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A highly efficient uranium grabber derived from acrylic fiber for extracting uranium from seawater

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Abstract

Acrylic fiber can be chemically converted to an amidoxime and carboxylate containing chelating adsorbent by a two-step synthesis method for extraction of uranium from seawater. A portion of the nitrile groups in the fiber is first converted to amidoxime using hydroxylamine followed by conversion of another portion of the nitrile groups to carboxylate with NaOH. At an optimized ratio of amidoxime/carboxylate (about 1:1), the chelating fiber in real seawater shows a higher uranium adsorption capacity and shorter saturation time compared with similar high-surface-area chelating fibers developed recently using a radiation-induced grafting method. The saturation capacity of uranium is estimated to be 7.73 grams per kilogram of adsorbent at 20 °C and the half-saturation time is about 15.7 days. The fiber shows a vanadium/uranium ratio of about 1 in real seawater tests. The low vanadium adsorption capacity of the fiber is attributed to the branch-chain amidoxime groups formed by the specified amidoximation process. This

simple and low-cost synthesis method can be scaled up to mass produce the chelating fiber for recovering metals from various aquatic environments including production of uranium from seawater.

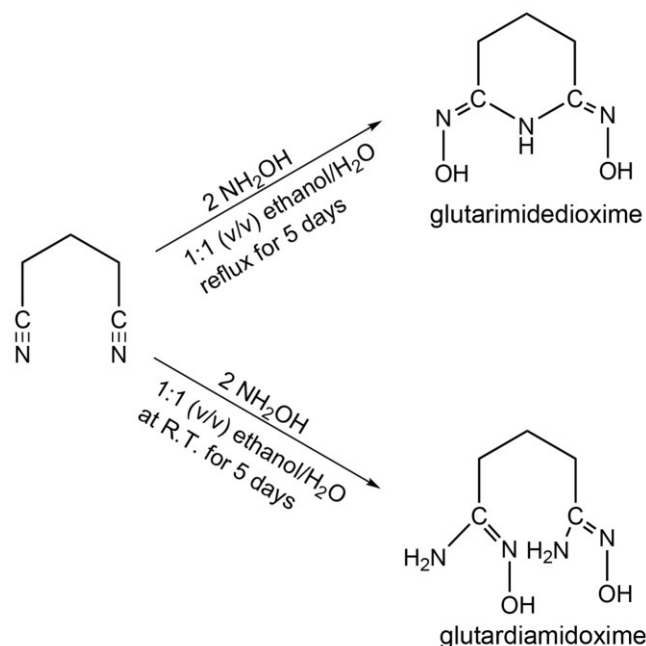
Introduction

Research in developing techniques for extracting uranium from seawater is of considerable current interest.¹⁻¹¹ One reason which drives scientists to develop techniques of sequestering uranium from ocean is the prediction that the land-based uranium reserves would be depleted by the end of this century based on the current production rate.^{1, 2} Uranium exists in seawater at a very low concentration (about 3 ppb) and as highly stable uranyl tris-carbonato complexes, primarily in the form $\text{Ca}_2[\text{UO}_2(\text{CO}_3)_3]$.¹² Because of the enormous volume of seawater, the total amount of uranium in ocean is estimated to be a thousand times greater than the land-based uranium resources.^{1, 2} As early as 1964, the idea of extracting uranium from seawater was discussed by Davies et al. in a Nature paper.¹³ In the past decades, many different materials were tested to evaluate their ability for sequestering uranium from seawater.^{1, 2, 14, 15} Among them, amidoxime and carboxylate containing polymer fiber adsorbents appear most promising because of their high uranium adsorption capacity and stability in seawater. The carboxylate groups are necessary to make the polymer adsorbent hydrophilic whereas the amidoxime groups provide strong

