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A MODELING STUDY OF
GASEOUS RN-222, XE-133, AND HE-4
FOR URANIUM EXPLORATION

by

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1980

Work performed under Bendix Field Engineering Corporation Grand Junction
Operations Subcontract No. 78-076-L, and Bendix Contract DE-AC13-76GJ01664

Prepared for the United States Department of Energy
Grand Junction, Colorado

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TABLE OF CONTENTS

	Page
SUMMARY	viii
1.0 INTRODUCTION	1
2.0 STEADY-STATE MODELS FOR AN ORE BODY COVERED BY A PASSIVE OVERBURDEN	8
2.1 Diffusion of Rn-222 and Xe-133 through a Passive Overburden	8
2.2 Diffusion of He-4 through a Passive Overburden	15
2.3 Advection/Diffusion of Radiogenic Gases Through a Passive Overburden	24
3.0 STEADY-STATE MODELS FOR AN ACTIVE OVERBURDEN CONTAINING TRACE URANIUM AND THORIUM	32
3.1 Diffusion of Rn-222 and Xe-133 in an Active Overburden	32
3.2 Diffusion of He-4 in an Active Overburden	39
4.0 MULTIPLE-LAYER MODELS FOR RADIOGENIC GASES IN A ROCK COLUMN	50
4.1 A Multiple-Layer Model for Rn-222 and Xe-133 in a Rock Column	50
4.2 A Multiple-Layer Model for He-4 in Soil	54
5.0 TRANSIENT MODELS FOR ATMOSPHERIC PRESSURE EFFECTS ON RADIOGENIC GASES IN A ROCK COLUMN	63
6.0 COMPARISON OF MODEL RESULTS TO EXPERIMENTAL DATA	72
6.1 Summary of Data	76
6.2 Comparisons to Rn-222 and Daughter Products	77
6.3 Comparisons to He-4 Data	90
7.0 CONCLUSIONS	96
REFERENCES	98
NOMENCLATURE	101

Table of Contents (cont.)

	Page
APPENDIX I Experimental Data from Array I	103
APPENDIX II Experimental Data from Array II	107

LIST OF TABLES

	Page
1 Uranium, Actinium, and Thorium Decay Series	2
2 Detection Limits for Radon-222 and Daughter Products	3
3 Detection Ranges for a Planar Ore Body Covered by Active Overburden	37
4 Helium-4 Excess (ppb) at 1 m Depth Caused by a Planar Ore Deposit with Active Overburden	46
5 An Illustration of the Multiple-Layer Model	55
6 Layer-Averaged Data from Array I	81
7 Layer-Averaged Data From Array II	82
8 Correlation of Model Results to Pb-210 and Rn-222 Data	86

LIST OF ILLUSTRATIONS

	Page
1 Steady-State Diffusion Model Results for Rn-222 and Daughter Products in a Passive Overburden	11
2 Steady-State Diffusion Model Results for Xe-133 in a Passive Overburden	12
3 Excess He-4 in Soil Gas Produced by Various Grades of 1-Meter-Thick Uranium Ore	20
4 Effect of Rn-222 Emanation on He-4 Concentration Over a 1-Meter-Thick Uranium Ore Deposit	21
5 Excess He-4 in Pore Gas Produced by a 1-Meter-Thick Uranium Ore Deposit	23
6 Effect of Constant Soil Gas Velocity on Steady-State Rn-222 Profiles in a Passive Overburden	26
7 Effect of Constant Soil Gas Velocity on Steady-State Xenon-133 Profiles in a Passive Overburden	27
8 Effect of Constant Soil Gas Velocity on Steady-State Profiles of He-4 in a Passive Overburden	30
9 Profiles of Radon-222 and Daughter Products in a Uranium-Bearing Rock Covering an Ore Deposit	36
10 Profiles of Xe-133 in Active Overburdens ($U/Th = 1:4$) Covering a Uranium Ore Deposit	38
11 Profiles of Excess He-4 in Active Overburdens ($U/Th = 1:4$)	43
12 Profiles of Excess He-4 in Active Overburdens of Various U/Th Ratios ($U = 4$ ppm)	44
13 Comparison of Formulae for Calculating He-4 in Soil Gas	48
14 An Illustrative Profile of Rn-222 Calculated by the Multiple-Layer Model	56
15 An Illustrative Profile of Xe-133 Calculated by the Multiple-Layer Model	57

List of Illustrations (cont.)

	Page
16 Illustrative Profiles of He-4 Calculated by the Multiple-Layer Model	61
17 Variation of Rn-222 or Xe-133 Activity in a Passive Overburden Caused by Barometric Pumping with a 24 Hour Period	66
18 Effect of Pumping Period on Rn-222 Variations in a Passive Overburden	68
19 Effect of Rock Permeability on Rn-222 Variations Caused by Barometric Pumping	69
20 Effect of Rock Porosity on Rn-222 Variations Caused by Barometric Pumping	70
21 Generalized Geologic Map of Great Divide Basin with Location of Red Desert Research Site	74
22 Deep-Hole Sampling Arrays at the Red Desert Research Site	75
23 Fluorometric Uranium Concentrations and Layer Constructions for Array I	78
24 Fluorometric Uranium Concentrations and Layer Constructions for Array II	79
25 Comparison of Model Results to Field Data for Array I (Rn-222 and Daughter Products)	83
26 Comparison of Model Results to Field Data for Array II (Rn-222 and Daughter Products)	84
27 Comparison of He-4 Model Results to Field Data (expressed as excess He-4)	91
28 Comparison of Model Results to Field Data (expressed as δ ‰)	92

SUMMARY

This work presents one-dimensional mathematical models to simulate the transport of gaseous radon-222 (Rn-222), xenon-133 (Xe-133), and helium-4 (He-4) away from uranium ore deposits. The resulting concentrations of indicator nuclides in the overburden are used to infer the detectability of ore deposits by emanation methods.

In the case of homogeneous, non-radioactive formations, Rn-222 and some of its daughter products are calculated to be detectable at distances of several tens of meters from a planar uranium ore deposit (1 m thickness, 0.6% U_3O_8 , 20% emanation). When the overlying rock-sediment column is assumed to contain 4 ppm uranium, the masking effect of locally produced radon reduces detection range to 15 m (based on a 5/1 signal-to-background ratio). The same distance applies for observing a Xe-133 anomaly in an active overburden near a planar uranium deposit.

Models of He-4 diffusion in rock yield highly uncertain results because measurements of diffusion coefficients in actual rock types are lacking and because the flux of helium from deep within the earth is generally unknown. If a diffusion coefficient near 10^{-1} cm^2/sec is assumed (based on the Penman equation for dry soils), the helium concentration 20 m distant from the previously mentioned ore will be 0.5 ppb greater than the ambient level, which is not detectable. If a diffusion coefficient as low as 10^{-5} cm^2/sec is assumed, the same ore could produce a 3.5 ppm helium excess at this range. Comparisons of model results to field data suggest that He-4 diffusion coefficients of 10^{-4} to 10^{-5} cm^2/sec are appropriate. It is speculated that moisture in the rock column could reduce the coefficient significantly compared to the dry-soil case.

Inhomogeneity in rock formations is simulated by a multiple-layer model. Each horizon may be assigned uranium and thorium concentrations as well as a diffusion coefficient and physical properties. The model has been tested with deep-hole data from a piedmont sedimentary formation located in central Wyoming. Calculated results are highly correlated with measurements of Pb-210 (a solid daughter product of Rn-222). A comparison of fluorometric uranium data to gamma spectral measurements suggests the migration and deposition of Ra-226 near the water table. Modeling results are improved when this process is taken into account.

A constant soil gas velocity of 1×10^{-4} cm/sec causes indicator concentrations to change by several orders of magnitude. If steady upward soil gas motion exists in nature, the detectability of uranium ore by emanation methods will be significantly different from that indicated by pure diffusion models.

Barometric influences on gas transport are simulated by time-dependent numerical models. Sinusoidal variations in atmospheric pressure cause sinusoidal changes in gas concentrations which are attenuated with increasing depth. The effect is less than ± 15 percent near the soil surface for Rn-222 and Xe-133, while He-4 exhibits a maximum variation of 0.4 percent.

1.0 INTRODUCTION

The emanation method of uranium exploration consists of measuring the abundance of one or more uranium decay products at some distance from the orebody itself. The halo of decay products expands the exploration target and improves the chances of detection. This method assumes that indicator nuclides migrate away from the ore by some physio-chemical mechanism such as diffusion or solution in groundwater. The indicators must remain at detectable concentrations and be distinguishable from background levels.

This study is concerned with gas-phase transport of Rn-222, Xe-133, and He-4 away from uranium ore deposits. The first of these indicator nuclides, Rn-222, is a member of the uranium series decay chain (Table 1) and has a 3.82 day half-life. The second, Xe-133, is a spontaneous fission product which has a half-life of 5.26 days. Finally, He-4 is a stable nuclide created from alpha particles emitted by various members of the uranium, actinium, and thorium decay series.

Radon-222 has been studied more widely as a uranium indicator than either Xe-133 or He-4. Radon-222 is relatively easy to measure by means of its alpha emissions. This nuclide has greater significance because several of its daughter products are also detectable and become additional uranium indicators (Table 2).

Early investigations of Rn-222 in soil gas have been reviewed by Tanner (1964). A large portion of these studies have been performed in the Soviet Union and are summarized in a radiometric prospecting manual authored by Alekseev, Grammakov, Nikonov, and Tafeev (1957). According to this source, field measurements of Rn-222 in the vicinity of uranium ore deposits lead to the following conclusion:

TABLE 1

Uranium, Actinium and Thorium Decay Series

Uranium Series		Actinium Series		Thorium Series	
Nuclide	Half-Life	Nuclide	Half-Life	Nuclide	Half-Life
Uranium-238	4.5×10^9 yr.	Uranium-235	7.13×10^8 yr.	Thorium-232	1.41×10^{10} yr.
Thorium-234	24.1 days	Thorium-231	25.6 hr.	Radium-228	6.7 yr.
Protactinium-234	2.28 min.	Protactinium-231	3.48×10^4 yr.	Actinium-228	6.13 hr.
Uranium-234	2.50×10^5 yr.	Actinium-227	22.0 yr.	Thorium-228	1.91 yr.
Thorium-230	8.0×10^4 yr.	Thorium-227	18.2 days	Radium-224	3.64 days
Radium-226	1.62×10^3 yr.	Radium-223	11.7 days	Radon-220	55 sec.
Radon-222	3.82 days	Radon-219	3.92 sec.	Polonium-216	0.15 sec.
Polonium-218	3.05 min.	Polonium-215	1.83×10^{-3} sec.	Lead-212	10.64 hr.
Lead-214	26.8 min.	Lead-211	36.1 min.	Bismuth-212	60.6 min.
Bismuth-214	19.7 min.	Bismuth-211	2.15 min.	Polonium-212	304 nsec.
Polonium-214	1.6×10^{-4} sec.	Thallium-207	4.79 min.	Thallium-208	3.10 min.
Lead-210	22.3	Lead-207	Stable	Lead-208	Stable
Bismuth-210	5.0 days				
Polonium-210	138.4 days				
Lead-206	Stable				

TABLE 2

DETECTION LIMITS FOR RADON-222 AND DAUGHTER PRODUCTS

Nuclide	Type of Disintegration	Half-life	Detection Limit (dps/cm ³ soil)
Rn-222	α	3.82 d	3.6×10^{-4} (a)
Po-218	α, β	3.05 m	(b)
Pb-214	β	26.8 m	(b)
At-218	α	2.0 s	(b)
Bi-214	α, β	19.7 m	(b)
Po-214	α	1.64×10^{-4} s	(b)
Tl-210	β	1.32 m	(b)
Pb-210	β	22 y	1.0×10^{-3} (c)
Bi-210	β	5.0 d	1.0×10^{-3} (d)
Po-210	α	138 d	1.0×10^{-3} (e)
Tl-206	β	4.2 m	(b)
Pb-206	Stable		5ppm (f)
He-4	Stable		10ppb (g)

Notes:

- (a) Assumes a soil-porosity of 0.15 and 1 liter of soil gas sample introduced into a ZnS scintillation detector.
- (b) Half-life of nuclide considered too short for direct measurement by any technique of sensitivity comparable to that of radon-222.
- (c) Lead-210 decays by beta emission with end-point energy of 61 KeV which is too low for convenient measurement. Lead-210 activity is determined from bismuth-210 activity.
- (d) Assumes a soil aliquot of 50g is available for radiochemical separation and beta counting.
- (e) Assumes a soil aliquot of 400g is available for radiochemical separation and alpha spectroscopy.
- (f) Analysis of 1 gm of soil by chemical separation and isotope dilution mass spectrometry.
- (g) Measurement by mobile mass spectrometer (Reimer et al 1979).

Experience has shown that emanation surveys produce positive results in sediment covered areas if the thickness of the capping does not exceed 5-7m. This depth determines the average common penetration of the mutually connected radium and radon anomalies.

Alekseev et al. (1957).

In the 1930s, Grammakov and other Russian investigators published a series of mathematical expressions to characterize the diffusion and advection of Rn-222 in soil. These solutions are grouped into prospecting categories by Alekseev et al. (1957). They include one-dimensional, cylindrical, and spherical geometries. Results are used to calculate diffusion coefficients from radon measurements and to approximate the effective range of emanation methods.

More recent theoretical studies reported by Clements (1974), and by Clements and Wilkening (1974), derive and test one-dimensional models for gas migration in soil. Profiles of Rn-222 measured in a laboratory column agree with those predicted for both diffusive conditions and for a steady flow of soil gas. The same authors report time-dependent models for the variation in Rn-222 flux to the atmosphere caused by linear changes in barometric pressure. An important part of this work is the formulation of a differential equation which characterizes the one-dimensional advection and diffusion of a gaseous radioactive species in a homogeneous soil:

$$\frac{\partial C}{\partial t} = \frac{D}{\epsilon} \frac{\partial^2 C}{\partial z^2} - \frac{1}{\epsilon} \frac{\partial}{\partial z}(VC) - \lambda C + \phi \quad (1-1)$$

where:

- C = activity concentration expressed per unit of void volume of the soil, dps/cm^3 (disintegrations per second per cubic centimeter) ⁽¹⁾
- t = time, sec
- D = molecular diffusion coefficient of the species in the soil, cm^2/sec
- ϵ = porosity of soil; ratio of void to bulk volume
- Z = space dimension, cm
- V = velocity (current density) of soil gas, cm/sec ; volume of gas flowing per unit time per unit of geometric area
- λ = decay constant of the radioactive species, sec^{-1}
- ϕ = production rate of the radioactive species expressed per unit void volume of the soil, $\text{dps/cm}^3/\text{sec}$.

