Sorption of Rare-Earth Elements and Ac on UTEVA Resin in Different Acid Solutions

G. Marinov a, b, A. Marinova a, M. Milanova b, S. Happel c, N. A. Lebedev a, Abigail Drokhlyansky d, Nijat Mirzayev a, b, D. V. Karaivanov a, f, and D. V. Filosofov a

aDLNP Department of Radiochemistry, Joint Institute for Nuclear Research, Dubna, Russian Federation; bDepartment of Inorganic Chemistry, University of Sofia, Sofia, Bulgaria; cR&D Department, Triskem International, Bruz, France; dDepartment of Physics, MIT, Cambridge, MA, USA; eLaboratory of Radiochemistry, Institute of Radiation Problems of National Academy of Sciences of Azerbaijan, Baku, Azerbaijan; fLaboratory of Nuclear Electronics and Mössbauer Spectroscopy, Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

ABSTRACT

The distribution of some rare-earth elements (REEs) on Uranium and TETraValent Actinides (UTEVA) resin was determined from different concentrations of inorganic (HCl, HNO₃, HClO₄, HPF₆) and one organic acid – CCl₃COOH. Low sorption of all REEs in the range of 1 M – 5 M HNO₃ was observed. In more concentrated HNO₃, a rapid increase of the distribution coefficients ($K_d$) was noticed with an increase in the atomic number of the lanthanides as well as in Y and Sc. The system UTEVA–CCl₃COOH showed a higher selectivity for Eu(III). Chromatographic elution profiles were checked in order to confirm the obtained $K_d$ values.

KEYWORDS

REE; UTEVA; distribution coefficients; inorganic acids; trichloracetic acid

Introduction

The 15 lanthanides (Ln) together with scandium and yttrium are often described as the rare-earth elements (REEs). The REEs are divided in two subgroups, i.e. light rare-earth elements (LREEs) from lanthanum to europium and heavy rare-earth elements (HREEs) from gadolinium to lutetium. Some authors include yttrium in the heavy REE and exclude scandium due to its much smaller ionic radius.¹,² All REEs have wide applications in modern technologies, such as in magnets, electronics, lasers, scientific research, etc. These applications usually require purifying the elements before use.³⁻⁸ These elements also appear as decay products in spent nuclear fuel. To reuse this fuel, it needs to be regenerated; therefore, effective methods for separating or purifying the actinides (An), such as Ac, Th, U, etc., from REE (III) have to be applied.⁹⁻¹¹ Other than that, the purification of REE from An is important for use in medicine as radiopharmaceuticals.¹²,¹³

Chromatographic extraction is a promising way for the separation and purification of elements. In recent years, there has been a significant development of extraction chromatographic resins; one such resin is UTEVA (Uranium and TEtraValent Actinides). UTEVA is a commercially available resin with main application in the separation of tetravalent An, and it consists of the extractant dipentyl pentylphosphonate (DP[PP]) coated on an inert support.¹⁴ Recently, distribution coefficients ($K_d$) for a number of elements were determined for UTEVA resin, but so far no data is available for REE on this resin.¹⁵ The main purpose of UTEVA is the separation of tetravalent An; moreover, there is information about one trivalent An (Am (III)) in HNO₃. Am (III) has chemical properties similar to those of the lanthanides, and mostly to those of Eu, so by its properties it is in the middle of the Ln row. The properties of the elements from the Ln row gradually change from one...
end to the other, so there is need for more information on the behavior of the REEs on this extracting resin in order to correctly evaluate the possibility for the separation of REEs and An.

Therefore, the distribution of REEs and Ac on UTEVA resin with elution solutions HNO₃, HCl, HPF₆, HClO₄, and CCl₃COOH is the focus of the present research. Subsequently, an additional study was carried out with solutions containing trace amounts of Th and large amounts of Nd and Yb. Considering the fact that the trivalent state of REE is the most common one and that there are An with the same valent state, it is worth determining the $K_d$ for REE (III) with the UTEVA resin.

