

National Analytical Management Program (NAMP)
U.S. Department of Energy Carlsbad Field Office

Radiochemistry Webinars

Actinide Chemistry Series

▪ Analytical Chemistry of Uranium and Plutonium



*In Cooperation with our
University Partners*



UNIVERSITY of CALIFORNIA • IRVINE

Meet the Presenter...

Ralf Sudowe

Dr. Ralf Sudowe has extensive experience in the areas of nuclear and radiochemistry, particularly in the development of radioanalytical separations for actinide and transactinide elements, as well as fission products. He is currently an Associate Professor of Health Physics and Radiochemistry at the University of Nevada Las Vegas. He received a M.S. degree in Chemistry from the Philipps-University Marburg in Germany in 1995, and a Ph.D. in Nuclear Chemistry from the same institution in 1999. Dr. Sudowe spent two years as Visiting Postdoctoral Fellow in the Nuclear Science Division at Lawrence Berkeley National Laboratory and then worked for five years as Staff Scientist in the Nuclear Science and Chemical Sciences Division at LBNL before joining the faculty at UNLV in 2006. He is a member of the American Chemical Society, the American Nuclear Society, and the Health Physics Society.



At UNLV, Dr. Sudowe teaches courses in radioanalytical chemistry, radiation detection, environmental health physics and radiation biology, as well as laboratory courses in radiochemistry and radiation detection instrumentation. His research focuses on the development and optimization of advanced radioanalytical methods for environmental monitoring, nuclear forensics and safeguards, and emergency response. The goal is to make radioanalytical methods available that have lower detection limits for the radionuclides of interest, facilitate the fast analysis of a large number of samples, and allow assay of unusual sample matrices such as urban rubble and process streams. The research utilizes a variety of modern analytical tools to obtain a better understanding of the fundamental properties of the separation process and to elucidate the role that interfering elements have on the technique. In addition, Dr. Sudowe studies the chemical and nuclear properties of transactinide elements and is involved in target preparation and cross section measurements for stockpile stewardship science.

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UNLV

Analytical Chemistry of Uranium and Plutonium

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**National Analytical Management Program (NAMP)
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TRAINING AND EDUCATION SUBCOMMITTEE



Analytical Techniques

Technique
Mass Spectrometry
Radiation Detection
Laser Fluorescence Spectroscopy (Uranium)
UV/Vis Spectroscopy
XANES/XAFS
EDX Techniques

Tracers

- Factors to consider for tracer selection:
 - Half-life
 - Short: Frequent purification required
Loss during analytical procedure
 - Long: Insufficient specific activity
 - Decay mode
 - Interferences
 - Decay energy
 - Mass
 - Availability and cost

Tracers (cont)

- Tracer solutions should be prepared from high-purity reagents to minimize contaminants.
- They should be stored under acidic conditions (>2 M) to prevent losses to the vessel walls.
- Pu tracers should be stored in glass; however, uranium tracers should be stored in Teflon to prevent leaching of U from the glass.
- U leached from the glass might otherwise interfere with mass spectrometric analysis.

Uranium Tracer

Tracer	Alpha Energy	Half -life	Use
U-232	5.320 MeV	68.9 y	α
U-233	4.824 MeV	$1.59 \cdot 10^5$ y	MS
(U-236)	4.494 MeV	$2.34 \cdot 10^7$ y	α

- Uranium-232 is commonly used as a tracer in alpha spectroscopy.
- Uranium-233 can be used as a tracer for ICP-MS measurements.

Plutonium Tracer

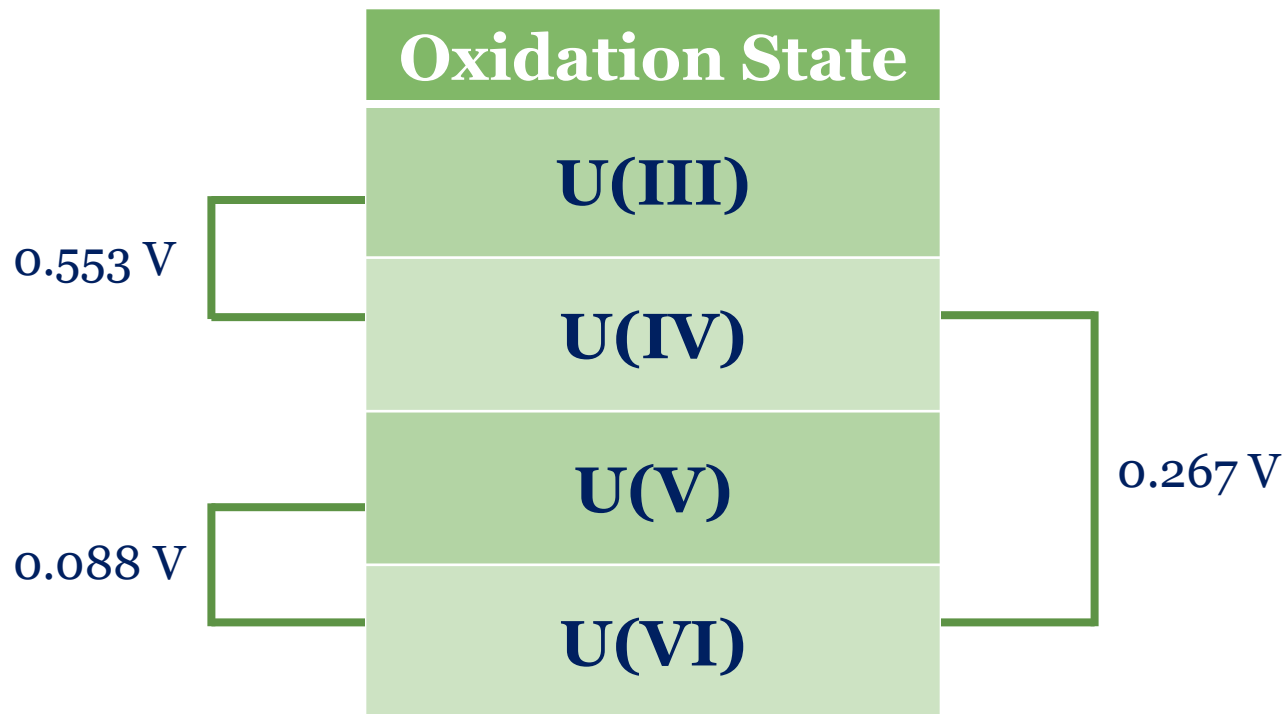
Tracer	Alpha Energy	Half -life	Use
Pu-236	5.768 MeV	2.858 y	α
Pu-242	4.900 MeV	$3.73 \cdot 10^5$ y	α , MS
Pu-244	4.589 MeV	$8.08 \cdot 10^7$ y	MS

- ^{236}Pu and ^{242}Pu are both used as tracers for alpha spectroscopy.
- The decay of ^{236}Pu to ^{232}U has to be taken into account when analyzing both Pu and U in the same sample.

