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Recycle of enriched Mo targets for economic production of $^{99}Mo/^{99m}Tc$ medical isotope without use of enriched uranium

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Abstract

A new recycle process for recovery of enriched ^{98}Mo or ^{100}Mo used for production of $^{99}Mo/^{99m}Tc$ medical isotope was developed. In this process, Mo is precipitated from spent NorthStar Mo/Tc generator solution containing ~200g/L Mo as K_2MoO_4 in 5M KOH using acetic acid and then washed with nitric acid. High purification factors from potassium were achieved, and typical Mo recovery yields were ~95%. The recycle process was performed with up to 260g of Mo per batch and can be easily implemented for processing of up to 400g of Mo.

Keywords

^{99}Mo, enriched molybdenum, accelerator, production, purification, recycle

Introduction

Lately, a lot of attention has been paid to a potential shortage of the world's supply of $^{99}Mo/^{99m}Tc$ [1-7]. Currently, most of the ^{99}Mo is produced by the fissioning of ^{235}U in high-enriched uranium targets (HEU, generally 93% ^{235}U) [1] using aging reactors. A major supplier of ^{99}Mo is Nordion, Inc., (Ottawa, Canada) providing ~40 percent of the world's supply. However, the Chalk River Laboratories' NRU reactor, which produces ^{99}Mo for Nordion, plans to cease production in 2016. [2, 8-9]. The majority of the US supply of ^{99}Mo is provided by Nordion and Mallinckrodt [1]. The US currently consumes about 50% of the world's production of ^{99}Mo. The National Nuclear Security Administration's Material Management and Minimization office works with U.S. commercial entities and the national laboratories to accelerate the establishment of a reliable supply of the ^{99}Mo by supporting a diverse set of technologies to produce ^{99}Mo without the use of highly enriched uranium. Recently, several possible technologies were proposed for the production of ^{99}Mo/^{99m}Tc or directly ^{99m}Tc without use of uranium targets [10-11]: i) by linear accelerators using fast neutrons ^{100}Mo(n,2n)^{99}Mo reaction [12], or photonuclear reaction with photon source from bremsstrahlung ^{100}Mo(γ,n)^{99}Mo [13-19], ii) direct production of ^{99m}Tc in cyclotrons using ^{100}Mo(p, 2n)^{99m}Tc [8, 20-23], or iii) neutron capture on ^{98}Mo [24-27]. These technologies offer a lower-cost alternative to reactor production using fissioning of ^{235}U, but generally with a lower yield of ^{99}Mo or ^{99m}Tc. To produce significant activities of ^{99}Mo (several TBq of ^{99}Mo, 1000Ci=37TBq), enriched ^{100}Mo or ^{98}Mo needs to be used for all these non-uranium alternatives (enriched ^{100}Mo could be available for ~ \$1000/g for kg quantities). Use of Mo targets requires a major change in the generator technology to accommodate for the high concentration of Mo. The main advantage of all these proposed technologies is very limited waste stream, because only limited or no further purification/separation is needed.

Argonne National Laboratory, in cooperation with Los Alamos and Oak Ridge National Laboratories and NorthStar Medical Technologies, LLC, is developing technology for the production of ^{99}Mo. As a short-term solution, NorthStar is planning to produce ^{99}Mo via ^{98}Mo(n, γ)^{99}Mo reaction at the University of Missouri Research Reactor, and as a long-term solution using photonuclear reaction ^{100}Mo(γ, n)^{99}Mo. For economic production of ^{99}Mo, both technologies require enriched Mo material (^{98}Mo or ^{100}Mo). To accommodate for low specific activity of Mo-99, separation of ^{99m}Tc from the ^{99}Mo (and the rest of Mo present in the target) is performed using the RadioGenix® generator from NorthStar. The RadioGenix® uses ABEC resin, consisting of monomethylated polyethylene glycol

