ANL/CSE-14/24

Plant-Scale Column Designs for SHINE Target Solutions

Chemical Sciences and Engineering Division

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CONTENTS

FIGURES

TABLES

TABLES (Cont.)

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PLANT-SCALE COLUMN DESIGNS FOR SHINE TARGET SOLUTIONS

1 INTRODUCTION

Argonne is assisting Morgridge Institute for Research (MIR) in their efforts to develop SHINE, which is an accelerator-driven process that will most likely utilize a uranyl sulfate solution for the production of Mo-99. An integral part of the process is the development of a plant-scale column for the separation and recovery of Mo-99. Argonne has collected data from batch studies and small-scale column experiments to input into VERSE (Versatile Reaction Separation), a dynamic simulation package developed by Dr. Linda Wang at Purdue University to design large-scale separation processes using data obtained on a much smaller scale. Plant-scale column designs have been generated for several target solution configurations with uranium concentrations varying from 90 to 150 g-U/L, Mo concentrations ranging from 1.73×10^{-3} to 3.55×10^{-3} mM, and solution volumes varying between 142 L and 395 L. Direct down-scale column results have confirmed the validity of most of the plant-scale designs, because typically less than 1% Mo is found in the effluent and 90-100 ± 5% Mo can be recovered under the appropriate stripping conditions.

To design a Mo-recovery system for the SHINE project, batch, breakthrough, and pulse tests were conducted to determine isotherm, mass transfer, and system parameters. The VERSE program was used to calculate the mass-transfer zone under various loading times and velocities to design Mo separation and recovery columns employing a pure titania sorbent with 110-micron particles and 60 Å pores. The plant-scale column designs assume a temperature of 60^{o}C for most configurations and 80^{o}C for feed solutions containing 130 g-U/L uranyl sulfate. VERSE-designed recovery systems have been tested and verified in laboratory-scale experiments, and it has been shown that this approach is successful.

2 EXPERIMENTAL

2.1 BATCH STUDIES

The uptake of Mo(VI) was determined by equilibrating 1 mL of a Mo-99 spiked aqueous solution with a known amount (10 ± 1 mg) of sorbent for 24 hours at 60°C or 80°C using a thermostated shaker bath. Aqueous solutions contained tracer Mo-99 and 10^{-10}–10^{-4} M Mo added as $Na_2MoO_4 \cdot 2H_2O$ in the presence of uranyl sulfate (90-150 g-U/L). After equilibration, the solution was withdrawn and filtered by using a syringe fitted with a PVDF membrane filter with 0.22-μm pore size.

2.2 PREPARATION OF MO-99 SPIKE SOLUTION

Molybdenum-99 was obtained from a spent Tc-99m generator (provided by Hot Shots Nuclear Medicine). The initial activity of Mo-99 in a generator is typically between 1 and 10 Ci. However, we receive a Tc-99m generator when the activity remaining in the generator is insufficient for patient administration. Typically, a spent Tc-99m generator contains 0.1–0.3 Ci of Mo-99, which is more than enough for our tracer batch and column work.

Molybdenum-99 was removed from the generator by placing a serum vial containing 1 M NH_4OH on the needle labeled “Saline Charge”. Then, an evacuated serum vial was placed on the needle labeled “Receiver”. When no more bubbles appeared in the “Receiver” vial, the “Receiver” bottle was removed from the generator. The Mo-99 spiked solution was prepared by bringing the solution to dryness on a hot plate and re-dissolving it in 0.1 M H_2SO_4.

2.3 COUNTING OF MO-99

The amount of activity in the aqueous samples was determined with a germanium detector. Molybdenum-99 was quantified by measurement of its 739 keV γ-ray. The activity of Mo-99 in each sample was corrected for decay. The extent of radionuclide uptake in batch studies was expressed in terms of a distribution coefficient, K_d, shown in equation (1).

$$K_d = \left(\frac{A_o - A_s}{W}\right) \Bigg/ \frac{A_s}{V} \tag{1}$$

Here, A_0 and A_s represent the aqueous phase activity (μCi) before and after equilibration, respectively, W is the dry weight of the sorbent (g), and V is the volume of the aqueous phase (mL).

2.4 URANIUM CONCENTRATION

Inductively coupled optical emission spectroscopy (ICP-OES) was used to determine the concentration of uranium, and the error associated with these measurements is ± 5%.