Other recent studies of Rn-222 are discussed by Smith, Barreto, and Pournis (1976) and by Tanner (1978). Current uranium surveys employ near-surface measurements of Rn-222 over large geographical areas. Anomalies have been correlated with uranium deposits buried at depths of the order of 100 m (Tanner, 1968). Theoretical studies include the presentation of finite-difference techniques for diffusion calculations by Soonawala and Telford (1975). A two-layer model for Rn-222 diffusion in a uranium mill tailings pile has been derived and verified by Clements, Barr, and Marple (1978). Finally, Jeter, Martin, and Schutz (1977) extended one-dimensional models to the spontaneous fission products Kr-85 and Xe-133 and simulated the influence of periodic barometric changes on Rn-222 transport in soils.

⁽¹⁾ The equation may be expressed either in terms of concentration (atoms/cm^3) or activity concentration (dps/cm^3). The latter is a direct measure of the former.

Literature concerned with He-4 as a mineral deposit indicator has been reviewed by Dyck (1976). Because this gas is non-radioactive and chemically inert, it can migrate great distances from its origin. The primary source of He-4 may be deep within the earth's crust (Eremeev, Sokolov, Solovov, and Yanitskii, 1972). In this case, the chief utility of near-surface He-4 measurements is to locate deep fractures and zones of high permeability which may be associated with various mineral deposits or geothermal energy sources.

Several studies of He-4 in soil gas have found no anomalies associated with known uranium deposits (Dyck, 1976). Others have found positive correlations (Goldak, 1974; Reimer and Otton, 1976; Pogorski, Quirt and Blascheck, 1977). Measurement of He-4 dissolved in groundwater appears more promising as a prospecting method (Clarke and Kugler, 1973; Dyck, 1976).

Mathematical analyses of helium diffusion in soil gas have been presented by Grammakov, Glebovskaya, and Khaykovich (1961, 1965). These works contain steady-state and time-dependent models for various configurations of soil, ore, and basement rock. The results indicate that a buried uranium deposit would not produce a significant helium excess near the earth's surface unless the overburden were relatively impermeable (characterized by diffusion coefficients of 10^{-4} or 10^{-5} cm²/sec). The results are not truly comparable to field data because actual measurements of He-4 diffusion coefficients are lacking and because the flux of helium from the basement rock can only be estimated.

Newton and Round (1961) have simulated helium migration deep within the earth's crust under the assumption that the sole mechanism is molecular diffusion through stagnant pore water. Several transient models are applied over geological time scales. The results indicate a slow transport process which may not account for the helium flow from the earth's crust. Golubev, Osipov, and Yanitskiy (1970) maintain that ascending fluid motion dominates diffusion as a transport process. Measurements of He-4 dissolved in groundwater can be fit to an advection/diffusion model if a logarithmic variation in vertical flow is assumed.

The work presented herein is an extension of the modeling study of Jeter, Martin, and Schutz (1977). Gas-phase transport of Rn-222, Xe-133 and He-4 are simulated in one dimension. The detectability of a planar ore deposit within a uranium-free formation (here referred to as "passive overburden") is investigated first. Models are then presented to evaluate the effects of trace uranium and thorium in the overburden.

Multiple-layer models are developed in this work in order to provide a more realistic characterization of geological formations. Each layer may be assigned physical characteristics and a unique concentration of U and Th. Results are compared to vertical profile measurements obtained in the Red Desert of Wyoming, USA.

Effects of soil gas flow are evaluated by steady-state and transient models. The barometric pumping model developed in the previous investigation is extended to include trace uranium and thorium in the overburden.

2.0 STEADY-STATE MODELS FOR AN ORE BODY COVERED BY A PASSIVE OVERBURDEN

This chapter considers several fundamental vertical transport models for the migration of radiogenic gases through soils which contain no uranium or thorium. The cases of Rn-222 and Xe-133 have been treated in the previous study (Jeter, Martin, and Schutz, 1977) but are restated in section 2.1 for completeness. The case of He-4 is introduced in section 2.2. Effects of steady flow of soil gas are considered in section 2.3.

2.1 Diffusion of Rn-222 and Xe-133 through a Passive Overburden

The one-dimensional advection/diffusion equation (1-1) can be simplified to characterize steady-state diffusion in a passive soil. The production term is zero because all the radioactive species are derived from the lower boundary of the model (i.e., from the uranium ore). Furthermore, the velocity term and the temporal derivative are assumed to be zero because only steady-state diffusion is considered. Equation 1-1 then becomes:

$$\frac{D}{\epsilon} \frac{d^2C}{dz^2} - \lambda C = 0. \quad (2-1)$$

The space coordinate (Z) is arbitrarily chosen to be directed downward and to have a zero value at the earth's surface (the upper boundary of the model). The interface between soil and the underlying uranium ore is designated $Z = L$, forming the lower boundary of the model.

Two boundary conditions are necessary to solve equation 2-1. At the earth's surface, the activity is maintained at zero due to interaction with the atmosphere ($C = 0$ at $Z = 0$). At the lower boundary of the model,

a constant activity flux for the radioactive species is specified having been derived from the assumed thickness, grade and emanation properties of the underlying uranium ore. Fick's law of diffusion is used to relate this activity flux to the activity concentration gradient at the lower boundary:

$$F = -D \frac{dC}{dz} \quad \text{at} \quad z = L$$

where: F = activity flux of the radioactive species at the lower boundary of the model, dps/cm²/sec

The solution of equation 2-1 with the stated boundary conditions is

$$C(z) = \frac{-F}{D W} \frac{\sinh \left(\frac{W z}{L} \right)}{\cosh \left(\frac{W L}{L} \right)} \quad (2-2)$$

where: $W = \sqrt{\frac{\epsilon \lambda}{D}}$

Equation 2-2 may be solved to give Rn-222 or Xe-133 concentrations in a passive overburden if the flux term F can be evaluated. This term has been related to the properties of the ore deposit (Jeter et al., 1977)

$$F_{Rn} = - 4.75 \times 10^{-2} (\text{ORETHK}) (\text{OREGRD}) (\text{EMRATE}), \quad (2-3)$$

$$F_{Xe} = - 1.38 \times 10^{-9} (\text{ORETHK}) (\text{OREGRD}) (\text{EMRATE}) \quad (2-4)$$

where: F_{Rn} = Rn-222 activity flux across the lower boundary, dps/cm²/sec
(negative when directed upward)

F_{Xe} = Xe-133 activity flux across the lower boundary, dps/cm²/sec

ORETHK = Thickness of ore deposit, m

OREGRD = Grade of ore, % U₃O₈

EMRATE = Fraction of the radiogenic gas which escapes the ore deposit in the upward direction.

Figures 1 and 2 show profiles of Rn-222 and Xe-133 calculated by equation 2-2⁽²⁾. Both cases illustrate a 0.6 percent U₃O₈ ore deposit, 1 m thick, covered by 100 m of passive overburden. Three values of the diffusion coefficient were run for each case as shown near the profiles. The lowest value of 0.006 cm²/sec was used by Robertson (1969) for a modeling study of Xe-133 in soil. The other two values were discussed by Moore and Poet (1978) for modeling Rn-222 in soil. The intermediate value of 0.02 cm²/sec is considered the most typical value for soil and is supported by the theoretical and experimental study of Clements (1974).

The profiles in Figures 1 and 2 are straight lines at depths greater than a few meters indicating their nearly exponential nature. At shallower depths they depart from exponential and tend toward zero activity at $Z = 0$ (the boundary condition) according to the hyperbolic character of equation 2-2.

---

(2) In order to present a consistent set of units for gaseous and solid species, all gas activities are multiplied by the soil porosity to allow expression in terms of dps/cm³ overburden. The meaning of C (equation 1-1) remains unchanged, however, in that activity trapped within mineral grains is excluded.

FIGURE 1

STEADY-STATE DIFFUSION MODEL RESULTS
FOR RN-222 AND DAUGHTER PRODUCTS
IN A PASSIVE OVERBURDEN

FIGURE 2

STEADY-STATE DIFFUSION MODEL RESULTS
FOR Xe-133
IN A PASSIVE OVERBURDEN

Radon-222 concentrations illustrated in Figure 1 have additional significance because of the assumption of steady state. At each point in the rock column a radioactive equilibrium will exist between the constant Rn-222 activity and its daughter products which are listed in Table 2. As a consequence, steady-state profiles of radon activity in the rock column also indicate activity of all daughter nuclides. This is an important consideration in geochemical prospecting because the various daughter products may present advantages in measurement compared to Rn-222.

Detectability of the uranium deposit modeled in Figure 1 may be ascertained with reference to Table 2. By transferring the detection limit of any nuclide in the table onto the activity axis and drawing a vertical line, it can be determined at what distance from the ore the soil will exhibit a measurable activity. As an example, Rn-222 has a detection limit of 4×10^{-4} dps/cm³ soil. Transferring this value vertically onto Figure 1 shows that the ore at 100 m produces measurable radon concentrations at depths greater than 70 m (assuming $D = 0.02$ cm²/sec). The detection range is consequently 30 m from the ore. If a diffusion coefficient of 0.006 cm²/sec is assumed, the same graphical method results in a detection range of 18 m. Increasing the diffusion coefficient to 0.05 cm²/sec expands the range to 47 m.

The detection range of Xe-133 can be similarly derived from Figure 2. This nuclide can be measured to a level of 3.6×10^{-9} dps/cm³ soil using a large-volume sampling system.⁽³⁾ Transferring this value to Figure 2 indicates that xenon could be detected at depths greater than 85 m (assuming $D = 0.02$ cm²/sec).

The steady-state diffusion model indicates detectability of Rn-222 (and its daughter products) and Xe-133 at several tens of meters from the ore. Judgement on the physical validity of this result must be reserved, however, until some of the simplifying assumptions are removed. In particular, the effects of trace U and Th in the overburden are considered in section 3, and effects of soil gas velocity are treated in section 2.3 and in section 5.

---

(3) Xenon is removed from a 1 m³ air sample by a cryogenic and chromatographic separation system. The radioactivity of the gas is measured in a 100 cm³ static proportional counter.

2.2 Diffusion of He-4 through a Passive Overburden

The one-dimensional equation which describes the diffusion of He-4 through a passive overburden in steady state is:

$$\frac{D}{\epsilon} \frac{d^2C}{dz^2} + \phi(Z) = 0 \quad (2-5)$$

Equation 2-5 differs from 2-1 in that there is no decay term (He-4 is a stable gas). Furthermore, there is a depth-dependent production term $\phi(Z)$ caused by the alpha decay of Rn-222 and its daughters in the overburden. It is important to note that although the overburden is "passive" in that it is assumed to contain no U or Th, it nevertheless produces He-4 by decay of Rn-222, Po-218, Po-214, and Po-210 derived from the underlying body of ore. The source of He-4, therefore, is expanded beyond the limits of the ore deposit itself.

An expression for the local production term $\phi(Z)$ is derived by noting that in secular equilibrium each of the three alpha emitting daughters of Rn-222 produces a helium atom at the decay rate of Rn-222 itself. Consequently, the local production rate (atoms/cm³void/sec) is four times the steady-state activity of Rn-222 (dps/cm³void). Referring to equation 2-2, the production rate becomes

$$\phi(Z) = \frac{-4 F_{Rn} \sinh(WZ)}{D_{Rn} W \cosh(WL)} \text{ atoms/cm}^3\text{void/sec} \quad (2-6)$$

Substituting expression 2-6 into 2-5 and collecting terms yields

$$\frac{D}{\epsilon} \frac{d^2C}{dz^2} + G \sinh(WZ) = 0 \quad (2-7)$$

where:
$$G = \frac{-4 F_{Rn}}{D_{Rn} W \cosh (WL)}$$

Equation 2-7 requires two boundary conditions. At the overburden surface, we specify a helium concentrations equal to the atmospheric value:⁽⁴⁾

$$C = C_{atm} = 1.3 \times 10^{14} \text{ atoms/cm}^3 \text{ void at } Z = 0.$$

At the base of the rock-sediment column the helium flux from the ore is related to the concentration gradient by Fick's law:

$$F_{He} = -D \frac{dC}{dZ} \text{ at } Z = L.$$

The solution to equation 2-7 with the stated boundary conditions is

$$C = C_{atm} + \left(\frac{G \cosh (WL)}{D W} - \frac{F_{He}}{D} \right) Z - \frac{G}{D W^2} \sinh (WZ). \quad (2-8)$$

It is often convenient to express the He-4 concentration in terms of a difference from the atmospheric concentration:

$$C_{excess} = C - C_{atm}. \quad (2-9)$$

---

(4) The atmospheric concentration was calculated from the nominal value of 5.24 parts-per-million by volume using the ideal gas law. A pressure of 1 atm and a temperature of 20° were assumed.

This is accomplished by omitting the first term in equation 2-8. Moreover, a concentration may be expressed in parts-per-million (ppm) or parts-per-billion (ppb) as follows: (5)

$$C \text{ (ppm)} = C \text{ (atoms/cm}^3\text{void)} \times 4.0 \times 10^{-14} ;$$

$$C \text{ (ppb)} = C \text{ (atoms/cm}^3\text{void)} \times 4.0 \times 10^{-11} .$$

In order to use equation 2-8, the helium flux F_{He} must be expressed in terms of the uranium ore characteristics. An ore having OREGRD percent U_3O_8 and a bulk density of 2.2gm/cm^3 will contain $(1.866 \times 10^{-2})(\text{OREGRD}) \text{ gm U/cm}^3$ ore. Of this, 99.28 percent is U-238. An ore layer ORETHK meters thick will contain $4.687 \times 10^{21} (\text{OREGRD})(\text{ORETHK}) \text{ atoms U-238/cm}^2 \text{ ore}$. With $\lambda = 4.87 \times 10^{-18}/\text{sec}$ (6), the number of U-238 atoms decaying by alpha emission is $2.28 \times 10^4 (\text{OREGRD})(\text{ORETHK}) \text{ dps U-238/cm}^2 \text{ ore}$.

In secular equilibrium, each of the eight alpha emitters in the uranium chain produces a helium atom at the decay rate of U-238. The first three of these are solid (U-234, Th-230, Ra-226) and produce helium at the location of the ore itself. The next nuclide (Rn-222) is a gas, however, of which the fraction EMRATE has escaped the orebody. This source of helium is treated separately as indicated in equations 2-5 and 2-6. Consequently, a fraction $(1-\text{EMRATE})$ of the Rn-222 remains bound in the mineral and produces four helium atoms for each equilibrium disintegration (Rn-222, Po-218, Po-214, Po-210). Accounting for all alpha emitters remaining in the ore,

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(5) According to the ideal gas law, 1 cm^3 of gas at 1 atm pressure and 20°C contains 2.51×10^{19} molecules. Consequently, $2.51 \times 10^{13} \text{ atoms He/cm}^3$ represents 1 ppm and $2.51 \times 10^{10} \text{ atoms He/cm}^3$ represents 1 ppb. The reciprocals of these quantities are the conversion factors indicated.