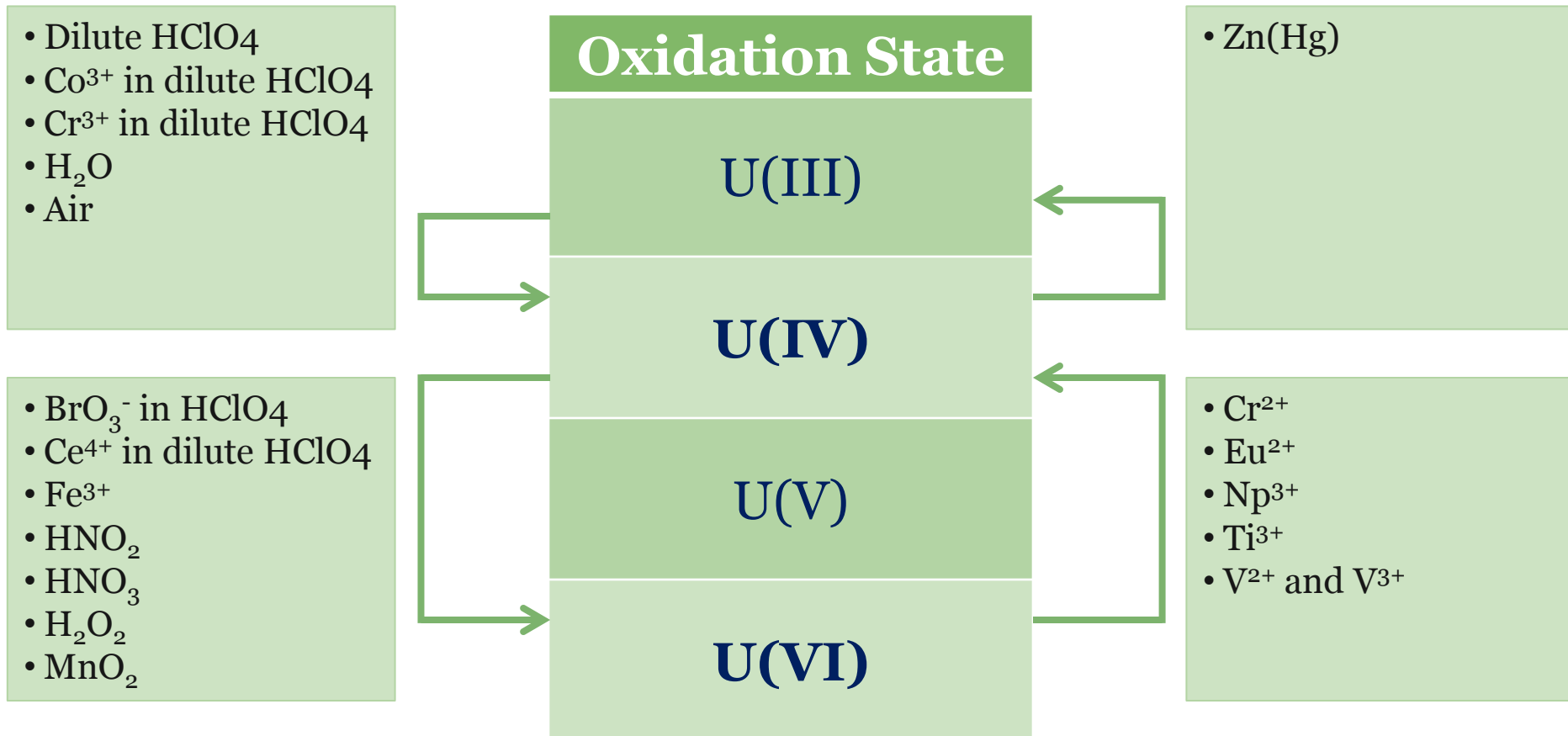
Oxidation/Reduction Chemistry

- The fact that uranium and plutonium can exist in multiple oxidation states plays an important role in the analytical chemistry of uranium and plutonium.
- Many radioanalytical techniques utilize the ability to manipulate the oxidation states to achieve separation from interfering elements.

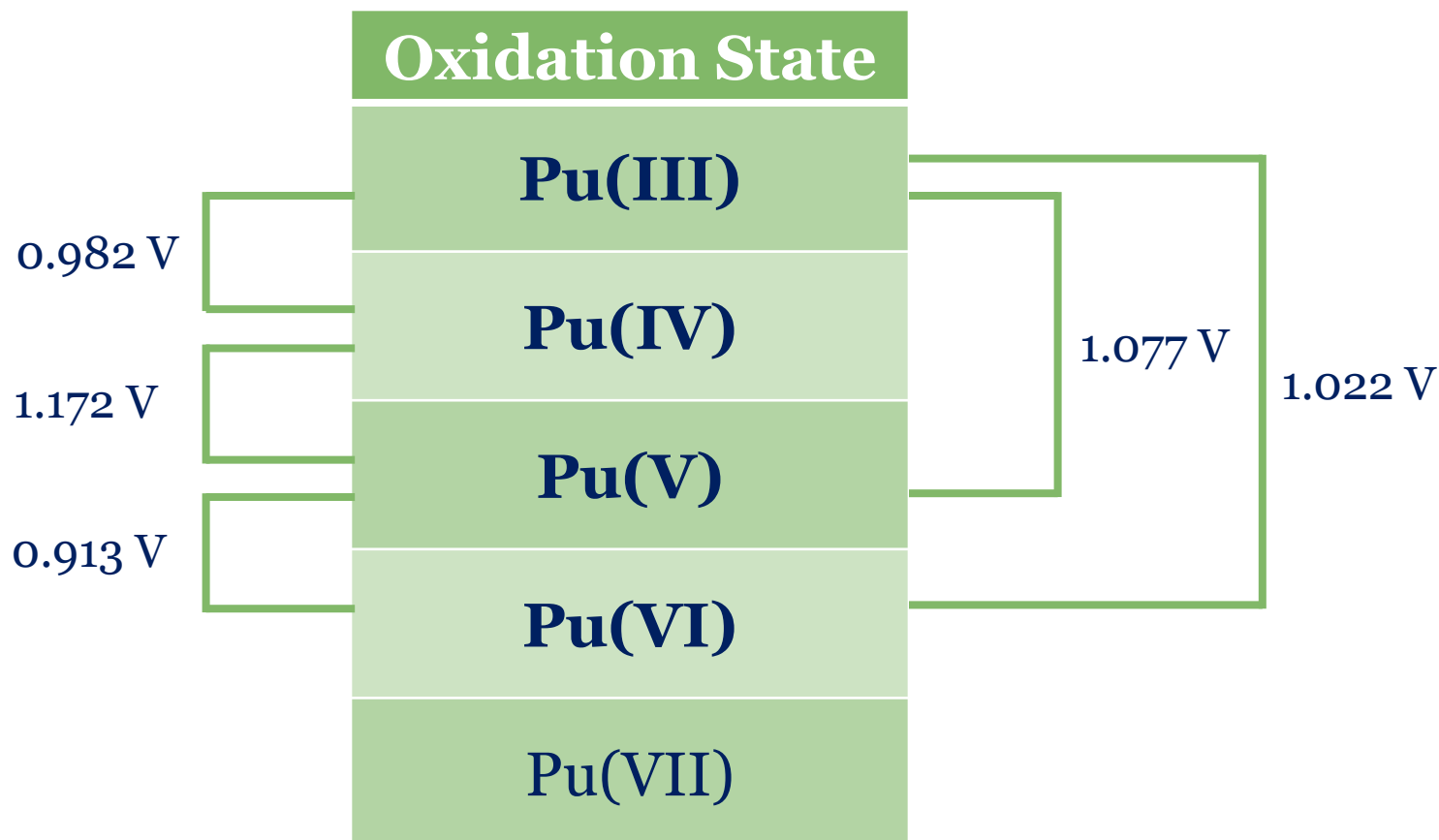
Oxidation States of Uranium



U Oxidizing and Reducing Agents



Oxidation States of Plutonium



Source: Morss, L. R., Edelstein, N. M., Fuger, J. (Editors), *The chemistry of the actinide and transactinide elements*, Springer (2006)

Oxidation States of Plutonium (cont)



Source: Clark, D. L., *The chemical complexities of plutonium*, Los Alamos Science 26 (2000)

Oxidation States of Plutonium (cont)

	Peak (nm)
Pu(III)	244, 561, 601, 665
Pu(IV)	653, 470
Pu(V)	1131, 569
Pu(VI)	830, 504, 623
Pu(VII)	638

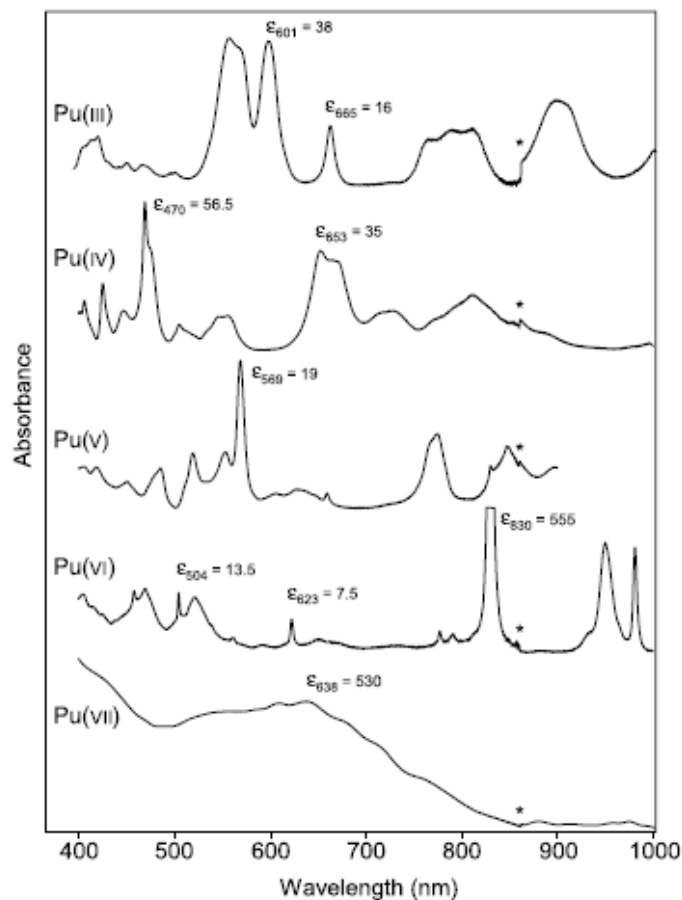


Fig. 7.115 Electronic absorption spectra of major plutonium aqua ions recorded at 25°C. The asterisk marks a spectrophotometer grating change. Plutonium(III) recorded on 1.89 mM solution in 1 M HClO₄ using 1 cm cell. Plutonium(IV) recorded on 2.91 mM solution in 1 M HClO₄ using 1 cm cell. Plutonium(V) recorded on 10.2 mM solution in 1 M (Na₂H)ClO₄ solution at pH 3.14 using 1 cm cell. Plutonium(VI) recorded on 0.89 mM solution in 1 M HClO₄ using 1 cm cell. Plutonium(VII) recorded on 20 mM solution in 2.5 M NaOH using 1 cm cell (spectra courtesy of Phillip D. Palmer of Los Alamos National Laboratory).

