



Radionuclide Partition Coefficients for the BNL Site

For the Saturated and Unsaturated Zones

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February, 1999

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Partition Coefficients (K_d) in the Saturated Zone

The partition coefficient (K_d) is defined as the concentration of a species of interest on the solid phase divided by the concentration of that species in the liquid phase, at steady-state. Therefore the lower the K_d , the less sorption takes place. It is a parameter that is readily incorporated in chemical transport models. The K_d approach to the partitioning of contaminants between soil and water in groundwater flow systems, is based on the assumption that sorption reactions are in equilibrium and are reversible. As a contaminant plume advances along flow paths, the movement of the front is retarded (relative to the movement of the groundwater) as a result of transfer of part of the contamination mass to the solid phase. If the input of contaminant mass to the system is discontinued, contaminants will be transferred back to the liquid phase as lower-concentration water flushes through the previously contaminated zone.

Several sets of soil/water partition coefficients (K_d) have been measured using BNL site specific soils and groundwater (with tracers added). They were all reported earlier through internal memos or reports. The K_d s obtained for various radionuclides are determined experimentally with soils taken from different locations and depths around site. In each experiment the site specific soil and water taken from that same geoprobe boring were used. Generally tracer radionuclides were used. However, for samples from the BGRR area, water taken from the sump was used for Cs-137 and Sr-90 K_d experiments. Values of K_d in the saturated zone are summarized in Table 1, as ranges and an average. Soil sample identifications, locations, and descriptions are provided in Table 2 and Figure 1. Other experiments, specific to the unsaturated zone at the BGRR, are discussed below. In addition, each data source, including methods, is reproduced in Appendix A, including figures documenting isotherm experiments for the various soil samples used.

Table 1. Summary K_d (mL/g) Values for BNL Soils in the Saturated Zone

	Cs-137	Sr-85/90	Ra-226	U	Am-241	Pb-214	Tc-99
Range	44-1800	2 - 90	120-3000	7-20	2,800 - 32,000	30 - 150	0.003-0.013
Average	460	14	920	13	3,000	105	0.008
Best value for soil at depth	190	7	500	13	3,000	100	0
Best value for surface soil	1,800	50	3,000	13	3,000	100	---
number of samples, n	6	9	6	7	4	4	2

The values of n above are the number of different locations or depths from which soil was sampled for K_d evaluations. Each K_d value (and n) may be the result of three to five individual experiments which are used to construct an isotherm. Average values reported above include

skewed to high values. This is the result of preferential uptake of some elements on the fine-grained detritus, weathering products and Fe oxides found at the surface. The one set of measurements of K_d of surface soil was made with soil from the 650 sump outfall. Best estimates for samples at the surface and at depth (in the saturated zone of the subsurface) are also given above. Please bear in mind that these values represent an average of samples from selected locations. Overall, for samples at depth, I believe they approach reasonable sitewide averages. However, the surface soil values should only be applied to the 650 sump outfall. Locally, values may vary depending on mineralogy and grain size of the soil, as well as composition of the water flowing through it.

Table 2. Location of Sampling Stations used for K_d Determinations

Sample ID	Depth (ft)	Location	Soil Description	pH*
106-08	38-40	Princeton Ave., south of railroad tracks, south of landfill	medium sand, light brown, little gravel	6.1
98-46	28-30	SE of HWMF on firebreak	white medium sand & quartz gravel	6.1
98-46	123-125	SE of HWMF on firebreak	white, medium to coarse sand	6.1
066-136	0-2 unsaturated	Building 650 Sump outfall	mixed sand and fines, Fe oxide yellow	NA
066-136	16-18	Building 650 Sump outfall	medium grained sand w/ gravel	6.4
086-105	60	Ballfield 100 ft E of 7 th Ave.		6.2
076-325	46	2 ft SE of valve pit behind 650	white, fine grained sand, some gravel	6.2
AOC9-GP-04 075-104	46-48 unsaturated	SE of BGRR, S of filters	brown, medium sand small % gravel and fines, black grains	NA
AOC9-GP-04 075-104	66-68	SE of BGRR, S of filters	brown, medium grained sand, few grains of very coarse sand, pink feldspar & muscovite noted	7.18
AOC9-GP-05 075-105	46-48 unsaturated	SW of BGRR	white, medium to coarse sand, very little fines	NA
AOC9-GP-05 075-105	68-70	SW of BGRR	medium to fine brown sand, black grains noted	7.15

* pH of groundwater

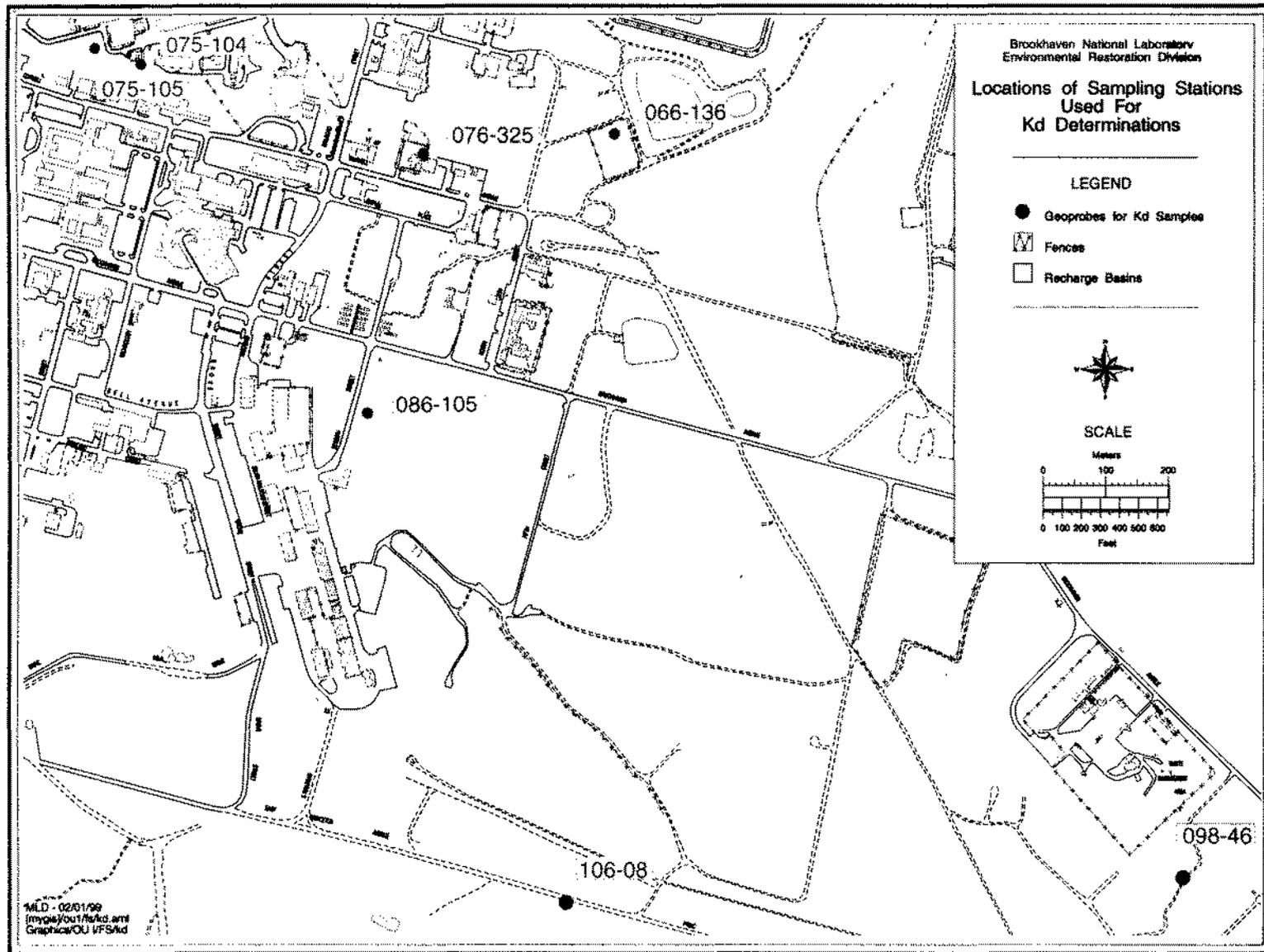


Figure 1. Map showing locations of boreholes for soil samples used for K_d determinations.

Contaminant Travel Time

Assuming a groundwater seepage velocity of 270 ft/yr, the travel time for contaminants can be estimated from the retardation coefficient, which is the ratio of the groundwater velocity to the contaminant velocity. Mathematically, it is expressed as:

$$R = 1 + \rho K_d / n$$

where ρ = bulk density = 1.6 g/cm³ (typical BNL soil density)

K_d = distribution coefficient (cm³/g)

n = water filled porosity = 0.24 (typical BNL aquifer porosity)

The radionuclide transport rate is the groundwater seepage velocity divided by the retardation coefficient.

$$V_c = V_w / R$$

where V_c = contaminant velocity and V_w = water velocity. If $K_d = 0$, the retardation coefficient = 1 and the contaminant moves with the speed of the groundwater. Based on K_d values in table 1, estimates of the rate of contaminant transport are given in Table 3 as averages for the BNL site. An average groundwater seepage velocity is taken to be 270 feet/year.

Table 3: Transport rates for selected radioactive contaminants

Radionuclide	K_d	R	Transport rate (ft/yr)
Tritium	0	1	270
Tc-99	0	1	270
Sr-90	7	48	6
Cs-137	190	1,268	0.2
Ra-226	500	3336	0.1
Am-241	3,000	20,000	0
Pb	100	668	0.4
U	13	88	3

Relationship of K_d to Soil Depth

There appears to be a relationship of decreasing K_d for some elements with depth of soil. This is generally reasonable considering the increasing grain size with depth and the lack of coatings and fines associated with this material. While Cs exhibits no such relationship; Sr and Ra do (recognizing the small number of samples). Figure 2 illustrates this for Sr. The soil from the surface at the 650 outfall, and the two samples from the BGRR area do not fit the regression line, but the remainder of samples provide a reasonable fit. The soil at the BGRR has been heavily disturbed, but these samples are from a depth of 68 feet which should be well below any such activity.

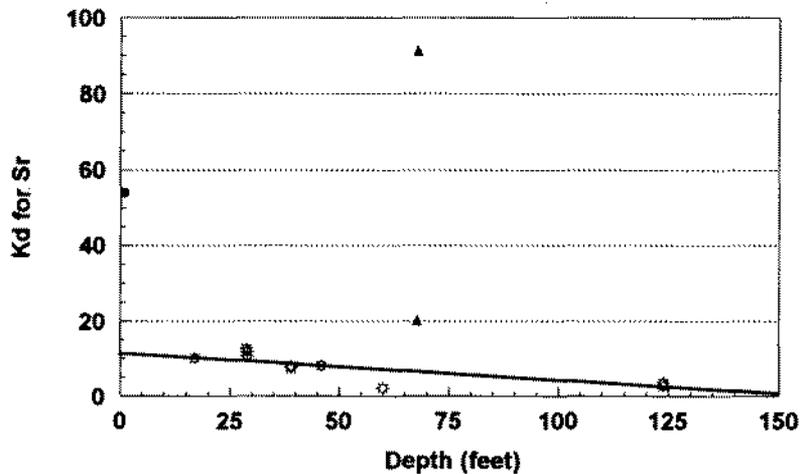


Figure 2. The relationship of Sr K_d with sample depth. With the exception of the two samples from the BGRR which have greater K_d values than expected, there appears to be a trend of decreasing K_d for Sr, with depth. The equation for the line is $K_d = (-0.07 \times \text{depth}) + 11.4$. Triangles are the BGRR samples and the circle is the surface soil at the 650 sump outfall.

For Ra-226, as shown in Figure 3, there is also a reasonable fit to a linear regression of K_d versus depth. In this case the BGRR samples, as well as the 650 outfall surface sample, fit the regression. Values of K_d for uranium are shown in Figure 4. Values of K_d are greater in the top 20 feet of the soil column and then remain constant (average of 13) with depth. The two samples with the highest values are from the 650 outfall, but these are also the shallowest samples; consequently there may be a chemical effect at this site or the difference may be related simply to depth/mineralogy.

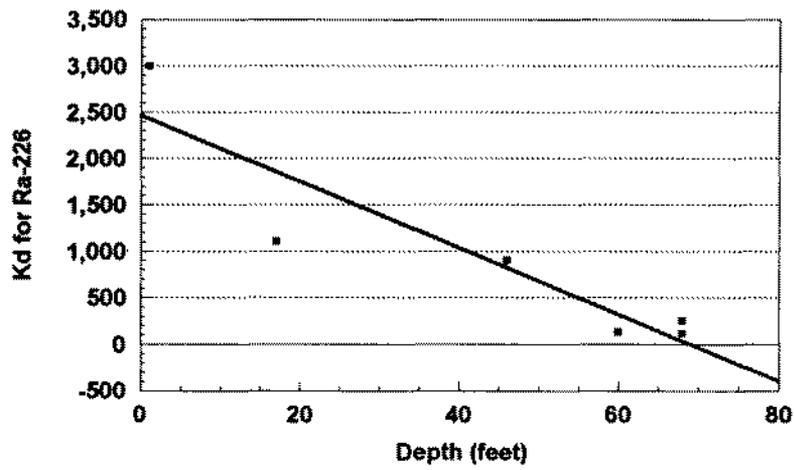


Figure 3. Relationship of the K_d for Ra-226 to soil depth, illustrating a relatively strong dependence. The equation for the regression is $K_d = (\text{depth} \times -35.7) + 2463$. The correlation coefficient, R^2 , is 0.84.

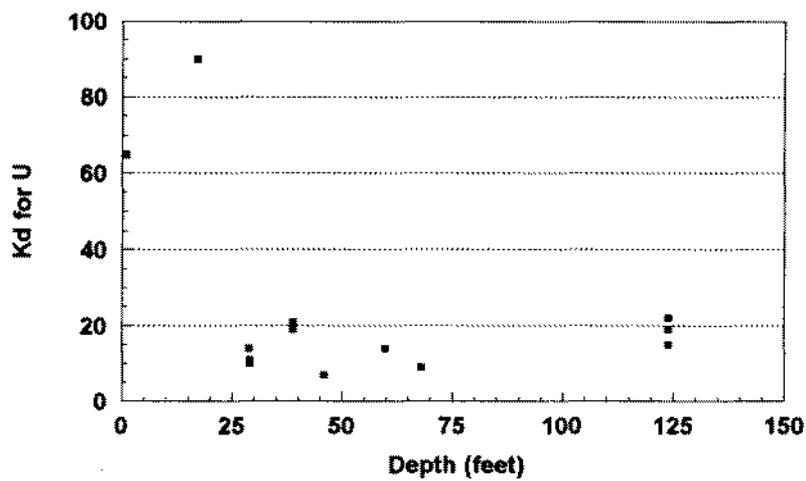


Figure 4. Except for the two shallowest samples the relationship of K_d of uranium to depth is constant, with an average of 13.

Methods for Saturated Zone K_d Determinations

Batch sorption experiments were used to explore uptake of radionuclides in the saturated zone. In most cases a series of batch tests was done at different tracer concentrations. When the results are plotted on a graph with the Y-axis being the concentration of the contaminant on the solid, and the X-axis being its concentration in the liquid, this is called an isotherm. This is done for values taken at the end of the experiment, so it shows the relationship of how much is sorbed on the soil relative to how much contaminant remains in solution. When the regression line of an isotherm is linear, the K_d (in mL/g) is the slope of that line. In this way we can examine the effect of changing concentration of contaminants on K_d . Sometimes, at high contaminant concentrations the plot begins to become horizontal. This indicates that the soil is becoming saturated with the contaminant and is unable to retain any more. Generally we are interested in relatively low concentrations of contaminants, and these tend to fall in the linear range of the data. Using different concentrations of contaminant simulates the condition of contaminated water flowing into the aquifer and being diluted by groundwater. Isotherms are also useful in showing a statistical relationship in the data that allows a quality check on each data point.

Usually radioactive tracers are used to do the sorption experiments. These are obtained as acid solutions from commercial sources and are diluted several times before use. For the experiment stock dilution, site specific ground water is usually used. The tracer is added to the groundwater and the pH is checked and adjusted back to the original pH of the ground water. Different quantities of this tracer are then added to ground water for use in the experiments. Aliquots of these solutions are withdrawn and saved as reference solutions. The solution is then mixed with weighed amounts (from 1-10 g) of damp (as received) soil. The moisture content of the soil is determined on separate aliquots of soil. Each of these batch experiments typically consist of 100 g of water and tracer combined. To obtain different radionuclide contents the mixture of groundwater and tracer is changed, keeping the total volume constant. After several days (usually a week) of gentle mixing on a shaker table some of the water is removed and filtered through a 0.45 μm syringe filter (Nalgene, surfactant free cellulose acetate). The filtered liquid samples are analyzed and compared to the liquid references that were taken before the soil was added. The quantity of contaminant sorbed on the solid is determined by difference between the concentrations in the reference and the sample. The reference samples are treated the same way as the samples, including filtration, so if any sorption takes place on container walls, it is automatically corrected in the calculations.

