**Estimating Calibration Equations
for Predicting Ra-226 Soil
Concentrations Using RTRAK
In-Situ Detectors at the
Ambrosia Lake, New Mexico,
Umtra Site**

R. O. Gilbert M. L. Miller
H. R. Meyer C. Begley

June 1988

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ESTIMATING CALIBRATION EQUATIONS FOR
PREDICTING Ra-226 SOIL CONCENTRATIONS
USING RTRAK IN-SITU DETECTORS AT THE
AMBROSIA LAKE, NEW MEXICO, UMTRA SITE

R. O. Gilbert
H. R. Meyer(a)
M. L. Miller(b)
C. Begley(a)

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Pacific Northwest Laboratory
Richland, Washington 99352

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- (a) Chem-Nuclear Systems, Incorporated
Albuquerque, New Mexico
(b) Roy F. Weston, Incorporated
Albuquerque, New Mexico

SUMMARY

This report describes a field study conducted at the Ambrosia Lake, New Mexico, UMTRA site to obtain data for calibrating the RTRAK Sodium Iodide (NaI) detectors for estimating concentrations of Ra-226 in surface soil. The statistical analyses indicate that the data are useful for estimating the calibration equations. Several statistical models are used to evaluate which model is best as a basis for the calibration equations. A procedure is provided for using the estimated calibration equations and extensive RTRAK measurements to estimate the average Ra-226 concentration on 100-m² land areas to determine whether additional remedial action is needed.

The UMTRA Project office proposes to use the RTRAK for cleanup verification of surface Ra-226 contamination. The system enables 100% coverage of areas having undergone remedial action. The sensitivity of the system enables verification at less than 5 pCi/g averaged over 100 m², as specified by the Environmental Protection Agency (EPA) standards (40 CFR Part 192). This analysis demonstrates RTRAK's ability to meet reasonable standards of statistical accuracy, using commonly accepted procedures.

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CONTENTS

SUMMARY	iii
ACKNOWLEDGMENTS	v
1.0 INTRODUCTION	1.1
2.0 RTRAK AND THE DESIGN OF THE FIELD STUDY	2.1
2.1 THE RTRAK SYSTEM	2.1
2.2 AMBROSIA LAKE STUDY PLAN	2.1
3.0 METHODS FOR ESTIMATING THE CALIBRATION EQUATIONS	3.1
3.1 PURPOSE	3.1
3.2 REGRESSION MODELS	3.1
4.0 RESULTS AND DISCUSSION	4.1
4.1 SOIL CONCENTRATIONS AND IN-SITU DATA	4.1
4.2 LINEAR REGRESSION	4.1
4.2.1 Ra-226 Soil Concentrations Versus 609 keV Measurements	4.1
4.2.2 Ra-226 Soil Concentrations Versus 1764 keV Measurements	4.6
4.3 MULTIPLE LINEAR REGRESSION	4.9
4.4 ESTIMATING MEAN ²²⁶ RA SOIL CONCENTRATIONS FOR 100-m ² AREAS USING THE RTRAK	4.10
4.5 TESTING FOR COMPLIANCE WITH THE EPA LIMIT	4.10
4.6 VARIABLES AFFECTING THE CALIBRATION EQUATIONS	4.12
5.0 CONCLUSIONS	5.1
6.0 REFERENCES	6.1

FIGURES

2.1	Pattern of Soil Plugs and RTRAK Detector Readings and N Locations at the Windblown Contaminated Tracts at Ambrosia Lake	2.3
4.1	Estimated Linear Regression Equation with 95% and 99% Confidence Intervals for Predicting Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using RTRAK 609 keV (cps) Measurements. Model 1 (Equation 1 in the Text) was Used to Obtain this Regression	4.5
4.2	Estimated Linear Regression Equation with 95% and 99% Confidence Intervals for Predicting <u>Mean</u> Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using <u>Mean</u> RTRAK 609 keV (cps) Measurements. Model 1 (Equation 1 in the Text) was Used to Obtain this Regression	4.5
4.3	Estimated Regression Equation with 95% and 99% Confidence Intervals for Predicting <u>Mean</u> Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using <u>Mean</u> RTRAK 609 keV (cps) Measurements. Model 2 (Equation 2 in the Text) was Used to Obtain this Regression	4.7
4.4	Comparison of the Regression Equations in Figures 4.2 and 4.3	4.7
4.5	Estimated Linear Regression Equation with 95% and 99% Confidence Intervals for Predicting <u>Mean</u> Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using <u>Mean</u> RTRAK 1764 keV (cps) Measurements. Model 1 (Equation 1 in the Text) was Used to Obtain this Regression	4.8
4.6	Estimated Regression Equation with 95% and 99% Confidence Intervals for Predicting <u>Mean</u> Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using <u>Mean</u> RTRAK 1764 keV (cps) Measurements. Model 2 (Equation 2 in the Text) was Used to Obtain this Regression	4.8
4.7	Comparison of the Regression Equations In Figures 4.5 and 4.6	4.9

TABLES

4.1	226Ra Concentrations (pCi/g) of ~500-g Soil Samples, and 609 keV and 1764 keV Readings (cps) Taken Using the Four RTRAK Detectors at 20 Locations in Windblown Contaminated Tracts at Ambrosia Lake, New Mexico	4.2
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1.0 INTRODUCTION

The United States federal government is required to perform remedial action on inactive uranium mill-tailings sites operated under contract to the federal government, and on properties that had been contaminated by the tailings. Remedial action is required if the average concentration of Ra-226 in soil over any area of 100-m^2 exceeds the background level by more than 5 pCi/g for the first 15 cm of soil below the surface, or if the average concentration exceeds 15 pCi/g for subsequent 15-cm thick layers of soil.

