²¹⁴ Po	164 μs	α	7.69	none
²¹⁰ Pb	22.3 y	β	0.0065	46(4)
²¹⁰ Bi	5.0 d	β	0.389	none
²¹⁰ Po	138.4 d	α	5.3	none
²⁰⁶ Pb	Stable	--	----	----

Where:

A_0 . Radioactivity at time zero.

λ = Half-life decay constant (t^{-1}). The decay constant is equal to $0.693/t_{1/2}$, where $t_{1/2}$ is the half-life in the same units as t . For ^{238}U , λ is $1.411 \times 10^{-10} \text{ y}^{-1}$.

Considering the extremely long half-life of ^{238}U , making decay corrections is usually academic. However, when ^{238}U decays to ^{234}Th which is also radioactive, it is important to know the ^{234}Th activity. The relationship between the parent nuclide and the daughter product, when the half-life of the parent is much greater than the daughter, is termed secular equilibrium. The activity for the daughter A_2 as a function of the parent's activity A_1 and time t is given by Equation 5.

$$A_2 = A_1(1 - e^{-\lambda_2 t}) + A_{20}e^{-\lambda_2 t} \quad \text{Equation 5}$$

Where:

A_{20} . Radioactivity of the daughter at time zero.

λ_2 . Half-life decay constant for the daughter.

In many cases A_{20} is zero and after 10 half-lives of the daughter, the above equation reduces to $A_2 = A_1$. Because the half-life of ^{238}U is 3 orders of magnitude greater than any of the daughter products in the ^{238}U series, for a sample that has been undisturbed, all of

the daughters are in secular equilibrium. This is the case for uranium as found in nature, i.e., uranium ores.

If the equilibrium is disturbed, or if the activity of three or more daughters must be determined, the equations become much more complex. To determine the activity present for any daughter A_2, A_3, A_4, A_5 , etc., H. Bateman formulated a solution. Friedlander and Kennedy (1949) detailed the **Bateman Solution** which is depicted in Equations 6, 7, and 8.

$$N_n = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t} + \dots C_n e^{-\lambda_n t} \quad \text{Equation 6}$$

$$C_1 = \frac{\lambda_1 \lambda_2 \dots \lambda_{n-1}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1) \dots (\lambda_n - \lambda_1)} N_1^0 \quad \text{Equation 7}$$

$$C_2 = \frac{\lambda_1 \lambda_2 \dots \lambda_{n-1}}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2) \dots (\lambda_n - \lambda_2)} N_1^0, \text{ etc.} \quad \text{Equation 8}$$

Where:

N_n = The number of atoms of nuclide n , for the parent isotope $n = 1$

N_1^0 = The number of atoms of the parent nuclide at time zero.

λ_n = The decay constant of nuclide n .

C_n = Coefficients to simplify computations.

The Bateman solution has two limitations: 1) it assumes only the parent nuclide exists at time zero and 2) it is based only on numbers of atoms. To determine the activity of individual nuclides the number of atoms for a nuclide is multiplied by its decay constant ($A_n = \lambda_n N_n$).

For a simple nuclide decay, Equation 4 is desirable. Equation 5, for secular equilibrium, works when a simple parent/daughter relationship exist. However, because of the long chain of decay products and that radon (a noble gas) loss potentially disturbs the equilibrium, the Bateman solution must be employed to determine the decay product activities until equilibrium is re-established.

Radon

Radon (^{222}Rn) is one of the noble gases and is produced as the first decay product of ^{226}Ra . Radon has been extensively studied and measured (EPA 1990) because of its potential adverse health effects. As mentioned earlier, electret ion chambers are a widely used method to measure concentrations of radon in air. Radon in soil, or its escape from soil, presents a special problem when using electret ion chambers to measure uranium concentrations in soil.

As radon is generated, the radon atoms tend to move away from their original location until their recoil energy is totally transferred into the soil (DOC 1981). Depending on the soil characteristics, such as moisture content, porosity, density, etc., a certain portion of the radon collects in the pores of the soil. The fraction of the total amount of radon that escapes from the solid particles of the soil into the pores is the radon emanation coefficient (Yu 1993). Yu's review of studies which determined

emanation coefficients for radon in various types of soils covered a range from 0.02 to 0.7. Yu uses a default value of 0.25 for radiation dose calculations when the specific type of soil is not known. The emanation coefficient provides an estimate of the radon which is free to escape into the air. For soil and minerals the radon must then diffuse through various distances to actually escape in to the air.

The sampling of soil usually involves digging by hand and dispensing the soil in a suitable container. This processing agitates the sample and potentially liberates some of the trapped radon. Samples are dried and ground in preparation for analysis. These two steps account for most of the radon loss. Unpublished work by the staff (Roberts 1993) in the Measurement Applications and Development group at the Oak Ridge National Laboratory estimated the overall loss of radon (during the sampling and subsequent processing) from the soil to be between 10 and 20 percent. If an emanation coefficient of 0.25 is assumed, then a majority of the radon in the pore spaces is possibly lost during the sampling and subsequent processing. As mentioned earlier, 8 alpha particles are emitted in the uranium decay series, with radon and its short lived daughters emitting 3 of the alphas. When a portion of the radon is lost, the overall secular equilibrium is disturbed and some fraction of the 3 alphas is unavailable for analysis.

Uranium Standards Preparation

The preparation of uranium standards for this work followed procedures typical of those in analytical laboratories. Santoliquido (1991) suggested several recommendations to the ASTM method for uranium standard preparation which were incorporated into this work. The most significant recommendation was to perform

independent analysis of the standards and preferably by different analytical techniques. Even though the source material and the background soil were thoroughly mixed, the problem of non-homogenous standards can still be a problem (Olsen and Bernabee 1988). Olsen and Bernabee concluded that standards (even 200 mesh) do not remain homogenous on standing. The non-homogeneous standard introduces only minor error in gamma analysis because the gamma radiation is only slightly attenuated. However, non-homogeneous standards used for alpha and beta analysis can alter the results by orders of magnitude. This is because the ranges of alpha particles in solids are on the order of tens of micrometers. Sources with a thickness greater than the effective range of the alpha particles are referred to as "infinitely thick" (Phoenix et al. 1993).

III. Materials and Equipment

The Electret Ion Chamber for Uranium in Soil Analysis

The E-PERM® electret ion chambers used in this study are commercially available from Rad Elec Inc. The electrets have an initial voltage of about 700 volts and are considered expended when the voltage drops below 200 volts. Recharging the electrets is not feasible, except by the manufacturer. Figure 2 depicts the physical layout of the chamber. The electret material is a wafer of Teflon™ and the walls of the ionization chamber are constructed out of non-conductive plastic. The electret's plastic shell is threaded for easy and secure attachment to the plastic chamber. The bottom of the chamber is open which allows the chamber to be placed over the sample to be analyzed. The volume of the chamber is 50 cm³; however, the actual air volume is slightly less when in use due to the volume of the soil sample.

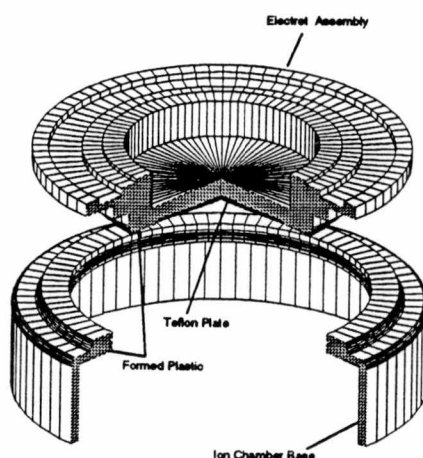


Figure 2 Electret ionization chamber.

Uranium Standards

As previously mentioned, two common forms of ^{238}U encountered in radiological characterization are depleted uranium where ^{238}U , ^{234}Th , and ^{234}Pa are in secular equilibrium and ore where the entire ^{238}U decay series is in equilibrium. Therefore, ^{238}U standards were made for both forms in varying concentrations. Since residual contamination cleanup guidelines for ^{238}U in soil have been established at specific DOE sites (Rodriguez et al. 1992) at values of 30 pCi/g, the ^{238}U standards were made in concentrations of 10, 30, 50, and 100 pCi/g for both forms of ^{238}U . A soil standard containing naturally occurring amounts of radionuclides (Berven et al. 1981) was used as a background standard. In preparing the standards, both the source materials and the background soil used to dilute the source material were dried for at least 8 hours at 110°C and passed through a 200 mesh sieve. The standards were prepared in plastic petri dishes (2.5 inch diameter) because they are convenient for use in analysis by both electret ion chambers and gamma spectroscopy.

The depleted uranium standards (10, 30, 50, and 100 pCi/g) were prepared from depleted uranium oxide powder. Since the specific activity of ^{238}U is $0.33\ \mu\text{Ci/g}$, producing standards in the pCi/g range would be challenging at best. Therefore, 0.1 grams of the $0.33\ \mu\text{Ci/g}$ standard was diluted by 1000 times with clean soil to produce 100 grams of $\approx 330\ \text{pCi/g}$. The total desired mass of each of the four depleted uranium standards was 20 grams. To prepare each of the needed standards, Equation 9

below was used to determine the aliquot M of the 330 pCi/g standard when mixed with $(20 - M)$ grams of the clean soil would produce a standard of C pCi/g.

$$M = \frac{20 \text{ g} \times C}{330 \text{ pCi/g}} \quad \text{Equation 9}$$

The calculated aliquot of the 330 pCi/g standard was accurately weighed (± 0.01 g) and placed in a petri dish. A balance of 20 grams was carefully weighed into a petri dish for each standard and sealed. The standards were analyzed by a gamma spectroscopy system using high purity germanium detectors. After all experimental work, the standards were once again analyzed. Table 2 shows the analytical results of the depleted uranium standards.

Table 2 Depleted uranium standards

Depleted U Standard Id	²³⁸ U Concentration, pCi/g †		
	Initial	Final	Average
U10	11 ± 11	11 ± 2	11 ± 6
U30	37 ± 2	33 ± 6	35 ± 3
U50	61 ± 11	56 ± 7	59 ± 6
U100	118 ± 19	113 ± 13	115 ± 12

† Indicated counting error is at the 95% confidence level ($\pm 2\sigma$).

The ore type standards were prepared from an EPA pitchblende standard issued as part of their quality assurance program. The pitchblende standard was 320 pCi/g making subsequent standard preparations a routine operation. Aliquots from the

pitchblende standard were weighed to produce 20 gram standards of the appropriate concentrations using the same methodology as for the depleted uranium standards above. These were analyzed in the same manner as the other standards. Table 3 shows the analytical results of the pitchblende standards as well as the background soil used to make the dilutions.

As recommended by Santoliquido (1991), independent analysis was performed and the results are shown in Tables 4 and 5. The analytical results are from different laboratory equipment and different methods than the high purity germanium detectors.

Other radioactive sources used during this work are uniquely identified by ORNL source identification numbers and are listed in Table 6. The ^{230}Th source is an alpha source with sufficient radioactivity to rapidly assess the response of the electrets. The ^{137}Cs source was used to perform response checks to verify that the portable radiation survey instruments were working properly.

Table 3 Uranium standards from pitchblende.

Normal U Standard Id	^{238}U Concentration, pCi/g [†]		
	Initial	Final	Average
Soil	2 ± .8	1 ± .7	1.5 ± .5
U10+D	12 ± 3	13 ± 4	12 ± 3
U30+D	37 ± 4	36 ± 8	37 ± 5
U50+D	55 ± 5	53 ± 11	54 ± 6
U100+D	110 ± 12	104 ± 17	107 ± 10

[†] Indicated counting error is at the 95% confidence level ($\pm 2\sigma$).

Table 4 Results of independent analysis of depleted uranium standards.

Depleted U Standard Id	²³⁸ U Concentration, pCi/g [‡]		
	Gross Beta	Gross Gamma, NaI	Gamma Spec HPGe
U10	8 ± 2	11 ± 2	11 ± 6
U30	34 ± 2	33 ± 4	35 ± 3
U50	71 ± 8	57 ± 6	59 ± 6
U100	123 ± 14	121 ± 5	115 ± 12

[‡] Indicated counting error is at the 95% confidence level ($\pm 2\sigma$).

Table 5 Results of independent analysis of uranium pitchblende standards.

Normal U Standard Id	²³⁸ U Concentration, pCi/g [‡]		
	Gross Beta	Gross Gamma NaI	Gamma Spec HPGe
Soil	3 ± 1	1.6 ± 1	1.5 ± .5
U10+D	11 ± 2	12 ± 2	12 ± 3
U30+D	34 ± 4	34 ± 3	37 ± 5
U50+D	57 ± 4	57 ± 3	54 ± 6
U100+D	116 ± 5	113 ± 4	107 ± 10

[‡] Indicated counting error is at the 95% confidence level ($\pm 2\sigma$).

Table 6 Radioactive sources used.

Source Identification	Nuclide(s)	Use
EPA-1 Pitchblende	²³⁸ U Decay Series	Calibration standard for gamma spectrometer system
TH-230-3827	²³⁰ Th	Quality control check on new electrets
M-3080	¹³⁷ Cs	Routine calibration check of portable instruments
U-238-3829	Depleted Uranium	Fabrication of standards

Equipment

General

All equipment used in this work is owned by the DOE and maintained and operated at the Oak Ridge National Laboratory. The equipment is calibrated and maintained in accordance with ANSI N323 (ANSI 1978) where applicable.

Gamma Spectrometer

A gamma spectrometer system using high purity germanium (HPGe) detectors was used during this work to accurately determine the ^{238}U and other nuclide concentrations in each of the standards. The HPGe detector produces signals proportional to the energies of the gamma radiation interacting within the detector crystal with a very high resolution. These signals are processed by a multichannel analyzer interfaced to desktop computer. The computer (and software) provides a visual image of the spectrum as samples are analyzed and compares the collected data to libraries of known nuclides and calibration data to report both quantitative and qualitative results. Figures 3 and 4 show the spectra of depleted uranium and ^{238}U decay series, respectively. See Table 1 for the energies of the different nuclides.

This is the usual means by which environmental uranium samples are analyzed. However, to obtain satisfactory results for samples with less than 30 pCi/g ^{238}U , counting times of 4 hours are common and large shields must be used to reduce background radiation.

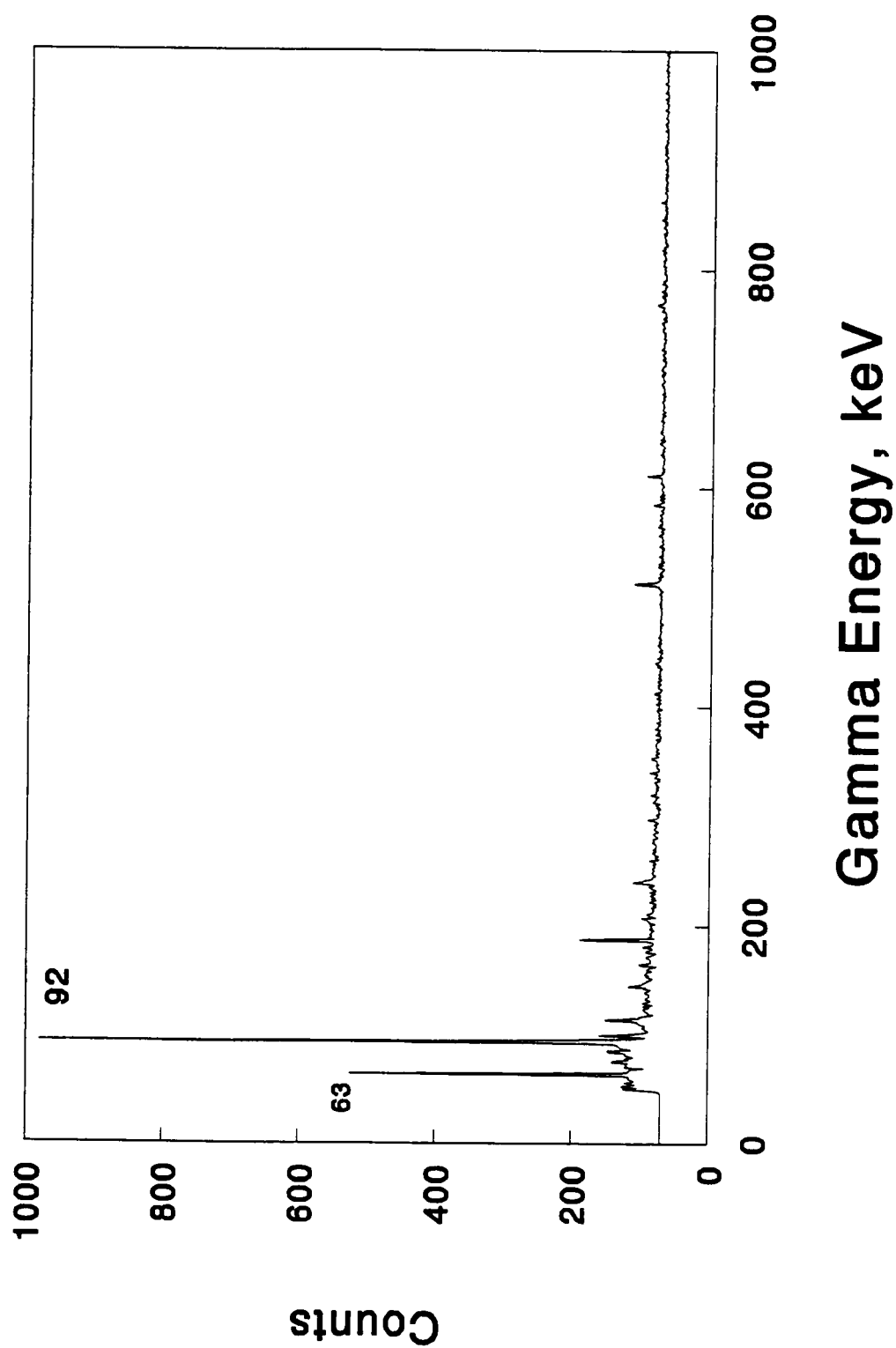


Figure 3 Gamma ray spectrum of ^{238}U (depleted uranium) using a high purity germanium detector.

