CONF-9505101--7

ANL/ES/CP--86536

Plutonium Mobility Studies in Soil Sediment Decontaminated by Means of a Soil-Washing Technology

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ABSTRACT

The ACT*DE*CON^{SM} process extracts plutonium from contaminated soils/sediments by means of a series of washings with a blend of chemicals, that includes a chelating agent, an oxidant, and carbonates. At the end of the process, the Pu level in the soil is lowered to 25-30 pCi/g from an initial contamination level averaging 500 pCi/g. The radionuclide still present in the soil at the end of the treatment must be strongly immobilized in or onto the soil particles to minimize the risk of its percolation to the aquifer and/or uptake by vegetation. This paper reports the investigation of residual Pu mobility as K_d (distribution coefficient) in the treated soil/sediment.

Six batches of contaminated soil were treated simultaneously by means of the ACT*DE*CON^{SM} process. Some batches of the treated soil were amended with a standard fertilizer treatment of compost and nutrient and brought to pH 8.5. The treated soil, treated and fertilized soil, and the untreated controls were then incubated at 18°C for 90 days. At four different times, a small aliquot of soil was retrieved from each of the batches and contacted with rainwater for six days to determine the Pu solid /liquid distribution and K_d.

Results indicated that a higher total amount of Pu was leached from the untreated soil, probably as a consequence of the higher content of available/exchangeable Pu in this soil compared with the treated ones. Treated/fertilized soils showed Pu leaching at intermediate levels between those for treated and untreated soils, at least for the first 30 days of incubation. K_d values at the beginning of the incubation period were significantly lower in the untreated and treated/fertilized soils compared with those for the treated-only, but at 90 days, these values were substantially equal among the three different soils. Traces of the chelant were detectable only in treated, unfertilized soil.

INTRODUCTION

The ACT*DE*CON^{SM} process extracts plutonium and uranium from contaminated soils/sediments by means of a series of washings of the contaminated material with a blend of chemicals, among which are a chelating agent, an oxidizing agent, and carbonates. A series of rinsing cycles follows the washing phase, the purpose ofthe rinsing cycles is to completely remove the ACT*DE*CON^{SM} chemicals together with all the mobilized radionuclides. At the end of the process, the soil's activity level is expected to be reduced to approximately 25-30 pCi/g, (1 pCi = 10^{-12} Ci) from an average initial level of 500 pCi/g. It is important that the radionuclide still present in the soil at the end of the treatment is strongly immobilized in or onto the soil particles, minimizing the risk of its percolation into groundwater and/or uptake by vegetation in significant amounts.

The mobility of plutonium, which determines its uptake by plants and leaching into groundwater, is dependent on chemical species of the plutonium (Pu) remaining in the soil, time, microbial metabolism, and soil chemical/physical conditions.

The purpose of the experiment considered here is to evaluate Pu mobility before and after a treatment that has drastically affected its chemical form and bonding to soil particles. Traces of some of

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the reagents might still be in the soil, even after the best technological rinsing performance, thus maintaining some of the Pu in a mobilized form, and/or the residual Pu might be less strongly attached to the soil particles after the treatment as a result of an incomplete action of the chemicals.

The objective of this study was to investigate the mobility of the Pu not removed by the ACT*DE*CON^{SM} treatment, thereby determining its potential for being taken up by the vegetation and/or to be leached through the sediment profile into the aquifers. The problem of ensuring that all the mobilized plutonium and the chelating agent are removed from the system at the end of the process has been recognized as a materials handling issue, and it will be addressed as such elsewhere. Since Pu mobility as a function of its chemical form and bonding into the soil matrix was the research priority in this study, the potential presence of Pu in mobile forms from incomplete rinses (due to technical problems) was minimized by rinsing the soil of the process chemicals as much as possible.

Distribution coefficient (K_d) studies are used to assess the adsorption/desorption of radionuclides onto soil/liquid phases. Such studies have been widely used in the determination of sorption properties of sediments, soils, and several materials, such as clays, rocks, etc. They have also been utilized in assessing the potential desorption of radionuclides from contaminated sediments to waters. K_d is defined as the concentration of the element in the soil (dry basis) to the concentration of the element in the aqueous phase, which is in equilibrium with the soil (expressed in milliliters per gram [mL/g]).

