

DIPEX: A New Extraction Chromatographic Material for the Separation and
Preconcentration of Actinides from Aqueous Solution

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Abstract

A novel extraction chromatographic resin consisting of a liquid diphosphonic acid supported on an inert polymeric substrate for the sorption of actinides from strongly acidic chloride media is described. The resin is shown to exhibit stronger affinity for actinides in the tri-, tetra-, and hexavalent oxidation states and superior selectivity for americium (III) over aluminum (III) or iron (III) than an analogous chelating ion exchange resin containing chemically bonded geminally-substituted diphosphonic acid functionalities. These properties, along with the comparative ease of recovery of sorbed actinides, make the resin readily applicable to the separation and preconcentration of actinides, as a group, from complex matrices such as soils and bioassay samples.

Keywords: actinides, extraction chromatography, preconcentration, diphosphonic acids

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1. Introduction

The separation and preconcentration of radionuclides from environmental and bioassay samples for subsequent determination is complicated by the presence of a number of the common constituents of such samples, among them silica, various metal ions (*e.g.*, Al(III), Ti(IV), Bi(III), and Fe(III)), and certain anions, particularly phosphate. As a result, the separation of actinides, lanthanides, and other species of environmental interest (*e.g.*, Ra) from these samples generally involves time-consuming, expensive, and sometimes hazardous procedures. The separation of actinides from the large excess of matrix substances present in urine, feces, or soil samples, for example, can involve a cumbersome combination of precipitation reactions, extraction, and ion exchange (1).

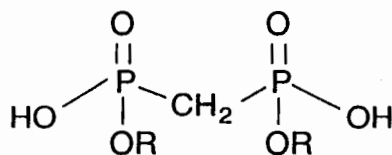
One class of neutral, bifunctional organophosphorus extractants, the alkyl(phenyl)-N,N-dialkylcarbamoylmethylphosphine oxides (abbreviated as CMPO's) has been found useful in the recovery of actinides and lanthanides from acidic solutions containing these and other metal species (2). In combination with tri-n-butyl phosphate (TBP), one of these extractants, the octyl(phenyl)-N,N-diisobutyl- derivative, has provided the basis of an extraction chromatographic resin capable of selectively recovering actinides from a number of complex matrices (1, 3, 4). This material, referred to as the TRU™ resin, has a number of attractive features, among them the possibility of the sequential elution of individual actinides. The sorption of actinides by this resin is not particularly strong, however, when significant quantities of complexing anions (*e.g.*, fluoride, phosphate, or oxalate) are present in the sample (3). This presents a particular problem in attempts to recover actinides from soil samples, as hydrofluoric acid is generally added to dissolve the silica present.

Recent work in this laboratory has led to the development of a new chelating ion exchange resin, Diphonix®[®], containing geminally-substituted diphosphonic acid groups chemically bonded to a styrene-based polymer matrix. This resin has been shown to exhibit extraordinarily strong affinity for the actinides, particularly those in the tetra- and hexavalent oxidation states. This strong affinity for actinides, together with the relatively high acidity of the gem-diphosphonic acid group, enable the resin to sorb actinides efficiently from very acidic solutions. This behavior has been attributed to the ability of the resin to chelate actinides through either ionized or neutral diphosphonic acid ligands, leading to metal complexes of high stability (5).

Because of its strong retention of actinides, this resin has found application in the treatment and characterization of mixed and transuranic wastes (6) and in analytical procedures for the separation and preconcentration of actinides from a variety of biological and environmental samples (7, 8). Two problems have been encountered in

the use of the Diphonix resin in these procedures, however. First, although the uptake of Am(III) by the resin is higher than that obtained with conventional cation exchange resins over a wide range of mineral acid concentrations, Am (III) distribution ratios from 1-10 M HNO₃ are only 10²-10³ (5), making americium uptake susceptible to competition for active sites on the resin from other cations present in the sample at much higher concentrations. For example, Fe(III) and Al(III), important constituents of soils, can compete with Am(III), making it necessary to reduce their concentration by sample dilution, addition of fluoride ion (for Al), or reduction to a less extractable species (for Fe) (5). Next, tetra- and hexavalent actinides, as well as trivalent iron, are so strongly retained by the resin that they can only be removed by concentrated (≥ 0.5 M) solutions of water-soluble diphosphonic acids, compounds which contain the same functional group as the resin. Before further processing of the actinides, the aqueous diphosphonic acid must be decomposed. This decomposition, however, yields solutions containing high concentrations of phosphoric acid, an acid whose presence can lead to problems in subsequent separation steps. One possible alternative involves destroying (via wet oxidation) the entire bed of resin on which the actinides are sorbed. Wet oxidation of several grams of resin, although feasible, is time and reagent-consuming, however, because the polymeric backbone of the resin must also be destroyed.

In this report, we demonstrate that the problems of insufficient retention of trivalent actinides and difficult actinide stripping/recovery can be largely overcome by employing an extraction chromatographic (9-14) resin (hereafter referred to as Dipex™) consisting of a new compound, bis(2-ethylhexyl)methanediphosphonic acid (**1**, with R = 2-ethylhexyl), H₂DEH[MDP], supported on an inert polymeric substrate.



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This compound contains the same diphosphonic acid functional group as the Diphonix resin, but two of the four ionizable hydrogens have been replaced by a C-8 alkyl group to make the molecule more lipophilic. Solutions of H₂DEH[MDP] in an organic diluent can be regarded as a liquid Diphonix resin and thus, would be expected to exhibit an affinity for actinides comparable to that of Diphonix itself. The extraordinary affinity for

actinides of *o*-xylene solutions of H₂DEH[MDP] has, in fact, been confirmed in a recent solvent extraction study (15).

2. Experimental

2.1 Materials.

Bis(2-ethylhexyl)methanediphosphonic acid was prepared and purified as reported previously (15). The pure compound (MW = 400.44, $\rho = 1.05$ g/L) is a colorless, viscous oil which is insoluble in water, but soluble in organic diluents.

The Dipex resin was prepared by impregnating 20-50 μm particle size Amberchrom CG-71ms acrylic ester resin beads (16) (Supelco, Bellefonte, PA) with H₂DEH[MDP]. The impregnation procedure was essentially the same as that described previously (1, 17, 18), but isopropanol, not methanol, was used to dissolve the extractant. The resultant material, which contained 40% (w/w) of the extractant, had a picnometric density of 1.11 g/L. This material is now commercially available from EiChroM Industries, Inc. (Darien, IL).

The Diphonix resin used in this study was obtained from EiChroM Industries. The resin was 50-100 mesh and was received in the H⁺ form.

The radioisotopes ⁴⁵Ca, ⁵⁹Fe, and ¹⁵²⁻⁴Eu were obtained from Isotope Products Laboratories (Burbank, CA). In the uptake experiments involving Fe(II), the ⁵⁹Fe tracer was reduced with ascorbic acid. ²³¹Pa was obtained from ANL stocks and ²²⁷Ac milked from it on an AG-MP1 anion exchange column (Bio-Rad Laboratories, Richmond, CA) using 8 M HCl. ²²³Ra was milked from ²²⁷Ac sorbed on an extraction chromatographic column containing bis(2-ethylhexyl) phosphoric acid (HDEHP) (19) with 0.01 M HNO₃. ²⁴¹Am, ²³³U, ²³⁹Pu, and ²³⁰Th were obtained from ANL stocks. ²³³U and ²³⁰Th were purified by standard procedures prior to the extraction experiments. Plutonium was maintained in the tetravalent oxidation state by making its solutions 0.05 M in sodium nitrite. ²³⁹Np was milked from ²⁴³Am using the procedure described previously (20). In uptake experiments involving ²³⁹Np, solutions were made ca. 0.01 M in Fe(II) and 0.11 M in hydroxylammonium nitrate to ensure that neptunium would be present as Np(IV). The ferrous nitrate stock solution (0.2 M) was prepared using ferric nitrate and a large excess of hydroxylammonium nitrate (2.2 M). The radioisotopes were used only at tracer levels.

Hydrochloric acid solutions were prepared using the UltrexTM acid (J.T. Baker Chemical Co., Phillipsburg, NJ) and water from a Milli-Q2 purification system. All other reagents were of analytical grade and were used without further purification.

2.2. Procedures.

Uptake experiments. The sorption of various ions by the Dipex resin from hydrochloric acid solutions was measured by equilibrating a known volume of a tracer-spiked acid solution of appropriate concentration with a known weight of resin following the same procedure reported previously (17, 18, 20). A one hour mixing time was used, a time longer than that required for the attainment of equilibrium. After centrifugation, an aliquot of the solution was withdrawn and filtered using a syringe equipped with a PVDF (polyvinylidene difluoride) membrane filter (0.2 μm pore size) with a Luer lock (Whatman, Inc., Clifton, NJ).