Source: Morss, L. R., Edelstein, N. M., Fuger, J. (Editors)
The chemistry of the actinide and transactinide elements,
 Springer (2006)

Pu Oxidizing and Reducing Agents

- BrO_3^- in dilute acid
- Ce^{4+} in HCl
- $\text{Cr}_2\text{O}_7^{2-}$ in dilute acid
- NO_2^- in HNO_3
- IO_3^- in dilute acid
- MnO_4^- in dilute acid
- HNO_2

- Ag_2O in HNO_3
- NaBiO_3 in HNO_3
- Nitric acid
- MnO_4^- in dilute HNO_3
- Ce^{4+} in dilute HNO_3
- O_3 in dilute H_2SO_4

Oxidation State

Pu(III)

Pu(IV)

Pu(V)

Pu(VI)

- I^- in HCl
- $\text{NH}_2\text{OH}\cdot\text{HCl}$ in dilute acid
- Zn in dilute HCl
- SO_2 in dilute acid
- Ascorbic acid
- Ti_3^+ in HCl

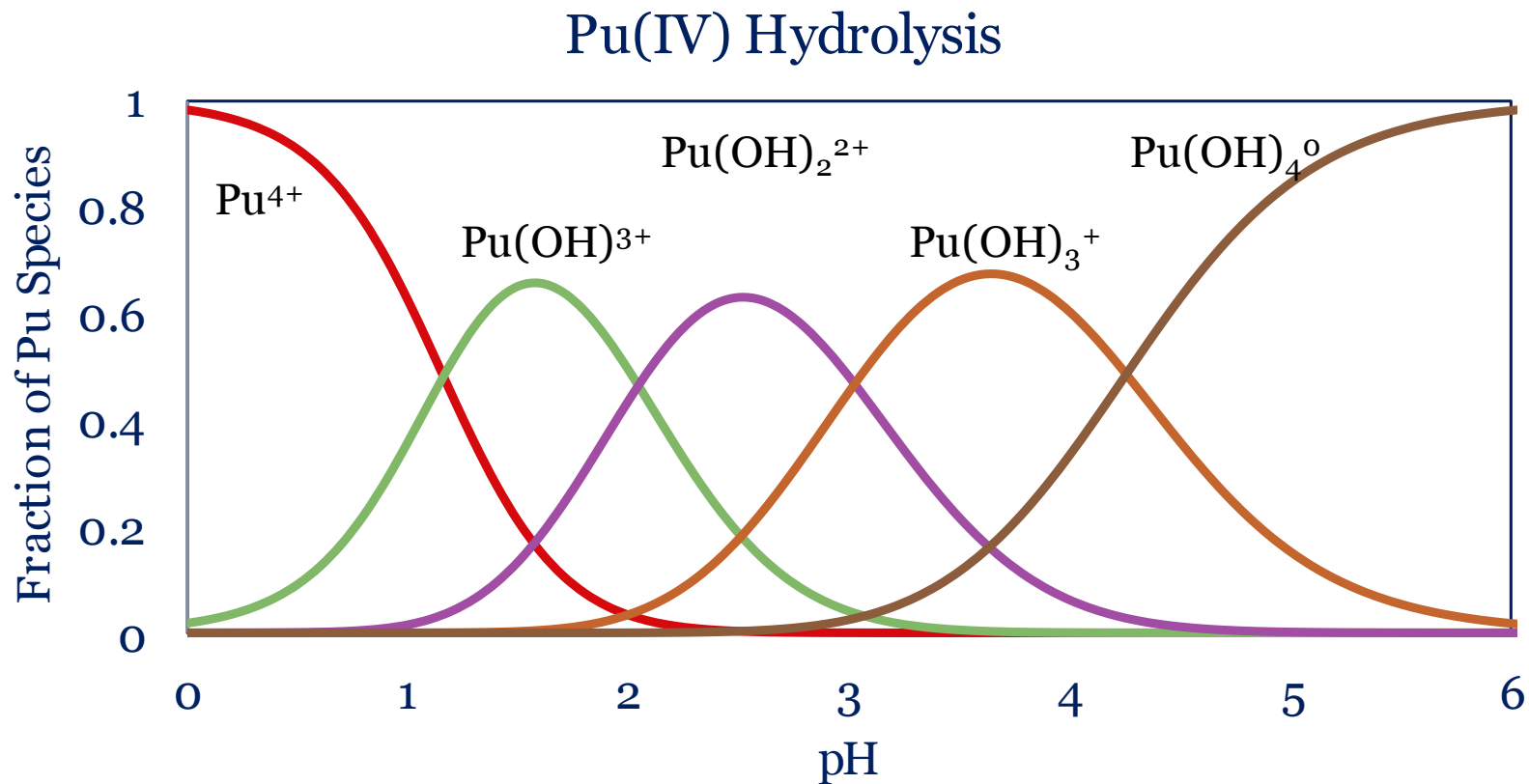
- I^- in HNO_3
- Fe^{2+} in HCl
- NO_2^- in HNO_3
- Hydrazine in HNO_3
- H_2O_2 in HNO_3
- Ti^{3+} in HClO_4
- $\text{C}_2\text{O}_4^{2-}$ in HCl

Plutonium Hydrolysis

- In aqueous solutions, all oxidation states of Pu exist as positive ions.
- In the absence of complexing anions, Pu tends to undergo hydrolysis.
- This can result in the irreversible formation of Pu colloids or “Pu polymer.”
- Potential for hydrolysis decreases as:



Plutonium Hydrolysis (cont)



Modeled using Geochemist Workbench, LLNL database.

Plutonium Hydrolysis (cont)

- The presence of colloids can have significant effect on analytical techniques.
- There is no visual indication of the presence of polymer in solution.
- Chemical properties of colloidal Pu differ from those of free Pu(IV).
 - Different behavior in solvent extraction and ion exchange
- Added tracer will not exchange with colloidal Pu.
 - Faulty yield determination

Plutonium Hydrolysis (cont)

- Pu hydrolysis is enhanced:
 - In solutions with high concentrations of Pu(IV)
 - In solutions with low acidity
 - At elevated temperatures

Plutonium Hydrolysis (cont)

- To minimize Pu hydrolysis:
 - Acid concentrations below 0.5 M should be avoided even if complexing anions are present.
 - Tracer solutions of Pu should be stored in the form of Pu(III).
 - An oxidation-reduction step should be performed before performing any dilutions.

Separation Techniques

Technique
(Co) Precipitation
Solvent Extraction
Ion Exchange
Extraction Chromatography

Ion Exchange Separations

- A large number of radioanalytical methods for U and Pu are based on the use of strongly basic anion exchange resins.
- Strongly acidic cation exchange resins have been utilized to a much lesser extent.
- Chelating or other types of exchange resins have played only a minor role.

Ion Exchange Separations (cont)

- Radiochemical separation of U and Pu by anion exchange can be carried out in:
 - Hydrochloric acid systems
 - Nitric acid systems
 - Sulfuric acid systems
 - Organic solvent/mineral acid systems

Anion Exchange – HCl

Distribution Coefficients of Actinides and Other Metal Ions on Strong Base Anion Exchange Resins in Pure Aqueous HCl Solutions

Metal Ion	Molarity of HCl						
	1	2	4	6	8	10	12
Ac(III)	<-----No adsorption----->						
Th(IV)	<-----No adsorption----->						
Pa(IV)	<-----No adsorption----->						
Pa(V)	~2 0	~20	~100	2 x 10 ³	~2 x 10 ⁴	10 ⁵	—
	<1	<1	<1	~100	~500	~10 ³	~10 ³
U(VI)	~1	~10	~100	~500	~10 ³	~10 ³	~10 ³
	~2	~10	~180	~800	~10 ³	~10 ³	~800
	~2	~50	~200	~600	~800	~600	~300
U(IV)	<1	<1	<1	~1	~50	>10 ²	>10 ²
U(III)	<-----No adsorption----->						

Anion Exchange – HCl (cont.)

Distribution Coefficients of Actinides and Other Metal Ions on Strong Base Anion Exchange Resins in Pure Aqueous HCl Solutions

Metal Ion	Molarity of HCl						
	1	2	4	6	8	10	12
Np(III)	<-----No adsorption----->						
Np(IV)	~1	~1	~2	~40	300	~500	—
	<1	<1	<1	~20	~700	>10 ³	>10 ³
	<1	<1	<1	~10	~700	~2 x 10 ³	~8 x 10 ³
Pu(III)	<-----No adsorption----->						
Pu(IV)	<1	<1	<1	~30	>10 ³		
Pu(VI)	Strongly adsorbed from HCl >6M						
Trivalent trans-Pu elements	Slight adsorption						

Anion Exchange – HCl (cont)

- Trivalent actinides are not at all or only slightly adsorbed.
- Adsorption of tetravalent species increases as:
$$U(IV) < Np(IV) < Pu(IV)$$
- No adsorption of Th(IV) or Pa(IV).
- Hexa- and pentavalent actinide elements are strongly retained, especially at $[HCl] > 6.0 \text{ M}$.