coordination sites for uranyl ions. Moreover, according to theoretical analysis, the adsorbability of uranium may involve synergistic effects of both amidoxime and carboxyl groups in the fiber adsorbent.¹⁶ Recently, scientists at Oak Ridge National Laboratory (ORNL) synthesized one type of high-surface-area polymer fibers with amidoxime and carboxylic acid functional groups using a radiation induced grafting technique.^{17, 18} The method involves grafting of acrylonitrile and itaconic acid to a high-surface-area polyethylene fiber with high energy electrons followed by chemical conversion of the nitrile groups to amidoxime groups with hydroxylamine. The ORNL adsorbent shows a uranium adsorption capacity of 4.48 grams uranium per kg of the polymer fiber after 56 days of exposure in a seawater flume system, which is higher than any previously reported uranium adsorption capacities of amidoxime-carboxylate containing fiber adsorbents.¹⁸ The ORNL fiber also grabs other metals from seawater particularly vanadium which has a concentration factor an order of magnitude higher than that of uranium on a molar basis.¹⁷⁻¹⁹ Vanadium appears to be a potential competing metal for sequestering uranium from seawater.²⁰⁻²² Several reports suggest that minimizing vanadium adsorption is one possible way of improving uranium extraction efficiency from seawater using this type of polymer adsorbents.²¹⁻²⁴ Attempts of utilizing polyacrylonitrile (PAN) as a starting material to produce amidoxime-containing polymer adsorbents for sequestering uranium from seawater were reported in the literature.²⁵⁻²⁷ This approach is attractive because PAN is commercially available in large

quantities. However, the results of seawater tests of the amidoxime-containing adsorbent prepared from PAN were not impressive and further research effort in this direction was basically abandoned. So far, the feasibility of using PAN or acrylic fiber (Orlon or yarn) as starting material for preparation of amidoxime and carboxylate containing fiber adsorbent for extracting uranium from seawater has not been extensively explored. Little information is known in the literature regarding chemical nature of the amidoxime-based polymer adsorbents derived from these nitrile containing polymer fibers.

Recent theoretical studies to evaluate the mechanisms of uranyl adsorption with amidoxime-based fibers were based on uranyl reactions with glutarimidedioxime (cyclic form) and glutardiamidoxime (open-chain) as model molecules.^{28, 29} The cyclic glutarimidedioxime (a tridentate ligand) has received much attention because it has a greater binding constant with uranyl ions relative to the open-chain glutardiamidoxime.²⁹ The conditions for synthesis of glutarimidedioxime and glutardiamidoxime by the reaction of hydroxylamine with glutaronitrile are different as shown in Scheme 1.^{28, 29} To improve uranium extraction efficiency of the polymer fiber, many recent studies focused their efforts on formation of the cyclic structure of the amidoxime groups in the amidoximation process by reflux at elevated temperatures.^{14, 17-19, 26, 30, 31} In a number of recent reports, polymer fibers containing mainly the cyclic imide-dioxime groups were utilized for extraction of uranium from seawater with good results.^{17-19, 30, 31}



Scheme 1 Synthesis of glutardiamidoxime and glutarimidedioxime from glutaronitrile

A recent NMR study shows that pentavalent vanadium (Na_3VO_4) reacts effectively with the cyclic glutarimidedioxime in 0.5 M NaCl aqueous solutions (pH = 8.3) to form a 1:1 complex.³² The branch-chain glutardiamidoxime molecule does not form any detectable complexes with vanadium ions in the NMR study^{23, 32} and potentiometric titration experiments²³. Abney and co-workers utilized X-ray absorption fine structure (XAFS) spectroscopy to investigate ORNL high-surface-area amidoxime-based fibers following deployment in natural seawater revealed that vanadium was bound solely to the cyclic imide-dioxime.^{23, 33} This appears consistent with the high vanadium extraction in previous uranium-from-seawater reports utilizing glutarimidedioxime dominated polymer fibers.^{17-19, 30, 31} The stability constant of vanadium complex with

glutarimidedioxime is extreme large ($\log \beta = 53.0 \pm 0.4$).²³ Because of the strong bonding, elution of vanadium from the amidoxime-based adsorbents is difficult. Vanadium could be eluted under harsh conditions such as 3 M HCl at 60 °C for 2 hr²⁰ and the process would destroy the adsorbents.³ How to develop this type of chelating fibers with high uranium and low vanadium adsorption capabilities becomes an important question for further improvement of their seawater uranium extraction efficiencies for possible commercial applications.