(PEG)-5000 covalently bound to a polystyrene support [28]. The ABEC resin is highly selective for Tc from highly alkaline solutions while Mo passes through the column and is recovered for another milking. This allows efficient separation of Tc from highly concentrated Mo solution. Irradiated Mo-metal targets are dissolved in H_2O_2, and Mo is converted to K_2MoO_4 by addition of KOH. The advantage of using KOH over NaOH is higher Mo solubility in KOH [17]. Used generator solution needs to be treated to recover valuable enriched Mo (^{100}Mo or ^{98}Mo) for future production of Mo targets. One of the possible ways to recycle Mo is the conversion of K_2MoO_4 in 5 M KOH solution into MoO_3 powder that can be further reduced to Mo metal [29]. Recovery of Mo during the reduction of Mo from MoO_3 to MoO_2 and Mo metal is nearly quantitative [29].

The most challenging step is purification of Mo from potassium. The starting ^{100}Mo enriched material usually contains ≤100 mg-K/kg-Mo. However, the spent generator solution contains about 1.8 kg-K/kg-Mo. One requirement is that the impurities in the recycled material need to be at the same or below the concentration present in the starting material to facilitate acceptance for use of recycled ^{100}Mo by the FDA (U.S. Food and Drug Administration). Therefore, the amount of potassium in purified MoO_3 powder should be below 100 mg-K/kg-Mo. Recently, Bénard et al [8] reported about 85% recovery yield for recycled enriched ^{100}Mo material, although no process was discussed on how the recycle was performed. Gagnon et al. [30] reported similar recovery yields ~87% from metal to metal for ammonium molybdate system. Authors discuss that ammonium molybdate is better starting material for Mo reduction than MoO_3, because it shows increased density for sintered Mo. It should be noted that increased density is not the only parameter that drives the target production. Target density under certain sintering condition can severely affect the dissolution kinetics of the target in hydrogen peroxide [31-32].

Here we report a simple and very effective method for recycle of enriched Mo targets that achieves very high purification factors from potassium and provide high Mo yields (~95%). Cyclotron production of ^{99m}Tc, and accelerator production of ^{99}Mo using ^{100}Mo enriched targets with a recycle process that can handle several hundred grams of Mo per batch can be a very attractive and cost-effective alternative to fission made molybdenum.

The general scheme for the molybdenum cycle from the target production through the recycle of the spent Mo solution is illustrated in Figure 1.

Figure 1 Diagram of molybdenum cycle from the disk production through the recycle process

Experimental

^{99}Mo was obtained from Lantheus as a 1Ci ^{99m}Tc generator (TechneLite). A starting solution of K_2MoO_4 (0.2 g-Mo/mL) in 5 M KOH solution was prepared by dissolving MoO_3 in KOH. Concentrated nitric acid (70% vol HNO_3), glacial acetic acid and ammonium hydroxide were trace-metal grade-purity. HNO_3 and HCl used for ICP-MS analysis were Optima grade. All other chemical reagents used in this work were of analytical-reagent-grade purity and were used without further purification. All aqueous solutions were prepared with deionized water with a resistivity ≥18 MΩ•cm.

Small-scale experiments

For small-scale experiments, precipitation of Mo was performed by adding acid: acetic acid (AcOH), nitric acid (HNO_3) and sulfuric acid (H_2SO_4) or ethanol (EtOH) to a solution of K_2MoO_4 in 5 M KOH (0.2 g-Mo/mL). The Mo precipitate was then repeatedly washed with concentrated AcOH and/or HNO_3 acid using a vortex mixer. The wash solution was separated from the Mo precipitate using a Beckman Allegra X-30 centrifuge at 3400 rcf (relative centrifugal force) for 5-10 minutes. After a final wash, the precipitate was re-dissolved in NH_4OH, acidified by HCl, and analyzed for K content using inductively coupled plasma mass spectrometry (ICP-MS), PerkinElmer SCIEX ELAN DRC II. Recovery of Mo for experiments with ^{99}Mo was determined radiometrically using a high purity germanium detector (Ortec) using a peak at 739.5 keV and using ICP-MS for experiments performed without ^{99}Mo tracer.