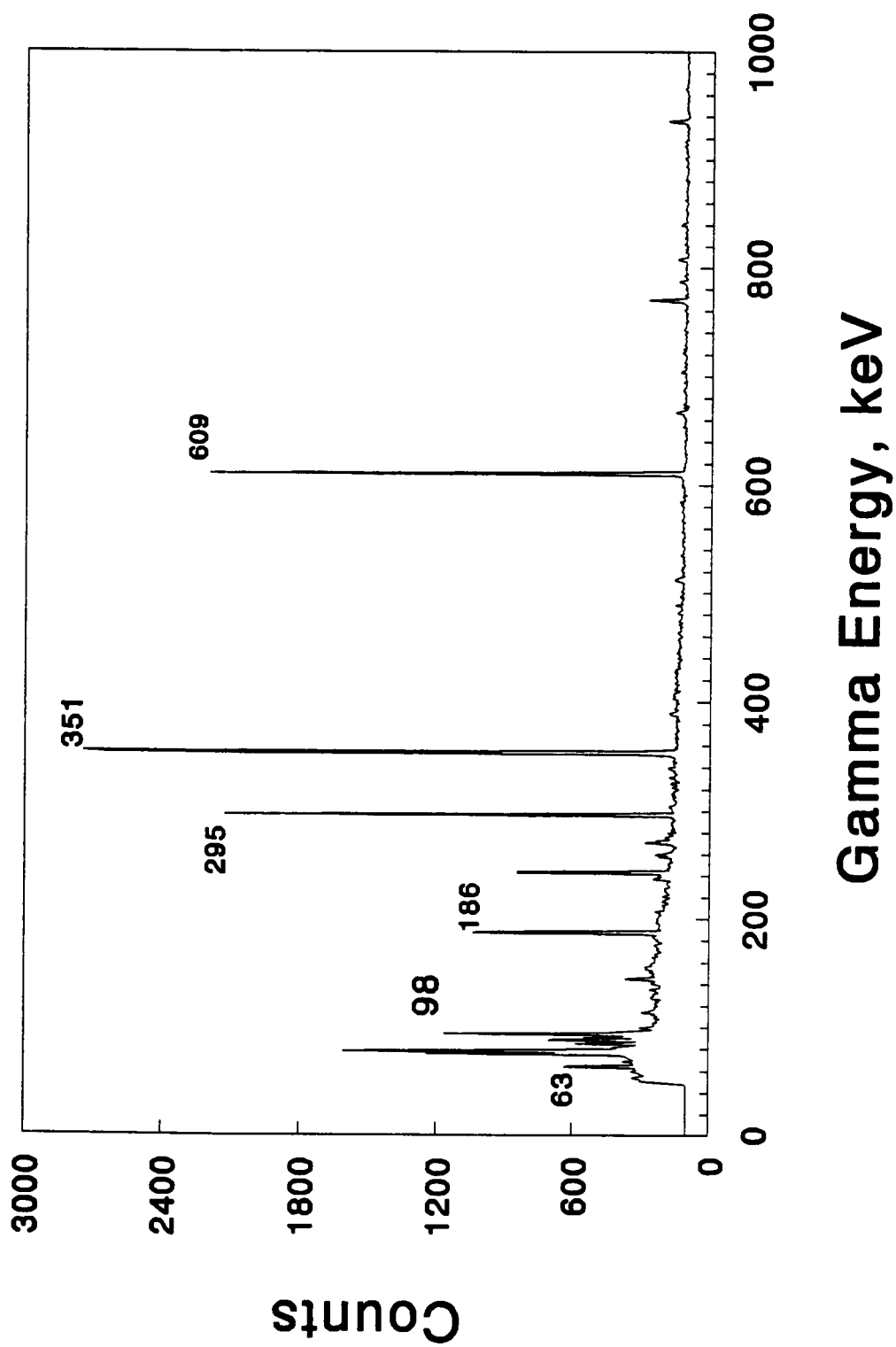


Figure 4 Gamma ray spectrum of the ^{238}U series using a high purity germanium detector.

GM "Pancake" Detector

The Geiger-Muller (GM) type detector has long been used to measure radiation (Turner 1986). Unlike the gamma spectrometer, the GM detector cannot identify the nuclide emitting the radiation, but it can be portable and is very efficient at detecting beta radiation, and therefore, is widely used for determining surface contamination. The variety of GM detector used in this study is known as a "pancake" detector because of its flat cylindrical shape. During this work at the end of each evaluation using electrets, measurements of beta activity were made for each of the uranium standards. For an electroplated source of ^{238}U , the GM pancake is typically 20 percent efficient at detecting the beta radiation.

ZnS Detector

The zinc sulfide (ZnS) detector is a scintillation device where alpha particles cause the ZnS to emit pulses of light which are amplified by a photo-multiplier tube and then registered as a count rate. Because alpha particles have a very short range (no more than a few centimeters) the ZnS detector must be almost nearly in contact with the alpha source. Detection of alpha particles is further complicated in that small amounts of most any material attenuates the alphas and thus masks their presence. During this work at the end of each evaluation using electrets, measurements of alpha activity were made for each of the uranium standards. For a plated alpha source, ZnS detectors are typically 14 percent efficient at detecting the alpha radiation.

NaI Scintillation

The sodium iodide (NaI) detector measures gamma radiation by sensing pulses of light caused by the gamma radiation's interaction in the NaI crystal. The light pulses are amplified by a photo-multiplier tube and then registered as a count rate. These instruments are used in both field and laboratory applications. In field applications they can be used to conduct a walk-over scan of suspect surfaces. In this mode of operation, ^{238}U concentrations of greater than 80 pCi/g can be readily detected in surface soils. During this work at the end of two runs using electrets, measurements of gamma activity were made for each of the uranium standards.

Electret Reader

The electret reader is the device used to determine the electrostatic charge of the electrets. The one used for this study is a model SPER-1, serial number 261, manufactured by Rad Elec, Inc. The electrets are placed in a designated holder and a shutter is opened to expose a capacitive detector to the electrostatic field of the electret. The calculated voltage is a function of the electret's dielectric properties and the air gap between the electret and the capacitive detector. The instrument is calibrated by the manufacturer and is verified in calibration by means of reference electrets supplied by the manufacturer. Calibration checks are performed daily when the reader is in use.

Environmental Monitoring Equipment

During the course of the experimental work, the temperature, humidity, and barometric pressure were monitored. The intent was not to establish any particular correlation but to possibly explain any deviation of a specific measurement from other similar measurements. The instruments used were commercial grade with no certification or routine calibration. The barometer was spot checked against a certified instrument located at a nearby meteorological monitoring station with less than a 10 percent error observed. The laboratory space where this work was located has temperature and humidity controls therefore the range of these parameters was limited.

Sample Drying and Grinding Equipment

All uranium soil standards used were dried in laboratory grade electric ovens at 110°C for a minimum of 8 hours. The dried material was processed through a rotary wheel grinding machine and sieved through a 200 mesh screen. All equipment was cleaned and checked for radioactive contamination after each use.

IV. Experimental Procedure and Data

Overview

The experimental work was divided into three major areas:

- 1) determining the potential effects of radon escaping from the sample matrix,
- 2) determining the electret's response to exposure to uranium contamination in soil, and
- 3) testing the derived correlations to determine the electret ionization chamber performance under field conditions to predict uranium concentration in soil.

Three other areas of data collection included:

- 1) quality control checks on individual electrets and daily checks of the electret reader,
- 2) measuring the prepared uranium soil standards with portable radiation survey instruments typically used in field surveys, and
- 3) measuring the ambient environmental conditions while the electret ionization chambers were being exposed to radioactive sources.

Radon Loss Determination

Loss of radon from a sample containing natural uranium during collection and processing must be understood and compensated for (when required) in order to prevent analytical results from being biased low. The approach to quantitatively understand radon

losses was to first mathmatically model the radioactivity profile as a function of different radon loss fractions. Then experimentally drive radon out of standards and evaluate against the models. Using Equation 5, the time for radon and its short lived daughters to return to secular equilibrium can be determined. If all the radon in the pore spaces were lost, 5 days would be required for the radon to return to 90 percent of its original concentration. For a field screening method, a holding time of 5 days for a soil sample is not acceptable and therefore the radon loss must be minimized or compensated for in a worst case scenario.

To model the effect of losses of radon during sample collection and processing, a computer algorithm, dubbed EQUIL, was developed in Turbo C++³. Turbo C++ was chosen because of its ability to generate a very fast executable module. The source code for EQUIL is given in Appendix 1. The program is very specific in nature and is not "user friendly" as it requires the user to compile and link the program each time any parameter is changed. Also, the output is an ASCII file of columns of numbers, which must be imported by some other program for data manipulation or graphics.

As mentioned earlier, once a portion of the radon is lost, then the daughter equilibriums are disturbed. EQUIL takes each of the nuclides in the ^{238}U series beginning with ^{226}Ra and ending with ^{214}Po and applies the Bateman solution (Equations 6, 7 and 8) to each nuclide as if it is the parent of its own separate series. At $t = 0$, each nuclide has an arbitrary activity of 100 except radon which is assigned a value representative of the fraction retained, i.e., 10 would represent a 90 percent lost of radon. At specific time

³ Turbo C++ is a registered trademark of Borland International, Inc.

intervals the inventory for each nuclide is calculated from each of the series, taking into account each nuclide as it decay from and grows into each series. The time increment begins at 1 minute for the first 10 minutes, then is increased to 10 minutes until 500 minutes have elapsed, and then 100 minute intervals are used for the balance of the simulation of 10,000 minutes. A simulation time of 10,000 minutes (≈ 7 days) approaches the time when secular equilibrium is re-established and is longer than any hold time expected for a field screening method.

Figure 5 shows the results of a total loss of radon from the sample as the various daughters re-establish equilibrium. Note that ^{214}Bi and ^{214}Po are shown as a single line. This is because ^{214}Po having only a 164 micro-second half-life is always in secular equilibrium with its parent, ^{214}Bi . EQUIL was modified and run for radon retentions of 10, 25, 50, 75, 90 percent. The results for 25 and 75 percent radon retention are shown in Figures 6 and 7, respectively. For each of the runs of EQUIL, the total alpha activity was determined as a function of time as shown in Figure 8. Experimental work was conducted to determine which of the lines in Figure 8 best fit the radon loss resulting from sample collection and processing specific to this work.

The likely causes of radon loss from samples are primarily agitation (aeration), heating, and low atmospheric pressure operations. Aeration occurs when 1) the contaminated soil is first removed from its surface or subsurface location; 2) the sample is ground to a powder; and 3) the sampled is processed through a 200 mesh sieve. The radon loss from heating occurs during the drying process at 110°C . The sample is

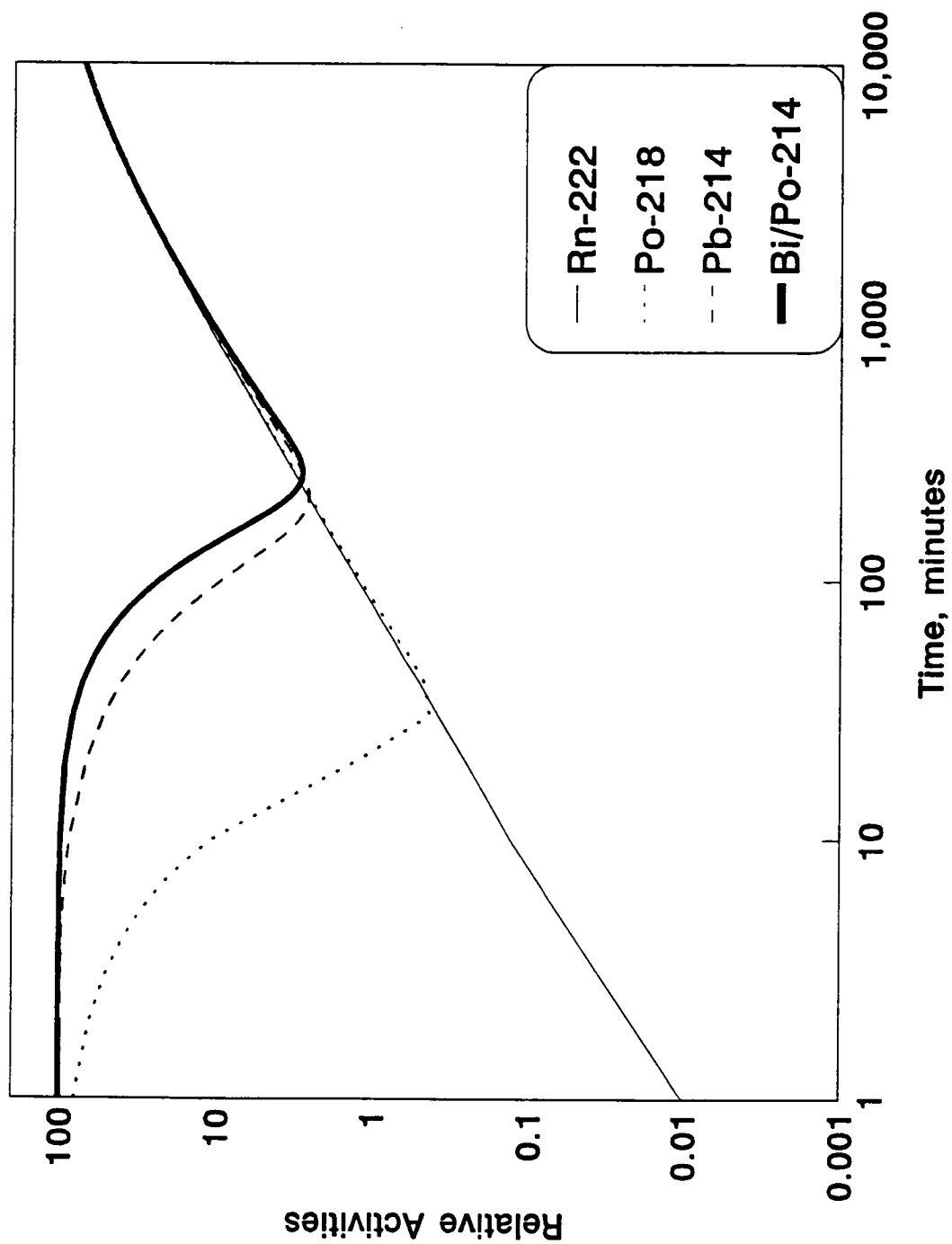


Figure 5 Relative activities of radon and daughter products after a total loss of radon.