U(VI) – Hydrochloric Acid

0.1 – 0.5 M	0.5 – 4.0 M	4.0 – 6.0 M	6.0 – 12.0 M
UO_2^{2+}	UO_2Cl^+	UO_2Cl_2	UO_2Cl_3^-

- Adsorption on strongly basic anion exchanger:
 - Begins at [HCl] greater than 0.5 M
 - Increases rapidly with increasing [HCl]
 - Highly crosslinked resins (X8):
 $(\text{UO}_2\text{Cl}_3)^-$
 - Higher charge on slightly cross-linked resins (X4):
 $[\text{UO}_2\text{Cl}_4 \cdot \text{H}_3\text{O}(\text{H}_2\text{O})\text{Cl}_4\text{UO}_2]^{3-}$

U(VI) – Hydrochloric Acid (cont)

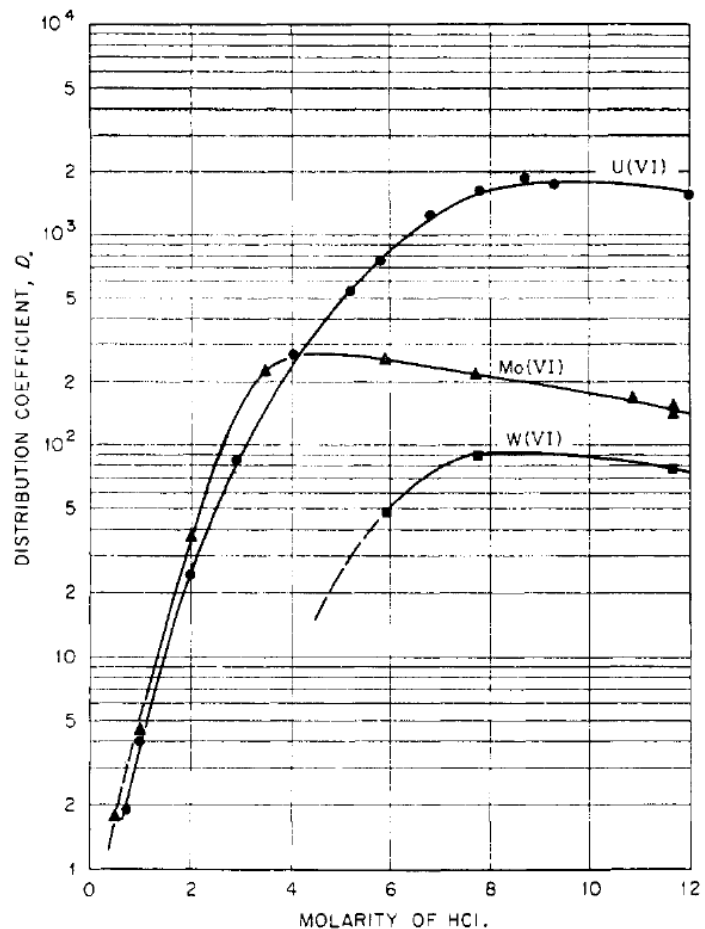


Fig. 1.—Adsorption of Mo(VI), W(VI) and U(VI) from HCl solutions.

Source: Kraus, K.A., Nelson F., Moore, G.E., *Anion-exchange studies XVIII: Molybdenum(VI), tungsten(VI), uranium(VI) in HCl and HCl-HF solutions*, Journal of the American Chemical Society 77, 3972 (1955)

U(IV) – Hydrochloric Acid

0.5 – 2.0 M	2.0 – 6.0 M	6.0 – 9.0 M	9.0 – 12.0 M
U^{4+}	UCl_3^+	UCl_2^{2+}	UCl_6^{2-}

- Adsorption on strongly basic anion exchanger:
 - Strongly retained from 8 – 12 M HCl
 - Species retained on the resin:
 $(UCl_6)^{2-}$

U(IV) – Hydrochloric Acid (cont)

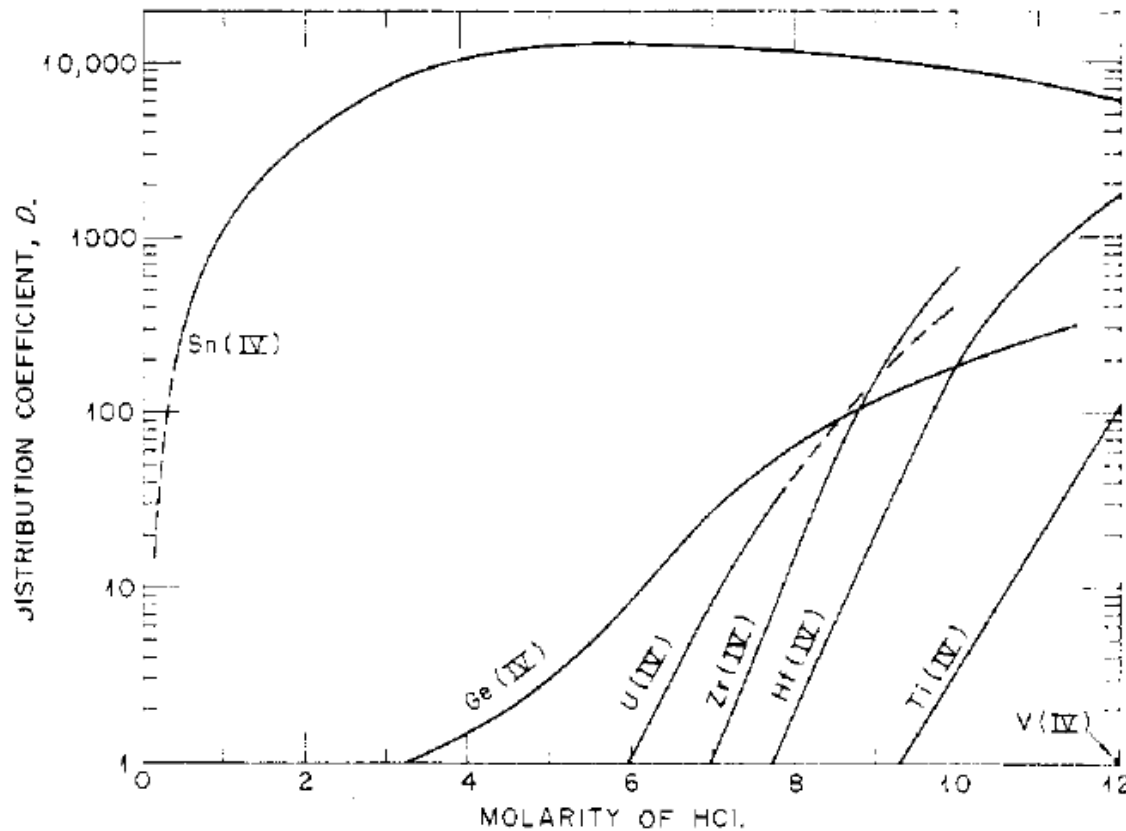


Fig. 1.—Adsorbability of M(IV) ions from HCl solutions.

Source: Kraus, K.A., Moore, G.E., Nelson F., *Anion-exchange studies XXI: Th(IV) and U(IV) in hydrochloric acid – Separation of thorium, protactinium and uranium*, Journal of the American Chemical Society 78, 2692 (1956)

U(III) – Hydrochloric Acid

- No adsorption on an anion exchanger has been observed from concentrated LiCl solutions.
- Spectral evidence for formation of an anionic complex at [HCl] above 7.0 M.

Uranium – Hydrochloric Acid

- Uranium affinity for strongly basic anion exchanger is higher from HCl than from HNO₃.
- However, the selectivity from pure hydrochloric acid solutions is not very high.
- A number of interfering metal ions form anionic complexes as well.
- They are therefore coadsorbed together with U.
- Coadsorption of Fe(III) can be prevented by reduction to Fe(II) with, e.g., ascorbic acid.

Uranium – Hydrochloric Acid (cont)

- U(VI) is most frequently eluted from strong basic anion exchange resins with 0.1 M or 1.0 M HCl.
- A large number of other eluents can also be used.
- All of these eluents can also be used to strip U(IV).
- In addition U(IV) can be eluted with 8.0 M HCl - 0.1 M HF.
- This allows separation from U(VI), which is still retained on the resin under these conditions.

Pu(IV) – Hydrochloric Acid

0.5 – 2.0 M	2.0 – 4.0 M	4.0 – 6.0 M	6.0 – 9.0 M	9.0 – 12.0 M
Pu^{4+}	PuCl^{3+}	PuCl_2^{2+}	PuCl_3^+	PuCl_6^{2-}

- Adsorption on strongly basic anion exchanger:
 - Strongly retained from 8 – 12 M HCl.
 - Species retained on the resin:
 $(\text{PuCl}_6)^{2-}$

Pu(IV) – Hydrochloric Acid (cont)

- A number of oxidizing agents can be used to ensure that all Pu is in the tetravalent state:



- These agents need to be used either shortly before sorption or added to the feed solution.

Pu(VI) – Hydrochloric Acid

- Pu(VI) is strongly adsorbed on anion exchange resins from 6.0 – 12.0 M HCl solutions.
- It is therefore completely coadsorbed if both oxidation states are present.
- Any Fe(III) present under these conditions can be removed by elution with 7.2 M HNO₃.