Counting of aqueous samples was performed with a Packard Cobra Autogamma counter (for gamma emitters) or via liquid scintillation (for alpha and beta emitters). Samples containing ^{223}Ra or ^{227}Ac were counted (alpha or gamma, respectively) after the establishment of secular equilibrium. (This requires several hours because of the 36.1 minute half-life of ^{211}Pb .) In experiments involving the uptake of Al, Bi, or Ti, the aqueous metal concentrations before and after equilibration with the Dipex resin were determined by ICP-AES. Weight distribution ratios, D, were calculated as follows:

$$D = ((A_0 - A_f) / A_f) (V/w)$$

where A_0 and A_f are the aqueous phase activity (cpm) before and after equilibration, respectively, w is the weight of resin (g) and V is the volume of the aqueous phase (mL). When very high values of D were expected, the amount of resin used in the distribution experiments was kept as small as possible (~ 0.2 mg) in order to leave a measurable activity in the aqueous phase. In all cases, however, the amount of metal was chosen so that the resin was always present in large excess. In this way, resin saturation was avoided. Duplicate experiments showed that the reproducibility of the D measurements was generally within 10% for values up to $\sim 10^4$. Above this, higher D values were accompanied by lower reproducibility, up to an uncertainty interval of about 50% for the highest D values. The D values measured in the uptake experiments with the Dipex resin were converted into capacity factors (*i.e.*, the number of free column volumes to peak maximum), k' values, by dividing the distribution ratios by 1.94. This factor includes the conversion of the weight distribution ratios to volume distribution ratios, and the ratio of the stationary phase to the mobile phase volume, V_s/V_m . For packed columns of the Dipex resin, this ratio was determined to be 0.196. (Details of this conversion can be found in a previous publication (17)).

Uptake kinetics. The experiments on uptake kinetics were performed using the same discontinuous technique described previously (21). Briefly, a series of 10-mL screw-cap test tubes, each containing the same (to within 10%) weighed amount of resin, and a 1.5 x 8 mm magnetic microbar, were used for each kinetic run. Time zero was taken as the time at which a known volume (typically 1 mL) of a solution containing a radiotracer was introduced into the test tubes and stirring was started. At various intervals, one of the test tubes was quickly centrifuged, a sample of the aqueous phase withdrawn from the tube and filtered, and the weight distribution ratio of the metal, D , determined as described above. In this way, a plot of the time dependence of D was obtained in which each experimental point is the result of the measurement performed on a single test tube.

Resin capacity. The capacity of the Dipex resin for various metal species was measured in batch experiments in which a weighed amount of resin (~20 mg) was stirred for several hours with 1 mL of a 0.1 M solution of the metal in 1 M HCl (for Th(IV), U(VI), Nd(III), and Fe(III)) or 0.01 M HCl (for Ca and Ba). The amount of metal ion taken in each experiment was such as to have a calculated five-fold excess of metal over extractant. After centrifugation and filtration (following the procedures described for uptake measurements), samples of the supernatant were analyzed by ICP-AES. The amount of metal sorbed by the resin was calculated by mass balance.

Resin stability. The resistance of the Dipex resin to extractant loss induced by acid washing was evaluated by passing aliquots of 2 M hydrochloric acid through a 1 g (ca. 3 mL) bed of the material and determining the phosphorus content of the column effluent by ICP-AES.

3. Results and Discussion

3.1. Kinetics of metal uptake.

Figure 1 depicts the kinetics of uptake of tracer levels of Am(III) and Fe(III) by the Dipex resin under a number of different conditions. In all cases, the equilibrium value is reached after about 20 minutes. Thus, the Dipex resin exhibits somewhat slower metal uptake kinetics than other extraction chromatographic resins developed previously in this laboratory. The TRU™ and U/TEVA™ resins, each of which is also based on an organophosphorus extractant, have been shown, for example, to require only 10 minutes to attain equilibrium (18). The slower kinetics observed for the Dipex resin were not entirely unexpected, however, because the extractant employed (undiluted H₂DEH[MDP]) is a very viscous oil.

3.2. Uptake of metal species.

Figure 2 depicts the acid dependency of the uptake of several representative actinides from 0.01 to 10 M HCl. As can be seen, retention of the actinides by the Dipex resin is extremely high, a result expected from analogous studies of the Diphonix resin (20) and of the extraction behavior of H₂DEH[MDP] in o-xylene (15). The shape of the acid dependency curves is also consistent with earlier results obtained with the Diphonix resin in HCl media (20). One noteworthy feature of these results is the remarkably strong retention of Am(III). Its k' values, in fact, exceed those of each of the other actinides up to 0.5 M HCl. Although the capacity factors for Am(III) decline rapidly at higher acid concentrations, they nonetheless remain well above 1000 over nearly the entire range of acidities examined.

Figure 3 shows the acid dependencies of the uptake of a number of non-actinide metal ions relevant in various analytical procedures involving environmental and bioassay samples. Of the metals investigated, Eu(III) and Fe(III) show the highest k' values, as expected from the behavior of lanthanides and actinides on the Diphonix resin (22) and the known affinity of the diphosphonic ligand for Fe(III) (15, 22). As reported previously for the Diphonix resin (5, 22), however, if Fe(III) is reduced to Fe(II), its k' values become much smaller. It is clear from the Eu(III) data that lanthanides will follow Am(III) in separation schemes involving Dipex.

Bismuth (III) and Ti(IV) have been included in Figure 3 because they are common and troublesome components of fecal and soil samples. As can be seen, the retention of Ti(IV) by the Dipex resin is very high over the entire acidity range. (Note that the k' values reported in Figure 3 for Ti(IV) are only a lower limit dictated by the sensitivity limit of the ICP-AES method.) In contrast, Bi(III) is not strongly sorbed from HCl solution by the Dipex resin, a result of the strong chloride complexes formed by this ion. Similar results were reported previously with the Diphonix resin (22).

The behavior of the alkaline earth cations on the Dipex resin is essentially the same as that observed previously with the Diphonix resin, and is consistent with the results of solvent extraction studies using o-xylene solutions of H₂DEH[MDP]. Little if any selectivity is exhibited among the alkaline earths, an aspect of the chemistry of diphosphonic acids which has been discussed previously (15, 23).

Figure 4 shows a comparison of the acid dependencies of Am(III), Ac(III), and Al(III) uptake by the Diphonix and Dipex resins. Here, the data are reported as V_{max}, the number of free column volumes to peak maximum. (For the Dipex resin, V_{max} is equal to k', while for the Diphonix resin, it was calculated by multiplying the weight distribution ratios by the Diphonix bed density (0.304 g of dry resin/mL bed volume))

(22). Although the selectivity sequence of the two resins for the three ions is the same, Al(III) is significantly less strongly retained and Am(III) dramatically more strongly retained on the Dipex resin. A likely explanation of this phenomenon is that in the Dipex resin, the diphosphonic acid ligands are not attached to a rigid polymeric network and thus, can more easily rearrange around a given metal ion to satisfy its coordination requirements. As a result, the extraordinary complexing power of the diphosphonic acid ligand can be better exploited with an extraction chromatographic resin than with a polymeric chelating ion exchange resin.

The data of Figure 4 have two important practical consequences. First, because the separation factor of Am over Al is so large on the Dipex resin, little interference should be expected in the uptake of actinides from samples containing large concentrations of aluminum. Next, the high retention of Ac(III), together with the comparatively low k' values of Ra (II) (Figure 3) make possible the separation of ^{228}Ra from its ^{228}Ac daughter. This property could be exploited for the development of analytical procedures for the determination of ^{226}Ra and ^{228}Ra in environmental samples.

3.3. Resin capacity

Table 1 summarizes the results of capacity measurements for several metal ions on the Dipex extraction chromatographic resin. (The values expressed in mg/mL of bed were calculated from those expressed in mg/g resin using the measured bed density value of 0.352 g/mL.) It is clear from these data that the capacity values are sufficiently high to permit efficient uptake of actinides by the resin. With the exception of Fe(III), however, the theoretical capacities (based on the metal:extractant stoichiometric ratios required for neutralization of charge) are not reached under the experimental conditions. There are several possible reasons for this behavior. First, the undiluted extractant is probably highly aggregated through intra- and intermolecular hydrogen bonding and thus, a portion of it may not be available for interaction with metal ions. Also, the complexes formed at high metal ion loadings are probably polymeric, so that their average composition may not correspond to the one based on charge neutralization. Finally, the undiluted extractant is a very viscous oil, probably making diffusion of the metal complexes toward the interior of the resin beads very slow.

3.4. Resin Stability.

Extraction chromatography typically involves contacting a relatively small volume of a highly dispersed organic extractant having some finite water solubility with a much larger volume of aqueous phase. As a result, the possibility of extractant (*i.e.*, stationary phase) loss and the accompanying deterioration in column performance must be considered for any new resin. For this reason, a column of the Dipex resin was

subjected to washing with a series of aliquots (4 x 25 FCV, followed by 4 x 100 FCV) of 2 M hydrochloric acid and the effluent analyzed to determine its phosphorus content. The loss of extractant was not found to be significant, averaging less than 4% per 100 FCV over the range examined. Most of this loss (nearly 60%) occurred in the first 25 FCV of rinsing. Because the working capacity of the resin (*i.e.*, the maximum recommended loading) does not normally exceed 20% of its total capacity, a loss of this magnitude would not be expected to have any appreciable effect on the performance of the resin in an ordinary run.