We have recently examined the chemistry of converting nitrile groups in acrylic fiber to amidoxime and carboxylate functional groups using ¹³C CP/MAS solid-state NMR and vibrational spectroscopy to control amidoxime configuration and its ratio to carboxylate for optimizing uranium adsorption capacity. We found that conversion of nitrile groups in original acrylic fibers using 1 M NaOH does not proceed effectively. However, if a portion of the nitrile groups in the original acrylic fiber is already converted to amidoxime, further conversion of the nitriles groups to hydroxyl groups occurs effectively in 1 M NaOH at room temperature. Thus, acrylic fiber can be converted to amidoxime and carboxylate containing polymer fibers using a two-step sequential reaction process, i.e. amidoximation using hydroxylamine followed by carboxylation with NaOH as illustrated in Fig. 1. The ratio of the two functional groups in the fiber can be monitored by FTIR spectroscopy. The fiber adsorbent prepared by this procedure has a gel-like property. However, when it is immersed in a salt solution such as seawater, it changes to a fiber-like material

immediately and disperses nicely in flowing seawater. The details of our synthetic procedure and some key properties of the synthesized fiber including nature of the amidoxime groups and adsorption capacities of uranium, vanadium, and other metals in seawater are given in this paper.

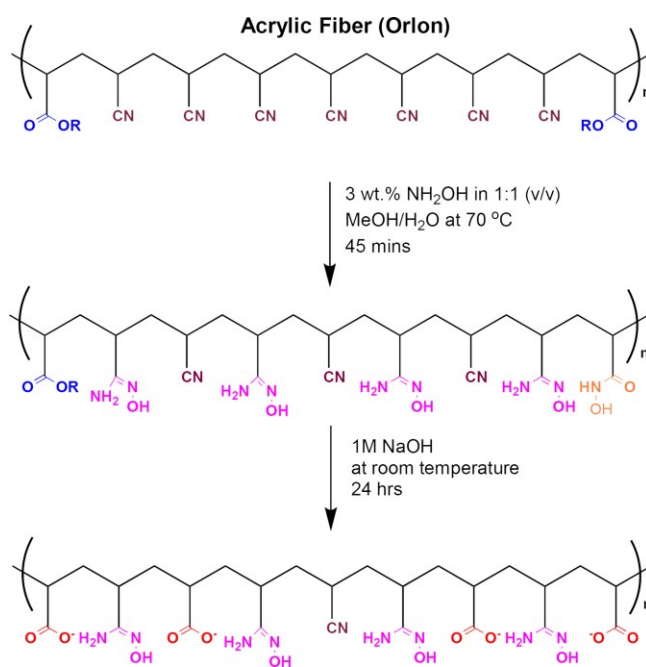


Fig. 1 Conditions of the two steps for converting acrylic fibers to amidoxime and carboxylate containing polymer adsorbent

Experimental section

Synthesis of LCW amidoxime and carboxylate containing fiber adsorbent

The acrylic fiber used initially in this investigation is common acrylic yarn (100% acrylic or Orlon) which is available from many fabric stores. The fiber is made of polyacrylonitrile with some ester copolymer (<15%) as shown in Fig. 1. According to our preliminary experiments,

even recycled yarn (100% acrylic) can be used as starting material for synthesizing this amidoxime-carboxylate containing fiber adsorbent. Long textile-grade acrylic fibers (92% acrylonitrile and 8% methyl acrylate monomers) from Kaltex were later used to make braids 20–25 cm in length for seawater flume tests. Our procedure of converting the acrylic fibers to amidoxime-carboxylate containing polymer adsorbents involves the following two steps:

1. Immerse the fibers in a 1:1 (v/v) methanol/water solution with 3% by weight of hydroxylamine (NH_2OH) at room temperature (about 21 °C) for 1 hour and then heat the solution at 70 °C for 45 minutes. FTIR spectra show that about 50% of the nitrile groups of the original acrylic fibers are converted to amidoxime groups. The treated fibers are washed with water several times for the next step of treatment.
2. The washed fibers are placed in a sodium hydroxide (1 M NaOH) solution at room temperature (about 21 °C) for 24 hours. The alkaline solution converts nitrile groups to carboxylate groups as shown in the FTIR spectra given in Fig. 2. Conversion of nitriles to carboxylate is sufficient under the specified condition with a small fraction of the nitrile peak still detectable in the FTIR spectrum (Fig.2). The presence of some nitrile groups in the final product contributes to the mechanical strength of the polymer adsorbent.^{27, 34,}

³⁵ Without nitrile groups, the resulting fiber shows a more gel-like property.

