Introduction

Up to now, nuclear power, which has an important role in the global energy scenario, mainly depends on the uranium fuel cycle. With the gradual consumption of uranium resources, thorium, as a fertile material, has attracted increasing attention due to its abundant reserves, and excellent nuclear and physical properties. In the thorium fuel cycle, the fissile isotopic of $^{233}\text{U}$, which can produce a large amount of energy and some fission products (FPs), such as Zr, Nb and Ru by further nuclear fission, would be generated by neutron adsorption of $^{232}\text{Th}$. As with the uranium fuel cycle, the reprocessing of irradiated thorium, in which the essential requirements are the recovery and decontamination of Th and U, is also an important component of the thorium fuel cycle. In the procedure of reprocessing process development, the accurate analysis of Th, U and FPs can provide an important guarantee for process monitoring and control. Taking the analysis of FPs for example, it is essential to calculate the decontamination factor of FPs in the process and quality analysis of Th and U product. In the previous reports, various radioactive and spectroscopic methods have been developed to meet the analysis demand of FPs. In the “hot” test and real spent fuel reprocessing, the FPs possess high-level radioactivity, thus they are usually preferentially determined by using a radioactivity analysis method, such as $\gamma$ energy spectrum and liquid scintillation counter. However, the “cold” research is the necessary step before the “hot” test and real spent fuel reprocessing. In this step, the simulated feed solution containing stable isotopes of FPs without radioactivity is used, so the spectroscopic methods including atomic emission spectrometry (AES) and mass spectrometry (MS) are usually available for determination of trace FPs. Among these methods, inductively coupled plasma mass spectrometry (ICP-MS) has attracted special attention due to its simultaneous measurement capability, wide analytical dynamic range and high sensitivity. A number of studies have focused on the application of ICP-MS for determining the trace metal elements in nuclear materials like uranium and thorium. Similar to the U-Pu fuel cycle, the FPs generated by irradiation of Th-based fuel usually include alkali metal, alkali earth metal, Zr group, Ru group and rare earth metal with yields from $1 \times 10^{-4}\%$ to $1\%$ according to the burnup. So, the analyte signal of trace FPs would be suppressed or enhanced due to the matrix effects of thorium, thus causing the bias sensitivity and analytical results in quantitative analysis. Moreover, the contamination of instruments due to direct nebulization of high matrix salt solution into ICP-MS is another restriction. Hence, an efficient pretreatment for the selective removal of thorium from the FPs is an essential requirement prior to their accurate determination in Th-based fuel reprocessing.

For the reprocessing of Th-based spent fuel, the first step is to dissolve the spent fuel in $\text{HNO}_3$ or $\text{HCl}$ medium, so the trace FPs would be associated with the thorium matrix in $\text{HNO}_3$ or $\text{HCl}$ medium. For the former, several techniques such as solvent extraction, extraction chromatography and ion-exchange can be used for the removal of thorium matrix for the precise analysis of trace FPs. Thereinto, due to the generation of a large volume of organic radioactive waste in solvent extraction and the short term stability in extraction chromatography, the ion exchange with favorable selectivity and
stability has been extensively studied for the removal of thorium matrix dissolved in HNO₃ medium. The treatment for this kind of sample was usually directly operated in HNO₃ system. Bunney and Fairs elucidated the anion exchange behavior of various elements in 0.1 - 14 mol L⁻¹ of HNO₃ medium to achieve the radiochemical separations between them; Danon and Mohapatra also reported an independent ion-exchange method for separation of Pu from a macro amount of Th in HNO₃ medium. However, for the trace FPs associated with thorium matrix in HCl medium, there have been few studies on the removal of large amounts of thorium. If they are directly treated by using HNO₃ medium, the existence of Cl⁻ in the sample would have an adverse effect on the separation of thorium and trace FPs.