Most tracers are gamma emitters and can be analyzed by gamma spectroscopy on an intrinsic germanium gamma detector (Canberra). For example Sr-85, Cs-137, Ra-226, Pb-214 and Am-241 are all analyzed by gamma spectroscopy. U is analyzed by inductively coupled plasma optical emission spectroscopy. Tc-99 is analyzed by liquid scintillation. Usually, isotherms are generated, however, Am-241 has a very high K_d , making the use of isotherms impractical. Consequently its K_d was determined by individual batch experiments. The geochemical behavior of Am is quite similar to Pu; consequently K_d values determined for Am can be applied to Pu. Sr-85 is used in place of Sr-90, because Sr-90 is a pure beta emitter and much more difficult to detect than Sr-85 which has a gamma ray at 511 keV due to positron annihilation. The geochemical behavior of the two radionuclides is identical.

Calculations are done on a spread sheet program. Exact weights and radionuclide count rates of samples are recorded. The activity on the soil is determined by difference between the activity of the reference and the sample. Corrections must be made for exact volumes in each bottle as well as soil weights. The dry weight of the soil is calculated based on moisture contents of subsamples of the soil. Ultimately, the activity of the tracer must be determined per gram of soil and per gram of water, at the end of the experiment. K_d is determined by dividing the activity on the solid by its activity in the liquid. To produce an isotherm, the two activities are plots against each other, for a set of experiments. The regression line (if the plot is linear) is the averaged k_d .

Radionuclide Partitioning Between Soil and Water in the Unsaturated Zone

A study was conducted on soil samples from the unsaturated zone (depth of 44-46 feet) near the Brookhaven Graphite Research Reactor (BGRR). Calculation of K_d in the unsaturated zone is not straight forward. The value can only be assessed by devising an experiment in which the soil and solution are allowed to remain in contact under unsaturated conditions, and then at some time the contaminant is rinsed from the system. To do this under continuously unsaturated conditions requires a great deal of time. In addition, issues of preferential flow paths often make results of these tests questionable. A different scenario was adapted for this work. It is assumed that water leaked from the deep drain sump into the unsaturated zone under building 701. It is then assumed that, at some time, water is able to access the unsaturated zone, rinsing the contaminant down toward the saturated zone.

Methods

Experiments were done by packing a set of small plastic columns with soil taken from each of the two geoprobe sites. This soil was from the unsaturated zone at depths of about 45 feet from surface. Weights of the columns were taken before and after packing. One mL of undiluted sump water was pipetted into each column. This water contains about $3 \mu\text{Ci/L}$ of Sr-90 and $0.02 \mu\text{C/L}$ of Cs-137. The columns were allowed to stand open, in a hood, for varying times before they were sampled. Each column was sampled by first weighing the column and sand to determine moisture loss, then the sand was decanted into a bottle containing 124 mL of groundwater which is 100 pore volumes. Porosity had been determined earlier by saturating a column with distilled water. Each bottle was placed on a shaker table for at least one hour. Then a water sample was removed by plastic syringe and filtered through a $0.45 \mu\text{m}$ syringe filter. Aliquots were weighed into plastic scintillation vials prior to gamma counting.

To determine if 100 pore volumes of clean water are enough to elute from the soil all of the contaminant that is available to return to solution, an experiment was conducted in which samples of soil (from columns that had been previously contaminated) were rinsed with clean groundwater in a series of four desorption steps. For each desorption step, soil from a column was decanted into a plastic centrifuge tube, weighed, and 40 g of groundwater were added. The tubes were placed on a Nutator for approximately one hour, then centrifuged at 5000 RPM for 20 minutes. Liquid was then withdrawn and filtered through a $0.45 \mu\text{m}$ syringe filter for gamma analysis.

The soil from the saturated zone and the unsaturated zones were treated differently, as described above. However, to understand the relationship of sorption between the saturated and unsaturated systems, it is necessary to use the same K_d method, as a common point of comparison. To do this, 0.5 mL of a mixed tracer of Cs-137, Sr-85, Ra-226 and Pb-214 was added to 49.5g of filtered groundwater. Five mL were withdrawn from each for use as a reference counting solution. Then about 2 g of moist soil were weighed into the bottles. The bottles were put on a shaker table for 7 days. They were then sampled, the liquid filtered and analyzed by gamma spectroscopy for all four isotopes.

Results of Unsaturated Zone Analysis

Results of the unsaturated zone tests are shown in Figure 5. The K_d for Cs-137, as a result of the contaminated soil being rinsed in 100 pore volumes of groundwater, is about 1100 for GP-04 and 3100 for GP-05. Soil from an unsaturated column of each soil was rinsed at: 5, 19, 34, 50, 92 days. No change in sorption was observed as the time to sampling increased. Assuming porosity of 24%, rainfall of 42 inches per year and recharge of 50% of the rain, the annual rainfall at BNL is equivalent to about 8 feet of saturated soil column. With 100% recharge the annual rainfall is equivalent to about 16 feet of saturated soil column. If contaminants leaked from the sump, they are about 15 feet from the watertable, or (conservatively) about one pore volumes of annual rainfall. These data, then, reflect partitioning that would take place after 100 pore volumes, which is equivalent to 100 years of rainfall.

To determine what the relationship is between the number of pore volumes rinsing the soil and the quantity of Cs-137 released, two soil samples were serial rinsed with 33 pore volumes for each of four rinse intervals. Results are shown in Figure 6. Soil from GP-05 showed a slow but constant release of Cs-137 over the four intervals; with about 0.26% released from the soil per interval. GP-04 started at a higher release rate (0.87%) but it decreased rapidly. Over the course of this experiment, 129 pore volumes of rinse water (equivalent to about 120 years of rain) were applied to the soil, resulting in about 2.8% and 1% releases from GP-04 and GP-05 respectively. This indicates that Cs-137 is released from the soil, but only very slowly.

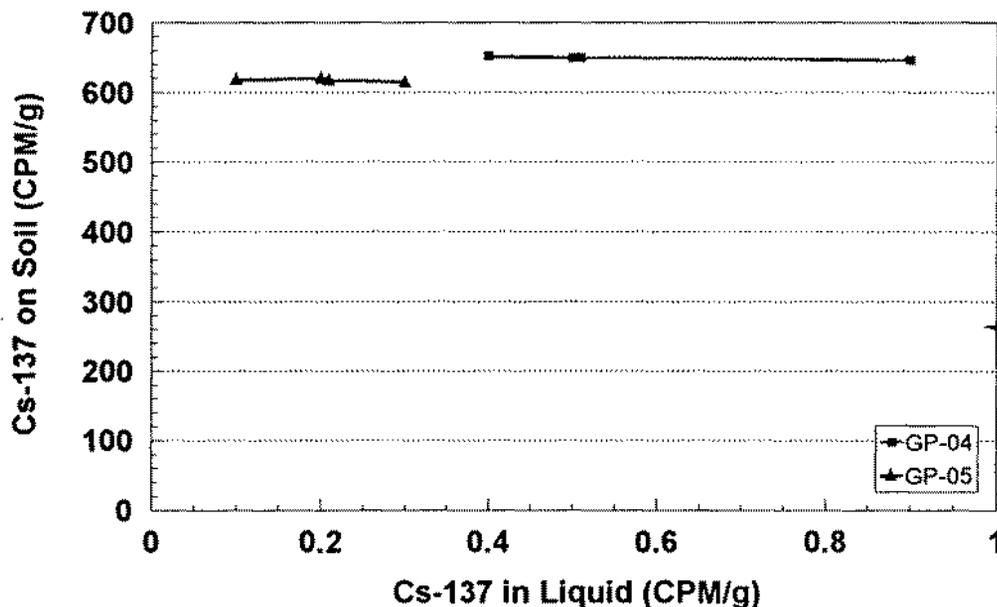


Figure 5. Results of unsaturated zone K_d experiments showing the desorption of Cs-137 after 100 pore volumes of groundwater flowed through the system. Note the very low concentrations of Cs-137 returned to the water from the contaminated soil. The K_d for GP-04 is 3100 and for GP-05 it is 1100.

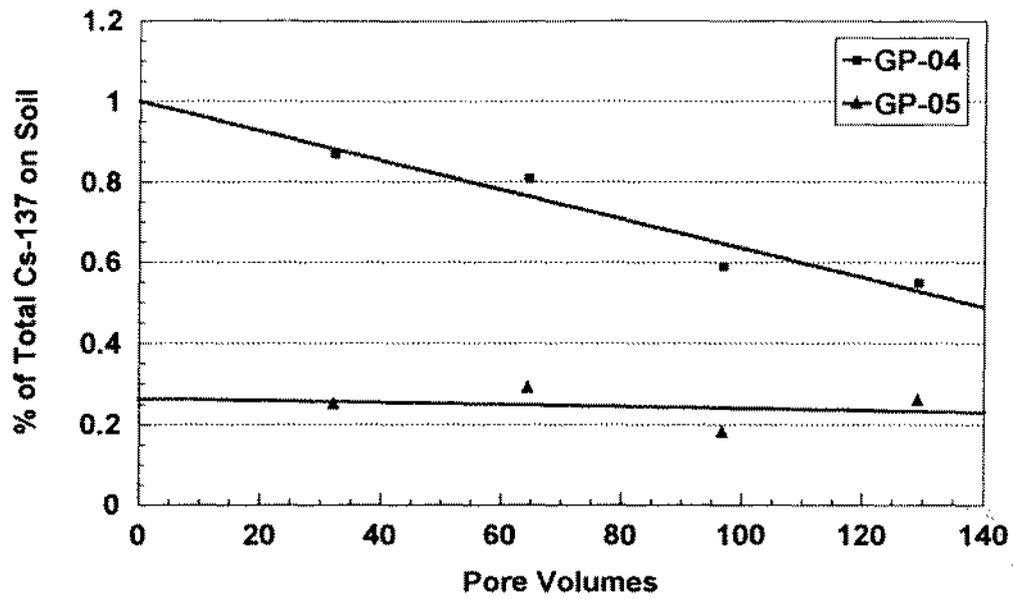


Figure 6. Desorption of Cs-137 from vadose zone soils, using up to 129 pore volumes of water, resulted in very little release of Cs-137 from the soil to the water. In the final rinse of GP-04 less than 0.6 % of the total Cs-137 was released.

Appendix A

Source Documentation for K_d Determinations

**Partitioning of Radionuclides Between Soil and Water:
Soil from the Building 650 Outfall**

Mark Fuhrmann
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Introduction

The partition coefficient (K_d) is defined as the concentration of a species of interest on the solid phase divided by the concentration of that species in the liquid phase, at steady-state. Therefore the lower the K_d , the less sorption takes place. It is a parameter that is readily incorporated in chemical transport models. The K_d approach to chemical partitioning of contaminants in groundwater flow systems is based on the assumption that sorption reactions that partition the contaminants between the liquid and solid phases are in equilibrium (or at least they are steady state) and are reversible.

Values of K_d were determined for two soil samples taken at the Building 650 Outfall. They were taken from two depths in the same core (066-136) and are described in Table 1.

Table 1. Samples from the 650 Outfall

Sample ID	Depth (ft)	Location	Soil Description
066-136	0-2 unsaturated	Sump outfall	mixed sand and fines, Fe oxide yellow
066-136	16-18 saturated	Sump outfall	medium grained sand w/ gravel

Methods

Batch sorption experiments were used to explore uptake of radionuclides from the 650 outfall. In most cases a series of batch tests were done at different tracer concentrations. When the results are plotted on a graph with the Y-axis being the concentration of the contaminant on the solid, and the X-axis being its concentration in the liquid, this is called an isotherm. This is done for

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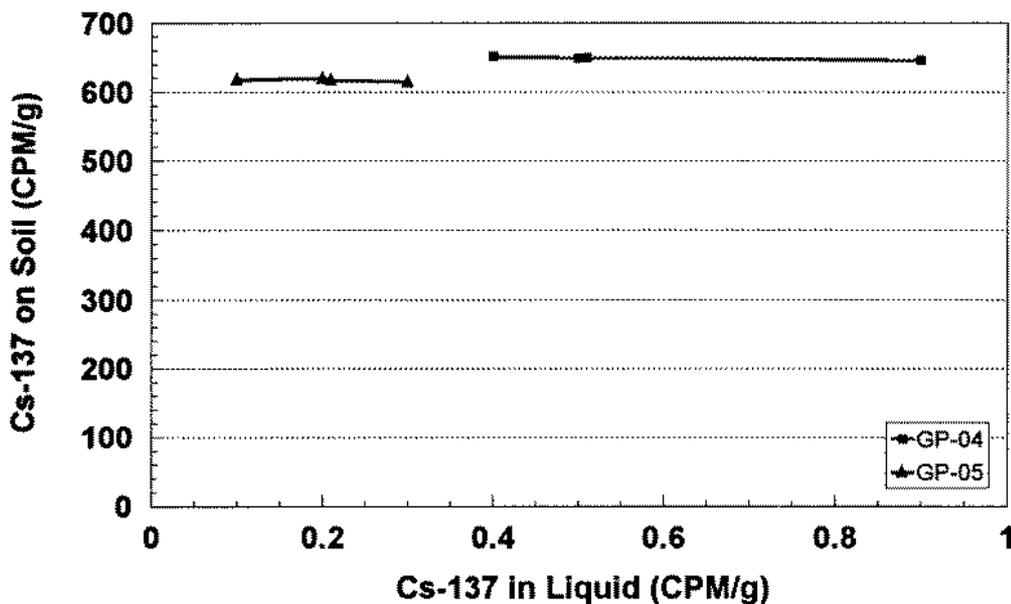


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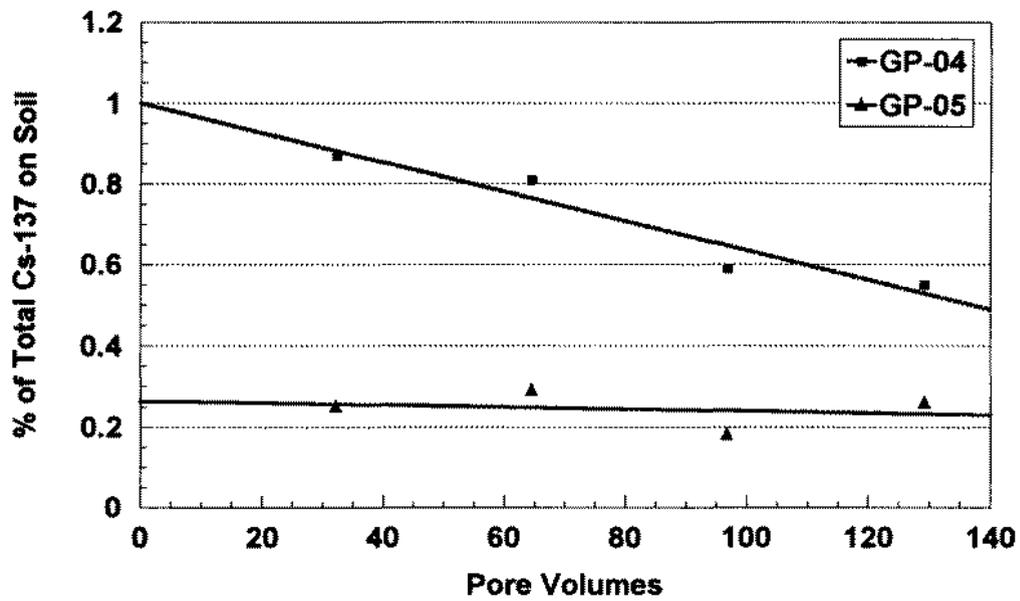


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values taken at the end of the experiment, so it shows the relationship of how much is sorbed on the soil relative to how much contaminant remains in solution. When the regression line of an isotherm is linear, the K_d (in mL/g) is the slope of that line. In this way we can examine the effect of changing concentration of contaminants on K_d . Sometimes, at high contaminant concentrations the plot begins to become horizontal. This indicates that the soil is becoming saturated with the contaminant and is unable to retain any more. Generally we are interested in relatively low concentrations of contaminants, and these tend to fall in the linear range of the data. Using different concentrations of contaminant simulates the condition of contaminated water flowing into the aquifer and being diluted by groundwater. Isotherms are also useful in showing a statistical relationship in the data that allows a quality check on each data point.

Several sets of experiments were done to determine the K_d values of various elements.

