

Extraction Separation of Am(III) and Eu(III) with Thermosensitive Gel introducing TPEN Derivatives

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Abstract – A thermal-swing chromatographic process using a thermosensitive gel copolymerized with NIPA (*N*-isopropylacrylamide) and TPPEN (*N,N,N',N'*-tetrakis(4-propenyloxy-2-pyridylmethyl)ethylene-diamine) was studied for the separation of Am(III) from Eu(III). Firstly, the radiolysis of the TPPEN-NIPA gel was tested by the γ -ray irradiation and the α nuclide adsorption. The extraction separation of Am(III) was not influenced in the radioactive environment of the proposed process. Next, the TPPEN-NIPA gel was immobilized in porous silica particles and the applicability of the gel-immobilized silica to the proposed process was tested. Am(III) was extracted selectively in the gel-immobilized silica at 5°C and the separation factor of Am(III) over Eu(III) was evaluated to be 3.7. The distribution ratio of Am(III) was reduced to less than 1/20 by increasing temperature from 5°C to 40°C. These results indicate that the TPPEN-NIPA gel is applicable to the thermal-swing chromatographic process for the MA recovery.

INTRODUCTION

Solvent extraction technique is applicable widely to the nuclear wastes treatment such as the reprocessing of spent nuclear fuel and the recovery of long-lived nuclides from the high-level liquid wastes (HLW). However, this separation technique has a serious disadvantage that large amounts of secondary wastes are generated. Recently, we proposed a new low-emission separation process using thermosensitive gel instead of solvent extraction, called thermal-swing chromatographic process. In this study, the applicability of the thermal-swing chromatographic process to the partitioning process of trivalent MAs (minor actinides) and lanthanides is discussed.

The principle of nuclide separation using thermosensitive gel is shown in Fig.1 [1-4]. The extractability of object metal ion is controlled by the conformational change of polymer network with the volume phase transition of thermosensitive gel. When an encapsulating ligand is copolymerized with a thermosensitive polymer (See Fig.1(b)), a metal ion is coordinated easily to the encapsulating ligand in the gel swollen in the temperature range below LCST (Low Critical Solution Temperature) and released from the encapsulating ligand in the gel shrunken in the temperature range above LCST. The absorption and elution of metal ion are attained by temperature control. Therefore, further chemicals are not

added to the extraction process. The consumption of chemicals will be reduced essentially by introducing the thermal-swing extraction technique.

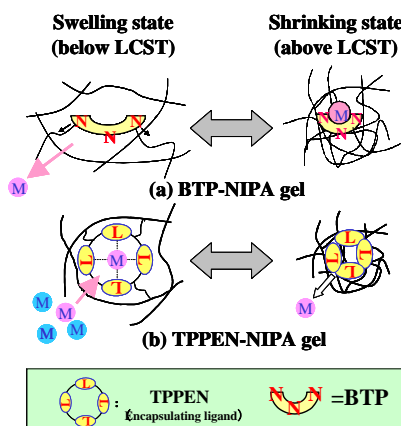


Figure 1 Concept of thermal swing extraction using thermosensitive gel

Poly *N*-isopropylacrylamide (poly NIPA) is suitable as a backbone polymer of thermosensitive gel to realize the concept of Fig.1. A functional monomer that can extract object metal ion selectively is copolymerized with NIPA. Previously, a prototypic gel, a NIPA gel copolymerized with an organophosphate ligand, 2-methacryloyloxyethylacidphosphate (MR), was synthesized and the extraction of Am(III) and

Eu(III) ions was tested [1]. These ions were captured by the ionic exchange with the MR molecules in the gel shrunken in the temperature range above LCST (34°C) and were partly released from the gel swollen in the temperature range below LCST. The capture and release of metal ion was repeated stably by thermal swing operation. Next, we tried to synthesize a thermo-sensitive gel copolymerized with NIPA and BTP (2,6-di(3-vinylbenzyl-1,2,4-triazol-5-yl)pyridine), which is a famous nitrogen-donor ligand used in the SANEX process developed in France and separates effectively trivalent MAs (Am and Cm) from lanthanides by applying to the solvent extraction process or the extraction chromatography process (Fig.1(a)). Although the BTP-NIPA gel was synthesized successfully, high separation factor of Am(III) over Eu(III) was not observed. Am(III) was adsorbed as a 1:1 complex of Am ion and BTP, which was quite different from that observed in the solvent extraction process. Therefore, high separation factor is not expected for the BTP-NIPA gel.