Typically, K_d studies are carried out in batch or column mode. The K_d value may be influenced by the solid/liquid ratio, the pore size and type of filter used in separating the liquid phase, the ionic strength and pH of the liquid used, the grain size of the solid fraction, and the presence and amount of other competing ions in the extracting solution. In the present case, the needed information was related to differences found among different conditions of the same soil, rather than to the assessment of absolute values. Therefore, the influence of the testing conditions was considered of lesser importance and minimized by carefully maintaining the same conditions throughout the test. However, a worst-case scenario was chosen in selecting the batch method (which allows for more shearing of the soil), the solid/liquid ratio, and the contact liquid (rainwater vs. discharge water obtained at the original Mound site).

Analysis of soil particle size and visual observation from attempted solids separation have shown that the Mound soil has a very low permeability (Rogers, 1975 (1) reports a water permeability of 0.1-1.0 m/yr in Mound clay), and its fine fraction is very difficult to separate from the liquid phase. Because column studies might not be able to provide leachate at all, and derived long retention times might confound Pu leachability and the presence of the chelating agent during the initial time after treatment, a batch-contact method was again preferred for this study.

Preliminary data from previous tasks suggested that to achieve the needed soil revegetation after cleanup, some restoration of fertility conditions should be done in the treated soil. Addition of organic matter has been controversially related to both increased immobilization of Pu and potential solubilization by chelation by soluble fractions of decaying organic matter. Alteration of pH also is known to affect Pu mobility. Therefore, this study investigated the effect on Pu mobility of a typical soil fertility restoration intervention.

MATERIALS AND METHODS

The experiment was structured in two phases. A preliminary study was conducted at the beginning to select testing conditions, and a full-blown testing phase that adopted the conditions selected in the preliminary phase followed.

The soil used in this experiment was obtained from the contaminated Miami-Erie Canal, next to the Mound site (Miamisburg, Ohio). Chemical and texture analyses performed during other investigations on similar material (obtained from uncontaminated portions of the same canal and treated with the ACT*DE*CON^{SM} solution in a simulation test) gave the data reported in table 1, which were used to determine the amounts of organic matter and nutrients to be restored in the treated/fertilized soil.

Preliminary studies were conducted on treated and untreated soils derived from previous ACT*DE*CON^{SM} demonstrations as part of the Mound-Selentec Treatability Study Project. The purposes of the preliminary K_d determination were (1) to obtain an orientative value of K_d, (2) to better focus the work of the following studies, and (3) to select the type of contact water that would prove more aggressive in mobilizing Pu (thereby constituting the "worst-case scenario" for the following experiments). Two aliquots of each sample, equivalent to 0.300 g each of dry soil were each placed in a 1,000-mL plastic bottle, to which 300 mL of rainwater collected at Mound or Mound discharge (basin) water was added. The lids were closed, and the water-soil suspension was stirred with a magnetic stirrer for one week. Samples of approximately 50 mL each were taken at 24 h, 48 h, and one week, filtered on a 0.45-mm millipore filter membrane, and analyzed for Pu according to standard methods reported elsewhere (2,3,4).

For the full-blown experiments, approximately 2 kg of contaminated moist soil was thoroughly mixed in a plastic tray, cleared of evident stones and root debris, and sampled for Pu and moisture analysis. Nine aliquots of moist soi, each one equivalent of 40 g of dry soil, were then accurately weighed and placed in nine plastic, 1000-mL centrifuge bottles, numbered from 1 to 9. While bottles 7, 8, and 9 were sealed and left aside as control (untreated soil), the other six soil bottles were subjected to the ACT*DE*CON^{SM} treatment according to Selentec' s proprietary procedure, which includes five washes with the ACT*DE*CON^{SM} solution, followed by three rinses with deionized water and solids separation by centrifugation for 30 min at 2000 rpm.