Radioactive tracers: Cs-137, Sr-85, and Ra-226 (which also included Pb-214) were used for one set of sorption experiments as a mixed tracer. Sr-85 is a short-lived ($t_{1/2} = 64.8$ days) gamma-emitter (a gamma ray at 511 keV due to positron annihilation) which is commonly used in place of Sr-90; a pure beta emitter that requires chemical separations for analysis. The two radionuclides behave identically, but Sr-85 is easier to detect and safer to use. These tracers are obtained as acid solutions from commercial sources and are diluted several times before use. For the experiment, location specific ground water was filtered, and weighed into plastic bottles. The tracer was added to the groundwater and the pH was checked and, if necessary, adjusted back to the original pH of the ground water (pH = 6.4). Different quantities of this tracer, ranging from 0.25 to 2.00 mL were then added to ground water for use in the experiments. The weight of the groundwater originally added to the bottles was adjusted so that the total weight was 50.0 g. Aliquots, 5 mL each, of this water were withdrawn and saved as reference solutions. Weighed amounts (about 2.0 g) of damp (as received) soil were then added to the liquid. The moisture content of the soil was determined on separate aliquots of the same soil. After eight days of gentle mixing on a shaker table, about 5 mL of the water were removed and filtered through a 0.45 μm syringe filter (Nalgene, surfactant free cellulose acetate). The filtered liquid samples were analyzed and compared to the liquid references that were taken before the soil was added. The quantity of contaminant sorbed on the solid was determined by difference between the

concentrations in the reference and the sample. The reference samples were treated the same way as the samples, including filtration, so if any sorption takes place on container walls, it is automatically corrected in the calculations.

Most tracers are gamma emitters and can be analyzed by gamma spectroscopy on an intrinsic germanium gamma detector (Canberra). For example Sr-85, Cs-137, Ra-226, Pb-214 and Am-241 were all analyzed by gamma spectroscopy. U was analyzed by inductively coupled plasma optical emission spectroscopy.

Isotherms were generated for all radionuclides tested, except for Am-241. This element has a very high K_d making the use of isotherms impractical. Consequently its' K_d was determined by batch experiments. The geochemical behavior of Am is quite similar to Pu; consequently K_d values determined for Am can be applied to Pu. Sr-85 is used in place of Sr-90, but the geochemical behavior of the two radionuclides is identical.

Calculations were done on a spread sheet program. Exact weights and radionuclide count rates of samples were recorded. The activity on the soil was determined by difference between the activity of reference and of the sample. Corrections are made for exact volumes in each bottle as well as soil weights. The dry weight of the soil was calculated based on moisture contents of subsamples of the soil. Ultimately, the activity of the tracer was determined per gram of soil and per gram of water, at the end of the experiment. K_d was determined by dividing the activity on the solid by its activity in the liquid. To produce an isotherm, the two activities are plotted against each other, for a set of batch sorption experiments. The regression line (if the plot is linear) is the averaged k_d .

Results

Partition coefficients (K_d) for Cs-137, Sr-85, Ra-226, Am-241 (which can be taken to be similar to Pu), U, and Pb-214 between soils from the 650 sump outfall and groundwater (with tracers added). These values are summarized in Table 2. Most of the values were determined by isotherms which are attached as figures 1 through 4. The high values for the surface soil are

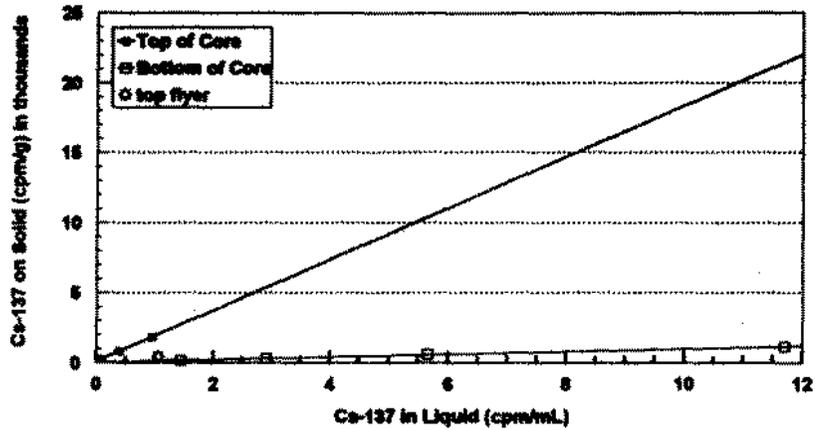
reasonable since the soil was finer grained than the bottom soil. Also, its color indicates more iron coating (which sorbs many contaminants) on grains, and organic matter. Only Cs, Sr, and Ra appear to be sensitive to the compositional differences between the surface soil and the soil at depth.

Table 2.

K_d Values (mL/g) for soil at the 650 Sump Outfall

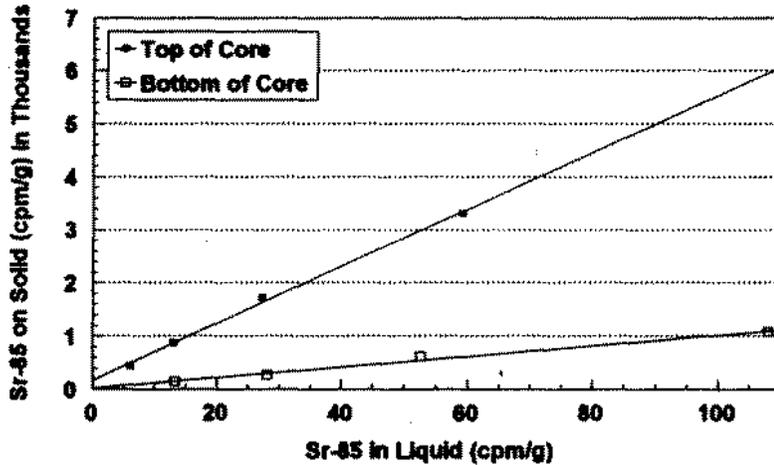
Sample	Cs-137	Sr-85	U	Am-241	Ra-226	Pb-214
0-2'	1800	54	65	3000	3000	150
16-18'	95	10	90	3900	1100	140

Analysis for U by ICP had poor sensitivity. A detection limit of 1 ppm was used to calculate minimum K_d values based on a non-detect in the liquid phase. It was not possible to construct an isotherm from these data. The difference in the Am-241 values is probably not real. It is the result of small differences in the count rate in the liquid phase after most of the Am-241 was sorbed.



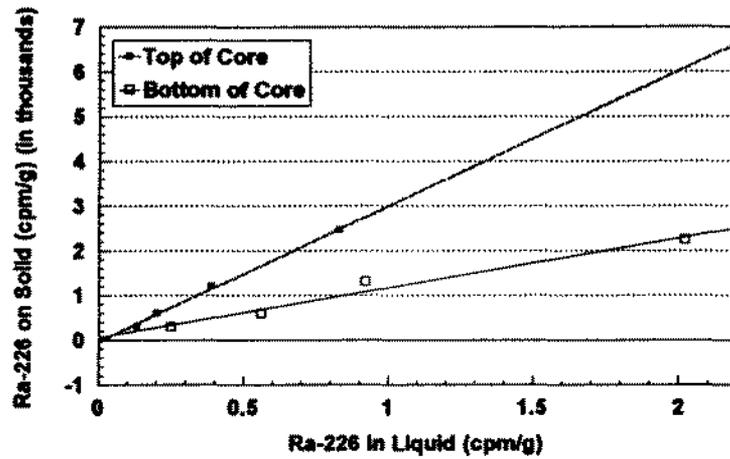
core top: slope = 1827 $R^2 = 0.998$
 core bottom: slope = 95 $R^2 = 0.997$

Figure 1. Isotherm for Cs-137 for the 0-2 feet and 16-18 feet sections at the 650 outfall.



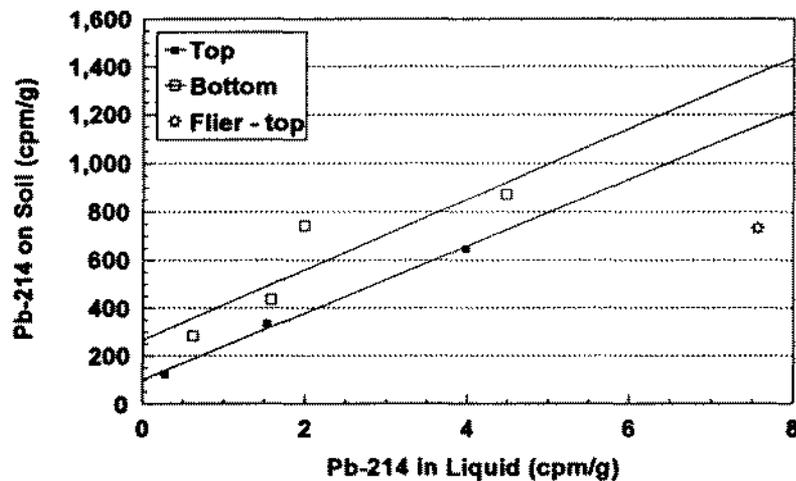
Core Top: Slope = 53.6 $R^2 = 0.998$
 Core Bottom: Slope = 9.9 $R^2 = 0.985$

Figure 2. Isotherms for Sr -85 for the 0-2 feet and 16-18 feet sections of the core from the 650 outfall.



Core Top: Slope = 3025 $R^2 = 0.997$
 Core Bottom: Slope = 1117 $R^2 = 0.973$

Figure 3. Isotherms for Ra-226 for the 0-2 feet and 16-18 feet sections of the core from the 650 outfall.



Top: slope = 139, $R^2 = 0.995$
 Bottom: slope = 146, $R^2 = 0.793$

Figure 4. Isotherms for Pb-214, for the 0-2 feet and 16-18 feet sections of the core from the 650 outfall. The sorption of Pb on the 0-2 feet section may be saturated at about 750 cpm/g.

Brookhaven National Laboratory
MEMORANDUM

Date: Feb. 9, 1999
To: J. Brower
From: M. Fuhrmann
Subject: Effect of EDTA on K_d of Am-241

In a set of quick experiments I have determined that the presence of EDTA at low concentrations (0.325 ppm) does influence the behavior of Am-241 that has been previously sorbed on soil.

Methods

An experiment was done with the four solutions remaining from the Am-241 K_d experiments on soil from the building 650 outfall, conducted in November and reported in my memo to you of December 2, 1998. The objective was to determine if the addition of EDTA to the solution, at concentrations observed in groundwater, would result in any desorption of Am-241 that had been added as a tracer. The bottles, containing solutions and soil, were reweighed and the quantity of liquid remaining in them was recalculated. Then, 0.5 mL of a 52 ppm solution of disodium-EDTA were added to each bottle, resulting in concentrations of about 0.325 ppm, which approximate the concentration of EDTA observed by A. J. Francis in a well between the HO recharge basins, near the 650 outfall. After 4 days on a shaker table, the solutions were sampled with plastic syringes, filtered through 0.45 μ m syringe filters, and weighed into counting vials. They were analyzed for Am-241 by HPGe gamma detectors.

Results

In the soil-groundwater mixture, uptake of Am-241 by the soil left little activity remaining in the water. With the addition of low concentrations of Na_2 -EDTA no observable difference in sorption took place on the surface soil. However, on the two bottom samples (16-18 feet), between 5.3 and 6.3 % of the previously sorbed Am-241 was returned to solution. The K_d of the two surface soils was unchanged on average, given the error at these low count rates. The K_d of the bottom soil decreased from an average of 3900 to an average of 775. Results are shown in Table 1. This decrease is significant and may or may not have a consequence with regard to transport of Am-241. If the Am-241 that has returned to solution is complexed with the EDTA then one would expect it to move with the same velocity as groundwater. However, it is possible that the EDTA eluted some other component of the solid phase material (e.g. Fe from a coating) and this resulted in release of Am-241 also. Another possibility is that the EDTA complexed with the solid phase surface and displaced some of the Am-241. If that Am-241 is ionic, then it will sorb as the EDTA concentration decreases. Although the K_d was lowered, it is still relatively large and indicates that most of the Am-241 is still sorbed. Another issue is the form of the EDTA in the groundwater. It may not be the disodium form, which is commonly used in laboratories. It has gone through the AGS cooling systems and into the groundwater; as a result it may have formed complexes with other elements. Behavior of the EDTA found in the groundwater may not be the same as the reagent used in these experiments.

Table 1.

Effect of 0.325 ppm EDTA on Sorption of Am-241

Sample	Before sorbing in water, cpm/g	After sorbing in water, cpm/g	K_d in water	After sorbing in EDTA, cpm/g	K_d in EDTA
0-2 feet #1	9.76	0.19	3700	0.24	2400
0-2 feet #2	8.27	0.24	2400	0.16	3200
16-18 feet #1	8.34	0.17	3600	0.70	720
16-18 feet #2	9.6	0.17	4200	0.71	830

Brookhaven National Laboratory

MEMORANDUM

Date: Feb. 9, 1999
To: J. Brower
From: M. Fuhrmann
Subject: K_d values at the 650 outfall, amended

This memo amends my memo to you dated Dec.2, 1998. In that memo I recounted my observation of Cs-137 in an Am-241 K_d sample, and ascribed this to be desorption from the soil. The implications of this observation are quite serious. Consequently, I have now rechecked those results and have resampled and reanalyzed the experiment. No Cs-137 was observed in the resampled solutions. I believe that cross contamination took place during filtration or pipetting. While my procedures allow for checking cross contamination during production of the experimental solution and references, it cannot pick up problems that result from a previously contaminated pipette tip inadvertently being reused at the end of the experiment. Steps have been taken to correct a repetition of this problem.

Brookhaven National Laboratory
MEMORANDUM

Date: Dec. 2, 1998
To: J. Brower
From: M. Fuhrmann
Subject: K_d values at the 650 outfall

I have determined partition coefficients (K_d) for Cs-137, Sr-85, Ra-226, Am-241 (which I take to be similar to Pu), U, and Pb-214 between soils from the 650 sump outfall and groundwater (with tracers added). The samples are from the top 2 feet of a geoprobe core and the bottom section at the water table, from between 16 and 18 feet. Most of the values were determined by isotherms which are attached. Also attached are the spread sheets for the calculations. The high values for the surface soil are reasonable since the soil was finer grained than the bottom soil. Also, its color indicates more iron coating (which sorbs many contaminants) on grains.

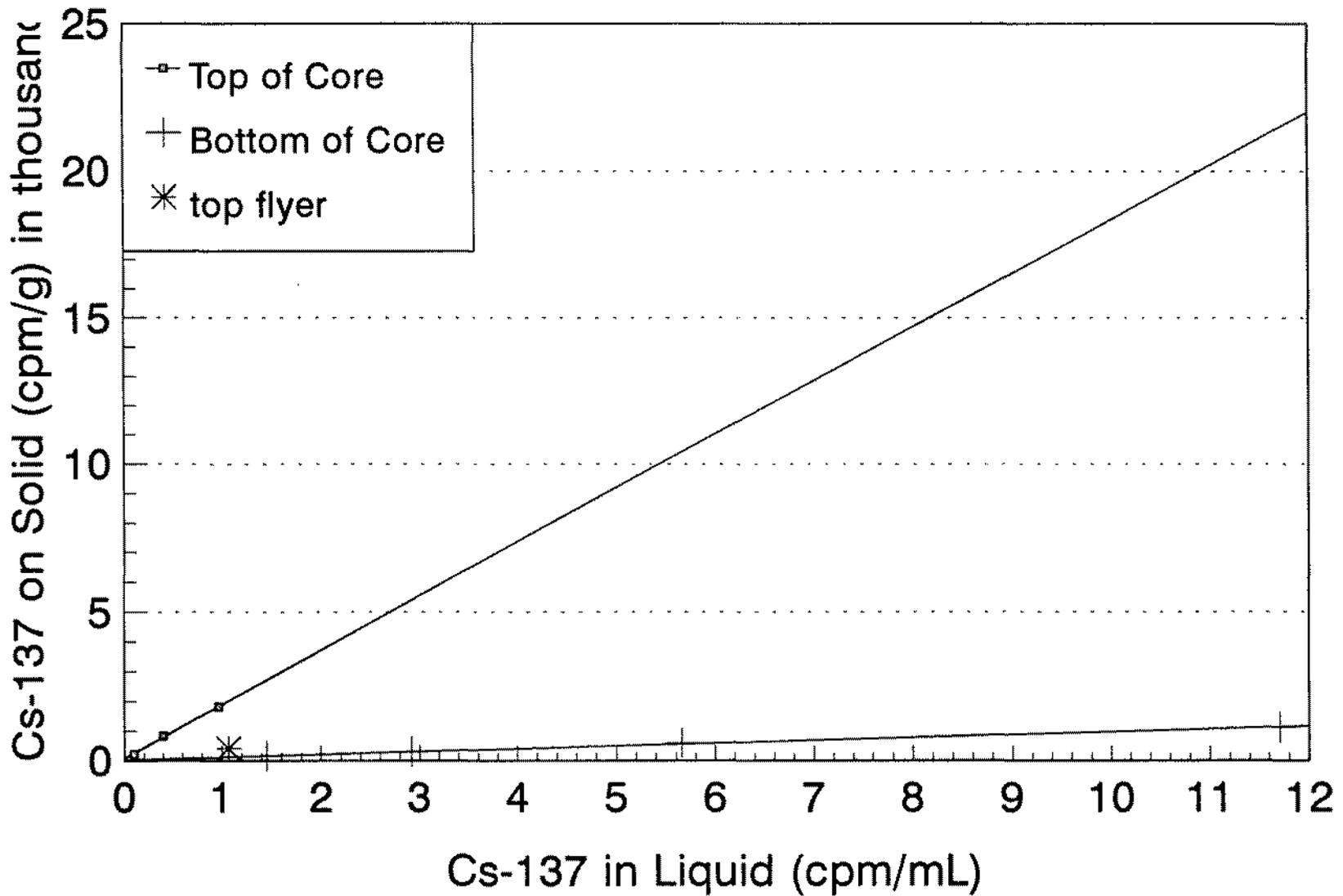
Analysis for U by ICP had poor sensitivity. I used a detection limit of 1 ppm to calculate minimum K_d values based on a non-detect in the liquid phase. The difference in the Am-241 values is probably not real. It is the result of small differences in the count rate in the liquid phase after most of the Am-241 was sorbed.

