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Association of Fallout $^{239+240}Pu$ and ^{241}Am with Various Soil Components in Successive Layers of a Grassland Soil

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The association of $^{239+240}Pu$ and ^{241}Am from the global fallout with various soil components was investigated in six successive layers of an undisturbed grassland soil (Alfisol) from 0 to 30 cm by a sequential extraction procedure In this way, the fractions readily exchangeable, bound to carbonates, bound to iron and manganese oxides, bound to organic matter, and residual (mineral) were determined The results revealed that these radionuclides are in most soil layers primarily attached to the soil organic matter (in general >57%) but to a considerable extent also attached to oxides and minerals As a result, the readily exchangeable fraction of these actinides 30–40 years after their deposition is rather low (for Pu, <1%) Significant differences between the partitioning of Pu and Am are observed for all fractions, even though they are rather small for the bound to organic matter fraction [with the exception of the 5–10-cm layer in the A_h horizon, where much more Pu (67%) than Am (18%) is associated with organic matter] In the fraction bound to oxides, more Am is found than Pu, in the residual fraction (minerals) of most soil layers, more Pu than Am is present. In all soil layers, the readily exchangeable fraction of Am is significantly higher than that of Pu (on average by a factor of 7) The results are also discussed in relation to the long-term vertical migration rates as determined recently for both radionuclides in the same soil and with respect to possible soil reclamation procedures

Introduction

Various long-lived isotopes of plutonium (^{238}Pu, $^{239+240}Pu$, ^{241}Pu) were deposited on the soil surface with the global fallout of atmospheric weapons testing 30–40 years ago Because ^{241}Pu disintegrates to ^{241}Am (half-life 432.6 yr), this latter actinide element is also found in our environment, even though to a much smaller extent. Subsequent to the deposition on the soil surface, these radionuclides begin to infiltrate slowly into the soil, where they can be taken up to some extent by plant roots and may eventually arrive also in the groundwater From the presently observed vertical concentration profiles of these elements in several soils, however, it must be concluded that actinides are sorbed rather tightly by various soil components (clay minerals, hydrous oxides, soil organic matter) and are thus rather immobile Because the association of actinides with the various soil components controls their availability for migration and plant uptake, several investigations on this subject, even though mainly for Pu, exist (*1–18*) It seems, however, that a detailed study on the simultaneous association of Pu and Am from the global fallout with soil components in successive layers of a soil is not available On the other hand, such an investigation would not have been possible much earlier because these radionuclides were present then only in the surface layer of the soil

Information on the fractionation of a contaminant in the soil, i e , on its partitioning among the various solid fractions of the soil as well as on the easily available or readily exchangeable fraction can be obtained by sequential elution procedures A recently rather frequently applied method for this purpose is the procedure described by Tessier et al (*19*) With this method, it is possible to determine the fractions readily exchangeable, bound to carbonates, bound to iron and manganese oxides, bound to organic matter, and residual While the Tessier procedure has been frequently applied to study the fractionation of stable heavy metals in the soil, it was obviously not yet applied to study in an analogous way the fractionation of fallout Pu and Am

The purpose of the present investigation was therefore to determine simultaneously the above fractions by the Tessier procedure for fallout $^{239+240}Pu$ and ^{241}Am in an undisturbed grassland soil This soil was selected because we recently also determined at the same site the long-term migration rates of fallout Pu and Am (*20*) In this way, it was possible to examine also to which extent these experiments are useful for the interpretation of the observed migration rates of Pu and Am in a given soil layer

Because the physicochemical properties of an undisturbed soil vary with depth, the association of these elements with soil components was determined in the six soil layers 0–2, 2–5, 5–10, 10–15, 15–20, and 20–30 cm Below this depth, the amount of fallout Pu and Am was too small to be extractable Due to the very low activity concentrations of fallout $^{239+240}Pu$ and especially of ^{241}Am in the soil, samples of 500 g from each layer had to be taken for the extractions