At the end of the procedure, a composite sample of the treated soil was prepared by retrieving one gram of material from different parts of each of the six bottles of treated soil and mixing all the aliquots together very accurately with a glass rod. A 1-g aliquot was then dried at 105°C to determine the moisture level and was analyzed for Pu. Two other aliquots were then weighed to obtain the equivalent of 0.300 g of dry soil, and each aliquot was placed in a 500-mL glass flask. Equivalent aliquots of the control soil sample (cumulative sample) were also weighed and placed in similar flasks. To each of the flasks was added 300 mL of Mound rainwater; the flasks were then sealed with parafilm, and their contents were gently stirred for six days. After six days, an aliquot of the soil suspension was filtered with a 0.45-mm-millipore membrane and sampled for Pu and chelant HPCL analysis (first K_d contact at day 4 from soil washing).

Three days after completion of the ACT*DE*CON^{SM} treatment, the soil in bottles 4, 5, and 6 was slurried with 80 mL of deionized water, neutralized with 0.1 N sulphuric acid to pH 8-8.5, and then centrifuged for 16 min to remove the excess liquid (pH of supernatant was 8.35). To each bottle was then added 3 g of dry yard-waste compost, 10 mg KH_2PO_4, 26 mg urea, and 0.5 mL of mixed, nonchelated microelements. After the soil in the nine bottles was accurately mixed, rechecked, and had an equalized moisture level, the nine bottles were placed in the incubator at 16-18°C.

At days 19, 30, and 90 from the beginning of the experiment, an aliquot of soil from each bottle was weighed (0.300 g of dry soil) and contacted with 300 mL of rainwater (according to the previously described method) for six days to determine the second, third, and fourth K_d value series. Chelant analysis was performed only on the samples from contacts at 4 and 19 days. The analytical method adopted for the chelant determination was a slightly modified version of Bergers and de Groot (1994) (5), and the analyses were performed by the ANL Analytical Chemistry Laboratory.

RESULTS

Contaminated soil had a starting activity of ^{238}Pu of 844 pCi/g dry basis, which decreased to 77.3 pCi/g dry basis in the treated soil. Results from the preliminary studies are summarized in Table 2, and the results of the K_d studies are summarized in Tables 3 and 4 and in Figures 1-4.

The results of the statistical evaluation of the Pu dissolutions and K_d data (Bonferoni's Multiple Means Comparison test) are summarized in Tables 6 and 7. These tables report all comparisons between two of the obtained mean values that were statistically significant at the probability level of 95% ($\alpha = 0.05$) or 99% ($\alpha = 0.01$).

The preliminary K_d evaluation conducted on Selentec-treated soil gave important information to shape the subsequent experiment. In general, a higher dissolution of plutonium was obtained by using rainwater rather than basin water. The effect was more evident in untreated soil. Treated soil consistently released less Pu than untreated soil, and this smaller value might be confounding the differences between the waters used. Equilibrium was probably reached within 24 h, but the data appear not to vary significantly in the three filtration times. K_d varied between 7×10^4 and 1.2×10^6, with most of the data within the 10^5 range.

On the basis of variance (ANOVA), both K_d values and dissolution values (fCi/L) obtained in the subsequent full-scale experiment showed significant differences ($\alpha = 0.01$), which were induced by the type of treatment and by the day of contact. Further statistical testing (Bonferoni multiple mean comparison test) showed that these differences were imputable to a number of direct comparisons between mean values of Pu dissolution and K_d (see Tables 6 and 7).

Untreated soil gave dissolution values (Pu dissolution in fCi/L values, Table 3) that were significantly different ($\alpha = 0.01$) and approximately 10 times higher than those obtained with treated samples. Significant differences were also found between dissolution from treated/fertilized and untreated soil samples at 19, 30, and 90 days. The anticipated trend toward increased dissolution of plutonium in treated/fertilized soil vs. treated soil is confounded by the high variability of the data and is not confirmed by the statistical analysis. The same can be said about the dissolution from treated soil at all contact times.

The higher degree of dissolution obtained from untreated soil at 30 and 90 days is, on the other hand, confirmed as significantly different from the lower dissolution levels obtained during the first two contacts in the same soil.

K_d values (Table 4) at 4 days from the soil treatment showed no significant difference induced by the ACT*DE*CON^{SM} treatment. At 19 days, however, K_d values obtained from treated soils were significantly higher than those obtained from treated/fertilized and untreated soils. These differences decreased with time and were not statistically significant at 90 days from the treatment. To further confirm this trend, treated and untreated soils gave K_d values at 4 days that were statistically higher than those obtained at 30 and 90 days. Treated/fertilized soil gave K_d values not statistically dissimilar from those of untreated soil at 19, 30, and 90 days. Differences between treated and treated/fertilized soil were significant only at 19 days.