Due to the high cost of sampling and analyzing soil samples for Ra-226, considerable effort has been made to evaluate the use of in-situ radiation detectors for determining Ra-226 concentrations in soil (e.g., Marutzky et al. 1986, 1984; Williams et al. 1987; Gilbert et al. 1988). A requirement for the use of in-situ detectors is that a calibration equation be developed to convert with known accuracy the in-situ detector measurements into Ra-226 concentrations in soil.

Use of a gamma-based (in-situ) technique is in keeping with the UMTRA cleanup standards promulgated by the EPA in the January 5, 1983 Federal Register, Subpart C, 192.20(3)(b)(1): "In most cases, measurement of gamma exposure rates above and below the land surface can be used to show compliance with paragraph 192.12(a)" (EPA Radium-226 soil contamination standards).

On October 29, 1987, soil samples were collected and in-situ detector readings were taken at the windblown mill-tailings area at Ambrosia Lake, New Mexico. The detectors accumulated counts of the 609 keV and 1764 keV Bi-214 (Bismuth) peaks at 20 field locations where composite surface soil samples were also taken. This study was conducted to obtain data to calibrate for this site the four NaI in-situ detectors mounted on the front of a four-wheel-drive tractor called the RTRAK. The UMTRA Project Office proposes to begin use of the RTRAK for cleanup verification of surface contamination in areas not affected by interfering radiation from existing tailings piles. The system enables 100% coverage verifying remedial action for Ra-226 contamination. The sensitivity of the system should be capable of verifying cleanup at less than 5 pCi/g averaged over 100-m^2 , as specified by the EPA standards.

In this report we describe and interpret the statistical regression analyses conducted using these data to obtain calibration equations for the site. We also discuss the factors such as barometric pressure and disequilibrium between Ra-226 and its radon daughters that affect the calibration equation. In addition, we show how the in-situ-detector measurements may be used with calibration equations to estimate the average Ra-226 concentrations in surface soil of 100-m² areas so that compliance with the EPA limit for Ra-226 can be determined. The purpose of these analyses is to demonstrate that data provided by RTRAK meets reasonable standards of statistical accuracy, using commonly accepted procedures.

In Section 2.0 we describe the RTRAK system and the design of the field study conducted at Ambrosia Lake. The methods used to statistically estimate the calibration equations are discussed in Section 3.0, and the results and discussion of these analyses are given in Section 4.0. In Section 4.0 we also show how to estimate the mean Ra-226 soil concentrations in 100-m² areas using the calibration equations. Final conclusions and recommendations for further calibration studies are given in Section 5.0.

2.0 RTRAK AND THE DESIGN OF THE FIELD STUDY

2.1 THE RTRAK SYSTEM

The RTRAK is a four-wheel-drive tractor equipped with four NaI detectors, their supporting equipment, an industrial-grade IBM PC, and a commercial microwave auto-location system. The detectors are independently mounted on the front of the tractor and can be hydraulically lifted and angled. Wheels that support the detectors are also used to maintain a distance of 12 inches from the ground during monitoring except during extreme variations in terrain. Each detector has a tapered lead shield that restricts its field of view to about 24 inches, with overlap between adjacent detectors. The RTRAK takes gamma-ray readings while moving at a constant speed of 1 mph. When a reading above a prespecified level is encountered, red paint is sprayed on the ground to mark those locations. The automatic microwave locator system provides x-y coordinates with the gamma-ray count data. This automatic feature permits real-time map generation to assist in control of contamination excavation and cleanup verification mapping.

The NaI detectors count selected radon daughter gamma peaks that are related to Ra-226. Hence, the detectors do not directly measure Ra-226, the radionuclide to which the EPA standard applies. Radon is a gas, and the rate that it escapes from the soil depends on several factors including soil moisture, source depth distribution, soil radon emanating fraction, barometric pressure, soil density, and soil composition. The calibration of the detectors must take these variables into account so that radon daughter gamma peaks can be accurately related to Ra-226 soil concentrations under field conditions.

2.2 AMBROSIA LAKE STUDY PLAN

At Ambrosia Lake, the RTRAK took 2-second interval gamma-ray counts at locations in different regions of the wind-blown mill-tailings area while traveling at 1 mph. Counts of gamma-ray 609 keV and 1764 keV Bi-214 peaks were taken. Both peaks were recorded because, while the 609 keV peak produces more counts per unit time than the 1764 keV peak, the latter peak is less affected by interfering radionuclides that can affect the 609 keV peak. The RTRAK took measurements in different regions of the site so that Ra-226 soil

concentrations would cover a range from about 3 pCi/g to greater than 20 pCi/g. This range of concentrations was needed to assure that adequate data was obtained for estimating the calibration equations.