All fractions obtained by using selective reagents are to some extent only operationally defined, and the corresponding results obtained cannot necessarily be used also for a quantitative interpretation They will yield, however, a very valuable information if they are used as in the present case to detect only relative differences in the association of two (or more) elements in the same soil layer

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TABLE 1

Properties of Grassland Soil (Slightly Wet Alfisol)[a]

	horizon				
	A_h			A_l	B_t
depth	0–2	2–5	5–10	10–20	20–40
pH ($CaCl_2$)	4 6 ± 0 15	4 3 ± 0 15	4 4 ± 0 15	4 3 ± 0 15	4 2 ± 0 15
clay (%)	42 ± 2	30 ± 2	30 ± 2	30 ± 2	31 ± 2
silt (%)	40 ± 2	54 ± 2	55 ± 2	55 ± 2	55 ± 2
sand (%)	18 ± 2	16 ± 2	15 ± 2	15 ± 2	14 ± 2
total N (%)	0 59 ± 0 1	0 43 ± 0 1	0 31 ± 0 1	0 19 ± 0 1	0 13 ± 0 1
organic matter (%)	12 4 ± 1 0	7 4 ± 1 0	5 5 ± 1 0	3 0 ± 1 0	2 4 ± 1 0
Ca^{2+} (mmol kg^{-1})[b]	48 ± 2	46 ± 2	46 ± 2	40 ± 2	34 ± 2
Mg^{2+} (mmol kg^{-1})[b]	25 ± 1	15 ± 1	15 ± 1	13 ± 1	15 ± 1
CEC (mmol kg^{-1})	113 ± 6	78 ± 4	75 ± 4	71 ± 4	66 ± 3

[a] The errors given are σ errors [b] Exchangeable

Experiment Section

Site. The sampling location is situated about 40 km northwest of Munich, 545 m above sea level Because there are no nuclear installations within 100 km, the soil can be expected to contain actinides deposited only by the worldwide fallout of above-ground weapons testing The mean annual precipitation is 800 mm, the mean annual temperature 7 3 °C All sampling locations were selected on a flat area to exclude precipitation runoff The vegetation is permanent grassland, undisturbed by agricultural tillage processes for at least 40 yr

Soil. In the German soil classification system, the soil is classified as Parabraunerde, slightly pseudovergleyt In the U S system, this corresponds to a slightly wet Alfisol, (Aqualf) Alfisols are characterized by an illuvial horizon (B_t) in which silicate clays have accumulated In the topsoil, where the radionuclides investigated are presently localized, the following horizons (German system) were observed in the profile A_h (0–10 cm, organic layer, intermediately decomposed, abundant roots), Al (10–20 cm, yellowish-brown to yellow, abundant roots), B_t (20–40 cm, grayish-brown, few roots) Several physicochemical properties of these soil horizons are given in Table 1 The following methods were used to obtain these values particle size, sieving and sedimentation, total N, Kjeldahl method, organic matter, oxidation of the organic matter by potassium dichromate in sulfuric acid, Ca^{2+} and Mg^{2+}, by exchange versus NH_4, CEC, by exchange versus 1 M NH_4Cl at pH 7

Sampling and Sample Preparation. All soil samples were taken in June 1990 with a frame (50 × 50 cm) at five plots of the grassland within an area of about 5 × 5 m The A_h horizon was subdivided in layers of 0–2, 2–5, and 5–10 cm, the A_l horizon was subdivided in the layers 10–15 and 15–20 cm From the B_t horizon, the layer 20–30 cm was sampled

Before the sequential elution of the actinides, the air-dried soil from each layer was sieved to 2 mm for the removal of stones and roots (ca 10% in the 0–2-cm layer, <3% in the deeper layers) and mixed Subsequently, to obtain a representative sample of each layer, the corresponding layers from each of the five plots were mixed carefully