Chelant analysis by HPLC (Table 5) was conducted on the filtered liquid from the first two contacts. As expected, no chelant was detected in the samples derived from the untreated soil. Treated soil samples showed traces of chelant at 4 days and more evident values at 19 days. Treated/fertilized soil showed no detectable presence of chelant at 19 days, in contrast with soil that had been only treated.

DISCUSSION

Preliminary K_d studies tested Pu dissolution at different equilibration times. Some variation of the dissolution levels was found, and it is uncertain whether the equilibrium was reached at 24 h. Therefore, the decision was made to adopt a six-day equilibration time for the subsequent experiments. Although the term K_d is adopted in this paper for simplicity, equilibrium is not demonstrated, so a better definition of the obtained ratio would be R_d (Distribution ratio).

The data obtained in this series of contacts are consistent with those usually found in the literature. Literature data show a wide range of adsorption/desorption K_d values in soil/sediment solutions. Ranges vary between 10 and 10^6 mL/g, depending on soil characteristics, total radionuclide concentration or activity, and whether the experiment is an evaluation of environmental samples or a simulation experiment (8,9). In the case of simulation experiments, the leaching system adopted (batch, column) and the use of artificially spiked solutions/solids are of fundamental importance in determining the K_d found. Usually, the lower K_d values found were from those tests in which samples were artificially spiked, generally at significantly higher activity levels (µCi, rather than pCi). In nature, plutonium K_d values for marine, riverine, and lacustrine environments have been reported as rather constant at 1×10^4 to 1×10^6 (8,10,11).

The total amount of plutonium that was leached by rainwater from the contaminated, untreated Mound soil proved in this experiment to be consistently higher (about ten times) than the amount extracted by rainwater from the same soil after it was treated with ACT*DE*CON^{SM}. This phenomenon can be explained by the fact that treated soil was de-facto poorer in Pu, as well as by the sequential extraction findings by Selentec (1994) (6), which showed that the ACT*DE*CON^{SM} treatment removed most of the readily available and exchangeable Pu, leaving in the soil the most strongly bound Pu. A sequential extraction technique was used by Selentec, during other investigations in this project, to understand Pu associations in Mound contaminated samples before and after treatment with the modified ACT*DE*CON formulation. Results suggest that in the untreated soil, about 0.2% is readily available/exchangeable, more than 50% is bound to the organic matter, another 40-43% is associated with the oxides, and 3% is insoluble. In this case, the reagents used were calcium chloride, tetrasodium pyrophosphate, oxalic acid-oxalate, and total acid dissolution, respectively. After the ACT*DE*CON^{SM} treatment, the residual Pu was 0.1% exchangeable, 13% organic-associated, 43% oxide-associated, and 43% insoluble.

K_d values of treated and untreated soil were initially comparable and tended to decrease in both soil conditions (i.e., to increase Pu mobilization into the liquid phase) with time. Over short interval times, the ACT*DE*CON^{SM} treatment seemed to induce a higher K_d, but the difference with untreated soil decreased over longer time intervals, and at 90 days the K_d values in treated and untreated soils were equal. The fertilization treatment induced a significant decrease in the K_d of the first contacts and made the values for treated/fertilized soil comparable with those obtained from untreated soils. In other words, the fertilization increased the ratio of Pu that was extracted by the rainwater and filtered through the 0.45-µm filter to the level of untreated soil. At the end of the testing period, the data were equal for the three different soil conditions; thus, in terms of time interval, fertilization appears to have decreased the time needed for the residual plutonium in treated soil to reach K_d values analogous to those of untreated soil. In no case did the treated soil (with or without fertilization) give K_d values lower than those of untreated soils, so a higher relative mobility of the residual plutonium was not suspected.

Plutonium mobility has been evaluated in the literature by distribution coefficients studies, as well as by speciation and sequential chemical extraction studies and by analyzing plant uptake after cultivation in Pu-contaminated soil. Some of the effects of varying soil conditions have been studied more in the literature relating Pu mobility to its accumulation in plant tissues. This is the case in the evaluation of the effects of soil amendments and fertilization.