I observed a significant quantity of Cs-137 in the liquid from the Am-241 experiment using soil from the surface. About 70 pCi/mL were found. This is surprising since typically Cs has a relatively high K_d and little is observed in the liquid. That Cs-137 was not found in other samples in such quantities (or at all) implies that a highly heterogeneous source of mobile Cs-137 is present in the surface soil. The procedure that I use precludes any contaminants from the lab entering the experiment without being observed in the reference sample too. As a result, I am sure that this Cs-137 entered the experiment from the soil.

K_d Values for soil at the 650 Sump Outfall

Sample	Cs-137	Sr-85	U	Am-241	Ra-226	Pb-214
0-2'	1800	54	65	3000	3000	150
16-18'	95	10	90	3900	1100	140

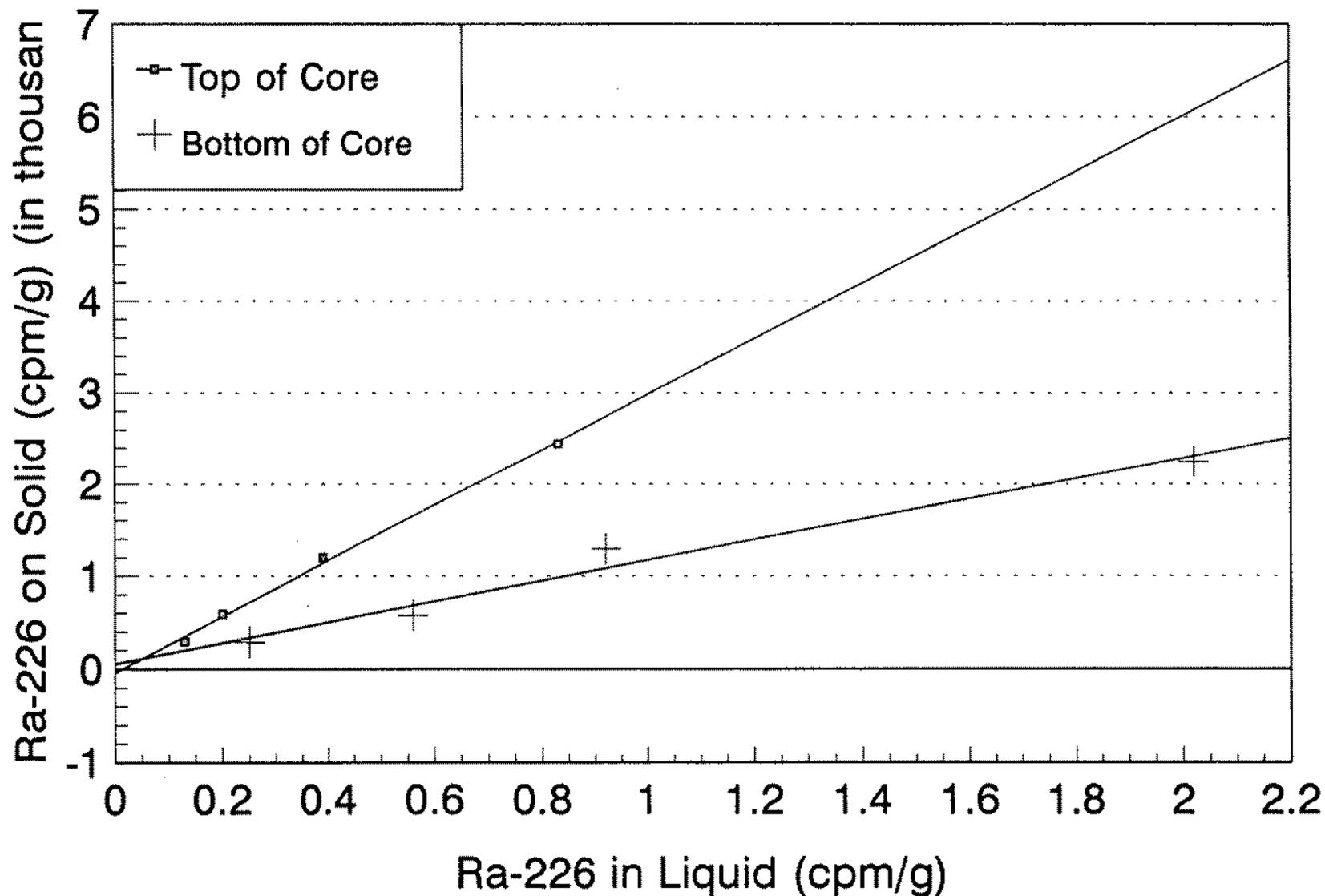
650 Sump Outfall Isotherms for Cs-137



core top: slope = 1827 $R^2 = 0.998$

core bottom: slope = 95 $R^2 = 0.997$

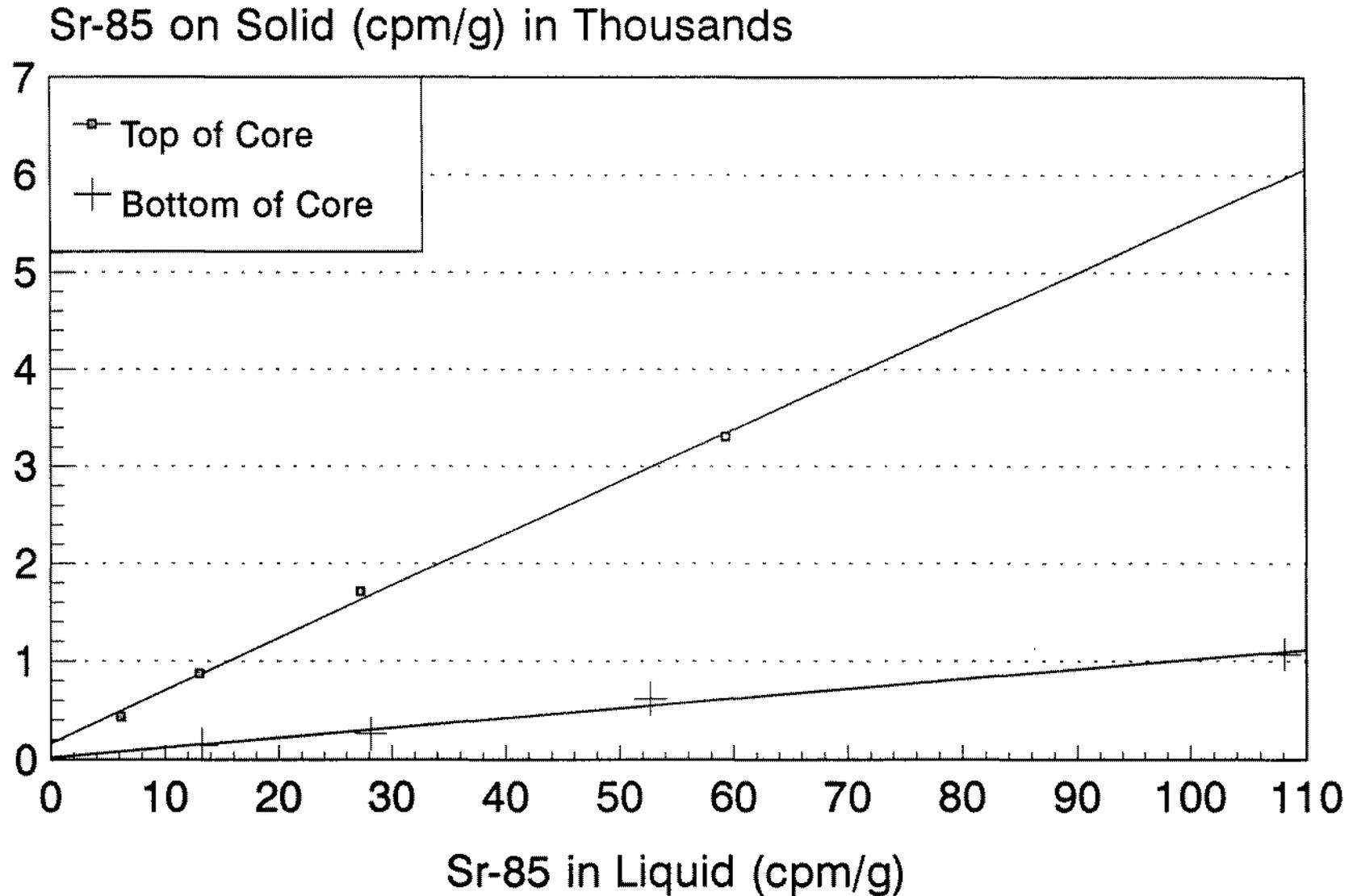
650 Sump Outfall Isotherms for Ra-226



Core Top: Slope = 3025 $R^2 = 0.997$

Core Bottom: Slope = 1117 $R^2 = 0.973$

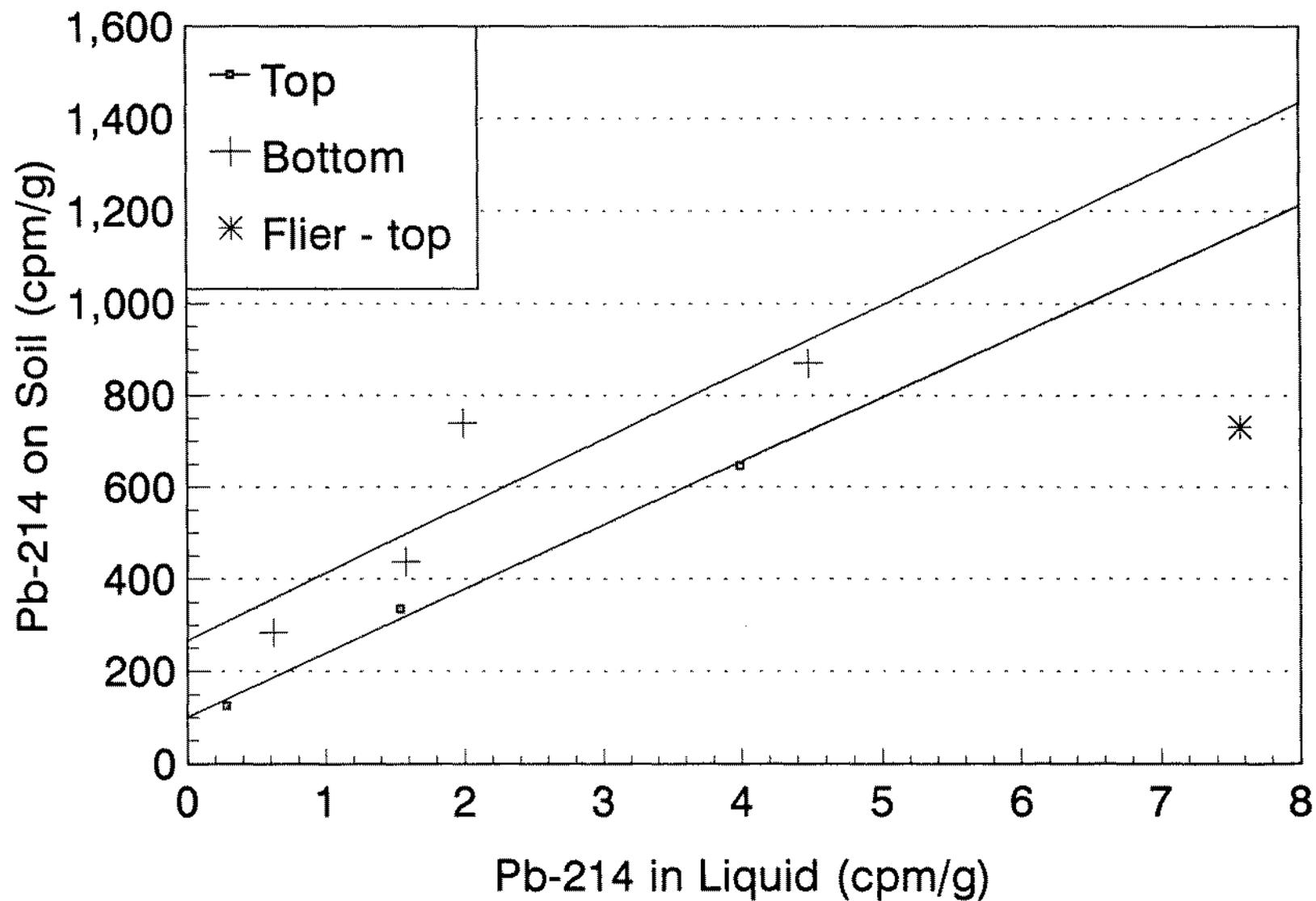
650 Sump Outfall Isotherms for Sr-85



Core Top: Slope = 53.6 $R^2 = 0.998$

Core Bottom: Slope = 9.9 $R^2 = 0.985$

Pb-214 Isotherms for Soil from the 650 Outfall



Top: slope = 139, $R^2 = 0.995$

Bottom: slope = 146, $R^2 = 0.793$

Brookhaven National Laboratory
MEMORANDUM

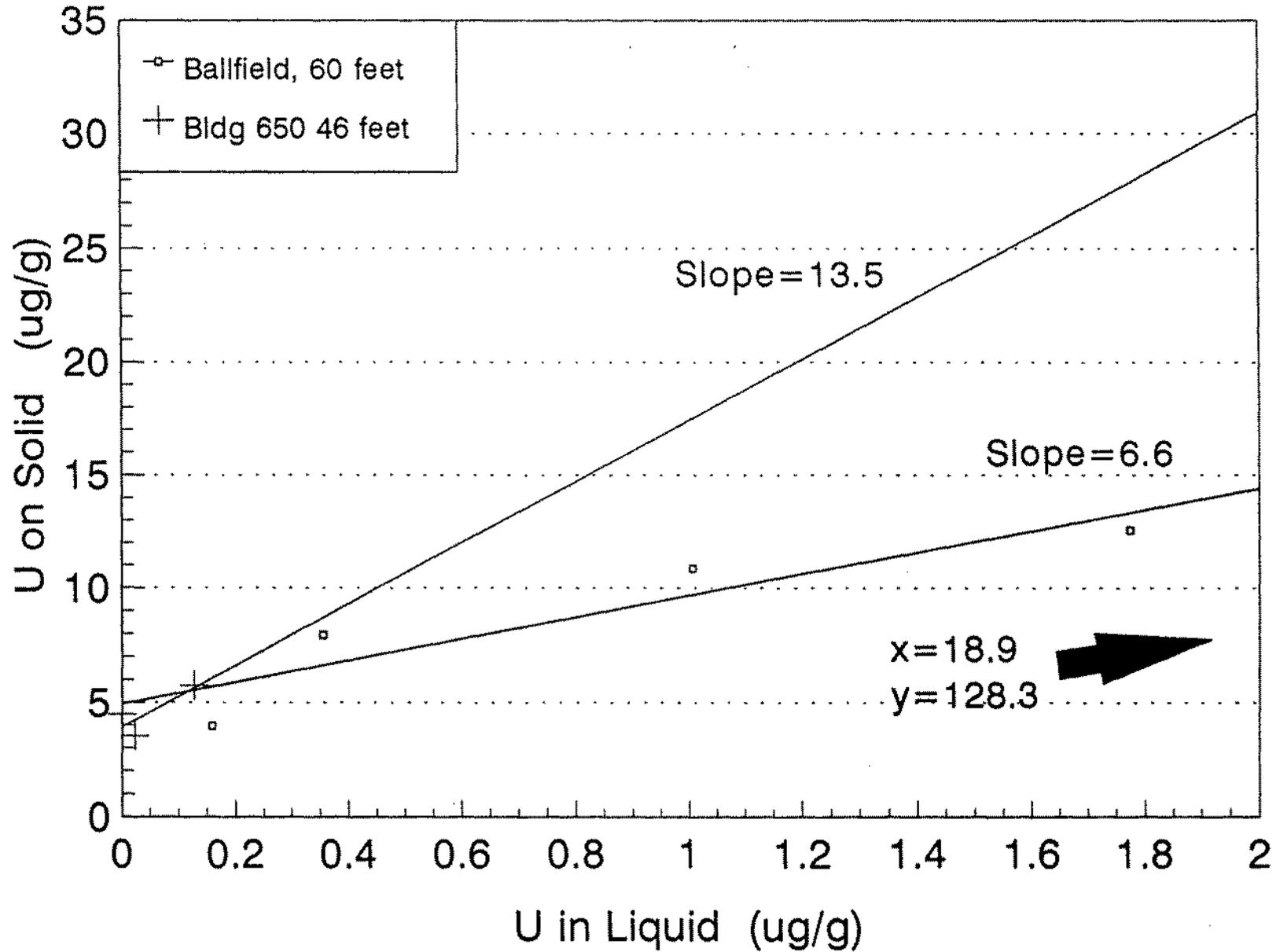
Date: December 10, 1996
To: J. Brower
From: M. Fuhrmann MF
Subject: BNL Kd Values

Determinations of K_d 's for Cs, Sr, U, Ra and Tc were made on soil samples from two locations in OU-4; the ballfield at 60 feet depth and behind building 650 at 46 feet. These K_d values were determined by the generation of isotherms. The slopes of the isotherms are linear and the K_d 's are therefore the slopes of the isotherm plots. The experiments were conducted using groundwater taken during the geoprobe sampling at each location. Tracer was added to the water and the pH was maintained at the natural value. Table 1 gives the K_d 's for each location. Attached are figures of the isotherms for each element.