2.5 COLUMN DESIGN PARAMETERS

The parameters and physical properties of uranyl sulfate given below were input into VERSE to design the plant-scale columns for the five target solution configurations being considered by SHINE. Table 1 shows the calculated density and viscosity values for the different uranyl sulfate solutions. Note the following:

1. The sorbent used for the Mo-recovery column is S110, a pure titania sorbent with 110 micron particles and 60 Å pores.

2. Langmuir isotherm parameters were estimated from Mo batch data measured for solutions with varying Mo concentrations in solutions containing 90 and 150 g-U/L uranyl sulfate at 60°C and 130 g-U/L uranyl sulfate at 80°C.

3. The Brownian diffusivity (D_∞) value of $HMoO_4^-$ in water at 25 °C (viscosity=0.8851 cP) was reported to be 8.3×10^{-4} cm^2/min.[1,2]

4. The density of a 130 g-U/L uranyl-sulfate solution at pH 1 was determined experimentally to be 1.16 g/mL at 80 °C. The densities of the remaining solutions were calculated by fitting data found in the literature.[3,4] (See Table 1.)

5. Viscosities for the target solutions were estimated by fitting published data obtained at 20.0, 30.0, 44.8, 59.8, 75.0, and 90.0 °C.[5] (See Table 1.)

6. The axial dispersion (*Eb*) was estimated with the Chung and Wen correlation (1968).[6]

7. The mass transfer coefficient (*kf*) was estimated with the Wilson and Geankoplis data (1966).[7]

8. Sorbent intra-particle voidage was obtained from the manufacturer, $\varepsilon p = 0.40$. Total void fraction, εt, was determined experimentally to be 0.608 and inter-particle voidage (εb) was calculated to be 0.35 ($\varepsilon t = \varepsilon b + \varepsilon p \times (1 - \varepsilon b)$).

TABLE 1 Calculated Values for the Density and Viscosity of Uranyl Sulfate Solutions at 60°C and 80°C

Conc. (g-U/L)	Density (ρ) (g/mL)	Viscosity (μ) (cP)	Temperature (°C)
90	1.1	0.59	60
104.2	1.12	0.61	60
130	1.16*	0.47	80
124.8	1.15	0.64	60
146.8	1.18	0.68	60

* Value was determined experimentally using a Mettler-Toledo density meter.

3 LANGMUIR MODEL RESULTS

The uptake of Mo was determined in a batch mode as a function of increasing Mo concentration. It was shown previously that Mo adsorption on titania sorbents follows Langmuir behavior.[8] There are four basic assumptions associated with the Langmuir model:

1. All adsorption sites are equal.

2. Adsorbing species do not interact with each other.

3. The adsorption mechanism does not vary for the same species.

4. The adsorbing species will form a single monolayer and only occupy free adsorption sites.[8]

The Langmuir-type adsorption is modeled by equation (2), where q_i represents the amount of species i adsorbed on the sorbent, a_i is the linear isotherm parameter, b_i is the non-linear isotherm parameter, and C_i represents the aqueous-phase concentration of i in equilibrium with q_i.

$$q_i = \frac{a_i * C_i}{(1 + b_i C_i)} \tag{2}$$

Langmuir-type data were obtained in solutions containing 90 and 150 g-U/L uranyl sulfate at 60°C and 130 g-U/L at 80°C. Figures 1-3 show the Langmuir data obtained in uranyl sulfate solutions containing 150 g-U/L at 60°C, 90 g-U/L at 60°C, and 130 g-U/L at 80°C. The data were fit to the Langmuir model using Origin 8.5.1. Table 2 shows the “a” linear and “b” non-linear parameters input into VERSE to design the plant-scale columns for the five target solutions (see Section 4.1). The same “a” and “b” values obtained in a 90 g-U/L uranyl sulfate solution were used to generate column designs for a 104.2 g-U/L uranyl sulfate solution. Additionally, the same “a” and “b” values obtained in a 150 g-U/L uranyl sulfate solution were used to generate column designs for a 124.8 and a 146.8 g-U/L uranyl sulfate solution.