Pu(III) – Hydrochloric Acid

- Pu(III) is not adsorbed on strong basic anion exchangers from pure aqueous solutions of 1.0 – 12.0 M HCl.

Pu(III) – Hydrochloric Acid (cont)

- Reduction to Pu(III) can therefore be used to prevent uptake on the resin or for rapid elution.
- Some of the reducing agents that can be added to the feed solution or the eluent are:



Pu – Hydrochloric Acid

- In addition to these reducing agents, HCl-HF mixtures, e.g., 0.36 M HCl – 0.01 M HF, can be used for the rapid elution of plutonium.
- Dilute solutions of HCl, e.g., 0.1 M HCl, can also be used for this purpose.

Anion Exchange – Nitric Acid

Distribution Coefficients of Actinides and Other Metal Ions on Strong Base Anion-Exchange Resins in Pure Aqueous Nitric Acid Solutions

Metal Ion	Molarity of nitric acid							
	1	2	4	6	8	10	12	14
Ac(III)	<-----Negligible or no adsorption----->							
Th(IV)	1	~5	50	216	323	227	~100	~51
	<1	2	20	140	200	—	—	—
	—	~16	50	200	300	~220	—	—
Pa(V)	~1	~6	~12	~30	~50	~40	~20	~15
U(VI)	~2	~3	~7	~12	~16	~10	~8	~6
	<1	<1	~3	~6	~6	—	—	—
	—	—	5	10	~10	—	—	—
U(IV)	~2	~16	~100	—	—	—	—	—

Anion Exchange – Nitric Acid (cont.)

Distribution Coefficients of Actinides and Other Metal Ions on Strong Base Anion-Exchange Resins in Pure Aqueous Nitric Acid Solutions

Metal Ion	Molarity of nitric acid							
	1	2	4	6	8	10	12	14
Np(IV)	~50	~100	~10 ³	>10 ³	>10 ³	>10 ³	~10 ³	600
Np(V)	Maximum K _d of about 15 in ~10 M HNO ₃							
Np(VI)	Maximum K _d of about 15 in ~10 M HNO ₃							
Np(III)	<-----Negligible or no adsorption----->							
Pu(IV)	~100	~300	10 ³	>10 ³	>10 ³	>10 ³	>10 ³	~700
Pu(VI)	Same behavior as Np(VI) or U(VI)							
Pu(III)	<-----Negligible or no adsorption----->							
Trivalent trans-Pu elements	<-----No adsorption----->							

Anion Exchange – Nitric Acid (cont)

- Trivalent actinides show negligible or no adsorption on strong base anion exchange resins.
- Actinide elements with stable tetravalent states are strongly retained from pure aqueous solutions of nitric acid.
- These systems are therefore well suited for the isolation of Th(IV) and Pu(IV).
- U(VI) and Pu(VI) are adsorbed to some extent.

U(VI) – Nitric Acid

- U(VI) is only weakly adsorbed on strong base anion exchange resins from nitric acid.
- Two complexes have been found to adsorb:



- Maximum adsorption is reached between 6.0 – 8.0 M HNO_3 .
- Above 8.0 M, the uptake decreases again with increasing acid concentration.

U(VI) – Nitric Acid (cont)

- The weak adsorption of U from HNO_3 is used to:
 - Separate U from metal ions that are strongly retained from nitric acid, e.g., Th and Pu.
 - Separate U from elements that are not retained at all, e.g., Al and Fe.

U(VI) – Nitric Acid (cont)

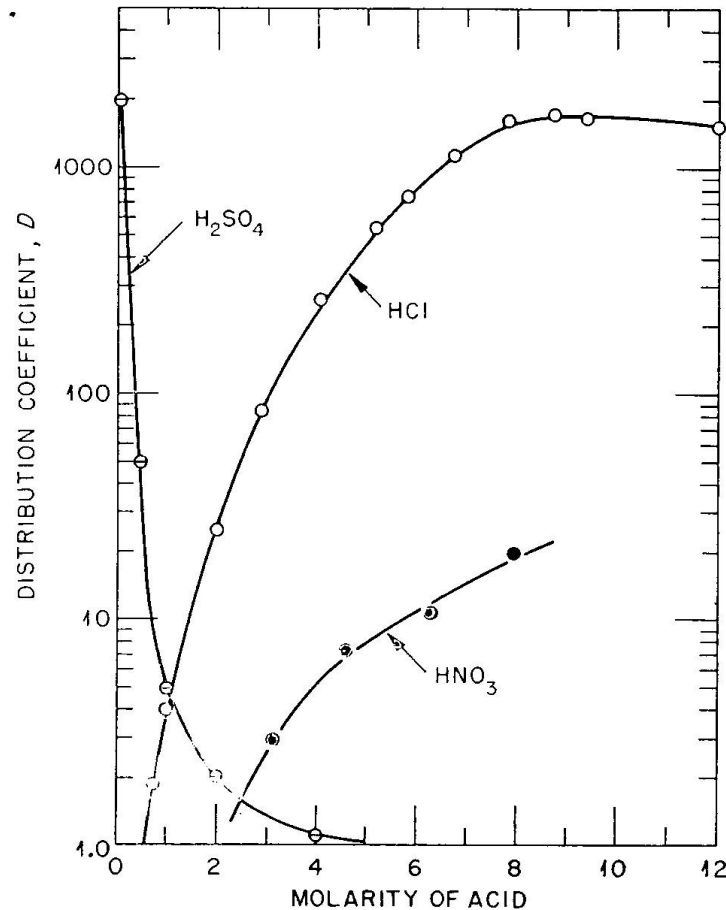


Figure 2. Adsorption of U(VI) from various mineral acids

Source: Kraus, K.A., Nelson F., *Anion-exchange studies of the fission products*, Proceedings of the international conference on the peaceful uses of atomic energy, Volume 7, p. 113, Session 9B. 1, P/837 United Nations (1956)

U(IV) – Nitric Acid

- U(IV) forms negatively charged complexes, such as $\text{U}(\text{NO}_3)_6^{2-}$, at $[\text{HNO}_3]$ greater than 3.0 M.
- These complexes are stronger retained on the resin than the U(VI) nitrate species.
- However, the adsorption of U(IV) from nitric acid solutions has found no wide analytical application.

Pu(III) and Pu(VI) – Nitric Acid

- Pu(III) is not retained by anion exchange resins.
- Pu(VI) is adsorbed to about the same extent as U(VI) or Np(VI).

Pu(IV) – Nitric Acid

- Pu(IV) forms a $[\text{Pu}(\text{NO}_3)_6]^{2-}$ complex in nitric acid solutions.
- This is also most likely the species that adsorbs on strong basic anion exchangers.
- The stability of this complex is so high that Pu(IV) already sorbs to the resin from dilute nitric acid, e.g., 1.0 M HNO_3 .

Pu(IV) – Nitric Acid (cont)

- The adsorption increases very strongly with increasing nitric acid concentration.
- It reaches a maximum with a distribution ratio of up to 10,000 between 7.0 and 9.0 M HNO₃.
- The affinity of Pu(IV) under these conditions is significantly higher than that of Th(IV) or Np(IV).

Pu(IV) – Nitric Acid (cont)

- Pu is therefore best adsorbed on basic anion exchangers as the tetravalent species from 7.0 – 9.0 M HNO₃.
- To ensure that all Pu is present as Pu(IV), the solution is typically treated with NaNO₂ at elevated temperatures.
- Sometimes this treatment is preceded by the reduction of all Pu to the Pu(III) state.

Pu(IV) – Nitric Acid (cont)

- To achieve complete and rapid elution, the Pu(IV) has to be freed from the nitrate complex.
- This can be achieved by:
 - Reducing the Pu(IV) to Pu(III)
 - Lowering the nitrate concentration
 - Addition of a reagent forming a Pu(IV) complex with an even greater stability
- The acidity of the eluent has to be high enough to prevent hydrolysis of Pu.

Pu(IV) – Nitric Acid (cont)

- Some of the eluents containing reducing agents that have been used for quantitative elution are:
 - Eluents containing iodide (HI or NH_4I)
 - Eluents containing hydroxylamine hydrochloride or hydrazonium chloride
 - Eluents containing other reductants, e.g., SO_2 or ferrous sulfamate

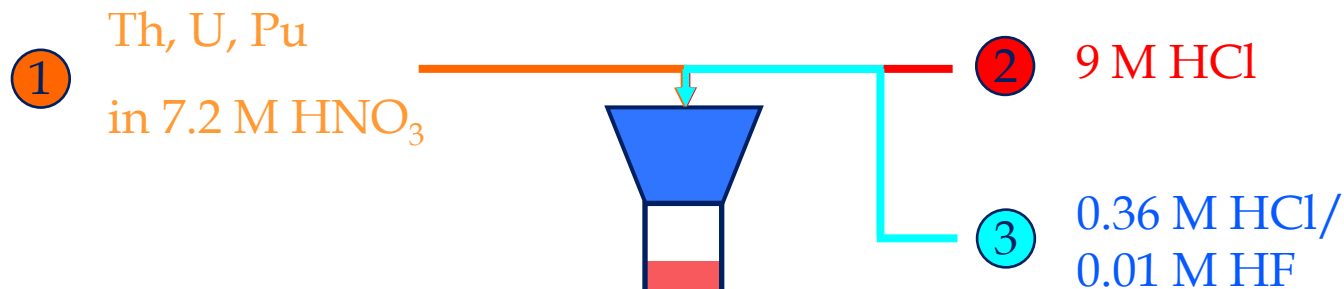
Pu(IV) – Nitric Acid (cont)

- Presence of F^- prevents hydrolysis of Pu even at very low concentration.
- The $(PuF_6)^{2-}$ complex formed is not as strongly adsorbed by an anion exchanger as the nitrate complex.
- Systems containing fluoride can therefore be used for the rapid and effective elution of Pu(IV).