The ester group's $\text{C}=\text{O}$ stretching peak at 1736 cm^{-1} becomes barely detectable after the synthesis

suggesting that most of the ester groups in the acrylic fiber are converted to carboxylate groups in the NaOH treatment step. Conversion of ester to carboxylate in alkaline solution is known to occur. Moreover, a broad C=O stretching band at around 1750 cm^{-1} indicates that a small amount of the carboxylate groups is converted to carboxylic acid groups ($-\text{COOH}$) during rinsing with deionized water. The fiber adsorbent was also characterized by solid-state ^{13}C NMR shown in Figure 3. The chemical shifts at 183 and 177 ppm are assigned to the carboxylate ($-\text{COO}^-$) and carboxylic acid ($-\text{COOH}$) group, respectively, consistent with the literature.³⁶ Ester is also known to react with hydroxylamine to form hydroxamic acid^{37, 38} which may explain the change in the 1736 cm^{-1} peak after the amidoximation step. The hydroxamic acid group has a strong carbonyl absorption at about 1640 cm^{-1} ^{39, 40}, a medium-intensity amide II band near 1550 cm^{-1} , and a strong N–O band at about 900 cm^{-1} .^{39, 40} However, the three bands of the hydroxamic acid group overlap with amidoxime characteristic bands, C=N, N–H, and N–O, respectively.^{39, 40} The final distribution of the chemical groups in the fiber adsorbent is estimated to be 46% amidoxime, 45% carboxylate, and 9% nitrile. Our method of estimating the amidoxime/ COO^- ratio and $-\text{CN}$ intensity in the fiber adsorbent is described in the Supplementary Information. The adsorbent so prepared does not require KOH conditioning¹¹ because nitrile converts to carboxylate directly in 1 M NaOH at room temperature.

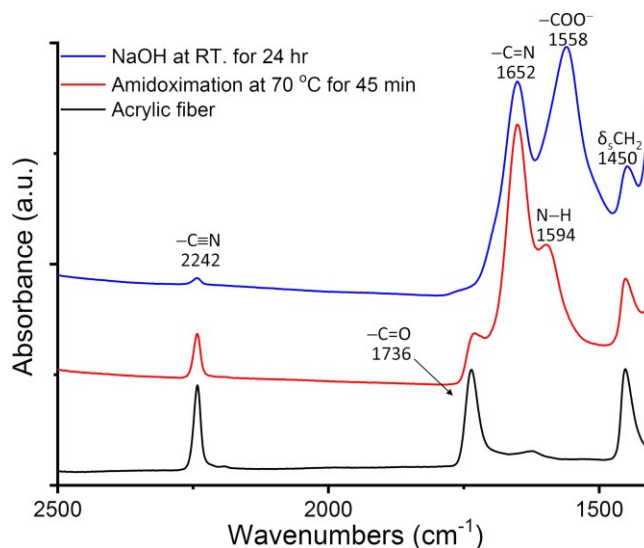


Fig. 2 FTIR spectra of the original acrylic fiber (black), after amidoximation (step 1, red), and after NaOH treatment (step 2, blue). Conditions: Step 1, NH_2OH 70 °C 45 minutes; Step 2, NaOH room temperature 24 hours. (The spectra were normalized to the $-\text{CH}_2-$ in-plane bending or scissoring band ($\delta_s\text{CH}_2$) at 1450 cm^{-1})

Seawater uranium adsorption tests

Marine tests of the uranium adsorption capacity of the new polymer fiber adsorbent were performed in the Pacific Northwest National Laboratory (PNNL) Marine Sciences Laboratory located in Sequim, Washington. Ambient seawater was pumped from the Sequim Bay into a flowing column system at a flow rate of approximately 2 cm/s and the water temperature was controlled at $20\pm 1^\circ\text{C}$.^{5,41} A flow-through channel (flume) system was used for seawater exposure of braided fiber adsorbents under controlled temperature ($20\pm 1^\circ\text{C}$) and flow-rate (1.5 L/min) conditions. About 10 g dry weight of braided adsorbent material was mounted in the flumes for seawater exposure. Over the course of seawater exposure (56 days), small portions ($\sim 100\text{ mg}$)

were taken from braided adsorbents on a weekly basis. The pH, salinity, temperature, trace elements, and DOC of flume seawater were monitored throughout the experiment as previously described in the literatures.^{5, 8, 10, 41, 42}

Analytical methods and instrumentation

The FTIR spectra were acquired on dry adsorbent samples using a ThermoNicolet 6700 FTIR spectrometer. FTIR measurements were made with a SplitPea attenuated total reflection (ATR) accessory (Harrick Scientific) along with a silicon internal reflection element used as a reflection medium. High resolution FTIR spectra in the range of 4000 to 700 cm^{-1} were acquired using 500 co-added scans at 2 cm^{-1} resolution with Norton-Beer “medium” apodization function. The FTIR spectra were normalized to the 1450 cm^{-1} peak, the methylene group in-plane bending or scissoring band ($\delta_s\text{CH}_2$), to facilitate comparison.