K_d (mL/g) Values for BNL Soil, OU-4

Location	Cs-137	Sr-85	Ra-226	U	Tc-99
Ballfield, 60'	44	2	130	14	0.013
Bld 650, 46'	320	8	900	7	0.003

U Isotherms for BNL Soil



Partition Coefficients of Radionuclides in Soil from the BGRR

Mark Fuhrmann

Environmental and Waste Technology Center

Brookhaven National Laboratory

Introduction

Given the potential for radioactive contamination of soil and groundwater in the vicinity of the BGRR, it is important to determine the partitioning of radionuclides between the soil and groundwater, under site specific conditions. In this study, the sorption of radionuclides on soil in the saturated zone near the BGRR was investigated. In addition, an analysis of sorption and desorption in the unsaturated zone was undertaken. One possible pathway for contaminant entry to the environment is from a hypothetical leak in the deep drain sump, an area where contaminated water has accumulated. Leaks from this area would flow into unsaturated soil under the building, soil that presumably is very dry. Consequently we have done a set of experiments to examine the retention of radionuclides on soil under conditions that, initially, are unsaturated.

The partition coefficient (K_d) is defined as the concentration of a species of interest on the solid phase (soil) divided by the concentration of that species in the liquid phase, at steady-state. Therefore the lower the K_d , the less sorption takes place. It is a parameter that is readily incorporated in groundwater chemical transport models. The K_d approach to partitioning of contaminants in flowing groundwater systems is based on the assumption that sorption reactions are in equilibrium and are reversible. In nature, this is not necessarily so. For some elements (notably Cs) once sorption has taken place on certain minerals, it is difficult to remove all of it from the solid phase with clean water. In fact, we have experimented with using a variety of reagents to remove Cs-137 from soil taken from the BNL Hazardous Waste Management Facility yard and found that a maximum of only about 11% could be removed [Fuhrmann et al., BNL-63679, 1996]. In column desorption experiments conducted on soil from West Valley, NY,

sorption of Sr-90 is much more reversible, with most (if not all) Sr desorbing .

We have determined partition coefficients (K_d) for Cs-137, Ra-226, Pb-214, U, Am-241 and Sr-90 under saturated conditions using soils from two locations at the BGRR, from below the water table. We have also determined K_d values and the relationship between sorption and desorption for Cs-137 and Sr-90 in the unsaturated zone. These site specific K_d values can be used as inputs to models of local contaminant transport.

Soil and Water Samples

A set of soil and groundwater samples were obtained by geoprobe from near the BGRR on May 24, 1998. These materials were used for laboratory determinations of partition coefficients of a set of selected radionuclides. The locations of the two geoprobe sites are shown in Figure 1. Vadose zone soil was taken at 44 to 46 feet from surface at each location. Saturated zone soil and associated water samples were taken at 68 to 70 feet at GP-05 and at 66 to 68 feet for GP-04. The sample from the saturated zone at GP-04 was a medium grained brown sand, visually poorly sorted with a few grains of very coarse sand as well as some silt. Pink feldspar and moscovite were noted. The moisture content was 13.9%. The sample from GP-05 was a medium to fine grained brown sand with some black grains noted; with a moisture content of 22.8%. The pH of water from these samples was 7.18 for GP-04 and 7.15 for GP-05.

Methods

Saturated Zone. Batch sorption experiments were used to explore uptake of radionuclides in the saturated zone. For Cs-137 and Sr-90, sorption was determined using water from the deep drain sump as the source of the radionuclides. This provides the most realistic water chemistry for the scenario described above because water from the sump may be a local contaminant. In these experiments we determined how much sorption took place at different concentrations of contaminant by diluting the sump water with groundwater taken at each geoprobe boring. The water was then mixed with weighed amounts of soil. Each of these batch experiments consisted of 100 g of water and tracer combined. To obtain different radionuclide contents the mixture of

groundwater and tracer (or sump water) was changed, keeping the total volume constant. Each batch was placed in a 100 mL polyethylene bottle along with about 6g of moist, as received soil. The moisture content of the soil was determined on separate aliquots of soil. After several days (usually a week) of gentle mixing on a shaker table some of the water was removed and filtered through a 0.45 μm syringe filter (Nalgene, surfactant free cellulose acetate). The filtered liquid samples were analyzed and compared to liquid references that were taken before the soil was added. The quantity of contaminant sorbed on the solid was determined by difference between the concentrations in the reference and the sample.

Cs-137 was analyzed by gamma spectroscopy on an intrinsic germanium gamma detector (Canberra). Samples for Sr-90 analysis were sent to the S & EP laboratory. They were analyzed by a new method using element specific ion exchange disks (Empore, 3M). First the solutions were passed through Cs specific disks to remove Cs from the liquid. Then the water was passed through Sr specific disks which were analyzed for Sr-90 by gas flow proportional counting.

For other radionuclides of interest, we were unable to use the sump water because of its' very low concentrations of these radionuclides. In this case we used tracers, adding them to the groundwater and adjusting the pH. Ra-226, Pb-214 and Am-241 were all analyzed by gamma spectroscopy. U was analyzed by inductively coupled plasma optical emission spectroscopy. In each case isotherms were generated except for Am-241. This element has a very high K_d making the use of isotherms impractical. Consequently its' K_d was determined by batch experiments. The geochemical behavior of Am is quite similar to Pu; consequently K_d values determined for Am can be applied to Pu.

Using different concentrations of contaminant simulates the condition of sump water flowing down into the aquifer and being diluted by groundwater. In this way we can examine the effect of changing concentration of contaminants on K_d . To do this, most of the K_d values were determined by the generation of isotherms. In isotherms the concentration of the radionuclide on the solid is plotted on the y-axis; and its concentration in the liquid is plotted on the X-axis. This

is done for values taken at the end of the experiment, so it shows the relationship of how much is sorbed relative to how much contaminant remains in solution. When the regression line of an isotherm is linear, the K_d (in mL/g) is the slope of that line.

Unsaturated Zone. For the interaction of sump water with soil in the unsaturated zone a different approach was needed. Experiments were done by packing a set of small plastic columns with soil taken from each of the two geoprobe sites. This soil was from the unsaturated zone at depths of about 45 feet from surface. Weights of the columns were taken before and after packing. One mL of undiluted sump water was pipetted into each column. The columns were allowed to stand open, in a hood, for varying times before they were sampled. Each column was sampled by first weighing the column and sand to determine moisture loss, then the sand was decanted into a bottle containing 124 mL of groundwater which is 100 pore volumes. Porosity had been determined earlier by saturating a column with distilled water. Each bottle was placed on a shaker table for at least one hour. Then a water sample was removed by plastic syringe and filtered through a 0.45 μm syringe filter. Aliquots were weighed into plastic scintillation vials prior to gamma counting. Isotherms could not be generated from this data. Instead, K_d was calculated from the quantity of radionuclide that returned to solution from the soil. As before, the concentration on the soil was determined by difference.

It is useful to know the relationship between the quantity of radionuclide desorbed compared to the quantity of water rinsing the contaminant from the soil. Consequently, an experiment was conducted in which samples of soil (from columns that had been previously contaminated with sump water) were rinsed with clean groundwater in a series of four desorption steps. Soil from a column was decanted into a plastic centrifuge tube, weighed, and 40 g of groundwater were added. The tubes were placed on a Nutator for approximately one hour, then centrifuged at 5000 RPM for 20 minutes. Liquid was then withdrawn and filtered through a 0.45 μm syringe filter for gamma analysis. Another aliquot of water was added and treated the same way. Each aliquot of 40 g of rinse water was equivalent to about 32 pore volumes.

The soil from the saturated zone and the unsaturated zones were treated differently, as described above. However, to understand the relationship of sorption between the saturated and unsaturated systems, it is necessary to use the same K_d method, as a common point of comparison. To do this, 0.5 mL of a mixed tracer of Cs-137, Sr-85, Ra-226 and Pb-214 was added to 49.5 g of filtered groundwater. Five mL were withdrawn from each for use as a reference counting solution. Then about 2 g of moist soil were weighed into the bottles. The bottles were put on a shaker table for 7 days. They were then sampled, the liquid filtered and analyzed by gamma spectroscopy for all four isotopes.

RESULTS

Saturated Zone

Results for the batch K_d experiments (saturated zone) are summarized in Table 1.

Isotherms for Cs-137 are shown in Figures 2a and 2b as two isotherms each, one for each geoprobe soil sample. In Figure 2a, the isotherms are linear so the slope is the K_d . At GP-04 the K_d for Cs-137 is 240 and at GP-05 it is 260. Figure 2b indicates that with higher loadings of Cs-137 the soil is starting to saturate with respect to Cs-137 sorption. As a result, the K_d has started to decline. This took place in experiments in which soil was exposed to undiluted sump water and sump water that was diluted only 5-fold. From this, the soils capacity to retain Cs-137 is about 370,000 to 500,000 pCi/g.

Isotherms for Sr-90 are shown in Figures 3a and 3b. The K_d value for GP-04 is 90 mL/g and for GP-05 it is 20 mL/g. Both isotherms are linear to high activities of Sr-90, consequently these values should be appropriate for use even at high contaminant loadings. However, it appears that the capacity of the soil for Sr-90 was reached with the most concentrated two samples of GP-04. In each case the soil sorbed about 45,000 pCi/g. The correlation coefficients are greater than 0.99, indicating that the statistics on the data are good and implying that it is appropriate to make linear interpolations.

Results for the Ra-226 isotherms are shown in Figure 4. Both are linear, with GP-04 having a K_d

value of 119 and GP-05 having a value of 255. Pb-214 was present in the Ra-226 tracer, as a daughter of the Ra. Isotherms for this radionuclide are shown in Figure 5. Sample GP-04 has a K_d for Pb-214 of 32, while GP-05 has a K_d value of about 110. These values may be applied only to very low concentrations of Pb in groundwater. They should not be regarded as appropriate for concentrations exceeding more than a few ppb. At greater concentrations, processes other than sorption, such as precipitation, probably dominate removal of Pb from solution.

The isotherms for U are shown in Figure 6. These data are problematic because the U seems to precipitate from solution above a concentration of 2 to 2.5 ppm. Below that concentration sorption seems to be the operative process, with both GP-04 and GP-05 having a combined slope of about 9. That U would precipitate at concentrations of a few ppm is consistent with recently published data indicating solubilities of 10^{-7} to 10^{-8} M/L or 23 to 2.3 ppm in low ionic strength solutions (Casas et al., *Geochimica et Cosmochimica Acta*, Vol. 63, pp.2223 - 2231).

No isotherms were generated for Am-241. Typically this is a difficult radionuclide to measure K_d for because of its very great capacity to stick to soils. Results of single batch K_d experiments for GP-04 and GP-05 are 31,700 and 27,600 respectively. Because of the similar geochemical behavior of Pu, these values can also be applied to Pu transport.

Table 1. K_d Values for Soil from the Saturated Zone at the BGRR

Core	Cs-137	Sr-90	U	Ra=226	Am-241	Pb-214
GP-04	240	90	9	120	32,000	30
GP-05	260	20	9	250	28,000	100

Sorption and Desorption in the Unsaturated Zone

Calculation of K_d in the unsaturated zone is not straight forward. The value can only be assessed by devising an experiment in which the soil and solution are allowed to remain in contact under unsaturated conditions, and then the contaminant is rinsed from the system. To do this under continuously unsaturated conditions requires a great deal of time. In addition, issues of preferential flow paths often make results of these tests questionable. A different scenario was adapted for this work. It is assumed that water leaked from the sump into the unsaturated zone under building 701. It is then assumed that, at some time, water is able to access the unsaturated zone, rinsing the contaminant down toward the saturated zone.

Results are shown in Figure 7. The K_d for Cs-137, as a result of the contaminated soil being rinsed in 100 pore volumes of groundwater, is about 1100 for GP-04 and 3100 for GP-05. Soil from an unsaturated column of each soil was rinsed at: 5, 19, 34, 50, and 92 days. No change in sorption was observed as the time to sampling increased. BNL receives annual rainfall that is equivalent to 10 to 15 feet of saturated soil column. If contaminants leaked from the sump, they are about 15 feet from the watertable, or about one pore volume of annual rainfall. These data, then, reflect partitioning that would take place after 100 years of rainfall.

To determine what the relationship is between the number of pore volumes rinsing the soil and the quantity of Cs-137 released, two soil samples were rinsed serially with 33 pore volumes for each of four rinse intervals. Results are shown in Figure 8. Soil from GP-05 showed a slow but constant release of Cs-137 over the four intervals; with about 0.26% released from the soil per interval. GP-04 started at a higher release rate (0.87%) but it decreased rapidly. Over the course of this experiment, 129 pore volumes of rinse water (equivalent to about 130 years of rain) were applied to the soil, resulting in about 2.8% and 1% releases from GP-04 and GP-05 respectively. This indicates that Cs-137 is released from the soil, but only very slowly. Results for Sr-90, which is expected to be much more mobile, are still (Jan. 27, 1999) outstanding, but they will be incorporated in the final version of this report when they become available.

The much higher K_d values determined for the unsaturated zone, is probably the result of conditions of the experiment, which were selected to roughly approximate a real scenario at the BGRR. However, it also is possible that the soils in the unsaturated zone have much greater K_d values than those from the saturated zone. To compare the K_d values of the soils from the saturated and unsaturated zones, K_d s were determined using a multitracer groundwater solution. The soils from both the saturated zone and the unsaturated zone were tested using the same saturated batch test. In this way the relative K_d values of the soil at the two locations could be compared. Results are shown in Table 2.

Table 2. K_d Values from Soil from Saturated and Unsaturated Zones for Comparison of the Relative K_d s of the Two Soil Samples

Sample	Cs-137	Sr-85	Ra-226	Pb-214
GP-04 Saturated Zone	150	6	150	82
GP-04 Unsaturated Zone	110	5	70	64

Overall, the K_d values of the material from the saturated and unsaturated zones are quite similar. Values of K_d are slightly lower in the unsaturated zone than in the saturated. This is probably the result of differences in grain size and mineralogy and/or mineral coatings on grains. The great differences in K_d between the saturated (batch) tests and the unsaturated (column) tests must be the result of the experimental procedures which were designed to reflect conditions in the saturated and unsaturated zones. The values in Table 2 do not necessarily compare to those of Table 1 since they were conducted with somewhat different methodology (i.e. multitracers); this experiment was meant only to allow a comparison between the two soil samples. This being the case, the high values from the unsaturated experiments can be applied to the soil under the BGRR, assuming it is similar to the samples taken along side the building.