Materials and methods

The radioactive tracers $^{46}$Sc, $^{88}$Y, $^{139}$Ce, $^{155}$Eu, $^{153}$Gd, $^{173}$Lu, $^{225}$Ac, and $^{227}$Th were used in this research, allowing all measurements to be performed by gamma spectrometry. All Ln isotopes were produced through proton irradiation of a metallic Ta target on the Phasotron (at the Joint Institute for Nuclear Research (JINR), Russia). The other isotopes were obtained as follows: Sc was acquired from a proton-irradiated V target, Y from a Mo target, and Th and Ac from a Th target. For the Th experiment, stable Nd and Yb oxides were used (standard – ТУ 48-4-523-90). To analyze the radionuclides, an Ortec γ-ray spectrometer with an HPGe detector system and Samar software was used. The dead time of the detector was always kept below 7%.[16]

The acquisition of Ln(III) for the research involved dissolving the irradiated Ta target and separating the Ln(III) isotopes as a group prior to separating the individual Ln(III) from one another. This was accomplished by placing ammonium α-hydroxyisobutyrate in a column filled with the small cation-exchange resin Aminex A6.[17]

UTEVA resin (with sizes 100–150 μm and 50–100 μm) was provided by Triskem International (Bruz, France) and used without further processing. All acids used were of analytical grade from Himmed, Sigmatec (Moscow region, Russia) and Sigma-Aldrich Co. LLC.

Distribution coefficients

Calculation of $K_d$

$K_d$ [mL/g] was calculated using the ratio of radioactivities:

$$K_d = \frac{C_{eq1}}{C_{eq2}} = \frac{A_0 - A_{eq}}{A_{eq}} \times \frac{V}{m}$$

where $C_{eq1}$ is the equilibrium concentration in the organic phase, $C_{eq2}$ is the equilibrium concentration in the aqueous phase, $A_0$ [Bq] is the activity of the initial solution, $A_{eq}$ [Bq] is the activity of the equilibrium solution, $V$ [mL] is the volume of the equilibrium solution, and $m$ [g] is the mass of the resin.

Chemical procedure for the determination of $K_d$

All solutions containing the chosen radionuclides were evaporated to dryness under an IR lamp. Afterward, the samples were converted to the corresponding form (i.e. nitrate, chloride, etc.). The stock solutions were obtained by diluting the resulting dry samples with 1 M solutions of their respective acids (HNO₃, HCl, HPF₆, HClO₄, and CCl₃COOH).

Three types of spiked solutions were prepared, containing:

1. $^{46}$Sc, $^{153}$Gd, $^{139}$Ce, and $^{88}$Y for each acid type,
2. $^{155}$Eu, $^{173}$Lu, and $^{225}$Ac for each acid type, and
3. $^{227}$Th for HNO₃ with large amounts of Nd and Yb both in nitrate form.
The following batch technique was used to determine the $K_d$: dry UTEVA resin (particle size 100–150 μm) with mass 50 mg was placed in test tubes (Eppendorf®). Then, 1 mL of radionuclide spiked solutions with specific acid concentrations was added to each resin sample and mixed for 48 hours. All mixed samples were analyzed by γ-ray spectrometry. After mixing, the aqueous phase was filtered through a 20-μm polymer filter (by Triskm international). Around 0.9 mL samples were taken for analysis by γ-ray spectrometry. The $^{225}$Ac samples were measured after ingrowth of the daughter radionuclide $^{221}$Fr (1 hour). To precisely measure the volume, 1 mL of radionuclide spiked solutions was mixed with resin and the filtered aliquot was weighed.

**Chromatographic elutions**

Column elutions were carried out to confirm the $K_d$ and observe the behavior of Ln under certain conditions. The experiments were made using a glass column (h = 14.5 cm; d = 3.3 mm) filled with UTEVA resin (particles size 50–100 μm). The smaller resin size was chosen to enhance the separation efficiency. The elution in the system UTEVA–CCl$_3$COOH was isocratic with 0.05M trichloroacetic acid. In the UTEVA–HNO$_3$ system, the separation was completed in steps: first, the spiked solution was loaded with 16 M HNO$_3$, and then the column was washed with 2 mL 16 M HNO$_3$, followed by 13 mL 10 M HNO$_3$.