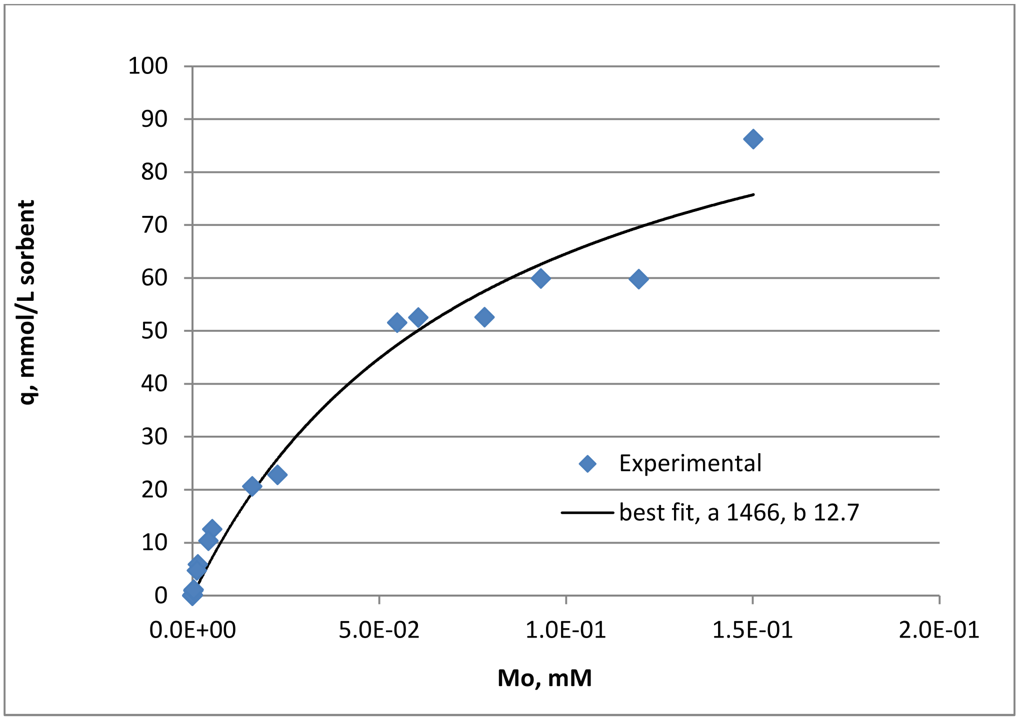

FIGURE 1 Plot of Langmuir Type Adsorption on a Titania Sorbent in the Presence of a 150 g-U/L Uranyl Sulfate Solution with Origin Best Fit at 60^{o}C