3.5 Matrix effects.

Cations. Figure 5 summarizes the effect of increasing concentrations of Ca(II), Al(III), Fe(III), and Fe(II) on the k' value of Am(III) on the Dipex resin at various acidities. As expected, the effect of high concentrations of Ca(II) on the retention of Am(III) is not significant. The effect of Al(III) addition is more pronounced, but this effect is much less than that observed when Am(III) is sorbed on the Diphonix resin (24). Moreover, the matrix effect due to Al(III) can be further reduced by addition of hydrofluoric acid. The presence of Fe(III) leads to a significant decrease in the retention of Am(III), as expected from the data of Figures 2 and 3. This interference with actinide uptake by the Dipex resin is the single most serious matrix effect. It can easily be minimized, however, by the addition of a reducing agent capable of converting Fe(III) to Fe(II) (*e.g.*, ascorbic acid). The effectiveness of this approach in minimizing the effect of iron on Am(III) uptake by the resin is clearly illustrated in Figure 5, which shows that Fe(II) concentrations of up to 0.4 M have little effect on Am(III) retention. Similar results with the Diphonix resin have been reported previously (5, 24).

Anions. Figure 6 shows the effect of HF on the retention of titanium (IV) and representative actinides in the tri-, tetra-, and hexavalent oxidation states. The data indicate that, although the k' values of U(VI) and Np(IV) decline rapidly at the highest acid concentrations, up to ~2 M HF can be tolerated without any serious adverse effect on the retention of actinides. These results are consistent with those obtained previously with the Diphonix resin (24); their semi-quantitative interpretation based on known formation constants for actinide fluoride complexes has been given previously (25). Undoubtedly, similar conclusions also apply for the Dipex results.

Particularly important is the behavior of Ti(IV), a potential interferent in the uptake of actinides (Figure 3). As can be seen, in the presence of sufficient hydrofluoric acid, the k' values of Ti(IV) are reduced sufficiently (because of the formation of anionic fluoride complexes) that the presence of titanium no longer constitutes a problem. Other metal ions which form strong anionic fluoride complexes (*e.g.*, Zr(IV) and Al(III)) are

expected to behave in the same way. Thus, HF can be used to complex potential cationic interferents while having little detrimental effect on the retention of the actinides on the Dipex resin. In the case of soil samples, which always contain siliceous material, the fact that the Dipex resin is insensitive to high concentrations of hydrofluoric acid makes possible the addition of sufficient HF to convert the silica to water-soluble H_2SiF_6 . This procedure eliminates the need to volatilize silicon as gaseous SiF_4 , with obvious benefits to the environment.

Figure 7 shows the effect of increasing concentrations of sulfuric and phosphoric acids on the retention of Np(IV) by the Dipex resin. (Np(IV) was chosen for these experiments because similar experiments conducted with the Diphonix resin had indicated that tetravalent actinides were the most affected by the presence of these acids (24, 25).) The results indicate that the affinity of the Dipex resin for the tetravalent actinides is so high that even in the presence of 4 M acid, the k' values remain high enough for their efficient separation from the sample matrix. The rationale for this behavior has been described previously for the Diphonix resin (25). Undoubtedly, this explanation applies to the Dipex resin as well.

3.6. Actinide recovery.

It has been reported previously (5, 20) that the only way to efficiently recover actinides sorbed on Diphonix resin is to use as the stripping agent water-soluble diphosphonic acids, compounds which contain the same functional group as the resin. This should also apply to the removal of actinides sorbed on the Dipex resin, although the higher affinity of Dipex for the actinides could make stripping more difficult. Figure 8 reports the uptake (expressed as weight distribution ratios, D) of representative actinides and Fe(III) from solutions containing 1-hydroxyethane-1,1-diphosphonic acid (HEDPA), an inexpensive and commercially available stripping reagent, by the Diphonix and Dipex resins. The data confirm that stripping the actinides from Dipex resin is indeed more difficult. Even a 1 M solution of HEDPA, for example, would not remove the tetravalent actinides from the resin in a few column bed volumes.

With the Diphonix resin, the HEDPA stripping solution (usually 0.5 M) is decomposed through wet oxidation or pyrolysis to phosphoric acid, and the actinides are co-precipitated into a calcium phosphate matrix. The calcium phosphate is then dissolved in nitric acid and further processed for the separation of the individual actinides (7). An alternative method of recovery is to extrude the resin bed from the column and decompose the resin in much the same way as the HEDPA. Both of these procedures, however, are time-consuming and cumbersome. An alternative, which provides a simple means of recovering the actinides, is possible with the Dipex resin. That is, rather than

stripping the actinides with HEDPA, one can remove the entire stationary phase from the inert support with an alcohol (*e.g.*, isopropanol). Because the volume of H₂DEH[MDP] is only ~15% of the column bed volume, a 1 mL bed volume column would contain only ~150 μ L of H₂DEH[MDP]. After evaporation of the alcohol, this small amount of material (containing the H₂DEH[MDP] and sorbed actinides) can be readily destroyed. The actinides can then be recovered from the resulting phosphoric acid residue by adding nitric acid and loading the solution onto one of the various actinide-selective extraction chromatographic columns described previously (1, 3, 4, 7, 18). Preliminary experiments have shown that 5-10 free column volumes of isopropanol quantitatively remove the stationary phase from a Dipex column and that the H₂DEH[MDP] residue can be destroyed by four treatments with 30% H₂O₂ in the presence of a sodium vanadate catalyst.

4. Conclusions

An extraction chromatographic resin consisting of bis(2-ethylhexyl)methane diphosphonic acid sorbed on an inert polymeric support provides a simple and efficient method for the isolation of actinides from aqueous solution. Even trivalent actinides, traditionally the least extractable of actinides, are very strongly retained by the resin. Comparison of the resin to the analogous polymeric chelating ion exchange resin (Diphonix) indicates that the extraction chromatographic material exhibits stronger affinity for actinides and superior Am/Fe and Am/Al selectivity. In addition to its remarkable affinity for the actinides, the Dipex resin has other attractive features, among them insensitivity to high concentrations of hydrofluoric acid (which facilitates actinide separations from potential interferents such as Al and Ti) and ready recovery of sorbed actinides by alcohol stripping and wet oxidation of the stationary phase. These properties can be exploited in the separation and preconcentration of actinides (as a group) from complex matrices such as bioassay samples, soils, and other environmental samples. Figure 9 illustrates one possible application, the preconcentration of Am(III) from a sample of river water for subsequent determination. As can be seen, sorption of the metal is quantitative up to a sample volume/resin mass ratio of 4000 (250 mg resin/L of sample). Complete procedures for the separation and preconcentration of actinides from a variety of samples are currently under development and will be the subject of a future publication.

Acknowledgments

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Table 1. Capacity of the Dipex resin for selected metal ions

<u>Metal ion</u>	<u>Capacity (mg/g resin)</u>	<u>Capacity (mg/mL bed)</u>	<u>Extractant:metal mole ratio</u>	
			<u>Theoretical</u>	<u>Experimental</u>
Th(IV)	86.1	30.3	2	2.7
U(VI)	145.7	51.3	1	1.6
Nd(III)	45.4	16.0	1.5	3.2
Fe(III)	32.1	11.3	1.5	1.7
Ca(II)	45.0	15.8	1	2.7
Ba(II)	45.0	15.8	1	3.0