The Solid-state ^{13}C NMR spectra were acquired on a Bruker Avance 500 MHz NMR spectrometer. In general, about 100 mg of sample was loaded into a zirconium oxide rotor. The ^{13}C chemical shifts were referenced using adamantane as an external standard.⁴³ Magic angle was set by maximizing number of rotational echoes observed in the ^{79}Br NMR free induction decay of solid KBr.⁴³

The adsorbent materials exposed to seawater were washed with deionized water to remove salts. The dried fibers (~100 mg) were weighed and then digested with 10 ml of a high-purity

(Trace element Grade, Fisher Scientific) 50% aqua regia acid mixture for 3 h at 85 °C. Analysis of uranium and other trace elements adsorbed to the LCW adsorbent was conducted using a Perkin-Elmer 7300 inductively coupled plasma optical emission spectrometer (ICP-OES). All adsorption loading data were normalized to a salinity of 35 to correct for the small variations in salinity during the exposure time periods. Determination of elements in natural seawater samples was conducted using a Thermo Scientific ICapTM Q inductively coupled plasma mass spectrometer (ICP-MS) equipped with an online pre-concentration system (seaFAST S2TM automated sample introduction system, Elemental Scientific).⁴⁴ DOC content in seawater was measured by high-temperature catalytic oxidation (HTCO) with a Shimadzu TOC-L_{CSH} TOC analyzer.

Results and discussion

The ratio of the amidoxime/carboxylate groups formed in the acrylic fiber can be controlled by the reaction conditions including temperature and reaction time using FTIR spectroscopy. When the amidoximation reaction is carried out at 70 °C for about 45 minutes, the product contains mainly the branch-chain diamidoxime groups which should reduce vanadium adsorption. A ¹³C CP/MAS solid-state NMR spectrum of the fiber produced under the specified conditions is shown in Fig. 3. For comparison, the ¹³C CP/MAS solid-state NMR spectrum of an amidoxime-

carboxylate containing fiber prepared by a radiation-induced grafting method is also given in the inset (green color) of Fig. 3. This adsorbent contains mainly the cyclic imide-dioxime groups.¹⁸

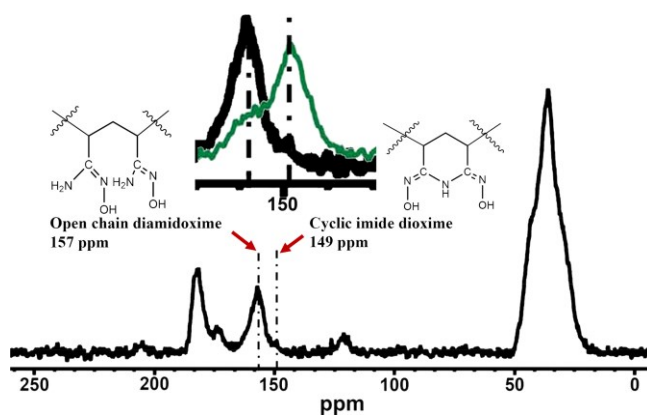


Fig. 3 ¹³C CP/MAS solid-state NMR spectrum of acrylic fiber after hydroxylamine reaction at 70 °C for 45 min. The green color spectrum on the inset is grafting produced amidoxime-containing fiber reported in the literature¹⁸. The signal at 157 ppm is assigned to acyclic amidoxime accompanied by a relatively small shoulder at 149 ppm assigned to cyclic imide dioxime. The chemical shifts at 183 and 177 ppm are assigned to the carboxylate (–COO[–]) and carboxylic acid (–COOH) groups, respectively.³⁶ A small signal observed at 121 ppm is assigned to the nitrile (C≡N) group. The huge broad peak at 36 ppm is assigned to the –CH₂ and –CH groups of the polymer backbone chain.