The authors proposed the use of an encapsulating ligand, TPEN, instead of BTP to realize the concept of gel extraction shown in Fig.1. Jensen et al. reported that the complex formation between Am(III) and TPEN in nitrate aqueous solution was about 100 times that between Eu(III) and TPEN [5]. From these results, we proposed a synergistic extraction process of Am(III) with TPEN and carboxylic acid as a synergist for the recovery of trivalent MAs [6,7].

Then, high separation factor above 100 was observed by the formation of a 1:1 complex of Am(III) and TPEN. Furthermore, we prepared a hydrophobic TPEN derivative connecting alkyl groups to 4 pyridyl groups of TPEN, TBPEN (*N,N,N',N'*-tetrakis[4-(2-butyloxy)-2-pyridinylmethyl]-1,2-ethylenedi-amine), and made clear that the extraction behavior of Am was not affected by the introduction of alkyl groups to four pyridyl rings[8,9]. The high separation factor more than 100 can be attained by the solvent extraction technique. These results will be presented in our other paper [10].

These solvent extraction studies aroused our desire for the synthesis of new monomer. We prepared TPPEN (*N,N,N',N'*-tetrakis(4-propenyloxy-2-pyridyl-methyl)ethylenediamine), whose structure is similar to that of TBPEN, and tested the extraction of trivalent MAs with a new NIPA gel copolymerized with TPPEN [4]. The chemical structures of NIPA, TPEN, TBPEN and TPPEN were shown in Fig.2. In this study, the radiolysis tests of TPPEN-NIPA gel by the γ -irradiation and α -nuclide adsorption and the synthesis of a chromatographic sorbent by introducing the TPPEN-NIPA gel in porous silica are carried out to discuss the practicability of TPPEN-NIPA gel. Finally, the applicability of the TPPEN-NIPA gel to the thermal-swing chromatographic process proposed for the continuous recovery of MAs is discussed by the aid of the process simulation using the results of extraction tests.

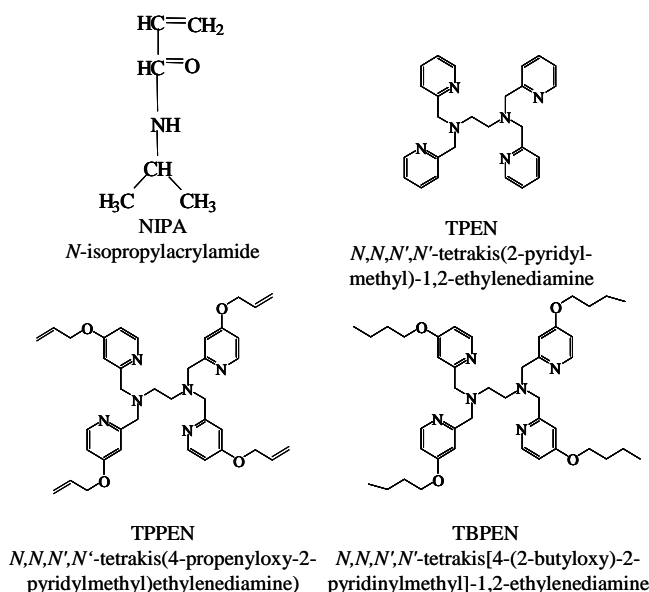


Figure 2 Chemical structures of NIPA, TPEN, TPPEN and TBPEN

EXPERIMENTAL

Synthesis of TPPEN and TBPEN

Two similar TPEN derivatives, TPPEN and TBPEN, were prepared for the extraction tests of Am(III) and Eu(III). Synthetic routes of TPPEN and TBPEN were considered by referring to the paper on the synthesis of TPEN analogs [11]. 2-chloromethyl-4-propenyloxy pyridine reacted with 1,2-ethylenediamine in a K_2CO_3 solution. Then, a slight amount of hexadecyltrimethylammonium chloride was added in the K_2CO_3 solution as a phase-transfer catalyst. The solution was adjusted to a pH value more than 8 and stirred vigorously at 25°C for 3 d. The product was extracted into diethylether and purified by a silica-gel column. The product yield was about 56%. TPPEN was produced effectively by the improvement of synthesis scheme.