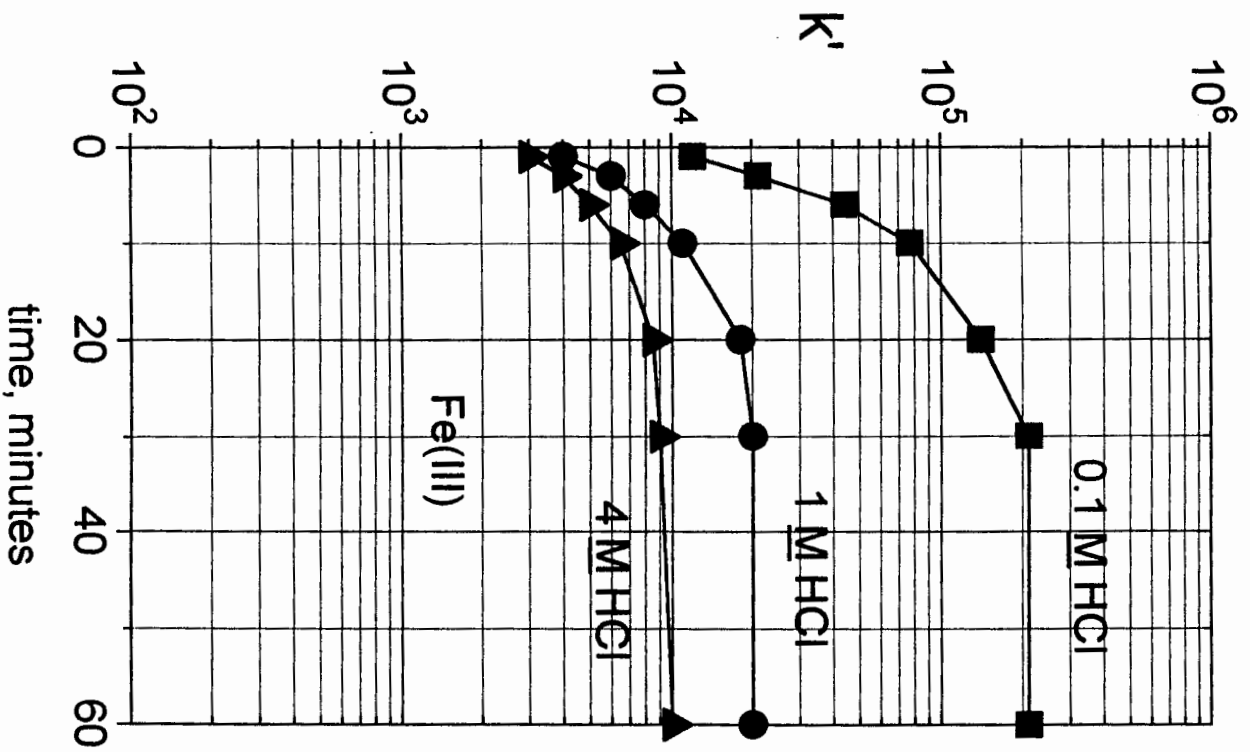
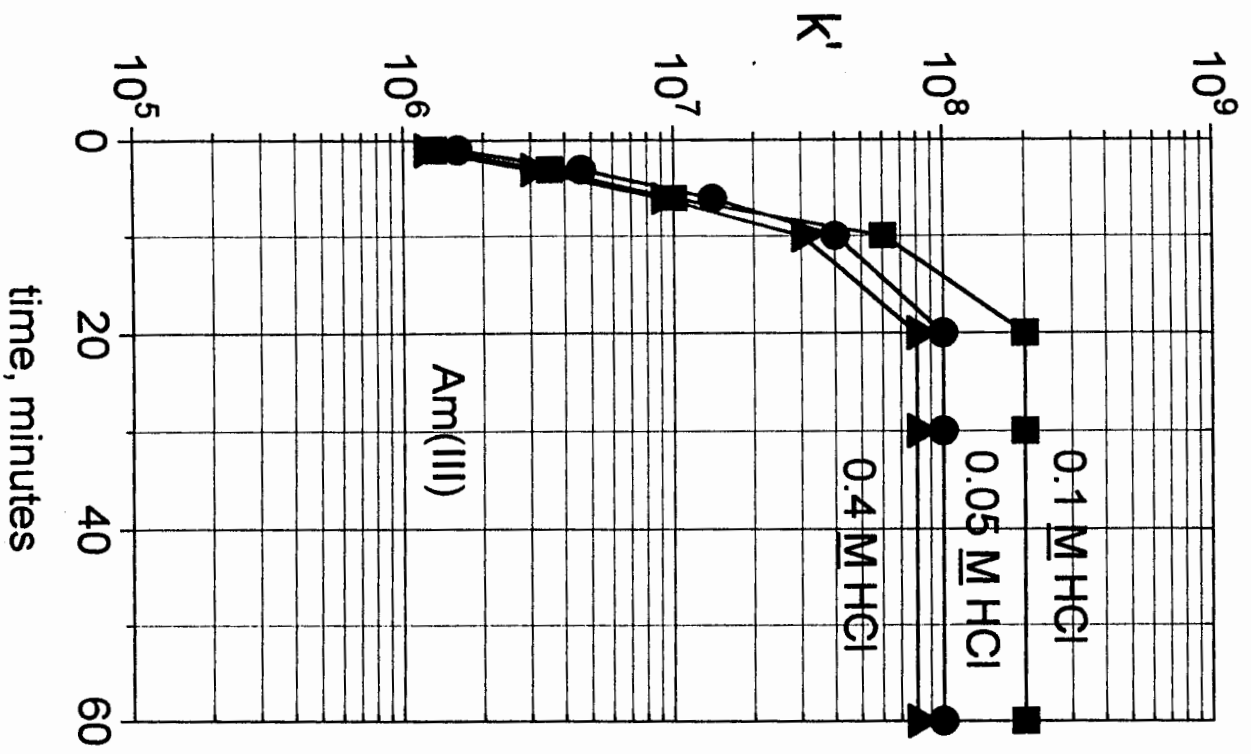
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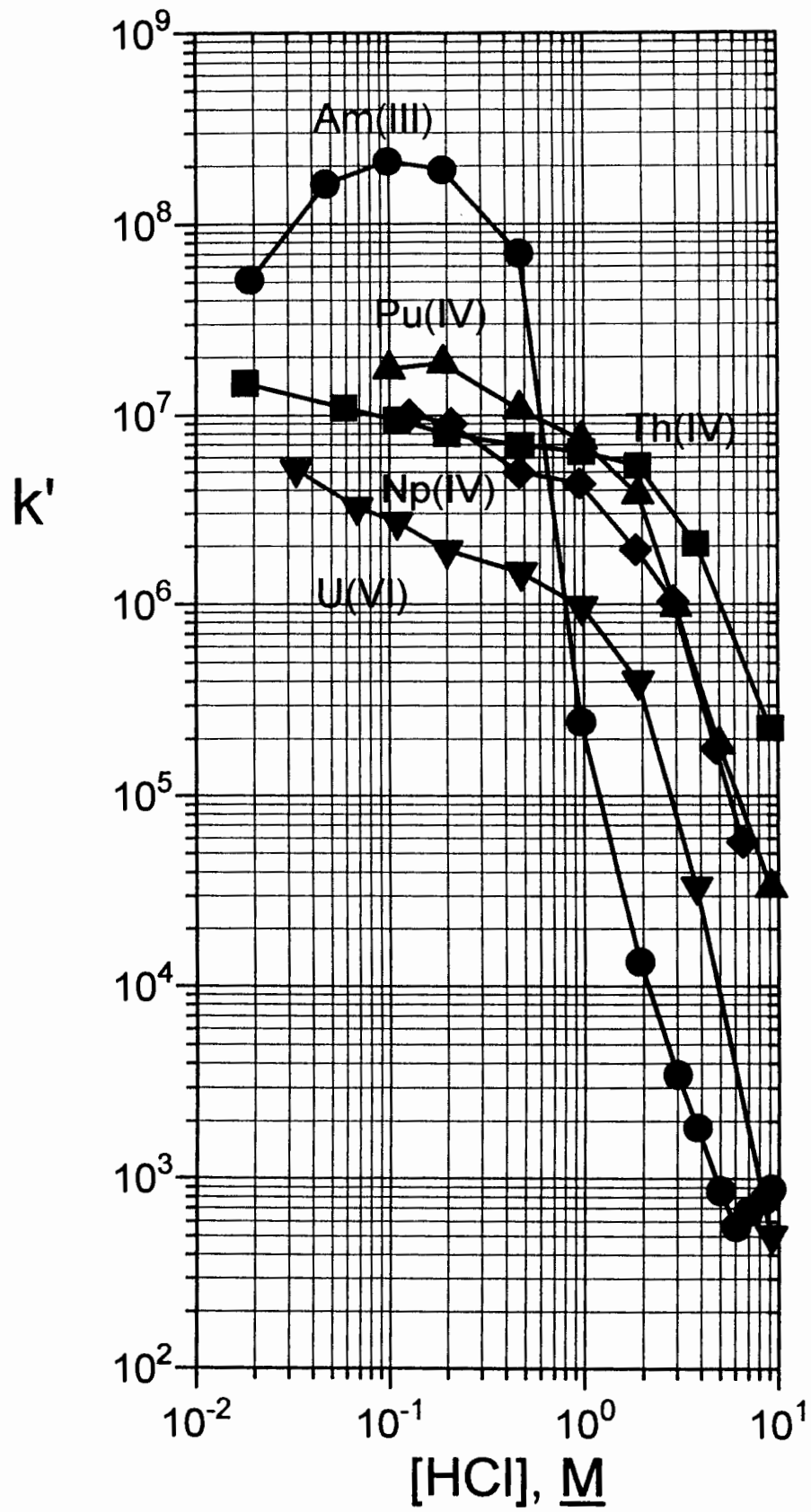
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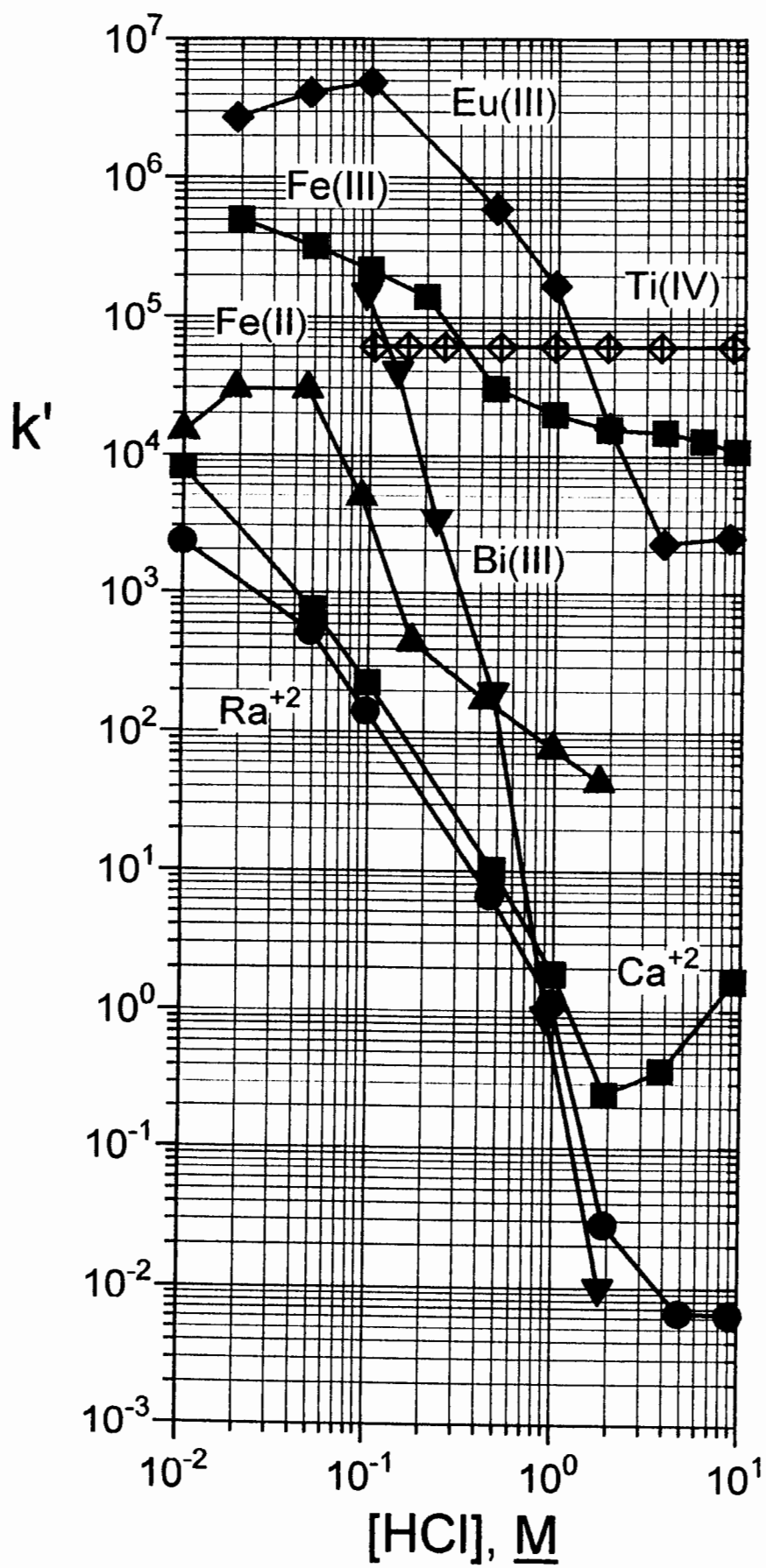
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Figure Captions