(6) This value is derived from a half-life of 4.51×10^9 years according to a standard reference (Lederer, Hollander and Perlman, 1967). Other sources may indicate slightly different values.

the U-238 chain production of helium is

$$[4+4(1-EMRATE)] \ 2.28 \times 10^4 \ (OREGRD)(ORETHK) \ \text{atoms He-4/cm}^2 \ \text{ore/sec.}$$

Production of helium by the actinium series is derived by noting that 0.72 percent of the uranium in the ore is U-235. The rate of U-235 atom decay by alpha emission is $1.06 \times 10^3 \ (OREGRD)(ORETHK) \ \text{dps U-235/cm}^2 \ \text{ore.}$

In secular equilibrium, each of the seven alpha emitters in the actinium chain produces a helium atom at the decay rate of U-235. Unlike the uranium series, the gaseous radon isotope (Rn-219) has such a short half-life (4 sec) that its escape from the ore can be ignored. The helium production rate by the actinium series then becomes $7.42 \times 10^3 \ (OREGRD)(ORETHK) \ \text{atoms He/cm}^2 \ \text{ore/sec.}$

Adding the two production figures and re-arranging terms yields

$$P_{\text{He}} = - \left[1.90 \times 10^5 - (9.12 \times 10^4) EMRATE \right] (OREGRD)(ORETHK) \ \text{atoms He/cm}^2 \ \text{ore/sec.} \quad (2-10)$$

The negative sign in expression 2-10 is used to specify that the helium flux is upward. This is equivalent to assuming the presence of an impenetrable boundary underlying the ore. In addition, equation 2-10 implies that helium escapes the ore at the same rate at which it is produced (an assumption of

steady state). The equation therefore represents the maximum helium flux available from a planar uranium ore deposit.

Figure 3 shows He-4 profiles in a passive overburden calculated for various grades for a 1-meter-thick uranium orebody. This case represents a dry rock column having a porosity of 0.15. The diffusivity of He-4 in soil gas was calculated to be 0.07 cm²/sec by the Penman equation (Penman, 1940).

$$\frac{D}{D_o} = 0.66 \epsilon \quad (2-11)$$

where: D = diffusivity in soil gas (cm²/sec)

D_o = diffusivity in air (cm²/sec)

ϵ = rock porosity

A value of D_o was chosen to be 0.73 cm²/sec according to measurements of helium diffusion in both nitrogen and oxygen (Reid and Sherwood, 1966).

The profiles of excess helium in Figure 3 are nearly straight because the term $-\frac{F_{He}}{D} z$ is dominant in equation 2-8. In fact, if the radon

emanation of the ore is set equal to zero, equation 2-8 reduces to

$$C = C_{atm} - \frac{F_{He}}{D} z \quad (2-12)$$

This linear relationship was also derived by Grammakov et al. (1961) by neglecting the emanation of radon from the orebody.

Figure 4 gives a more precise illustration of the influence of radon emanation on excess helium profiles. This plot was derived from equation 2-8 by varying EMRATE (and hence F_{Rn} and G according to 2-3 and 2-7).

FIGURE 3

EXCESS HE-4 IN SOIL GAS
 PRODUCED BY VARIOUS GRADES
 OF 1-METER-THICK URANIUM ORE
 (PASSIVE OVERBURDEN)

FIGURE 4
 EFFECT OF RN-222 EMANATION
 ON HE-4 CONCENTRATION OVER
 A 1-METER-THICK
 URANIUM ORE DEPOSIT

The results shown in Figure 4 have been normalized to the zero emanation case (equation 2-12). Effects of radon emanation are maximum within 10 m of the ore and become less than 1/2 percent through the rest of the overburden column.

Variation of porosity (ϵ) in equation 2-8 has a negligible effect because it does not influence the dominant term $\frac{F_{HE}}{D} Z$. The porosity does not appear in equation 2-12⁽⁷⁾.

Significant changes in helium profiles can be produced by varying the diffusion coefficient D . Grammakov et al. (1965) used values of 10^{-3} , 10^{-4} and 10^{-5} cm²/sec to represent the diffusion coefficient of He-4 in rock. These values are not based upon measurement but were chosen to represent a probable range. The physical situation considered is diffusion through interconnecting pores of the rock analogous to the soil-gas case. The model does not include rock pores which are sealed.

The profiles in Figure 5 illustrate diffusion of helium from a uranium ore through a passive overburden. When a value of 10^{-5} cm²/sec is used for D , helium concentrations at the ore surface are calculated to be 4 ppm higher than the atmospheric value. The concentration decreases with distance from the ore, however. Figure 5 indicates an excess He-4 concentration of 0.5 ppm in rock pore gas at a depth of 10 m and 45 pph at a

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(7) The diffusion coefficient, D , has been defined by Fick's law as the ratio of flux to the interstitial gas concentration gradient (Clements, 1974) Porosity has a direct effect if concentrations are converted to a bulk basis.

FIGURE 5

EXCESS HE-4 IN PORE GAS
 PRODUCED BY A 1-METER-THICK
 URANIUM ORE DEPOSIT

(PASSIVE OVERBURDEN)

near-surface sampling depth of 1 meter. The latter concentration would be detectable with mobile equipment described by Reimer et al. (1979) which has a sensitivity of 10 ppb. The hypothetical ore deposit at 100 m would not produce a detectable He-4 anomaly at 1 m depth, however, if a diffusion coefficient of 10^{-4} cm²/sec or greater is assumed. These results must be considered preliminary because the influence of trace uranium and thorium in the overburden and in the underlying strata has not yet been modeled (see sections 3 and 6).

Newton and Round (1961) used a diffusion coefficient of 10^{-5} cm²/sec to characterize the migration of helium through water-saturated sedimentary rock. This was considered a maximum value because the diffusion coefficient for helium through plain water has been measured at 3×10^{-5} cm²/sec (Arnold, 1930). Although the present model does not include any complex phenomenon such as solubility, Figure 5 may be used to approximate the magnitude of diffusion effects in a water-filled porous medium.

2.3 Advection/diffusion of Radiogenic Gases through a Passive Overburden

The influence of constant soil gas velocity on the transport of Rn-222 and Xe-133 in passive overburden has been discussed in the previous study (Jeter et al., 1977). The results will be restated for completeness and then expanded to include the transport of He-4.

Equation 1-1, for the case of constant velocity, becomes

$$\frac{D}{\epsilon} \frac{d^2C}{dz^2} - \frac{V}{\epsilon} \frac{dC}{dz} - \lambda C + \phi = 0 \quad (2-13)$$

The production term (ϕ) is zero for Rn-222 or Xe-133 migrating through a passive overburden. Boundary conditions for these gases can be chosen

similarly to those previously used. At the overburden surface the activity is maintained at zero ($C = 0$ at $Z = 0$). At the interface between overburden and ore, however, the flux boundary condition must include an advection term:

$$F = -D \frac{dC}{dz} + VC \quad \text{at } Z = L$$

The solution to this differential equation with the stated boundary conditions is the following:

$$C(Z) = H \left(e^{r_1 Z} - e^{r_2 Z} \right) \quad (2-14)$$

where: $r_1 = \frac{V}{2D} + \frac{1}{2} \sqrt{\frac{V^2}{D^2} + \frac{4\epsilon\lambda}{D}}$

$$r_2 = \frac{V}{2D} - \frac{1}{2} \sqrt{\frac{V^2}{D^2} + \frac{4\epsilon\lambda}{D}}$$

$$H = \frac{F}{\left(\frac{-Dr_1 + V}{e^{r_1 L}} \right) + \left(\frac{r_2 D - V}{e^{r_2 L}} \right)}$$

Figures 6 and 7 demonstrate the effect of constant velocity on profiles of ^{222}Rn and ^{133}Xe . A single ore depth of 100 meters and a diffusion coefficient of $0.02 \text{ cm}^2/\text{sec}$ are chosen for these illustrations. Soil gas velocities of $\pm 1 \times 10^{-4} \text{ cm/sec}$ are shown along with the pure diffusion case. Velocities of this magnitude are found near the overburden surface as a result of atmospheric pressure changes (section 5).

The illustrative profiles in Figures 6 and 7 show near-surface activity variation of a factor of ten million or more compared to the pure diffusion case. If velocity effects this large were actually obtained, the detectability of uranium would be changed significantly from the results of sections 2.1 and 2.2. Mogro-Campero and Fleischer (1976) have suggested that

FIGURE 6

EFFECT OF CONSTANT SOIL GAS VELOCITY
ON STEADY-STATE RN-222 PROFILES
IN A PASSIVE OVERBURDEN

FIGURE 7

EFFECT OF CONSTANT SOIL GAS VELOCITY
ON STEADY-STATE XENON-133 PROFILES
IN A PASSIVE OVERBURDEN

the geothermal gradient would cause fluid convection within the earth. This mechanism may produce long-term motion and exert an influence similar to that expressed by equation 2-14. It is evident that advective transport merits consideration in models simulating the migration of uranium daughter products.

Steady advection/diffusion of He-4 through a passive overburden is also described by the differential equation 2-13. In this case, however, the production term ϕ is retained because of Rn-222 decay within the soil column. As described in section 2.2, the local production of He-4 (atoms/cm³ void/sec) is four times the steady-state activity of Rn-222 (dps/cm³ void). Under conditions of constant velocity this Rn-222 activity is given by equation 2-14. Consequently, the differential equation to be solved for helium is

$$\frac{D}{\epsilon} \frac{d^2C}{dz^2} - \frac{V}{\epsilon} \frac{dC}{dz} + 4H \begin{pmatrix} r_1 z & r_2 z \\ e & -e \end{pmatrix} = 0 . \quad (2-15)$$

The boundary conditions appropriate to solving equation 2-15 are:

$$C = C_{atm} \quad \text{at} \quad z = 0$$

$$F_{He} = -D \frac{dC}{dz} + VC \quad \text{at} \quad z = L .$$

The solution then becomes

$$C = M + Ne^{\frac{V}{D}z} + \frac{4\epsilon H}{r_1(V - Dr_1)} e^{r_1 z} + \frac{4\epsilon H}{r_2(Dr_2 - V)} e^{r_2 z} \quad (2-16)$$

where:

$$M = \frac{4\epsilon HD}{(V-Dr_1)V} \left(1 - \frac{V}{Dr_1}\right) e^{r_1 L} + \frac{4\epsilon HD}{(Dr_2-V)V} \left(1 - \frac{V}{Dr_2}\right) e^{r_2 L} + F_{He}$$

$$N = C_{atm} - M - \frac{4\epsilon H}{r_1(V-Dr_1)} - \frac{4\epsilon H}{r_2(Dr_2-V)}$$

Figure 8 illustrates the effect of constant soil gas velocity on steady-state profiles of He-4 in a passive overburden. Equation 2-16 was used to calculate helium concentration using velocities of $\pm 1 \times 10^{-4}$ cm/sec. The results differ from those of Rn-222 and Xe-133 (Figures 6, 7) in that concentration effects increase as the ore is approached. The results are similar in magnitude, however, being 10^{-5} to 10^7 at maximum.

In considering the physical meaning of Figures 6, 7 and 8, it must be recognized that the conditions chosen are not realistic. The boundary condition used at the ore surface

$$F = -D \frac{dC}{dz} + VC$$

specifies an upward flux of the radiogenic gas regardless of the magnitude or direction of the soil gas velocity. In reality, velocity effects within and below the ore should be considered. Figures 6 through 8, then, are not accurate representations of the effects of steady soil gas flow. They do demonstrate, however, that a soil gas velocity of 10^{-4} cm/sec would dominate diffusion as a transport mechanism. A larger scale advection/diffusion

FIGURE 8

EFFECT OF CONSTANT SOIL GAS VELOCITY
ON STEADY-STATE PROFILE OF HE-4
IN A PASSIVE OVERBURDEN

model is required to find whether steady soil gas flow is feasible (by geothermal convection or by some other mechanism) and what the effect would be on distributions of the radiogenic gases.

3.0 STEADY-STATE MODELS FOR AN ACTIVE OVERBURDEN CONTAINING TRACE URANIUM AND THORIUM

Several one-dimensional models are presented in this section to simulate the steady-state diffusion of radiogenic gases in overburden which contain trace uranium and thorium. Different boundary conditions are used at the base of the overburden column in order to represent an ore deposit or an impermeable surface.

3.1 Diffusion of Rn-222 and Xe-133 in an Active Overburden

Equation 1-1 can be simplified to represent steady-state diffusion in an active soil as follows:

$$\frac{D}{\epsilon} \frac{d^2C}{dz^2} - \lambda C + \phi = 0 \quad (3-1)$$

The production term ϕ is specified to be constant in this section indicating constant concentration of U and Th in the overburden column.

Boundary conditions for equation 3-1 are chosen as in section 2.1:

$$\begin{aligned} C &= 0 & \text{at } Z &= 0 \\ F &= -D \frac{dC}{dz} & \text{at } Z &= L \end{aligned}$$

The latter expression refers to a flux of the radiogenic gas from an underlying ore deposit. If this flux is set equal to zero the expression represents an impenetrable barrier $\left(\frac{dC}{dz} = 0\right)$.

The solution to equation 3-1 with the stated boundary conditions is:

$$C = A e^{WZ} + B e^{-WZ} + \phi/\lambda \quad (3-2)$$

where: $W = \sqrt{\frac{\epsilon \lambda}{D}}$

$$A = - \frac{e^{-WL} \left(\frac{F}{DW} + \frac{\phi}{\lambda} e^{-WL} \right)}{1 + e^{-2WL}}$$

$$B = \frac{\frac{F}{DW} e^{-WL} - \frac{\phi}{\lambda}}{(1 + e^{-2WL})}$$

The coefficients A and B are easily modified for the case of an impenetrable boundary by setting $F = 0$.

In order to use equation 3-2, the production term ϕ must be related to the uranium and thorium content of the soil. Production of Rn-222 will be considered first. A soil having U parts per million of uranium will contain $0.993 \times 10^{-6} \rho U$ grams U-238 per cm^3 bulk where ρ is the bulk density. The rate of U-238 decay by alpha emission is $1.226 \times 10^{-2} \rho U$ dps U-238/ cm^3 bulk. In secular equilibrium, one atom of Rn-222 is produced for each disintegration of U-238 giving $1.226 \times 10^{-2} \rho U$ atoms Rn-222/ cm^3 bulk/sec. The emanation fraction, E, is defined as that portion of the radon produced which escapes into the interconnecting pore space and becomes part of the soil gas. The production may be expressed in activity units by multiplying by $\lambda_{\text{Rn-222}}$ ($2.1 \times 10^{-6}/\text{sec}$). Carrying out this operation and dividing by the porosity (ϵ) to convert to a void volume basis yields:

$$\phi_{\text{Rn}} = 2.57 \times 10^{-8} \frac{\rho EU}{\epsilon} \text{ dps/cm}^3 \text{ void/sec.} \quad (3-3)$$

The production of Xe-133 is derived from spontaneous fission of both uranium and thorium. As discussed in the previous report (Jeter et al., 1977) natural uranium undergoes 7.2×10^{-3} fissions/sec/gm U (Segre, 1952). With a fission yield of 6.77 percent (Meek and Rider, 1972), a soil containing U ppm uranium will produce 4.87×10^{-10} pU atoms Xe-133/cm³ bulk/sec. This figure may be converted to activity units by multiplying by $\lambda_{\text{Xe-133}}$ (1.52×10^{-6} /sec). Allowing for the emanation fraction (E) and the porosity (ϵ), we obtain a contribution of 7.4×10^{-16} pEU/ ϵ dps Xe-133/cm³ void/sec.