While the RTRAK was moving at 1 mph, it sprayed red paint on the ground directly under each of the 4 detectors at the beginning and ending of each 2-second count time. Immediately after the RTRAK readings were taken, three to five surface soil samples were collected equidistantly (on the detector centerline) between the two paint marks for each of the four detectors (Figure 2.1). These soil samples were collected to a depth of approximately 15 cm using a hand auger. The soil samples for each detector were emptied into a plastic bucket and mixed vigorously by hand for about 10 seconds. Then a small metal can was filled with ~500-g of the mixed soil. The can lid was taped in place for transportation to the laboratory.

Within two or three days, the wet weight of the soil in each can was determined, the can was sealed air-tight, and the soil was analyzed for Ra-226 (wet-weight basis). The cans were then stored for ~30 days, after which time the soil was again analyzed for Ra-226 (wet-weight basis). The cans were then opened and the soil was dried. The cans were again sealed and analyzed for Ra-226. Following a 30-day waiting period the soil samples were again analyzed for Ra-226, yielding what is referred to in this report as "ingrown" Ra-226 dry-weight concentrations. These "ingrown" data were used to estimate the calibration equations presented below. The 30-day waiting period is necessary to allow Ra-226 to come into equilibrium with its radon daughters. The measurements that are made immediately after the soil is collected are lower than the measurements made after 30 days, since the radiation being counted is associated with daughters of the short-lived gas Rn-222 (radon).

FIGURE 2.1. Pattern of Soil Plugs and RTRAK Detector Readings at N Locations at the Windblown Contaminated Tracts at Ambrosia Lake.

3.0 METHODS FOR ESTIMATING THE CALIBRATION EQUATIONS

3.1 PURPOSE

The purpose of the Ambrosia Lake study was to obtain NaI-detector in-situ measurements and Ra-226 concentrations at the same set of field locations so that the relationship between these two types of measurements could be determined using statistical regression analyses. The desired result of the regression analyses is a regression line that can be used to accurately predict the ingrown 30-day Ra-226 concentration (pCi/g dry weight) in a ~500-g sample of surface soil on the basis of a 2-second gamma scan by the RTRAK detectors as the RTRAK is moving at 1 mph over the spot where the soil sample is subsequently collected. The assumption is made that the 500-g soil sample is representative of the surface soil within the region scanned by the detector during the 2-second counting time.

A requirement of the regression (calibration) line is that it yields accurate predictions when soil concentrations are between 3 and 10 pCi/g. This region is of particular importance since the EPA limit is 5 pCi/g above background, and background at most mill-tailings areas is believed to be less than 5 pCi/g.

3.2 REGRESSION MODELS

Four regression models were examined to determine which model gave the most accurate predictions of ingrown (30-day) Ra-226 soil concentrations. The first model examined was the simple linear (straight-line) model

$$\text{Model 1: } Y_i = \alpha_1 + \beta_1 X_i, \quad (1)$$

where α_1 and β_1 are the unknown intercept and slope of the straight line, respectively, Y_i is the ingrown Ra-226 concentration for the soil sample collected at the i^{th} field location, and X_i is the in-situ detector measurement at the i^{th} location. Model 1 was used to construct regressions for both the 609 keV data and the 1764 keV data.

The second model examined was a simple linear (straight-line) model in the logarithmic scale, i.e.,

$$\text{Model 2: } \ln Y_i = \alpha_2 + \beta_2 (\ln X_i) , \quad (2)$$

where α_2 and β_2 are the unknown intercept and slope, respectively, of the straight line, $\ln Y_i$ is the natural logarithm of the ingrown Ra-226 concentration of the soil sample collected at the i^{th} field location, and X_i is the natural logarithm of the in-situ detector measurement at the i^{th} location. Model 2 was evaluated for both the 609 keV data and the 1764 keV data.

The third and fourth models examined were the multiple linear regression models

$$\text{Model 3: } Y_i = \alpha_3 + \beta_3 X_{1i} + \beta_4 X_{2i} \quad (3)$$

$$\text{Model 4: } \ln Y_i = \alpha_4 + \beta_5 (\ln X_{1i}) + \beta_6 (\ln X_{2i}) \quad (4)$$

where α_3 , β_3 , β_4 , α_4 , β_5 , and β_6 are unknown parameters, and X_{1i} and X_{2i} are the 609 keV and 1764 keV measurements, respectively, at the i^{th} location.

The Ambrosia Lake soil concentrations and in-situ measurements were used to estimate the parameters of these models using well known linear least-squares regression techniques [see, e.g., Snedecor and Cochran (1980, chapters 9 and 17)]. For Models 1 and 3 (Equations 1 and 3) we used the standard assumption that the error in predicting soil concentrations using the estimated parameters in the models is additive and has a normal (bell-shaped (Gaussian)) distribution with constant variance about the regression line for any given value of X_i . For Models 2 and 4 (Equations 2 and 4) we assumed these three conditions applied to the error in predicting the natural logarithms of the soil concentrations.