**Results and discussions**

$K_d$ of REE and Ac

The ranges in the concentration of the mineral acids used were: 0.01 M–15.8 M HNO$_3$, 0.01 M–10 M HCl, 0.01 M–8.9 M HClO$_4$, and 0.01 M–3 M HPF$_6$ (Fig. 1).

Based on the results in the system, the following can be said about the UTEVA-mineral acids.

HNO$_3$: In high concentrations of HNO$_3$, the separation of Lu and Y from the LREEs and Ac presents an interesting result. Also, in low concentrations of HNO$_3$, Sc can be separated efficiently from the other REE and Ac. This can be due to its smaller ionic radii compared with the other researched elements.

![Figure 1](image_url). Distribution coefficients for Sc, Y, Ce, Eu, Gd, Lu, and Ac on UTEVA resin with mineral acids. All elements with a $K_d$ value below 1 are not retained on the resin.
HCl: Scandium is retained in the lowest and highest concentrations alike, except for in the range of 1 M–3 M HCl. Regarding the other elements, they are not retained at any concentration of HCl, leading to the possibility of purifying Sc.

HClO₄: Sc can be separated from Y, Ce, Eu, Gd, Lu, and Ac in all concentrations, although the latter group of elements has some retention on the resin in high concentrations.

HPF₆: The use of HPF₆ may enable the separation of Sc and Gd from the other REE, since both elements are not retained unlike the others in HPF₆. It may be possible to separate Ac from LREE in the range of 0.05–3 M HPF₆ and from HREE in the range of 0.03–0.1 M HPF₆. The range above 3 M HPF₆ was not investigated because of the highly reactive nature of this acid, as well as to avoid compromising the integrity of the resin.

Sc differs from the other REEs in all acids, which could be due to its smaller ionic radii, allowing it to have pronounced differences in its properties toward the sorbent. The sorption of Sc is similar to that of Hf and Zr, which have very close ionic radii to that of Sc.\(^\text{[15]}\)

For the UTEVA–organic acid system, the following can be said.

CCl₃COOH: With the UTEVA–CCl₃COOH system, Sc could be separated from Ln. Ac has a similar distribution to that of Ln (Fig. 2). From the acquired data, it appears possible to separate Eu from Gd and LREE from HREE with 0.05 M–0.1 M CCl₃COOH. In CCl₃COOH, Sc has a \(K_d\) > 1000 throughout the entire range of concentrations, except in 3 M CCl₃COOH, where the \(K_d\) drops to 130 (Fig. 3).

Similarities observed in the chemical behaviors and distributions of Ln(III) and Ac(III) can be explained based on the similar ionic radii of these trivalent elements.

There is data available on the distributions of some Ln and Ac, which has been reported for the Triskem resins – TRU (TRansUranian elements), LN (LaNthanides), and DGA (DiGlicolAmide). However, the common choice of eluent is HNO₃ and on some occasions HCl.\(^\text{[18]}\) Researching additional eluting solutions is a key step toward the optimization of separation processes.

---

**Figure 2.** Distribution coefficients for Y, Ce, Eu, Gd, Lu, and Ac on UTEVA resin with CCl₃COOH.
The $K_d$ results for Sc show a similar distribution in three of the mineral acids used, namely HNO$_3$, HCl, and HClO$_4$ (Fig. 3). Throughout the range of concentrations, the $K_d$ for Sc in HPF$_6$ is less than one, such that it shows no retention on the resin. In the organic acid CCl$_3$COOH, the $K_d$ is higher at low concentrations, while an increase in concentration leads to lower values. At the highest concentration of CCl$_3$COOH, the $K_d$ value is high enough for the element to be retained on the resin. These results show that Sc can be retained and eluted with a combination of acids, as well as with one single medium.

Sc can be separated from Th in the range of 0.05 M–10 M HNO$_3$ because the determined $K_d$ for Sc are with the lower values than those of Th; in some cases, the difference of $K_d$ reaches one order of magnitude.

**Chemical processes**

There are a number of suggested possible extraction mechanisms for the extraction of metal ions on an extraction resin.\textsuperscript{19} The extraction process could proceed by different reactions. The following mechanisms describe the possible equilibrated states.