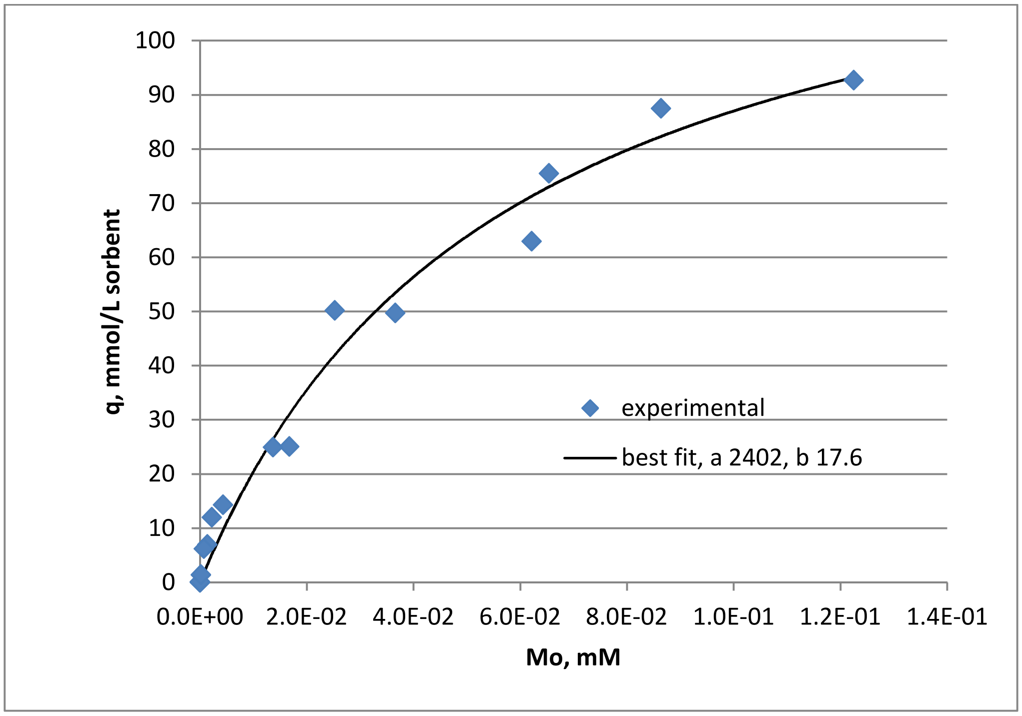

FIGURE 2 Plot of Langmuir Type Adsorption on a Titania Sorbent in the Presence of a 90 g-U/L Uranyl Sulfate Solution with Origin Best Fit at 60^{o}C

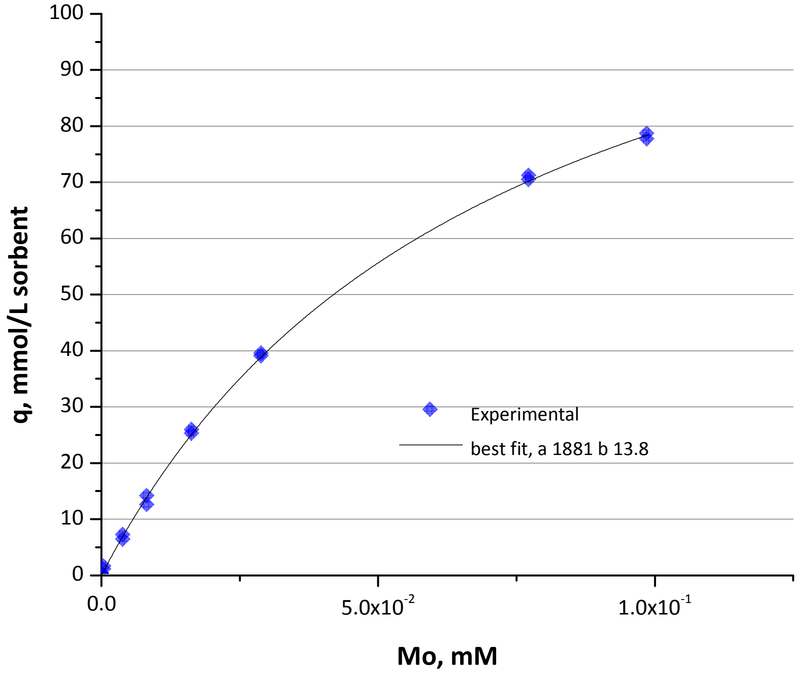

FIGURE 3 Plot of Langmuir Type Adsorption on a Titania Sorbent in the Presence of a 130 g-U/L Uranyl Sulfate Solution with Origin Best Fit at 80°C

TABLE 2 The "a" and "b" Parameters for the Five Target Solutions

U Concentration (g-U/L)	Temperature (°C)	Langmuir "a" value	Langmuir "b" value (mM^{-1})
90	60	2402	17.6
104.2	60	2402	17.6
124.8	60	1466	12.7
130	80	1881	13.8
146.8	60	1466	12.7

4 RESULTS AND DISCUSSION

4.1 PLANT-SCALE COLUMN DESIGNS

Table 3 shows the five target solution configurations being considered by SHINE Medical Technologies for the production of Mo-99. Potential column designs were developed for loading the target solution onto the column over periods of 2, 4, and 6 hours. Tables 4-8 show the potential column designs for the different configurations with a loading time of 2 hours. In these tables, the mass-transfer zone (MTZ) was calculated for each column diameter based on the linear velocity required to complete loading the column in the specified time period. The column length was increased by 10% above the MTZ and rounded up to the nearest centimeter to account for system parameter uncertainties. The column volume, mass of sorbent, pressure drop, and sorbent loading were calculated from the column geometry. Plant-scale column designs for the different configurations with loading times of 4 and 6 hours are shown in Appendix A.