Sequential Extraction of Pu and Am The sequential extraction of these radionuclides from the soil samples was performed according to Tessier (*19*) A 500-g sample of soil from each soil layer was used for that purpose To facilitate agitation of the aqueous suspensions, the extractions were always performed in batches using 100 g of soil each For the subsequent determination of $^{239+240}Pu$ and ^{241}Am, the resulting five extracts were combined Because the pH of the soil investigated was rather low (see Table 1), carbonates were not present in any soil layer For this reason, the fraction bound to carbonates was not isolated

(i) Readily Exchangeable Ions A 100-g of sample of soil was extracted with 1 L of NH_4OAc, (1 M) at room temperature for 1 h while stirring from above Subsequently, the suspension was first passed through a paper filter (Schleicher & Schuell, 589 Black, coarse grade) and finally through a membrane filter (0 45 μm) The soil was then rinsed with ca 500 mL of distilled water After filtration, this rinse water was added to the above solution phase for analysis

(ii) Bound to Iron and Manganese Oxides The residue from above was extracted with 1 L of 0 04 M NH_2OH HCl in 25% (v/v) acetic acid at 85–95 °C for 6 h with occasional agitation The subsequent separation of the liquid phase and rinsing of the soil were performed as above

(iii) Bound to Organic Matter The residue from above was resuspended in water, stirred, and heated to 80 °C Then H_2O_2 (30%), adjusted to pH 2 with HNO_3, was added very slowly In total, about 750 mL of H_2O_2/100 g of soil was added in 6 h After cooling, 250 mL of 3 2 M NH_4Ac in 20% (v/v) HNO_3 was added, and the samples were agitated for 30 min

(iv) Residual The residual solid contains mainly primary and secondary minerals, which might hold the radionuclides extremely tightly The above residual was therefore treated with 1 L of HNO_3 (1 1) and stirred for 6 h at 80 °C As shown by Veselsky (*21*), Pu and Am from the global fallout are in this way completely liberated from the soil

Determination of Pu and Am $^{239-240}Pu$ and ^{241}Am were determined in the extracts by α-spectrometry subsequent to a radiochemical separation and purification Because of the considerable amounts of natural interfering α-emitters (such as Th) extracted from the large soil samples, rather extensive purification steps are necessary

Pretreatment of the Extracts The chemical composition of the above four extracts (i–iv) is quite different Because, however, the procedure used for the separation of Pu and Am requires that these elements are present in HNO_3 (1 + 1), the extracts were treated before analysis as follows

Fractions i and ii After addition of the yield tracers ^{242}Pu and ^{243}Am, the solution was stirred, and its volume was reduced to 20–30 mL by gentle heating while slowly

adding H_2O_2 (30%, total amount of H_2O_2 used ca. 100 mL) After cooling, 50 mL of HNO_3 (concentrated) was added, the beaker was covered by a watch glass, and the solution was heated gently until no further fumes were visible Finally, the mixture was evaporated to dryness at low heat and taken up in 200 mL of HNO_3 (1 1)

Fraction iii After addition of the yield tracers (see fraction i), excess H_2O_2 was removed by reducing the volume to about 300 mL at low heat The volume was then made up to 1 5 L by distilled water, and the hydroxides were precipitated by the addition of KOH. After filtration, the residue was dissolved in HNO_3 (concentrated) and brought to a volume of 400 mL by the addition of nitric acid to such an extent that the final concentration of HNO_3 was 1 1 (as checked by titration)

Fraction iv After addition of the yield tracers (see fraction i), the volume was first reduced by heating to 400 mL. Subsequently, it was made up to 800 mL by the addition of nitric acid to such an extent that the final concentration of HNO_3 was 1 1 (as checked by titration) The comparatively large final volume was necessary to minimize the formation of precipitates in the extract

Separation of Pu For the radiochemical separation and purification of Pu and Am, we employed commercially available, highly specific extractants supported on an inert substrate A very efficient separation and purification of Pu in environmental samples, using TEVA●Spec, was described by us recently (*22*) For soils, the first step of this procedure consists of treating the sample with boiling nitric acid (1 1), followed by extracting Pu with tridodecylamine (TLA) Because the original extracts (i–iv) were for that purpose converted to HNO_3 (1 1) solutions (see above), Pu can be extracted immediately by using TLA. The subsequent steps for purification of this Pu fraction and the electrodeposition on stainless steel disks are described in detail in ref 22