Natural thorium undergoes 4.2×10^{-5} fissions/sec/gm Th 232 (Segre, 1952). With a Xe-133 yield of 3.85 percent (Meek and Rider, 1972), a soil having Th ppm of thorium will contribute 2.46×10^{-18} pETH/ ϵ dps Xe-133/cm³ void/sec to the soil gas. The two production terms may be added to give:

$$P_{\text{Xe}} = \left(7.41 \times 10^{-16} \text{ U} + 2.46 \times 10^{-18} \text{ Th} \right) \frac{\rho E}{\epsilon} \text{ dps Xe-133/cm}^3 \text{ void/sec} . \quad (3-4)$$

When equation 3-2 is used to model rock overlying a uranium ore deposit, the flux of Rn-222 can be calculated from the properties of the ore by equation 2-3. In the case of Xe-133, the flux may be calculated by equation 2-4, or by the following relationship which allows for the thorium content of the ore:

$$P_{\text{Xe}} = \left(1.38 \times 10^{-9} \text{ OREGRD} + 5.41 \times 10^{-16} \text{ ORETh} \right) \left(\text{EMRATE} \right) \left(\text{ORETHK} \right) \quad (3-5)$$

where: $ORETH = \text{Th-232 content of the ore, ppm.}$

Figure 9 illustrates Rn-222 profiles calculated by equation 3-2 for several values of trace uranium in soil. Characteristics of the overburden and the underlying uranium orebody are indicated on the plot. The profiles exhibit a constant value of $\phi\epsilon/\lambda \text{ dps/cm}^3 \text{ soil}$ (or $\phi/\lambda \text{ dps/cm}^3 \text{ void}$) at intermediate depths. Activity decreases as the soil surface is approached representing diffusive loss to the atmosphere. The influence of the atmosphere extends to approximately 10 m depth under the conditions illustrated.

Radon activities in Figure 9 increase as the uranium ore is approached. For an overburden containing 4 ppm U, the activity becomes 5 times the background level at a distance of 15 m from the ore. This distance can be considered a detection range and it is about half that derived in section 2.1 based on a passive overburden. The prospecting problem illustrated here is one of detecting an activity which is higher than a background level; the problem discussed in section 2.1 is one of instrumentation limitations in the absence of a background activity level. Other values of detection range are listed in Table 3A based on different signal-to-background criteria.

A simplified case may also be demonstrated in Figure 9. In the absence of an orebody, the vertical profiles at intermediate depths indicate the constant values of activity which prevail at all depths below the atmospheric influence. These values would also hold if the rock layer were infinitely thick (but still maintaining the prescribed values of ϕ , λ , and ϵ).

FIGURE 9

PROFILES OF RADON-222 AND DAUGHTER PRODUCTS
IN A URANIUM-BEARING ROCK COVERING
AN ORE DEPOSIT

TABLE 3

Detection Ranges for a Planar Ore
Body Covered by Active Overburden

A. Radon-222 and Daughter Products
(Parameters from Figure 9)

Overburden U (ppm)	2 x background range (m)	5 x background range (m)	10 x background range (m)
2	20	17	12
4	17	15	11
10	16	13	8
20	13	11	6
40	11	9	4

B. Xenon-133
(Parameters from Figure 10)

Overburden* U(ppm) Th(ppm)	2 x background range (m)	5 x background range (m)	10 x background range (m)
20 80	16	13	11
40 160	13	10	9

* Lower values of U and Th excluded because the Xe-133 background level produced is below the detection limit (see Figure 10 and Text).

FIGURE 10

PROFILES OF XE-133 IN
ACTIVE OVERBURDENS (U/Th = 1:4)
COVERING A URANIUM ORE DEPOSIT

Figure 10 shows Xe-133 profiles calculated by equation 3-2 for overburden rock containing trace U and Th in a ratio of 1:4. The underlying uranium ore has the same characteristics as Figure 9. Because of instrumentation limitations⁽⁸⁾, Xe-133 activities at intermediate depths could only be detected for the two most active overburdens (20, 40 ppm U). In these cases, a significant increase in activity is found at 10 to 15 meters from the ore (Table 3B). This is about the same detection range calculated in section 2.1, based on a passive overburden.

3.2 Diffusion of He-4 in an Active Overburden

The differential equation which characterizes one-dimensional diffusion of He-4 in steady-state has been given in section 2.2:

$$\frac{D}{\epsilon} \frac{d^2C}{dz^2} + \phi(Z) = 0 \quad (2-5)$$

In the case of an active overburden, however, the local production term has more components than were considered previously:

$$\phi(Z) = \phi_1 + \phi_2 + \phi_3 + \phi_4(Z) \quad (3-6)$$

where:

- ϕ_1 = local production rate of helium by uranium series decay, expressed per unit of void volume, atoms/cm³ void/sec
- ϕ_2 = local production rate of helium by actinium series decay, atoms/cm³ void/sec
- ϕ_3 = local production rate of helium by thorium series decay, atoms/cm³ void/sec
- $\phi_4(Z)$ = local production rate of helium by decay of interstitial Rn-222 and its daughters, atoms/cm³ void/sec

---

(8) See footnote (3), section 2.

By a reasoning process similar to the derivation of F_{He} in section 2.2, the local production of helium by the uranium series is

$$\phi_1 = \left[4 + 4(1-E) \right] 1.226 \times 10^{-2} U\rho/\epsilon \text{ atoms He/cm}^3\text{void/sec.} \quad (3-7)$$

This expression accounts for the alpha emitting nuclides which remain at the location of the U-238 itself; that fraction (E) of the Rn-222 which escapes into the soil gas is treated separately as indicated in equation 3-6.

The production of helium by the actinium series is also derived by a process similar to that in section 2.2:

$$\phi_2 = 4.00 \times 10^{-3} U\rho/\epsilon \text{ atoms He-4/cm}^3\text{void/sec.} \quad (3-8)$$

The thorium series contains 6 alpha emitters. The radon isotope (Rn-220) has a 55 second half-life, so its escape can be discounted. The production of helium by a rock containing Th ppm thorium-232 becomes

$$\phi_3 = 2.45 \times 10^{-2} \text{Th}\rho/\epsilon \text{ atoms He/cm}^3\text{void/sec.} \quad (3-9)$$

Helium production by interstitial Rn-222 is influenced by its mobility. A steady-state model must first be solved to derive the radon concentration profile. As outlined in section 3.1, the solution for Rn-222 is

$$C_{\text{Rn}} = A e^{WZ} + B e^{-WZ} + \phi_{\text{Rn}}/\lambda \text{ dps/cm}^3\text{void/sec.} \quad (3-2)$$

Expressions for evaluating A, B and ϕ_{Rn} are given in section 3.1. In secular equilibrium, Rn-222 and its 3 alpha-emitting daughter nuclides produce a total of 4 He-4 atoms per disintegration of Rn-222, resulting in:

$$\phi_4 (Z) = 4 \left[A e^{WZ} + B e^{-WZ} + \phi_{Rn-222}/\lambda \right] \text{ atoms He/cm}^3\text{void/sec.} \quad (3-10)$$

The production terms given in equations 3-7, 3-8, 3-9, and 3-10 may be combined and substituted into the differential equation 2-5 to give

$$\frac{D}{\epsilon} \frac{d^2C}{dZ^2} + 4Ae^{WZ} + 4Be^{-WZ} + Q = 0 \quad (3-11)$$

$$\text{where: } Q = \left[(2-E)4.90 \times 10^{-2} + 4.00 \times 10^{-3} \right] U\rho/\epsilon + 2.45 \times 10^{-2} \text{ Th } \rho/\epsilon + 4 \phi_{Rn}/\lambda_{Rn} \text{ atoms He/cm}^3\text{void/sec.}$$

Equation 3-11 implies that helium escapes into the pore spaces at the same rate at which it is produced, i.e., the emanation of helium is unity. This is an assumption of steady state which maximizes the helium production from the rock. Helium concentrations within the mineral grains can be many times the soil gas concentration, however, without violating this assumption.

Boundary conditions for the solution of equation 3-11 are chosen as in section 2.2:

$$C = C_{atm} \quad \text{at } Z = 0$$

$$F = -D \frac{dC}{dZ} \quad \text{at } Z = L$$

The latter boundary condition refers to a helium flux from an underlying body of uranium ore. Expression 2-10 may be used to evaluate F_{He} , or it may be modified to allow for the thorium content of the orebody as follows:

$$F_{He} = -ORETHK \left[OREGRD (1.90 \times 10^5 - 9.15 \times 10^4 \text{ EMRATE}) + 5.38 \text{ Th} \right] \text{ atoms He/cm}^2/\text{sec.} \quad (3-12)$$

The solution of equation 3-11 with the stated boundary conditions is

$$C = -\frac{4A\epsilon}{DW^2} e^{WZ} - \frac{4B\epsilon}{DW^2} e^{-WZ} - \frac{Q\epsilon}{2D} Z^2 + RZ + T \quad (3-13)$$

$$\text{where: } R = \frac{Q\epsilon L}{D} + \frac{4\epsilon}{WD} \left(A e^{WL} - B e^{-WL} \right) - \frac{F_{He}}{D}$$

$$T = \frac{4\epsilon}{DW^2} (A + B) + C_{atm}$$

The equation may be modified for the case of a rock layer alone by setting $F_{He} = 0$ and $F_{Rn} = 0$. The latter change affects A and B as indicated in equation 3-2.

Figures 11 and 12 display profiles of excess He-4 calculated by equation 3-13 for various concentrations of U and Th in overburdens. Both an ore boundary and an impenetrable boundary are shown for comparison. These plots are based on a diffusion coefficient of $0.07 \text{ cm}^2/\text{sec}$, representing a dry soil according to the formula in section 2.2. The results indicate helium concentrations which are less than 1 ppb above the atmospheric value. This helium excess would not be detectable using mobile equipment described by Reimer et al (1979). If a lower diffusion coefficient is assumed, however, the helium excess

FIGURE 11

PROFILES OF EXCESS HE-4 IN
 ACTIVE OVERBURDENS ($\text{U/Th} = 1:4$)

FIGURE 12

PROFILES OF EXCESS HE-4 IN
 ACTIVE OVERBURDENS OF VARIOUS U/Th RATIOS
 ($U = 4 \text{ ppm}$)

becomes larger. The quantity $(C - C_{\text{atm}})$ in equation 3-13 is inversely proportional to D ; diminishing D by a factor of 10 causes a tenfold increase in the calculated helium excess.

Table 4 illustrates the detectability of a hypothetical ore deposit by measuring He-4 concentrations in soil gas at a depth of 1 m. Entries are calculated by equation 3-13 for assumed diffusion coefficients of 10^{-3} , 10^{-4} , and 10^{-5} cm²/sec. These values are not based upon measurement but were chosen by Grammakov et al. (1965) to represent a probable range for helium diffusion in rock. Table 4 indicates that an ore deposit at 50 m or 100 m could produce a helium excess which is several tens of ppb greater than that produced by the overlying rock (with $D = 10^{-5}$ cm²/sec). If the analytical equipment mentioned above were moved from a zone containing only rock to a zone where similar rock covered the ore deposit, a helium anomaly could be detected. This result must be considered hypothetical because of the uncertainty in assigning a diffusion coefficient and because the influence of underlying sources of helium has not been simulated. These subjects are considered in section 6.3.

If it is assumed that both the overburden and the ore emanate no Rn-222, then equation 3-13 simplifies to

$$C = C_{\text{atm}} + \left(\frac{\phi_{\text{He}} \epsilon L}{D} - \frac{F_{\text{He}}}{D} \right) z - \frac{\phi_{\text{He}} \epsilon}{2D} z^2 \quad (3-14)$$

TABLE 4

Helium-4 Excess (ppb) at 1 m Depth Caused by a
Planar Ore Deposit with Active Overburden
(underlying sources of helium excluded)

A. Ore at 100 m
(parameters from Figure 11)

Overburden		$D = 10^{-3} \text{ cm}^2/\text{sec}$		$D = 10^{-4} \text{ cm}^2/\text{sec}$		$D = 10^{-5} \text{ cm}^2/\text{sec}$	
U(ppm)	Th(ppm)	rock only	rock plus ore	rock only	rock plus ore	rock only	rock plus ore
2	8	.03	.49	.3	4.9	3	49
4	16	.07	.53	.7	5.3	7	53
10	40	.17	.63	1.7	6.3	17	63
20	80	.35	.81	3.5	8.1	35	81
40	160	.70	1.16	7.0	11.6	70	116

B. Ore at 50 m
(parameters from Figure 11)

Overburden		$D = 10^{-3} \text{ cm}^2/\text{sec}$		$D = 10^{-4} \text{ cm}^2/\text{sec}$		$D = 10^{-5} \text{ cm}^2/\text{sec}$	
U(ppm)	Th(ppm)	rock only	rock plus ore	rock only	rock plus ore	rock only	rock plus ore
2	8	.02	.47	.2	4.7	2	47
4	16	.03	.49	.3	4.9	3	49
10	40	.09	.54	.9	5.4	9	54
20	80	.17	.63	1.7	6.3	17	63
40	160	.35	.80	3.5	8.0	35	80

where: $\phi_{\text{He}} = 0.102 U\rho/\epsilon + 0.245 \text{Th}\rho/\epsilon$.

Parabolic equations of this sort have been derived by Grammakov et al. (1961, 1965) by ignoring the effects of radon emanation⁽⁹⁾. Equation 3-14 gives a good approximation to equation 3-13 in most cases. Within 10 meters of an orebody the two equations give results which agree within one percent (Figure 13). In a homogeneous overburden layer with no nearby ore, the results are nearly identical. Equation 3-14, therefore, is adequate for modeling purposes, and it is preferred because of its simplicity.

When the emanation of Rn-222 is ignored, the term EMRATE vanishes from the flux equation (3-12). This equation may be further modified to express uranium in units of ppm and to include density as a variable:

$$F_{\text{He}} = -\rho (\text{ORETHK}) [10.2U + 2.45\text{Th}] \text{ atoms He/cm}^2/\text{sec.} \quad (3-15)$$

Equation 3-15 applies either to an orebody or to any body of overburden or basement rock underlying the modeling zone.

It is important to note that the assumption of steady state used in this work implies that He-4 diffusivity need not be considered at depths greater

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(9) The equations used by Grammakov (1961, 1965) appear somewhat different because the production term is defined on a bulk basis. In addition, the production of He-4 by uranium is 5% lower than in this work because the effect of U-235 was not considered by Grammakov.