When Model 2 and Model 4 are exponentiated to put them in the untransformed scale, they take the form

$$Y_i = \exp(\alpha_2) X_i^{\beta_2} \quad (5)$$

and

$$Y_i = \exp(\alpha_4) X_{1i}^{\beta_5} X_{2i}^{\beta_6} \quad (6)$$

respectively. The regression results for Model 2 and Model 4 presented in the next section are given in this untransformed scale so that they may be compared more easily with the regression results for Model 1 and Model 3 which are also in untransformed scale.

The least-squares regression lines are used to predict the Ra-226 soil concentration at a location where an in-situ measurement is taken. However, there will be some error in this prediction due to variability in the data used to estimate the regression equations. (This variability will be seen in the next section.) Hence, for each model we also estimate upper and lower limit values that have a specified probability of including the true Ra-226 soil concentration.

4.0 RESULTS AND DISCUSSION

4.1 SOIL CONCENTRATIONS AND IN-SITU DATA

In Table 4.1 are listed the ingrown Ra-226 concentrations (pCi/g) of the ~500-g soil samples and the 609 keV and 1764 keV gamma-ray counts-per-second (cps) measurements taken by the four NaI RTRAK detectors. Also listed in Table 4.1 are the initial measurements of Ra-226 soil concentrations obtained on the dried soil samples. Notice that the ingrown concentrations are always larger than the initial concentrations, about 75% larger on the average for these samples. For this reason we have used only the 30-day ingrown data in the following regression analyses.

Notice in Table 4.1 that the Ra-226 concentrations for Pacific Northwest Laboratory (PNL) ID numbers 1, 2, 3, and 10 for all four RTRAK detectors are the same or similar in value and are all less than or equal to 2 pCi/g. The Ra-226 concentrations for these samples were below the measurement detection limit. The data for these samples in Table 4.1 are upper limits on the measured values rather than the measured values themselves. Regression analyses were first conducted on the full set of data as listed in Table 4.1. Then the regressions were repeated after deleting the upper-limit data and their accompanying in-situ measurements. There were negligible differences in the estimated equations for these two cases. The regression results given below were those obtained after deleting the upper-limit data.

4.2 LINEAR REGRESSION

4.2.1 Ra-226 Soil Concentrations Versus 609 keV Measurements

Figure 4.1 shows the ingrown Ra-226 data plotted versus the 609 keV measurements taken at the same locations. Also shown is the estimated coefficient of multiple determination (r^2), the estimated regression equation, and the 95% and 99% one-tailed confidence limits for the Ra-226 concentration of a soil sample for any given 609 keV measurement as obtained assuming Model 1 is appropriate. The quantity r^2 is the percentage of the variability in the

TABLE 4.1. Ra-226 Concentrations (pCi/g) of ~500-g Soil Samples, and 609 keV and 1764 keV Readings (cps) Taken Using the Four RTRAK Detectors at 20 Locations in Windblown Contaminated Tracts at Ambrosia Lake, New Mexico.

PNL ID	Filename	Data Set	Detector Number	609 KeV cps	1764 KeV cps	Ra-226(a) Ingrown	Ra-226(a)(b) Initial
3	BKG1.MAP	18	1	12	0	1.5	1.3
10	PCI5-10.MAP	13	1	24	5	1.6	1.3
1	BKG1.MAP	10	1	13	3	1.6	1.3
2	BKG1.MAP	15	1	15	1	1.6	1.3
6	PCI5-10.MAP	6	1	20	5	3.5	2.4
13	PCI10-15.MAP	16	1	32	7	4.0	2.0
4	PCI5-10.MAP	3	1	25	5	4.1	1.9
7	PCI5-10.MAP	8	1	20	6	5.0	2.5
5	PCI5-10.MAP	5	1	27	4	5.9	2.9
8	PCI5-10.MAP	10	1	22	4	6.2	3.4
11	PCI5-10.MAP	14	1	27	5	7.3	4.1
9	PCI5-10.MAP	12	1	23	5	7.4	4.4
12	PCI10-15.MAP	14	1	30	6	9.2	4.2
15	PCI10-15.MAP	20	1	27	6	9.9	5.2
14	PCI10-15.MAP	18	1	31	8	13.4	8.0
18	PCIHI.MAP	16	1	38	13	21.8	13.0
20	CHECK3.MAP	2	1	52	9	23.9	11.1
17	PCIHI.MAP	6	1	54	11	24.4	13.5
16	PCIHI.MAP	2	1	55	10	27.2	14.1
19	CHECK2.MAP	2	1	55	13	29.9	17.3
1	BKG1.MAP	10	2	11	1	1.3	1.3
10	PCI5-10.MAP	13	2	22	4	1.3	1.3
2	BKG1.MAP	15	2	16	2	1.3	1.5
3	BKG1.MAP	18	2	13	2	1.4	1.3
6	PCI5-10.MAP	6	2	22	1	2.6	1.3
5	PCI5-10.MAP	5	2	21	4	3.0	1.8
4	PCI5-10.MAP	3	2	21	3	4.0	2.2
11	PCI5-10.MAP	14	2	21	4	5.9	3.6
8	PCI5-10.MAP	10	2	22	3	6.8	3.7
18	PCIHI.MAP	16	2	38	8	7.0	4.6
14	PCI10-15.MAP	18	2	27	6	8.5	3.8
7	PCI5-10.MAP	8	2	24	4	8.6	4.6
9	PCI5-10.MAP	12	2	24	3	8.9	4.4
15	PCI10-15.MAP	20	2	29	4	9.1	3.9
13	PCI10-15.MAP	16	2	27	5	10.1	4.5
12	PCI10-15.MAP	14	2	31	7	13.8	6.6
16	PCIHI.MAP	2	2	50	11	21.8	13.0
19	CHECK2.MAP	2	2	43	8	24.5	13.6
20	CHECK3.MAP	2	2	41	8	24.6	12.7
17	PCIHI.MAP	6	2	55	12	37.4	22.2
2	BKG1.MAP	15	3	14	1	1.3	1.3
1	BKG1.MAP	10	3	15	3	1.4	1.3
3	BKG1.MAP	18	3	14	4	1.6	1.3