Large-scale processing

Large-scale experiments were performed in 2-L bottles using ~300 mL of K_2MoO_4 solution (~0.2g-Mo/mL) in 5 M KOH. About 1.5 L of glacial AcOH was used to precipitate Mo from a 300 mL of solution. Freshly formed precipitate was mixed for 10 min at 7000-10000 rpm using a Silverson L5M-A overhead mixer, and then centrifuged at ~6200 rcf for 10 min using a large capacity centrifuge (Sorvall RC 12BP+). The centrifuge is capable of processing six 2 L bottles. After the final nitric-acid wash, the MoO_3 precipitate was first dried in the bottle at 80°C for a few hours and then transferred into a beaker and dried at 160°C to remove the remaining HNO_3 and dehydrate the MoO_3 precipitate. The dried MoO_3 was ground into powder. Aliquots of the MoO_3 powder were re-dissolved in NH_4OH and acidified by HCl, and the concentration of the metals of interest was determined using ICP-MS.

Results

Small-scale experiment

Precipitation of Mo

Several reagents were tested to precipitate Mo from highly alkaline solution. Table 1 shows the effectiveness of potassium removal by different reagents as well as Mo losses in precipitation step. For these experiments, 1 mL of K_2MoO_4 in 5 M KOH (0.2 g-Mo/mL) was combined with 5 mL of each reagent listed in Table 1.

Table 1. Mo Losses and Removal of Potassium for Different Reagents Used to Precipitate Mo.

Reagent Used to Precipitate Mo[a]	Mo Lost	K Removed
Glacial AcOH	0.2–2%	75–85%
EtOH	~0–0.2%	30-45%
4:1 v/v EtOH:AcOH	0–0.4%	30-40%
15.9 M HNO_3	5–20%	80-90%

[a] AcOH = acetic acid; EtOH = ethanol

Besides reagents listed in Table 1, we also investigated H_2SO_4. HNO_3 and H_2SO_4 are strong acids; therefore, adding these acids to a highly alkaline solution causes a highly exothermic neutralization reaction. If H_2SO_4 is carefully added to K_2MoO_4 in 5 M KOH in 1:1 v/v ratio, a white precipitate containing Mo forms. However, when more H_2SO_4 is added, both phases collapse and form a gelatinous suspension, which prevents purification of Mo from potassium. A combination of sulfuric and acetic acid was also tested, but a significant portion of Mo was found to be soluble in the mixtures. Careful addition of HNO_3 forms a yellow precipitate containing Mo and a clear liquid phase. When ethanol is added to a highly alkaline Mo solution, a white precipitate containing K_2MoO_4 is formed. Since AcOH is a weak acid ($K_a=1.8\times10^{-5}$) it is likely that the white precipitate that forms after precipitating Mo consists of various mixed K-Mo species, and possibly dimeric or polymeric Mo species that are predominant in the pH=2-4 region and high Mo concentrations [33]. The benefit of using AcOH is that the neutralization reaction is mild. After precipitation of molybdenum with AcOH followed by centrifugation (6200 rcf), over time a fine white precipitate that contains Mo can form. This is most likely due to the formation of soluble polymeric Mo species that predominate at pH~4 [34]. These species probably decompose over time to the hydrated MoO_3 and form a fine precipitate. Therefore, it is important to allow sufficient time for this conversion and collect the secondary precipitate in order to keep Mo recovery as high as possible. It should be noted that in order to achieve ~100 mg-K/kg-Mo in the final Mo product, 99.995% of starting potassium has to be removed during Mo recovery process. To achieve this purity level, multiple washes of the Mo precipitate are needed.

Washing step

Based on the data presented in Table 1, nitric and acetic acid were studied in more detail. Experimental data on the effectiveness of AcOH and HNO_3 as washing agents are presented in Table 2.