FIGURE 13

COMPARISON OF FORMULAE FOR
CALCULATING He-4 IN SOIL GAS

than the modeling zone. Helium is an inert gas which is not subject to radioactive decay. Once produced and released into the interconnecting pore space ⁽¹⁰⁾, it migrates away from the parent rock without attenuation and (under the assumption) without time-dependent buildup. The flux of helium from a given column of earth is equal to the total production rate within that column. This relationship is expressed by equation 3-15, which contains no diffusion coefficient.

A further implication of steady state is that helium fluxes are additive. Equation 3-15 may be separately applied to successive layers of basement rock and the results may be summed. The assumption of steady state and its implications are also discussed by Grammakov et al. (1965).

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(10) In this study we assume that helium escapes into the pore space at the same rate at which it is produced within the mineral. Refer to the discussion following equation 2-10.

4.0 MULTIPLE LAYER MODELS FOR RADIOGENIC GASES IN A ROCK COLUMN

The models considered in the previous chapter have specified constant concentrations of uranium and thorium within a single formation or layer of rock. Planar uranium ore deposits have been characterized only by the fluxes of radiogenic gases which they supply to the base of an overburden rock column; no attempt has been made to model within the ore itself.

Geologic formations are often manifested in a series of layers. Each layer may be characterized by distinct physical and mineralogical parameters. In order to simulate such features, this section considers multiple-layer models in one dimension. The problem is approached in a general way to encompass any number of layers with assignable characteristics.

A further advantage of the multiple layer model is that mathematical simulation can be carried out within and below a uranium ore deposit. The ore is not treated as a separate emanating body, but rather it is treated as a layer which has a relatively high uranium content and assignable physical characteristics.

4.1 A Multiple Layer Model for Rn-222 and Xe-133 in a Rock Column

The approach used in this section is to derive a general mathematical expression for each layer of rock. The expressions are then linked by appropriate interfacial boundary conditions resulting in a system of simultaneous algebraic equations. The equations are solved simultaneously to yield coefficients which permit the calculation of gas concentration at any point within any layer.

In the case of Rn-222 or Xe-133 diffusion, each stratigraphic layer is characterized by the differential equation 3-1. This equation may be subscripted to designate the assignable parameters in layer i as follows:

$$\frac{D_i}{\epsilon_i} \frac{d^2C}{dz^2} - \lambda C + \phi_i = 0. \quad (4-1)$$

The general solution of 4-1 is

$$C = A_i e^{W_i Z} + B_i e^{-W_i Z} + \phi_i / \lambda \quad (4-2)$$

where $W_i = \sqrt{\frac{\epsilon_i \lambda}{D_i}}$ and A_i, B_i are constants to be determined from the boundary conditions.

At each interface between layers two boundary condition equations may be written:

$$C_i = C_{i+1} \quad (4-3)$$

$$D_i \frac{dC_i}{dz} = D_{i+1} \frac{dC_{i+1}}{dz} \quad (4-4)$$

where the subscripts refer to layer i and its underlying neighbor i+1. The

former boundary condition specifies equality of concentration across the interface; the second specifies equality of flux across the interface. There are two additional boundary conditions one at the rock column surface ($C=0$ at $Z=0$) and one at the base of the bottom layer ($dC/dZ = 0$ at $Z = L$).

Substituting the general solution 4-2 into all boundary condition equations having the form of 4-3 yields a set of $N-1$ linear algebraic equations, where N is the total number of layers:

$$A_i e^{(W_i \ell_i)} + B_i e^{(-W_i \ell_i)} + \phi_i / \lambda = A_{i+1} e^{(W_{i+1} \ell_i)} + B_{i+1} e^{(-W_{i+1} \ell_i)} + \phi_{i+1} / \lambda$$

$$i = 1, 2, \dots, N-1. \quad (4-5)$$

In this expression, ℓ_i is the depth (Z value) of the interface underlying layer i . Similarly, differentiation of 4-2 and substitution into all boundary condition equations having the form of 4-4 gives another set of $N-1$ linear algebraic equations:

$$D_i W_i \left(A_i e^{W_i \ell_i} - B_i e^{-W_i \ell_i} \right) = D_{i+1} W_{i+1} \left(A_{i+1} e^{W_{i+1} \ell_i} - B_{i+1} e^{-W_{i+1} \ell_i} \right)$$

$$i = 1, 2, \dots, N-1. \quad (4-6)$$

The two remaining boundary conditions at the rock column surface and at the base of the bottom layer may be expressed as:

$$A_i + B_i + \phi_i/\lambda = 0. \quad (4-7)$$

$$A_N e^{W_N L} - B_N e^{-W_N L} = 0. \quad (4-8)$$

Equations 4-5, 4-6, 4-7, and 4-8 constitute a set of $2N$ simultaneous algebraic expressions which contain N unknowns designated A_i and another N unknowns designated B_i , $i = 1, 2, \dots, N$. The multiple layer problem is defined by first assigning values to the parameters of each layer (D_i , ϵ_i , W_i , λ_i , ϕ_i). The production terms ϕ_i may be derived from the rock properties by equation 3-3 for Rn-222 and by equation 3-4 for Xe-133. The multiple layer problem is then solved by employing an algorithm for the simultaneous solution of the $2N$ algebraic equations⁽¹¹⁾. Calculation of the radiogenic gas concentration at any desired depth is accomplished by identifying the layer number i , then looking up the values of A_i and B_i from the simultaneous solution, and then applying equation 4-2.

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(11) A computerized Gauss-Jordan algorithm with maximum pivot strategy has been used in this work (Carnahan, Luther and Wilkes, 1969).

Table 5 and Figure 14 illustrate a Rn-222 profile calculated by the multiple-layer model. Table 5A shows the characteristics of 6 layers used as input data. The first and fourth layers represent shale; the second and sixth layers represent sandstone; the third and fifth layers represent sandstone with uranium mineralization. Diffusion coefficients were obtained by equation 2-11 using the indicated porosity data and a value of $0.13 \text{ cm}^2/\text{sec}$ for Rn-222 diffusion in air (Clements, 1974).

Calculated activities of Rn-222 shown in Table 5 and Figure 14 exhibit strong maxima at the locations of the enriched layers. Activity is twice the background value at a distance of 19 m from the shallower mineralization and is 5 times background at a distance of 13 m. These ranges are similar to those displayed in Table 3 (representing a similar ore deposit with a single layer of overburden). The deeper mineralized layer contains 1/10 as much uranium ($0.06\% \text{ U}_3\text{O}_8$) and causes peak Rn-222 concentrations which are 10 times lower.

A profile of Xe-133 activity resulting from the multiple layer model appears in Figure 15. Input data is the same as shown in Table 5A. Features of the Xe-133 profile resemble those of Rn-222. Because the detection limit is $3.6 \times 10^{-9} \text{ dps/cm}^3 \text{ rock}$ (section 2.1), the shallower deposit would produce a detectable concentration at a range of 15 meters.

4.2 A Multiple-Layer Model for He-4 in a Rock Column

The approach used in this section is parallel to that of the preceding section. Helium diffusion in each stratigraphic layer is characterized by the differential equation 2-5, which may be subscripted to designate layer i as follows:

$$\frac{D_i}{\epsilon_i} \frac{d^2C}{dz^2} + \phi_i(Z) = 0 \quad (4-9)$$

TABLE 5

An Illustration of the Multiple - Layer Model

A. Input Data

Layer No.	Description	Thickness m	Porosity	Diffusivity Cm ² /sec	Density gm/cm ³	Emanation of Rn-222	Uranium ppm	Thorium ppm
1	shale	20	.20	.017	2.3	.2	4	16
2	sandstone	20	.30	.026	2.5	.3	8	32
3	sandstone with U mineralization	1	.15	.013	2.5	.5	5088	20
4	shale	19	.20	.017	2.3	.2	4	16
5	sandstone with U mineralization	1	.15	.013	2.5	.5	500	20
6	sandstone	19	.30	.026	2.5	.3	4	16

B. Calculated Results

Depth, m	Rn-222, dps/cm ³ soil	Depth, m	Rn-222, dps/cm ³ soil
1	8.855 E-03	45	1.960 E 00
2	1.424 E-02	50	1.936 E-01
5	2.073 E-02	55	1.516 E-01
10	2.256 E-02	60	1.411 E 00
15	2.399 E-02	61	9.432 E-01
20	3.939 E-02	65	2.950 E-01
25	8.409 E-02	70	5.889 E-02
30	2.108 E-01	75	3.875 E-02
35	1.681 E 00	78	3.734 E-02
40	1.892 E 01	79	3.721 E-02
41	1.062 E 01	80	3.717 E-02

FIGURE 14

AN ILLUSTRATIVE PROFILE OF Rn-222
CALCULATED BY THE MULTIPLE-LAYER MODEL

FIGURE 15

AN ILLUSTRATIVE PROFILE OF Xe-133
CALCULATED BY THE MULTIPLE-LAYER MODEL

As indicated in equation 3-6, the production term $\phi_i(Z)$ has four components. The last of these components requires a steady-state solution for the Rn-222 profile. By analogy to 3-11, the differential equation representing helium diffusion in layer i becomes:

$$\frac{D_i}{\epsilon_i} \frac{d^2 C}{dZ^2} + 4 A_i e^{W_i Z} + 4 B_i e^{-W_i Z} + Q_i = 0 \quad (4-10)$$

where:

A_i, B_i = coefficients obtained from the multiple-layer Rn-222 model

$$Q_i = \left[(2-E_i) 4.90 \times 10^{-2} + 4.00 \times 10^{-3} \right] U_i \rho_i / \epsilon_i + 2.45 \times 10^{-2} Th_i \rho_i / \epsilon_i + \phi_{Rn_i} / \lambda_{Rn}$$

$$\phi_{Rn_i} = 2.58 \times 10^{-8} \rho_i E_i U_i / \epsilon_i$$

The general solution of equation 4-10 is

$$C = \frac{4\epsilon_i}{D_i W_i^2} \left[A_i e^{W_i Z} + B_i e^{-W_i Z} \right] - \frac{Q_i \epsilon_i}{2D_i} Z^2 + R_i Z + T_i \quad (4-11)$$

where the constants R_i and T_i are to be determined from the boundary conditions. At each interface between layers, there are two boundary conditions given by equations 4-3 and 4-4. Substituting the general solution 4-11 into 4-3 yields a set of N-1 linear algebraic equations, where N is the total number of layers:

$$\frac{-4\epsilon_i}{D_i W_i^2} \left[A_i e^{W_i \ell_i} + B_i e^{-W_i \ell_i} \right] - \frac{Q_i \epsilon_i}{2D_i} \ell_i^2 + R_i \ell_i + T_i =$$

$$\frac{-4\epsilon_{i+1}}{D_{i+1} W_{i+1}^2} \left[A_{i+1} e^{W_{i+1} \ell_i} + B_{i+1} e^{-W_{i+1} \ell_i} \right] - \frac{Q_{i+1} \epsilon_{i+1}}{2D_{i+1}} \ell_i^2 + R_{i+1} \ell_i + T_{i+1}$$

$$i = 1, 2, \dots, N-1. \quad (4-12)$$

In this expression, ℓ_i refers to the depth (Z value) of the interface underlying layer i.

In a similar manner, differentiation of equation 4-11 and substitution into boundary condition 4-4 yields an additional N-1 algebraic equations:

$$\frac{-4\epsilon_i}{W_i} \left[A_i e^{W_i \ell_i} - B_i e^{-W_i \ell_i} \right] - Q_i \epsilon_i \ell_i + D_i R_i = \frac{-4\epsilon_{i+1}}{W_{i+1}} \left[A_{i+1} e^{W_{i+1} \ell_i} - B_{i+1} e^{-W_{i+1} \ell_i} \right]$$

$$- Q_{i+1} \epsilon_{i+1} \ell_i + D_{i+1} R_{i+1} \quad i = 1, 2, \dots, N-1. \quad (4-13)$$

The remaining two boundary conditions at the rock column surface ($C = C_{atm}$ at $Z=0$) and at the base of the bottom layer ($dC/dZ = 0$ at $Z = L$) may be expressed as:

$$\frac{-4\epsilon_1}{D_1 W_1^2} (A_1 + B_1) + T_1 = C_{atm} \quad (4-14)$$

$$\frac{-4\epsilon_N}{W_N} \begin{bmatrix} W_N^L & -W_N^L \\ A_N e^{W_N^L} & -B_N e^{-W_N^L} \end{bmatrix} - Q_N \epsilon_N^L + D_N R_N = 0 \quad (4-15)$$

Equations 4-12, 4-13, 4-14, 4-15 represent a set of $2N$ simultaneous algebraic expressions which contain N unknowns of the form R_i and another N unknowns of the form T_i , $i = 1, 2, \dots, N$. The multiple-layer helium model is initiated by assigning values of diffusivity, porosity, thickness, density, emanation, U content and Th content to each stratigraphic layer. The multiple-layer Rn-222 model described in section 4.1 is then solved to yield the coefficients A_i and B_i for each layer. These values are inserted into equations 4-12 through 4-15 which are then solved simultaneously by the algorithm previously described. This process yields the coefficients R_i and T_i for each layer. The He-4 concentration at any depth is derived by identifying the layer number i , looking up the values of A_i , B_i , R_i , and T_i , and then applying equation 4-11.

Figure 16 shows He-4 profiles calculated by the multiple-layer model. The input data used are shown in Table 5 except for helium diffusion coefficients which are shown on the figure. The profiles differ from those of Rn-222 and Xe-133 in that no peaks are shown at the locations of uranium

FIGURE 16

ILLUSTRATIVE PROFILES OF He-4
CALCULATED BY THE MULTIPLE-LAYER MODEL

mineralization. This result is explained by the absence of He-4 decay. The enriched layers at 40 m and at 60 m do cause inflections in the plotted curves.

The left-most profile in Figure 16 employs diffusion coefficients calculated by equation 2-11 which characterizes a dry soil. The excess helium levels are below the detection limit of 10 ppb for the mobile analyser described by Reimer et al. (1979). Profiles to the right result when these diffusivities are divided by 10 and 100, as indicated. With D near $10^{-3} \text{cm}^2/\text{sec}$, the excess helium is detectable at depths below 15 m. A diffusion coefficient less than $10^{-4} \text{cm}^2/\text{sec}$ would be required to produce a detectable excess at 1 m. This result is consistent with those discussed in Section 3.2 and illustrated in Table 4. Diffusion coefficients for helium in rock and in overburden containing moisture are discussed in Section 6.2.

5.0 TRANSIENT MODELS FOR ATMOSPHERIC PRESSURE EFFECTS ON RADIOGENIC GASES IN A ROCK COLUMN

Variations in atmospheric pressure can cause motion of soil gas which may influence the migration of radionuclides. Clements (1974) and Clements and Wilkening (1974) used one-dimensional numerical models to determine variability in the flux of natural radon from the soil into the atmosphere. Barometric effects of up to 60 percent were predicted and measured in the field for linear changes in atmospheric pressure.