TABLE 4.1 (Continued)

PNL ID	Filename	Data Set	Detector Number	609 KeV cps	1764 KeV cps	Ra-226(a) Ingrown	Ra-226(a)(b) Initial
10	PCI5-10.MAP	13	3	26	6	2.0	1.3
4	PCI5-10.MAP	3	3	21	4	3.5	1.4
14	PCI10-15.MAP	18	3	28	7	5.6	3.4
6	PCI5-10.MAP	6	3	22	3	5.8	3.7
9	PCI5-10.MAP	12	3	23	6	6.0	3.9
5	PCI5-10.MAP	5	3	21	5	6.2	3.5
7	PCI5-10.MAP	8	3	22	7	6.5	3.6
11	PCI5-10.MAP	14	3	21	6	6.6	4.1
18	PCIHI.MAP	16	3	40	7	8.2	4.4
13	PCI10-15.MAP	16	3	27	7	10.5	4.3
8	PCI5-10.MAP	10	3	23	4	11.3	5.8
15	PCI10-15.MAP	20	3	36	4	12.7	5.7
12	PCI10-15.MAP	14	3	29	7	19.0	7.0
20	CHECK3.MAP	2	3	38	11	21.1	11.7
16	PCIHI.MAP	2	3	46	12	26.1	15.3
19	CHECK2.MAP	2	3	46	10	31.3	16.8
17	PCIHI.MAP	6	3	58	14	32.0	16.6
10	PCI5-10.MAP	13	4	17	5	1.3	1.3
3	BKG1.MAP	18	4	11	3	1.3	1.9
2	BKG1.MAP	15	4	12	2	1.3	1.3
1	BKG1.MAP	10	4	12	3	1.4	1.3
4	PCI5-10.MAP	3	4	20	3	3.9	1.5
6	PCI5-10.MAP	6	4	19	4	5.0	2.5
11	PCI5-10.MAP	14	4	18	4	5.0	3.7
14	PCI10-15.MAP	18	4	30	7	5.1	2.4
7	PCI5-10.MAP	8	4	27	5	5.2	3.1
8	PCI5-10.MAP	10	4	24	4	5.2	3.4
5	PCI5-10.MAP	5	4	25	4	5.3	3.0
9	PCI5-10.MAP	12	4	20	3	6.0	3.7
15	PCI10-15.MAP	20	4	27	8	8.3	5.3
12	PCI10-15.MAP	14	4	25	8	8.8	3.4
13	PCI10-15.MAP	16	4	27	10	10.1	4.3
18	PCIHI.MAP	16	4	51	11	12.9	7.2
20	CHECK3.MAP	2	4	47	11	25.2	11.8
17	PCIHI.MAP	6	4	63	14	29.8	16.3
19	CHECK2.MAP	2	4	45	11	32.1	14.6
16	PCIHI.MAP	2	4	57	13	33.1	19.0

(a) Ra-226 data for PNL ID numbers 1, 2, 3, and 10 are upper-limit values. See Section 4.1 for details.

(b) Prior to Rn-222 daughter ingrowth

Ra-226 measurements that is explained by their correlation with the 609 keV measurements. If $r^2 = 1$, then all the data points would fall exactly on the straight line.

There is considerable scatter in the data about the fitted regression line due in part to the fact that the in-situ detector is looking at a larger volume of soil than the ~500-g samples that were analyzed for Ra-226. This scatter indicates that there was a range of observed Ra-226 soil concentrations for a given 609 keV measurement.