The interactions mechanisms (IA–IVA) are often presented for chromatographic extraction.
When working with excess of acid in the aqueous phase, there is a strong possibility for the interactions of the acid with the extractant:

\[
\begin{align*}
\text{Me}^{n+} + n\text{A}^- + sL & \rightleftharpoons (\text{MeL})^{s+} + n\text{A}^- && (I) \\
(\text{MeL})^{s+} & \text{nA}^- + sH^+ + (s-n)\text{A}^- && (II) \\
(\text{MeL})^{s+} & \text{nA}^- + sH^+ + (s-n)\text{A}^- && (III)
\end{align*}
\]

The processes presented below can be considered when using trace amounts of the targeted metals and excess of acid \([\text{H}^+ \gg [\text{Me}^{n+}]]\).

\[
\begin{align*}
\text{H}^+ + \text{A}^- + \frac{1}{2} & \rightleftharpoons (\text{HL})^+ + \text{A}^- && (I) \\
(\text{HL})^+ & \frac{1}{2}\text{A}^- && (II)
\end{align*}
\]

where \(\text{H}^+\) is a proton, \(\text{A}^-\) is the acid anion, \(\text{L}\) is the ligand, and \(\text{Me}^{n+}\) is a metal ion. The underlining represents the species that are in the organic phase. \(\rightleftharpoons\) - represents separated ion pairs. Contact ion pairs are represented in the reactions product with no symbol and no space between the positive and negative ions (as in (III)).
The mechanism can change with different concentrations of acid and/or Me$^{n+}$. When working with low concentrations of Me$^{n+}$ and excess of acid in the aqueous phase, there is a strong possibility for the interactions of the acid with the extractant as presented in (IB) through (IVB). The Me$^{n+}$ can than interact with these stages by mechanisms (IC-VIE) with different concentrations where the Me$^{n+}$ will substitute the H$^+$ ion. It should be said that the acids strength increases in the order: CCl$_3$COOH, HNO$_3$, HCl, HClO$_4$, HPF$_6$. For the two strongest acids (HClO$_4$, HPF$_6$), the expected mechanisms for their interaction with the extractant are (IA) and (IIA) as for HClO$_4$, HPF$_6$, those reactions can switch depending on the concentration of the acid. For the other three (CCl$_3$COOH, HNO$_3$, HCl), the most likely mechanisms are (IIIA) and (IVA) as they too can switch depending on the concentration of the acid. The mechanisms B, C, D, and E can be considered for the Me$^{n+}$ interaction with the medium. The products (V) and (VI) present intermediate states. In the case of ion interactions, there could be ion pairs. For CCl$_3$COOH, HNO$_3$, and HCl, the most probable mechanisms are (III) and (IV) B, C, D, and E; as for HClO$_4$, HPF$_6$ (II) and (III) B, C, D, and E are possible or (V) and (VI) C, D, and E if the reaction is considered as an ion mechanism. The number of interacting extractant molecules (s) taking part in the reactions is limited and difficult to determine as it is coated and fixed onto the resins base.

The results for Sc in HNO$_3$, HCl, and HClO$_4$ represent the change in mechanism with the reversal of the slope of the curve. There is no sorption of Sc with HPF$_6$ in the UTEVA resin. For Sc distribution in the organic phase, there is a minimum requirement for two of the acids anions to coordinate closely together; for PF$_6^-$ this is not fulfilled.

**K$_d$ of Th in large amounts of Nd and Yb**

The separation of Th and U from large amounts of Ln is an important point of interest. Thus far, tetravalent elements and U have been thoroughly investigated on UTEVA in nitric acid solutions. However, to date, no data has been published concerning the distribution of Ln on UTEVA. Using the distribution ratios described above and the previously published data for Th, a study of K$_d$ was performed.[14] For large amounts of Ln, two representatives were chosen: Nd from the light REE and Yb from the heavy REE. Nitric acid solutions of the two lanthanides were prepared and then the batch technique described above was applied.