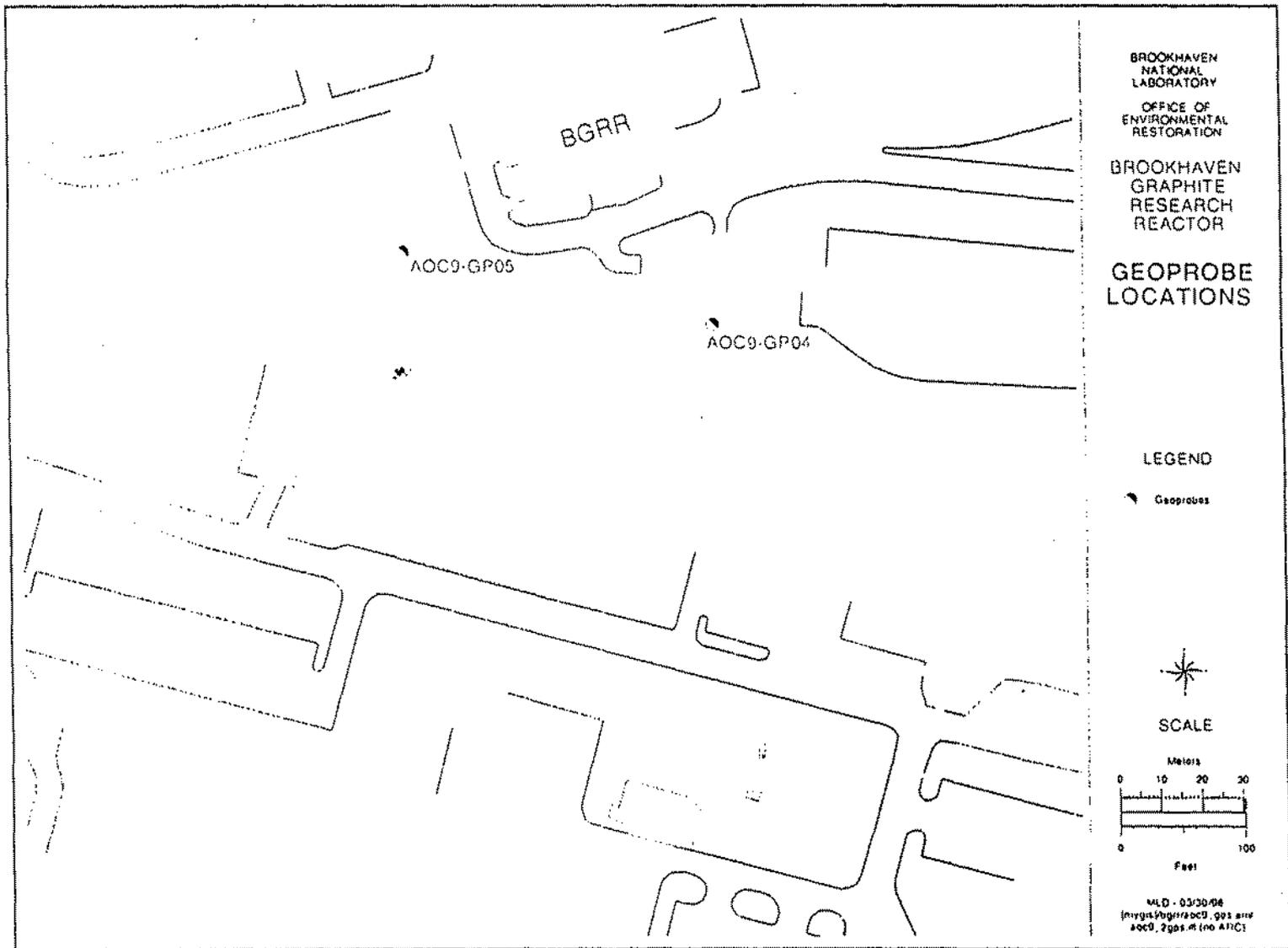
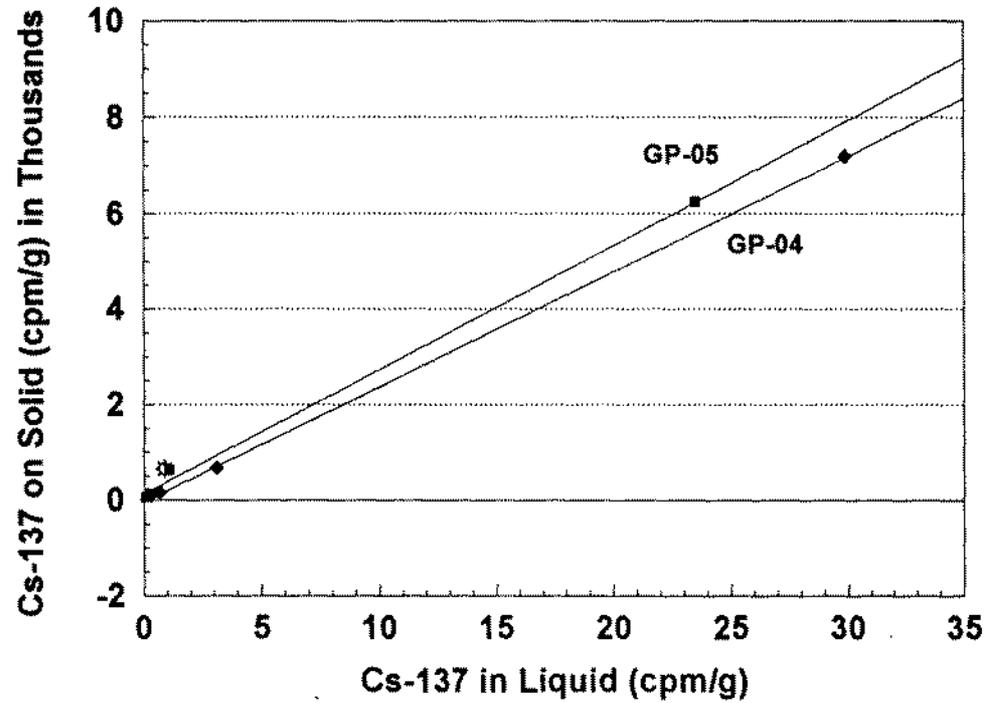
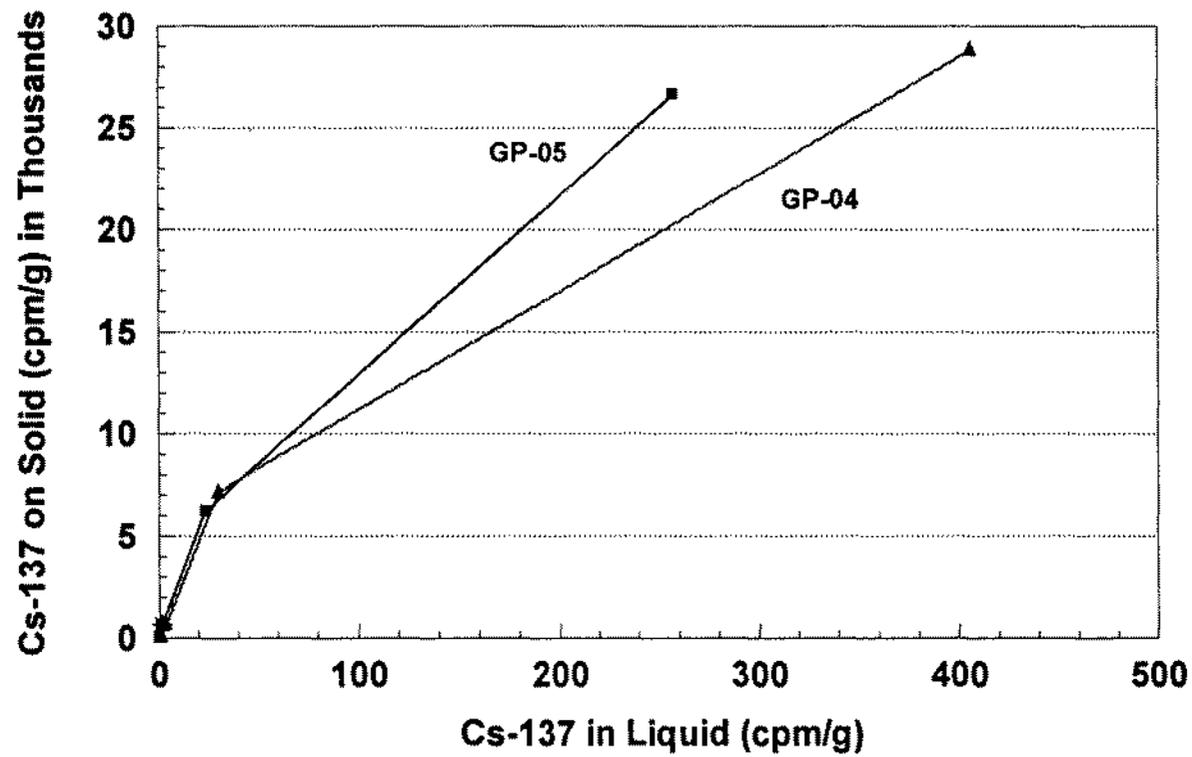


Figure 1. Locations of geoprobe sampling stations GP-04 and GP-05.



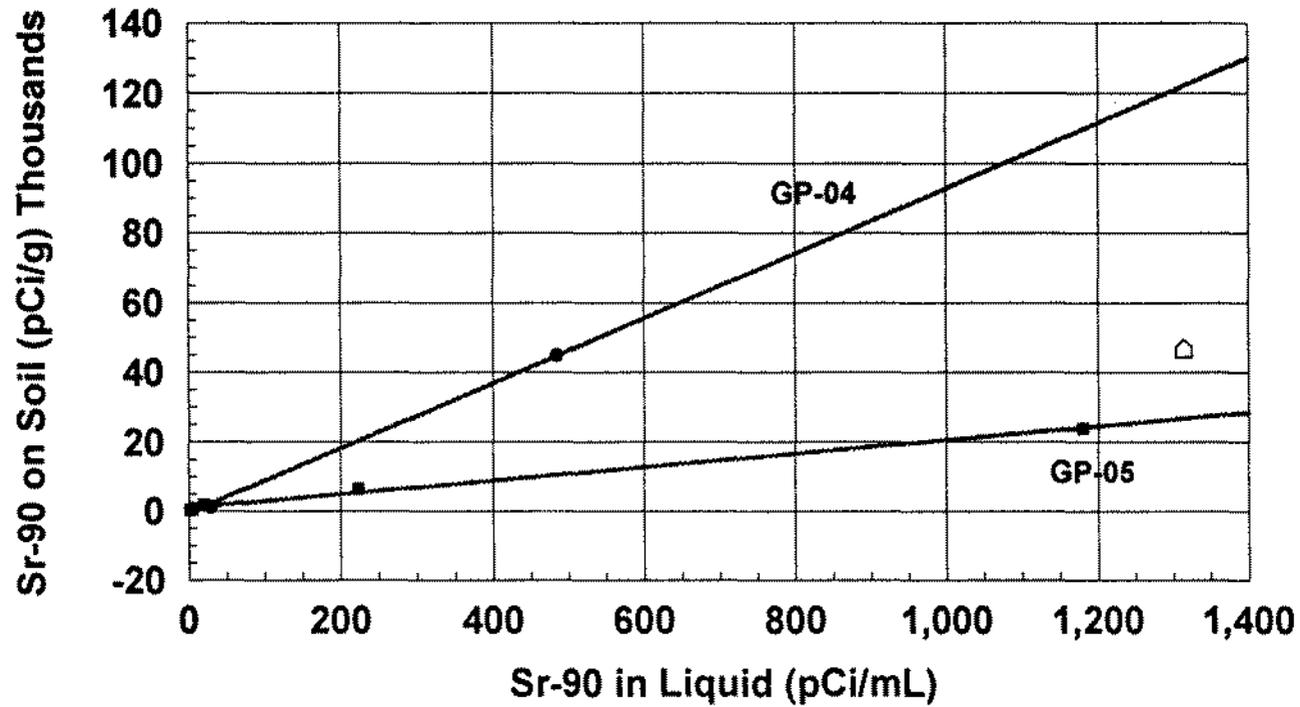
Slope for GP-04 = 241 R2 = 0.999
 Slope for GP-05 = 260 R2 = 0.998
 Data for the first four points only

Figure 2a Cs-137 isotherms for GP-04 and GP-05 showing the four linear data points for each sample set. Values of K_d are equal to the slopes and can be used for Cs-137 contamination levels below about 7,000 cpm/g on the soil.



Slope for GP-04 = 241 R2 = 0.999
 Slope for GP-05 = 260 R2 = 0.998
 Data for the first four points only

Figure 2c. The high concentrations of Cs-137 in the sump water saturates the sorption capacity of the soil, causing the K_d to decrease when soil concentrations are above approximately 7,000 cpm/g.



GP-04; slope = 93.3, $R^2 = 0.999$ (4 points)

GP-05; slope = 19.6, $R^2 = 0.994$ (5 points)

Figure 3a. Isotherms for Sr-90; the regressions are linear, consequently the slopes are the K_d values. This plot is for very high activities of Sr-90. The point to the far right is for GP-04 and indicates that the soil is saturated with Sr-90.

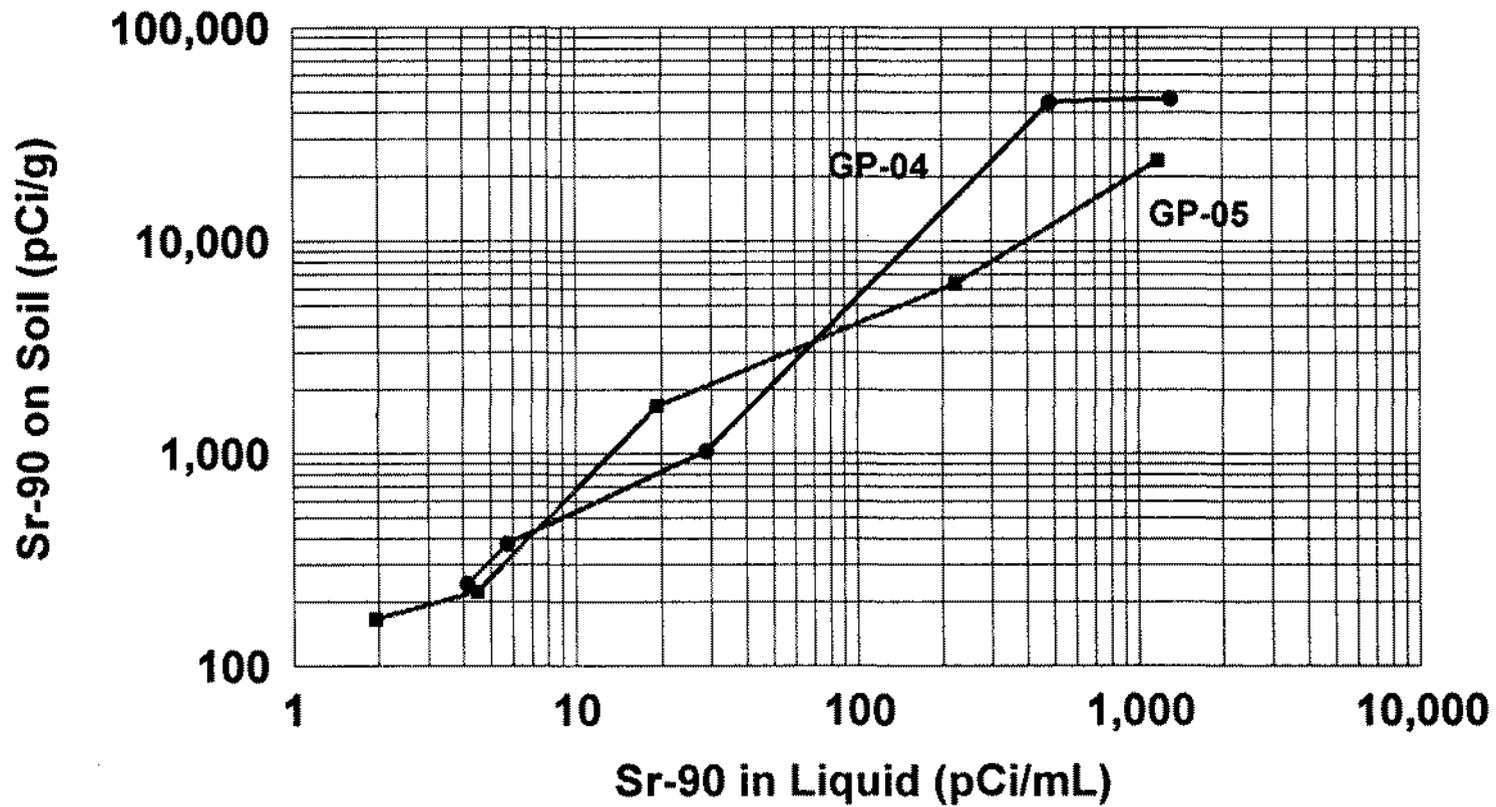
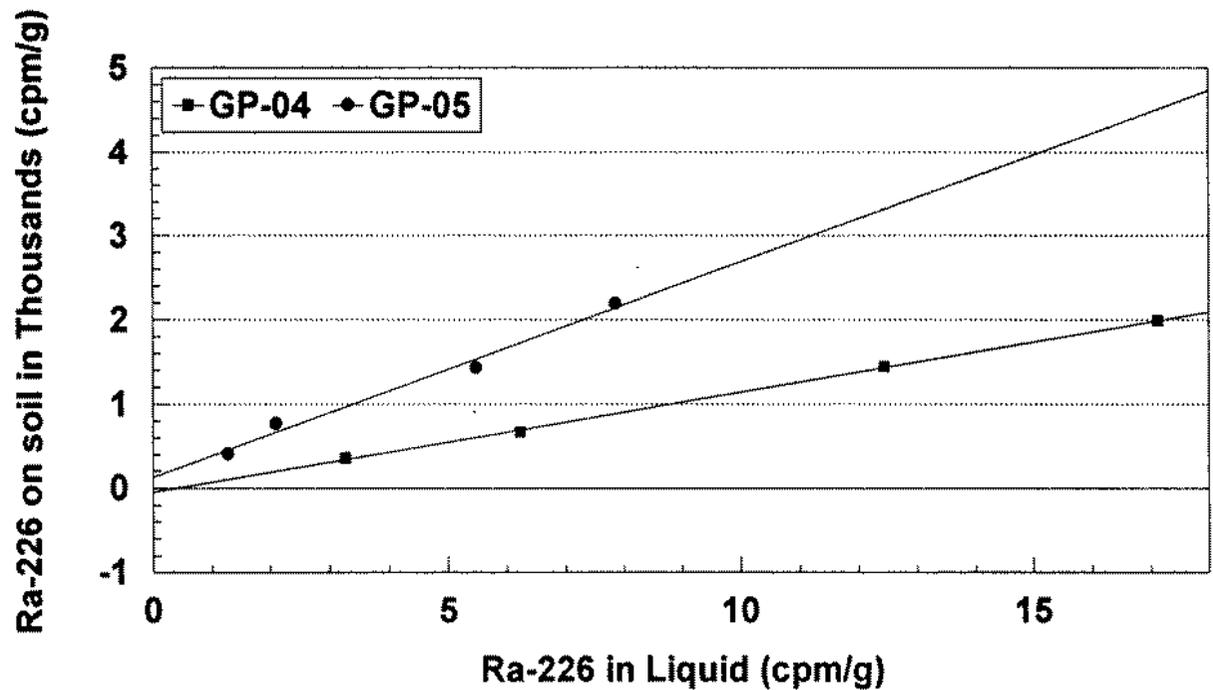


