Accelerator-Driven Production of Fission ^{99}Mo

A.J. Youker, S.D. Chemerisov, P. Tkac, J.F. Krebs, D.A. Rotsch, M. Kalensky, T.A. Heltemes,
K. Alford, J.P. Byrnes, R. Gromov, L. Hafenrichter, A.S. Hebden, J.L. Jerden, C.D. Jonah,
V. Makarashvili, K.J. Quigley, J.F. Schneider, D.C. Stepinski, K.A. Wesolowski, and
G.F. Vandegrift

Nuclear Chemical Engineering
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439
United States of America

ABSTRACT

Results are reported for the production of ^{99}Mo from the accelerator-driven subcritical
fission of a low enriched uranium (LEU) aqueous solution. Phase I of these experiments
used a 5 L uranyl sulfate solution with a ^{99}Mo end-of-irradiation production limit of 2 Ci.
The separation, recovery, and purification of ^{99}Mo were demonstrated using the recycled
solution. Fission product partitioning trends will be shown for the recovery column,
concentration column, and LEU Modified Cintichem process. The results from a 1.4 Ci
^{99}Mo production run, where the final product was sent to GE Healthcare for testing, will
be highlighted. The information gained during Phase I has significantly impacted the
design and implementation of Phase II. Phase II focuses on an end-of-irradiation
production of 20 Ci of ^{99}Mo and a fission power density similar to the production facility
in a 20 L LEU uranyl sulfate solution.

1. Introduction

Approximately five liters of uranyl sulfate solution has been irradiated at the linear accelerator (LINAC) nine separate times as part of the Phase I mini-SHINE experiments. Each irradiation was performed by impinging the linac electron beam on a water-cooled tantalum target, which was located in a dry well of the target vessel holding the five liters of target solution. The irradiation times varied from 2 to 40 hours of total beam time on the target. Full processing was completed for 6 of the 9 uranyl sulfate irradiations performed. Full processing included:

- Passing the irradiated uranyl sulfate solution through a titania Mo-recovery column, washing the column with sulfuric acid and then washing it with water, and stripping the Mo from this column with base.
- Acidifying the Mo-product with nitric acid and passing it through a second titania column (concentration column), followed by nitric-acid and water washes, and stripping the Mo from the column using an alkaline solution.
- After acidification with nitric acid, purifying the product using the LEU-Modified Cintichem (LMC) process.

A full description of the phase I mini-SHINE system and all experimental results can be found elsewhere [1].

Most initial titania-column results were qualitative because isotope activities in the feed solution were low due to poor mixing and/or cross contamination between samples during the retrieval process. However, qualitative partitioning results showed that ^{99}Mo, ^{95}Zr, and ^{131}I adsorb on titania with the greatest affinity, but the majority of fission products were found in the column effluent. Results from the concentration column feed and final Mo-product showed that ^{103}Ru, ^{131}I, ^{133}I, ^{127}Sb, ^{125}Sn, and ^{105}Rh were the biggest contaminants that co-eluted with the first Mo-product. Purity specifications were met for the final Mo-product for all of the irradiations except the third irradiation, where the concentration of NaOH used to strip the Mo from the first titania column was increased from 0.1 to 1 M, which most likely changed the chemical form of Ru, making it more difficult to remove [1].

Results from the final irradiation where the ^{99}Mo product was shipped to GE Healthcare in the United Kingdom and successfully loaded onto their ^{99m}Tc generator and tested with two radiopharmaceutical kits will be highlighted [2]. In addition, Phase I data and results showed that modifications to the Phase II separation system were necessary to obtain the quantitative partitioning data; demonstrate a mass balance for U, Mo, and other fission products; reduce dose to personnel; and minimize the potential contact between the acidic uranium solution and hydroxide solutions. Cold testing of the improved Phase II system is underway, and initial tests show that the modifications made will allow for better data collection.