Table 2. Distribution of K and Mo in AcOH and HNO_3 fractions. Balance of Mo and K is affected by some carryover of washing solution into Mo precipitate. Starting solution: 5 mL of K_2MoO_4 in 5 M KOH (0.2 g-Mo/mL)

step	volume, mL	reagent	K, %	Mo, %	mg of K/kg of Mo
precipitation	25	17.4 M AcOH	80.0%	0.5%	
wash #1	25	17.4 M AcOH	8.8%	0.1%	
wash #2	25	17.4 M AcOH	2.3%	0.2%	
wash #3	25	15.9 M HNO_3	13.7%	0.8%	
wash #4	25	15.9 M HNO_3	3.3%	0.4%	
		product	**1.05%**	**95.15%**	**20219**
precipitation	25	17.4 M AcOH	78.1%	0.5%	
wash #1	25	17.4 M AcOH	7.4%	0.1%	
wash #2	25	15.9 M HNO_3	15.6%	1.2%	
wash #3	25	15.9 M HNO_3	3.9%	0.6%	
wash #4	25	15.9 M HNO_3	0.9%	0.3%	
		product	**0.50%**	**96.86%**	**9403**
precipitation	25	17.4 M AcOH	81.5%	0.6%	
wash #1	25	15.9 M HNO_3	23.4%	1.3%	
wash #2	25	15.9 M HNO_3	3.0%	0.3%	
wash #3	25	15.9 M HNO_3	0.6%	0.2%	
wash #4	25	15.9 M HNO_3	0.2%	0.2%	
		product	**0.14%**	**96.48%**	**2703.1**
precipitation	25	15.9 M HNO_3	84.9%	5.4%	
wash #1	25	15.9 M HNO_3	11.2%	0.5%	
wash #2	25	15.9 M HNO_3	1.4%	0.3%	
wash #3	25	15.9 M HNO_3	0.2%	0.3%	
wash #4	25	15.9 M HNO_3	0.04%	0.4%	
		product	**0.017%**	**91.96%**	**347.3**

If acetic acid is used for precipitation, about 80% of the potassium is removed with <1% Mo losses. However, when HNO_3 is used to precipitate Mo, the Mo losses in first precipitation step are significant (Tables 1-2). Results clearly show that HNO_3 is more effective in removing potassium during the wash step and the sooner the AcOH is replaced by HNO_3 to wash the Mo precipitate, the more effective the removal of potassium is.

Similar to the case with the AcOH precipitation, a fine Mo precipitate forms in the solution over time (after several hours) after the first HNO_3 wash. This could be due to the presence of soluble dimeric species that temporarily form through the protonation of molybdenum trioxide [35]. Formation of such Mo species is common mostly in strongly acidic, non-complexing media, such as perchloric acid [35], but may form in the presence of HNO_3 as well. To eliminate Mo losses, samples after the precipitation step with acetic acid and the first HNO_3 wash were allowed to sit for at least 24 hours. This significantly improved the recovery yields of Mo.

Data in Table 3 show the effectiveness of potassium removal when HNO_3 is used after precipitation of Mo using acetic acid. Small-scale experiments showed that the best potassium removal and Mo recoveries are obtained when acetic acid is used to precipitate Mo followed by washing the Mo precipitate with concentrated HNO_3.

Table 3. Effect of number of HNO_3 washes and mixing time on removal of potassium after precipitation of Mo using glacial acetic acid. Minimum of 24 hours were allowed after precipitation step and first HNO_3 washing step to recover Mo from the fine precipitate that forms after these steps.

precipitation	Mixing time, min	# HNO_3 washes	K removed, %	Product content	
				Mo, %	**mg of K/kg of Mo**
AcOH	4	6	99.956%	98.11%	777.3
AcOH	4	8	99.985%	99.51%	261.2
AcOH	4	10	99.992%	99.37%	142.7
AcOH	4	12	99.996%	96.74%	71.6
AcOH	10	12	99.999%	~100%	14.7
AcOH	10	14	99.999%	~100%	10.8

Large-scale processing

Based on the results from small-scale experiments, large-scale experiments were performed by precipitating Mo with glacial acetic acid followed by washing with 70% HNO_3. The major steps of the process are outlined in Figure 2.