Figure 4.1 also shows that a 609 keV measurement of about 23 cps corresponds to a soil concentration of 6.5 pCi/g, where 6.5 pCi/g is the approximate EPA limit for Ra-226 at Ambrosia Lake since the background at that site is about 1.5 pCi/g. Hence, the regression equation indicates that if the 609 keV measurement at a location equals ~23 cps, there is approximately a 50-50 chance that the concentration of Ra-226 for a 500-g soil sample removed from the scanned area would have a concentration exceeding 6.5 pCi/g.

Also shown in Figure 4.1 is the 609 keV measurement (~7 cps) that corresponds to the upper 99% (one-tailed) confidence limit value for an individual soil sample of 6.5 pCi/g. That is, if we assume the regression equation is valid at these very low concentration levels for which no data were obtained, then if we observed a 609 keV measurement of ~7 cps, there would be approximately one chance in a hundred that the concentration of Ra-226 of a 500-g soil sample would exceed the EPA limit of 6.5 pCi/g. However, the assumption that the equation is valid at very low concentration levels cannot be confirmed with the presently available data.

The regression equation in Figure 4.1 was estimated using the 64 data points for the four individual detector measurements and soil concentrations at 16 locations. However, the ultimate goal of taking in-situ measurements with the RTRAK is to estimate average Ra-226 concentrations over 100-m² areas. For that purpose it is desirable to average the measurements for the four soil samples at a given location, and to regress these averages on the average of the four in-situ detector measurements at that location.

The four detectors at a location scanned an area of 8 ft by 2 ft (16 ft², or ~1.5-m²) (Figure 2.1). The average soil concentration for this ~1.5-m² area

FIGURE 4.1. Estimated Linear Regression Equation with 95% and 99% Confidence Intervals for Predicting Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using RTRAK 609 keV (cps) Measurements. Model 1 (Equation 1 in the Text) was Used to Obtain this Regression.

FIGURE 4.2. Estimated Linear Regression Equation with 95% and 99% Confidence Intervals for Predicting Mean Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using Mean RTRAK 609 keV (cps) Measurements. Model 1 (Equation 1 in the Text) was Used to Obtain this Regression.

was based on the 12 soil samples that were composited to form the four 500-g soil samples. Figure 4.2 shows the regression of the average (arithmetic mean) soil concentration versus the average (arithmetic mean) 609 keV measurement for the 1.5-m² areas. We see that the regression equation is almost identical to the regression equation estimated using the individual data points (Figure 4.1), but the scatter about the regression line is considerably reduced. That is, if we average the four detector readings together, we can get a considerably better (more accurate) estimate of average soil concentrations than is possible using individual detector measurements. The remaining regression results in this paper were obtained using average in-situ and soil data.

Figure 4.3 shows the regression results obtained using Model 2 for the 609 keV data. Note that the r^2 value (0.91) is almost identical to that obtained using Model 1 in Figure 4.2 (0.92). The 609 keV measurement that corresponds to an average of 6.5 pCi/g of Ra-226 in the composite soil sample is also about the same size as in Figure 4.2 (~23 cps). However, the 609 keV measurement that corresponds to the upper 99% confidence-limit value of 6.5 pCi/g is somewhat larger than that in Figure 4.2 (~16 cps instead of ~12 cps). These comparisons are evident in Figure 4.4 where the regression results from Figures 4.2 and 4.3 are superimposed on the same graph for comparison purposes. The 609 keV values of 12, 16, or 23 cps, or similarly derived limits for other probability levels, could be used during excavation surveys by the RTRAK to indicate small areas that may need remedial action.

4.2.2 Ra-226 Soil Concentrations Versus 1764 keV Measurements

In Figures 4.5 and 4.6 are shown the regressions of average Ra-226 concentrations on average 1764 keV measurements for Model 1 and Model 2, respectively. The r^2 values are slightly smaller than those obtained for the 609 keV regressions in Figures 4.2 and 4.3 (0.85 versus 0.92). This indicates the 1764 keV measurements may not predict Ra-226 concentrations quite as accurately as the 609 keV measurements, at least at Ambrosia Lake.

In Figure 4.7 the regressions in Figures 4.5 and 4.6 are superimposed to show that the regression equations for the two models are very similar and the limit lines are dissimilar. These same conclusions were reached for the 609 keV regressions (Figure 4.4). Of course, the extension of the upper limit

FIGURE 4.3. Estimated Regression Equation with 95% and 99% Confidence Intervals for Predicting Mean Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using Mean RTRAK 609 keV (cps) Measurements. Model 2 (Equation 2 in the Text) was Used to Obtain this Regression.

FIGURE 4.4. Comparison of the Regression Equations in Figures 4.2 and 4.3.

FIGURE 4.5. Estimated Linear Regression Equation with 95% and 99% Confidence Intervals for Predicting Mean Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using Mean RTRAK 1764 keV (cps) Measurements. Model 1 (Equation 1 in the Text) was Used to Obtain this Regression.

FIGURE 4.6. Estimated Regression Equation with 95% and 99% Confidence Intervals for Predicting Mean Ra-226 Concentrations (pCi/g) in Surface Soil at the Ambrosia Lake Windblown Contaminated Tracts Using Mean RTRAK 1764 keV (cps) Measurements. Model 2 (Equation 2 in the Text) was Used to Obtain this Regression.