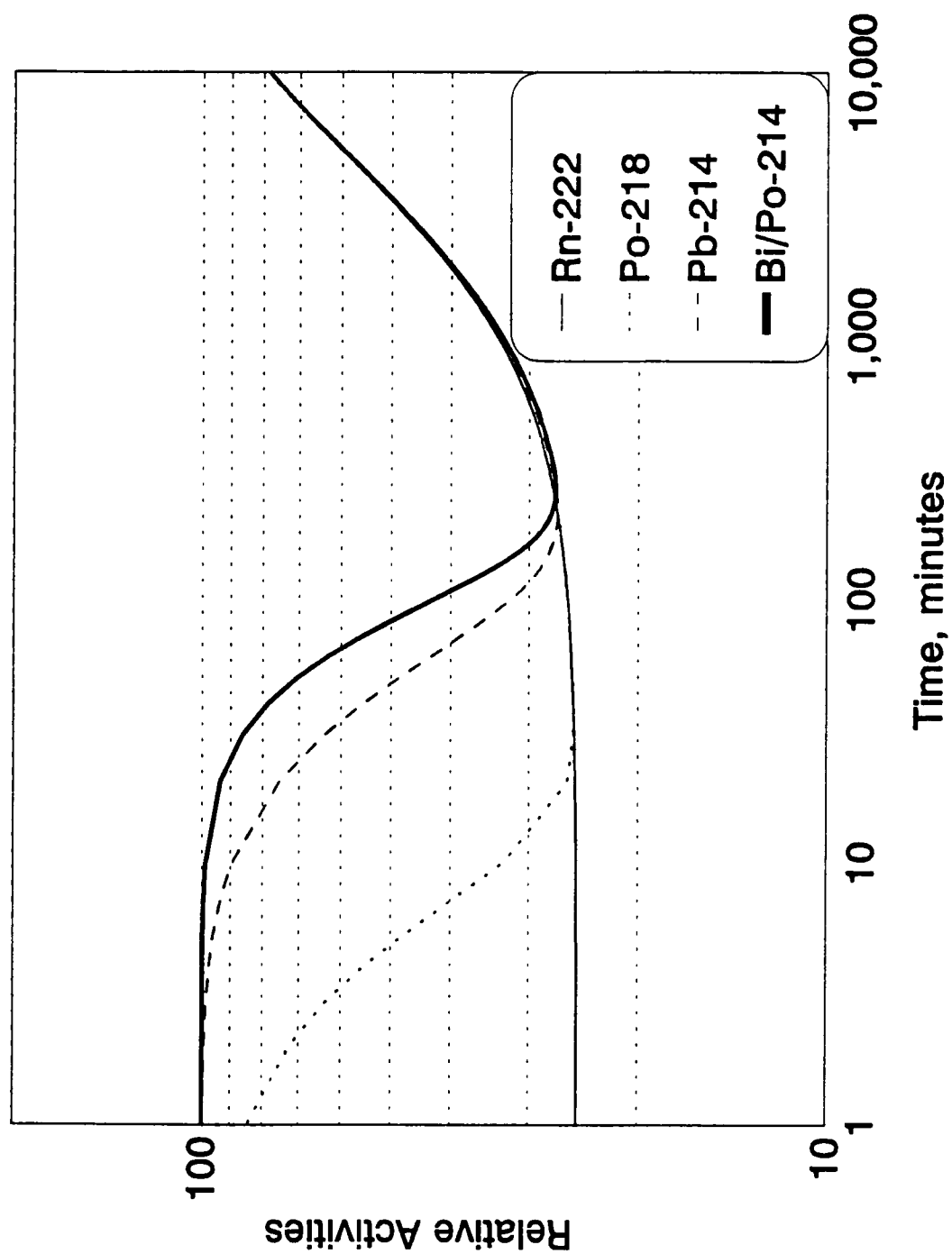


Figure 6 Relative activities of radon and daughter products after a 75% loss of radon.

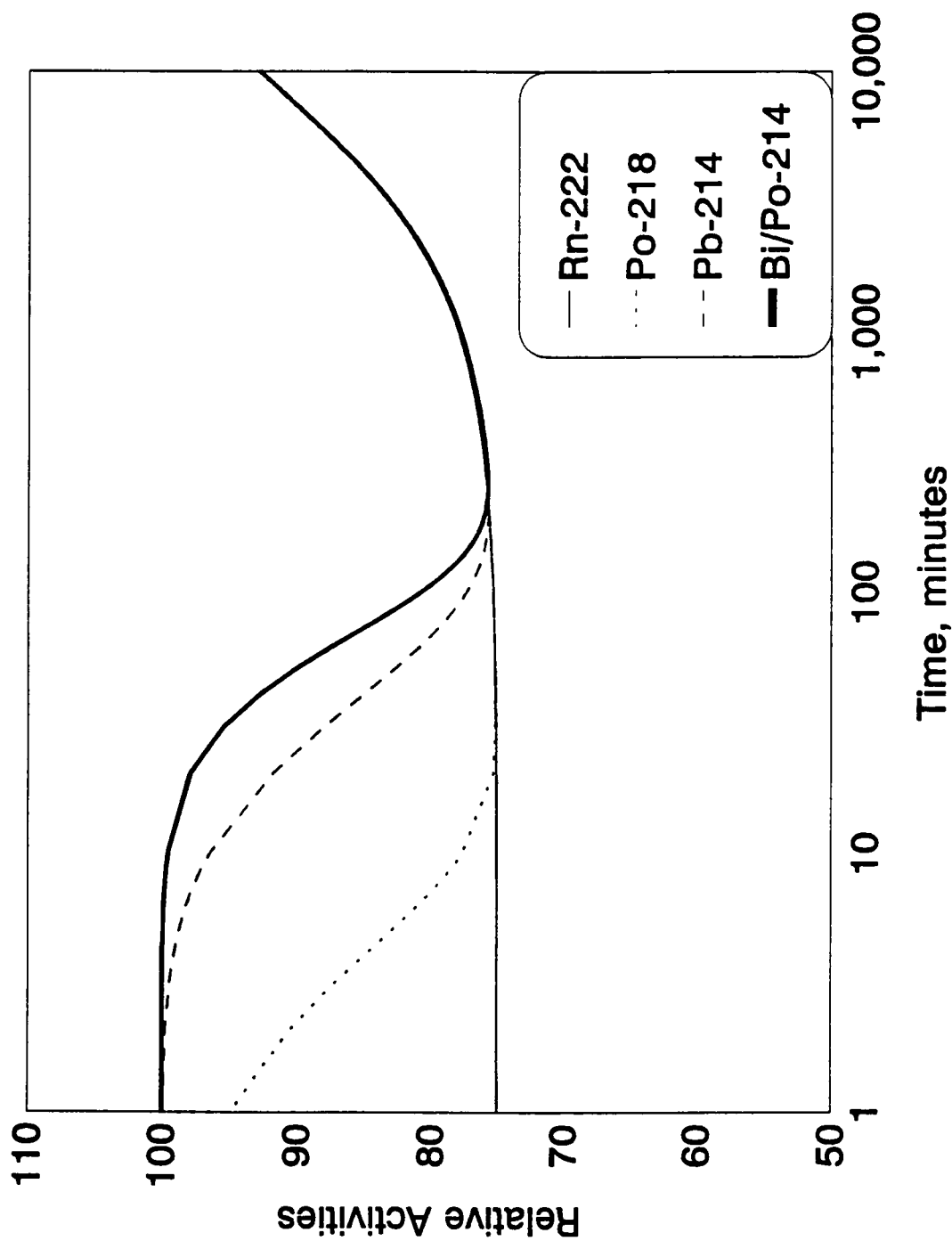


Figure 7 Relative activities of radon and daughter products after a 25% loss of radon.

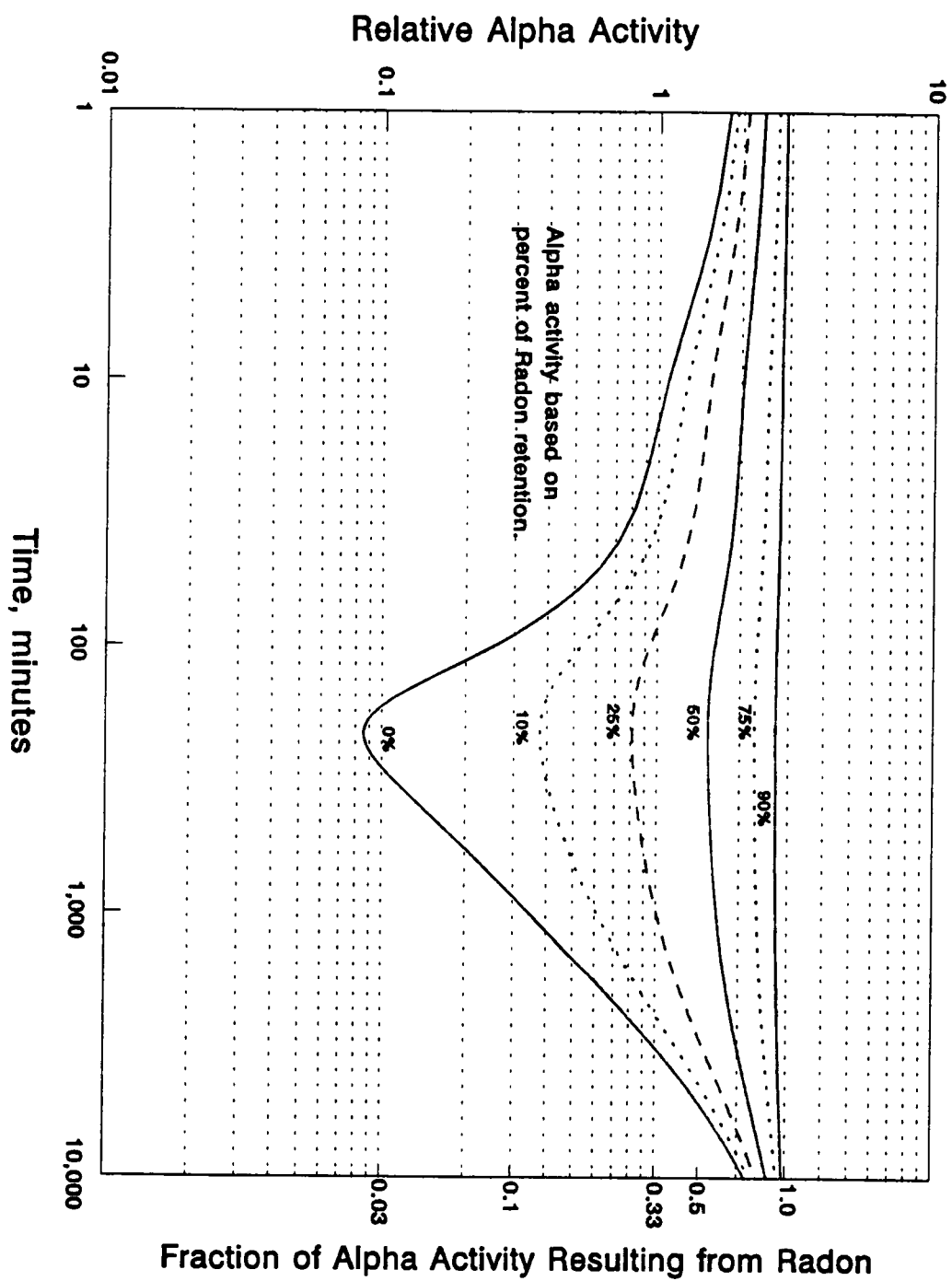


Figure 8 Total relative alpha activity vs. time for different retention percentages of radon in soil after an instantaneous release.

subjected to a less than atmospheric pressure during grinding when a fume hood is used to control contamination. Each of these three potential radon loss mechanisms are possible, but only the aeration and heating are considered applicable to this field screening technique.

Each of these two loss mechanisms were investigated using a concentrated pitchblende standard (powder form). The concentrated pitchblende standard provided a high counting rate thus giving good counting statistics in a short counting time. The pitchblende standard was analyzed before and at specific time intervals after it was subjected to each loss mechanism.

The aeration was accomplished by shaking the standard for 20 minutes in a laboratory mixing machine. The standard was opened to the atmosphere, re-sealed, and shaken for an additional 20 minutes. This test far exceeds any potential aeration expected during field operations. The retained radon activity was determined by analyzing the decay and in-growth of ^{214}Pb with a gamma spectrometer. Prior to agitation, the pitchblende standard was analyzed to determine the equilibrium radioactivity of ^{214}Pb because ^{214}Pb is the first of the radon daughters with sufficient gamma radiation for quantitative analysis. Immediately following the agitation process, the standard was analyzed hourly for 72 hours and periodically thereafter. Figure 9 shows the analysis results (normalized to the equilibrium activity of ^{214}Pb) and overlaid with the curves predicting the ^{214}Pb radioactivity as a function of time and the radon retention fraction as calculated by the software EQUIL. While the data points are scattered, the 0.94

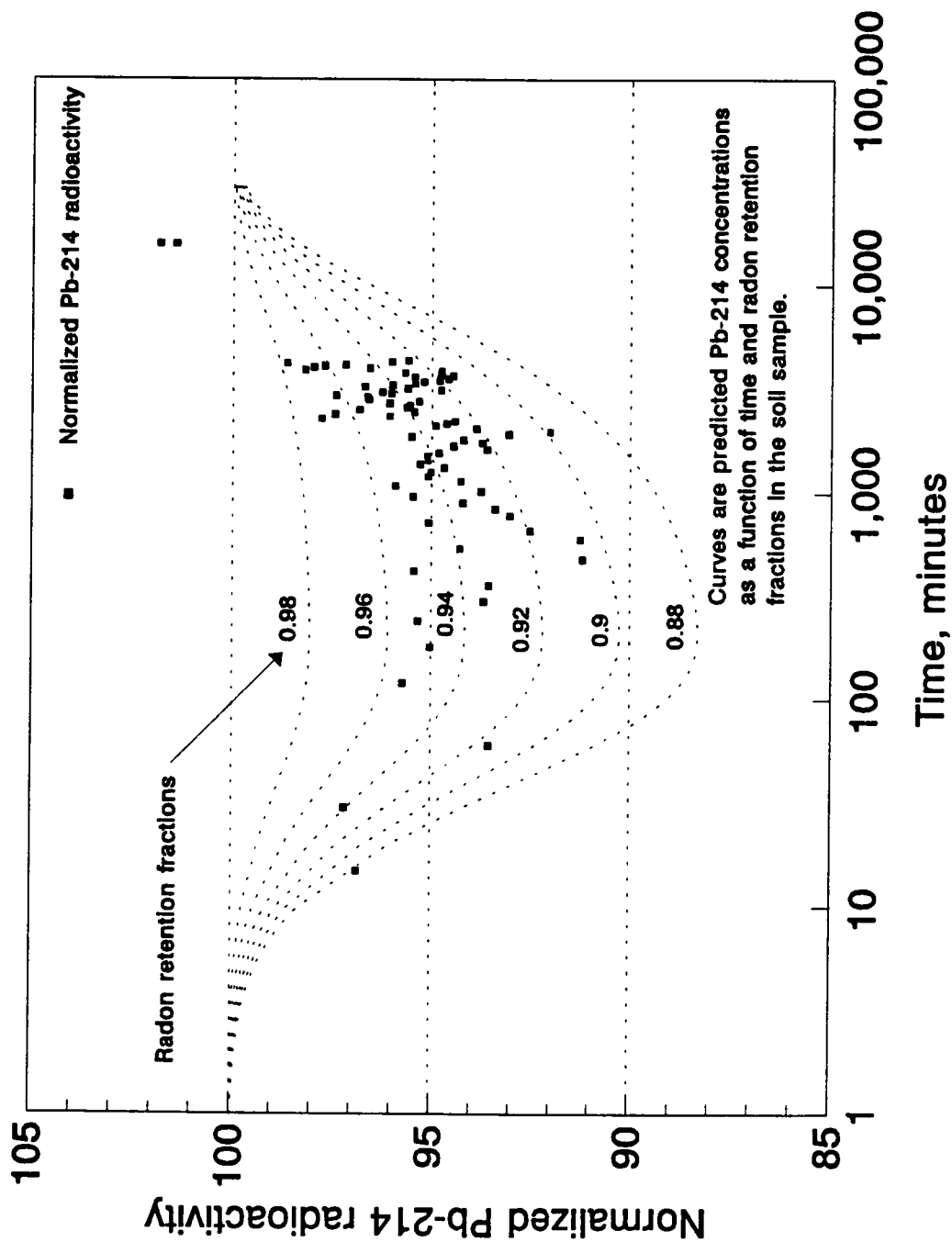


Figure 9 Measured ^{214}Pb radioactivity data following sample agitation and predicted ^{214}Pb radioactivity as a function of radon retention fractions.

retention fraction best approximates the data as determined by calculating the standard deviation for each curve compared to the experimental data. The standard deviations for the retention curves 0.96, 0.94, and 0.92 are 2.1, 1.2 , and 1.8, respectively.