Separation of Am The above aqueous phase of the TLA extraction was not discarded because it contains Am To purify Am subsequently, the following procedure also using highly specific extractants supported on an inert substrate was developed The aqueous phase of the TLA extraction was evaporated to dryness, and the residue was dissolved in 50 mL HNO_3 (4 M) while heating If, after addition of 80 mL of distilled water the solution was not clear, it was filtered through a membrane filter (1 2 μm), and the residue was dissolved again with HNO_3 While stirring, the pH of the solution was adjusted to pH 9 with a 25% ammonia solution. Am was extracted with freshly prepared Tri-*n*-octylphosphine oxide [TOPO, prepared by dissolving 3 9 g of TOPO in 50 mL of cyclohexane and washing it in a separating funnel first with 50 mL of HCl (8 5 M), then with 50 mL of HNO_3 (6 M), and finally with 50 mL of HNO_3 (0 1 M)] After extracting Am with TOPO for 5–10 min, the aqueous phase was discarded, and the organic phase was washed three times each with 30 mL of HNO_3 (0 1 M) without shaking For the reextraction of Am from the organic phase, 50 mL of HCl (8 5 M) was used This aqueous reextract was shaken for 3 min with 100 mL of diisopropyl ether, and the aqueous phase was collected in an evaporating dish After adding 1 mL of $NaHSO_4$ (0 1 M), the solution was evaporated to dryness The dry residue was disintegrated with HNO_3 (concentrated) and H_2O_2 (30%), dissolved in ca 40 mL of HNO_3 (2 M), and 20 mg of La + 0 5 g of nitrate were added. After making up the solution to 100 mL with distilled water, the hydroxides were precipitated with NH_4OH, separated by filtration, and dissolved in HNO_3 (2 M) Subsequently, the volume was adjusted to 20 ± 1 mL, and the HNO_3 concentration was adjusted to 2 M The solution was then fed at a flow rate of ≤1 mL min^{-1} to a column containing 0 7 g of TRU●Spec (EIChroM Industries, Inc , Darien, IL, particle size, 50–100 μm, dimensions of the column, 18 cm long, inner diameter, 3 76 mm, bed volume, 2 mL) In this way, Am and La remain on the column Other elements were removed by washing the column with 20 mL of HNO_3 (2 M) at the same flow rate Am and La were then stripped with 20 mL of HNO_3 (0 05 M) at a rate of ≤0 5 mL min^{-1}, ref 23) The eluted solution was made up to 40 mL with distilled water, and Am was coprecipitated with lanthanum hydroxide by adding 1 mL of NH_4OH while stirring for 15 min and gentle heating The precipitate was filtered and dissolved overnight in 10 mL of NH_4SCN (2 M)–HCOOH (0 1 M) while stirring For the subsequent separation of Am from La, the solution was fed to a column containing TEVA●Spec (particle size, 80–160 μm, column dimensions as above, also from EIChroM Industries, Inc) at a rate of ≤1 mL min^{-1} The column was then washed at the same rate with 15 mL of NH_4SCN (0 1 M) + HCOOH (0 1 M) The eluate (containing La) was discarded Am was finally stripped with 25 mL of HCl (0 25 M) at a rate of ≤0 5 mL min^{-1}, ref 24) The eluted solution was collected in quartz crucibles, and traces of organic material were destroyed with HNO_3, $HClO_4$, and KNO_3 After fuming with H_2SO_4, Am was deposited on a stainless steel disk at pH 2 in ammonium sulfate solution

α-Spectrometry α-Spectrometry of the Am and Pu isotopes was performed using a 300 mm^2 silicon surface barrier detector (α efficiency 10–20%) The resolution was 40–50 keV fwhm at 4–6 MeV The background counts were ≤5/10 000 min The detection limit for this counting time was about 0 1 mBq of $^{239+240}Pu$ and ^{241}Am