Experimental

2.1   Separation and Gas Systems

The Phase I mini-SHINE separation system consisted of 2 gloveboxes, multiple solenoid valves to operate the system, 1 pump, and 3 sample ladders to collect 7–8 samples during irradiation and column processing. The separation system was operated remotely using LabView software during irradiation and processing; however, samples were retrieved manually 8–24 hours post-irradiation. The He overhead gas system was held slightly subatmospheric and constantly recycled through a H_2/O_2 recombiner. Gases generated from water radiolysis were analyzed using a residual gas analyzer (RGA), and oxygen was added for the first several hours during irradiation to keep hydrogen below 1% as a safety measure. All gases generated were collected in a gas collection system kept at sub-atmospheric pressure to prevent the release of fission gases. A uranyl sulfate solution containing stable Mo was added as sodium molybdate was irradiated and passed through a titania column (S110 Sachtopore sorbent, ZirChrom Separations, Inc. Anoka, MN) (2 cm ID × 10 cm L stainless steel column, 31.4 mL bed volume) in the up-flow direction to prevent the entrapment of fission gases and concentrate the Mo product at the base of the column. The column was washed with 10 column volumes (CV) of pH 1 H_2SO_4 (300 mL, 40 mL/min, up-flow direction) to wash off uranium and any remaining un-adsorbed fission products. Next, the column was washed with 10 CVs of H_2O (300 mL, 40 mL/min, up-flow direction) to remove any residual acid before the NaOH wash. To adjust the pH of the column prior to stripping the Mo, the column was washed with 3.3 CVs of 1 M NaOH (100 mL, 20 mL/min, down-flow direction). Finally, the Mo-product was stripped from the column using 30 CVs of 0.1 M NaOH (900 mL, 20 mL/min, down-flow direction) and sent directly to a hot cell for more processing. All column operations were performed at 80°C.

2.2   Hot Cell Operations

The Mo-strip solution was pumped directly from the recovery column into a vessel inside a hot cell (Bigfoot). After the Mo solution was sampled, it was transferred to a second vessel, and the pH was adjusted to 2 using 8 M HNO_3. Pre-equilibration, loading, and washing steps were carried out at 80°C. An Omnifit, BenchMark column packed with titania (S40 Sachtopore sorbent, ZirChrom Separations, Inc. Anoka, MN) (1 × 1 cm, 0.8 mL bed volume) was pre-equilibrated with 36 mL of 0.01 M HNO_3 and subsequently loaded with 0.9–1 L of an acidified Mo solution at 16 mL/min in the up-flow direction. Subsequently, the column was washed with 20 mL of 0.01 M HNO_3 and 20 mL of H_2O at 16 mL/min in the up-flow direction at 80°C. During the Mo product-stripping step, the initial 10 mL of strip solution was loaded and eluent was collected in the water wash collection flask (to remove the water present to account for the 15 mL system dead volume). Subsequently, Mo was stripped with 25 mL of 1 M NaOH in the down-flow direction at 4 mL/min at 70°C. As the last step, lines were rinsed with 16 mL of water and the water was collected as waste. Total concentration column processing time was roughly 65 minutes. Samples of the eluent, acid wash, water wash, waste, and final product were collected for analysis. The purpose of this column was to concentrate the Mo-product prior to entry into the LEU Modified Cintichem process.

The strip solution from the concentration column was acidified using 10 M HNO_3 to a final concentration of ~1 M HNO_3. The Mo solution was then purified using the LMC process where iodide was precipitated as AgI by adding NaI and $AgNO_3$ in the first step. The remaining silver was precipitated by adding HCl. The next step in the LMC process was the addition of a Mo carrier, and Ru and Rh hold-back carriers to prevent their co-precipitation with the Mo. To keep Mo in the hexavalent oxidation state, potassium permanganate was added. After the addition of ABO (alpha benzoin oxime), a white flocculate precipitate formed and was collected on a fritted column with glass beads. The Mo-ABO precipitate was then washed multiple times with 0.1 M HNO_3 and then dissolved in a $NaOH/H_2O_2$ solution upon heating. The solution containing Mo and re-dissolved ABO was passed through a combination column that consisted of activated charcoal, hydrous zirconium oxide (HZO—acts as a cation exchanger), and Ag/C resin. Before the solution was loaded onto this column, the precipitation of trace iodide was repeated by adding NaI and $AgNO_3$. The AgI precipitate was collected on the combination column and Mo was eluted with ~ 55 mL of 0.2 M NaOH. If I_2 was present, it reacted with silver metal on the Ag/C column to form insoluble AgI.