The other TPEN derivative, TBPEN, was synthesized according to the same procedure as TPPEN. 4-(2-butyloxy)-2-chloromethylpyridine was prepared and reacted with 1,2-ethylenediamine under the presence of the phase-transfer catalyst, hexadecyltrimethylammonium chloride. Then, the product yield of TBPEN was evaluated to be 34%.

Synthesis of TPPEN-NIPA Gel

A thermosensitive gel, TPPEN-NIPA gel, was synthesized by the copolymerization of TPPEN and NIPA in N,N-dimethylformamide (DMF), which was carried out by the radical polymerization using N,N'-azobis(isobutyronitrile) (AIBN) as an initiator. The monomer mixture of TPPEN and NIPA were kept at 75°C for 12 h and the TPPEN-NIPA gel was obtained [4]. The content of TPPEN is adjusted in the range of 0.5 to 3 mol%. The gel obtained was washed, dried and crushed. The swelling behavior of the TPPEN-NIPA gel was observed in water. The powder of TPPEN-NIPA gel was packed in a 10ml graduated cylinder and was immersed in pure water. The swelling ratios were evaluated from the temperature change in the height of gel packed in water.

Immobilization of TPPEN-NIPA Gel in Porous Silica

The porous silica particles, which has penetrated macropores of 0.6 μ m in the average diameter and the pore volume of 0.59 ml/g, are prepared and immersed in an organic solution dissolving NIPA monomer (0.031 mol/l), TPPEN monomer (9.3×10^{-4} mol/l) and a slight

amount of AIBN in DMF. The silica particles impregnated with these monomers were filtered from the monomer solution. The content of monomer solution in the porous silica particles was adjusted properly by removing the excess monomers from the silica particles by a basket-type centrifugal separator. The monomers of TPPEN and NIPA in the porous silica particles were polymerized under the conditions of 60°C and 12hr. After the polymerization, the silica particles were washed several times to remove unreacted monomers and DMF and dried. The content of TPPEN-NIPA gel was evaluated from the weight change of porous silica before and after the polymerization.

Extraction Tests of Am(III) and Eu(III) with TBPEN

TBPEN was dissolved in toluene and the concentration of TBPEN in the organic phase was adjusted to 1mM. A NH_4NO_3 solution containing trace amounts of $^{241}Am(III)$ (100 Bq/ml) and $^{152}Eu(III)$ (400 Bq/ml) was prepared as an aqueous phase. The pH value in the aqueous solution was adjusted in the range of 4 to 6. 3mL of the aqueous solution was added in a centrifuge tube. The centrifuge tube was shaken vigorously for 90 min at 25°C. After shaking, the aqueous solution was phase-separated from the organic solution by the centrifuge and the radioactivities of Am(III) and Eu(III) in these two solutions were measured by a high-purity germanium gamma-spectrometer system. From these results, the distribution ratios of Am and Eu were calculated.

Radiolysis tests of TPPEN-NIPA gel

Two radiolysis tests, the irradiation of γ -ray to TPPEN-NIPA gel and the adsorption tests of α nuclide into the gel, were carried out to confirm the practicability of TPPEN-NIPA gel in the radioactive environment. Four TPPEN-NIPA gels with different TPPEN contents of 0.5 to 3 wt% were synthesized, as shown in Table 1. For all gels, the irradiation amount of γ -ray was kept at 10 kGy, which corresponds to that irradiated to TPPEN-NIPA gel in the MA recovery process for one year. Next, we tried the adsorption test of α nuclide (^{244}Cm , $t_{1/2} = 18yr$) for one week. Total energy released by the α decay of ^{244}Cm corresponds to about 10 kGy.

The extraction tests of Am(III) and Eu(III) were carried out for the TPPEN-NIPA gels before and after these radiolysis tests. The experimental procedure is similar to that of the former section. Each 3ml of the aqueous solution containing slight amounts of $^{241}Am(III)$ (100 Bq/ml)

and $^{152}\text{Eu}(\text{III})$ (400 Bq/ml) was added in two centrifuge tubes. The solution temperatures of these tubes were kept at 5°C and 40°C, respectively, and each 10 mg of dried TPPEN-NIPA gel powder was added. The extraction equilibrium of Am(III) and Eu(III) with the TPPEN-NIPA gel was attained by shaking the tubes vigorously for 90 min. After centrifuge, the radioactivities of Am(III) and Eu(III) in the aqueous solutions were measured by a high-purity germanium gamma-spectrometer system. The distribution ratio was calculated from these radioactivities of Am(III) and Eu(III).