Extraction of uranium and vanadium from seawater

Several preliminary tests were performed to optimize the uranium adsorption capacity of the fiber adsorbent. The uranium adsorption capacities of polymer fiber adsorbents produced by the chemical process described above with different NH₂OH treatment time (amidoximation time) are given in Table 1. According to our seawater tests, the fiber containing equal molar ratio of

amidoxime to carboxylate groups (about 45% each, after 45 min of amidoximation time as shown in Table 1) gave the best uranium adsorption result. A small fraction of the original nitrile groups remaining in the fiber would enhance the mechanical strength of the material.^{27, 34, 35} Moreover, when all nitrile groups on the acrylic fiber surface are converted to amidoxime groups (180 min amidoximation), the fiber basically is not able to extract appreciable amount of uranium from real seawater. Comparing the FTIR spectra (Fig 2S in Supplementary Information) of amidoxime-containing fibers with 45 min and with 180 min amidoximation, the -COO^- band at 1595 cm^{-1} cannot be detected in the latter because it only has about 8% carboxylate groups in the fiber. This result implies that carboxylate functional groups play an important role in sequestering uranium from real seawater.

Table 1 Uranium and vanadium adsorption capacity of amidoxime-carboxylate containing polymer adsorbents derived from acrylic yarn under different amidoximation time at 70 °C.

Amidoximation Time (min)	Vanadium (g/kg) ^a	Uranium (g/kg) ^a	V/U ratio
15	0.19 ^b	0.01 ^b	19.0
30	3.78 ± 0.23	2.86 ± 0.14	1.32 ± 0.10
45	3.74 ± 0.21	3.61 ± 0.20	1.04 ± 0.08
60	3.03 ± 0.20	2.89 ± 0.12	1.05 ± 0.08
90	1.18 ± 0.09	0.23 ± 0.02	5.13 ± 0.59
180	0.35 ^b	0.01 ^b	35.0

^aVanadium and uranium adsorption capacity (g of metal/kg of adsorbent) after 21 days of exposure in filtered natural seawater is normalized to 35 psu. Average of 3–5 replicate seawater adsorption

experiments except for 15 min and 180 min. The performance of adsorbents in real seawater was at a temperature of 20 ± 1 °C and a flow rate of $250\text{--}300$ mL min^{-1} (~ 2 cm s^{-1} linear velocity) by active pumping through a multi-channel flowing column system.

^b Average of duplicate seawater adsorption experiments.

The polymer fiber with this composition showed a very high uranium adsorption capacity (greater than 3.0 g uranium per kg of adsorbent after 21 days of exposure to the seawater, Fig. 4a) in the flowing seawater column tests. The polymer fiber also showed a low vanadium/uranium adsorption ratio (1.04 in unit of g metal per kg fiber) relative to the adsorbents contained mainly cyclic imide-dioxime groups reported in the literature.^{17-19, 30, 31, 45} Subsequent scale-up tests utilizing a circulating seawater flume system^{5, 41} with braids made of ~ 10 grams of the fiber adsorbent confirmed the initial column test results. The uranium adsorption capacity of the braid reached 6.02 grams uranium per kg of adsorbent after 56 days of exposure in the real seawater at 20 °C (Fig. 4b) and the uranium/vanadium adsorption ratio remained close to unity. Using the one-site ligand saturation model^{5, 41}, the estimated saturation capacity of uranium in seawater is about 7.73 grams per kg of adsorbent. The half-saturation time (15.7 days) is also shorter than those reported (>20 days) for the grafting produced amidoxime-containing fibers.^{17-19, 41}