2.3   *Gamma Counting*

All samples generated in the target solution and Mo-recovery gloveboxes were gamma counted using a HPGe detector (Ortec) and spectra were analyzed using GammaVision software (Ortec). The detector was calibrated for efficiency using an Eckert & Ziegler multinuclide standard. Due to the complex spectra of multiple radionuclides that were present in most of the samples, only certain radionuclides could be clearly identified (Table 1). To better detect ^{99}Mo activity in the column effluent and acid wash, it is assumed that transient equilibrium has occurred during gamma counting of all samples, so the half-life of ^{99}Mo (65.9 h) was used as the half-life for the ^{99m}Tc. Due to their short half-lives, ^{132}I was tracked with the half-life of its parent, ^{132}Te and ^{97}Nb was tracked with the half-life of its parent, ^{97}Zr.

Table 1. List of nuclides, their half-life, gamma used for analysis, and branching ratio at the corresponding energy analyzed.

Radionuclide	Half-life	Gamma Peak Analyzed (keV)	Branching Ratio at Energy Analyzed
^{132}Te	78.2 h	49.82	14.40%
^{132}I[2]	78.2 h	522.68	16.09%
^{147}Nd	11.0 d	91.1	27.90%
^{99}Mo	65.9 h	181.07	6.00%
^{99m}Tc[2]	65.9 h	140.5	87.20%
^{237}U	6.75 d	208.01	21.90%
^{239}Np	56.5 h	277.6	14.10%
^{143}Ce	33 h	293.27	42.80%
^{105}Rh	35.4 h	318.9	19.20%
^{151}Pm	28.4 h	340.06	22.40%
^{140}Ba	12.7 d	423.7	3.15%
^{103}Ru	39.25 d	497.08	91%
^{133}I	20.8 h	529.87	87%
^{91}Sr	9.5 h	555.56	61.50%
^{131}I	8.04 d	636.97	7.30%
^{97}Nb[2]	16.9 h	657.92	98.20%
^{137}Cs	30 y	661.66	85.10%
^{127}Sb	92.4 h	685.5	35.70%
^{97}Zr	16.9 h	743.36	98%
^{95}Zr	64 d	756.73	54.50%
^{95}Nb[1]	34.97 d	765.81	99.80%
^{131m}Te	30 h	793.77	13.80%
^{136}Cs	13.2 d	818.51	99.70%
^{125}Sn	9.6 d	1088.9	4.20%
^{156}Eu	15.2 d	1230.69	8.80%
^{135}I	6.57 h	1260.41	28.90%
^{140}La[1]	40.27 h	1596.21	95.40%

[1] Daughter isotope whose activity at EOB could not be accurately calculated from counting data.

[2] Daughter isotope whose activity at time of counting is indicative of mother's behavior.

3.   Results

Mini-SHINE Irradiation #6

The sixth mini-SHINE irradiation with LEU uranyl sulfate solution and processing was performed on October 26, 2015. The total time for the beam on the target was 20 hours, with 17 hours at full power (~10 kW). Based on the activity in the feed for the concentration column, 1.42 Ci of ^{99}Mo were produced at the end of bombardment. After irradiation, the ^{99}Mo was separated, concentrated, and purified. Approximately 1.1 Ci were shipped to GE Healthcare (United Kingdom) on Tuesday, October 27th where the Mo product was successfully loaded on a ^{99m}Tc generator and tested with 2 radiopharmaceutical kits [2].