Even though the sorbent utilization for the different configurations can be increased by 28-32% by increasing the loading time from 2 to 4 hours and by 42-44% by increasing the loading time from 2 to 6 hours, we decided saving time was more important than using less sorbent. The optimal column designs being considered and tested on a laboratory scale are for a

TABLE 3 Target Solution Configurations Being Considered by SHINE

Uranyl Sulfate Conc. (g-U/L)	Vol. (L)	Fission Power (kW)	Mo (mmol)	Mo (mM)	Mo-99 (Ci)
90	395	112.7	7.03E-01	1.78E-03	5000
104.2	257.7	97.2	6.06E-01	2.35E-03	4313
130	262	87.5	5.50E-01	2.10E-03	3882
124.8	178.3	85.1	5.31E-01	2.98E-03	3776
146.8	142.3	80.9	5.05E-01	3.55E-03	3589

TABLE 4 Preliminary Designs for Recovery of Mo from 395 L of 90 g-U/L and 1.78 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 2-h loading time, 3.3-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/Sorbent Mass (Ci/g)
12	29.1	18.25	20	2262	2941	0.87	1.70
15	18.63	11.77	13	2297	2986	0.36	1.67
20	10.48	6.73	8	2513	3267	0.13	1.53
25	6.71	4.39	5	2454	3191	0.05	1.57
30	4.66	3.13	4	2827	3676	0.03	1.36

TABLE 5 Preliminary Designs for Recovery of Mo from 257.7 L of 104.2 g-U/L and 2.35 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 2-h loading time, 2.1-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/Sorbent Mass (Ci/g)
12	18.99	12.28	13	1470	1911	0.38	2.26
15	12.15	7.93	9	1590	2068	0.17	2.09
20	6.84	4.53	5	1571	2042	0.05	2.11
30	3.04	2.13	3	2121	2757	0.01	1.56

TABLE 6 Preliminary Designs for Recovery of Mo from 262 L of 130 g-U/L and 2.10 x 10^{-3} mM Mo at 80°C (S110, 99.9% recovery, 2-h loading time, 2.2-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (L)	Sorbent Weight (kg)	ΔP (atm)	Mo-99 / Sorbent Mass (Ci/g)
10	27.82	17.36	20	1.6	2.04	0.63	1.90
12	19.32	12.04	14	1.6	2.06	0.30	1.89
15	12.37	7.80	9	1.6	2.07	0.13	1.88
20	6.96	4.43	5	1.6	2.04	0.04	1.90

TABLE 7 Preliminary Designs for Recovery of Mo from 178.3 L of 124.8 g-U/L and 2.98 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 2-h loading time, 1.5-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/Sorbent Mass (Ci/g)
10	18.92	15.66	17	1335	1736	0.53	2.18
15	8.41	7.07	8	1414	1838	0.11	2.05
20	4.73	4.06	5	1571	2042	0.04	1.85
25	3.03	2.67	3.5	1718	2233	0.02	1.69

TABLE 8 Preliminary Designs for Recovery of Mo from 142.3 L of 146.8 g-U/L and 3.55×10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 2-h loading time, 1.2-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/Sorbent Mass (Ci/g)
10	15.1	12.97	14	1100	1429	0.37	2.51
12	10.49	9.07	10	1131	1470	0.18	2.44
15	6.71	5.87	7	1237	1608	0.08	2.23
20	3.77	3.39	4	1257	1634	0.03	2.20

loading time of 2 hours. Another way to increase sorbent utilization is to decrease Mo recovery from 99.9% to 99% in VERSE, but that option is not being pursued. From a separation and recovery standpoint, the optimal configuration should have the highest Mo concentration and lowest feed volume. The target solution that looks most promising is 146.8 g-U/L because it has the best sorbent utilization and smallest column sizes. Lowering the column volume has at least two benefits: (1) decreasing the volume and mass of the spent column material in the waste and (2) lowering the volumes of the column wash streams and the Mo-product stream.

Under the conditions modeled in this study, the calculated mass transfer area is nearly proportional to the inverse of the linear velocity. Therefore, the geometry of the column, as long as the volume is kept constant, is not a key factor. The column geometry should be sized for easy, reliable packing to maintain the pressure drop in the column relatively low and to accommodate other economic and operational factors.

Based on having the column pressure drop below 0.5 atm and a column geometry that can be easily and reliably packed, the following is suggested:

- For recovery of Mo in 2 hours, the recommended column is 10 x 14 cm (ID x L) utilizing ~1.4 kg of sorbent with a ΔP = 0.37 atm. The projected acid wash volume for this design is 5.5 L, water wash is 5.5 L, and the Mo-product volume is 22-33 L.