In the present study, to develop a method for the direct determination of some typical FPs with μg-mg L⁻¹ level in thorium and HCl matrix, the anion exchange behavior of FPs and Th in various solutions, especially the effect of Cl⁻ on the exchange behavior in HNO₃ medium, was investigated, and the model experiments were carried out to optimize the parameters for the pre-separation of thorium matrix. Furthermore, the performances of this method, such as recovery, precision and detection limit were also discussed.

**Experimental**

**Instrumentation**

The ICP-AES analyses were carried out using a PerkinElmer Optima 8000 spectrometer, with WinLab32-Ver. 5.2 operating software for full control of all instrument functions and data handling, to determine the concentration of residual thorium after column separation. The instrumental operating conditions and analytical wavelength are listed in Table 1.

The ICP-MS analyses were carried out using a PerkinElmer NexION 300D spectrometer combined with glass homocentric nebulizer to determine the concentration of trace fission elements. The instrumental operating conditions are listed in Table 2.

**Samples and reagents**

A multielement stock solution (1 mg L⁻¹ of Zr, Nb, Ru, Ce, Eu, Sr, Cs, Y and La) was prepared by mixing single-element standard solution (1000 mg L⁻¹ of each element, purchased for calibrating the ICP-MS were prepared by appropriate dilution of 1000 mg L⁻¹ of each element, purchased for calibrating the ICP-MS were prepared by appropriate dilution of the 1 mg L⁻¹ stock solution with 2% HNO₃. The instrumental operating conditions are listed in Table 1.

The operating conditions for ICP-AES measurement

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| RF power                   | 1.6 kW                     |
| Plasma gas flow rate       | Argon 17 L min⁻¹           |
| Auxiliary gas flow rate    | Argon 1.2 L min⁻¹          |
| Carrier gas flow rate      | Argon 1.02 L min⁻¹         |
| Scan type                  | Peak hopping               |
| Detector                   | Digital detector           |
| Solution uptake rate       | 0.25 mL min⁻¹              |
| Integration time           | 1000 ms                    |
| Scan number                | 20                         |
| Repeat                     | 3                          |
| Measured isotopes          | ¹⁰³Rh (internal standard), ¹⁰⁰Zr, ¹⁰⁰Ru, ¹⁰⁸Sr, ¹⁰⁴Y, ¹⁴⁰Ce, ¹⁵³Eu, ¹³³Cs, ¹³⁷La |

A 10 μg L⁻¹ of Rh internal standard solution in the ICP-MS analysis was prepared by dilution of 1000 mg L⁻¹ Rh standard solution (from the National Center of Analysis and Testing for Nonferrous Metals and Electronic Materials (Beijing, China)) with 2% HNO₃. The different concentrations of thorium standard solutions for calibrating the ICP-AES were prepared by diluting the 1000 mg L⁻¹ thorium standard solution (in 2 – 5% HNO₃, Accustandard, USA) with 2% HNO₃. The thorium matrix solution was prepared by dissolving ThO₂ (99.999% for wt, obtained from ChangChun Institute of Applied Chemistry, Chinese Academy of Sciences) in concentrated HCl and adjusting the HCl concentration. The fission elements solution was prepared by dissolving MCl₂ (M denotes Zr, Nb, Ru, Ce, Eu, Sr, Cs, Y and La, purchased from Sinopharm Chemical Reagent Co., Ltd) in 10% HCl (v/v). The thorium and FPs solutions were used to optimize the elution conditions of the analyte elements and for the recovery test. Anion exchange resin (Dowex1 × 8, 100 – 200 mesh, chloride form) was obtained from Sigma-Aldrich.