Pu(IV) – Nitric Acid (cont)

- The adsorption rate of Pu(IV) increases with increasing temperature.
- In addition, the adsorption rate is significantly higher for resins with lower cross-linking.
- Both of these factors also apply to the elution.
- Temperatures about room temperature and less cross-linked resins are therefore often used.
- Increased temperature may, however, promote Pu hydrolysis in very dilute eluents.

Example of Th/U/Pu Separation



Adapted from:

1. Kressin, I.K., Waterbury, G.R., The quantitative separation of plutonium from various ions by anion exchange *Analytical Chemistry* 34, 1598 (1962)
2. Talvitie, N.A. Radiochemical determination of plutonium in environmental and biological samples by ion exchange *Analytical Chemistry* 43, 1827 (1971)

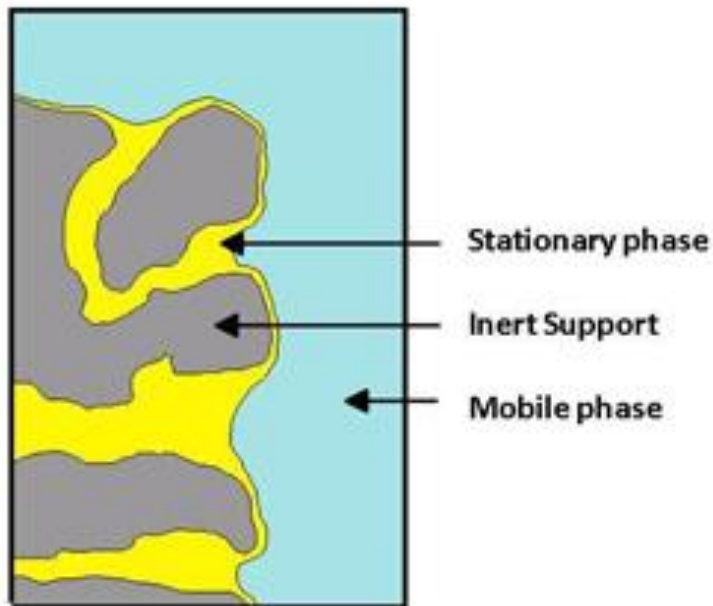
Extraction Chromatography

- Extraction chromatography (EXC) is a special form of liquid-liquid column chromatography.
- In regular partition chromatography, the analyte undergoes little or no chemical change.
- Extraction, however, typically involves chemical changes and the formation of specific complexes.
- These complexes then facilitate the transfer of the ionic solute into the organic phase.

Extraction Chromatography (cont)

- The term extraction chromatography is used if the stationary phase is an organic liquid and the mobile phase an aqueous solution.
- EXC couples the selectivity of the extractants used in liquid-liquid extraction with the multi-stage character of a chromatographic process.
- This method now provides a favorable alternative to ion exchange for many analytical separations.

Extraction Chromatography (cont)



$$D_w = \frac{A_r}{m_r} \div \frac{A_s}{V_s}$$

$$A_r = A_o - A_s$$

$$k' = D_w \times F$$

- Results expressed in terms of k' values.
 - Number of free column volumes to peak maximum
- k' value dependent on the resin.

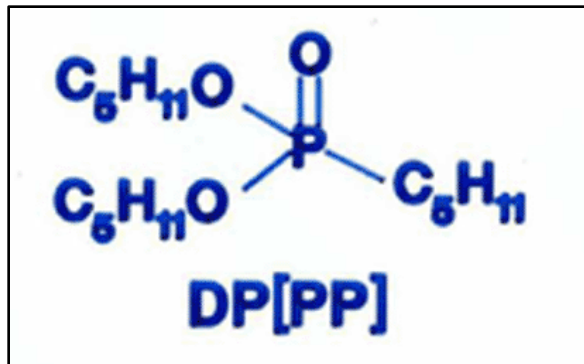
Extraction Chromatography (cont)

Resin	Application	D_w/k'
UTEVA	Th, U, Np, Pu	1.7
TRU	Fe, Th, Pa, U, Np, Pu, Am, Cm	1.8
TEVA	Tc, Th, Np, Pu, Am	1.9
DGA	Actinides, lanthanides	1.75

UTEVA Resin

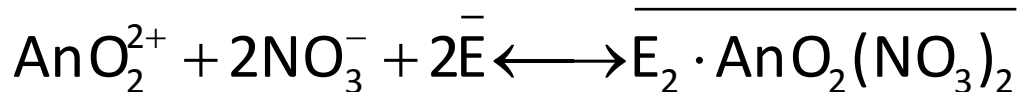
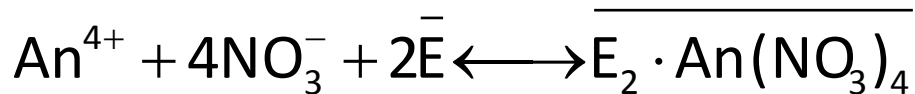
Extractant:

- Diamyl, amyolphosphonate (DAAP)

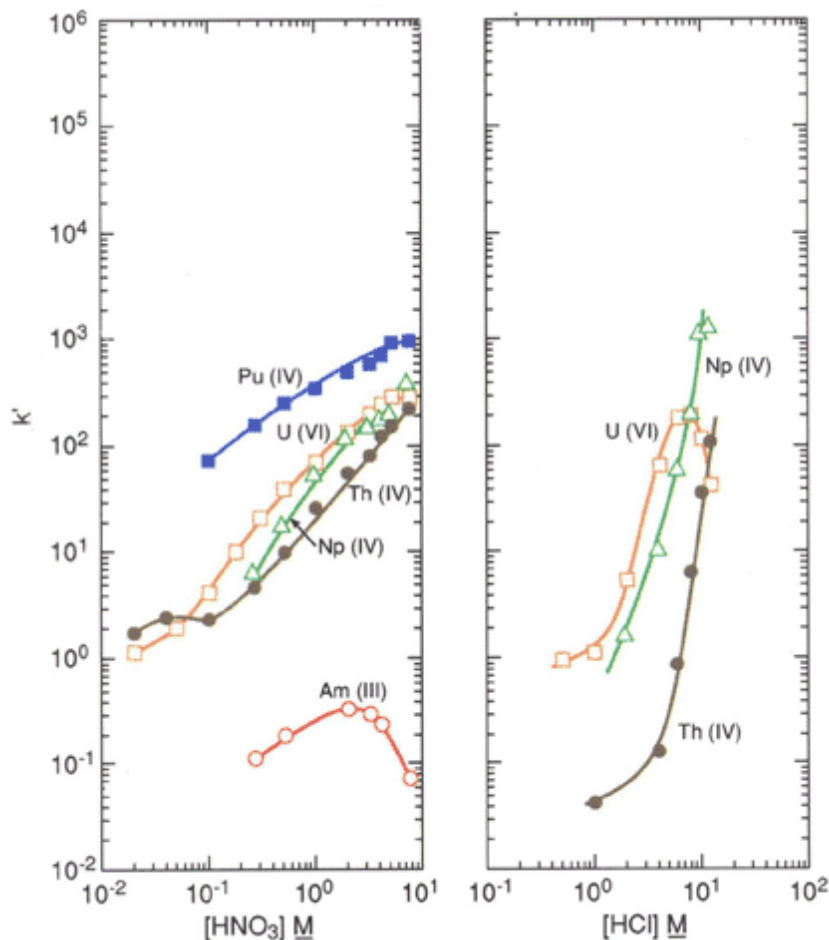


Main applications

- Uranium measurements in environmental samples
- Sample preparation of high uranium content samples
- Sequential determination of U, Pu, and Am
- Measurement of actinides in urine



UTEVA Resin (cont)



$[\text{HNO}_3]$	k'
0.3 M	$\text{Pu} > \text{U} > \text{Np(IV)} \approx \text{Th} > \text{Am}$
8.0 M	$\text{Pu} > \text{Np(IV)} \approx \text{U} \approx \text{Th} > \text{Am}$

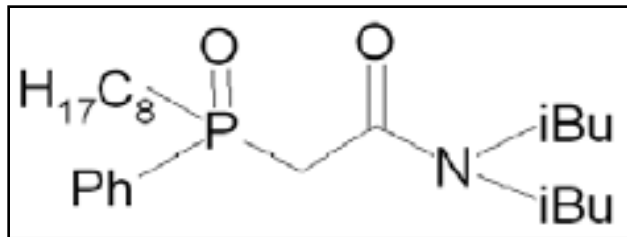
$[\text{HCl}]$	k'
3.0 M	$\text{U} > \text{Np(IV)} > \text{Th}$
8.0 M	$\text{Np(IV)} > \text{U} \approx \text{Th}$