Estimation of Errors and Quality Control The errors (coefficients of variation) of the analytical determinations were generally less than 10% Quality control over the accuracy of the data was assured by analyzing standard reference samples for $^{239+240}Pu$ and ^{241}Am For ^{241}Am, we used the Freshwater lake sediment, NBS Standard Reference Material 4354 Certified value for ^{241}Am, 1 1 Bq kg^{-1}, 95% tolerance level, ±30% Found (mean of four replicate determinations) 1 13 ± 0 22 Bq kg^{-1} (2 σ SD) In the case of $^{239+240}Pu$, Soil-6 from the International Atomic Energy Commission, Vienna, Austria, was used Certified value 1 04 (0 96–1 11) Bq kg^{-1} Found (mean of four replicates) 0 97 ± 0 05 Bq kg^{-1}

Results and Discussion

Total Activity Concentrations of $^{239+240}Pu$ and ^{241}Am. The total activities of $^{239+240}Pu$ and ^{241}Am observed in each soil layer are given in Table 2 They can be obtained either by summation of all the amounts extracted sequentially or, more directly, after extracting these radionuclides completely with HNO_3 (1 + 1) in one step according to Veselsky (*21*) from aliquots of the corresponding soil samples Because the latter values are more accurate, they are given in Table 2 for the total activities Within experimental error, they agreed with the corresponding ones obtained from the sum of the four extracted fractions The data show that the highest activity concentrations for both $^{239+240}Pu$ and ^{241}Am on a "Bq/kg" basis are presently found in the 2–5-cm layer; slightly less was observable in the 5–10-cm layer On a "Bq m^{-2} cm^{-1} thickness" basis, the maximum

TABLE 2

Total Activity Concentrations of $^{239+240}Pu$ and ^{241}Am in Various Layers of Grassland Soil[a]

soil layer (cm)	$^{239+240}Pu$ (mBq kg^{-1})	$^{239+240}Pu$ (mBq m^{-2} cm^{-1})	^{241}Am (mBq kg^{-1})	^{241}Am (mBq m^{-2} cm^{-1})
0–2	330 ± 35	2 2 ± 0 2	100 ± 20	0 66 ± 0 1
2–5	386 ± 32	3 3 ± 0 3	130 ± 25	1 1 ± 0 2
5–10	340 ± 27	3 6 ± 0 3	110 ± 14	1 2 ± 0 1
10–15	160 ± 15	2 0 ± 0 2	57 ± 9	0 72 ± 0 1
15–20	76 ± 10	0 96 ± 0 1	20 ± 4	0 25 ± 0 06
20–30	38 ± 4	0 53 ± 0 1	12 ± 3	0 16 ± 0 05