Extraction Tests of Am(III) and Eu(III) with Porous Silica immobilizing TPPEN-NIPA gel

The extraction of Am(III) and Eu(III) with the porous silica immobilizing TPPEN-NIPA gel was measured in the same manner as that shown in the previous section. The porous silica particles immobilizing TPPEN-NIPA gel (10mg) were weighted and added in a NH_4NO_3 solution containing $^{241}\text{Am}(\text{III})$ (100 Bq/ml) and $^{152}\text{Eu}(\text{III})$ (400 Bq/ml) in a vial. The vial was shaken vigorously for 90 min. The aqueous solution was sampled and the radioactivities of $^{241}\text{Am}(\text{III})$ and $^{152}\text{Eu}(\text{III})$ were measured. From these data, the distribution ratios of Am(III) and Eu(III) were calculated.

RESULTS AND DISCUSSION

Swelling Behavior of TPPEN-NIPA gel

Figure 3 shows the swelling curves of the TPPEN-NIPA gel with the TPPEN content of 1 mol%, where white and black keys denote the swelling ratios measured by decreasing temperature from 45°C to 5°C and those by increasing temperature from 45°C to 5°C and those by increasing

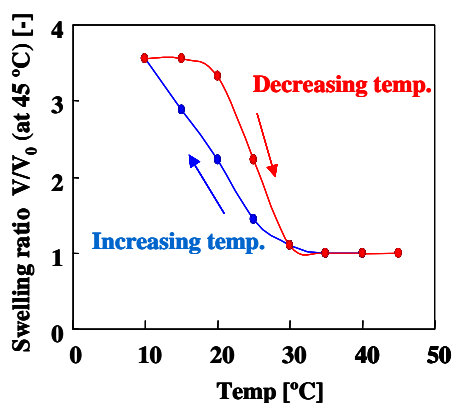


Figure 3 Swelling behavior of TPPEN-NIPA gel

temperature from 5 °C to 45 °C, respectively. The swelling ratio, defined as the gel volume normalized by that at 45 °C, increased with decreasing temperature. The TPPEN-NIPA gel showed clear thermosensitive phase transition. The temperature change of swelling ratio, which occurs by the hydration of NIPA, was repeated stably. The swelling behavior is sufficient for the deformation or configurational change of functional ligand with temperature, as shown in Fig.1.

Solvent Extraction of Am(III) and Eu(III) with TBPEN in Toluene

At first, the extraction separation of Am(III) and Eu(III) with TBPEN was tested. Figure 4 shows the relation between the equilibrium pH and the distribution ratios of Am(III) and Eu(III). At pH4.3, the separation factor of Am(III) over Eu(III), $S_{Am/Eu}$, defined as D_{Am}/D_{Eu} , was evaluated to be 125, which corresponds to that of BTP and is a sufficient value to design a separation process of Am(III). TBPEN is an effective extractant for the selective extraction of Am(III). The introduction of alkyl groups to pyridine rings of TPEN does not affect the separation performance of trivalent MAs. TPPEN that is similar to TBPEN may shows high separation performance for Am(III). Furthermore, you should be noted that TBPEN is a hydrophobic TPEN derivative and is applicable to a solvent extraction process of trivalent MAs. The application of hydrophobic TPEN derivatives to the solvent extraction process is discussed in details in the other paper [9].

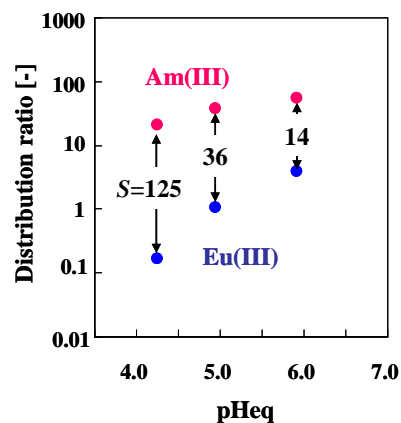


Figure 4 Extraction of Am(III) and Eu(III) with TBPEN in toluene.