Source: Horwitz, E.P. et al., *Separation and preconcentration of uranium from acidic media by extraction chromatography*, *Analytica Chimica Acta* **266**, 25 (1992)

TRU Resin

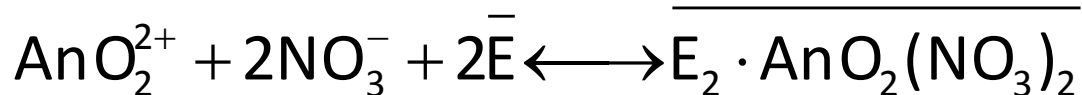
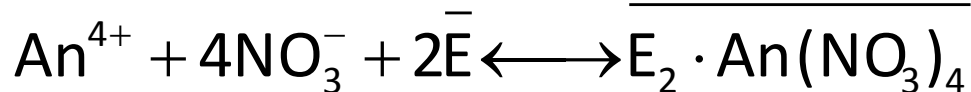
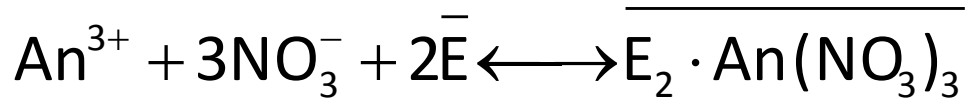
Extractant:

- Octylphenyl-N,N-di-isobutyl carbamoyl phosphine oxide (CMPO) in tributylphosphate

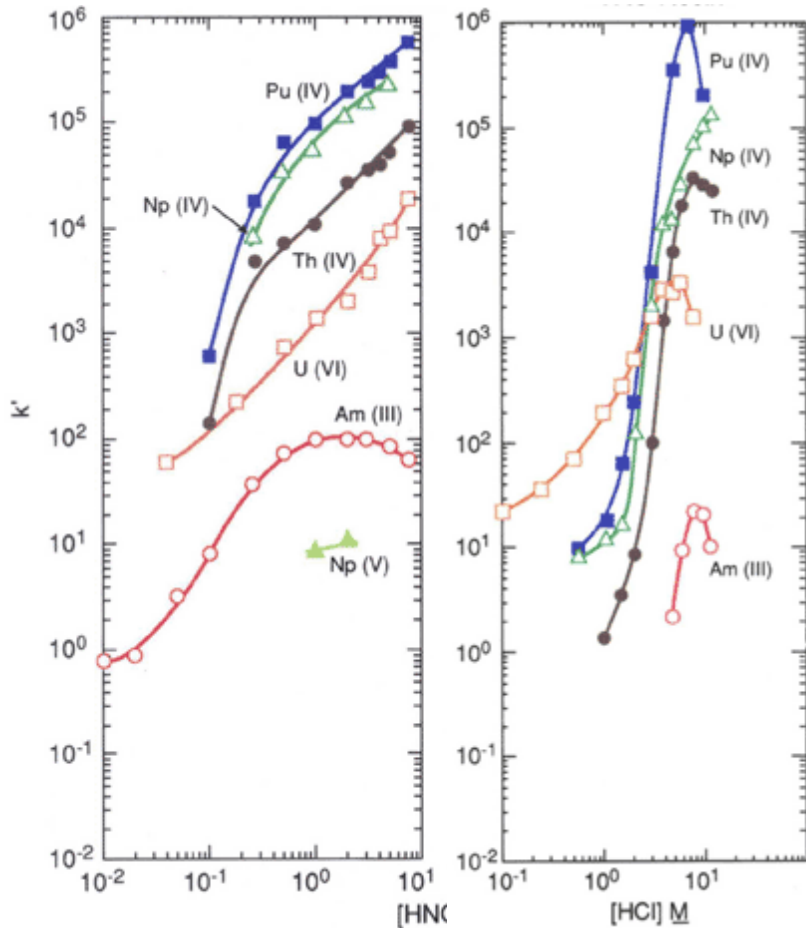


Main applications

- Separation of actinides
- Separation of Fe(III)



TRU Resin (cont)



$[HNO_3]$	k'
0.2 M	Pu > Th \approx U > Am
3.0 M	Pu \approx Np(IV) > Th > U > Am

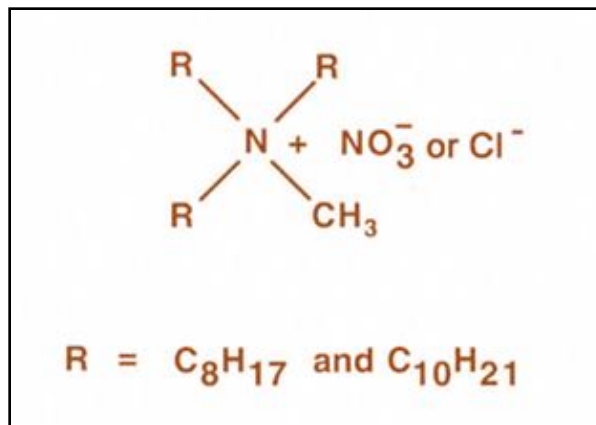
$[HCl]$	k'
1.0 M	U > Pu \approx Np(IV) > Th
8.0 M	Pu > Np(IV) \approx Th > U > Am

Source: Horwitz, E.P. et al., *Separation and preconcentration of actinides from acidic media by extraction chromatography*, *Analytica Chimica Acta* **281**, 361 (1993)

TEVA Resin

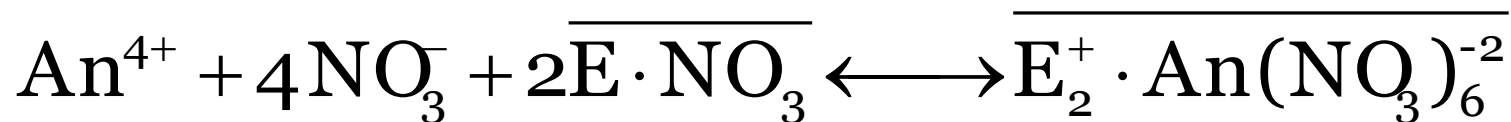
Extractant:

- Trialkylmethylammonium nitrate or chloride (Aliquat-336)

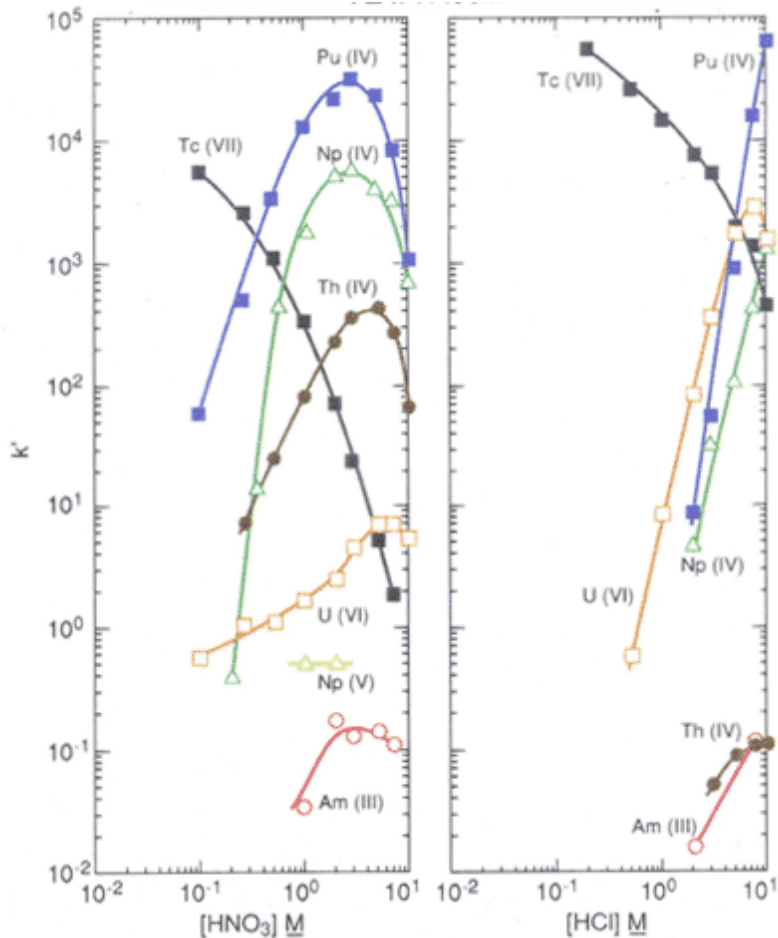


Main applications

- Separation of actinides (IV) and (III)
- Separation of light lanthanides (La-Eu) and Am
- Separation of technetium



TEVA Resin (cont)