4.2 DOWN-SCALE COLUMN EXPERIMENTS

Several laboratory-scale column experiments were performed in an effort to test the plant-scale column designs derived from VERSE calculations. The column sizes that were tested were chosen based on the availability of the columns and the amount of feed volume. Results from 1 to 4 down-scale experiments are shown in Table 9 for each of the different target solution configurations being considered by SHINE. All column experiments employed a depleted uranium solution as uranyl sulfate (pH 1) with stable Mo at the specified concentration added as sodium molybdate and tracer Mo-99.

TABLE 9 Results for the Down-Scale Column Experiments for the Five Target Solution Configurations

U Conc. (g-U/L)	Mo Conc. (mM)	Feed Volume (mL)	Column ID (cm)	Column L (cm)	% Mo Effluent	% Mo Recovered	Loading Velocity (cm/min)	Stripping Velocity (cm/min)	Feed Temp. (°C)
90	1.73E-03	441	1	8	0.3	82*	5	5	60
90	1.73E-03	288	1	5	1.0	90	3	3	60
90	1.73E-03	372	1	5	0.7	100	4	4	60
90	1.73E-03	468	1	5	1.1	94	5	5	60
104	2.35E-03	504	1	3	0.2	96	3.1	1.6	60
125	2.98E-03	196	0.66	5	0.1	100	4.7	2.3	60
130	2.10E-03	665	1	5	0.08	100	7	3.5	80
130	2.10E-03	665	1	5	0.11	86	7	7	80
130	2.10E-03	665	1	5	0.33	81**	7	3.5	80
146	3.55E-03	364	1	4	0.66	92	3.8	1.9	60
146	3.55E-03	364	1	4	0.1	66	3.8	3.8	60

* 1 M NH_4OH used to elute Mo was not heated.

** 1 M NH_4OH used to elute Mo was heated to 80°C, which created numerous bubbles.

The feed solution was heated to 60 or 80°C prior to being loaded onto the column. The column was kept at 60 or 80°C using heat tape, and stainless steel coils wrapped in heat tape were placed immediately before and after the column inlet and outlet to ensure the temperature of the solution entering the column was maintained at 60 or 80°C. The strip solution was heated to 70°C to achieve optimal Mo recovery because lower Mo recoveries were observed when the strip solution was kept at room temperature or heated to temperatures $\geq$80°C. Each column experiment was performed as follows:

1. Column was equilibrated with 10 column volumes (CVs) of 0.1 M H_2SO_4.

2. Feed solution (heated to the appropriate temperature) was loaded onto the column at a specific linear velocity in the up-flow direction (to concentrate Mo on the bottom of the column and prevent entrapment of fission gases for future column runs with irradiated solutions).

3. Column was washed with 5 CVs of 1 M H_2SO_4 in the up-flow direction (to ensure any adsorbed Pu is removed from the column for future runs with irradiated solutions).

4. Column was washed with 5 CVs of H_2O in the up-flow direction (to remove any acid).

5. Molybdenum was eluted by passing 30 CVs of 1 M NH_4OH heated to 70°C through the column in the down-flow direction.

6. Column was washed with 5 CVs of H_2O in the up-flow direction. A freshly packed titania column was used for each experiment.

The plant-scale column designs generated using VERSE assume 99.9% Mo will be adsorbed and recovered. Direct down-scale column experiments show that 0.1-1.1% (standard deviation of ± 5% of the 0.1-1.1%) Mo is found in the effluent. Due to the error associated with the gamma counting results, 1% or less Mo in the effluent indicates good Mo adsorption and effective column design.

The Mo recoveries ranged from 66-100% (± 5%) for the down-scale column experiments. Results from these experiments suggest that the stripping velocity should be half of the loading velocity to achieve 90-100% (± 5%) recovery of Mo. For example, only 66% Mo was recovered when the loading and strip velocities were the same for the 146 g-U/L experiment; however, 92% Mo was recovered when the linear velocity for the strip solution was decreased from 3.8 to 1.9 cm/min. Additionally, the temperature of the strip solution should be maintained at 70^{o}C to ensure diffusion into the sorbent pores and release of Mo. For example, 82% Mo was recovered for the 90 g-U/L experiment when the strip solution was not heated, and 81% Mo was recovered for the 130 g-U/L experiment when the strip solution was heated to 80^{o}C. Moreover, 100% Mo was recovered under the same conditions for the 130 g-U/L experiment when the strip solution was heated to 70^{o}C. When the temperature of the strip solution exceeds ~70^{o}C, a significant number of bubbles form and are subsequently passed through the column, decreasing the amount of Mo recovered.