FIGURE 4.7. Comparison of the Regression Equations In Figures 4.5 and 4.6

lines down into the low concentration regions in the figures requires the assumption that the regression equations are valid for those regions.

4.3 MULTIPLE LINEAR REGRESSION

The multiple linear regression equation obtained using Model 3 was

$$Y_i = -11.7 + 0.884 X_{1i} - 0.591 X_{2i} \quad (7)$$

where X_{1i} and X_{2i} are the 609 keV and 1764 keV measurements, respectively, at the i^{th} location ($n = 16$ locations). The r^2 value was 0.92, which is the same as obtained when just the 609 keV measurements were used to estimate the average soil Ra-226 concentration over the 1.5-m^2 area (Figure 4.2). Hence, there appears to be no advantage to using Equation 7 rather than the simpler equation in Figure 4.2.

The multiple linear regression equation obtained using Model 4 and exponentiating the equation was

$$Y_i = 0.0306 (X_{1i})^{1.56} (X_{2i})^{0.264} \quad (8)$$

with an r^2 value of 0.91 ($n = 16$). This r^2 value is the same as obtained for Equation 7, which indicates both equations will do about equally well at predicting average Ra-226 concentrations. However, there appears to be no particular reason to use either Equation 7 or Equation 8 rather than the simpler equations in Figures 4.2 and 4.3.

4.4 ESTIMATING MEAN RA-226 SOIL CONCENTRATIONS FOR 100-m² AREAS USING THE RTRAK

The regression results obtained above may be used to estimate the average Ra-226 soil concentration (pCi/g) in 100-m² areas in wind-blown contaminated tracts at Ambrosia Lake. We illustrate the method using the regression equation in Figure 4.2, which is:

$$Y_i = -11.1 + 0.74 X_i \quad (9)$$

where Y_i is the estimated mean Ra-226 concentration over a 8-ft by 2-ft (1.5-m²) area, and X_i is the mean 609 keV cps reading for the 1.5-m² area.

The general approach is to first take mean RTRAK readings (X_i) over the entire 100-m² area (assumed here to be a 10-m by 10-m square). There will be 64 such means in each 100-m² area (assuming the RTRAK takes four parallel passes over the area with 16 mean readings per pass). Then the mean ($\bar{X}$) of the 64 means is computed and used to estimate the mean Ra-226 soil concentration ($\bar{Y}$) for the area as follows:

$$\bar{Y} = -11.1 + 0.74 \bar{X} \quad (10)$$

where $\bar{Y}$ is in units of pCi/g and $\bar{X}$ is in units of cps.

4.5 TESTING FOR COMPLIANCE WITH THE EPA LIMIT

$\bar{Y}$ as computed using Equation 10 would be compared with the EPA limit to determine if additional remedial action of that 100-m² area is required. If $\bar{Y}$ exceeds the limit, additional remedial action would be required. If $\bar{Y}$ does not exceed the limit, an upper confidence limit for $\bar{Y}$ would be

computed. If this upper confidence limit exceeds the EPA limit, then additional remedial action would be indicated.

To compute an upper confidence limit, it is necessary to estimate the uncertainty (variance) of $\bar{Y}$. Using the standard formula for the variance of $\bar{Y}$ for linear regression (see e.g., Snedecor and Cochran 1980, page 165; the square of Equation 9.9.1) we obtained using the data in Figure 4.2 that

$$\text{VAR}(\bar{Y}) \simeq 0.50 + 0.00356(\bar{X} - 32.2)^2 . \quad (11)$$

Then the upper confidence limit is calculated as follows:

$$UL_{\alpha} = \bar{Y} + t_{\alpha} \sqrt{\text{VAR}(\bar{Y})} , \quad (12)$$

where $\bar{Y}$ and $\text{VAR}(\bar{Y})$ are given by Equations 10 and 11, respectively, and t_{α} is the value from t table (e.g., Table A4 in Snedecor and Cochran 1980) for the desired confidence level (α) and $n - 2$ (14 in this case) degrees of freedom.

To illustrate, if the average of the sixty-four 609 keV 1.5-m² averages for a 100-m² plot is found to be 17 cps and we desire an upper 99% confidence limit, then $t_{0.99} = 2.624$ and

$$\begin{aligned} UL_{0.99} &= 1.48 + 2.624 \sqrt{1.3225} \\ &= 4.5 \text{ pCi/g} \end{aligned}$$

Hence, additional remedial action would not be required for this 100-m² plot since 4.5 pCi/g is less than the EPA limit of 6.5 pCi/g.

Rather than base the remedial action decision on the equation in Figure 4.2 as was done in the above example, a procedure based on the regression equation in Figure 4.3 could be used. In that case, equations of the form of Equations 10, 11, and 12 would still be used, but $\bar{Y}$ and $\text{VAR}(\bar{Y})$ would be computed using the natural logarithms of the Ra-226 and 609 keV 1.5-m² area averages. Then, once the upper limit ($UL_{0.99}$) was computed using Equation 12, the quantity $\exp(UL_{0.99})$ would be compared with the EPA limit of 6.5 to determine if additional remedial action was needed for the plot.