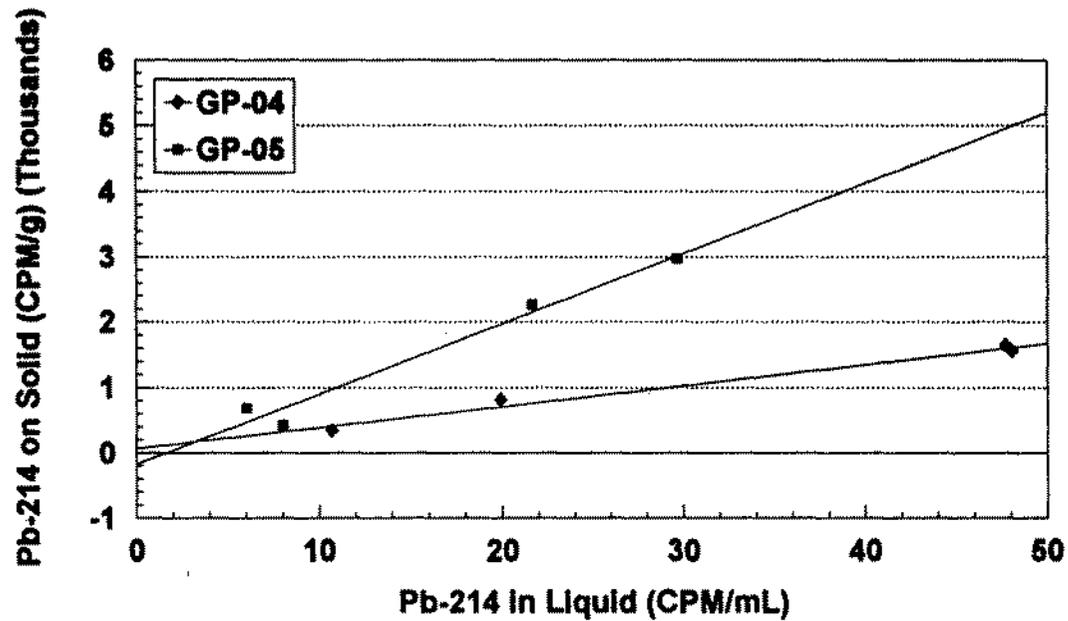
Figure 3b. A log-log isotherm of Sr-90 on the two soil samples from the BGRR, showing the data from Fig.3a. The soil at GP-04 saturates with respect to Sr at about 45,000 pCi/g., no more can be sorbed.



GP-04 slope = 119, R2 = 0.999

GP-05 slope = 255, R2 = 0.986

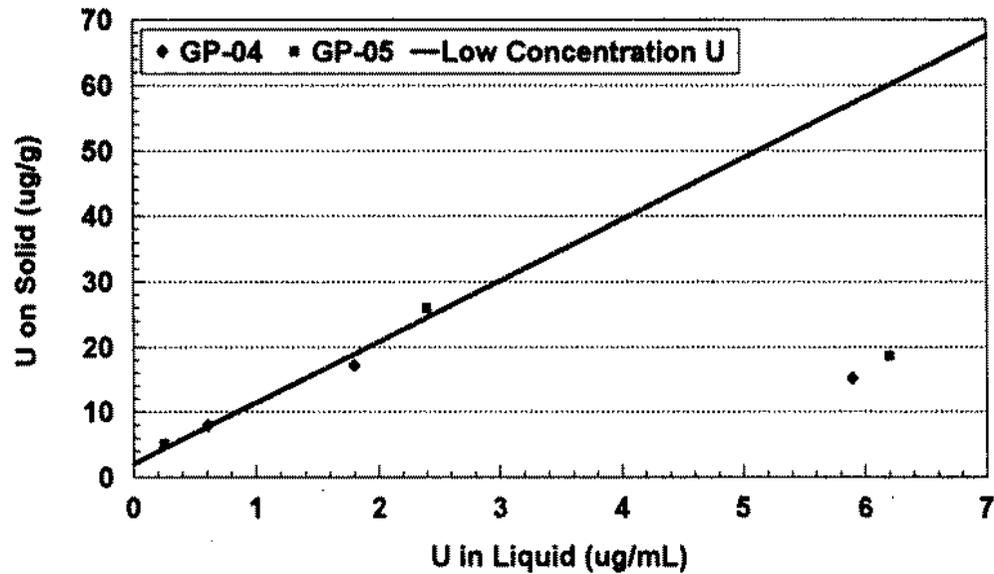
Figure 4. Isotherms for Ra-226 at GP-04 and GP-05. They are linear so K_d values are 120 for GP-04 and 250 for GP-05.



GP-04: R2 = 0.981, Slope = 32.2

GP-05: R2 = 0.972, Slope = 107

Figure 5. Isotherms for Pb-214 were determined from counts of Pb-214 that was present in the Ra-226 tracer. Concentrations of Pb in the tracer are exceedingly low. As a result the isotherms can be used for very low concentrations of Pb. However, for concentrations of environmental concern, where precipitation may be an issue, these values should not be used.



Regression of 4 low concentration points: $R^2 = 0.978$, slope = 9.3

Figure 6. Isotherms are shown for U in contact with soil from GP-04 and GP-05. The linear correlation is drawn through the four lower points, combining data from both cores. At slightly greater concentrations, as indicated by the two points to the right, U is well below the regression line. This implies that U may be removed from solution by precipitation. This suspicion would need to be confirmed through geochemical modeling or other techniques.

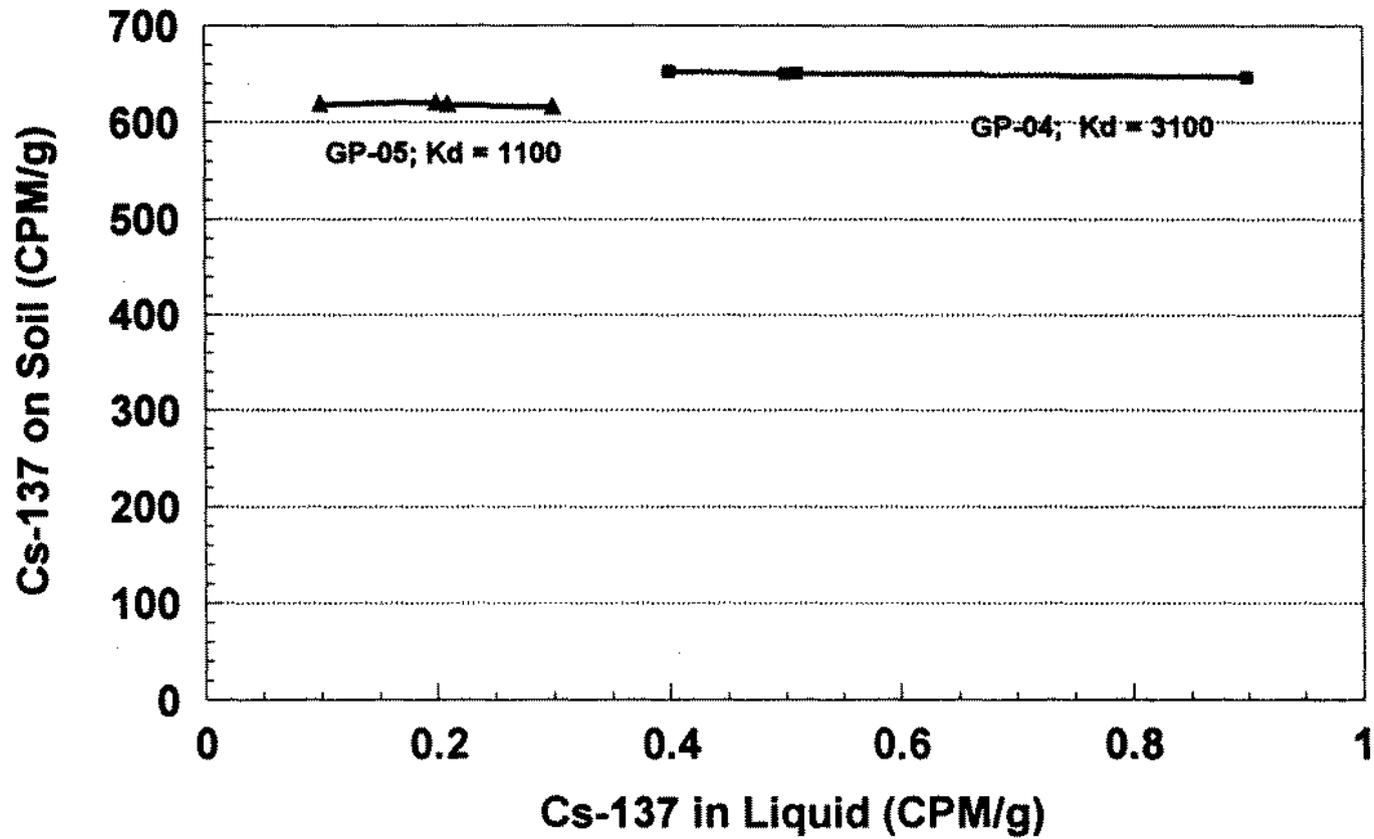


Figure 7. Partitioning of Cs-137 in unsaturated column experiments, after rinsing from the soil with 100 pore volumes of ground water. These plots show that there was no effect of residence time (from 5 to 91 days) of Cs-137 on the soil in the column. K_d are significantly greater than those determined in the batch, saturated experiments.