[a] The errors given are 2σ errors

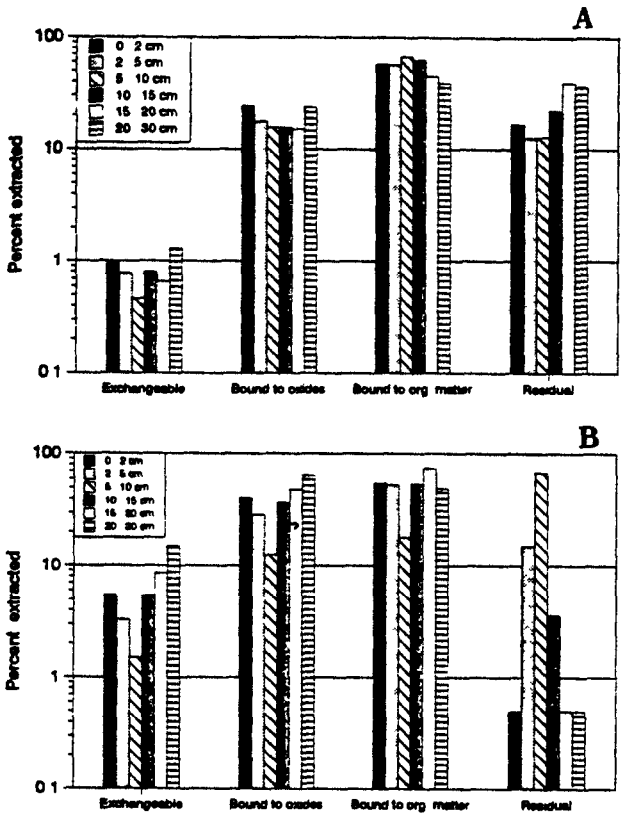

FIGURE 1 Percentages of global fallout $^{239+240}Pu$ (A) and ^{241}Am (B) found in the six layers of the grassland soil for the fractions readily exchangeable, bound to iron and manganese oxides, bound to organic matter, and residual Because the soil did not contain any carbonates, this fraction was not extracted

concentrations for both actinides are in the 5–10-cm layer The total amounts deposited were (summation over all layers) for $^{239-240}Pu$ 55 ± 6 Bq m^{-2} and for ^{241}Am 18 ± 2 Bq m^{-2} These values agree well with other observations in Germany (*25–27*)

Association of Pu and Am with Soil Components. The fractions of $^{239-240}Pu$ and ^{241}Am found in the four extracts of the six soil layers are each shown in Figure 1 They are given in percent with respect to the total amount of each radionuclide in the corresponding soil layer If one compares first the results obtained for $^{239+240}Pu$ and ^{241}Am for the fraction readily exchangeable ions, it is obvious that these values for each soil layer are considerably higher for ^{241}Am (1 5–15%) than for $^{239+240}Pu$ (0 5–1%) It can also be seen that the values for this fraction exhibit a minimum for both radionuclides in the 5–10-cm layer, i e , in the lower half of the A_h horizon. This might explain why the observed total activity concentrations of these radionuclides are still relatively high in this layer (see Table 2) On their passage through the soil, both actinides are obviously relatively immobile in this layer and are thus accumulated there to some extent

If one examines the bound to oxides fraction, it becomes apparent that a substantial fraction of these radionuclides is attached to it. 15–24% of $^{239+240}Pu$ and 12–64% of ^{241}Am Am thus seems to exhibit a somewhat higher tendency for the oxides than Pu

The soil component to which the largest amounts of these actinides are attached is the soil organic matter fraction Here one finds, depending on the soil layer, 39–67% of $^{239+240}Pu$ and 18–74% of ^{241}Am The differences between $^{239+240}Pu$ and ^{241}Am are however rather small for most soil layers Only in the 5–10-cm layer is Pu significantly higher enriched (67%) than Am (18%) The reason why Am in this layer is nevertheless hardly available for ion exchange (see readily exchangeable fraction) can be seen from the residual fraction Here, we observe that this radionuclide is in the 5–10-cm layer to a comparatively large extent (68%) attached to the residuals, i e , the soil minerals In the case of $^{239+240}Pu$, the fraction bound to residuals is much smaller for the 5–10-cm layer (only 17%) For this actinide, however, the fraction bound to organic matter is comparatively high in this layer This explains why the corresponding readily exchangeable fraction is again small

In contrast to the 5–10-cm layer, one observes in the first layer (0–2 cm) and in the deeper soil layers (15–20 and 20–30 cm) very small values for the residual fraction of Am (≤0 5%) as compared to Pu (17–39%) This may be understood by considering that the types of the soil minerals to which the radionuclides are attached are probably quite different in the various soil layers The large differences of the residual fraction between Am and Pu thus demonstrate that some of these minerals obviously exhibit quite different sorption properties for Am and Pu

The rather low values observed for the readily exchangeable fraction of Pu in contaminated soils are in agreement with earlier observations, where by using various extractants values of ≤3% were found for most soils (*5*) The fact that rather similar values were found in the present investigation show that after a period of 30–40 yr Pu is attached tightly to the various soil constituents Various earlier experiments also indicated that Pu is sorbed most extensively by the inorganic mineral phase of the soil (*5*) and to a much lesser extent by soil organic matter More recently, Livens et al (*28*) observed that about 60% of Pu is held by organic matter In the present investigation, the fraction to which most Pu was attached for most soil layers was also the soil organic matter fraction (>57%, with exception of the two layers below 15 cm) Because however no earlier comparable experiments on this soil exist, it cannot be decided whether this was already the case in earlier years or whether it is due to a long-term redistribution of Pu in the soil