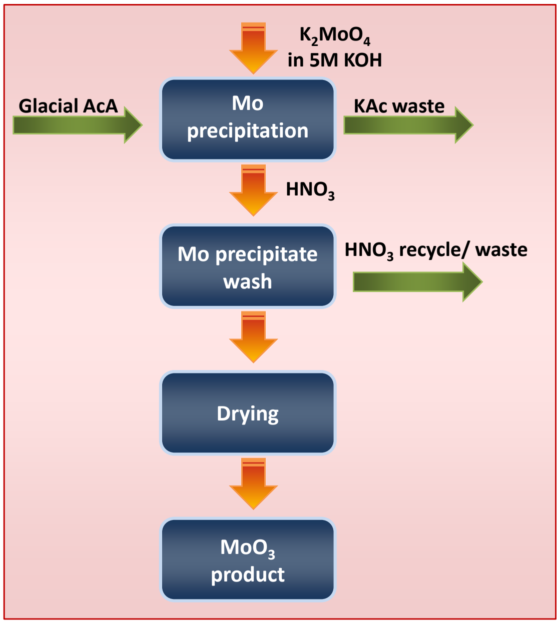

Figure 2. Flow diagram of Mo recovery process using acetic and HNO_3

Table 4. Mo and K Concentrations in the Starting Solution and Recovered Mo Material for Large-Scale Experiment[a]. Mo from ~300 mL of K_2MoO_4 solution was precipitated using ~1.5 L of AcOH.

Sample	Start Mo Solution, g	Total Start Mo, g	Total Start K, g	MoO_3 Product, g	Mo Product, g	K Product, mg	Mo Yield, %	mg of K/kg of Mo
Batch 1A	469.2	60.06	108.9	86.6	59.45	12.2	99.0	205
Batch 1B	468.3	59.94	108.7	85.4	56.51	5.7	94.3	102
Whole batch 1	937.5	120	217.6	172	115.95	17.9	96.6	154.4

[a] ICP-MS data reported with 10% uncertainty. K/Mo mole ratio: 4.44. c(Mo)=2.08M – 0.20g/mL, c(KOH)=5.07M. A volume of 3 L of acetic acid was used to precipitate Mo, and 24 L of HNO_3 was used in all washing steps per whole batch.

Table 4 shows the concentrations of K and Mo in the starting solution and in the recovered Mo material after the precipitation step with acetic acid and 8 washes with HNO_3. The large-scale experiment showed some promising results with a final potassium concentration of ~154 mg/kg-Mo after only 8 washes with HNO_3. In small-scale experiments, more than 10 washes were required to achieve this level of purity. This could be due to better mixing with an overhead mixer compared to vortex mixer. Moreover, very good Mo recovery was observed, with total yield of 96.6%. This could be attributed to the fact that precipitation step was performed by adding K_2MoO_4 solution into the acetic acid while mixing, which prevented the formation of the fine secondary precipitate that usually forms over time after centrifugation and positively affected the Mo recovery. Recovered MoO_3 material after drying at 160°C was analyzed using X-ray diffraction (XRD) and peaks were characteristic for MoO_3. MoO_3 was also dried at 500°C with no significant changes in XRD spectrum (Figure 3).

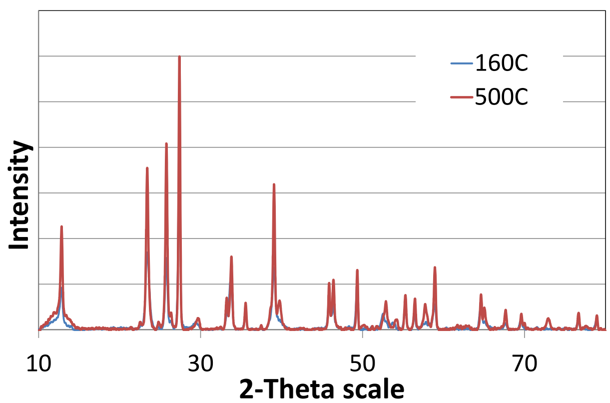

Figure 3. XRD spectra of final MoO_3 product heated at 160°C and 500°C.