The previous phase of this study (Jeter et al., 1977) addressed the problem of sinusoidal variations in atmospheric pressure which approximate barometric records and are termed "barometric pumping". A one-dimensional numerical model was used to simulate the Rn-222 variation in a passive rock overlying a uranium ore deposit. The model results showed a variation in radon concentration which decreased in amplitude with increasing depth. Near the earth's surface a ± 15 percent deviation from the steady-state (zero velocity) value was calculated.

In this work, the barometric pumping model is extended to include Xe-133 and He-4. In addition, trace U and Th concentrations in the enveloping strata and overlying rock are included for greater realism.

The transient model requires that all terms in equation 1-1 be retained. The equation may be re-arranged by carrying out the differentiation of the velocity term as follows:

$$\frac{\partial^2 C}{\partial z^2} - \frac{V}{D} \frac{\partial C}{\partial z} - \frac{1}{D} \left(\frac{\partial V}{\partial z} + \epsilon \lambda \right) C + \frac{\phi \epsilon}{D} = \frac{\epsilon}{D} \frac{\partial C}{\partial t} \quad (5-1)$$

In this work equation 5-1 is integrated by explicit numerical methods. The velocity term and the velocity derivative term are calculated from the flow model described in the previous study (Jeter et al., 1977). Both numerical solutions are incorporated into a single computer code; at each time step the pressure and velocity are calculated first followed by the concentration solution. The form of each iteration is

$$C_i^{n+1} = \left(A + B_i^{n+1} \right) C_{i-1}^n + \left(1 - 2A - Y_i^{n+1} \right) C_i^n + \left(A - B_i^{n+1} \right) C_{i+1}^n + \Delta t \phi$$

(5-2)

where:

i	=	spatial element index
n	=	temporal element index
Δt	=	iteration interval
ΔZ	=	spatial grid element length
A	=	$\frac{D \Delta t}{\epsilon (\Delta Z)^2}$
B_i^{n+1}	=	$\frac{\Delta t v_i^{n+1}}{2 \epsilon \Delta Z}$
Y_i^{n+1}	=	$\frac{\Delta t}{\epsilon} \left[\left(\frac{\partial v}{\partial z} \right)_i^{n+1} + \epsilon \lambda \right]$

At the uppermost grid point ($i=1$), the term C_{i-1}^n in equation 5-2 is replaced by C_{atm} because of the atmospheric boundary condition. For modeling Rn-222 and Xe-133, $C_{atm} = 0$; for modeling He-4, C_{atm} is a constant.

At the deepest grid point, the term C_{i+1}^n in equation 5-2 is

replaced by $\left[C_{i-1}^n + \frac{2\Delta Z}{D} \left(-F + V_i^{n+1} C_i^n \right) \right]$ because of the flux boundary

condition at the ore surface. When the flux term F is set equal to zero, the boundary condition represents a barrier to the movement of gas.

The initial condition used in the transient model is a steady-state profile calculated by equations given in Section 3. An iteration interval of 0.5 hour and a grid element length of 0.5 meter have been found to give a reasonable balance between accuracy of the solution and the computation time required. The solution exhibits some "drift" when simulating Rn-222 and Xe-133 in a passive overburden. This is caused by approximating spatial derivatives by the finite-difference technique and becomes noticeable when the concentration profile is nearly exponential (which is the case with a passive overburden). Trials of the model have shown that the solution does not drift continuously, but rather approaches a new steady state which is about 3 percent different from the initial condition. In order to suppress the apparent drift for passive overburdens, a slope/intercept correction amounting to 0-3 percent has been applied to the initial profile.

Figure 17 shows Rn-222 or Xe-133 variations at three depths calculated for a passive overburden. A sinusoidal fluctuation of atmospheric pressure

FIGURE 17

VARIATION OF Rn-222 OR Xe-133 ACTIVITY IN A PASSIVE OVERBURDEN
CAUSED BY BAROMETRIC PUMPING WITH A 24 HOUR PERIOD
($k = 50$ millidarcy)

is specified having an amplitude of 5mb and a period of 24 hours. Other conditions chosen are the same as listed in Figure 18. The response curves shown in Figure 17 are sinusoidal in shape and have a period of 24 hours. Response is attenuated with depth and lags the variation near the surface. Several oscillations are required to reach a periodic steady-state, as the sinusoid initially displays an upward trend even though the drift correction has been applied. Results are the same for Rn-222 and Xe-133 when activities are normalized to their initial values.

The effect of different pumping periods is shown in Figure 18. In the case of a passive overburden, the Rn-222 response becomes greater and reaches deeper when the pumping period is increased.

Figure 19 shows that increased permeability of the overburden rock causes a greater response to barometric pumping. When a permeability of 1000mD is specified, the Rn-222 response exceeds ± 10 percent at shallow depths.

The effect of porosity is shown in Figure 20. It is important to note that the porosity is varied without accompanying variation in the diffusion coefficient, and the activities are normalized to their steady-state values. The plot shows a decrease in pumping effect near the overburden surface as the porosity is increased, but this trend does not hold for greater depths.

Variations in the grade and emanation of the orebody produce no change in the response to barometric pumping.

Trials of the transient model simulating an active overburden result in the same relative variation of Rn-222 as found with a passive overburden if a barometric pumping period of 1 day is employed. Overburden rock containing uranium

FIGURE 18

EFFECT OF PUMPING PERIOD
 ON Rn-222 VARIATIONS IN
 A PASSIVE OVERBURDEN

FIGURE 19

EFFECT OF ROCK PERMEABILITY
 ON Rn-222 VARIATIONS
 CAUSED BY BAROMETRIC PUMPING
 (PASSIVE OVERBURDEN)

FIGURE 20

EFFECT OF ROCK POROSITY
ON Rn-222 VARIATIONS
CAUSED BY BAROMETRIC PUMPING
(PASSIVE OVERBURDEN)

concentrations up to 40 ppm exhibit the same response. The active overburdens differ when longer pumping periods are simulated. The pronounced effects depicted in Figure 18 do not appear, and the response remains nearly the same as the one-day case.

The barometric influence on He-4 concentration is smaller than for Rn-222 and Xe-133. This difference is attributed to the non-zero atmospheric concentration of He-4, to the lack of radioactive decay, and to the slight vertical concentration gradient in the rock column. Trials with both active and passive rocks indicate that maximum responses are less than 0.4 percent even when the largest value of permeability is employed (1000mD). Variations of this magnitude are probably of no significance to geochemical exploration. Moreover, these variations are small enough to be of questionable reliability when calculated by the present model. The conservation equation (1-1) is a constant density form which is used as an approximation. In reality, a barometric pressure variation of ± 5 mb causes a density variation of ± 0.5 percent.

6.0 COMPARISON OF MODEL RESULTS TO EXPERIMENTAL DATA

The evaluation of vertical models for radionuclide migration must be performed by comparison to vertical profile data in the laboratory or in the field. Detailed measurements of both the inputs to the model (uranium content, physical properties) and the outputs (Rn-222 or He-4 concentrations) must be obtained to determine whether the mathematical simulation is realistic.

There are few published studies which contain profile data in sufficient detail for verification purposes (section 1). The laboratory study of Clements (1974) has verified a homogeneous model for Rn-222 which is similar to equation 3-2. The same study contains experimental verification of both steady-state and transient advection/diffusion expressions resembling those developed in sections 2.3 and 5.0. Finally, a two-layer model of Clements, Barr, and Marple (1978) has been confirmed by measuring Rn-222 profiles in a uranium mill tailings pile.

Studies of He-4 discussed in section 1 include no vertical data suitable for model verification. Grammakov, Glebovskaya, and Khaikovich (1965) discuss near-surface helium data in comparison to model results, however. Measurements were performed on 12,000 soil-gas samples taken from areas containing no uranium ore. The average He-4 concentration was found to be 1.005 to 1.007 times the atmospheric value, i.e. an increment of 26 to 37 ppb. These values were stated to be in general agreement with a mathematical expression similar to equation 3-14. The comparison is valid only when diffusion coefficients near 10^{-4} cm²/sec are chosen. Similarly, models for

uranium ore deposits reported by these investigators produce significant concentrations of helium only if relatively impermeable rock is assumed to cover the mineralization.

This section reports recent vertical profile measurements performed by Bendix Field Engineering Corporation as part of the U.S. Department of Energy's National Uranium Resource Evaluation Program. The data were collected at a site in the Red Desert of central Wyoming, USA, as indicated on the geologic map in Figure 21. The site is located in the Eocene Battle Springs formation which is a sequence consisting of arkose, arkosic sandstone, and sandy claystone. This sequence is of piedmont fluvial and alluvial origin derived from the Granite Mountains and Green Mountain. Detrital coal, coaly trash, and poorly sorted carbonaceous siltstone beds are common in the formation and create host rock which is favorable for uranium deposits such as those found at Crook's Gap.

Two sampling arrays were established, one located over a known uranium ore deposit and the other located off the deposit (Figure 22). The vertical profile measurements taken which are pertinent to this study are: fluorometric uranium, gamma-spectral bismuth-214 (Bi-214), gamma-spectral thallium-208 (Tl-208), bulk density, Rn-222 emanation, porosity, Rn-222, Pb-210, and He-4/Ar-36 ratio. Observations in the first 5 categories are reported by Pacer (1978). The others are reported by Schutz (1980).

The emphasis of this section is to compare the measurements of gaseous radionuclides (and daughter products) to profiles calculated by various models developed in this work. The input data required by the models

FIGURE 21

FIGURE 22

DEEP-HOLE SAMPLING ARRAYS AT THE
RED DESERT RESEARCH SITE

are derived from the field measurements when available and are estimated when necessary.

6.1 Summary of Data

Tables of profile data from Arrays I and II are presented in appendices I and II, respectively. Portions of the data also appear in various tables and figures discussed in the following sections.

Schutz (1980) describes the sampling procedures in detail. Gas samples were pumped from tubes driven or bored into the earth and sealed from atmospheric contamination with drilling mud. SF_6 tracer was injected above the seals to determine their effectiveness. Core samples 76 cm length were taken from the bottoms of gas-sampling holes for analysis of Pb-210 and porosity.

Analyses performed at Teledyne Isotopes are also described by Schutz (1980). Radon-222 was determined by alpha assay of gas samples in a ZnS scintillation chamber. The method exhibits a precision of ± 20 percent at the 2σ (95%) confidence level. Helium-4/Argon-36 ratios were measured using a Nuclide 3-RMS-60 mass spectrometer with a precision of ± 1 percent. The Pb-210 contents of solid samples were determined radiochemically by beta assay of the daughter product Bi-210. This method measures the "leachable" Pb-210 fraction which can be dissolved from the solid using 6N hydrochloric acid. Analytical precision is ± 6 percent in addition to the beta counting error, becoming ± 15 percent for most samples. Finally, porosities of core samples were determined with ± 10 percent precision by first drying at 110°C and then measuring the volume of water required to fill the pore spaces.

Other analyses pertinent to this study were performed at Bendix Field Engineering Corporation. Samples were taken from cores at 5 ft. (1.5 m) intervals. Total uranium was measured by fluorometric analysis with a precision of ± 2 ppm for $2 < U < 15$ ppm and ± 15 percent for higher values of U. Uranium was also inferred by gamma spectral measurement of its remote daughter product Bi-214. This analysis, termed "KUT uranium", assumes secular equilibrium of the uranium decay series through Bi-214 (Table 1). Because the measurement is performed after hermetically sealing the sample and allowing Bi-214 to equilibrate with its long-lived precursor Ra-226, the values are more indicative of the abundance of Ra-226. Precision is ± 10 percent for $U < 10$ ppm, ± 6 percent for $10 < U < 20$ ppm, and ± 3 percent for higher values of U. Thorium measured as "KUT thorium" by gamma spectral analysis of its remote daughter Tl-208. The precision is the same as for KUT uranium.

Emanation of Rn-222 was measured at Bendix Field Engineering Corporation by sealing the solid sample in a metal can and analysing the ingrowth of Bi-214 after periods of 4 days and 20 days. This method exhibits a precision of ± 14 percent for $U < 10$ ppm, ± 9 percent for $10 < U < 20$ ppm, and ± 5 percent for greater values of U. Finally, bulk densities of core samples were determined by pycnometer with a precision of ± 1 percent.

6.2 Comparisons to Rn-222 and Daughter Products

Fluorometric uranium measurements from Arrays I and II at the Red Desert Research Site are shown in Figures 23 and 24, respectively. Uranium ore deposits are represented by horizontal bands in Figure 23. The thickness and grade of ore in these deposits may be alternatively expressed as: 2.5 ft. of 0.123 percent U_3O_8 , 6.0 ft. of 0.086 percent U_3O_8 , and 3.0 ft. of 0.136 percent U_3O_8 , in order of increasing depth.

FIGURE 23

FLUOROMETRIC URANIUM CONCENTRATIONS
AND LAYER CONSTRUCTIONS
FOR ARRAY I

FIGURE 24

FLUOROMETRIC URANIUM CONCENTRATIONS
AND LAYER CONSTRUCTIONS
FOR ARRAY II

Modeling of Rn-222 in this study is limited to the region above the water level at 65 m depth. This restriction is imposed because the models do not simulate any processes of groundwater leaching, gas solubility, or gas transfer across an air/water interface. An approximate calculation of the influence of the submerged ore deposits is considered later in this section, however.

Open boxes shown above the water level in Figures 23 and 24 depict rock layer constructions used as input data to the multiple layer model (section 4). These layers were delineated by visually grouping the uranium concentrations and then averaging properties within each group. Tables 6 and 7 display the averaged quantities for Arrays I and II, respectively.

Radon-222 profiles calculated by the multiple-layer model are shown in Figures 25 and 26, each illustrating two values of the diffusion coefficient. The plots also indicate measurements of soil gas Rn-222, "emanated Rn-222", and "leachable Pb-210" for comparison. The latter two nuclides require special explanations discussed below. Vertical broken lines in Figures 25 and 26 represent $E \cdot U_{\text{fluorometric}}$ derived from the layer-averaged quantities used as input data to the model⁽¹²⁾. These broken lines represent the activity of Rn-222 if it were in secular equilibrium with the rock layers which would be the case if no diffusive processes were in operation. Consequently, these lines represent the limiting output of the model as D approaches zero.

It is important to consider the basis upon which the solid daughter

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(12) The uranium content in ppm must first be multiplied by .0123 ρ to convert to units of dps/cm³ bulk.