Column effluent samples from the first titania column were collected after 30 minutes of feed solution passed through the column, and only one acid wash sample was collected after 3.75 minutes of washing the column with pH 1 sulfuric acid. Fission product partitioning trends showed that ^{95}Zr had the highest affinity for titania [1]. Other isotopes that qualitatively showed some adsorption on titania included ^{103}Ru, ^{132}I, ^{131}I, ^{136}Cs, ^{137}Cs, ^{132}Te, and ^{127}Sb [1]. Radionuclides that showed almost no adsorption on titania included ^{237}U, ^{239}Np, ^{140}Ba, ^{147}Nd, ^{151}Pm, ^{143}Ce, and ^{105}Rh [1]. Isotopes that were clearly present in the Mo-product solution included ^{103}Ru, ^{131}I, ^{132}I, ^{105}Rh, ^{125}Sn, and ^{127}Sb [1].

Activities detected in the concentration column (CC) fractions and their distributions are shown along with their 1 sigma values in Tables 2 and 3. Ru, Rh, and I were found in the CC eluent, but the amount of I was lower (50–60%) compared to the previous runs (80–90%). Surprisingly, ^{125}Sn was not removed during the CC washes and partitioned into the Mo-product from the CC. A white precipitate that formed after the acidification of the CC product solution was collected using a 40 mm 0.3 μm PP filter (Zenpure). 54.5% of ^{103}Ru and 25.1% of ^{105}Rh from the CC product were collected on the filter. Also, about 10% of ^{131}I and ^{133}I and 1.3% of ^{99}Mo were found on the filter [1].

Table 2. Activities detected in concentration column fractions, waste collected from CC, and the filter that was used to collect the solid that formed after eluting the final Mo-product. (>12 HL means greater than 12 half-lives have passed at the time of counting and no reliable results could be measured for that isotope.)

Radionuclide	Feed (mCi)	Eluent (mCi)	HNO_3 wash (mCi)	H_2O wash (mCi)	Waste (mCi)	^{99}Mo product (mCi)	Filter (mCi)
	(1σ, %)	(1 σ, %)	(1 σ, %)	(1 σ, %)	(1 σ, %)	(1 σ s, %)	(1 σ, %)
^{95}Zr	0.08	<0.03	<0.001	<0.0003	<0.0004	<0.05	<0.0004
	27						
^{95}Nb	<0.05	0.03	0.002	<0.0003	<0.0003	<0.03	<0.0002
		25	16				
^{99}Mo	1400	2.6	0.2	1.5	2.8	1500	20
	2.7	21	13	2.6	2.7	2.3	2.3
^{103}Ru	3.2	2.8	0.03	0.005	0.03	0.3	0.2
	2.2	1.9	2.4	3.4	2	9.3	1.9
^{131}I	190	100	5.3	1.4	0.8	28	2.8
	1.9	1.9	1.9	2	1.9	2.8	2
^{133}I	3300	1800	93	25	13	470	46
	1.9	1.9	1.9	1.9	1.9	1.9	2
^{136}Cs	0.1	<0.02	<0.0008	<0.0003	7.6	0.03	<0.0003
	13				7.6	26	
^{105}Rh	7.3	4.4	0.1	0.02	<0.02	1.9	0.5
	21	13	15	20		28	24
^{125}Sn	0.9	<0.4	0.03	0.01	0.06	1	0.008
	28		19	19	4.3	26	25
^{127}Sb	5.4	0.08	<0.003	<0.001	0.4	3.1	<0.004
	3.6	30			3.1	4	
^{91}Sr	<60	18	0.6	0.2	0.3	<10	>12 HL
		16	17	20	25		
^{135}I	4900	3000	160	41	23	770	>12 HL
	2.7	2.3	2.1	2.3	4.6	5.8	

Table 3. Distribution of multiple radionuclides in various fractions of concentration column.