Sample drying is important for two reasons, 1) the regulatory guidelines are given in pCi/g dry weight and 2) any moisture in the soil attenuates the alpha particles, and therefore soil drying is necessary. The test for radon loss by drying used a standard laboratory drying oven set a 150°C, 40°C higher than normal drying. Prior to heating, the pitchblende standard was analyzed to determine the equilibrium radioactivity of ^{214}Pb . The pitchblende standard was heated for 20 hours and then immediately analyzed once per hour for 24 hours and periodically thereafter. Figure 10 shows the results of the individual analysis. Program EQUIL was used to predict the ^{214}Pb radioactivity based on various retention fractions of radon. While the data points are scattered, the 0.9 retention fraction best approximates the data as determined by calculating the standard deviation for each curve compared to the experimental data. The standard deviations for the retention curves 0.94, 0.92, 0.90, and 0.88 are 3.5, 2.3, 2.1, and 3.1, respectively.

Electret Response to Uranium Sources

The response to uranium contaminated soil was determined by exposing electret ionization chambers to the soil standards of known uranium concentrations. Nine soil standards were prepared as detailed in section III. They consisted of 10, 30, 50, and 100 pCi/g each of natural uranium and depleted uranium and one uncontaminated (background) soil standard. A trial "run" consisted of exposing an electret ionization chamber to each of the nine standards and one chamber to no soil standard. The electret

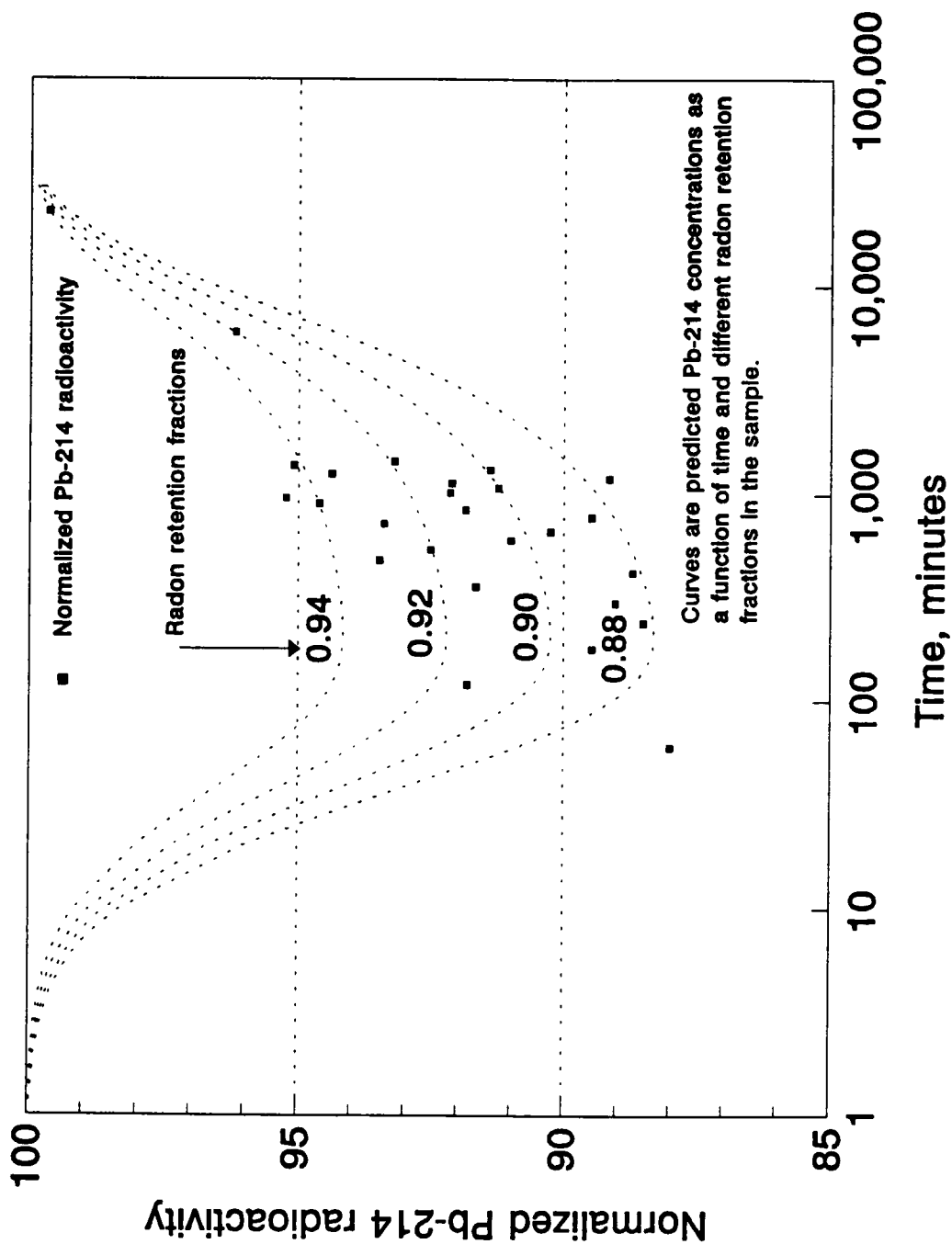


Figure 10 Measured ^{214}Pb radioactivity data following sample drying and predicted ^{214}Pb radioactivity as a function of radon retention fractions.

ionization chamber having no soil standard served as a control and measured the ambient background gamma radiation. In all, ten electret ionization chambers comprised a run. During each run, at non-specific time intervals, the following information was collected, 1) the date/time of data collection, 2) the current voltage potential of each electret, 3) the temperature, 4) humidity, and 5) barometric pressure. At the end of each run, direct radiation measurements of alpha, beta and gamma activity were made with portable survey instruments.

Five complete runs were conducted for each standard with 1 and 2 additional runs performed on the 50 and 100 pCi/gram natural ^{238}U standards, respectively. The additional runs were possible on the higher radioactive standards because of the relatively short time required to reduce the voltage potential of the electrets. The raw data are presented in Appendix 2. The initial electret voltages ranged between 354 and 707 volts depending on the past uses of the individual electrets. Once all the experimental runs were completed, the data was sorted by standard concentration and plotted for subsequent analysis. The run were allowed to cover time periods ranging from approximately 2 to 20 days to ensure the responses were linear and any voltage variability due to measurement error was minimized. While even 2 days is longer than expected analysis time during field use, the long exposure time, along with multiple voltage measurements, demonstrate that the electrets respond linearly over a short time period indicative of field use. The results of the runs are graphically presented in Figures 11 to 20. Tables 7 to 16 show the statistics of the collected data.

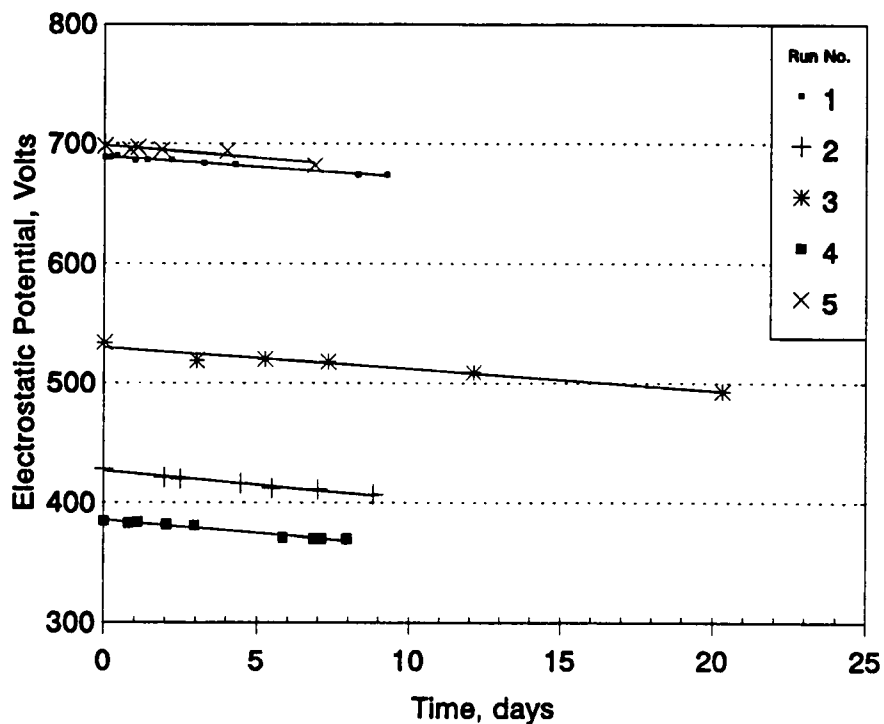


Figure 11 Electret ionization chamber response to normal background radiation, no soil standard in place.

Table 7 Statistics for electret ionization chambers response to background radiation.

Source Id.: Background - no source					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	1347	10	9.2674	1.73	.971
2	2212	7	8.8313	2.29	.972
3	2243	6	20.313	1.82	.950
4	2318	9	7.9583	2.17	.970
5	1388	6	8.0625	2.11	.860
Time weighted average slope =				1.98 ± 0.21	

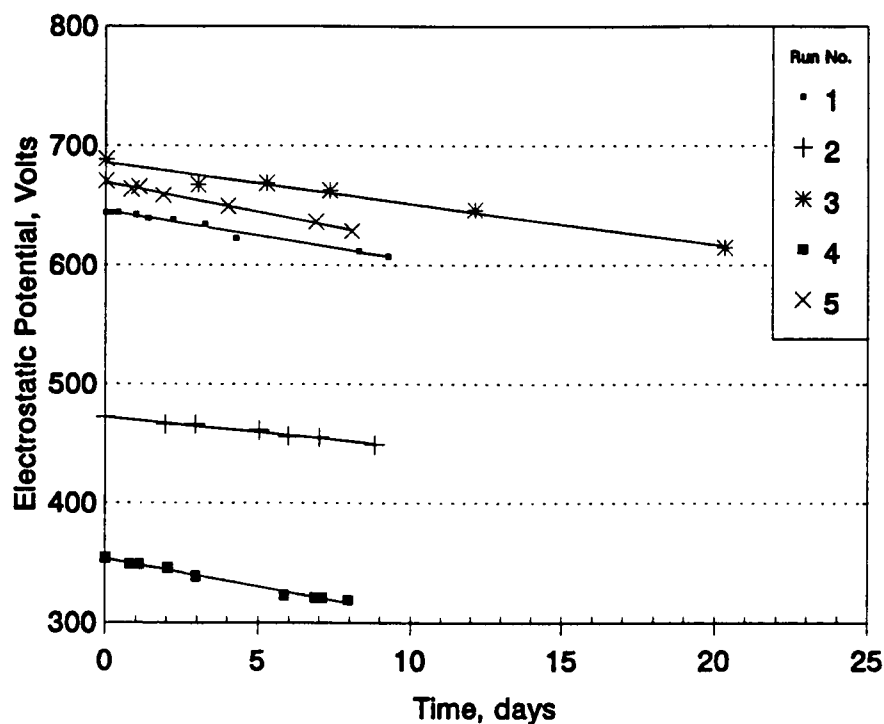


Figure 12 Electret ionization chamber response to normal background radiation from soil, no ^{238}U standard.

Table 8 Statistics for electret ionization chambers response to background radiation from soil.

Source Id.: Background - soil					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	2292	10	9.2674	4.17	.977
2	1417	7	8.8313	2.55	.980
3	2285	6	20.313	3.42	.975
4	1386	9	7.9583	4.66	.986
5	1542	6	8.0625	4.97	.993
Time weighted average slope =				3.82 ± 0.81	

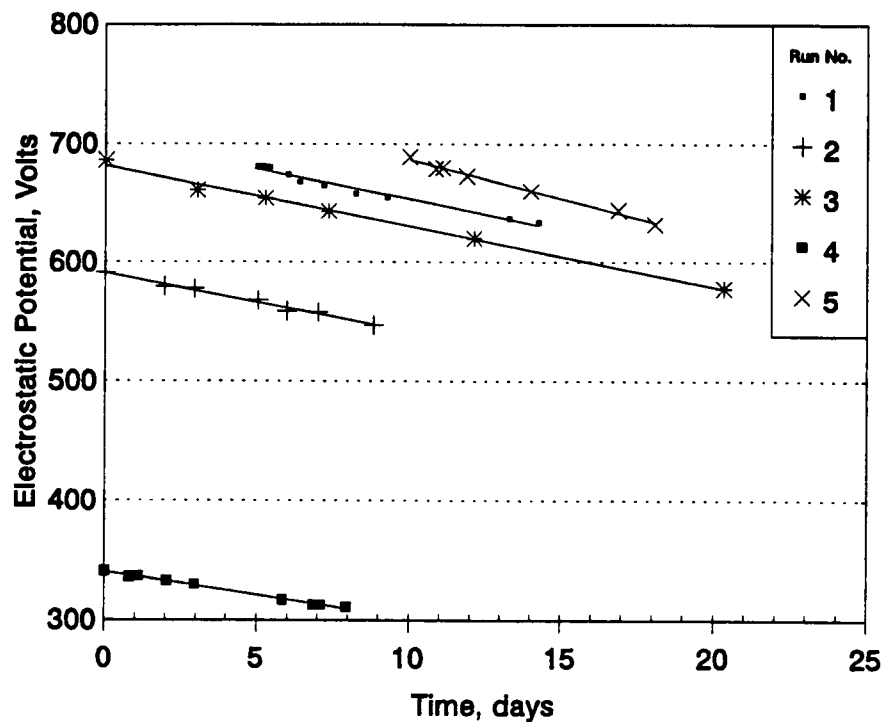


Figure 13 Electret ionization chamber response to soil with 10 pCi/g depleted uranium.

Table 9 Statistics for electret ionization chambers response to radiation from soil with 10 pCi/g of depleted uranium.

Source Id.: Uranium 10 pCi/g					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	2175	10	9.2674	5.12	.972
2	2178	7	8.8313	4.93	.988
3	1452	6	20.313	5.12	.993
4	1765	9	7.9583	3.87	.994
5	1349	6	8.0625	6.59	.992
Time weighted average slope =				5.12 ± 0.75	

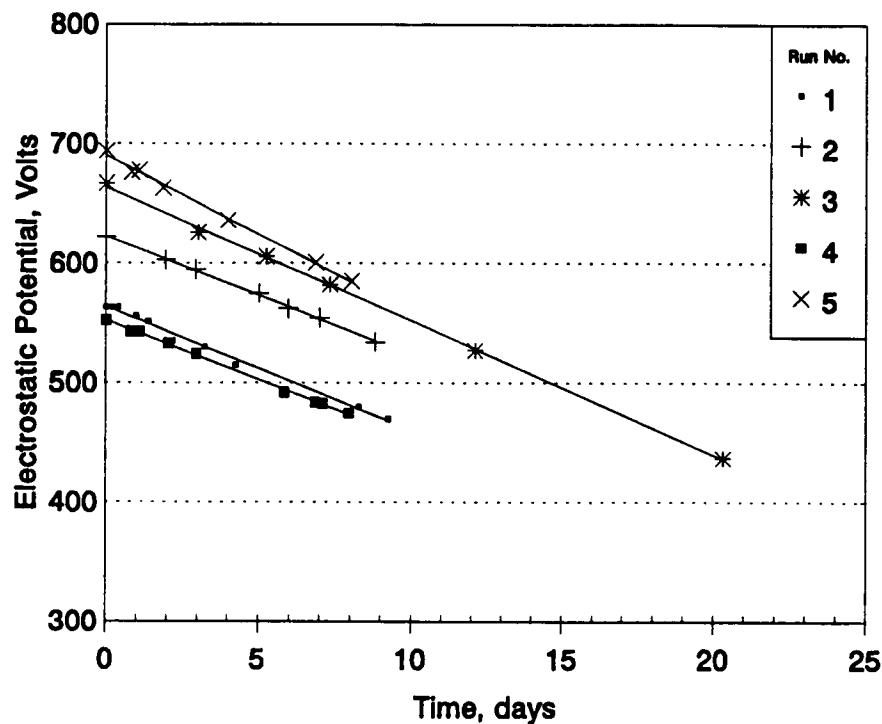


Figure 14 Electret ionization chamber response to soil with 30 pCi/g depleted uranium.

Table 10 Statistics for electret ionization chambers response to radiation from soil with 30 pCi/g of depleted uranium.