Extraction of Am(III) and Eu(III) with TPPEN-NIPA gel

The thermal-swing extraction of Am(III) and Eu(III) with TPPEN-NIPA gel was tested. Figure 5 shows the results of extraction tests at 5°C and 40°C. Am(III) was extracted selectively in the swollen gel at 5°C and was little extracted in the shrunken one at 40°C. These results suggest that the extracted Am(III) is released easily by the volume phase transition of gel from the swelling state to the shrinking one. The distribution ratio of Am(III) was reduced to about 1/8 by the volume phase transition from the swelling state (5°C) to the shrinking one (40°C). The separation of Am(III) from Eu(III) was observed at the swelling state of gel (5°C) and the separation factor was evaluated as about 18 at pH5.2. This value was lower than that by the solvent extraction tests ($S_{Am/Eu}=36$ at pH5, as shown in Fig.4). This may be because the free motion of TPEN derivative is restricted by the copolymerization with NIPA. The separation of Am and Eu is caused by the slight difference of the coordination between nitrogen donor and f-orbital of metal ion. Therefore, it seems that the decrease in the separation factor cannot be avoided essentially by the decrease in the freedom degree of TPPEN copolymerized with NIPA. However, we are encouraged by the significant separation factor observed for TPPEN-NIPA gel. This value is sufficient to establish the practical thermal-swing extraction process.

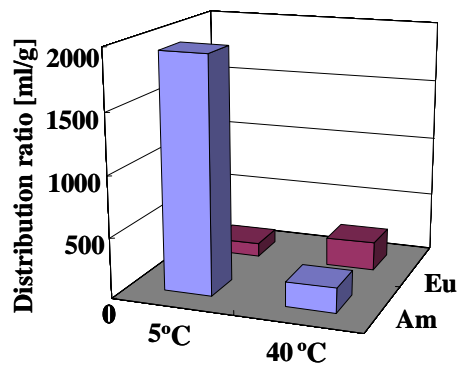


Figure 5 Extraction of Am(III) and Eu(III) with TPPEN-NIPA gel

Radiolysis of TPPEN-NIPA Gel

Figure 6 shows the percent extraction of Am(III) and Eu(III) before and after the γ -ray irradiation. The percent extraction of Eu(III) was little changed (Fig.6(a)) and that of Am(III) was slightly increased (Fig.6(b)). As a result, the separation factors of Am(III) over Eu(III) were increased by the γ -ray irradiation, as shown in Table 1. These results indicate that the gels do not sustain serious damage by the γ -ray irradiation. Many radicals are generated in the polymer chains by the amputation of polymer chains caused by the γ -ray irradiation. These radicals will be recombined with the neighboring ones. Thus, the polymer chains are restored without

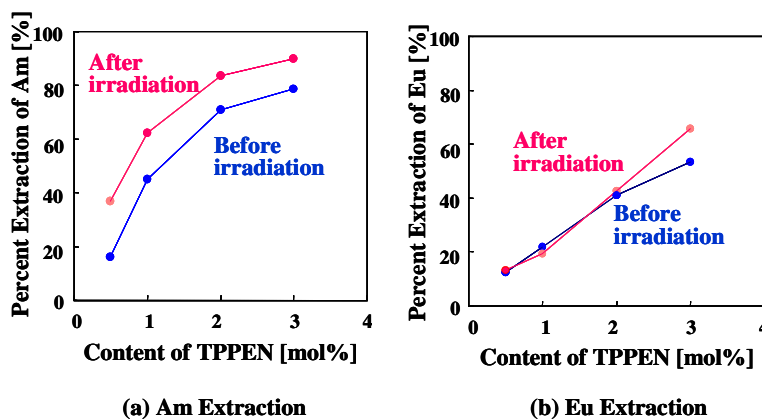


Figure 6 Extraction of Am(III) and Eu(III) with TPPEN-NIPA gels before and after γ -ray irradiation

Table 1 Summary of γ -irradiation tests

TPPEN content [mol%]	Equilibrium pH		Distribution ratio				SF _{Am/Eu}	
			Am-214		Eu-152		no irradiation	γ -ray irradiation
	no irradiation	γ -ray irradiation	no irradiation	γ -ray irradiation	no irradiation	γ -ray irradiation		
0.5	5.24	5.18	49 →	185	36 →	48	1.4	3.9
1	5.14	5.15	186 →	447	63 →	65	2.9	6.9
2	5.18	5.18	621 →	1441	176 →	213	3.5	6.8
3	5.2	5.19	957 →	2285	279 →	483	3.2	4.7