For the plant-scale operation, recovering ~80-85% of the Mo actually formed after purification will be viewed as a success. Since the expected Mo yield for the LEU-Modified Cintichem purification process is between 85 and 90%, the operation must recover 95% of the Mo. The column experiments completed thus far have not studied the effects of other fission and activation products on Mo adsorption and recovery or the effects of a high radiation field on the Mo redox chemistry. The mini-SHINE experiments will examine the effects of potential competing components on Mo adsorption and recovery because approximately 2 Ci Mo-99 and all other fission products will be produced by irradiating 5 L of a uranyl sulfate solution at the linac. Additionally, the effect of a high radiation field on Mo redox chemistry will be studied in the mini-SHINE experiments because, if less Mo is adsorbed or recovered on the titania column than what is expected, a portion of Mo(VI) may have been reduced to Mo(IV) or Mo(V). If this is the case, an oxidizing agent, such as potassium permanganate, can be used to ensure Mo is present as Mo(VI).

5 CONCLUSIONS AND FUTURE WORK

Several column designs have been generated for the SHINE target solution configurations, and down-scale column designs have been tested using non-irradiated uranyl sulfate solutions with stable Mo and tracer Mo-99. Overall, the down-scale experiments showed that any of the five potential target solution configurations can be used to design a column with the appropriate parameters needed for good Mo adsorption and recovery. During the down-scale column experiments, two important factors were identified to increase Mo recovery: (1) decreasing the stripping velocity by 50% compared to the loading velocity and (2) heating the strip solution to 70°C. Both factors will be implemented for the plant-scale operation.

Three parameters have been discussed that affect column efficiency—Mo concentration, uranium concentration, and feed flow rate. From a Mo-recovery perspective, target-solution designs with the highest power density (and, thus, the highest Mo concentrations), even with high uranium concentrations, will require the lowest volume columns. For example, the plant-scale column designs for the 146.8 g-U/L uranyl sulfate solution with a Mo concentration of 3.55×10^{-3} mM are the most efficient. For the recovery of Mo in 2 hours, the recommended column is 10 cm x 14 cm (ID x L) utilizing ~1.4 kg of sorbent with a pressure drop of 0.37 atm. The projected acid wash volume for this design is 5.5 L, water wash is 5.5 L, and the Mo-product volume is projected to be between 22 and 33 L. For any of the other target solution configurations, the plant-scale column designs with internal diameters of 10-12 cm for 2-h loading are the best options because they are the smallest columns and will minimize wash and waste volumes. Increasing the loading time was also discussed to increase overall column efficiency, but at this point, it is not being implemented.

Modifications to the current plant-scale column designs will most likely occur after results from the mini-SHINE experiments are obtained. The effect of potential competing components on Mo adsorption and recovery may increase the column sizes slightly; however, the length of the MTZ has already been increased by 10% to account for system problems. As a result, increasing the column size may not be necessary. Additionally, an oxidizing agent may need to be added to one or more steps during the plant-scale operation to ensure that Mo is present as Mo(VI).

Once the final SHINE target solution configuration has been determined, Langmuir data will be obtained for the proper uranium concentration and temperature. Additionally, if modifications are needed based on results from the mini-SHINE experiments, those will be implemented as well.

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APPENDIX A:

PLANT-SCALE COLUMN DESIGNS FOR THE POTENTIAL SHINE TARGET SOLUTION CONFIGURATIONS WITH LOADING TIMES OF 4 AND 6 HOURS

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APPENDIX A:

PLANT-SCALE COLUMN DESIGNS FOR THE POTENTIAL SHINE TARGET SOLUTION CONFIGURATIONS WITH LOADING TIMES OF 4 AND 6 HOURS

TABLE A-1 Preliminary Designs for Recovery of Mo from 395 L of 90 g-U/L with 1.78 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 4-h loading time, 1.7-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
10	20.96	18.07	19	1492	1940	0.6	2.58
12	14.55	12.64	14	1583	2058	0.31	2.43
15	9.31	8.19	9	1590	2068	0.13	2.42
20	5.24	4.73	6	1885	2450	0.05	2.04
25	3.35	3.13	4	1963	2553	0.02	1.96