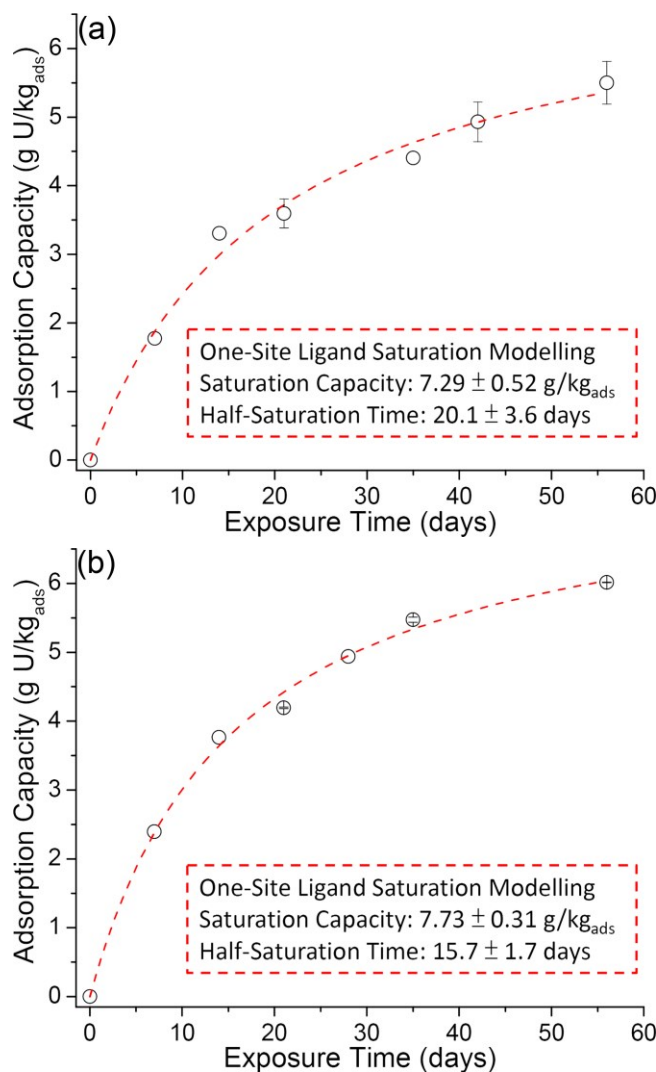


Fig. 4 Time-dependent uranium adsorption results (a) fiber adsorbent in a flowing column system, (b) braided adsorbent in a circulating seawater flume system.

A comparison of the LCW adsorbent with the amidoxime-based high-surface-area adsorbents synthesized by a radiation-induced grafting method in ORNL is given in Table 2. The LCW adsorbent shows a higher uranium and lower vanadium adsorption capacity from real seawater experiments. To the best of our knowledge, this fiber adsorbent derived from acrylic fiber

exhibits the lowest vanadium/uranium adsorption ratio from real seawater exposure tests among all amidoxime/carboxylate containing fibers reported in the literature.^{2, 45}

Table 2 Comparison with ORNL high-surface-area adsorbent

Adsorbent	Vanadium (g/kg) ^a	Uranium (g/kg) ^a	V/U ratio
LCW	6.38	6.02	1.06
ORNL-AF1 ^{b,17}	15.00	3.83	3.92
ORNL-AI11 ^{b,19}	17.00	3.35	5.07
ORNL-AF1DMSO ^{b,18}	17.92	4.48	4.00

^aVanadium and uranium adsorption capacity (g of metal/kg of adsorbent) after 56 days of exposure in filtered natural seawater is normalized to 35 psu.

^bData from references.¹⁷⁻¹⁹

The mechanism of vanadium adsorption by the LCW fiber is not understood. As mentioned previously, the branch-chain glutardiamidoxime molecule does not form any detectable complexes with VO_2^+ .^{23, 32} The vanadium coordination mode with the amidoxime groups attached to the fiber is likely to be different from that observed from single glutardiamidoxime molecules. A recent quantum chemical calculations based on the density-function theory appear to provide some clues about the coordination modes and bonding nature of vanadium with amidoxime/carboxylate containing fibers.⁴⁶ The study shows that amidoxime and carboxylate groups on single or double alkyl chains exhibit a synergistic effect for complexation with aqueous VO_2^+ species. The ΔG of the reactions forming vanadium complexes with mixed amidoxime and carboxylate complexes are

noticeably lower than those vanadium complexes formed with only amidoxime groups. Further research is needed to understand vanadium adsorption mechanisms by chelating fibers containing branch-chain amidoxime and carboxylate functional groups.

In the scale-up real seawater test (flume system), our adsorbent also exhibits the highest uranium adsorption capacity. One recent study reported the synthesis of amidoxime-based nanofiber adsorbent, prepared from composite of polyacrylamidoxime and montmorillonite by a blow-spin method. This nanofiber can reach high uranium adsorption capacity (9.59 grams per kg of adsorbent) in seawater exposure using small-scale (10 mg adsorbent) column adsorption test.¹⁶

However, the vanadium adsorption capacity of this nanofiber is still high ($V/U > 2$), as it is a cyclic imide-dioxime groups dominated adsorbent. There is no description on the scalability and performance consistency in seawater of this nanofiber material.