Ultrapure water (18.2 MΩ·cm, prepared by a Milli-Q purification system) was used throughout the experiment. Ultrapure HCl (37%, 12 mol L⁻¹, Suzhou Crystal Clear Chemical Co., Ltd, Suzhou, China) was used to dissolve ThO₂ to prepare the matrix solution. Ultrapure HNO₃ (73%, 16 mol L⁻¹, Suzhou Crystal Clear Chemical Co., Ltd) was used to prepare the eluent. NH₄F and NH₄Cl of analytical purity were used to prepare 8 mol L⁻¹ HNO₃-0.001 mol L⁻¹ F⁻ and 8 mol L⁻¹ HNO₃ with different concentrations of Cl⁻ respectively. All other solvents and reagents were of analytical pure or ultrapure grade and used without further purification.

**Determination of distribution coefficients**

The distribution coefficients of thorium and FPs on Dowex1 resin in various solutions were determined by using a batch adsorption experiment. A series of feed solutions with 37 mg L⁻¹ of Th, 37 μg L⁻¹ of typical FPs and different concentrations of HNO₃ were prepared. Then, 5.4 mL of the above solution was equilibrated with 0.1 g of Dowex1 resin for 4 h at the temperature of 20 ± 2°C. The concentration of thorium and FPs in the feed and aqueous phase after equilibration was determined by ICP-AES and ICP-MS, respectively. The distribution coefficients were calculated according to the Eq. (1):

$$K_d = \frac{C_a}{C_0} \times \frac{V}{m}$$

where $C_0$ is the initial concentration of cations in feed, $C_a$ is the concentration after equilibration, $V$ is the solution volume and $m$ is the mass of resin.

### Table 1 The operating conditions for ICP-AES measurement

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| RF power                   | 1.3 kW                     |
| Plasma gas flow rate       | Argon 15 L min⁻¹           |
| Auxiliary gas flow rate    | Argon 0.2 L min⁻¹          |
| Nebulizer gas flow rate    | Argon 0.55 L min⁻¹         |
| Detector                   | CCD                        |
| Observation                | Radial viewing             |
| Sample flow rate           | 1.5 mL min⁻¹               |
| Integration time           | 5 s                        |
| Repeat                     | 3                          |
| Wavelength                 | Th 401.91 nm               |

### Table 2 The operating conditions for ICP-MS measurement

| Parameter                  | Value                      |
|----------------------------|----------------------------|
| RF power                   | 1.6 kW                     |
| Plasma gas flow rate       | Argon 17 L min⁻¹           |
| Auxiliary gas flow rate    | Argon 1.2 L min⁻¹          |
| Carrier gas flow rate      | Argon 1.02 L min⁻¹         |
| Scan type                  | Peak hopping               |
| Detector                   | Digital detector           |
| Solution uptake rate       | 0.25 mL min⁻¹              |
| Integration time           | 1000 ms                    |
| Scan number                | 20                         |
| Repeat                     | 3                          |
| Measured isotopes          | ¹⁰³Rh (internal standard), ¹⁰⁰Zr, ¹⁰⁰Ru, ¹⁰⁸Sr, ¹⁰⁴Y, ¹⁴⁰Ce, ¹⁵³Eu, ¹³³Cs, ¹³⁷La |
Determination of elution curve

In order to optimize the parameter and determine the efficiency of removing thorium matrix from model samples using the proposed method, the column experiment was performed. First, the Dowex1 × 8 resin was slurry packed in a polypropylene column (9 mm i.d. × 7 cm) by gravity after soaking for at least 24 h in water. Then, the column was topped with glass wood to avoid the disturbance during sample and eluant introduction. Next, 20 mL of 1 mol L–1 HCl was passed through the column at a flow rate of 0.5 – 0.8 mL min–1 to remove impurities adsorbed on the resin, and then water was passed through the column until the eluate became neutral. Finally, 20 mL of 8 mol L–1 HNO3 was passed through the column to convert the resin into nitrate form and pre-equilibrate the column.

For the sample pretreatment, the model sample solution containing thorium and FPs in HCl medium was diluted with 8 mol L–1 HNO3, and passed through the column. Then, 8 mol L–1 HNO3 containing 0.001 mol L–1 F– or not was passed through the column to elute the trace FPs while thorium was retained at the column. The eluate was collected fractionally and the concentration of FPs and thorium in each fraction were determined by ICP-MS and by ICP-AES, respectively.