Radionuclide	Eluent	HNO$_3$ wash	H$_2$O wash	Waste	Product	Filter	Balance
^{99}Mo	0.2%	0.0%	0.1%	0.2%	103%	*1.3%	104%
^{103}Ru	87%	1.0%	0.2%	1.0%	10%	*54%	99%
^{131}I	54%	2.8%	0.8%	0.4%	15%	*10%	72%
^{133}I	54%	2.8%	0.8%	0.4%	14%	*9.9%	72%
^{135}I	60%	3.2%	0.8%	0.5%	16%	N/A	81%
^{136}Cs	0%	0.0%	0.0%	1.1%	31%	0.8%	32%
^{105}Rh	61%	2.0%	0.3%	0.0%	26%	*25%	89%
^{125}Sn	0%	3.6%	1.3%	6.2%	107%	*0.8%	119%
^{127}Sb	2%	0.0%	0.0%	7.2%	57%	0.1%	66%

*percent of activity present in CC product solution

Tables 4 and 5 show the distribution of activities in the LMC fractions. Only 6.3% of ^{103}Ru was present in the CC feed that was found in the LMC feed (RF-1), while an unusually high amount (10.5%) of iodine was present in the LMC feed. A significant amount of iodine in the raw fission waste (RFW), (filtrate from the Mo-ABO precipitation step) fraction (45%) suggests the presence of iodine or iodate, since the removal of iodide in the silver precipitation step is considered to be quantitative. The majority of Ru and Sb present in the LMC feed went to the RFW fraction, and only 2.2% of Ru was found in the LMC product [1]. 96.7% of the ^{99}Mo was recovered in the LMC process and the product met the radionuclidic purity specifications (Table 6). 55.5 g of final product solution containing 1.06 Ci of ^{99}Mo was then loaded into a cask and shipped to GE Healthcare for further analysis. According to the GE press release, ^{99m}Tc was separated using a DRYTEC™ and the ^{99m}Tc Generator was tested using the GE Healthcare ^{99m}Tc-based products: Myoview™ (kit for the preparation of ^{99m}Tc-Tetrofosmin for injection) and Ceretec™ (kit for the preparation of ^{99m}Tc Exametazime for injection) [2]. Quality control testing performed on the reconstituted kits indicated the feasibility for ^{99m}Tc radiopharmaceuticals prepared using the ^{99}Mo product made at Argonne.

Table 4. Activities detected in LMC fractions.

Radionuclide	RF-1 (mCi) (1σ, %)	RFW (mCi) (1σ, %)	LMC Product (mCi) (1σ, %)
^{95}Zr	<0.05	0.004 (8.8)	0.004 (4.0)
^{95}Nb	0.09 (11)	0.001 (16)	0.009 (2.2)
^{99}Mo	1300 (2.3)	3.1 (3.6)	1300 (2.3)
^{103}Ru	0.2 (15)	0.2 (1.9)	0.004 (3.1)
^{131}I	20 (3.0)	9.0 (1.9)	0.005 (26)
^{133}I	340 (1.9)	150 (1.9)	0.05 (2.9)
^{125}Sn	0.9 (19)	0.6 (3.7)	<0.003
^{127}Sb	2.9 (4.9)	3.3 (3.2)	<0.0006

Table 5. Distribution of multiple radionuclides in various fractions of LMC.

Radionuclide	RFW	LMC Product
^{95}Zr	7.8%	8.3%
^{95}Nb	1.4%	9.8%
^{99}Mo	0.2%	97%
^{103}Ru	79%	2.2%
^{131}I	45%	0.03%
^{133}I	43%	0.02%
^{125}Sn	66%	<0.3%

Table 6. Radionuclidic purity in ^{99}Mo product solution from the LEU-Modified Cintichem process.

Ratio	Determined Value 36 hrs after EOB	Product Specifications	Within Specification
^{131}I/^{99}Mo	5.3×10^{-6}	$\leq 5\times10^{-5}$	YES
^{103}Ru/^{99}Mo	4.9×10^{-6}	$\leq 5\times10^{-5}$	YES
$\Sigma\gamma$/^{99}Mo	0.0003%	0.01%	YES
$\Sigma\alpha$/^{99}Mo	1.2×10^{-10}	$\leq 1\times10^{-9}$	YES