Plutonium mobility is reported to vary with soil physical, chemical, and microbiological characteristics (12,13,14). Reasons for increased dissolution of radionuclides from soil have been related by various authors to such factors as pH and Eh changes, the direct presence of natural organic matter (such as decaying roots, which has complexing characteristics that prevent the readsorption of Pu onto soil particles; see Romney et al. 1970, cited in 13, and the production (induced by microbes/fungi) of extracellular metabolites able to complex Pu (15). Wang and Yu (1992)(16) conducted batch U-Th desorption studies by using alkaline soils (pH approximately 8.5); the desorption of the radionuclides increased as the pH of the contacting solutions was lowered, and humic acid additions were able to increase the desorption from soil by at least a factor of four (compared with that for deionized water). Rediske et al. (1955, cited in 13) reported a more than three times greater uptake of Pu from acidic rather than alkaline soil, and Romney et al. (1976, cited in 7) found that addition of sulfur was able to increase significantly the uptake of Americium and Pu-239-240 .

Nelson et al. (1987) (11), in a study of natural waters/sediment K_d values, describe natural dissolved organic compounds (DOC), such as humic materials, as important complexing agents for many metals in surface waters; they state that the formation of water-soluble, metal-organic complexes could be responsible for a decrease in adsorption of Pu in sediments associated with waters rich in DOCs. Garland et al. (1974) (17) reported an increased plant Pu uptake following incubation of a Ritzville soil (pH 6.8) with carbon and nitrogen to provide maximum microbial activity.

In the case of the present investigation, the fertilization treatment lowered the pH to a more vegetation-acceptable level and restored some of the organic matter and nutrients lost with the ACT*DE*CON^{SM} washes. Urea and potassium phosphate, as well as micronutrients, were supplied to ensure the potential for microbial life and utilization of the organic matter supplied. Both a decreasein pH and the presence of some microbial activity might be responsible for the temporarily increased plutonium mobility.

The presence of chelant measured in the first two contacts was contained within the expected order of magnitude and tentative limit value (15 mg/kg soil) set for the cleanup. At 19 days, chelant was present in measurable amounts in treated soil but not in treated/fertilized soil; this fact supports a hypothesis of either a degradation of chelant or its nonreversible adsorption onto organic amendment.

The lower chelant concentration found at 4 days might be explained either by the existing fluctuation among samples or by the longer time the 4-day aqueous sample was preserved prior to analysis (for increased analytical accuracy, all samples were analyzed at the same time), which might have allowed for a partial degradation of the chelant in the water. In this case, a faster degradation of the chelant in water rather than in soil would be necessarily assumed. The time-constrained effect of chelating agents and the derived inferred degradation is not new to the literature: in plant uptake experiments, where an increase in uptake was found if the radionuclide was supplied as chelated with EDTA, DTPA, or EDDHA, decreasing radionuclide mobility was found after the first period by Hale and Wallace (1970; cited in 7), who noticed a lower uptake of DTPA-Americium by plants after 30 days, and by Romney et al. (1976, 1978, 1985; cited in 7), who found that the chelator-increased radionuclide plant uptake diminished over successive harvests.

In any case, the lower levels of extracted Pu found in those cases where the chelant was detected suggest that the residual chelating agent was not an element of concern under these conditions for increased Pu activity in the contact water. The data on chelating agent, however, are too few to allow for a definite conclusion and should therefore be used as indicative values of what is possibly found in the soil after the ACT*DE*CON^{SM} treatment under the best available conditions (lab-scale work allows for much more precise operational conditions than pilot- or field-scale operations).