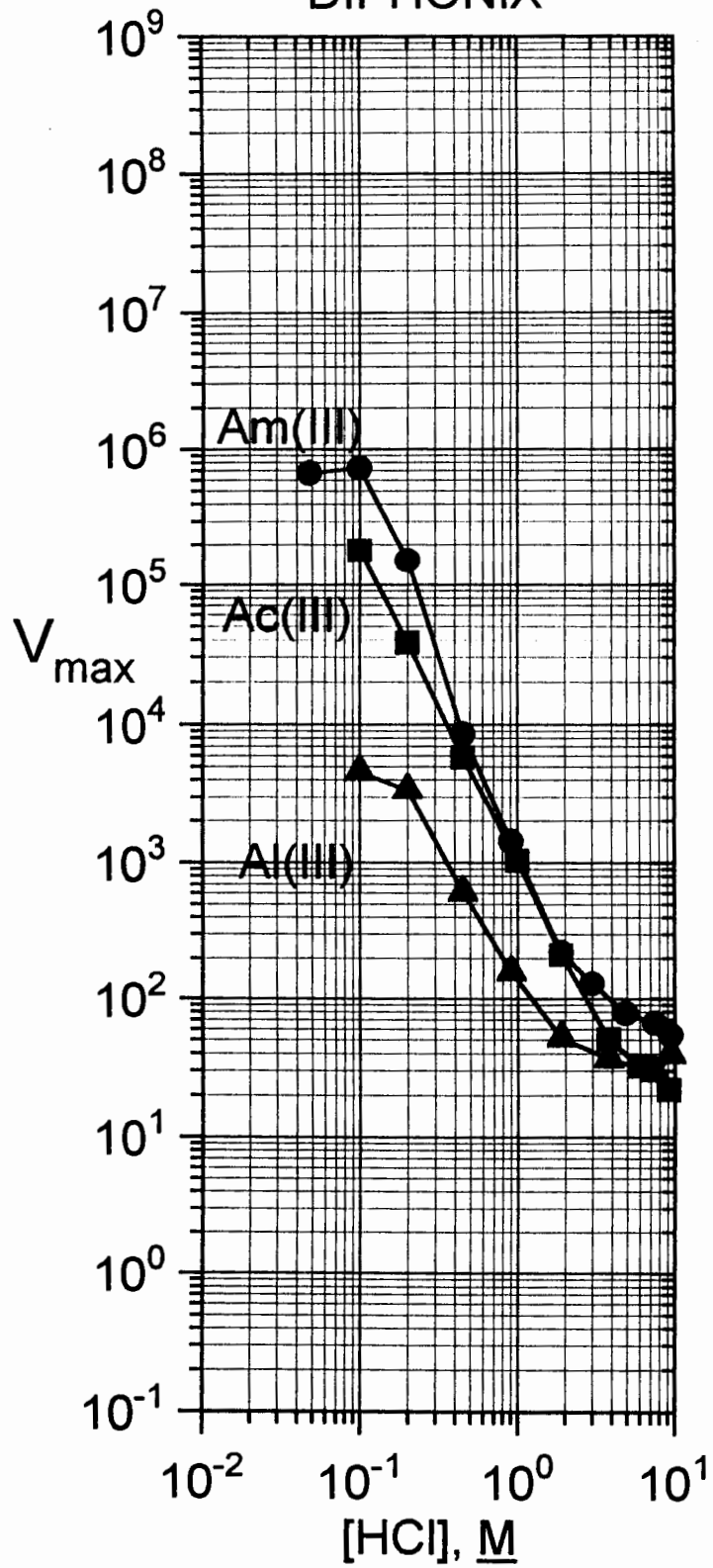
- Figure 1. Kinetics of uptake of Am(III) and Fe(III) from various HCl solutions by the Dipex resin (50-100 μm particle diameter).
- Figure 2. Acid dependency of the uptake of several actinide species by the Dipex resin
- Figure 3. Acid dependency of the uptake of several non-actinide species by the Dipex resin
- Figure 4. Comparison of the acid dependencies of the uptake of Am(III), Ac(III), and Al(III) by the Diphonix and Dipex resins
- Figure 5. Effect of increasing concentrations of Ca(II), Al(III), Fe(III), and Fe(II) on the uptake of Am(III) by the Dipex resin from 1, 2, and 4 M HCl
- Figure 6. Effect of increasing concentrations of hydrofluoric acid on the uptake of Am(III), U(VI), Th(IV), and Ti(IV) by the Dipex resin from 1 and 3 M HCl
- Figure 7. Effect of increasing concentrations of sulfuric and phosphoric acids on the uptake of Np(IV) by the Dipex resin from 1 and 3 M HCl
- Figure 8. Uptake of several actinide species by the Diphonix and Dipex resins from HEDPA solutions of increasing concentration
- Figure 9. Sorption of Am(III) by the Dipex resin from Des Plaines River water samples as a function of the sample volume / resin mass ratio