Gas Analysis Results

Mini-SHINE irradiation #6 took place in two parts due to the failure of a relay that caused an accelerator interlock to trip. Figure 1 shows part 1 of the experiment, and even though the initial oxygen concentration was 0.31%, an O_2/N_2 gaseous mixture was added to reduce the hydrogen concentration. After the addition of the oxygen, the hydrogen reached a steady state concentration of 0.17%. During the system purge to reduce radiation fields in the analytical system after the LINAC interlock tripped, the hydrogen rose to 0.20%. This part of the experiment was terminated at 586 minutes.
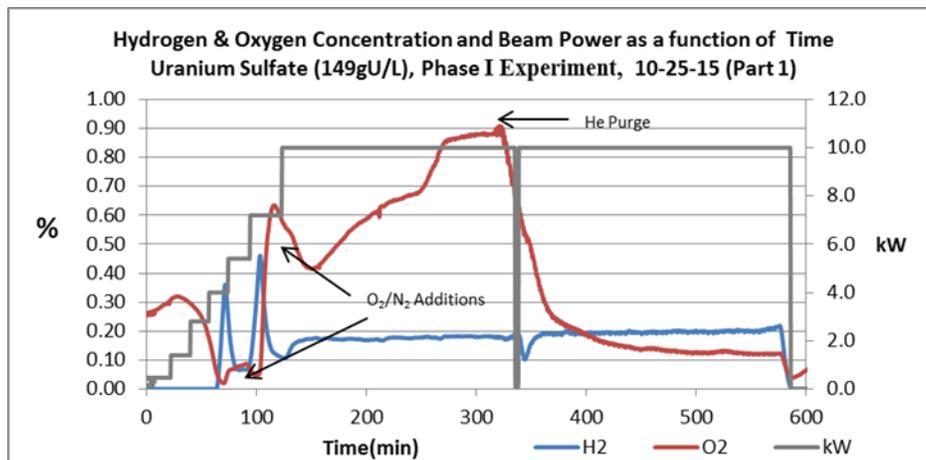
Figure 1. Hydrogen and oxygen concentration and beam power as a function of time (October 25, 2016).

4.   Discussion

Phase I mini-SHINE experiments generated a lot of useful data and showed that ^{99}Mo produced from an LEU uranyl sulfate solution could be recovered, separated, and purified to meet the European Pharmacopoeia purity specifications [3]. Phase II experiments, which include 20-L of an LEU uranyl sulfate solution, a depleted uranium target, and an end of bombardment ^{99}Mo production limit of 20 Ci, have been designed and modified based on lessons learned from the Phase I experiments. One of the biggest changes is a single shielded glovebox instead of two unshielded gloveboxes for the initial separation and sampling system, which can accommodate the increased amount of radioactivity for the Phase II experiments. The sample loops have been modified to prevent cross-contamination amongst samples by adding a separate flow path for each loop. In the Phase I experiments, a single flow path was shared by all sample loops. Changes to the sampling systems are being verified with cold dye tests to confirm that cross-contamination is not occurring, which will allow us to collect quantitative data for the initial recovery column fission product partitioning. In addition, a second pump and pathway have been added to the system to prevent the interaction of acidic and basic solutions, specifically the uranyl sulfate solution and base, which happened during the Phase I experiments and caused the precipitation of uranium in the Mo-product from the first titania column. Lastly, the titania column and effluent bottles will be shielded and kept below the glovebox due to the high dose rates measured with these items during the Phase I experiments. Testing the system with pH 1 sulfuric acid and a ^{99}Mo spike is expected soon, and if no issues are found, the same solution will be irradiated with the depleted uranium target in place. Uranium irradiations will commence once all commissioning steps are completed and formal approval by the US Department of Energy (DOE) has been issued.

References

[1] Vandegrift, G.F., Chemerisov, S.D., Youker, A.J., Tkac, P., and Kalensky M., Argonne National Laboratory, unpublished information, [2016].

[2] GE Healthcare, "It takes two: GE Healthcare and SHINE team up to solve longstanding radiopharmaceutical supply concerns in medical imaging" (http://www.genewsroom.com/press-releases/it-takes-two-ge-healthcare-and-shine-team-solve-longstanding-radiopharmaceutical, 2015).

[3] European Pharmacopoeia 7.0. Sodium molybdate (99Mo) solution (Fission). 01/2008:1923. Pgs. 999–1000.

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