CONCLUSIONS

Although these data represent a first evaluation of the soil environment after the ACT*DE*CON^{SM} treatment (and will be repeated as the ACT*DE*CON^{SM} and its application conditions are further refined), a few conclusions can be drawn. The higher Pu dissolution in rainwater recorded from original, untreated samples compared with the treated ones eases the concerns of a potential increase of Pu mobility induced by the ACT*DE*CON treatment. The trend of the K_d values over the time (i.e., the higher mobility of Pu in untreated samples at 19 and 30 days and its adjustment to comparable levels at 90 days) indicates that once the treatment was completed, and the rinsing phase carried out optimally, no evidence of increased Pu mobility could be detected in the treated soil compared with the original conditions. Also, in the case of a basic, most-likely reclamation intervention, no data supported the hypothesis of a higher Pu mobility. In the worst case (which was obtained at 30 days from the treatment), the K_d found in treated/fertilized samples was in the same range, if not slightly higher, than the one found in the untreated soil.

ACKNOWLEDGMENTS

Work supported by the U.S. Department of Energy, Office of Environmental Management, Office of Technology Development, under Contract W-31-109-Eng-38. This work was funded under the In Situ Remediation Integration Program. The authors express their appreciation for the support of the Project Manager, Michael Malone, at the U.S. Department of Energy, Office of Environmental Management, Office of Technology Development. Also our gratitude goes to Jerry McNally for his indispensable help in conducting the experiment, to John Taylor and Laura Skubal for the analytical work performed on the uncontaminated Mound soil, and to Bruce Schilling, ACL, for the chelant analyses. We would especially like to thank Chris Reilly, ANL's Environmental Research (ER) Division Director, as well as Mike Miller and Julie Jastrow of ER, for kindly making ER's facilities available to us, and Dave Peterson, ANL/ER, and Chuck Salsbury, ANL/ESH/HP, for their support in reviewing safety procedures and monitoring the experiment.

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Table 1. Results of chemical and texture/hydrometer analyses on untreated and treated uncontaminated mound soil (average of two replications, clean, untreated Mound soil).

Parameter	Untreated soil	Treated soil
pH	7.8	10.2
Cationic Exchange Capacity (cmol/kg)	35.7	N/A
Organic Carbon (%)	3.6	2.6
Total P (mg/kg)	1183	8.1
Total N (mg/kg)	2523	8.03
Bray PO_4 (mg/kg)	10.2	N/A
Extractable Bases (mg/kg)		
Ca	5914	181
Na	21	5806
Mg	648	138
K	155	194
Particle size (µm) %		
Medium, coarse, very coarse sand (>100)	12.5	N/A
Very fine sand (63 to 100)	0	N/A
Coarse silt (32 to 60)	4.5	N/A
Medium silt (17 to 31)	11.2	N/A
Fine silt (9 to 16)	19.4	N/A
Very fine silt (5 to 8)	31.2	N/A
Coarse clay (3 to 4)	0	N/A
Medium clay (1 to 2)	33.12	N/A
Fine clay (<1)	0	N/A
Texture class	silty clay loam	N/A

Table 2. ^{238}Pu activity and derived K_d on Selentec samples contacted with rainwater or basin water (preliminary K_d determination) (1fCi = 10^{-15} Ci).

	Untreated Soil		Treated Soil	
Item	Rainwater	Basin Water	Rainwater	Basin Water
Pu Activity, fCi/L in water				
at 24 h	5304	1227	88	132
at 48 h	6885	1454	213	142
at 1 week	4000	1000	374	45
Derived K_d				
at 24 h	$9.4 \times 10^4 \pm 0.9$	$4 \times 10^5 \pm 1$	$6.4 \times 10^5 \pm 1.1$	$4.2 \times 10^5 \pm 1.3$
at 48 h	$7.0 \times 10^4 \pm 0.7$	$3.4 \times 10^5 \pm 0.8$	$2.6 \times 10^5 \pm 0.7$	$4 \times 10^5 \pm 1.3$
at 1 week	$1.3 \times 10^5 \pm 0.06$	$5.0 \times 10^5 \pm 0.5$	$1.5 \times 10^5 \pm 0.2$	$1.25 \times 10^6 \pm 5$
pH at 24 h	7.06	7.74	7.10	7.43

Table 3. Plutonium extraction in the four K_d contacts as fCi/L.

Days	Treated Soil	Treated/Fertilized Soil	Untreated Soil
4	137[a]	N/A	1,879[a]
	4[b]		1,197
19	112[c]	292[c]	3,964[c]
	51	26	1,369
30	325[c]	856[c]	11,193[c]
	145	140	4,678
90	514[c]	488[c]	5,891[c]
	237	187	704

[a] Mean value of two replications.