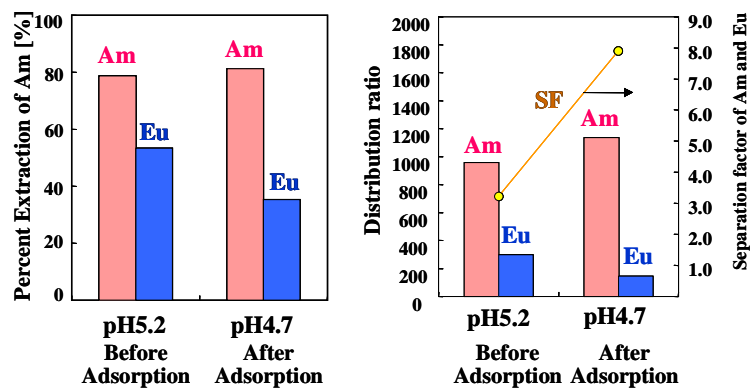


Figure 7 Extraction of Am(III) and Eu(III) with TPPEN-NIPA gel before and after α -adsorption test.

serious damage. The increase in the separation factor by the γ -ray irradiation is very interesting and arouses our interest. But, further analytical study for the irradiated polymer is required to make clear the reason. We do not have discussion on the enhancement of the separation factor in this study.

Next, we tried the adsorption test of α nuclide (^{244}Cm , $t_{1/2} = 18$ yr) for one week. Figure 7 shows the change of the percent extraction of Am(III) and Eu(III) before and after the α nuclide adsorption test. Then, total energy released by the α decay of ^{244}Cm corresponds to about 10 kGy, which is the same as that at the γ -ray irradiation tests. In the α nuclide adsorption test,

TPPEN. This adsorption test is very severe, because the energy released by the α decay of ^{244}Cm may be absorbed directly to the molecular structure coordinating a metal ion. However, the percent extraction of Am(III) made little difference for the gels before and after the α -nuclide adsorption test, whereas that of Eu(III) was slightly decreased. Thus, the separation factor of Am(III) over Eu(III) after the adsorption test was increased to twice that before the adsorption test. Although the same tendency was observed in the γ -ray irradiation tests, we do not have further discussion on the increase of separation factor. From the results of the γ -ray irradiation tests and the α -nuclide adsorption test, we conclude that

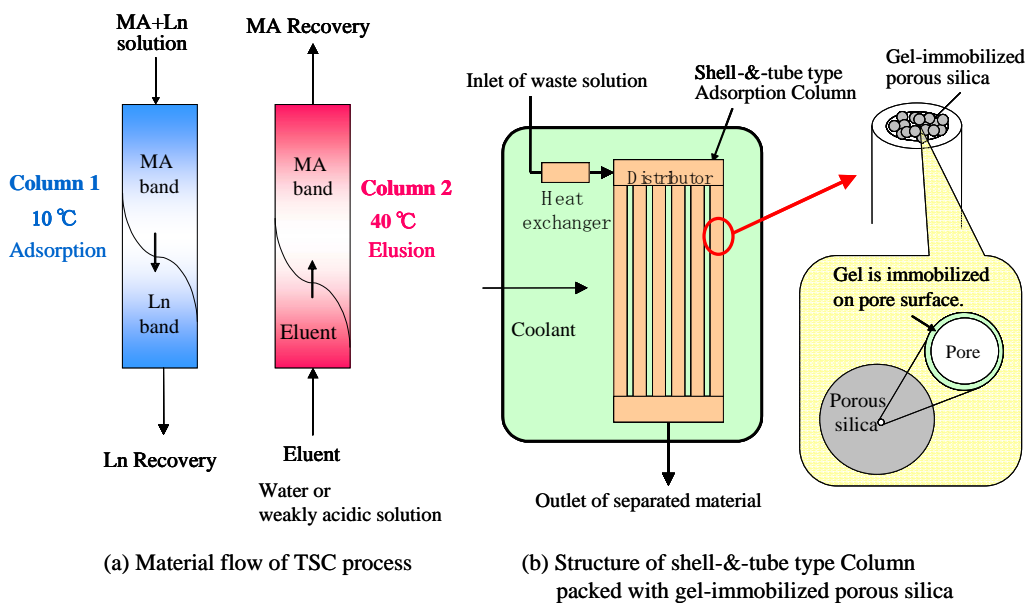


Figure 8 Thermal-swing Chromatography (TSC) process for continuous MA recovery. Cm(III) as well as Am(III) is encapsulated in the TPPEN-NIPA gel sustains no serious damage

in the radioactive environment of the trivalent MA separation process.