Recycle of HNO_3

Since significant quantities of HNO_3 are required to wash the MoO_3 precipitate to achieve low K levels in the final Mo product, we also investigated an option to recycle the HNO_3 used in the washing steps to remove potassium from the Mo precipitate. In this process, ~80% of K is present in the acetic acid fraction that is used to precipitate Mo. The first HNO_3 wash usually contains 15-20% of the starting K concentration. Concentration of potassium in later washes decreases rapidly (Table 5). HNO_3 from the 2^{nd} wash can be re-used for the next batch in the 1^{st} wash and so on. Also, if little to no K is present, e.g. if the first two HNO_3 washes are disposed, the rest of the HNO_3 fractions combined usually contain 100-200 mg-K/L and can be recycled using rotary evaporation.

Table 5. Concentration of potassium in HNO_3 washes determined using ICP-MS. ICP-MS data reported with 10% uncertainty

HNO_3 wash	K, ppm
1	11100
2	1960
3	500
4	220
5	15
6	4.7
7	0.7
8	0.3

Combined HNO_3 washes containing ~165 ppm of potassium were distilled by rotary evaporation. The potassium concentration in the recycled HNO_3 was very low (~0.1 ppm).

Processing of irradiated samples

Three ~1.5L batches of K_2MoO_4 solution in ~5 M KOH obtained after the dissolution of natural Mo targets irradiated at University of Missouri Research Reactor (MURR) were also processed. Main side reaction products Zr and Nb that are formed during irradiation were removed from the dissolved irradiated target using ferric co-precipitation. Solutions were allowed to decay and then shipped to Argonne. As received, the composition of the samples was determined using ICP-MS. Table 6 show the concentrations of Mo and K in the dissolved irradiated Mo-targets solutions and in the recovered MoO_3 powder.

Table 6. Mo and K Concentrations in Starting and Recovered Mo Material for Irradiated Mo target from MURR, total volume of Mo in ~5M KOH processed ~4.5L

batch #	Start Mo Solution, g	Total Start Mo, g	Total Start K, g	MoO_3 Product, g	Mo Product, g	K Product, mg	Mo Yield, %	K in Mo Product, ppm
1	2329.4	259.8	506.3	425.6	244.4	52.1	94.1%	213.3
2	2319.4	275.1	508.5	408.8	256.8	23.7	93.4	92.3
3	2296.9	271.7	496.4	408.1	260.3	10.7	95.8	41.2
						Average	94.4	115.6

Note: ICP-MS data reported with 10% uncertainty. Starting composition for batches 1-3: K/Mo mole ratio: 4.7; 4.53; 4.49, c(Mo)=1.86M; 1.93M; 1.93M, c(KOH)=5.05M; 4.89M; 4.8M. A volume of 7.4 -7.6L of acetic acid per batch was used to precipitate Mo, and 68-75 L of HNO_3 was used in all washing steps per batch.

In general, very consistent Mo recovery yields were obtained for all three MURR batches (5 samples were processed per batch) with an average Mo yield in the range of 94.4%.

Table 7 shows the concentrations of various elements in the starting solutions, and final purified MoO_3 product.