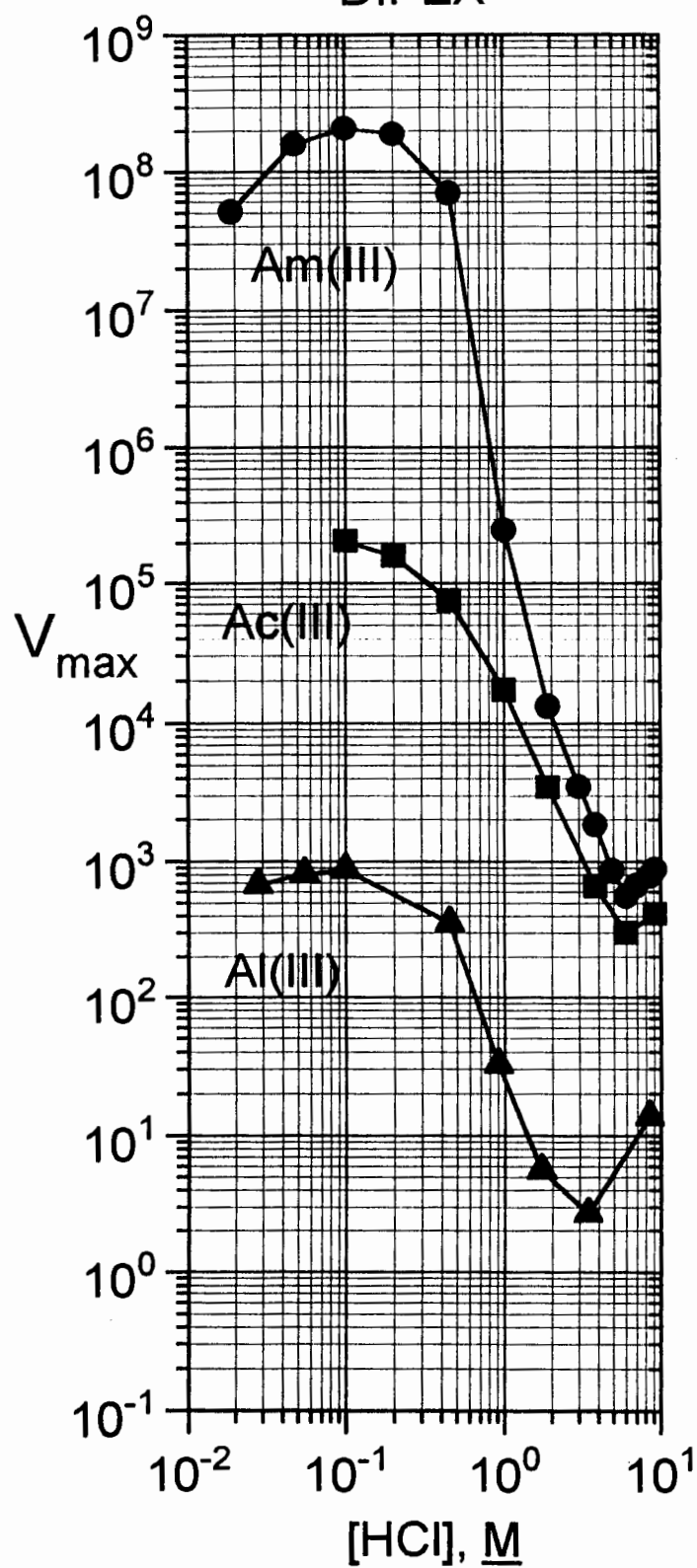


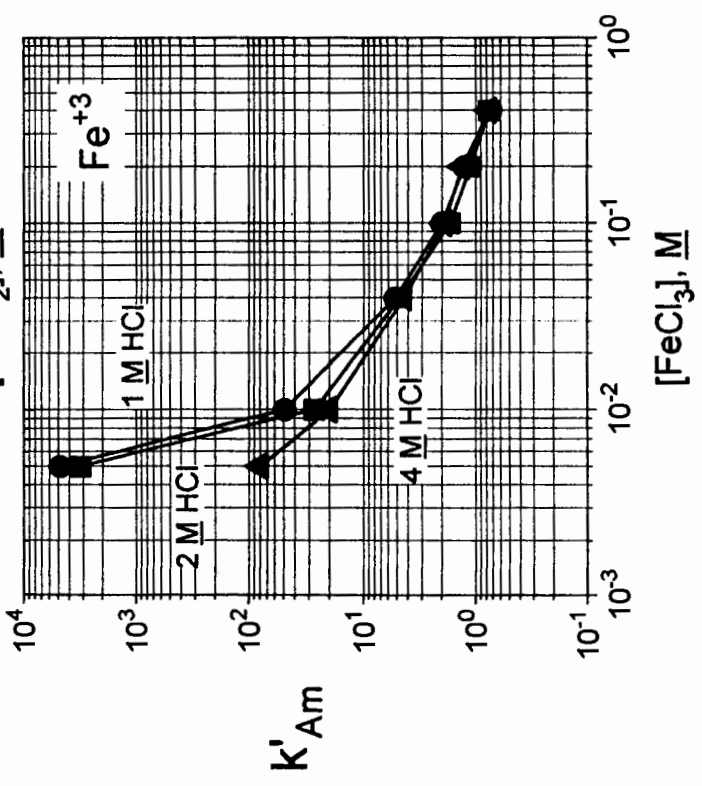
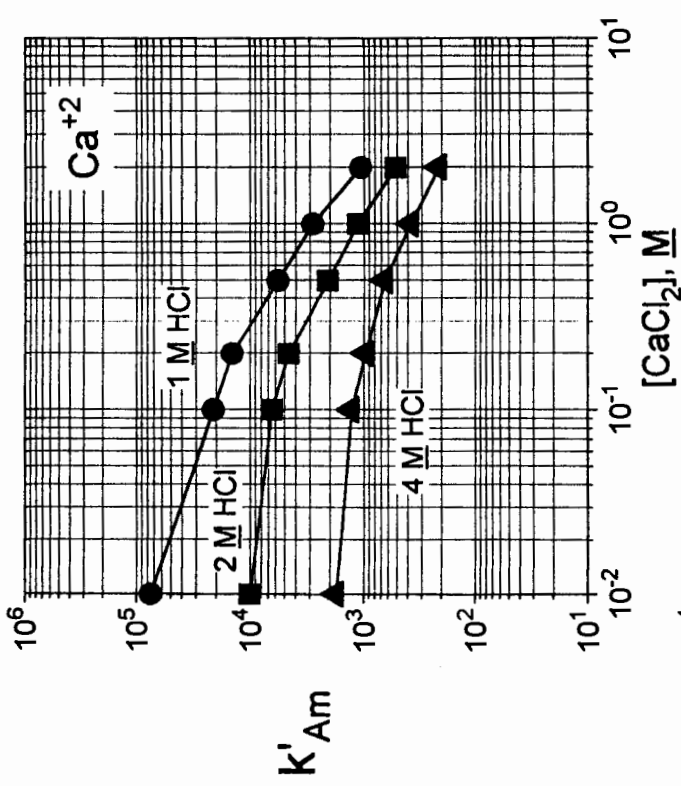
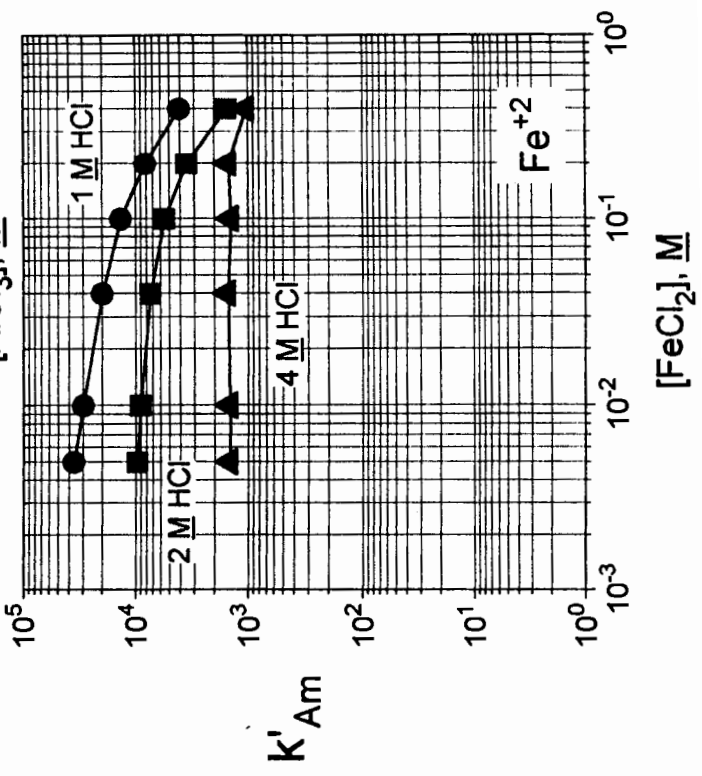
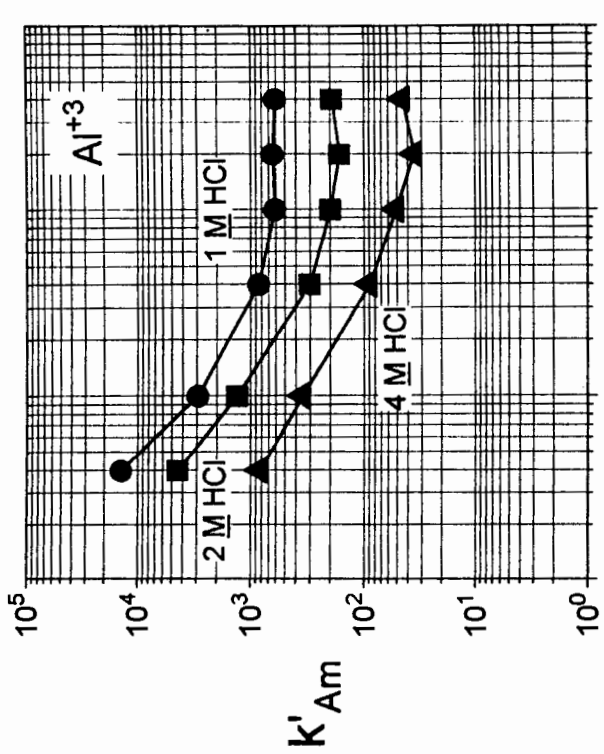