The results show that the K$_d$ for Th, in the presence of large amounts of Nd, follows the original distribution due to the low retention factor of Nd on the resin (Fig. 4).[14] However, the Th distribution in the presence of large amounts of the heavier element Yb decreases with an increase in the concentration (Fig. 5). This correlates with the data for the other heavy lanthanide Lu, for which the K$_d$ in high concentrations of HNO$_3$ increases. Large amounts of Yb adsorb on the resin, leaving most of the Th in the aqueous phase.

**Dynamic systems**

In addition to determining K$_d$ as described above, two elution profiles of REE were investigated for the system: UTEVA-HNO$_3$ and UTEVA-CCl$_3$COOH.

**Uranium and Tetravalent Actinides – UTEVA –HNO$_3$**

In the UTEVA–HNO$_3$ system, REEs were eluted consecutively with some overlap, using a column (described in “Materials and methods” and resins particle size of 50–100 μm) (Fig. 6). The order of elution followed the decreasing ionic radii of the REEs (Table 1).[11]

The LREEs in this system elute first similar to other methods based on extraction (namely HDEHP, DGA, etc.). The system shows good separation of LREEs from HREEs.

Solutions of HNO$_3$ acid with two concentrations (10 M and 16 M) were used to optimize separation. Here it can be seen that the elements eluted consequently rather than simultaneously. As the most commonly used acid, HNO$_3$ proved to be a suitable eluent in high concentrations for the separation of lanthanides on the UTEVA resin.
The second system studied in this research was isocratic elution through a glass UTEVA column with 0.05 M CCl$_3$COOH (Fig. 7). The elements with smaller ionic radii were eluted first, followed by the ones with larger ionic radii. It was observed that the HREEs were eluted as a group together with Y. From a scientific point of view, the elution of the Gd and Eu peaks with CCl$_3$COOH is a significant result. As this pair of adjacent radionuclides is the only one showing difference of the elution of the peaks, the elution profile of the studied REE confirms the above-determined K$_d$.

For both separation systems, UTEVA–HNO$_3$ and UTEVA–CCl$_3$COOH, the retention of the elements is in accordance with their determined K$_d$. 

_Uranium and TEtraValent Actinides – UTEVA –CCl$_3$COOH_

The second system studied in this research was isocratic elution through a glass UTEVA column with 0.05 M CCl$_3$COOH (Fig. 7). The elements with smaller ionic radii were eluted first, followed by the ones with larger ionic radii. It was observed that the HREEs were eluted as a group together with Y. From a scientific point of view, the elution of the Gd and Eu peaks with CCl$_3$COOH is a significant result. As this pair of adjacent radionuclides is the only one showing difference of the elution of the peaks, the elution profile of the studied REE confirms the above-determined K$_d$.

For both separation systems, UTEVA–HNO$_3$ and UTEVA–CCl$_3$COOH, the retention of the elements is in accordance with their determined K$_d$. 