Table 7. Concentrations of Various Elements in Starting and Recovered Mo Material for the Irradiated Mo Target from MURR, batch 1-3 (ICP-MS data reported with 10% uncertainty)

	starting concentration, ppm			**final product, ppm**		
	batch 1	**batch 2**	**batch 3**	**batch 1**	**batch 2**	**batch 3**
K	1,950,000	1,850,000	1,830,000	219	92.5	40.6
B	94.5	80.8	NA	ND	1.87	ND
Na	627	542	638	301	176	226
Mg	26	6.57	158	3.26	2.96	9.92
Al	38.3	31	35.6	5.00	4.56	7.74
Si	653	542	501	698	406	461
P	159	ND	ND	ND	ND	ND
Ti	40.6	36	34.5	28.5	24.5	25.0
Cr	2.38	ND	2.89	6.42	3.98	7.96
Mn	2.7	1.45	1.79	0.768	0.380	1.05
Fe	80.9	ND	ND	12.9	ND	24.7
Co	0.18	ND	ND	ND	ND	ND
Ni	0.69	2.37	3.18	1.13	0.748	2.98
Cu	2.74	3.30	ND	0.540	0.554	3.25
Zn	11. 7	ND	ND	2.22	2.28	6.14
Zr	0.37	ND	NA	0.102	ND	ND
Nb	8.97	3.07	NA	6.11	5.9	ND
Sn	3.36	ND	2.93	0.722	0.780	0.858
Sb	2.39	1.84	1.85	1.77	1.25	1.22
Cs	0.34	0.49	ND	0.938	0.680	0.666
W	36	ND	11.6	10.5	ND	1.70

Discussion

Although low Mo losses were observed when ethanol or its mixture with AcOH was used to precipitate Mo, multiple washes are needed to completely remove KOH, and in order to purify molybdenum from K, acid has to be used to precipitate Mo as an oxide. Due to the oxidation of ethanol by HNO_3, and possible formation of explosive ethyl nitrate, washing with AcOH must follow any step involving ethanol before adding HNO_3.

The average concentration of potassium in the final MoO_3 product for the MURR samples was slightly above 100 ppm. The elevated concentration of K in the Mo product in MURR batch 1 could be due to the highest starting K/Mo ratio, which could affect the efficiency of potassium removal. If more pure product is required, additional HNO_3 washes can be added when the starting K/Mo mole ratio is rather higher. It should be noted that when irradiated Mo targets are dissolved in peroxide and converted to base, Si and B are usually leached out from the glass. Also KOH can introduce some Na into dissolved target solution. In general, most of the contaminants are being removed during the process. Since Si is not soluble under acidic conditions, its removal is limited; however, silicon does not cause any significant issue regarding the production of side reaction products. An elevated concentration of sodium on the other hand, causes production of short lived ^{24}Na ($T_{1/2}$=15h) and long-lived ^{22}Na ($T_{1/2}$=2.6years), which increases the total gamma impurities in the product. Also when Ti is present in the target material, several Sc isotopes (mostly ^{47}Sc, ^{48}Sc and ^{44}Sc) may form through (γ, p) reactions, and therefore it is desirable for the starting concentration of Ti to be low. Another metal that can cause significant problems when present in starting material is W, which is a common Mo impurity. An elevated concentration of W can cause noticeable activities of ^{187}W, ^{185}W and ^{181}W in the Mo product. It should be noted that the experiments reported here were performed with natural Mo, and elevated concentrations of several elements were present in starting material, compared to the actual enriched ^{100}Mo or ^{98}Mo targets that have significantly lower concentration of troublesome elements e.g. the concentration of Ti and W in enriched ^{100}Mo material is ≤10 ppm, and the total gamma activity of side reaction products from Ti and W is not problematic. Nevertheless, it is worth noting that the concentration of majority of the elements in the purified product was below the concentration in starting enriched Mo-100 material (besides much higher starting concentration), and significant amount of troublesome elements such as W, Ti and Na are being removed during the recycle process.

CONCLUSIONS

We developed a simple process that can effectively recover enriched ^{100}Mo or ^{98}Mo materials by precipitating Mo using glacial acetic acid and subsequent washing with concentrated HNO_3. Typical recovery yields for Mo are ~95%, which is very important for the economic production of medical isotope $^{99}Mo/^{99m}Tc$ using enriched ^{98}Mo or ^{100}Mo targets. The recovery process is capable of achieving a very high purification factor for potassium. The process can be easily implemented for processing of up to 400 g of Mo per batch.

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