TABLE 6

Layer-Averaged Data From Array I

Layer No.	Thickness m	Porosity*	Density gm/cm ³	Emanation	Uranium (fluorometric) ppm	Uranium (KUT) ppm	Thorium (KUT) ppm
1	5	.32	2.67	.28	11.6	16.7	46.6
2	9	.32	2.64	.25	5.9	4.9	23.5
3	5	.32	2.69	.34	18.4	16.6	48.8
4	4	.32	2.66	.30	15.8	13.8	34.1
5	8	.32	2.53	.17	6.9	3.9	18.4
6	7	.32	2.65	.34	13.4	12.8	40.2
7	14	.32	2.65	.32	10.8	8.9	28.3
8	9	.32	2.67	.35	20.3	19.4	44.8
9	4	.30	2.67	.27	45.4	46.5	93.5

* Averaging based on 3 data points

TABLE 7

Layer-Averaged Data From Array II

Layer No.	Thickness m	Porosity*	Density gm/cm ³	Enanation	Uranium (fluorometric) ppm	Uranium (KUT) ppm	Thorium (KUT) ppm
1	11	.38	2.66	.31	9.0	11.4	32.2
2	5	.38	2.63	.26	1.7	3.1	16.1
3	12	.38	2.66	.29	8.6	9.3	31.4
4	11	.38	2.61	.22	13.1	8.3	24.7
5	7	.38	2.63	.06	6.9	3.8	17.6
6	5	.38	2.73	.27	50.9	51.1	97.0
7	9	.32	2.68	.28	15.0	7.8	42.1
8	5	.32	2.67	.43	22.3	56.3	50.1

* Averaging based on 3 data points

FIGURE 25

COMPARISON OF MODEL RESULTS TO
FIELD DATA FOR ARRAY I

(Rn-222 and Daughter Products)

Activity of Rn-222 or Daughter Products, dps/cm³ rock →

FIGURE 26

COMPARISON OF MODEL RESULTS TO
 FIELD DATA FOR ARRAY II

(Rn-222 and Daughter Products)

product Pb-210 may be compared to Rn-222 in soil gas. The model formulation in section 1 defines concentration such that results are expressed in terms of activity per unit volume of soil gas. Radon and its daughter products which are trapped within the mineral grains are excluded⁽¹³⁾. Consequently, when comparing soil gas Rn-222 or model results to measurements of solid daughter products, activity within the mineral grains must also be excluded. In the case of Pb-210, the analytical procedure itself accomplishes this objective because activity is dissolved from the rock surface by leaching in 6N hydrochloric acid. As a result, values of leachable Pb-210 can be used directly to evaluate the model performance.

Values of "emanated Rn-222" plotted on Figures 25 and 26 were calculated as $E \cdot U_{KUT}$. The gamma spectral measurement discussed in section 6.1 actually characterizes the abundance of Ra-226. Multiplying this quantity⁽¹²⁾ by the emanation fraction, E, yields the Rn-222 activity of soil gas in secular equilibrium with the rock. It is important to note that "emanated Rn-222" cannot be used to evaluate model performance; it represents the source strength of Rn-222, not its actual abundance which is influenced by diffusive gain or loss from surrounding regions. Only actual measurements of Rn-222 in soil gas or measurements of its solid daughter products can be used for model verification.

The model results shown in Figures 25 and 26 are compared quantitatively to Pb-210 and Rn-222 data in Table 8. Correlation coefficients are near 0.9 for leachable Pb-210 data. In Array I the correlation is improved slightly when near-surface data from station 107-53 are omitted. This station

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(13) See footnote (2), section 2.1

TABLE 8

Correlation of Model Results
to Pb-210 and Rn-222 Data

Array	Nuclide	Category	Correlation Coefficient	
			$D=.02\text{cm}^2/\text{sec}$	$D=.005\text{cm}^2/\text{sec}$
I	Pb-210	All data	.91	.88
		Station 107-53 excluded (0.3m, 1.5m)	.92	.90
	Rn-222	All data	-.04	.09
II	Pb-210	All data	.84	.79
		U_{kut} input for deepest layer	.98	.98
	Rn-222	All data	-.35	-.28

is located approximately 70 m from the deep-hole array. Lead-210 measurements from station 107-12, located approximately 30 m from the array, agree more closely with the model results (Figure 25).

In both arrays, Pb-210 data exceed the model predictions at deeper levels near the water table. This discrepancy is particularly noticeable in Figure 26 (Array II), suggesting that the high values are not caused by emanation from the uranium ore which underlies Array I only.

Elevated values of Rn-222 and daughter products near a water table can be caused by a process of dissolution and redeposition of Ra-226 (Smith, Barretto, and Pournis, 1976). Radium-226 is a member of the U-238 decay chain and is the precursor of gaseous Rn-222 (Table 1). It can be leached from rock by groundwater and separated from its uranium parent. Fluctuations in groundwater level can leave a crust of precipitated radium at the water table which results in elevated values of Rn-222 and its daughters.

The hypothesis of radium migration is strengthened by the KUT uranium data in Tables 6 and 7. As discussed in section 6.1, this measurement characterizes the abundance of Ra-226. Although the layer-averaged KUT data agrees closely with fluorometric uranium in most of the rock column, the deepest layer in Array II shows a large discrepancy (Table 7). The Ra-226 at this level appears to be unsupported by the uranium content and consequently must have been transported from another region.

A dashed box at the base of Figure 26 represents the KUT uranium content of the deepest layer. When this value is substituted for fluorometric uranium as an input to the model, higher Rn-222 values result which are represented by the dashed curve. This process causes a marked increase in the correlation of model results to Pb-210 data for Array II (Table 8). When

separation of radium from uranium is considered, therefore, the agreement of modeling results to leachable Pb-210 data is good.

Measurements of Rn-222 displayed in Figures 25 and 26 are generally lower than both the Pb-210 data and the modeling results. Correlation coefficients shown in Table 8 are low and even negative showing no agreement with the model. The discrepancy cannot be explained by analytical uncertainty because laboratory measurements of Rn-222 exhibit a precision of ± 20 percent. There exists considerable uncertainty in soil gas sampling, however. Replicate samples from the same hole have shown poor agreement (Schutz, 1980). Because of the mobile nature of soil gas, it is uncertain whether a given sample is derived from the immediate vicinity of the sampling tube or from another region through the action of the pumping process.

Lead-210 is the first long-lived daughter product of Rn-222 (Table 2). With its 22 year half-life, Pb-210 activity represents the time-averaged activity of its gaseous precursor. Consequently, Rn-222 values could not remain lower than Pb-210 for long periods of time. The lower values of Rn-222 observed were either caused by sampling error or were transitory in nature. In any case, the steady-state model presented here should reflect time-averaged behavior which is better represented by Pb-210 measurements.

The presence of groundwater at depths greater than 65 m in the Red Desert prevents the gas transport models developed in this work from being applied to the level of the uranium ore deposits. An estimate of the distance which Rn-222 can migrate through water by molecular diffusion can be made by the common "diffusion length" formula (Tanner, 1964):

$$h = \sqrt{D/\lambda} \quad (6-3)$$

This formula indicates the distance, h in cm., from a planar source at which the concentration of a radioactive species will be reduced to $1/e$ times its source value. Assuming a diffusion coefficient of 1×10^{-5} cm²/sec for Rn-222 in water, formula 6-3 yields a diffusion distance of 2 cm and a hundred-fold diminution of concentration over a distance of 10 cm (Tanner, 1964). It is evident that under these conditions a submerged orebody at 130 m depth would exert no influence on the radon concentrations near the water level at 65 m depth.

The ground water at the Red Desert site is in motion, so that the migration of radon might reach greater distances than estimated from the simple diffusion case. The groundwater flow rate at the Red Desert site is not known. According to the calculation method of Tanner (1964), normal groundwater flow rates of 1.5 m/yr to 1.5 m/day would produce hundred-fold diminution over distances of 0.1 m to 37 m. These flow rates apply to gravitational flow in one dimension, however, and are almost certainly too high to characterize upward flow under usual conditions. It is unlikely, therefore, that the uranium ore at a depth of 130 m at the test site could directly influence the activity of Rn-222 near the water level at 65 m. It remains possible that the Ra-226 product of the ore could migrate upward and indirectly influence the Rn-222, Pb-210, and Bi-214 activities near the groundwater level.

6.3 Comparisons to He-4 Data

Several profiles of modeling results are presented in Figures 27 and 28, together with measurements of He-4 in soil gas taken from Arrays I and II (Schutz, 1980). The plots differ in the units used to express He-4 concentration. The former indicates an excess referred to the nominal atmospheric concentration of 5.24 ppm; the latter is derived from a He-4/Ar-36 concentration ratio according to the formula

$$\delta \text{ ‰} = \frac{\left(\frac{\text{He-4}}{\text{Ar-36}}\right)_{\text{sample}} - \left(\frac{\text{He-4}}{\text{Ar-36}}\right)_{\text{air}}}{\left(\frac{\text{He-4}}{\text{Ar-36}}\right)_{\text{air}}} \times 100 . \quad (6-4)$$

The utility of this formula and the advantages of He-4/Ar-36 ratio measurements are discussed by Schutz (1980).

Helium profiles have been calculated by equation 3-14 because of its close agreement with more complex forms (section 3.2). Profiles marked "132 m overburden" simulate a column of earth extending to the ore level. An average uranium content of 20 ppm and an average thorium content of 36 ppm are used in the calculations as derived from measurements in Array II. Profiles marked "132 m overburden plus ore" include a helium flux from the orebodies calculated by equation 3-15 (8.7×10^4 atoms He/cm²/sec). In both the above cases, it is assumed that all helium produced is steadily released into the interconnecting pore space as discussed in section 3.2.

FIGURE 27

COMPARISON OF He-4 MODEL RESULTS
TO FIELD DATA

(expressed as excess He-4)

FIGURE 28

COMPARISON OF MODEL RESULTS
TO FIELD DATA

(expressed as δ %)

Profiles marked "average earth" in Figures 27 and 28 include a He-4 flux of 3.1×10^5 atoms/cm²/sec. This figure is obtained by dividing the earth's maximum helium loss rate of 5.1×10^{31} atoms/year (Damon and Kulp, 1958) by the earth's surface area. The average flux derived in this way is only 3.6 times that calculated for the ore in this study, and is 3.0 times the production of the rock column alone to a depth of 132m. Damon and Kulp (1958) indicate that the calculated loss of helium to outer space is only a few percent of the estimated helium production by the earth's crust suggesting that the planet is only partly outgassed. Accordingly, the assumption of steady-state used by Grammakov, Glebovskaya, and Khaikovich (1965), and in this study, may lead to a large overestimation of the helium production by rocks and ores.

Measurements of He-4 displayed in Figures 27 and 28 show considerable scatter. Those taken from Array I (over the orebody) are not greater than those taken from Array II. Modeling profiles fall in the measurement range only when the diffusion coefficient of He-4 in soil gas is assumed to be 10^{-5} to 10^{-3} cm²/sec. These coefficients are much smaller than the value of 0.07 cm²/sec calculated for a dry soil in section 2.2. A value of 5×10^{-5} cm²/sec fits the data best in that the modeling curve (overburden plus ore) divides the measurements equally. The correlation coefficient of calculated results to He-4 data is only 0.04, however. The model exhibits a trend of increasing helium concentration with depth but the field data fail to show a similar trend.

The general disagreement noted above may be caused either by inaccuracy of the input data or by fundamental oversimplification of the model itself. In the former category, one possible error is underestimation of the local helium flux to the zone of interest. Trapping of helium by geologic formations and channeling of its release to the surface is thought to be a common occurrence (Dyck, 1976; Ereemeev, Sokolov, Solovov, and Yanitskii, 1973). It

is this process, in fact, which is the basis of helium prospecting for petroleum deposits and for various ores; anomalously high helium concentrations indicate the presence of fracture zones. It is possible that the Red Desert site receives an enhanced flux of He-4 by such a process and that elevated concentrations are the result.

The hypothesis of helium channeling into the study area is opposed by observations of elevated concentrations in other studies. Specifically, the average of 12,000 soil gas samples reported by Grammakov, Glebovskaya and Khaykovich (1965) lies well above the "average earth" profile based on a diffusion coefficient of $0.07 \text{ cm}^2/\text{sec}$ (figures 27, 28). This comparison suggests that the model yields low concentrations in general. It must be remembered, however, that the helium flux of the "average earth" is based on a global mass balance; its applicability to any land mass is questionable.

A major uncertainty in the model is the diffusion coefficient for helium. The value of $0.07 \text{ cm}^2/\text{sec}$ is based on an empirical equation for dry soil rather than upon experiment (section 2.2). Moisture in the soil may have a pronounced effect on this coefficient⁽¹⁴⁾. Although no relevant investigations of He-4 coefficients have been found, the Soviet literature reviewed by Tanner (1964) includes moisture effects on Rn-222 diffusion in porous media. The data reveal a reduction of diffusion coefficient by more than an order of magnitude with the addition of 17 percent moisture to a fine sand. In cases of higher moisture content, a diffusion coefficient

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(14) Several measurements of moisture content were performed on soils from the Red Desert site by determining the weight loss upon heating in an oven at 105°C . The results were 3-7 percent to depths of 1m and 6-8 percent at greater depths (Schutz, 1980).

near that for water itself was found appropriate. These observations suggest that the process of He-4 diffusion in porous media could be dominated by moisture effects, even at moderate levels. This hypothesis is attractive because the model results in Figure 27 and 28 approximate the field observations when a diffusion coefficient appropriate to water (10^{-5} cm²/sec) is used.

Finally, it is possible that the diffusion model is too simple to represent the migration of He-4 in a porous medium which contains moisture. Processes of surface adsorption, solution, and inter-phase transfer may dominate. Such processes could be studied individually, or they could be approached collectively by determining empirical mass transfer properties. Further studies of these kinds must be performed to obtain an adequate model for helium migration in the earth.

7.0 CONCLUSIONS

The most fundamental mathematical models developed in this work simulate the steady-state diffusion of gaseous nuclides in homogeneous rock columns. In the case of a non-radioactive overburden, Rn-222 and some of its daughter products are calculated to be detectable at distances of several tens of meters from a planar uranium ore deposit (1m thickness, 0.6 percent U_3O_8 , 20 percent emanation). When the overburden is assumed to contain 4 ppm uranium, the masking effect of locally produced activity reduces the detection range to near 15m. The same distance applies to observing a Xc-133 anomaly in an active overburden near a planar uranium deposit.

Models of He-4 diffusion in a rock column yield highly uncertain results because measurements of diffusion coefficients in actual rocks are lacking and because the flux of helium from deep within the earth is generally unknown. If a diffusion coefficient near 10^{-1} cm^2/sec is assumed, the helium concentration 20 m distant from the previously mentioned ore will be 0.5 ppb greater than the ambient level, which is not detectable. If a diffusion coefficient as low as 10^{-5} cm^2/sec is assumed, the same ore could produce a 3.5 ppm helium excess at this range. Comparisons of model results to field data suggest that He-4 diffusion coefficients of 10^{-4} to 10^{-5} cm^2/sec are appropriate. These comparisons require assumptions concerning the deep helium flux, however.