**Figure 4.** Distribution coefficients of $^{227}$Th on UTEVA resin with 0.3, 1, and 2 M Nd(NO$_3$)$_3$. 

SOLVENT EXTRACTION AND ION EXCHANGE  

287
Figure 5. Distribution coefficients of $^{227}$Th on UTEVA resin with 0.3, 1, and 2 M Yb(NO$_3$)$_3$.

Figure 6. Elution profile of REE in the UTEVA-HNO$_3$ system with 16 M and 10 M HNO$_3$, UTEVA (particle size 50–100 μm). The volume of each collected fraction is 90 μL.
| CN | Ac³⁺ | La³⁺ | Ce³⁺ | Pr³⁺ | Nd³⁺ | Am³⁺ | Pm³⁺ | Sm³⁺ | Eu³⁺ | Gd³⁺ | Tb³⁺ | Dy³⁺ | Ho³⁺ | Er³⁺ | Tm³⁺ | Yb³⁺ | Lu³⁺ | Y³⁺ | Sc³⁺ |
|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| VI | 1.12 | 1.032| 1.010| 0.990| 0.983| **0.975**| 0.970| 0.958| 0.947| 0.938| 0.923| 0.912| 0.901| 0.890| 0.880| 0.868| 0.861| 0.900| 0.745|
| VII| –    | 1.100| 1.070| –    | –    | –    | –    | 1.020| 1.010| 1.000| 0.980| 0.970| –    | 0.945| –    | 0.925| –    | 0.960| –    |
| VIII| –   | 1.160| 1.143| 1.126| 1.109| **1.09**| 1.093| 1.079| 1.066| 1.053| 1.040| 1.027| 1.015| 1.004| 0.994| 0.985| 0.977| 1.019| 0.870|
| IX | –    | 1.216| 1.196| 1.179| 1.163| –    | 1.144| 1.132| 1.120| 1.107| 1.095| 1.083| 1.072| 1.062| 1.052| 1.042| 1.032| 1.075| –    |
| X  | –    | 1.270| 1.250| –    | –    | –    | –    | –    | –    | –    | –    | –    | –    | 1.120| –    | –    | –    | –    | –    | –    |
| XII| –   | 1.260| 1.340| –    | 1.270| –    | 1.240| –    | –    | –    | –    | –    | –    | –    | –    | –    | –    | –    | –    | –    |

Table 1: Effective ionic radii [Å] of all REE, Ac, and Am with different coordination numbers (CN).[1]
Conclusions

The values for $K_d$ of REEs on UTEVA determined in this work confirm the possibility for the separation of REEs from tetravalent An. As it was important to check the dependence of the sorption on UTEVA for large amounts of the trivalent REEs from the tetravalent An, the $K_d$ for Th in the presence of large amounts of Nd and Yb was researched. The low sorption of Nd allowed for Th to be sorbed onto the resin following its original sorption. When Yb was in large amounts, it is preferentially sorbed in high concentrations of HNO$_3$ and in the low range of acid concentration where Yb has low $K_d$ and Th has higher sorption.

The values for $K_d$ of REE on the UTEVA resin were confirmed via elution experiments. The results can be used for the future purification of tetravalent An from REEs. The $K_d$ values determined here show that Sc can be separated from the other REEs by using any of the studied acids with UTEVA. Furthermore, taking into account the data for Th, it can be said that Sc can be separated well from Th in nitric acid. Using highly concentrated nitric acid solutions allows for the separation of REE in the UTEVA–HNO$_3$ system. An efficient separation of tetravalent An from trivalent lanthanides can be performed using UTEVA with HCl. In the UTEVA–CCl$_3$COOH system, the values of $K_d$ for Ac are close to those for Ln, so Ac cannot be separated from Ln. However, this system shows that the pair of Eu and Gd does not elute simultaneously as Gd peaks before Eu.

ORCID

G. Marinov http://orcid.org/0000-0002-5252-0548

References

1. Shannon, R.D. Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. Acta Cryst. 1976, A32, 751–767. doi: 10.1107/S0567739476001551
2. Jha, Manis Kumar; Kumari, Archana; Panda, Rekha; Kumar, J. Rajesh; Yoo, Kyoungkeun; Lee, Jin Young. Review on hydrometallurgical recovery of rare earth metals. Hydrometallurgy. 2016, 165(Part 1), 2–26. doi: 10.1016/j.hydromet.2016.01.035
3. Xie, Feng; Zhang, Ting An; Dreisinger, David; Doyle, Fiona. A critical review on solvent extraction of rare earths from aqueous solutions. Miner. Eng. 2014, 56, 10–28. doi: 10.1016/j.mineng.2013.10.021.
4. Knutson, Hans-Kristian; Holmqvist, Anders; Nilsson, Bernt. Multi-objective optimization of chromatographic rare earth element separation. J. Chromatography A. 2015, 1416, 57–63. doi: 10.1016/j.chroma.2015.09.010.

5. Harlov, Daniel. Petrological and experimental application of REE- and actinide-bearing accessory minerals to the study of Precambrian high-grade gneiss terranes. GSA Memoirs. 2011, 207, 13–24. doi: 10.1130/2011.1207(02).

6. European Commission. Critical Raw Materials for EU, 2010.

7. European Commission. Report on Critical Raw Materials for EU, 2014.

8. Chakhmouradian, A.R.; Wall, F. Rare earth elements: minerals, mines, magnets (and more). Elements. 2012, 8(5), 333–340. doi: 10.2113/gselements.8.5.333.