Determination of thorium matrix effect for the analysis of trace FPs by ICP-MS

A series of solutions with 5 μg L–1 of FPs and different concentrations of Th in 2% HNO3 medium were prepared. The concentration of FPs in the above solutions was tested by ICP-MS using internal standard method. The differences of the FPs concentration between thorium matrix solution and FPs standard solution without thorium matrix were to estimate the matrix effect.

Results and Discussion

The thorium matrix effect on the determination of trace FPs

When the sample is introduced using nebulization in ICP-MS, the non-spectroscopic interferences known as matrix effect would be a problem for the trace determination in macro matrix. Table 3 shows the influence of coexistent thorium on the determination of quantitative FPs. It can be observed that the analyte signal suppression would increase with the increase of thorium concentration due to the matrix effect, and the matrix effect on FPs measured by ICP-MS using internal standard method can be attenuated when the thorium concentration is lower than 50 mg L–1. So, in order to accurately determine the trace FPs in thorium matrix, the sample should be pre-treated to remove the large amount of thorium.

Effect of nitric acid and chloride concentration on $K_d$

For the removal of Th matrix from trace FPs, maximum retention of thorium on the resin and elution of FPs from the resin are the leading criteria. Considering that Th can form anion complex and be adsorbed on anion resin well in HNO3 medium, meanwhile FPs can not be adsorbed, the sample pre-separation was performed in HNO3 medium. The effect of HNO3 concentration on the $K_d$ value of Th and FPs on Dowex1 resin was investigated. As shown in Fig. 1, the $K_d$ value of Th would increase with the concentration of HNO3 increasing to 8 mol L–1 HNO3 because the negatively charged complexes of thorium can be formed and dominant at higher HNO3 concentrations. However, it would decrease with the further increase of HNO3 concentration due to the competition effect between negatively charged complexes of thorium and NO3–. Furthermore, the FPs showed no or light adsorption on Dowex1 resin at various HNO3 concentrations. Thus, 8 mol L–1 HNO3 can be chosen as the medium to retain Th on the resin and elute FPs from the resin, achieving the separation of the two.

As mentioned above, the stronger adsorption of Th on Dowex1 resin could be observed at 8 mol L–1 HNO3 media. However, there is a large amount of Cl– in the sample with HCl medium. So, the effect of Cl– concentration on the adsorption of Th and

| $C_{Th}$/mg L–1 | $C_{FP}$/μg L–1 |
|----------------|-----------------|
| 0              | 4.921 4.933 4.960 5.071 5.071 4.992 4.993 4.991 4.991 |
| 20             | 5.098 4.878 4.988 5.065 4.974 4.853 5.001 4.795 4.927 |
| 50             | 4.566 4.426 4.647 4.572 4.513 4.556 4.761 4.505 4.613 |
| 80             | 4.243 4.137 4.399 4.321 4.190 4.201 4.561 4.215 4.129 |
| 100            | 4.121 3.906 4.339 4.080 3.973 4.090 4.379 4.167 4.060 |

| $K_d$ values of Th and FPs on Dowex1 at different concentrations of HNO3. |
|-------------------|-------------------|
| $C_{HNO3}$/mol L–1 |
| Zr    | Nb    | Ru    | Cd    | Eu    | Ce    | La    | Th    |
| 0    | 20    | 50    | 80    | 100   |
| 0.0  | 2.0   | 4.0   | 6.0   | 8.0   |
| 500  | 350   | 250   | 150   | 50    |
| 0    | 0.5   | 1.0   | 1.5   | 2.0   |