Source Id.: Uranium 30 pCi/g					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	7072	10	9.2674	10.28	.992
2	2243	7	8.8313	9.96	.998
3	2318	6	20.313	11.22	.999
4	1452	9	7.9583	9.87	.998
5	2186	6	8.0625	13.13	.996
Time weighted average slope =				10.94 ± 1.08	

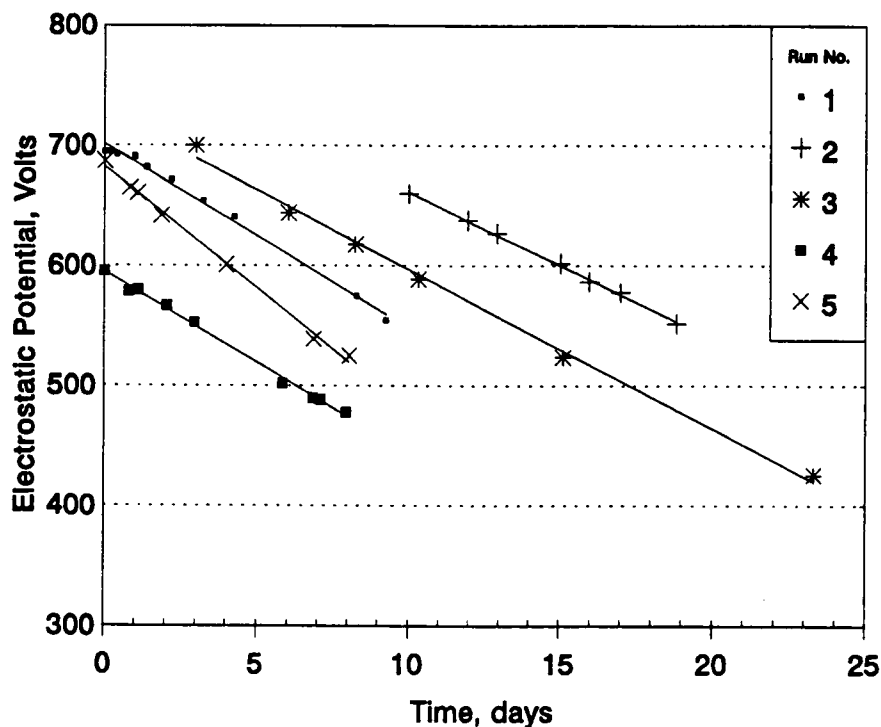


Figure 15 Electret ionization chamber response to soil with 50 pCi/g depleted uranium.

Table 11 Statistics for electret ionization chambers response to radiation from soil with 50 pCi/g of depleted uranium.

Source Id.: Uranium 50 pCi/g					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	2227	10	9.2674	15.30	.994
2	2227	7	8.8313	12.21	.998
3	1386	6	20.313	13.25	.998
4	2285	9	7.9583	15.10	.996
5	1512	6	8.0625	20.23	.997
Time weighted average slope =				14.74 ± 2.54	

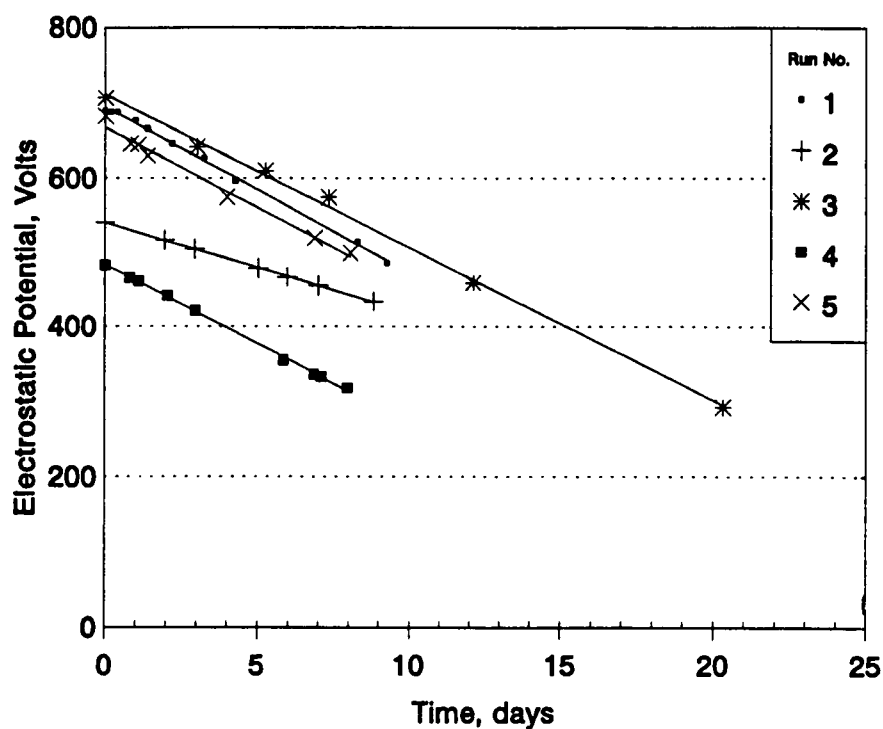
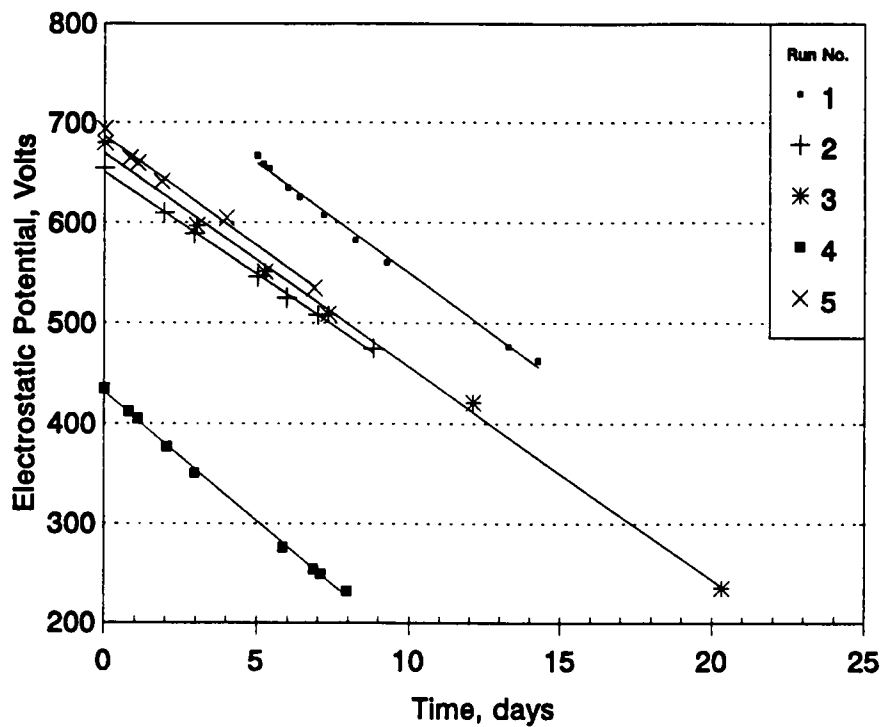


Figure 16 Electret ionization chamber response to soil with 100 pCi/g depleted uranium.

Table 12 Statistics for electret ionization chambers response to radiation from soil with 100 pCi/g of depleted uranium.

Source Id.: Uranium 100 pCi/g					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	2243	10	9.2674	22.2	.998
2	7072	7	8.8313	12.2	.999
3	1765	6	20.313	20.48	.997
4	2243	9	7.9583	21.3	.999
5	1735	6	8.0625	21.6	.986
Time weighted average slope =				21.2 ± 3.56	



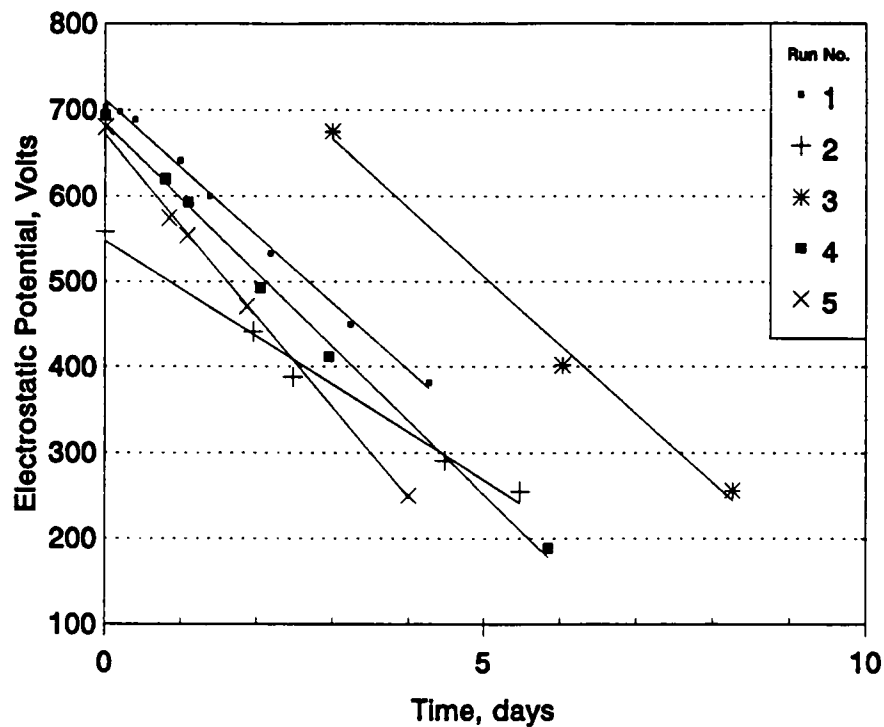


Figure 18 Electret ionization chamber response to soil with 30 pCi/g uranium and all decay daughters.

Table 14 Statistics for electret ionization chambers response to radiation from soil with 30 pCi/g of ^{238}U and all decay products.

Source Id.: Uranium decay series 30 pCi/g					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	1417	8	9.2674	78.72	.997
2	2292	5	8.8313	55.99	.986
3	2221	3	20.313	80.31	.993
4	2262	6	7.9583	86.69	.996
5	2191	5	8.0625	106.13	.999
Time weighted average slope =				80.85 ± 17.6	

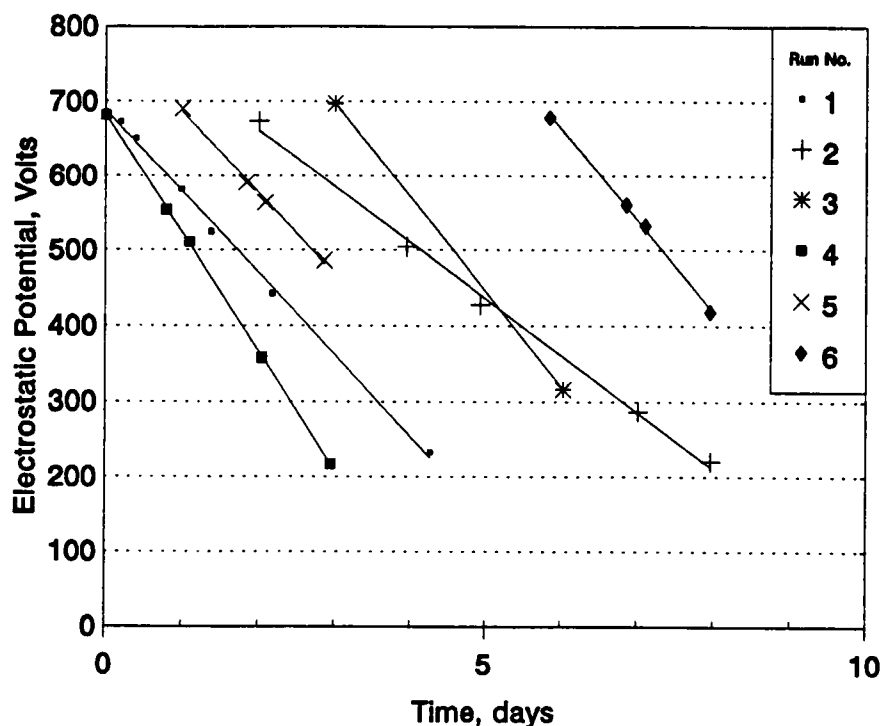


Figure 19 Electret ionization chamber response to soil with 50 pCi/g uranium and all decay daughters.

Table 15 Statistics for electret ionization chambers response to radiation from soil with 50 pCi/g of ^{238}U and all decay products.

Source Id.: Uranium decay series 50 pCi/g					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R ²
1	2212	7	3.2396	108.1	.998
2	1347	5	5.4771	75.1	.996
3	2220	2	3.0278	126.2	—
4	2298	5	2.9583	157.2	.999
5	2233	4	1.8681	109.4	.997
6	2288	4	5.0000	122.5	.998
Time weighted average slope =				112.4 ± 36	

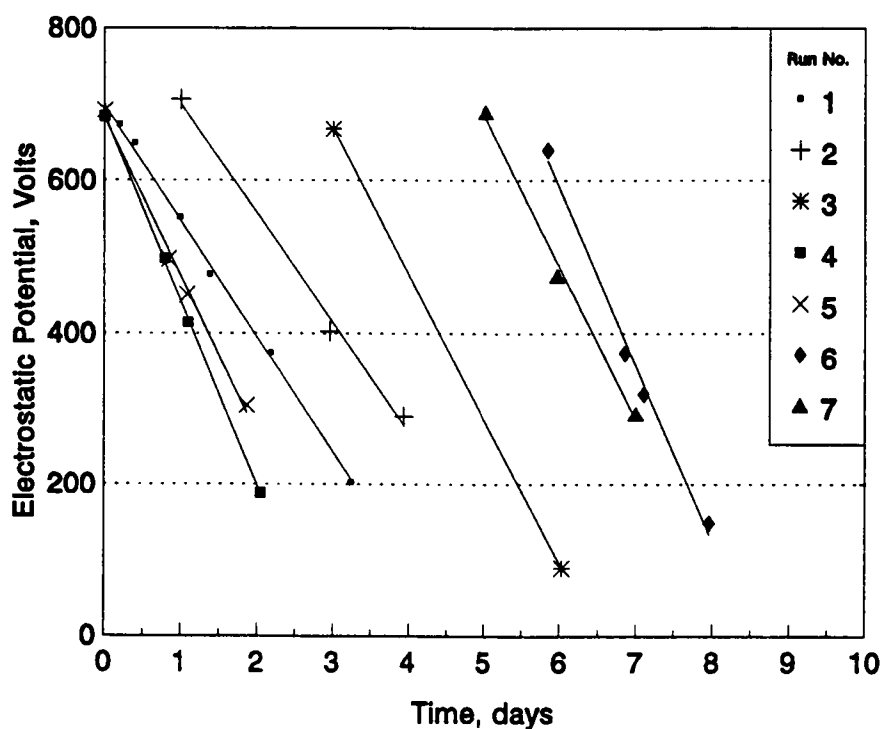


Figure 20 Electret ionization chamber response to soil with 100 pCi/g uranium and all decay daughters.

Table 16 Statistics for electret ionization chambers response to radiation from soil with 100 pCi/g of ^{238}U and all decay products.

Source Id.: Uranium decay series 100 pCi/g					
Run Number	Electret S/N	Number of Points	Elapsed Time, days	Slope, dV/dT	R^2
1	2235	7	3.2396	151.8	.997
2	1514	3	2.9354	143.6	.995
3	2198	2	3.0278	191.1	--
4	2267	4	2.0451	243.3	.999
5	1764	4	1.8681	207.2	.995
6	1708	4	2.1145	233.4	.993
7	2262	3	1.9791	199.7	.995
Time weighted average slope =				189.7 ± 49.6	

Tables 7 through 16 summarize the data for each standard by showing the slope for the each run and calculating the time weighted average slope with the error given at the 67 percent confidence level. Certain data points were omitted from the calculations because they were obviously in error. All of the omitted data were from run 2 and includes data for the 100 pCi/g depleted standard and the 30 and 50 pCi/g pitchblende standards. In each case the dV/dT was significantly less than for the other runs and likely explained by improper mixing prior to the run that resulted in a non-homogenous sample. This type of problem was expected as stated in Section II.

Field Testing

The ultimate goal of this work is demonstrate the applicability of the electret ionization chambers to determine the uranium soil concentration in samples in a field screening environment. An area of soil known to be contaminated with depleted uranium was located and likewise for natural uranium. Ten samples (≈ 30 g each) were collected from each area with a stainless steel trowel and placed in plastic containers. Each sample was "quick dried" in a microwave oven, ground by hand, passed through a 50 mesh screen, and a 20 g aliquot placed in a petri dish. One of the ten samples was collected from an area nearby the contaminated area so as to have at least one background soil sample. Along with the ten samples, the 30 pCi/g standard matching the same type of uranium was processed as a quality assurance measure. The daily quality check was performed on the electret reader and the voltage level was measured for each of the electrets used. The electrets were screwed into the plastic chamber and positioned over

the petri dishes containing the samples. All data were recorded on worksheets prepared for this work. The experiment was allowed to set overnight which would simulate the expected process during a typical radiological survey. The following morning the electrets were again measured for voltage to determine the dV/dT . The test samples were allowed to be analyzed the following night to give additional data for this work. This extra step would not normally be performed in actual field screening work. The completed worksheets are shown in Appendix 3 and the results are discussed in Section V.