[b] Standard deviation.

[c] Mean value of three replications.

Table 4. Plutonium distribution in solid/liquid fractions, as K_d.

Days	Treated Soil	Treated/Fertilized Soil	Untreated Soil
4	566,490[a]	N/A	563,777[a]
	14,673[b]		359,284
19	794,857[c]	266,404[c]	228,109[c]
	356,247	22,863	66,045
30	287,441[c]	92,045[c]	86,193[c]
	167,406	15,738	39,801
90	170,737[c]	172,300[c]	144,752[c]
	66,825	55,293	18,516

[a] Mean value of two replications.

[b] Standard deviation.

[c] Mean value of three replications.

Table 5. Chelant concentration in each liquid phase, K_d contact replication (mg/L).[a]

Days	Treated Soil	Treated/Fertilized Soil	Untreated Soil
4	6	n/a	< 5
	5		< 5
19	16	< 5	< 5
	13	< 5	< 5
	11	< 5	< 5

[a] Detection limit was 5 mg/L.

Table 6. Bonferoni multiple mean comparison test: significant comparisons on fCi/L data.[a]

Item	T4	T19	T30	T90	TF19	TF30	TF90	U4	U19	U30	U90
T4	/	-	-	-	-	-	-	-	b	c	c
T19		/	-	-	-	-	-	-	b	c	c
T30			/	-	-	-	-	-	b	c	c
T90				/	-	-	-	-	-	c	c
TF19					/	-	-	-	b	c	c
TF30						/	-	-	-	c	c
TF90							/	-	-	c	c
U4								/	-	c	b
U19									/	c	-
U30										/	c
U90											/

[a]T = treated soil, TF = treated + fertilized soil, U = untreated soil. Number represents days from treatment:
[b]Significant at α = 0.05; [c]Significant at α = 0.01.

Table 7. Bonferoni multiple mean comparison test: significant comparisons on K_d data.

Item	T4	T19	T30	T90	TF19	TF30	TF90	U4	U19	U30	U90
T4	/	-	b	c	b	c	c	-	b	-	c
T19		/	c	c	c	c	c	-	c	c	-
T30			/	-	-	-	-	b	-	-	-
T90				/	-	-	-	c	-	-	-
TF19					/	-	-	b	-	-	-
TF30						/	-	c	-	-	-
TF90							/	c	-	-	-
U4								/	b	c	c
U19									/	-	-
U30										/	-
U90											/

[a]T = treated soil, TF = treated + fertilized soil, U = untreated soil. Number represents days from treatment:
[b]Significant at α = 0.05; [c] Significant at α = 0.01.