| $K_d$ values of Th and FPs on Dowex1 at different Cl– concentrations in 8 mol L–1 HNO3 medium. |
|-------------------|-------------------|
| $C_{Cl}$/mol L–1 |
| Zr    | Nb    | Ru    | Cd    | Eu    | Ce    | La    | Th    |
| 0    | 0.0   | 0.4   | 0.8   | 1.2   | 1.6   | 2.0   |
| 50   | 350   | 250   | 150   | 50    | 0.5   | 1.0   | 1.5   | 2.0   |
50 mg thorium, 1.5 mL of the model solution was diluted into 3 mL by 8 mol L–1 HNO3 in the absence of Th matrix, 0.5 mL of model sample with anion exchange for accurately analyzing the concentration of column at the stage of sample load and FPs elution. Recoverya, among thorium and chloride.24 Nevertheless, the elution curve, it is found that Nb was partly retained on the resin, all FPs except Nb can completely be recovered by using 8 mol L–1 HNO3 as eluent at the stage of sample load and FPs elution.

Subsequently, due to the weak adsorption of FPs on Dowex1 resin, all FPs except Nb can completely be recovered by using 8 mol L–1 HNO3 as eluent, and the recovery was in the range of 97 to 115% (shown in Table 4). Finally, the column can be revived by eluting the Th using 1 mol L–1 HCl. In the above elution curve, it is found that Nb was partly retained on the column, and the recovery of Nb was less than 70%. Wish25 reported that the adsorption of Nb on anion exchange resin is dependent on the fluoride concentration, and it would decrease when the fluoride concentration increased from 0 to 0.6 mol L–1. In order to improve the recovery of Nb, trace fluoride was mixed with 8 mol L–1 HNO3 as eluent at the stage of FPs elution. Model solution was tested again, and the elution curve is shown in Fig. 4. All the FPs can be recovered by using 8 mol L–1 HNO3 with 0.001 mol L–1 fluoride as eluent, and the recovery yields varied from 95 to 115%. It is indicated that the adding of fluoride to the eluent was useful to elute Nb from anion exchange resin.

On the other hand, although some thorium would be eluted with FPs using 8 mol L–1 HNO3 with 0.001 mol L–1 fluoride because of the formation of strong cationic complex of thorium with fluoride ion, the concentration of Th was still less than 50 mg L–1 in the solution collected at the stage of sample load and FPs elution. In this case, the thorium matrix effects on the determination of trace FPs by ICP-MS can be ignored.

**Evaporation of the FPs eluates**

As mentioned above, the FPs can be separated from the Th matrix and collected at the stage of sample load and FPs elution. However, the collected sample solution can not be introduced into the instrument of ICP-MS directly because of the corrosion and matrix effect of high concentration of HNO3 in the eluate. So, after separation of FPs from the thorium matrix using anion exchange column, the eluate should be evaporated on a hot plate at an appropriate temperature to get rid of the large amount of HNO3. In this procedure, the heating temperature should be optimized because the high temperature would enhance the volatilization of some fission elements, such as Ru in the form of RuO2.26 On the contrary, the evaporation with low temperature was a time consuming process, and it may enhance the contamination of the sample. Thus, to optimize the evaporation temperature, the 30 mL of model solutions with about 10 – 30 ng of FPs in 8 mol L–1 HNO3–0.001 mol L–1 fluoride medium were heated and evaporated to near dryness, then the residue was dissolved in 10 mL of 2% HNO3 for ICP-MS analysis. The results are shown in Table 5.

As shown in Table 5, there was no significant evaporation loss of FPs when evaporation the temperature was 150°C, and the recovery varied from 96 to 105%. But when evaporated at higher temperatures, such as 240°C, a significant volatilization of Ru could be observed compared with 150°C. The reason is...