Use of the RTRAK for verification of cleanup of contamination will enable 100% coverage of the surface scanned. The sensitivity of the system should enable verification at less than 5 pCi/g averaged over 100-m², as specified by the EPA standards. Following final remedial actions and RTRAK scanning on all 100-m² plots, a limited number of soil samples would be collected and analyzed for Ra-226 to double check that remedial action has been effective.

It should be noted that Ra-226 concentrations for some individual soil samples may exceed the EPA standard even though the above upper confidence limit approach did not indicate additional remedial action was needed. This could happen because the confidence limit approach is concerned with the average Ra-226 concentration over the entire 100-m² plot, not with concentrations of individual soil samples or of soil samples representing 1.5-m² areas.

4.6 VARIABLES AFFECTING THE CALIBRATION EQUATIONS

As discussed in Section 1.0 there are several variables that can affect the calibration equation that relates Ra-226 soil concentrations to in-situ measurements of radon daughters. The most important of these variables is disequilibrium between Ra-226 and its radon daughters. Another important variable is the barometric pressure at the time the in-situ measurement is being made. As the barometric pressure decreases, more radon will escape from the surface soil, which will change the amount of disequilibrium present.

In this study the field in-situ measurements are related via a regression equation to the ingrown Ra-226 concentration. However, this equation could give biased estimates of Ra-226 if it were applied to in-situ measurements that were taken when the barometric pressure was substantially different from that present when the calibration measurements were taken. The bias due to this factor is believed to be less than 10%. However, additional data will be obtained to quantify the size of the bias likely to occur under different barometric-pressure conditions. This will be done during cleanup verification activities by taking repeat RTRAK in-situ measurements at the same locations over time during periods when the barometric pressure is changing. The barometric pressure will be read periodically at the same times the in-situ

measurements are being taken. Then the change in the in-situ measurements can be related quantitatively to the change in barometric pressure.

Two other variables that could bias estimates of Ra-226 concentrations obtained using the regression equations above are soil moisture conditions and depth of penetration of Ra-226 in the soil. Marutzky et al. (1986, Appendix C) found on the basis of 18 soil samples collected at Monticello, Utah that in-situ measurements should be increased by the factor of 1.09 to correct them for soil moisture conditions at that site. During verification activities a study will be conducted to determine the influence, if any, of soil moisture on RTRAK accuracy. As concerns depth of penetration of Ra-226 in soil, the RTRAK will be used only in areas where the Ra-226 is expected to be in the uppermost surface soil.

5.0 CONCLUSIONS

1. The principal conclusion of this study is that the RTRAK can be successfully used on the UMTRA project to measure average Ra-226 concentrations over 100-m^2 areas in accordance with EPA standards. The r^2 values for all the regression equations were quite high, and the soil concentration data covered the necessary range from 3 pCi/g to over 20 pCi/g.
2. The equation in Figure 4.2 may be used in conjunction with the procedure in Sections 4.4 and 4.5 to estimate the mean Ra-226 concentration (pCi/g) in surface soil of each 100-m^2 area and to determine if additional remedial action for each area is needed. Alternatively, the regression equation in Figure 4.3 in conjunction with the procedure using logarithmic-transformed data indicated in Section 4.5 may be used.
3. The upper confidence limit lines in Figures 4.2 through 4.7 apply to mean soil concentrations for 1.5-m^2 areas, whereas the upper limits computed as discussed in Section 4.5 apply to the mean soil concentration over the 100-m^2 plot. For that reason, the upper limit lines in the figures should not be used to decide at the verification stage whether additional remedial action for a 100-m^2 plot is needed. However, the upper limit lines in the figures may be useful at the active excavation stage for deciding where more soil needs to be removed.
4. If a site is remediated on the basis of the testing procedure in Sections 4.4 and 4.5, then some individual 500-g soil samples representing 1.5-m^2 areas or less that might be collected within any 100-m^2 plot might still exceed the EPA limit. This could happen because the procedure in Sections 4.4 and 4.5 is concerned with the mean soil concentration over the entire 100-m^2 plot rather than concentrations for individual 500-g soil samples representing 1.5-m^2 areas or less.
5. There appears to be no advantage to using multiple linear regression (Equations 7 and 8) in place of the equations in Figures 4.2 and 4.3 for estimating the average Ra-226 concentration in 1.5-m^2 areas or as a basis for making remedial action decisions at the verification stage as discussed in Sections 4.4 and 4.5.

6. There appears to be no advantage to using the equations in Figures 4.5 and 4.6 (for the 1764 keV measurements) in preference to the equations in Figures 4.2 and 4.3 (for 609 keV measurements) unless there are radionuclides present in the soil that interfere with the 609 keV measurements for estimating Ra-226.
7. Studies will be conducted during actual verification activities to determine the relationship between changing barometric pressure and repeated RTRAK in-situ measurements at the same locations and also to determine the influence, if any, of soil moisture on RTRAK accuracy.

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