TABLE A-2 Preliminary Designs for Recovery of Mo from 395 L of 90 g-U/L with 1.78 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 6-h loading time, 1.1-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
10	13.97	14.88	16	1257	1634	0.34	3.06
12	9.7	10.42	12	1357	1764	0.17	2.83
15	6.21	6.77	8	1414	1838	0.07	2.72
20	3.49	3.93	5	1571	2042	0.03	2.45

TABLE A-3 Preliminary Designs for Recovery of Mo from 257.7 L of 104.2 g-U/L with 2.35 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 4-h loading time, 1.1-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
8	21.36	20	21	1056	1372	0.7	3.14
10	13.67	12.7	14	1100	1429	0.3	3.02
15	6.08	5.53	6.5	1149	1493	0.06	2.89
20	3.42	3.19	4	1257	1634	0.02	2.64

TABLE A-4 Preliminary Designs for Recovery of Mo from 257.7 L of 104.2 g-U/L with 2.35 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 6-h loading time, 0.7-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
8	14.24	15.6	17	855	1111	0.38	3.88
10	9.11	10	11	864	1123	0.16	3.84
15	4.05	4.6	5.5	972	1264	0.03	3.41
20	2.28	2.67	3.5	1100	1429	0.01	3.02

TABLE A-5 Preliminary Designs for Recovery of Mo from 178.3 L of 124.8 g-U/L with 2.98 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 4-h loading time, 0.7-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
8	14.78	17.27	18	905	1176	0.44	3.21
10	9.46	11.17	12	942	1225	0.19	3.08
12	6.57	7.8	9	1018	1323	0.1	2.85
15	4.2	5.13	6	1060	1378	0.04	2.74

TABLE A-6 Preliminary Designs for Recovery of Mo from 178.3 L of 124.8 g-U/L with 2.98 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 6-h loading time, 0.5-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
6	17.52	25.34	26	735	956	0.75	3.95
8	9.85	14.37	15	754	980	0.24	3.85
10	6.31	9.27	10	785	1021	0.1	3.70
15	2.8	4.27	5	884	1149	0.02	3.29

TABLE A-7 Preliminary Designs for Recovery of Mo from 262 L of 130 g-U/L with 2.10 x 10^{-3} mM Mo at 80°C (S110, 99.9% recovery, 4-h loading time, 1.1-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (L)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
8	21.74	19.16	22	1.1	1440	0.55	2.70
10	13.91	12.4	14	1.1	1430	0.23	2.71
12	9.66	8.8	10	1.1	1470	0.12	2.64
15	6.18	5.8	7	1.1	1490	0.05	2.61

TABLE A-8 Preliminary Designs for Recovery of Mo from 262 L of 130 g-U/L with 2.10 x 10^{-3} mM Mo at 80°C (S110, 99.9% recovery, 6-h loading time, 0.7-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (L)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
6	25.76	28.32	31	0.9	1180	0.96	3.29
8	14.49	16	18	0.9	1180	0.31	3.29
10	9.27	10.4	12	0.9	1170	0.13	3.32
12	6.44	7.2	8	0.9	1180	0.06	3.29
15	4.12	4.71	6	0.97	1260	0.03	3.08

TABLE A-9 Preliminary Designs for Recovery of Mo from 142.3 L of 146.8 g-U/L with 3.55 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 4-h loading time, 0.6-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
6	20.97	25.21	26	735	956	0.95	3.75
8	11.8	14.27	15	754	980	0.31	3.66
10	7.55	9.19	10	785	1021	0.13	3.52
15	3.36	4.2	5	884	1149	0.03	3.12

TABLE A-10 Preliminary Designs for Recovery of Mo from 142.3 L of 146.8 g-U/L with 3.55 x 10^{-3} mM Mo at 60°C (S110, 99.9% recovery, 6-h loading time, 0.4-L/min rate)

Column ID (cm)	Velocity (cm/min)	$MTZ_{0.1\%}$ (cm)	Column Length (cm)	Column Volume (mL)	Sorbent Weight (g)	ΔP (atm)	Mo-99/ Sorbent Mass (Ci/g)
5	20.13	30.1	31	609	791	1.09	4.54
6	13.98	20.96	22	622	809	0.54	4.44
8	7.86	11.87	13	653	849	0.18	4.23
10	5.03	7.67	9	707	919	0.08	3.91

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