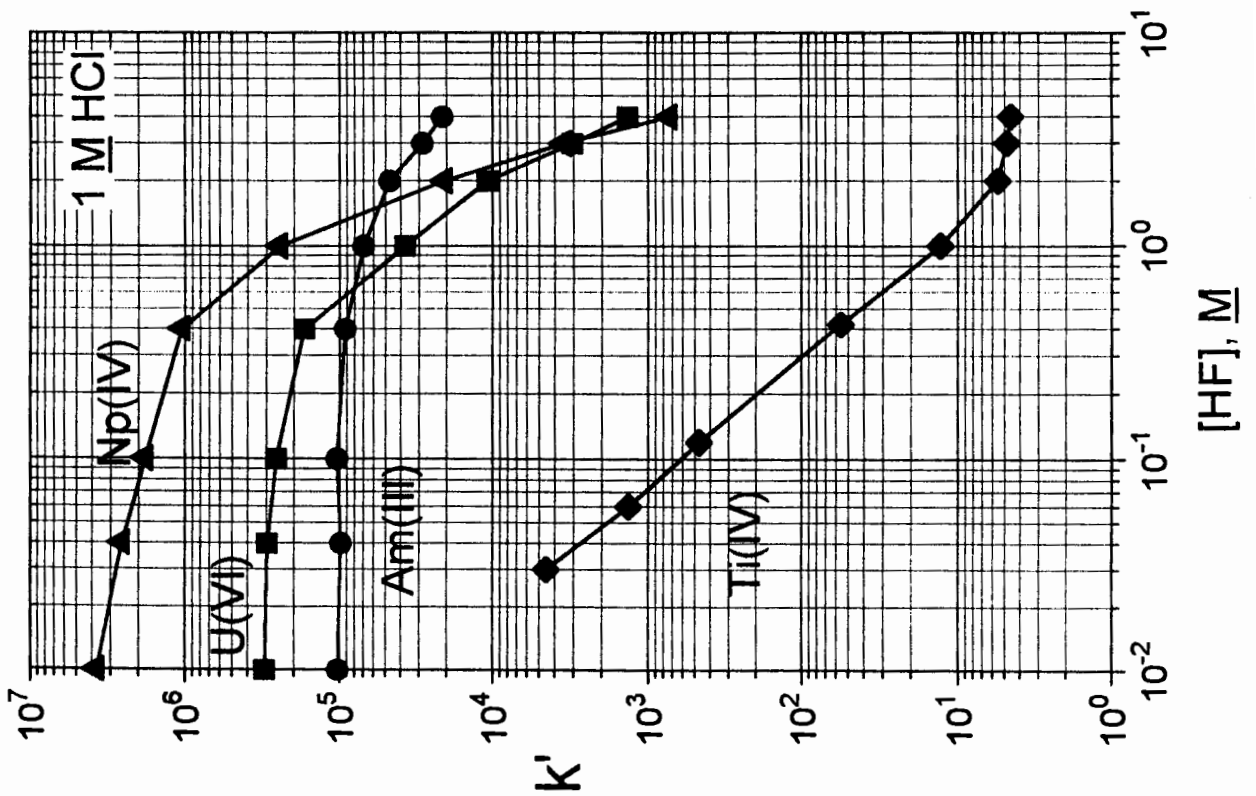
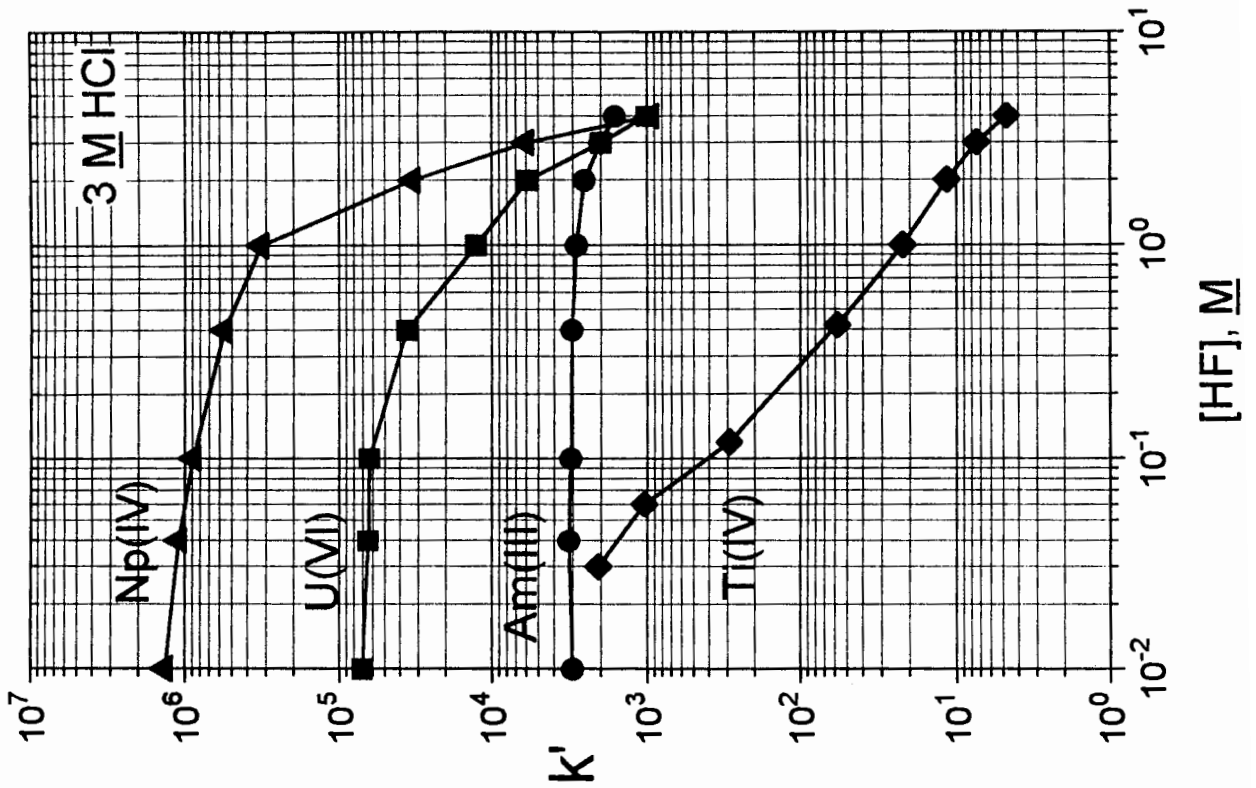
DIPHONIX