9. Polischuk, O.G.; Barabash, A.S.; Belli, P.; Bernabei, R.; Boiko, R.S.; Cappella, F.; Cerulli, R.; Danevich, F.A.; Incicchitti, A.; Laubenstein, M.; Mokina, V.M.; Nisi, S.; Poda, D.V.; Tretyak, V.I. Purification of Lanthanoids for Double Beta Decay Experiments. AIP Conference Proceedings. 2013, 1549, 124. doi: 10.1063/1.4818091.

10. Sun, Xiaoqi; Do-Thanh, Chi-Linh; Luo, Huimin; Dai, Sheng. The optimization of an ionic liquid-based TALSPEAK-like process for rare earth ions separation. Chem. Eng. J. 2014, 239, 392–398. doi: 10.1016/j.cej.2013.11.041.

11. Pin, Christian; Zalduegui, JoséFrancisco Santos. Sequential separation of light rare-earth elements, thorium and uranium by miniaturized extraction chromatography: application to isotopic analyses of silicate rocks. Anal. Chim. Acta. 1997, 339, 79–89. doi: 10.1016/S0003-2670(96)00499-0.

12. Borchardt, Paul E.; Yuan, Rui R.; Miederer, Matthias; McDevitt, Michael R.; Scheinberg, David A. Targeted actinium-225 in vivo generators for therapy of ovarian cancer. Cancer Res. 2003, 63, 5084–5090.

13. King, A. Gaylord; Miller, William, H.; Givens, Kenneth, R.; Bond, Andrew; Glascock, Mike; Rangaraj, Dharanipathy; Horwitz, E. Philip; McAlister, Daniel R. Approaches to manufacturing alpha emitters for radioimmunotherapeutic drugs. AIP Conference Proceedings. 2003, 680, 1133. doi: 10.1063/1.1619908.

14. Horwitz, E.P.; Dietz, Mark L.; Chiarizia, Renato; Diamond, Herbert. Separation and preconcentration of uranium from acidic media by extraction chromatography. Anal. Chim. Acta. 1992, 266, 25–37. doi: 10.1016/0003-2670(92)85276-C.

15. Marinov, G.M.; Marinova, A.P.; Medvedev, D.V.; Dadakhanov, J.A.; Milanov, M.M.; Happel, S.; Radchenko, V. I; Filosofov, D.V. Determination of distribution coefficients (Kd) of various radionuclides on UTEVA resin. Radiochimica Acta. 2016, 104(10), 735–742. doi: 10.1515/ract-2016-2582.

16. Filosofov, D.V.; Rakhimov, A.V.; Bozhikov, G.A.; Karaivanov, D.V.; Lebedev, N.A.; Novgorodov, A.F.; Sadikov, I.I. Isolation of radionuclides from thorium targets irradiated with 300-MeV protons. Radiochemistry 2013, 55(4), 410–417. doi: 10.1134/S1066362213040127.

17. Mo, Han Hen; Avdeeva, N.S.; Lebedev, N.A.; Novgorodov, A.F.; Halkin, V. A. Accelerated chromatographic separation of actinium and REE on DGA, Ln and TRU resins in nitric acid solutions. J. Radioanal. Nucl. Chem. 2015, 306(3), 707–711. doi: 10.1007/s10967-015-4331-y.

18. Ostapenko, V.; Vasilev, A.; Lapshina, E.; Ermolaev, S.; Aleev, R.; Totskii, Yu.; Zhuikov, B.; Kalmykov, S. Extraction chromatographic behavior of actinium and REE on DGA, Ln and TRU resins in nitric acid solutions. J. Radioanal. Nucl. Chem. 2015, 306(3), 707–711. doi: 10.1007/s10967-015-4331-y.

19. Filosofov, Dmitry V.; Lebedev, Nikolai A.; Radchenko, Valery; Rakhimov, Alimardon; Halkin, V. Frank. Behavior of actinium, alkaline, and rare earth elements in Sr-resin/mineral acid systems. Solvent Extr. Ion Exch. 2015, 33(5), 496–509. doi: 10.1080/07366299.2015.1046293.