Inhomogeneity in rock columns has been simulated by constructing multiple-layer models. Each rock layer may be assigned uranium and thorium concentrations as well as a diffusion coefficient and physical properties.

The models have been applied to deep-hole data obtained in central Wyoming, USA. The resulting profiles are in agreement with measurements of Pb-210 which is a daughter product of Rn-222. Observed activities near the groundwater level are higher than calculated, however, probably caused by radium leached from the underlying rock.

The effect of soil gas motion as an additional transport mechanism has been evaluated using both steady-state and transient models. A constant soil gas velocity of 1×10^{-4} cm/sec causes gaseous nuclide concentrations to change by several orders of magnitude. If steady soil gas motion exists in nature, the detectability of uranium ore by emanation methods will be significantly different from that indicated by the pure diffusion model.

A transient numerical model has been used to simulate barometric influences on the migration of Rn-222, Xe-133, and He-4 away from an ore deposit. Sinusoidal variations in atmospheric pressure cause sinusoidal changes in gas concentrations which are attenuated with increasing depth. The effect is less than ± 15 percent near the earth's surface for Rn-222 and Xe-133, while He-4 exhibits a maximum variation of 0.4 percent. The percentage barometric effect is the same in active and passive overburdens when a pumping period of 1 day is simulated. Passive soils exhibit a deeper and stronger response to longer periods, however. Increases in rock permeability and decreases in rock porosity result in greater barometric effects.

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NOMENCLATURE

C	=	activity or concentration expressed per unit of void volume of a rock, dps/cm ³ or atoms/cm ³
D	=	molecular diffusion coefficient of the species in rock, cm ² /sec
E	=	local emanation of a rock, fraction of radiogenic gas which escapes into the interconnecting pore space
EMRATE	=	fraction of radiogenic gas which escapes the ore deposit in the upward direction
F	=	flux of the radiogenic species at the lower boundary of the model, dps/cm ² /sec or atoms/cm ² /sec
h	=	dimunition distance, cm
i	=	layer or spatial element index (subscript)
l	=	depth to a layer interface, cm
L	=	depth of ore body below the earth's surface, cm
n	=	temporal element index (superscript)
N	=	number of rock layers
OREGRD	=	grade of ore, % U ₃ O ₈
ORETHK	=	thickness of ore deposit, m
ORETH	=	thorium content of ore, ppm
t	=	time, sec or hr
Δ t	=	iteration interval, sec
Th	=	thorium content of soil, ppm
U	=	uranium content of soil, ppm
V	=	velocity (current density) of soil gas, cm/sec; volume of gas flowing per unit time per unit of geometric area

Nomenclature (cont.)

Z	=	space dimension, cm
ΔZ	=	spatial grid element length, cm
ϵ	=	porosity of rock; ratio of void to bulk volume
λ	=	decay constant of the radioactive species, sec^{-1}
ϕ	=	production rate of the radiogenic species expressed per unit void volume of a rock, $\text{dps/cm}^3/\text{sec}$ or $\text{atoms/cm}^3/\text{sec}$
ρ	=	density, gm/cm^3

The following symbols designate parameter groups or coefficients:

A, B, G, H, M, N, Q, R, r_1 , r_2 , T, W, Y

APPENDIX I

Experimental Data from Array I

Z	ρ	E	U	U	Th	ϵ	Rn-222	Pb-210	δ He-4
m	gm/cm ³		(fluorometric) ppm	(KUT) ppm	(KUT) ppm		dps/cm ³ soil	(leachable) dps/cm ³ soil	percent
0.3								.069, .156	
1.5	2.67		4.2				.0147, .0668	.059, .127	191,10;7
3.1	2.68	.27	21.2	17.1	50.2				
4.6	2.67	.29	9.3	16.3	43.0				
6.1	2.65	.23	6.8	5.3	26.2				
7.6	2.64	.20	3.4	2.9	16.7				
9.2	2.65		.8	3.7	26.2				
10.7	2.60	.26	5.1	5.3	24.0				
12.2	2.66	.26	11.9	8.7	29.5				
13.7	2.64	.31	7.6	3.4	18.2				
15.3	2.67	.34	15.3	11.1	34.2				
16.8	2.68	.37	24.6	24.2	62.5				
18.3	2.71	.30	15.3	14.6	49.7				
19.8	2.63	.38	17.0	14.6	27.1				
21.4	2.69	.25	12.7	11.4	34.8				
22.9	2.67	.31	17.8	15.5	40.3				
24.4	2.66	.04	6.8	3.4	18.9				
25.9	2.65	.12	6.8	3.9	21.7				
27.5	2.65	.19	5.9	3.2	18.5				

Z	ρ	E	U (fluorometric)	U (KUT)	Th (KUT)	ϵ	En-222 dps/cm ³ soil	Pb-210 (leachable) dps/cm ³ soil	δ He-4 percent
m	gm/cm ³		ppm	ppm	ppm				
29.0	2.61	.11	7.6	4.4	15.1				
30.5	2.61	.38	7.6	4.5	17.9	.30	.0095, .0105	.176, .053	6, 1
32.0	2.64	.28	10.2	12.1	38.1				
33.6	2.65	.33	12.7	10.9	39.4				
35.1	2.66	.40	15.3	13.8	38.3				
36.6	2.67	.38	15.3	14.9	47.7				
38.1	2.65	.31	13.6	12.4	37.3				
39.7	2.62	.37	9.3	6.9	21.5				
41.2	2.62	.21	7.6	4.2	16.1				
42.7	2.73	.37	13.6	10.9	31.7				
44.2	2.66	.31	14.4	13.9	35.8				
45.8	2.66	.30	11.0	6.9	26.8				
47.3	2.66	.35	9.3	6.7	21.4				
48.8	2.65	.21	3.4	4.2	21.7				
50.3	2.65	.33	15.4	14.2	43.3				
51.9	2.66	.41	13.6	12.7	36.8				
53.4	2.67	.42	24.6	20.8	51.7				
54.9	2.66	.37	22.0	23.0	51.8				
56.4	2.69	.27	23.7	25.5	62.0	.34	.0348	.422	14, 0
58.0	2.67	.38	12.7	15.2	31.0				
59.5	2.65	.29	13.6	12.5	27.7		.0175	.931	2
61.0	2.65		25.4						

Z	ρ	E	U (fluorometric)	U (KUT)	Th (KUT)	ϵ	Rn-222 dps/cm ³ soil	Pb-210 (leachable) dps/cm ³ soil	δ He-4 percent
m	gm/cm ³		ppm	ppm	ppm				
62.5	2.65		46.6						
64.1	2.69	.27	44.1	46.5	93.5				
65.6	2.66		27.1						
67.1	2.67	.32	13.6	11.2	43.3				
68.6	2.65		23.7						
70.2	2.67	.32	18.7	21.0	32.6				
71.7	2.64	.32	4.2	13.1	26.8				
73.2	2.66	.34	4.2	13.1	34.1				
74.7	2.66	.33	27.1	53.2	40.5				
76.3	2.70	.33	11.0	21.5	59.7				
77.8	2.66	.29	12.7	19.8	60.5				
79.3	2.66	.39	8.5	11.8	40.6				
80.8	2.66	.35	30.5	32.6	37.6				
82.4	2.64	.25	27.1	27.7	39.8				
83.9	2.65	.31	17.0	17.1	42.1				
85.4	2.70	.31	33.9	21.5	39.6				
86.9	2.67	.35	12.7	72.1	29.1				
88.5	2.68	.28	24.6	30.6	41.8				
90.0	2.67	.30	11.9	19.3	42.4	.27		.042	15
91.5	2.68	.30	9.3	13.4	54.8				
93.0	2.67	.39	5.1	10.6	37.1				
94.6	2.68	.20	5.1	8.4	36.1				

Z	ρ	E	U (fluorometric)	U (KUT)	Th (KUT)	ϵ	Rn-222 dps/cm ³ soil	Pb-210 (leachable) dps/cm ³ soil	δ He-4 percent
m	gm/cm ³		ppm	ppm	ppm				
96.1	2.69	.31	6.8	11.2	43.2				
97.6	2.85	.31	62.8	62.3	41.5				
99.1	2.65	.33	13.6	22.3	34.1				
100.7	2.67	.22	6.8	19.0	24.0				
102.2	2.70	.26	33.9	34.7	44.3				
103.7	2.68	.16	13.6	21.2	45.7				
105.2	2.50	.32	111.9	107.6	62.0				
106.8	2.66		145.0						
108.3	2.64		121.3						
109.8	2.67	.26	61.1	54.0	19.1				
111.3	2.69	.21	23.7	23.0	32.7				
112.9	2.67		28.8						
114.4	2.74	.05	28.8	29.3	80.4				
115.9	2.68		17.8						
117.4	2.71	.22	36.5	35.3	68.3				
119.0	2.73	.19	105.2	82.1	157.5				
120.5	2.76	.16	72.9	58.2	142.2	.26		.050	9.6

APPENDIX II

Experimental Data from Array II

Z	ρ	E	U	U	Th	ϵ	Rn-222	Pb-210	δ He-4
m	gm/cm ³		(fluorometric) ppm	(KUT) ppm	(KUT) ppm		dps/cm ³ soil	(leachable) dps/cm ³ soil	percent
0.3								.069,.098	-.7,-.1
1.5	2.65	.37	5.1	7.2	25.8		.0440,.112	.157	-2,31
3.1	2.66	.23	14.4	22.8	49.8				
4.6	2.65	.23	12.7	13.6	36.3				
6.1	2.64	.35	5.9	5.7	19.8				
7.6	2.66	.38	5.1	8.6	24.5				
9.2	2.66	.29	10.2	10.4	35.0				
10.7	2.67	.32	10.2	11.3	34.1				
12.2	2.63	.26	2.5	3.3	14.5				
13.7	2.62		0.8	2.5	14.6				
15.3	2.63		1.7	3.5	19.3				
16.8	2.65	.25	11.0	9.0	24.5				
18.3	2.69	.30	9.3	11.4	51.3				
19.8	2.66	.33	7.6	9.5	42.2				
21.4	2.70	.34	18.7	18.1	47.5				
22.9	2.63	.31	5.1	6.0	16.9				
24.4	2.65	.36	5.9	7.5	24.7				
25.9	2.64	.26	5.9	7.4	27.6				
27.5	2.63	.16	5.1	5.3	16.6				

Z	ρ	E	U (fluorometric)	U (KUT)	Th (KUT)	ϵ	Rn-222	Pb-210 (leachable)	δ He-4 percent
29.0	2.64		22.0						
30.1	2.62		8.5	3.4	14.1	.28	.0243, .0187	.075, .108	27, 11, 33
32.0	2.63	.11	8.5	4.5	20.9				
33.6	2.48	.35	15.3	13.7	27.9				
35.1	2.62	.13	6.8	4.8	17.3				
36.6	2.65	.32	17.0	13.6	36.3				
38.1	2.64	.18	13.6	9.7	31.7				
39.7	2.63		7.6	3.8	20.2				
41.2	2.62		6.8	3.9	19.3				
42.7	2.64	.06	6.8	4.4	20.7				
44.2	2.65		5.9	3.0	10.3				
45.8	2.63		7.6						
47.3	2.77	.24	40.7	43.5	89.9	.48	.0295	.853	164, 5
48.8	2.72	.30	54.3	58.7	104.1				
50.3	2.69		57.7						
51.9	2.68		14.4						
53.4	2.59	.28	9.3	7.8	42.1				
54.9	2.59		28.0						
56.4	2.55		11.9						
58.0	2.57		11.9						
59.5	2.58		14.4					1.27	89
61.0	2.71	.40	28.8	57.6	56.4				
62.6	2.68	.40	16.1						
64.1	2.66	.48	22.0	75.1	43.7				

Z	ρ	E	U (fluorometric)	U (KUT)	Th (KUT)	ϵ	Rn-222	Pb-210 (leachable)	δ He-4 percent
65.6	2.67		21.2						
67.1	2.63		17.8						
68.6	2.68	.39	28.0	33.0	34.2				
70.2	2.66	.31	28.0	13.5	28.4				
71.7	2.65	.33	33.1	16.2	19.0				
73.2	2.70		33.5						
74.7	2.68		21.2						
76.3	2.69		25.4						
77.8	2.67		19.5						
79.3	2.66		62.8						
80.8	2.65		21.2						
82.4	2.66		17.8	33.0	24.9				
83.9	2.67		57.7	51.8	32.4				
85.4	2.64		16.1	23.6	21.7				
86.9	2.66		19.5						
88.5	2.66		22.0						
90.0	2.67		22.9	26.2	62.1	.32		.043	6
91.5	2.69		18.7						
93.0	2.72		9.3						
94.6	2.70		12.7						
96.1	2.66		11.0						
97.6	2.66		16.1						
99.1	2.70		11.0	10.6	33.6				
100.7	2.73		30.0						

Z	ρ	E	U (fluorometric)	U (KUT)	Th (KUT)	ϵ	Rn-222	Pb-210 (leachable)	δ He-4 percent
102.2	2.74		89.9						
103.7	2.74		102.6						
105.2	2.68	.31	35.6	37.3	93.2				
106.8	2.66		17.0						
108.3	2.67		15.3						
109.8	2.68		14.4						
111.3	2.68		33.1						
112.9	2.65	.35	33.1	31.9	73.7				
114.4	2.65		19.5						
115.9	2.65		10.2						
117.4	2.65	.24	11.9	18.6	54.3				
119.0	2.64	.19	11.0	15.2	40.2				
120.5	2.63		9.3						
122.0	2.63		18.7						
123.5	2.65		10.2						
125.1	2.68		39.0						
126.6	2.69		66.1						
128.1	2.66		54.3						
129.6	2.63		25.3						
131.2	2.64	.38	24.6	21.3	53.3				
132.7	2.68		22.0						

Z	ρ	E	U (fluorometric)	U (KUT)	Th (KUT)	ϵ	Rn-222	Pb-210 (leachable)	δ He-4 percent
134.2	2.65		26.3						
135.7	2.63		16.1						
137.3	2.63		17.0						
138.8	2.62		17.8						
140.3	2.63		16.1						
141.8	2.63		15.3						
143.4	2.19		12.7						
144.9	2.63		27.1						
146.4	2.63		37.3	33.5	50.9				
147.9	2.63		14.4						
149.5	2.61		26.3						
151.0	2.63		21.2						
152.5	2.65		18.7						
154.0	2.63		11.0						
155.6	2.64		14.4						
157.1	2.61		14.4						
158.6	2.65		8.5						
160.1	2.64		15.3						
161.7	2.64		17.0						
163.2	2.62		11.0						
164.7	2.64		12.7						
166.2	2.64		16.1						
167.8	2.62		11.9			.22		.42	12, 44

Page 1 of 2
Page 2 of 2

FOUR MODELING PROGRAMS (A,B,C,D) FOR "A MODELING STUDY OF
GASEOUS Rn-222,X3-133 AND He-4 FOR U EXPLORATION.BY:H.W.JETER