Electret Reader Calibration Check

Each day the electret reader was used, a calibration check was performed. The calibration check uses a reference electret supplied by the manufacturer of the electret reader. The reference electret is a highly stabilized electret whose voltage is precisely determined by Rad Elect, Inc. Reference electret number R1921 with a voltage potential of 252 volts was used to perform the daily checks. The daily calibration check data is presented in Appendix 4. In addition to providing assurance of a properly functioning instrument, the data also can be used to determine an error associated with the electret reader operation.

Electret Quality Control Check

Each electret was tested to determine if its response to a known radioactive source was statistically comparable to the other electrets used in this work. The radioactive source used was a ^{230}Th electroplated source with an activity of 10,680 disintegrations

(alphas) per minute. This radioactivity caused the electrets to decrease in potential by 30 volts in a 3 minute period. An electret whose response was outside a 95 percent confidence band was retested. If the electret failed a second time, it was discarded. The response check data are presented in Appendix 5.

Direct Radiation Measurements Using Portable Radiation Instruments

At the conclusion of each run involving the prepared standards, the direct radiation was measured using portable survey instruments typically used in field work. The instruments used are described in Section III. For the instruments capable of making a timed count, the counts were integrated over a 1 minute period. Otherwise the analog display was interpreted to give a count rate. In some cases multiple measurements were made as time permitted. The data are shown in Table 17.

Ambient Environmental Conditions

During each run the temperature, barometric pressure, and the relative humidity were measured and recorded in parallel with the electret readings. The information was collected only to document the environmental conditions and to possibly explain any abnormal electret readings or trends. A review of the correlation coefficients, R^2 , in Tables 7 through 16 show the data sets to be very linear; therefore, no analysis of the environmental conditions data was performed. The data are recorded on the run data sheets in Appendix 2.

Table 17 Results of the direct radiation measurements of the prepared uranium soil standards.

Run No.	Instr. Id.	Instr.		Soil Bkgr	Depleted Uranium. pCi/g				Uranium Decay Series. pCi/g				
		Bkgr	Bkgr		10	30	50	100	10	30	50	100	
Alpha, cpm													
1	3490-14S	0	1	1	2	0	0	3	1	2	7		
2	3490-14S	0	2	0	2	0	1	3	5	4	4		
3	3490-14S	1	0	1	1	2	1	0	2	5	5		
4	3490-14S	1	0	2	1	2	2	2	3	4	4		
5	3490-06S	1	2	2	1	0	1	2	4	6	12		
Average		0.6	0.5	1.2	1.4	0.8	0.8	2.0	3.0	4.7	6.4		
Beta, cpm													
1	3940-16P	41	62	59	103	117	202	93	137	250	396		
2	3490-04P	43	38	77	107	142	178	100	149	235	389		
3	3490-20P	33	52	69	82	115	168	79	147	237	376		
			51	53	75	124	155	68	136	229	350		
4	3490-13P	36	42	59	84	117	202	98	149	237	364		
		49	67	55	86	110	186	75	155	217	406		
		40	58		108		162	101	157	234	367		
5	3490-13P	47	50	56	76	112	180	101	146	205	385		
			52	67	87	115	156	89	139	208	399		
Average		41	52	62	90	119	177	89	146	228	381		
Gamma, kepm													
1	3490-96SG	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.8	2.9		
3	3490-40SG	3.1	3.1	3.1	3.1	3.1	3.1	3.2	3.2	3.3	3.4		

V. Discussion of Results

Effects of Radon Loss

The effects of radon loss from samples before being placed in the electret ionization chambers were studied in three ways. First, assuming a certain fraction of the radon would be lost, the radioactive decay of existing nuclides and ingrowth of radon and its daughters were modeled using EQUIL over time to show the relative effect of the radon loss. Secondly, a uranium standard was subjected to extreme agitation to maximize radon loss by aeration that would occur when a soil sample would be collected during field studies. Finally, a uranium standard was subjected to heating at 150°C to maximize the radon loss that occurs when soil samples are dried before being analyzed for radioactivity.

Interpretation of EQUIL Results

Central to using the results from EQUIL, is the understanding that radon and its first three daughters account for three of the alpha particles and one beta particle in the uranium decay chain. To demonstrate these relationships, the following example is provided.

A soil sample is collected and prepared in such a manner to lose 90 percent (or retain 10 percent) of the radon originally in the sample. Using Figure 8, the curve representing 10 percent retention can be used to determine the relative alpha activity from radon and its first 3 daughters as decay and ingrowth occur over time. The minimum alpha activity occurs at about 200 minutes

from the "instantaneous" loss of the radon. At 200 minutes the alpha activity is only about one eighth of what it would have been if no radon had been lost. Since this one eighth is of 3 alpha particles from radon and its daughters, 0.37 alpha particles can be added to the 5 other alpha particles in the decay chain to give 5.37 out of the initial 8 alpha particles. Dividing 5.37 by 8 suggests that at time 200 minutes, the electret ionization chamber is measuring only 67 percent of the alpha activity it would be measuring at equilibrium. Assuming a sample was being analyzed over night (≈ 840 minutes) an integration would show that the overall results of the measurements would be 31 percent low.

Two important assumptions are made to use this model. First, the model assumes the losses of radon to be instantaneous and simultaneous. In relative terms, the collection and processing times are fairly instantaneous compared to time at which minimum activity occurs (≈ 200 minutes). On the other hand, the losses are not simultaneous, but may occur vary from hours to days apart. A soil sample may be collected and held for a couple of days before processing or analysis by field screening. However, this dilemma is self-correcting. Since the minimum activity is at ≈ 200 minutes, any sample held past that time is starting to recover its lost alpha activity and any subsequent processing (at worst) will remove any radon that has grown in and thus reset the 200 minute clock.

The other assumption dictates that after time zero, no other radon losses occur from the soil sample. Once a sample is prepared and placed in a petri dish, a small amount of radon loss by natural transport would be expected. However, any released radon only escapes into the electret ionization chamber and remains there to decay and thus be detected.

Radon Loss by Agitation

The results of the agitation experiment were given in Figure 9. Since the ^{214}Pb radioactivity data in Figure 9 have been normalized, the associated counting error must be derived from the gross counting data. Because radioactive decay is a random process, a normal distribution can be assumed about a mean. Here the mean activity of the ^{214}Pb is changing with time therefore a reasonable approximation of the error bounds is $\pm$ two standard deviations (2σ) of the measurement. The values in Figure 9 are normalized to 22,900 (the equilibrium value for the sample configuration) counts in 5 minutes or about 4580 counts per minute. The 2σ error is 135 counts per minutes or about 3 percent. By observing Figure 9 a retention fraction of 0.94 was determined with most of the experimental data falling within the ± 3 percent.

Radon Loss by Drying

The results of the drying experiment were given in Figure 10. Figure 10 also being normalized, as Figure 9, can be handled the same way. The values are normalized to 9400 (the equilibrium value for the sample configuration) counts per 5 minutes or 1880 counts per minute. The 2σ error is 87 counts per minutes or about 4.6 percent. By observing Figure 10, a retention fraction of 0.9 was estimated with most of the experimental data falling within the ± 4.6 percent.

Combined Losses

The agitation and heating experiments were extremes of what is expected under normal conditions; however, only one type of soil was tested. It is assumed the radon

expelled by the agitation and the drying represented the same fraction available in the soil vapor spaces indicating the two independent mechanisms accomplished the similar results and their effects are not cumulative. Therefore, an overall retention fraction of 0.9 will be used to account for radon losses in the sample collection and processing during the field-testing portion of this work.

Electret's Response to Uranium in Soil

The electret ionization chamber response was determined for 8 different uranium soil standards, for a soil sample with no uranium added, and for background gamma radiation. The uranium soil standards were of two types; depleted uranium and uranium pitchblende. Four concentrations of each type were used to encompass the range important for field screening. See Tables 2 and 3 for the actual ^{238}U concentrations of the soil standards and the ^{238}U occurring naturally in the background soil.

Five runs were conducted which involved exposing the electret ionization chambers to the standards from periods of 2 to 20 days. These exposure times are much longer than expected for field screening, but are necessary to determine correlation factors representative of performance with little variance. Additional runs were conducted on the standards with the most radioactivity because the electrets were exhausted in a much shorter time.

While Equation 3 provides the fundamental relationship equating the measured voltage drop to radioactivity, it does not allow the subtraction of ambient radiation background and the natural radioactivity in soil. The term kA in Equation 3 must be

expanded to account for the types of radiation just mentioned. The following terms and relationships are developed to account for background radiation.

$$\left(\frac{dV}{dT}\right)_{\Gamma} = k_{\Gamma} \Gamma \quad \text{Equation 10}$$

$$\left(\frac{dV}{dT}\right)_s = k_s S \quad \text{Equation 11}$$

$$\left(\frac{dV}{dT}\right)_u = k_u A_u \quad \text{Equation 12}$$

$$\left(\frac{dV}{dT}\right)_{\text{overall}} = \left(\frac{dV}{dT}\right)_{\Gamma} + \left(\frac{dV}{dT}\right)_s + \left(\frac{dV}{dT}\right)_u \quad \text{Equation 13}$$

Where:

- $(dV/dT)_{\Gamma}$ = change in voltage with respect to time due to background gamma radiation, $V \text{ d}^{-1}$,
- k_{Γ} = proportionality constant for the background gamma radiation, $V \text{ d}^{-1} / \mu R \text{ h}^{-1}$,
- Γ = background gamma radiation, $\mu R \text{ h}^{-1}$,
- $(dV/dT)_s$ = change in voltage with respect to time due to background soil radiation, $V \text{ d}^{-1}$,

- k_s = proportionality constant for the background soil radiation,
 $V \text{ d}^{-1}/\text{pCi g}^{-1}$,
 S = background soil ^{238}U concentration, pCi g^{-1} ,
 $(\text{d}V/\text{d}T)_u$ = change in voltage with respect to time due to soil ^{238}U
concentration radiation, $V \text{ d}^{-1}$,
 k_u = proportionality constant for the soil ^{238}U concentration above
background, $V \text{ d}^{-1} / \text{pCi g}^{-1}$,
 A_u = soil ^{238}U concentration above background, pCi g^{-1} ,
 $(\text{d}V/\text{d}T)_{\text{overall}}$ = change in voltage with respect to time due to all radiation, $V \text{ d}^{-1}$,

Substituting Equations 10, 11, and 12 into equation 13 gives

$$\left(\frac{\text{d}V}{\text{d}T} \right)_{\text{overall}} = k_{\Gamma} \Gamma + k_s S + k_u A_u \quad \text{Equation 14}$$

Since the relationships in Equations 10 and 11 represent background radiation and can be measured simultaneously, they can be combined to give Equation 15. Substituting Equation 15 into Equation 14 and solving for k_u yields Equation 16. After the two numerator terms on the right side of the Equation 16 were determined experimentally for different values of A_u , values for k_u were calculated.

$$\left(\frac{\text{d}V}{\text{d}T} \right)_{\text{background}} = k_{\Gamma} \Gamma + k_u S \quad \text{Equation 15}$$

$$k_u = \frac{\left(\left(\frac{dV}{dT} \right)_{\text{overall}} - \left(\frac{dV}{dT} \right)_{\text{background}} \right)}{A_u} \quad \text{Equation 16}$$

Table 18 gives a summary of the data from Tables 7 through 16 and the calculated values for k_u for the depleted uranium and pitchblende standards at the radioactivity levels tested. The k_u value for depleted uranium was determined to be $0.18 \text{ v d}^{-1}/\text{pCi g}^{-1}$. The k_u for ^{238}U and its daughters in equilibrium was determined to be $1.99 \text{ v d}^{-1}/\text{pCi g}^{-1}$.

Table 18 Summary of data used to correlate electret response to depleted uranium and uranium pitchblende standards.

Standard Id	^{238}U Activity, pCi g^{-1}	Net activity, pCi g^{-1}	Slope, V d^{-1}	Net slope, V d^{-1}	k_u Slope/Activity, $\text{v d}^{-1}/\text{pCi g}^{-1}$
Background	2.2	0	3.82	0.00	
U10	11	8.8	5.12	1.30	0.15
U30	35	32.8	10.94	7.12	0.22
U50	59	56.8	14.94	11.12	0.20
U100	115	112.8	21.2	17.38	0.15
Average DU slope [†]					$0.18 \pm .07$
U10+D	12	9.8	22.02	18.20	1.85
U30+D	37	34.8	80.85	77.03	2.20
U50+D	54	51.8	112.4	108.58	2.08
U100+D	107	104.8	189.7	185.88	1.79
Average U+D slope [†]					$1.99 \pm .38$

[†] Indicated errors for the average slopes is at the 95% confidence level.

To check if the k_u values are consistent with the decay characteristics of the different nuclides present, the various decay particles' energies (see Table 1) are divided by the corresponding W value for the particles (see Section II for discussion of W values) and these quotients are summed as in Equations 17 and 18.

$$IP_{DU} = \sum_{^{238}\text{U}}^{^{234}\text{Pa}} \left(\frac{\alpha}{W_{\alpha}} + \frac{\beta}{W_{\beta}} \right) = 1.24 \times 10^5 \text{ ion pairs} \quad \text{Equation 17}$$

$$IP_{Useries} = \sum_{^{238}\text{U}}^{^{210}\text{Po}} \left(\frac{\alpha}{W_{\alpha}} + \frac{\beta}{W_{\beta}} \right) = 1.26 \times 10^6 \text{ ion pairs} \quad \text{Equation 18}$$

Where:

- α = the average alpha particle energy in electron volts (eV) for each nuclide emitting an alpha in the appropriate decay series.
- β = the average beta particle energy in electron volts (eV) for each nuclide emitting a beta in the appropriate decay series.
- W_{α}, W_{β} = the average energy in eV to create an ion pair in air for alpha and beta particles, respectively.
- $IP_{DU}, IP_{Useries}$ = the average number of ion pairs created per decay of ^{238}U for depleted uranium and the entire uranium series, respectively.

Since the number of ion pairs (IP) are directly proportional to dV/dT , values for IP are proportional to the corresponding k values. This relationship permits the statement of Equation 19 and the resulting calculations.

$$\frac{IP_{DU}}{IP_{Useries}} \propto \frac{k_{DU}}{k_{Useries}} \quad \text{Equation 19}$$

$$\frac{IP_{DU}}{IP_{Useries}} = \frac{0.124 \times 10^6}{1.26 \times 10^6} = 0.098 \quad \text{and} \quad \frac{k_{DU}}{k_{Useries}} = \frac{0.18}{1.99} = 0.091$$

The good agreement between the two ratios indicates the k values are reasonable. This also implies that it is possible to calculate k values for other nuclides, decay series and combinations thereof. By calculating the IP values for a nuclide or series as in Equation 17 and then applying Equation 19, k values could be determined.

Results of Field Testing of the Electret Ionization Chambers

As described in Section IV, testing of the electret ionization chambers was performed as would be expected during field screening. Worksheets designed for the collection of the data and calculating the resulting ^{238}U concentration were completed and are given in Appendix 3. For the depleted uranium contaminated soil samples, Equation 21, a simple rearrangement of Equation 16 was adequate to determine the ^{238}U concentration above background.

$$A_u = \frac{\left(\left(\frac{dV}{dT} \right)_{overall} - \left(\frac{dV}{dT} \right)_{background} \right)}{k_u} \quad \text{Equation 21}$$

To account for possible losses of radon in samples suspected of containing the entire ^{238}U decay series, a correction factor was included in the calculations as given in Equation 22. Since a retention of 0.9 was determined experimentally, Figure 8 indicates the relative alpha radioactivity decreases very little ($< 3\%$) from the potential radon loss. Since the radon and its immediate daughters contribute 3 of the 8 alpha particles, the radon loss correction factor, R_{cf} , is $\{(1-0.03) \times 3 + 5\}/8$ or 0.99. While the R_{cf} value of 0.99 used here is nearly insignificant, if different soil types are tested, the impact of radon loss should be determined on a case-by-case basis or a default retention value assumed.

$$A_u = \frac{\left(\left(\frac{dV}{dT} \right)_{overall} - \left(\frac{dV}{dT} \right)_{background} \right)}{R_{cf} k_u} \quad \text{Equation 22}$$

A summary of the field test results and comparison to laboratory analyses by gamma spectroscopy is shown in Table 19. There are two differences between the way the field test samples and the laboratory standards were prepared. The laboratory prepared standards (see Section III) were dried at a constant temperature of 110°C for a minimum of 8 hours whereas the field test samples were heated in microwave oven for 5 minutes. The laboratory standards were passed through a 200 mesh screen but the field test samples passed through a 50 mesh screen. Future work may be directed to determine the significance of these differences.