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**Table 4** The recovery of FPs during elution curve determination

| 90Zr | 93Nb | 99Ru | 88Sr | 89Y | 140Ce | 153Eu | 133Cs | 139La |
|------|------|------|------|-----|-------|-------|-------|-------|
| Added/μg | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 | 1.500 |
| Found/μg | 1.584 | 1.047 | 1.459 | 1.679 | 1.591 | 1.736 | 1.513 | 1.528 |
| Recoverya, | 105.6 | 69.8 | 97.3 | 111.9 | 111.7 | 106.0 | 115.8 | 109.0 | 101.9 |
| Recoveryb, | 112.2 | 95.8 | 99.8 | 112.5 | 112.1 | 107.1 | 115.5 | 110.1 | 108.5 |

a. Eluting the FPs with 8 mol L–1 HNO3.
b. Eluting the FPs with 8 mol L–1 HNO3–0.001 mol L–1 fluoride.

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**Fig. 3** Elution curve of model solution on Dowex1 column (without fluoride).

**Fig. 4** Elution curve of model solution on Dowex1 column (with fluoride).
that Ru would be oxidized to volatile RuO₄, which would escape to the vapor phase at high temperatures in the presence of concentrated HNO₃. So, for the removal of HNO₃ and avoid the loss of FPAs after the separation process, the optimal evaporation temperature was determined to be 150°C.

Validation of the method

To assess the application of this method, pure thorium oxide powder was dissolved in HCl and doped with known amounts of the FPAs. Then the solution was pretreated using a Dowex1 column as mentioned above. The analytical results of the FPAs are listed in Table 6 along with the percent relative standard deviations.  The method was found to be satisfactory for the determination of FPAs, offering a relative standard deviation ranging from 2 to 15% for all the elements studied and a recovery from 80 – 110%. It is concluded that there was no significant loss of FPAs in the pretreatment steps using the column, and the FPs can be eluted to be evaporated at 150°C, followed by the analysis using ICP-MS with internal standard online. The average recovery of the above method was in the range 80 – 110% and the RSD values were better than 10%.

Detection limit and quantification limit of the method

The detection limit of the method was calculated according to the IUPAC (3 times of standard deviation of 11 times method blank solutions signal/slope, viz. 3S, and the quantification limit of the method was calculated as 10 times of standard deviation of 11 times method blank solutions signal/slope, viz. 10S). As listed in Table 7, the detection limits and quantification limits of the method of each element were estimated from the linear calibration curves (correction coefficient was better than 0.999) in the range tested (0.1 - 10 μg L⁻¹) and were expressed in the amount of the element in the thorium solution. The values gave an indication of the reachable performance of the proposed method.

Conclusions

The pre-separation procedure combined with ICP-MS analysis for the precise analysis of trace FPAs in thorium matrix with HCl medium was proposed and tested by using batch equilibration experiment and column experiment. Under the optimum conditions, the thorium matrix can be selectively absorbed on the column, and the FPAs can be eluted to be evaporated at 150°C, followed by the analysis using ICP-MS with internal standard online. The average recovery of the above method was in the range 80 – 110% and the RSD values were better than 10%.

Table 6 Analytical values for FPAs in synthetic thorium samples using the proposed method (data in ng)

| FP     | SYN-1a | Recovery, RSD, % | SYN-2a | Recovery, RSD, % |
|--------|--------|------------------|--------|------------------|
| ²⁰₉Zr  | 103.9  | 102.8            | 6.3    | 20.8             |
| ⁹⁴Nb   | 86.7   | 73.9             | 5.2    | 17.3             |
| ¹⁰₃Ru  | 93.9   | 84.5             | 7.5    | 18.8             |
| ¹⁴⁰Ce  | 157.4  | 152.5            | 5.9    | 31.5             |
| ¹⁵³Eu  | 160.5  | 161.1            | 5.0    | 32.1             |
| ⁹⁰Zr   | 103.9  | 102.8            | 6.3    | 20.8             |
| ⁹³Nb   | 86.7   | 73.9             | 5.2    | 17.3             |
| ¹⁰₃Ru  | 93.9   | 84.5             | 7.5    | 18.8             |
| ¹⁴⁰Ce  | 157.4  | 152.5            | 5.9    | 31.5             |
| ¹⁵³Eu  | 160.5  | 161.1            | 5.0    | 32.1             |
| ⁹⁰Zr   | 103.9  | 102.8            | 6.3    | 20.8             |
| ⁹³Nb   | 86.7   | 73.9             | 5.2    | 17.3             |
| ¹⁰₃Ru  | 93.9   | 84.5             | 7.5    | 18.8             |
| ¹⁴⁰Ce  | 157.4  | 152.5            | 5.9    | 31.5             |
| ¹⁵³Eu  | 160.5  | 161.1            | 5.0    | 32.1             |