Extraction of Am(III) and Eu(III) by Porous Silica immobilizing TPPEN-NIPA Gel

For the application of gel-extraction technique to the trivalent MA separation process, we propose the thermal-swing chromatographic process, which consists of two chromatographic columns operated alternately at low and high temperatures, as shown in Fig.8. The process operation is the same as that of a typical thermal-swing adsorption process (Fig.8(a)). The procedure of process operation is as follows;

- (1) A waste solution containing MAs and lanthanides (Lns) is flown down to the cold column. MAs are adsorbed selectively and Lns are flown out from the cold column. Then, in the hot column, MAs adsorbed are recovered by an eluent (water or slightly acidic solution).
- (2) The temperature of the cold column is increased and MAs adsorbed are recovered by water or slightly acidic solution. Then, the temperature of the hot column is decreased and the waste solution with MAs and Lns is flown down.
- (3) The thermal-swing operations of (1) and (2) are repeated alternately between two columns and MAs in the waste solution are separated from Lns and recovered continuously.

In this process, a porous silica immobilizing TPPEN-NIPA gel is used as a chromatographic sorbent, as shown in Fig.8(b). The extraction of Am(III) and Eu(III) with the sorbent was tested and the applicability of this sorbent to the MA separation process was discussed.

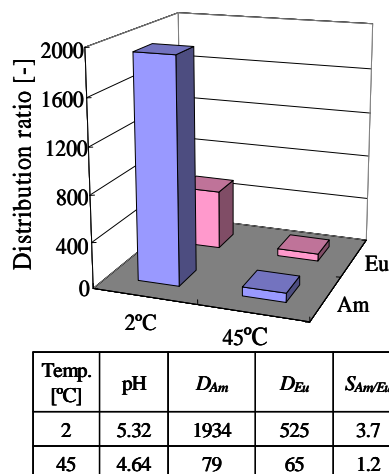


Figure 9 Extraction of Am(III) and Eu(III) with porous silica immobilizing TPPEN-NIPA gel.

Figure 9 showed the results of extraction tests of Am(III) and Eu(III) with the prepared sorbent. Am(III) was extracted selectively and the separation factor of Am(III) over Eu(III) was evaluated to be about 3.7 at 5°C. This value is lower than that for the direct extraction of Am(III) and Eu(III) with the TPPEN-NIPA gel ($S_{Am/Eu}=18$). This may be because the motion of thermosensitive gel is restricted by the immobilization of gel on the pore surface. However, if the multi-stage effect is desired for the thermal-swing chromatographic process, the separation factor of 3.7 may be sufficient for the separation of Am(III) from Eu(III). When temperature was increased from 5°C to 40°C, the distribution ratio of Am(III) was reduced to less than 1/20. Am(III) adsorbed can be recovered easily by the increase in temperature

Finally, the applicability of the proposed process to the practical MA separation was discussed by the dynamic process simulation. The mass transfer of metal ions in a chromatographic column shown in Fig.8 was calculated by solving the following diffusion equation,

$$\frac{\partial C_i}{\partial t} = D_{Li} \frac{\partial^2 C_i}{\partial z^2} - v \frac{\partial C_i}{\partial z} - \frac{1-\varepsilon}{\varepsilon} \rho_p \frac{\partial q_i}{\partial t} \quad (1)$$

where C_i , q_i , D_{Li} , v , ε and ρ_p denote the concentration of i -element in aqueous phase, the adsorption amount of i -element in solid phase, the axial dispersion coefficient, the void fraction of column and the density, respectively. The adsorption term, dq_i/dt , is described as

$$\frac{dq_i}{dt} = k_T a (C_i - C_i^*) = \frac{60De}{d^2} (C_i - C_i^*) \quad (2)$$

where $k_T a$, De , d and C_i^* denote the mass transfer coefficient, the intraparticle diffusion coefficient, the diameter of chromatographic sorbent and the concentration of i -element in aqueous solution equilibrated with adsorption amount, q_i , respectively. The equilibrium relation between C_i^* and q_i is represented as the Langmuir isotherm equation