Table 19 Summary of the field screening results and comparison to laboratory gamma spectroscopy analysis.

Sample Id	pCi/g (above background)			Success Bounds, pCi/g	
	Run 1	Run 2	Laboratory analysis [‡]	Lower (-25%)	Upper (+50%)
A1-1	84	36	24 ± 2	18	36
A1-2	100	86	98 ± 5	74	147
A1-3	10 (<12)	11 (<12)	12 ± 2	9	18
A1-4	2 (<12)	3 (<12)	0 ± 2	-	<18
A1-5	2 (<12)	11 (<12)	1 ± 2	-	<18
A1-6	43	61	35 ± 4	26	52
A1-7	2 (<12)	19	0 ± 2	-	<18
A1-8	2 (<12)	-6 (<12)	6 ± 2	-	<18
A1-9	18	19	-1 ± 2	-	<18
A1-10	35	28	24 ± 3	18	36
U30	37	37	35 ± 3	26	52
A2-1	0 (<2)	-1 (<2)	0 ± 2	-	<3
A2-2	0 (<2)	1 (<2)	-1 ± 2	-	<3
A2-3	28	28	20 ± 2	15	30
A2-4	60	61	43 ± 3	32	65
A2-5	17	17	13 ± 2	9	20
A2-6	-1 (<2)	0 (<2)	0 ± 2	-	<3
A2-7	0 (<2)	-1 (<2)	-1 ± 2	-	<3
A2-8	52	51	29 ± 3	22	44
A2-9	90	96	64 ± 4	48	96
A2-10	-2 (<2)	-1 (<2)	-1 ± 1	-	<3
U30+D	28	35	37 ± 5	28	55

[‡] Laboratory analyses were by gamma spectroscopy with the indicated error at the 95% confidence level.

The samples collected from the area contaminated with depleted uranium were designated A1-1 through A1-10. Sample A1-4 was collected as a background sample from a nearby location that should be representative of native soil. The uranium decay series samples were collected from a local shale outcrop containing natural uranium and its decay series. The uranium decay series were designated A2-1 through A2-10 with A2-1 being the background sample for this group.

The terminal objective of any analytical method is to accurately assess some parameter under certain circumstances. In this work ^{238}U soil concentration was to be analyzed in a location as close to the sampling site as practical. As shown in Table 19, the success of this field screening method is mixed. DOE suggest that field screening methods meet a Level 2 validation which only requires an accuracy of ± 100 percent (DOE 1992b). Personal experience demands a more restrictive success criteria but allowing more positive error. Success in this case was if the value measured by the electret ionization chamber was within -25 percent or +50 percent of the value determined by gamma spectroscopy when radioactivity was above background. For samples less than the detectable limit for the conditions, success was if the method calculated any value less than 50 percent above the detectable limit. A brief discussion on the detection limits for this method is provided later in this section. Even with these seemingly broad measures of success, some of the results from the field test do not meet the acceptance criteria.

The results for the depleted uranium samples show that 4 out of 20 values did not meet the criteria for success. Sample A1-1 was a factor 3 high for the first run but only

50 percent high on the second run. Sample A1-6 was only 20 percent high on run 1 but over 80 percent high for run 2. Sample A1-7 showed positive radioactivity when there was none. Sample A1-9 which had no measurable radioactivity above background showed positive in both runs and failing the success criteria in both runs. In both runs the correct concentrations for the ^{238}U standard was determined.

All of the results for the samples with the entire uranium series pass the success criteria except A2-8 which failed consistently high for both runs. The ^{238}U standards were also accurately assessed. Sample A2-9 produces consistently high results, but within the acceptance criteria. All of the results for samples with no radioactivity above background accurately reflected the absence of radioactivity.

In all cases where the electret ionization were grossly in error, the results were high. While over estimating the radioactivity is not the optimum, this result is preferred to under estimating the radioactivity. Over estimating the radioactivity generally draws attention to the sample and usually results in additional analyses.

Results of Electret Quality Control Checks

Prior to using each electret experimentally, the electret was checked to determine if its response to a known source was consistent with the other electrets. The source contained ^{230}Th electroplated to a steel disk. The emission rate of 10,680 alpha particles per minute over a three minute period caused a decrease in voltage of about 30 volts. The quality control check results are given in Appendix 4. The first 43 electrets tested lost an average of 30.4 volts with a standard deviation of 1.6 volts. Since radioactive decay is a random process, the distribution is gaussian and the 95 percent confidence

bounds are $30.4 \pm 2 \times 1.6$ or 27.2 and 33.6 volts. Because the electret reader does not display fractions of a volt, any electret whose voltage drop was outside the 27 to 34 volts was re-evaluated. Only two electrets (S/N 2292 and S/N 2236) responded improperly, dropping in voltage by 48 and 37 volts, respectively. On re-evaluation, they performed within the expected range. Two likely explanations include 1) inadvertently touching the electret surface or 2) accidentally allowing the electret to be exposed longer than the planned 3 minutes.

This response check is an important quality control measure for at least three reasons. While electrets are manufactured to specific standards, the manufacturer's quality control program is not infallible. Second, prior to use an electret could become damaged thus affecting its performance. Finally, there are several types of electrets that are similar in appearance and the possibility of using the wrong type of electret must be minimized.

Electret Reader Response Checks

The daily response check served two purposes; 1) to verify the electret reader is functioning properly, and 2) with many measurements of the same standard over time, a statement can be made regarding the error induced by reading the voltage of the electrets. The daily response checks are given in Appendix 3. The standard deviation of the voltage readings is 0.8 volts. Therefore, with 95% confidence, the electret reader should respond accurately within 1.6 volts of the true voltage value. This assumes the same precision over the voltage range encountered, generally 200 to 800 volts.

Results of the Portable Radiation Survey Instrument Measurements

At the end of each run, direct measurements of radiation were performed for alpha and beta radiation. Gamma radiation was measured only at the end of runs 1 and 3 because the type of instrument used only has a ratemeter and the variance from background was difficult to judge. All the results of direct radiation measurements are given in Table 17.

Although alpha particles have much more energy than the beta particles, their range is much shorter and attenuated easier, therefore are much more difficult to detect. For the depleted uranium standards, the change in count rate versus concentration is not noticeable. The count rate for the pitchblende while increasing with concentration is not significant enough to make quantitative decisions.

The measurement of the beta emission from the standards using typical radiation survey instrument produced results which may be useful in determining ^{238}U concentrations in soil. After subtracting the background count rate, a linear regression was performed for both set of standards. In both cases the linear fit was very good (R^2 values greater than 0.95). It is important to emphasize that the detectors were positioned over a dried standard, in a well-defined geometry, and the counts were integrated over a one minute period. Usually the detectors are used in a "scanning" mode searching for contamination that makes their response less sensitive. Nevertheless, using the detectors in a manner similar to the methods in this work has promise for field screening and should be further investigated.

Lower Limit of Detection

As with any analytical method it is important to be able to measure the parameter in question at a level lower than the guideline or compliance value. For this work the guideline value was established at 30 pCi/g of ^{238}U . As part of the experimental work, standards were prepared at one third the above value or 10 pCi/g. Table 18 shows that for both the depleted uranium and pitchblende standards the response to the 10 pCi/g standards is greater than background. Statistically a decision level L_c has been defined by Currie (1968) as follows.

$$L_c = (2.33)\sqrt{B} \quad \text{Equation 23}$$

Where:

2.33 = A combination of statistical parameters for paired observations with a confidence that the measurement is distinguishable from background and only 5 percent of the measurements will result in false positives.

B = Average background over the time period of interest.

For a time period of 14 hours and background of 3.82 V d^{-1} , B becomes 2.2 volts and L_c equals 3.48 volts. Therefore, for a 14 hour period, unless the electret's measured voltage drops by ≈ 6 ($2.2 + 3.48$) volts, the presence of ^{238}U contamination can not be deduced. If a decrease of 6 volts is used in Equation 21, along with a background of 2.2 volts and the appropriate k_u value, the minimum detectable concentration of ^{238}U above

background can be estimated. For depleted uranium the minimum detectable concentration above background calculates to be 12 pCi/g and about 2 pCi/g for the pitchblende material. Even though quantification of radioactivity less than the above values is not reasonable, Gilbert (1987) recommends reporting any calculated values, even negative ones.

Measurement Cost Estimates

One reason for choosing the electret ionization chamber method for conducting field screening is because of the low cost. A complete cost analysis is not attempted here but rather a description of cost in a generic sense. The only capital cost is the initial outlay for the electret reader and reference electrets, about \$1800 and \$200, respectively. The electret reader used in this work is one of the simpler models but is adequate for small scale operations. Features such as a built-in microprocessor, bar code reader, a computer interface, or an automated electret changer may be economically justified if large numbers of electrets are expected to be processed. An annual manufacturer calibration of the electret reader costs about \$200. The reusable plastic shells that form the ion chamber are \$15 each with the total number needed depending on the planned operation. Therefore with less than \$5000 all of the basic equipment needed to become "operational" can be procured.

The electrets are \$15 each and possibly less with a small rebate for "spent" electrets returned to the manufacturer. When analyzing samples with low amounts of radioactivity (≈ 50 pCi/g), a minimum of 5 analyses can be expected and for samples having only background radiation, as many as 40 individual analyses may be performed.

These figures place the electret cost per sample between \$0.40 and \$3.00. Assuming a fee of \$10 per sample is levied, less than 1000 samples will be needed to recover the initial investment.

Important to note is that the above costs do not include sample collection, sample processing, labor, quality assurance/control measures, and radioactive standards cost. These costs are inherent in any analytical method and therefore not quantified.

The implications of a low cost analysis have direct effects on project planning. Typical cost for an analysis by gamma spectroscopy varies between \$100 and \$200 per sample. If field screening is used to eliminate the need for some samples not to be analyzed by gamma spectroscopy, \$90 to \$190 per sample savings may be realized. If hundreds of samples are collected for a site/project, the savings are obvious. By reducing the cost per sample, the project engineer may desire more samples to provide a more detailed characterization.

Indirect savings are more difficult to quantify. The ability to analyze large numbers of samples in a timely manner gives the project engineer information on which to base decisions while field technicians and work crews still available. This on-hand information may also reduce the number of trips to a site. The ability to provide a field screening service may also be used as a marketing tool to obtain projects. While very real, these advantages are difficult to assign a monetary value.

VI. Conclusions

Correlation factors for electret ionization chambers response to depleted uranium standards and uranium pitchblende standards were experimentally determined to be 0.18 and 1.99 V d⁻¹/pCi g⁻¹, respectively. Electret ionization chambers were successfully used to determine the ²³⁸U concentrations in soil samples under conditions similar to those when field screening would be used. Eighty percent of the depleted uranium samples were within the success criteria and 90 percent of the uranium decay series samples met the success criteria. All of the results that failed the success criteria failed high, being the preferred direction of error. Other conclusions derived during this work are given below.

- Temperature, humidity, and barometric pressure effects can be ignored if typical indoor conditions are maintained. Loss of radon during sample collection and preparation was determined to bias the electret results one percent low for samples with the entire uranium decay series.
- The correlation factors determined are very specific and only apply to analyses performed under the same conditions and using the type materials as when the factors were determined. Some of the specifics include.
 - The nuclides and daughters present.
 - The sample and petri dish sizes.
 - The ionization chamber dimensions.
 - The electret type.

- The gross beta measurements of samples prepared for electret analysis provide screening data comparable in quality to the electret ionization chambers in a more timely manner for nuclides (or decay series) emitting beta particles.
- Inherent with analyzing samples for alpha emitting particles, non-homogeneous samples can significantly bias the results high or low. The electret ionization chamber method for ^{238}U is dependent on having a homogeneous sample and no single analysis can assure the analyst that the sample is indeed homogeneous.
- The major advantage of using electret ionization chambers relies on economy-of-scale. This advantage of the electret method is that once started, the samples need not be attended, where conventional nuclear counting of many samples requires constant attention to process the samples. The direct cost per sample was estimated to be \$3.

VII. Recommendations

While this method of field screening samples for ^{238}U is workable under certain conditions, additional work is recommended before making it available for use in field operations. The following recommendations are therefore mentioned.

- ▶ Investigate additional correlation values k empirically and experimentally for other nuclides, particularly alpha emitters.
- ▶ Investigate other sample sizes, chamber sizes, and sample containers to improve the overall sensitivity of the analysis.
- ▶ Perform a detailed economic analysis, with special emphasis on labor and material cost.
- ▶ Perform a detailed statistically based error analysis with comparison to classical nuclear counting methods for radioactivity.
- ▶ Conduct studies to evaluate potential problems arising from different sample drying methods and particle sizes (200 mesh vs 50 mesh) used to determine the correlation factors and when the samples are processed in the field setting.

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APPENDICES

APPENDIX 1

Computer Program EQUIL

```

/* program EQUIL */
/* This program uses the Bateman series equations */
/* to determine the equilibrium concentrations of the */
/* uranium daughters with varying amount of radon-222 */
/* removal rates. */
#include "stdio.h";
#include "math.h";
FILE *stream;
void Bateman (void);
double act_init[15] = {0.0,6*100.0, 0.0, 7*100.0};
double act_total[15] = {0.0,6*100.0, 5*0.0, 3*100.0};
d o u b l e h a l f l i f e [ 1 5 ] =
{1.0,2.345e15,34700.0,402.0,1.286e-9,4.068e9,8.415e8,
5505.84,3.05,26.8,19.9,2.728e-6,1.171e7,7218.72,199264.3};

/*      array #   Nuclide           Lamda           no
1      U-238
2      Th-234
3      Pa-234
4      U-234
5      Th-230
6      Ra-226           8.235E-10           1.214E11
7      Rn-222           1.259E-4            7.942E5
8      Po-218           0.2272             440.1
9      Pb-214           0.0286             3496.5
10     Bi-214           0.0382             2617.8
11     Po-214           2.54E5              3.9E-4
12     Pb-210
13     Bi-210
14     Po-210           */
int pn= 6;          /* parent nuclide pointer */
double n[15];
double lamda[15];      /* 0.693/half-life */
double activity[15];   /* fractional activity */
double n_0[15];        /* number of atoms @ time zero per 100 dpm*/
int t=0;              /* time in minutes */
int time_inc =1;      /* time increment in minutes */

/* main function */
void main (void)
{
    int i;
    double rrr;
    if((stream=fopen("rad_98.txt","w"))==NULL)
        printf("Can not Open file\n");

    rrr=0.98;          /*radon retention ratio */

```

```

for (i=1;i<=15;i++) {
printf("\n");
lamda[i]=0.693/half_life[i];
n_0[i]=100/lamda[i];
}
/* this will be the main loop incrementing time */
for (t=0;t<=30000;t+=time_inc){
    if(t==10) time_inc=10;
    if(t==500) time_inc=100;
    if(t==10000) time_inc=1000;
pn=6;
/* with pn=6 Ra-226 is the parent */
bateman();
    for(i=6;i<=11;i++)
    {
        act_total[i] += activity[i];
    };
/* with pn=7 Rn-222 is the parent */
pn++;
bateman();
    for(i=7;i<=11;i++)
    {
        act_total[i] += activity[i] * rrr;
    };

/* with pn=8 Po-218 is the parent */
pn++;

bateman();

    for(i=8;i<=11;i++)
    {
        act_total[i] += activity[i];
    };

/* with pn=9 Pb-214 is the parent */
pn++;

bateman();
    for(i=9;i<=11;i++)
    {
        act_total[i] += activity[i];
    };

/* with pn=10 Bi-214 is the parent */
pn++;
bateman();
    for(i=10;i<=11;i++)
    {
        act_total[i] += activity[i];
    };