[HNO ₃]	k'
0.3	Pu >> Th > U > Np(IV) >> Am
3.0 M	Pu > Np(IV) > Th >> U >> Am

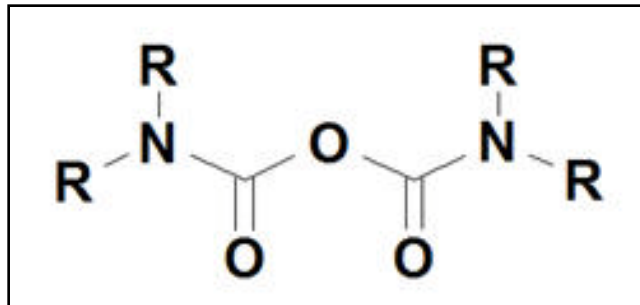
[HCl]	k'
3.0 M	U > Pu ≈ Np(IV) >> Th > Am
8.0 M	Pu > U > Np(IV) >> Th ≈ Am

Source: Horwitz, E.P. et al., *Separation and preconcentration of actinides by extraction chromatography using a supported liquid anion exchanger*, *Analytica Chimica Acta* **310**, 63 (1995)

DGA Resin

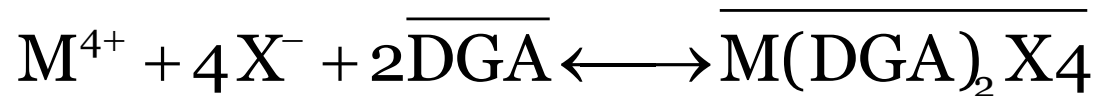
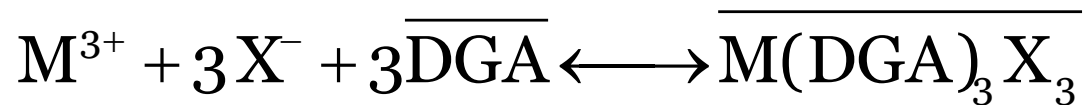
Extractant:

- N,N,N',N'-tetra-n-octyldiglycolamide (DGA normal)

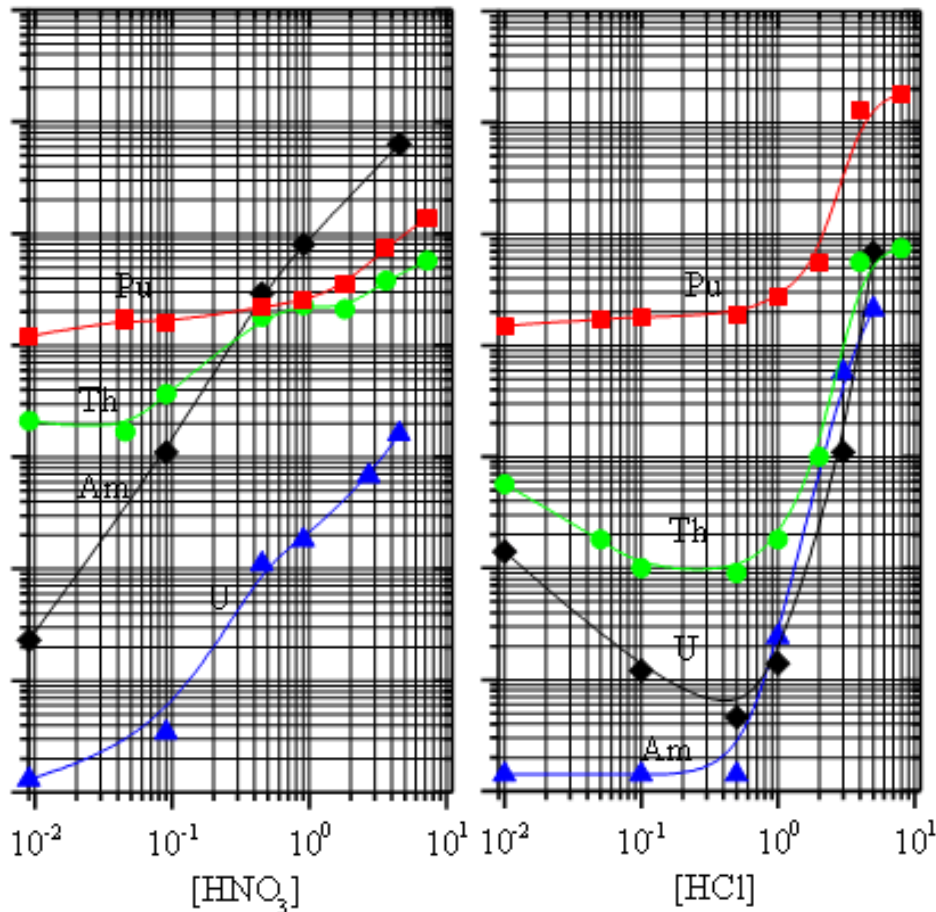


Main applications

- Separation of Am
- Separation of Ra/Ac and Ca/Sr/Y



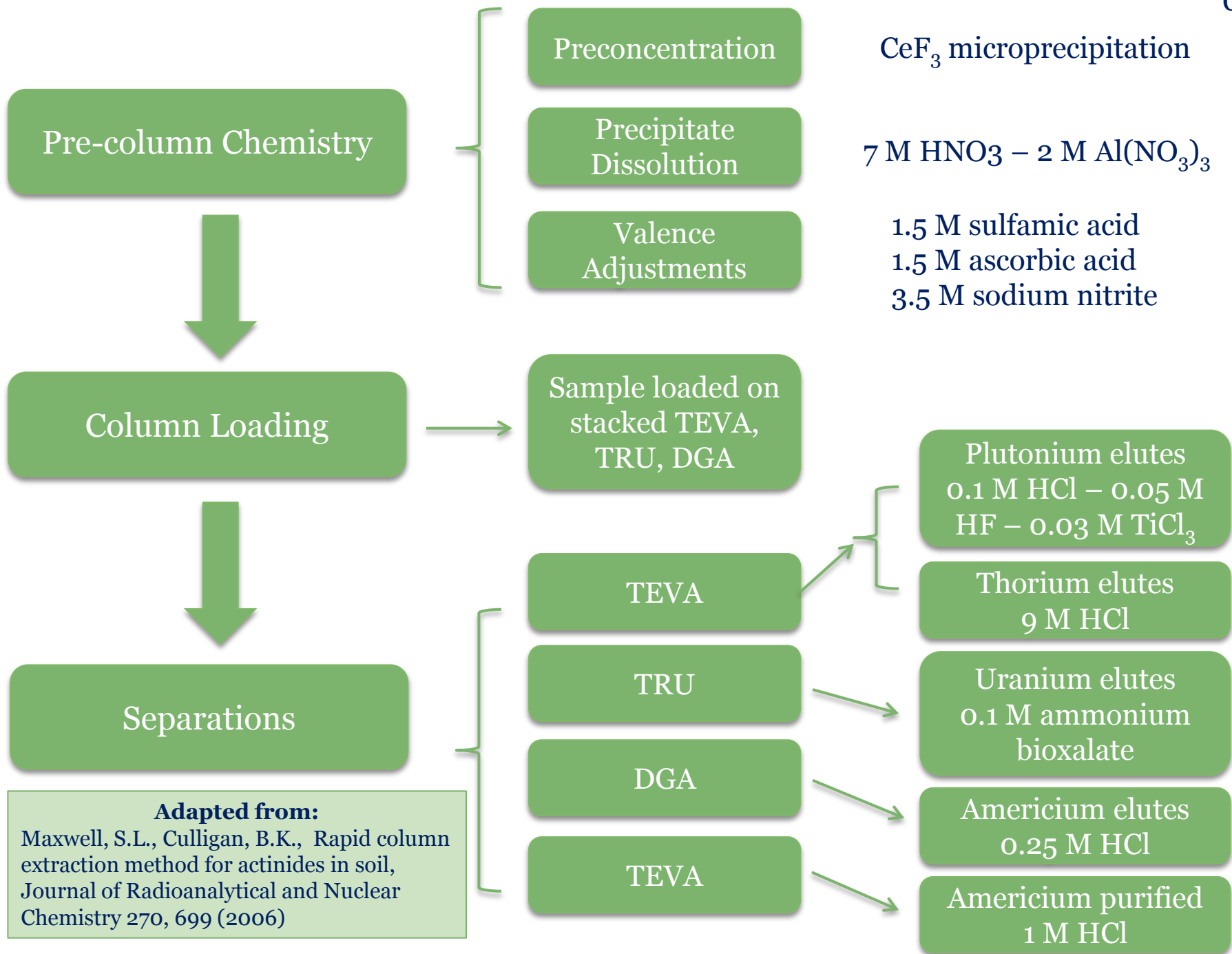
DGA Resin (cont)



[HNO ₃]	k'
0.1 M	Pu > Th > Am > U
1.0 M	Am > Pu ≈ Th > U

[HCl]	k'
0.1 M	Pu > Th > Am > U
5.0 M	Pu > Th ≈ Am ≈ U

Source: Horwitz, E.P. et al., *Novel extraction chromatographic resins based on tetraalkyldiglycolamides: Characterization and potential applications*, Solvent Extraction Ion Exchange **23**, 219 (2005)



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4. U.S. Department of Homeland Security Environmental Measurements Laboratory, *EML Procedures Manual*, 28th Edition, HASL-300 (1997)

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