Analogous experiments for fallout ^{241}Am in the soil seem not to be available Determination of binding constants of Am to humic acids indicate that this actinide is also bound strongly to soil organic matter (*28–31*) It was suggested, however, that Am should be more mobile than Pu since hydrolysis of Am(III) occurs more readily than hydrolysis of Pu(IV), see refs 28 and 29 This might be the reason for the significantly higher values observed in the present case for the readily exchangeable fraction of Am as compared to those of Pu

A detailed knowledge of the association of Pu and Am with various soil components is required (i) for modeling the long-term behavior of these elements in the soil with respect to transport processes and plant uptake and (ii) for developing effective remediation procedures for contaminated soils The present results show that even though Pu and Am exhibit a similar general pattern for the association with the most important soil components, significant differences exist nonetheless (see above) and should be considered in realistic models Especially in the case of Am, large differences are observable for different soil layers, notably for the readily exchangeable and the residual fraction (see Figure 1) This suggests that the association of Am with the various soil components responds more sensitively to differences in its physicochemical environment than Pu As a result, modeling the behavior of Am in the soil will probably be more complicated than that of Pu

From the results obtained for the readily exchangeable fraction, one might expect that Am should be more mobile than Pu For the present soil, this is not observed By evaluating for the same soil the observed depth profiles of these radionuclides with a compartment model that also takes into account the known deposition history of these radionuclides and the ingrowth of ^{241}Am from ^{241}Pu, almost identical migration rates were found for both actinides, even though they were different in the various soil layers (*20*) This suggests that possibly the readily exchangeable fraction as determined with the procedure described (elution with 1 M NH_4OAc at pH 8 2) is not quite adequate to characterize the relative mobilities of these elements in the soil This would not be too surprising because (i) the chemical composition of an in-situ soil solution is quite different with respect to the concentration and nature of the competing ions, (ii) differences in the kinetics of the sorption/desorption processes of different elements are not disclosed by sequential extraction procedures, even though they might be of great importance for the dynamics of the transport process in the soil (*32–34*), and (iii) the mobility of Pu might be influenced also by microbially catalyzed reduction processes (*35*) Alternatively, it is also conceivable that in the present soil Pu and Am are associated so tightly with the soil constituents that the vertical transport of these actinides occurs to a considerable extent in the form of colloids or very small soil particles or by bioturbation (*37*) In this case, the migration of these elements would only be to a small extent the result of nuclide-specific leaching processes (chromatographic transport) In any case, care has to be taken when drawing conclusions on the availability of actinides for migration processes from measurements of only the readily exchangeable fraction Future investigations on other soils should help to better understand these processes

Various engineering approaches exist for the reclamation of chemically degraded land For metals, the most important methods conceivable are in situ immobilization, in situ mobilization with controlled drainage, or soil washing with water and inorganic or organic solvents to remove part of the pollutants in the excavated soil (*38*) The present results suggest that immobilization or washing the soil with water will hardly be very effective for Pu- and Am-contaminated soils because these elements (especially Pu) are already largely immobilized Leaching processes to mobilize and remove these actinides from the soil will be most effective for Pu if the agent dissolves soil organic matter This will be, however, not quite as effective for Am-contaminated soils because in this case a substantial fraction of Am will remain on the sesquioxides of the soil The residual fraction cannot be eliminated by a realistic soil remediation procedure because it would involve an almost complete destruction of the soil For the present soil, our results then suggest that at least 10–30% of Pu and 0 5–60% of Am (depending on the soil layer) will still be present after a leaching process However, it can be expected that this fraction will be essentially unavailable for plant uptake for a long time

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