Table 7 Detection limit and quantification limit of the method (data in μg L⁻¹)

| FP     | ²⁰₉Zr | ⁹⁴Nb | ¹⁰₃Ru | ¹⁴⁰Ce | ¹⁵³Eu | ⁹⁰Zr | ¹⁰₃Ru | ¹³³Cs | ⁹⁰Y | ¹⁵³La |
|--------|-------|------|-------|-------|-------|------|-------|-------|-----|-------|
| 1      | 1.391 | 0.005| 0.000 | 0.029 | 0.002 | 0.223| 0.024 | 0.017 | 0.016|
| 2      | 1.354 | 0.005| 0.000 | 0.032 | 0.004 | 0.222| 0.028 | 0.019 | 0.023|
| 3      | 1.371 | 0.037| 0.001 | 0.030 | 0.003 | 0.216| 0.025 | 0.022 | 0.023|
| 4      | 1.377 | 0.014| 0.000 | 0.036 | 0.007 | 0.214| 0.029 | 0.023 | 0.028|
| 5      | 1.333 | 0.008| 0.000 | 0.063 | 0.011 | 0.215| 0.033 | 0.066 | 0.046|
| 6      | 1.238 | 0.004| 0.001 | 0.036 | 0.002 | 0.255| 0.023 | 0.015 | 0.020|
| 7      | 1.344 | 0.148| 0.071 | 0.027 | 0.005 | 0.169| 0.020 | 0.014 | 0.021|
| 8      | 1.324 | 0.050| 0.010 | 0.035 | 0.007 | 0.221| 0.020 | 0.016 | 0.031|
| 9      | 1.377 | 0.095| 0.009 | 0.050 | 0.010 | 0.215| 0.021 | 0.023 | 0.039|
| 10     | 1.397 | 0.062| 0.019 | 0.075 | 0.024 | 0.177| 0.021 | 0.036 | 0.064|
| 11     | 1.362 | 0.017| 0.027 | 0.045 | 0.003 | 0.223| 0.025 | 0.012 | 0.015|

Sₙ/μg L⁻¹ feed: 0.044, 0.045, 0.021, 0.015, 0.007, 0.023, 0.004, 0.015, 0.015
DL/μg L⁻¹ feed: 2.646, 2.684, 1.277, 0.921, 0.392, 1.390, 0.242, 0.928, 0.895
QL/μg L⁻¹ feed: 8.819, 8.946, 4.256, 3.070, 1.306, 4.633, 0.806, 3.093, 2.983

a. The detection limit of the proposed procedure, calculated by 3Sₙ × 10 mL/0.5 mL. b. The quantification limit of the proposed procedure, calculated by 10Sₙ × 10 mL/0.5 mL, where 10 mL was the volume of measured solution, and the 0.5 mL was the volume of sample to be separated.
15% for six repeat experiments. It is found that this method is simple and effective for the determination of \( \mu \)g·mg L\(^{-1}\) of FPs in 100 g L\(^{-1}\) of thorium matrix with HCl concentration below 8 mol L\(^{-1}\), and due to the similarity, it also can be used for the analysis of impurity content (like rare earth elements) in thorium fuel. The separation scheme will be studied in the future.

Acknowledgements

This work was supported by the “Strategic Priority Research Program” of the Chinese Academy of Sciences (grant number XDA02030400).

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