Figure 1. Plutonium Extraction in the Four Kd Contacts, Mean Values, fCi/L

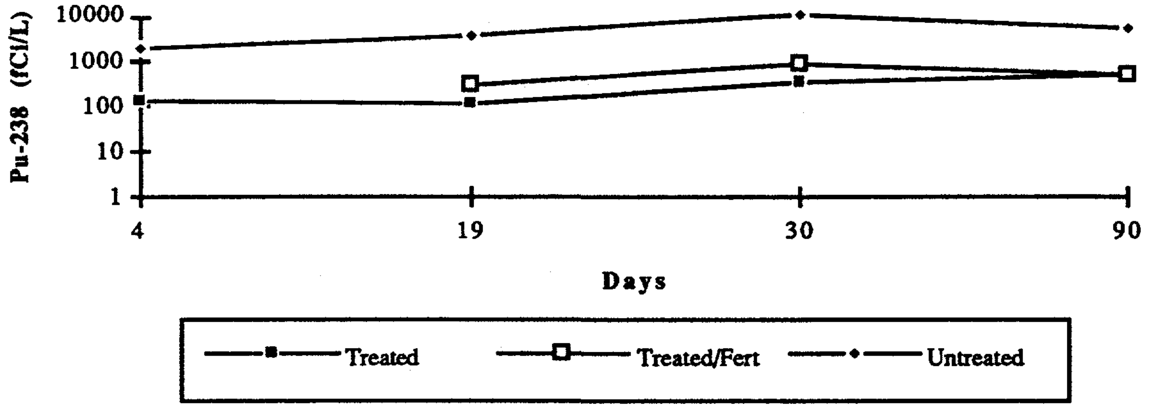
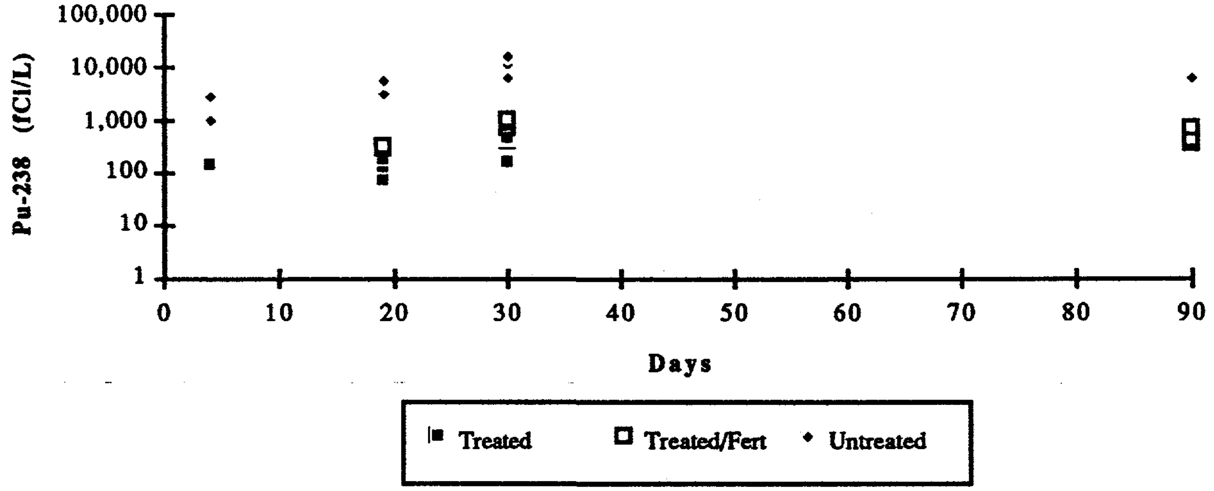


Figure 2. Plutonium Extraction in the Four Kd Contacts, fCi/L, All Replications.



T

Figure 3. Plutonium Distribution in Solid/Liquid Fractions, as Kd, Mean Values.

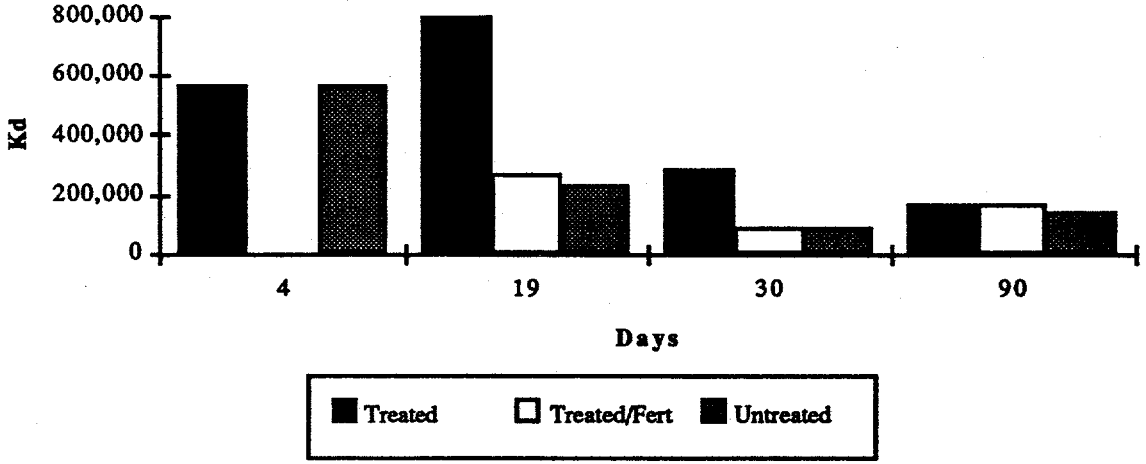


Figure 4. Plutonium Distribution in Solid/Liquid Fractions, Kd, All Replications