$$q = \frac{K q_i^\infty C_i^*}{1 + K C_i^*} \quad (3)$$

where K and q_i^∞ denote the adsorption constant and the maximum adsorption amount, respectively. When an aqueous solution with Am(III) and Eu(III) is supplied to the top of column, the breakthrough curves of these metals are calculated by solving Eqs.(1) and (2) simultaneously. Since the axial dispersion of Eq.(1) is negligible under the condition of low flow rate, an initial condition and a boundary condition are given simply as follow;

$$C_i=0 \text{ and } q_i=0 \text{ at } t=0 \text{ and } z>0 \quad (4)$$

$$C_i = C_i^0 \text{ at } t > 0 \text{ and } z = 0 \quad (5)$$

where C_i^0 denotes the concentration of i -element in the aqueous solution supplied to the top of column under these conditions, Eqs.(1) and (2) were solved numerically by the finite difference method.

The calculation conditions were summarized in Table 2. The length and diameter of tube in the chromatographic column were assumed as 1.0m and 0.03m, respectively. The gel-immobilized silica particles ($dp=300 \mu\text{m}$) were packed in the tubes. This particles show high separation factor of Am ($S_{Am/Eu}=3.7$) as a chromatographic sorbent. Therefore, the strict chromatographic operation is not needed. We can use large particles of $300 \mu\text{m}$ in diameter. The pressure drop of column is much lower than that for ordinary chromatographic processes.

Figure 10 shows the calculated breakthrough curves of Am(III) and Eu(III), which were calculated for the chromatographic column at 5°C under the condition that $S_{Am/Eu}=3.7$. The starting point of the breakthrough curve of Am(III) corresponds to the end point of breakthrough curve of Eu(III). These results suggest that Am(III) is separated completely from Eu(III) by a 1m-long

Table 2 Calculation conditions

Tube diameter [m]	0.03
Tube length [m]	1.0
Diameter of chromatographic sorbent [m]	3×10^{-4}
Flow rate of waste solution [ml/min]	20
Conc. of Am in waste solution [mol/L]	1×10^{-4}
Conc. of Eu in waste solution [mol/L]	1×10^{-2}
Intraparticle diffusivity, De [m^2/s]	5×10^{-11}
Adsorption coefficient for Am, K_{Am} [m^3/mol]	27.3
Adsorption coefficient for Eu, K_{Eu} [m^3/mol]	7.37
Maximum adsorption capacity, q_∞ [mol/g]	2×10^{-5}

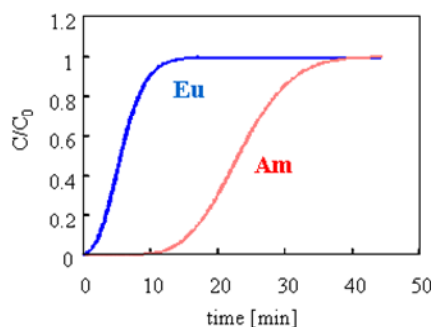


Figure 10 Breakthrough curves of Am(III) and Eu(III)

chromatographic column and the porous silica introducing TPPEN-NIPA gel is available as a practical chromatographic sorbent.

CONCLUSIONS

(1) A thermosensitive gel copolymerized with NIPA and TPPEN was synthesized and the selective extraction of Am(III) over Eu(III) was observed. The γ -ray irradiation tests (10kGy) and the long-term adsorption tests of α nuclide (^{244}Cm) were carried out for the TPPEN-NIPA gel. The extraction of Am(III) with the TPPEN-NIPA gel was not influenced by these radiolysis tests.

(2) The porous silica immobilizing TPPEN-NIPA gel was prepared as a chromatographic sorbent and the extraction of Am(III) and Eu(III) was tested. Am(III) was extracted selectively in the gel-immobilized silica at 5°C and then the $S_{Am/Eu}$ value was evaluated to be 3.7. By increasing temperature from 5°C to 40°C , the distribution ratio of Am(III) was reduced to less than 1/20.

(3) The separation of Am(III) and Eu(III) in a 1m-long chromatographic column packed with the gel-immobilized silica powder was estimated numerically by a mathematical model using the mass transfer theory. The calculation results indicated that Am(III) can be separated completely from Eu(III) and is available as a practical chromatographic sorbent.

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