The uranium adsorption capacity of our fiber material in a simulated salt solution (26.52 g per liter NaCl solution spiked with 9 ppm uranium) is very high, in the order of 242 grams of U per kg of adsorbent and the adsorption is rapid, basically near saturation in 1 hour. The uranium adsorption capacities of fiber adsorbents synthesized by radiation-induced grafting technique and atom-transfer radical polymerization (60–230 g U/ kg adsorbent) are lower than our adsorbent in a simulated solution.^{17-19, 30, 31, 47, 48} This implies that the material has a potential for uranium

remediation applications such as uranium contaminated waters in uranium mining areas or uranium manufacturing facilities.

Extraction of critical metals and valuable elements

Besides U and V, the LCW fiber also adsorbs a variety of transition metals including Co, Cr, Cu, Fe, Mn, Ni, Ti, Zn in seawater (Fig. 5) with good efficiencies. For example, the adsorption capacity of cobalt, a near-critical material according to DOE, is 0.27 g per kg representing a distribution coefficient (K_d)⁵ of about 10^7 between the fiber and seawater.⁵ This K_d value is an order of magnitude higher than that reported for the other similar amidoxime-containing fibers.⁵ Because of its high distribution coefficients for transition metals, the material may have applications in remediation and management of harmful metals in aquatic environments including contaminated waterways and industrial wastewaters.

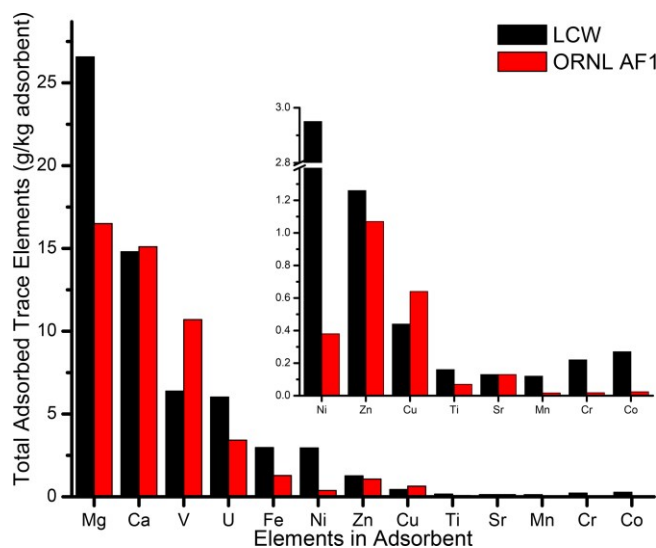


Fig. 5. Elements absorbed by the LCW amidoxime and carboxylate containing fiber adsorbent after 56 days of exposure in the PNNL circulating seawater flume system. The data of ORNL AF1 fiber is from reference⁵ for comparison. The inset is the expanded view for Ni, Zn, Cu, Ti, Sr, Mn, Cr, and Co.

Conclusion

Acrylic fiber can be used as starting material for synthesizing amidoxime and carboxylate containing chelating fibers for extracting uranium from seawater. This new fiber adsorbent has a higher uranium and lower vanadium adsorption capacities compared with other reported amidoxime-carboxylate containing fibers synthesized by radiation-induced grafting methods. Because the starting material is easily available and the synthesis procedure is simple, the process described in this paper appears highly attractive for mass production of the chelating fiber for various applications. This new method of producing low-cost and highly efficient chelating fibers may lead to practical commercial processes for production of uranium from seawater. The

material may also have various environmental toxic metals remediation and critical materials recycling applications. Further research along these directions is currently in progress.

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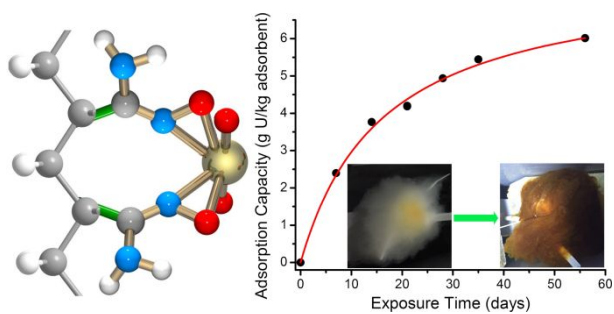
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Table of Contents (TOC)



The amidoxime and carboxylate containing chelating adsorbent derived from acrylic fiber shows a fast adsorption rate, high uranium and low vanadium adsorption capacities in real seawater tests.