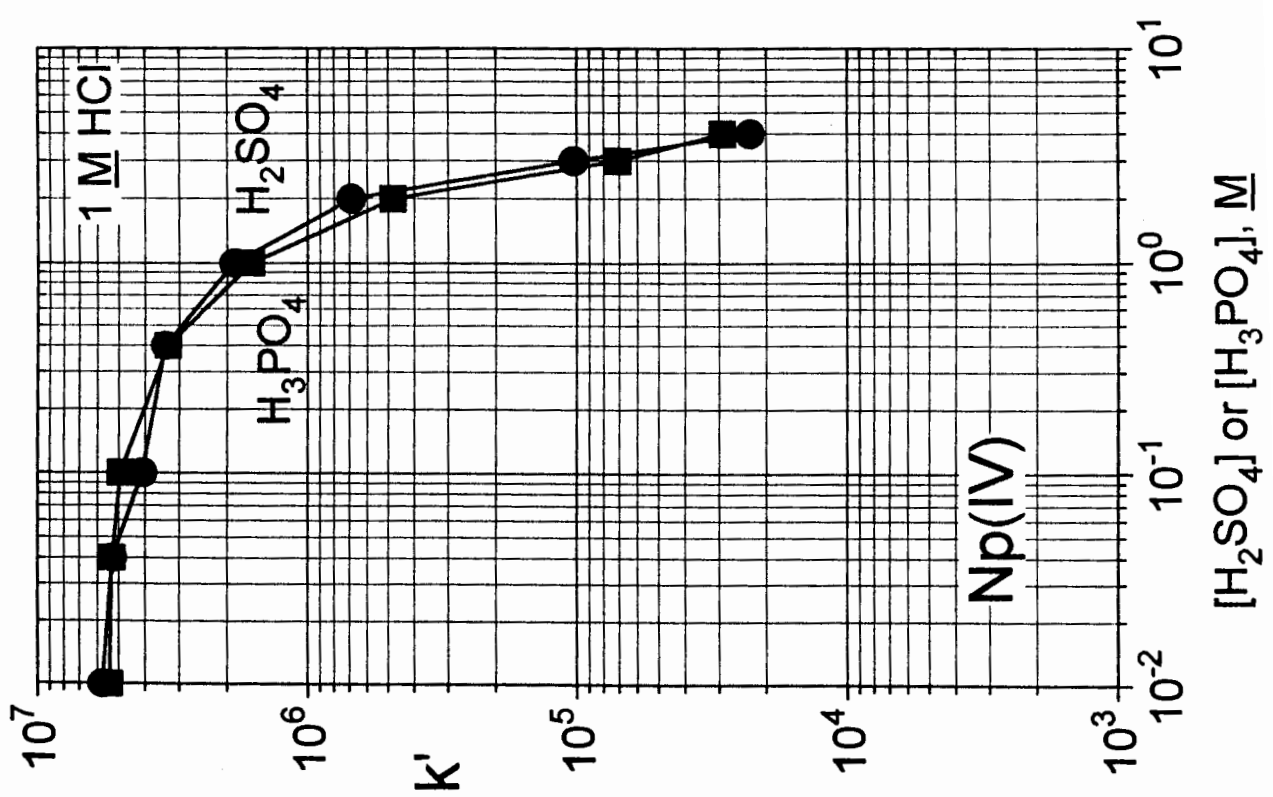
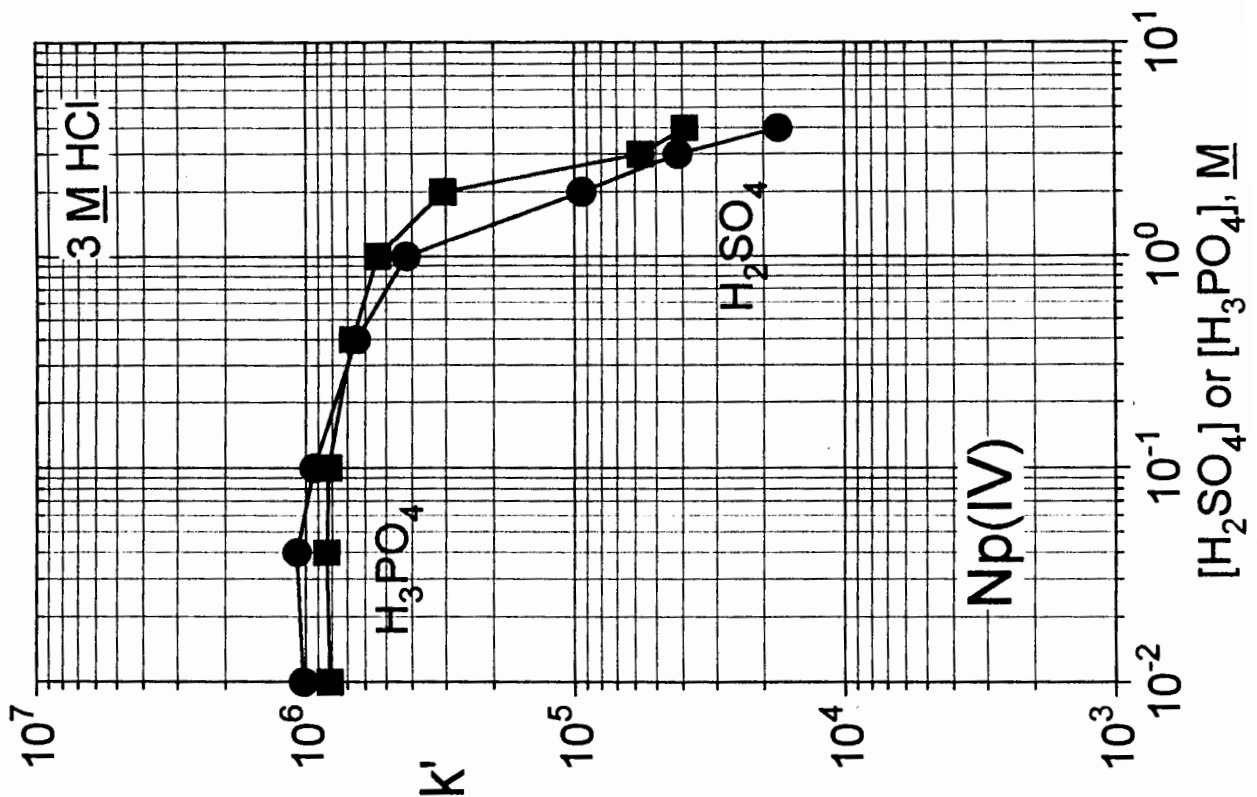


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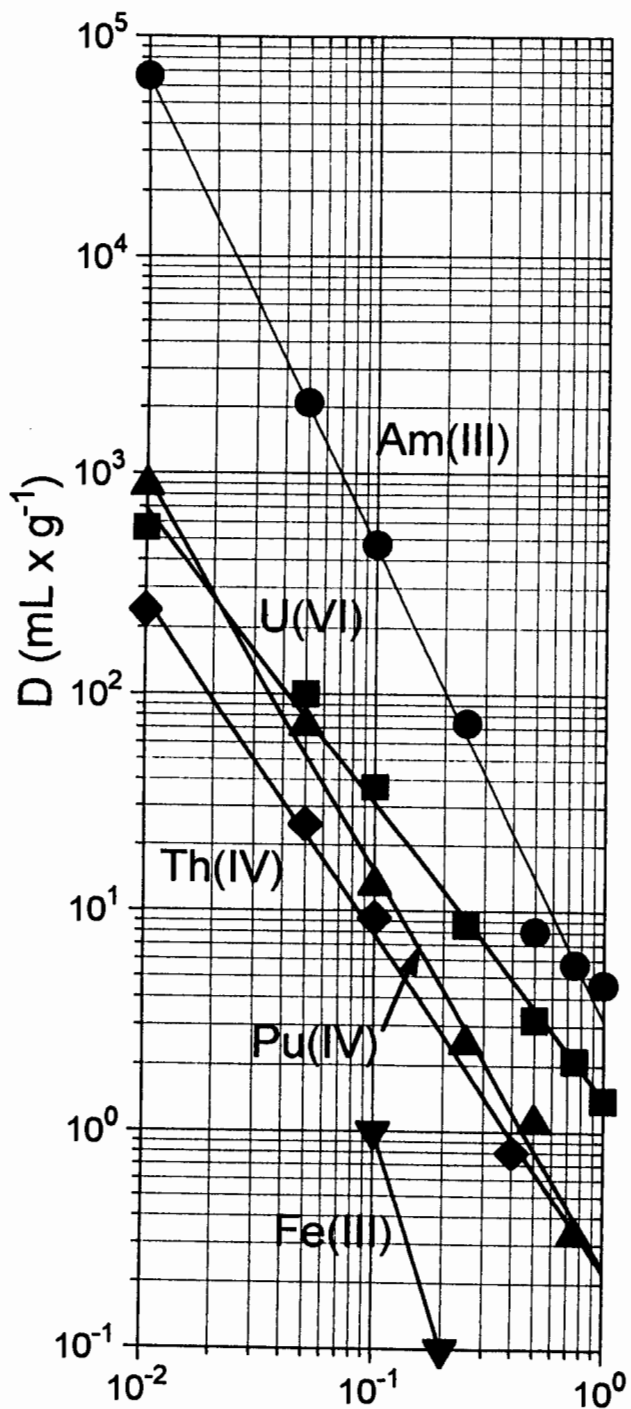




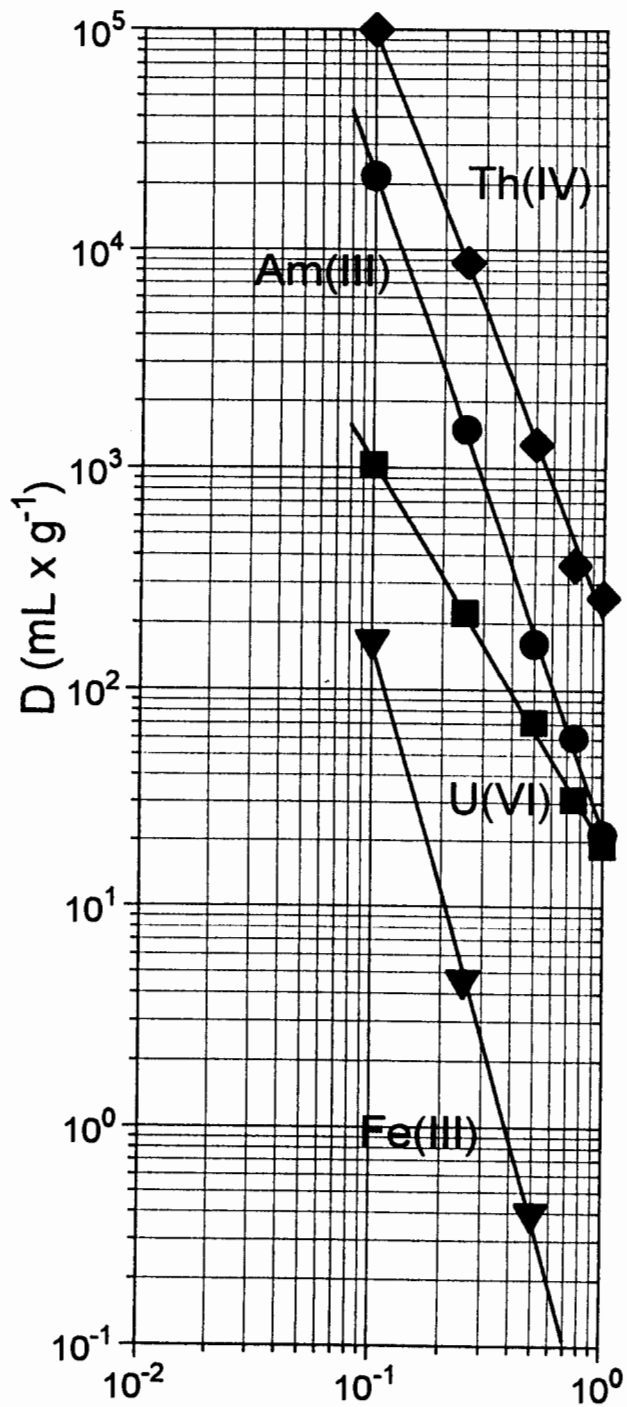




DIPHONIX



DIPEX



$[HEDPA]$, M

% Am(III) sorbed