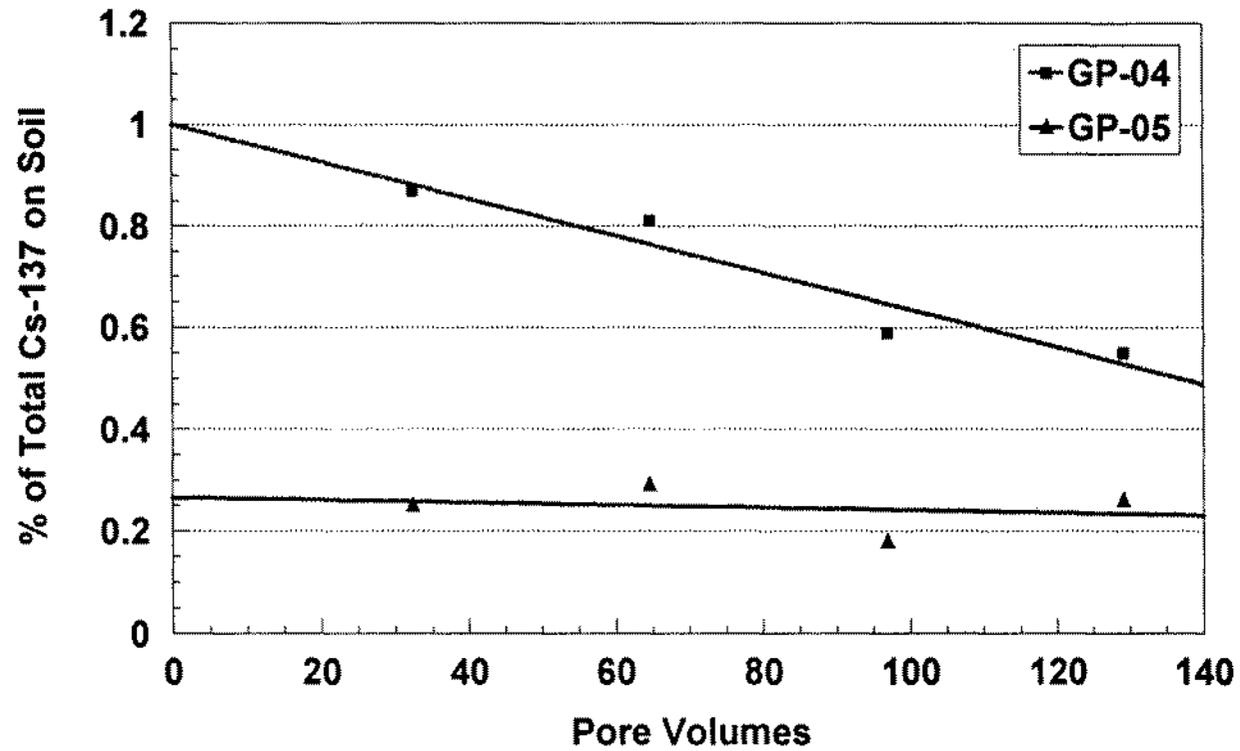
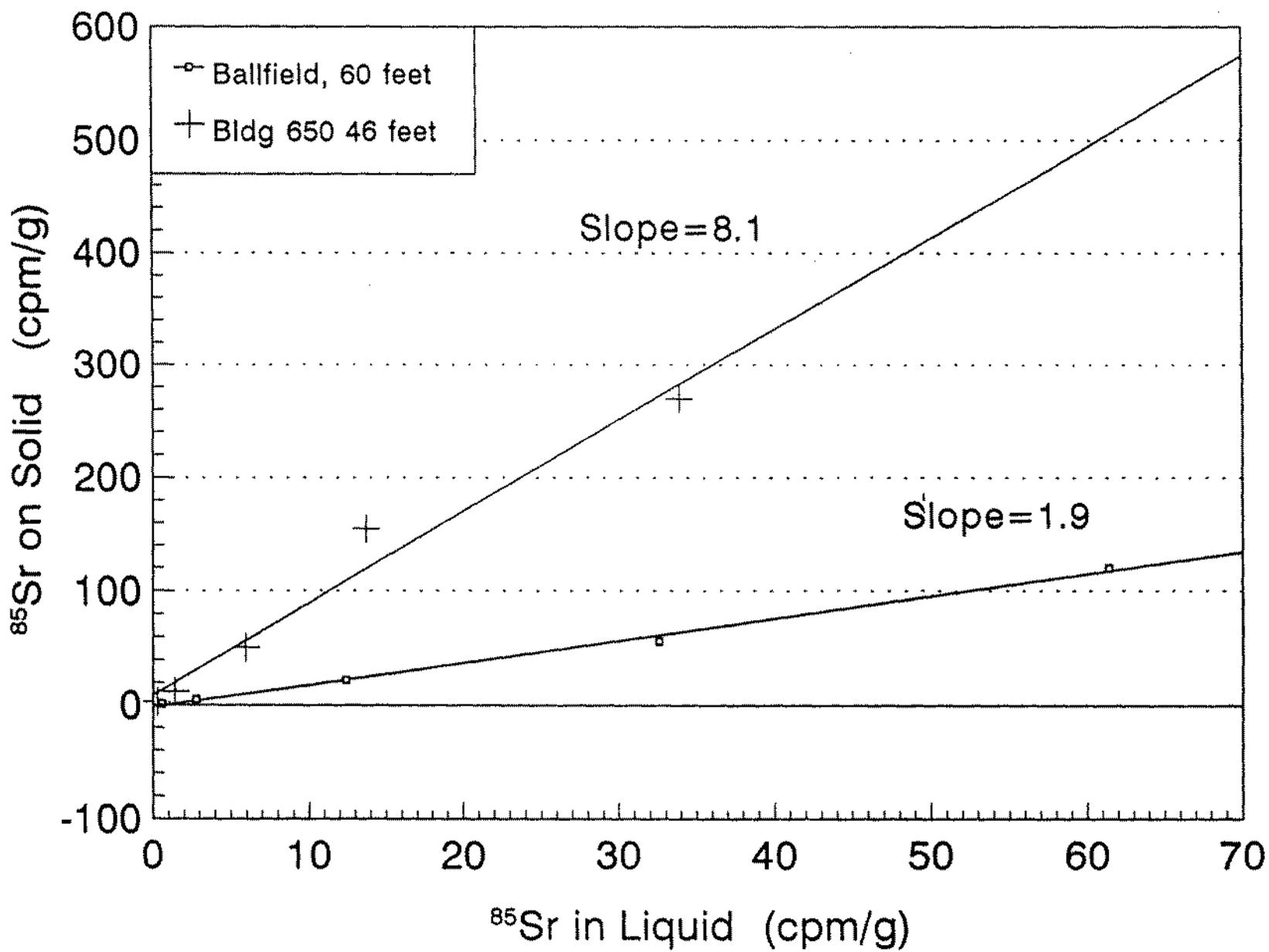
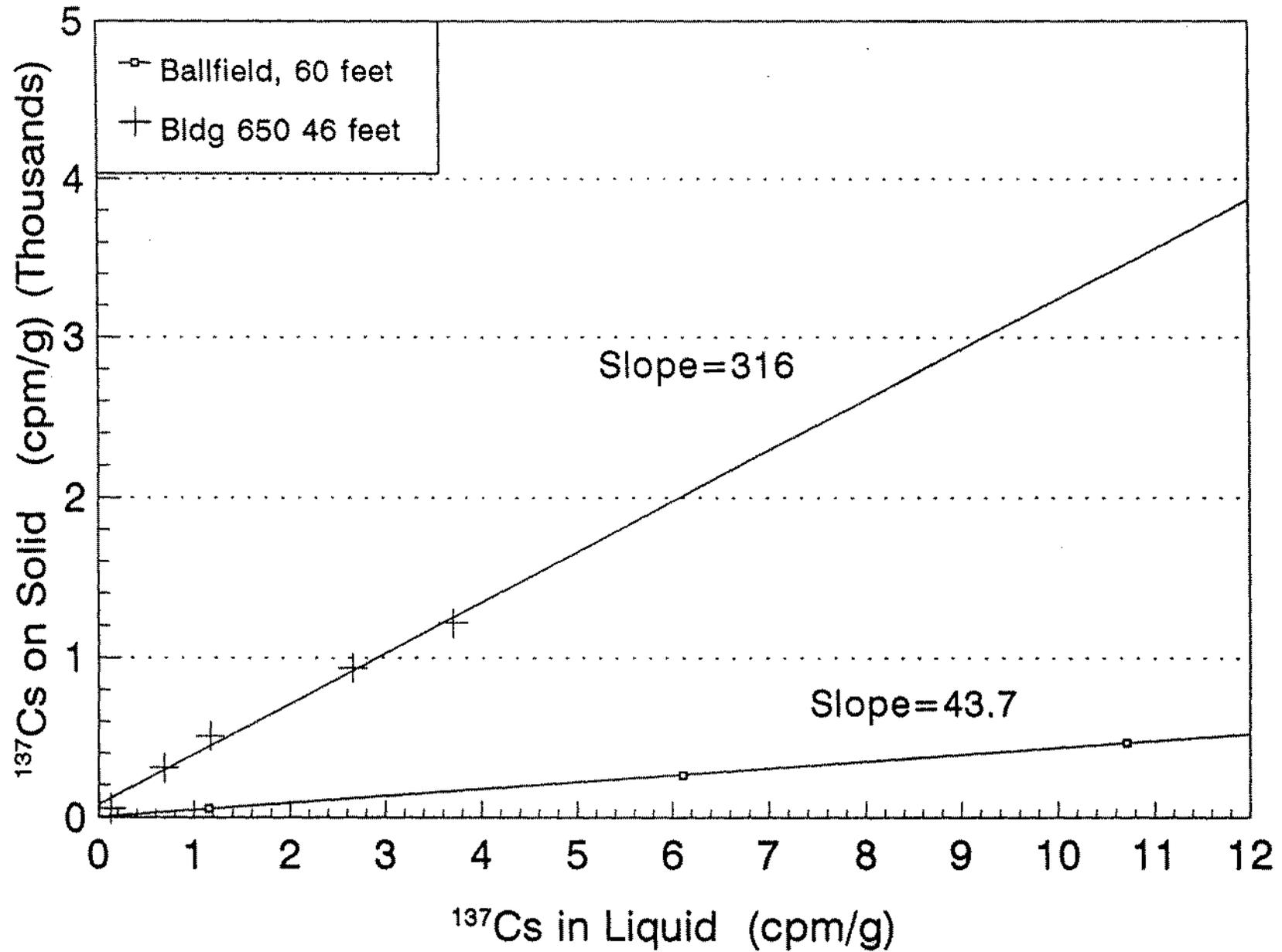


Figure 8. Desorption of Cs-137 from a two columns, using serial batch rinses. GP-05 slowly released Cs-137 at a constant rate of about 0.26% per interval. GP-04 released Cs-137 faster but the rate was steadily declining for each interval.

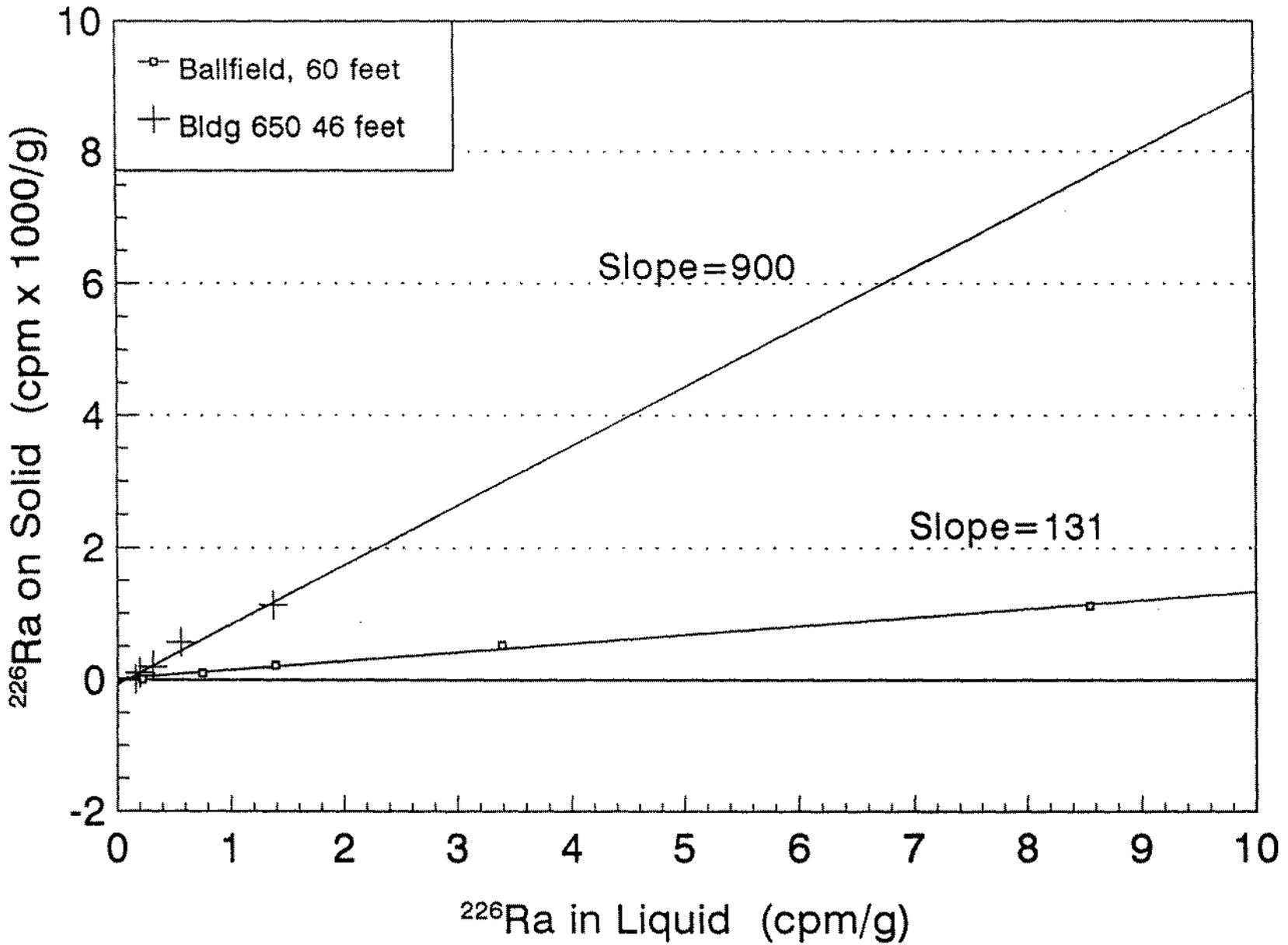
^{85}Sr Isotherms for BNL Soil



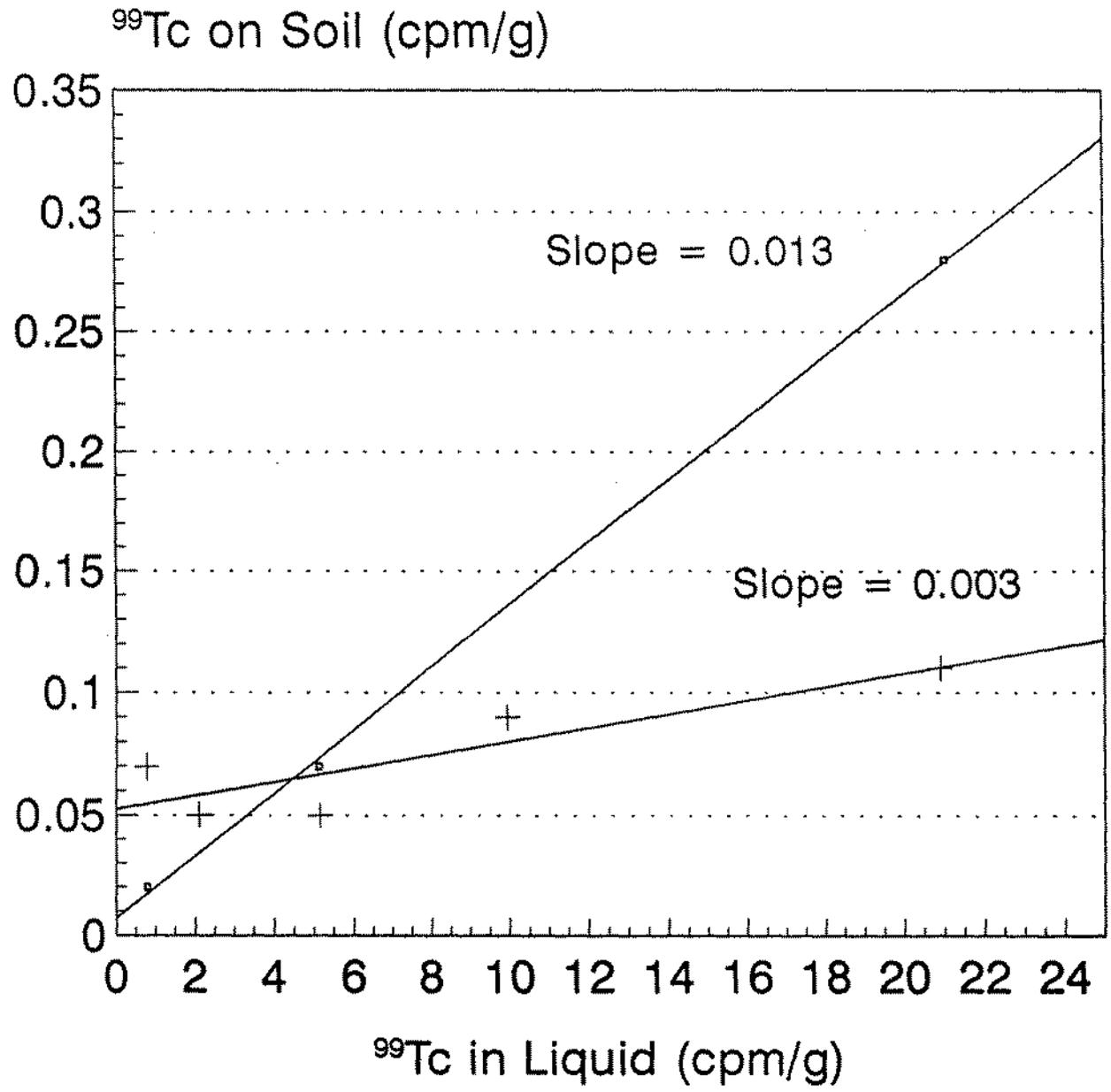
^{137}Cs Isotherms for BNL Soil



^{226}Ra Isotherms for BNL Soil



^{99}Tc Isotherm for BNL Soil



—□— Ballfield 60'
—+— Bldg 650 46'

MEMORANDUM
Brookhaven National Laboratory

Date: March 28, 1995

To: J. Brower

From: Mark Fuhrmann

MF

Subject: K_d Values for Sr and U.

A set of triplicate distribution coefficients (K_d) for ^{85}Sr have been determined on each of three samples of sand from BNL. The samples are:

1. 106-08 38-40' dated 3/14/94
2. 98-46 28-30' dated 3/09/94
3. 98-46 123-125' dated 3/10/94

The contact solution was groundwater from BNL to which a small concentration of a tracer (^{85}Sr) was added. We kept concentrations low in order to better replicate environmental levels of activity. The pH of the tracer was carefully adjusted to match the pH of the groundwater (pH = 6.1). Approximately 10 grams of wet sand were mixed with 40 grams of groundwater/tracer. This mixture was slowly stirred for six days to allow sufficient time for sorption to come to steady-state. We then removed an aliquot of the liquid, filtered it through a 0.45 μm membrane and counted the liquid on an intrinsic germanium gamma-detector. Counts from the sample solutions were compared to counts from the contact solution retained as a reference.

The aqueous phases of the uranium K_d experiments have been analyzed by ICP for uranium. We used very low concentrations of U for these measurements, with the assumption that K_d values will be low. It appears that this is not the case since all but one sample is below our detection limits for U. I have calculated the K_d based on the detection limit of 50 ppb. This gives K_d values of about 50 mL/g as a minimum. These experiments

Measurements of 27-35 on BNL soils 3/26/75

Date	Soil		Water		Porosimeter		Total		empty	
	wt	dry wt	wt	wt	wt	wt	liquid	Counting	visat	flite
27-31	9.85	8.995	39.79	0.857	46.81	6.17	10			
27-33	10.63	9.387	46.41	0.873	51.28	6.21	10			
27-35	10.02	9.168	40.20	0.878	41.42	6.19	10			
27-37	10.19	9.271	39.72	0.879	50.44	6.19	10			
27-39	9.89	9.061	40.49	0.886	51.66	6.22	10			
27-41	9.76	8.974	39.77	0.885	49.54	6.20	10			
27-43	9.76	8.988	39.88	0.888	49.89	6.23	10			
27-45	9.88	9.078	39.79	0.888	49.57	6.16	10			
27-47	9.88	9.078	39.88	0.888	49.86	6.27	10			
Average 6.19										

27-49

Date	Soil		Water		Porosimeter		Total		empty	
	wt	dry wt	wt	wt	wt	wt	liquid	Counting	visat	flite
27-49	9.89	9.284	45.42	0.886	46.30	6.25	10			
27-51	10.17	9.587	39.79	0.885	50.57	6.25	10			
27-53	10.17	9.587	40	0.888	46.88	6.271	10			
27-55	9.88	9.078	40.49	0.888	49.98	6.25	10			
27-57	10.17	9.587	40.4	0.887	51.57	6.25	10			
27-59	10.17	9.587	40	0.888	46.88	6.25	10			
27-61	10.17	9.587	40.49	0.887	51.57	6.25	10			
27-63	10.17	9.587	40.49	0.888	51.57	6.25	10			
27-65	10.17	9.587	40.49	0.888	51.57	6.25	10			
Average 6.25										