```

```

/* with pn=11 Po-214 is the parent */
pn++;
bateman();
    for(i=11;i<=11;i++)
    {
        act_total[i] += activity[i];
    };

/* test print */
printf("\n %06d",t);
fprintf(stream,"\n %06d",t);
for (i=7;i<=10;i++)
{
    printf("%10.2f ",act_total[i]);
    fprintf(stream,"%10.2f ",act_total[i]);
    act_total[i]=0.0;
}

}
printf("\n ");
fprintf(stream,"\n");

fclose(stream);
}
/* ***** */
/* Bateman equilibrium series calculations */
/* ***** */
/* This function calculates the daughter concentration growing in */
/* the parent nuclide indicated by variable "pn". */
void bateman(void)
{
    int k,j,pn_o;
    double c[7],e_factor[7];
    pn_o=pn; /* save original pointer */
    j=pn;
    /* Zero the activity array */
    for (k=1;k<=14;k++){
        activity[k]=n[k]=0.0;
    }
    for (k=1;k<=6;k++) {c[k]=1.0;}

    /* calculate the exponential decay factors */
    for (k=1;k<=6;k++){
        if(j>=14) break;
        e_factor[k]=exp(-lamda[j++]*t);
    }

    /* Decay of parent */
    n[pn]=e_factor[1]*n_o[pn];

    activity[pn]=n[pn]*lamda[pn];

;

```

```

/* decay of second nuclide in chain (first daughter) */
pn++;
    if(pn==13) goto wrap_up; /* no point in continuing */

c[1]= lamda[pn_o]/(lamda[pn_o+1]-lamda[pn_o]);
c[2]= lamda[pn_o]/(lamda[pn_o]-lamda[pn_o+1]);
n[pn]=c[1]*e_factor[1]+c[2]*e_factor[2];
n[pn]*=n_0[pn_o];
    activity[pn]=n[pn]*lamda[pn];

;
/* decay of third nuclide in chain (second daughter) */
pn++;
    if(pn==13) goto wrap_up; /* no point in continuing */

c[1]*= lamda[pn_o+1]/(lamda[pn_o+2]-lamda[pn_o]);
c[2]*= lamda[pn_o+1]/(lamda[pn_o+2]-lamda[pn_o+1]);
c[3] = lamda[pn_o]*lamda[pn_o+1]/((lamda[pn_o]-lamda[pn_o+2])
    *(lamda[pn_o+1]-lamda[pn_o+2]));
for (k=1;k<=3;k++){n[pn]+=c[k]*e_factor[k];}

n[pn]*=n_0[pn_o];
    activity[pn]=n[pn]*lamda[pn];

/* ***** */
/* Decay of fourth nuclide (third daughter) */
pn++;
    if(pn==13) goto wrap_up; /* no point in continuing */

c[1] *= lamda[pn_o+2]/(lamda[pn_o+3]-lamda[pn_o]);
c[2] *= lamda[pn_o+2]/(lamda[pn_o+3]-lamda[pn_o+1]);
c[3] *= lamda[pn_o+2]/(lamda[pn_o+3]-lamda[pn_o+2]);
c[4] = lamda[pn_o]*lamda[pn_o+1]*lamda[pn_o+2]/
    ((lamda[pn_o]-lamda[pn_o+3])*(lamda[pn_o+1]-lamda[pn_o+3])*
    (lamda[pn_o+2]-lamda[pn_o+3]));
for (k=1;k<=4;k++){n[pn]+=c[k]*e_factor[k];}
n[pn]*=n_0[pn_o];
    activity[pn]=n[pn]*lamda[pn];

/* ***** */
/* Decay of fifth nuclide (fourth daughter) */
pn++;
    if(pn==13) goto wrap_up; /* no point in continuing */

c[1] *= lamda[pn_o+3]/(lamda[pn_o+4]-lamda[pn_o]);
c[2] *= lamda[pn_o+3]/(lamda[pn_o+4]-lamda[pn_o+1]);
c[3] *= lamda[pn_o+3]/(lamda[pn_o+4]-lamda[pn_o+2]);
c[4] *= lamda[pn_o+3]/(lamda[pn_o+4]-lamda[pn_o+3]);
for (k=pn_o;k<=pn_o+3;k++){c[5] *= lamda[k];}
for (k=pn_o;k<=pn_o+3;k++){c[5] /= (lamda[k]-lamda[pn]);}
for (k=1;k<=5;k++){n[pn]+=c[k]*e_factor[k];}
n[pn]*=n_0[pn_o];

```

```

        activity[pn]=n[pn]*lamda[pn];

/* ***** */
/* Decay of sixth nuclide (fifth daughter) */
pn++;
    if(pn==13) goto wrap_up; /* no point in continuing */

c[1] *= lamda[pn_o+4]/(lamda[pn_o+5]-lamda[pn_o]);
c[2] *= lamda[pn_o+4]/(lamda[pn_o+5]-lamda[pn_o+1]);
c[3] *= lamda[pn_o+4]/(lamda[pn_o+5]-lamda[pn_o+2]);
c[4] *= lamda[pn_o+4]/(lamda[pn_o+5]-lamda[pn_o+3]);
c[5] *= lamda[pn_o+4]/(lamda[pn_o+5]-lamda[pn_o+4]);

for (k=pn_o;k<=pn_o+4;k++) {c[6] *= lamda[k];}
for (k=pn_o;k<=pn_o+4;k++) {c[6] /= (lamda[k]-lamda[pn]);}
for (k=1;k<=6;k++){n[pn]+=c[k]*e_factor[k];}

n[pn]*=n_0[pn_o];

        activity[pn]=n[pn]*lamda[pn];

wrap_up:  pn=pn_o; /* reset pn to it value before function call */

/*          PRINT OUT CALCULATIONS */
/*          printf("\n***** %d *****\n",pn); */
/*          for (k=6;k<=11;k++) {
/*              if (activity[k]<0.00001) {activity[k]=0.0;}
/*              printf(" %10.4G ", activity[k]); */
/*          }
/*          printf("\n-----"); */

}          /* END OF BATEMAN */

```

APPENDIX 2

Electret Ionization Chamber Run Data

RUN No. 1

Date /Time	Temperature, °F	Humidity, %	Atmos Pressure (in. Hg)	²³⁵ U Concentration, pCi/g (Electret Serial No.)									
				0 no soil (1374)	0, Soil (2292)	10 (2175)	30 (7072)	50 (2227)	100 (2243)	10+D (2178)	30+D (1417)	50+D (2212)	100+D (2235)
9/20 835	70	73	29.2	689	645	681	563	695	690	667	703	687	685
9/20 1308	70	77	29.2	689	645	681	563	695	689	659	698	673	674
9/20 1800	71	77	29.1	690	645	680	563	693	689	654	689	651	650
9/21 820	70	80	29.2	686	643	674	556	691	677	635	641	582	552
9/21 1740	72	61	29.15	687	640	668	551	682	667	626	600	525	478
9/22 1300	70	72	29.2	687	639	665	535	672	647	608	533	443	375
9/23 1420	72	75	29.25	684	635	658	530	654	627	583	450	233	203
9/24 1500	72	72	29.2	683	623	655	515	641	597	561	382	---	---
9/28 1545	69	60	29.1	674	612	637	480	574	515	477	---	---	---
9/29 1500	71	69	29.3	674	608	634	470	555	486	463	---	---	---
Radiation Type				Instrument No.									
ALPHA				3490-14S									
BETA				3490-16P									
GAMMA				3490-96SG									

RUN No. 2

† New Electret put in place, S/N 1708 690 volts.

RUN No. 3

94

Electret Ionization Chamber Run Data

RUN No. 4

Date /Time	Temperature, °F	Humidity, %	Atmos Pressure (in. Hg)	²³⁸ U Concentration, pCi/g (Electret Serial No.)									
				0 no soil (2318)	0 Soil (1386)	10 (2210)	30 (1452)	50 (2285)	100 (2243)	10+D (7072)	30+D (2264)	50+D (2298)	100+D (2267)
11/2 1330	68	45	28.8	385	354	341	552	596	483	435	694	682	684
11/3 0830	71	44	29.4	383	349	336	543	579	466	412	620	554	498
11/3 1545	72	46	29.4	384	349	337	543	580	462	405	593	511	415 ††
11/4 1435	74	58	29.2	382	346	333	533	567	442	377	493	358	182
11/5 1230	74	64	29.5	381	339	330	542/511†	553	422	351	412	217	---
11/8 0945	75	41	29.4	371	323	317	479+13	502	355	276	189	679 †	640 †
11/9 1000	72	44	29.6	370	321	313	471+13	490	336	254	---	561	374
11/9 1600	72	47	29.45	370	321	313	470+13	489	333	249	---	533	320
11/10 1230	73	48	29.5	370	319	311	462+13	478	318	232	---	419	148
Radiation Type				Instrument No.									
ALPHA				3490-14S									
BETA				3490-13P									
GAMMA				---									

† Electret was dropped and lost 13 volts.

†† Electret was dropped and lost 6 volts, add 6 volts to following reading.

‡ New electrets put in place S/N 2288, 679 volts and S/N 2262, 640 volts.

RUN No. 5

96

APPENDIX 3

Electret Ionization Chamber - Field Screening Worksheet						
Electret Reader S/N: <u>261</u>				Background Correction, B_c : <u>16 v/d</u>		
Depleted Uranium Response Factor, k_{DU} : <u>0.18</u>				Uranium Series Response Factor, $k_{Useries}$: <u>n/a</u>		
Site: <u>A1</u>				Radon loss factor, R_{cf} : _____		
Sample ID.	Electret S/N	V_i	T_i	V_f	T_f	$(dV/dT-B_c)/R_{cf}k$
A1-1	1771	686	8/16	665	8/17	84
A1-2	2212	354	1648	331	0900	100
A1-3	2227	241	↓	229	↓	10
A1-4	2236	595	↓	584	↓	2
A1-5	1388	268	↓	257	↓	2
A1-6	1662	657	↓	641	↓	43
A1-7	2312	669	↓	658	↓	2
A1-8	1356	680	↓	669	↓	2
A1-9	1461	634	↓	621	↓	18
A1-10	1417	400	↓	385	↓	35
STD 35 pCi/g	2175	432	↓	425	↓	37
A1-1	1771	664	8/17	649	8/18	36
A1-2	2212	332	1700	311	0900	86
A1-3	2178	496	↓	484	↓	11
A1-4	2236	584	↓	573	↓	3
A1-5	1388	257	↓	245	↓	11
A1-6	1662	638	↓	628	↓	61
A1-7	2312	659	↓	646	↓	19
A1-8	1356	669	↓	659	↓	-6
A1-9	1461	620	↓	607	↓	19
A1-10	1417	385	↓	371	↓	28
STD 35 pCi/g	2175	425	↓	418	↓	37

Electret Ionization Chamber - Field Screening Worksheet						
Electret Reader S/N: <u>261</u>				Background Correction, B_c : <u>16 v/d</u>		
Depleted Uranium Response Factor, k_{DU} : <u>n/a</u>				Uranium Series Response Factor, $k_{Useries}$: <u>2.0</u>		
Site: <u>A2</u>				Radon loss factor, R_{cf} : <u>0.99</u>		
Sample ID.	Electret S/N	V_i	T_i	V_f	T_f	$(dV/dT-B_c)/R_{cf}k$
A2-1	1771	649	8/18	638	8/19	0
A2-2	2212	311	1640	300	0840	0
A2-3	2178	483	↓	435	↓	28
A2-4	2236	571	↓	481	↓	60
A2-5	1662	626	↓	593	↓	17
A2-6	1388	243	↓	234	↓	-1
A2-7	2312	641	↓	633	↓	0
A2-8	1356	658	↓	578	↓	52
A2-9	1461	604	↓	474	↓	90
A2-10	1417	369	↓	361	↓	-2
STD 37 pCi/g	2175	418	↓	378	↓	28
A2-1	1771	638	8/19	633	8/19	-1
A2-2	2212	300	0840	293	1750	1
A2-3	2178	433	↓	406	↓	28
A2-4	2236	479	↓	427	↓	61
A2-5	1662	592	↓	573	↓	17
A2-6	1388	235	↓	229	↓	0
A2-7	2312	632	↓	627	↓	-1
A2-8	1356	576	↓	531	↓	51
A2-9	1461	474	↓	395	↓	96
A2-10	1417	361	↓	356	↓	-1
STD 37 pCi/g	2175	377	↓	349	↓	35

APPENDIX 4

Daily Electret Reader Check

Reference Electret Id. R1921
Reference Electret Voltage 252

Date	Response, Volts		Date	Response, Volts
8/10/93	253		10/1	252
8/11	252		10/2	252
8/12	252		10/4	252
8/13	251		10/5	252
8/17	251		10/6	251
8/18	253		10/8	251
8/19	252		10/11	251
8/23	251		10/13	252
8/24	251		10/15	252
8/27	252		10/20	252
9/7	252		10/28	252
9/8	251		11/2	252
9/9	251		11/3	252
9/10	253		11/4	252
9/13	250		11/5	253
9/14	250		11/8	251
9/15	251		11/9	252
9/17	252		11/10	252
9/18	250		11/14	250
9/20	250		12/6	251
9/21	251		12/7	252
9/22	251		12/8	252
9/23	252		12/12	253
9/24	251		12/13	251
9/28	251		12/14	252
9/29	252		12/16	252

APPENDIX 5

Electret Quality Check Out

Radioactive Source ID: Th230-3827 Exposure time 3 min

ELECTRET S/N	Initial Voltage, V_i	Final Voltage, V_f	Voltage Difference, $(V_i - V_f)$
SI2227	724	697	27
SI2220	728	697	31
SI1765	737	705	32
SI2292	725	677	48
SI2292	677	648	29
SI2178	696	666	30
SI1417	735	703	32
SI1386	726	693	29
SI2212	722	691	31
SI1514	736	704	32
SI1399	713	681	32
SI2221	705	675	30
SI2318	699	668	33
SI1452	727	693	34
SI2285	719	688	31
SI2198	697	667	30
SI1708	716	685	31
SI2235	735	702	33
SI7072	592	563	29
SI1347	722	692	30
SI2243	721	691	30

Electret Quality Check Out

Radioactive Source ID: Th230-3827 Exposure time 3 min

ELECTRET S/N	Initial Voltage, V_i	Final Voltage, V_f	Voltage Difference, $(V_i - V_f)$
SI2264	722	694	28
SI2298	711	682	29
SI2267	714	684	30
SI2262	671	640	31
SI2288	710	679	31
SI1388	728	698	30
SI1542	701	671	30
SI1349	718	689	29
SI2186	722	694	28
SI1512	721	687	34
SI2244	725	694	31
SI1735	717	687	30
SI2191	708	680	28
SI2233	722	691	31
SI1764	722	692	30
SI2210	713	683	30
SI2175	717	687	30
SI2188	462	430	32
SI1674	502	476	29
SI1839	626	598	28
SI1706	651	621	30

Electret Quality Check Out

Radioactive Source ID: Th230-3827 Exposure time 3 min

ELECTRET S/N	Initial Voltage, V_i	Final Voltage, V_f	Voltage Difference, $(V_i - V_f)$
SI1388	328	300	28
SI2178	529	500	29
SI2227	312	283	29
SI1417	443	413	30
SI2212	401	368	33
SI2175	463	433	30
SI1771	726	697	29
SI1662	725	694	31
SI1461	671	641	30
SI2312	707	677	30
SI1356	714	682	32
SI2236	701	664	37
SI2236	664	634	30
SI2188	642	430	32
SI1674	502	473	29
SI1839	626	598	28
SI1706	651	621	30
SI1362	693	662	31
SI1787	573	543	30
SI2248	686	655	31

VITA

Mr. Michael Edward Murray was born in Corona, California on March 31, 1956 to Mr. Robert E. Murray and Mrs. Sadie N. Murray. He graduated from Madison High School in Nashville, Tennessee in June of 1974 and then attended Tennessee Technological University. In June of 1978, after obtaining the B.S. degree in chemical engineering he began full time employment with the Tennessee Valley Authority (TVA). In 1983 he met the requirements to be a licensed engineer in the State of Tennessee. Most of his career with TVA was spent at the Watts Bar Nuclear Plant where he became involved with radiochemistry and environmental aspects of plant operations. In May of 1988, he began working at the Oak Ridge National Laboratory (ORNL) specializing the nuclear safety of radiochemical operations. Desiring to return to hands-on operation, in May of 1991, he transferred within ORNL to the Health and Safety Research Division and began managing radiological characterization surveys. As a part time student at the University of Tennessee he received the Master of Science degree in Environmental Engineering in December of 1994.

He is currently employed as the Radiological Survey Programs Manager in the Measurement Applications and Development group at ORNL. He is married to Paula Kay Murray and together they raise three daughters.

