Chemical Processing of mini-SHINE Target Solutions for Recovery and Purification of Mo-99

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ABSTRACT

Despite recent shortages and the increased availability of positron imaging tomography systems and radionuclides (e.g., ^{18}F), technetium-99m remains the workhorse of diagnostic nuclear medicine. ^{99m}Tc is produced from ^{99}Mo, which is most commonly produced by fission of U-235 in targets irradiated in research and test reactors. Argonne National Laboratory is assisting SHINE Medical Technologies to provide domestically produced ^{99}Mo from an accelerator driven non-critical aqueous solution of low enriched uranium, uranyl sulfate. Argonne is performing pilot-scale experiments using a LINAC-driven mini-SHINE facility to assist in this development. In phase-1, five liters of uranyl-sulfate solution is being irradiated to produce up to 2 Ci of ^{99}Mo. The irradiated target solution is processed using all unit operations envisioned in the SHINE facility to recover and purify ^{99}Mo. ^{99}Mo is isolated on a titania column and the target solution recycled for future production runs. The column is washed to remove residual uranium and purify ^{99}Mo. Molybdenum-99 is then eluted from the column in basic solution and transferred to a hot cell for further processing. This solution is acidified and concentrated by another far smaller titania column, the Mo-product solution is evaporated and acidified for final purification using the LEU-Modified Cintichem Process. The purified Mo-99 will be ready for shipment 24 hours after the end of irradiation.

1. Introduction

Radioisotopes are now commonplace in the detection and treatment of cancers and other ailments. Technetium-99m is the most commonly used radioisotope in diagnostic medicine, accounting for 80% of the 40 million procedures performed each year worldwide (16.7 million in the USA alone in 2012).[1] Technetium-99m is the daughter of molybdenum-99 which has historically been produced in non-domestic aging research reactors that use highly enriched uranium(HEU). Argonne National Laboratory with the National Nuclear Security Admiration's (NNSA) Global Threat Reduction Initiate (GTRI), in partnership with

commercial entities like SHINE Medical Technologies are developing technologies for the domestic production of ^{99}Mo for nuclear medicine while minimizing civilian use of HEU. SHINE is developing technology for the production of ^{99}Mo by fission of low enriched uranium-235 (LEU) in a subcritical aqueous solution using accelerator-based neutron generation.[2]

Argonne, using the Low Energy Accelerator Facility (LEAF), will use an electron/X-ray/neutron convertor (Phase I: tantalum convertor) to produce neutrons to fission 5 L of a LEU uranyl-sulfate (UO_2SO_4) solution. Argonne is currently testing a surrogate solution (sodium bisulfate, $NaHSO_4$) to satisfy safety protocols. To date, these 5 L "mini-SHINE" experiments consist of irradiation of water or $NaHSO_4$ solutions spiked with ^{99}Mo and stable Mo. During irradiation, numerous parameters were monitored: pH, conductivity, turbidity, and gas generation. After irradiation, the solution underwent an initial remote processing, followed by transferred and final processing in a hot cell. Safety control measures require that the system (solution) remains slightly sub-atmospheric and that no gases (iodinated gases in particular) escape from this system from irradiation to final product isolation. Therefore, all procedures were performed in closed vessel under sub atmospheric pressures. Off gases were collected in a gas collection system.

2. Experimental

2.1. Recovery Glove Box

A remote Mo-recovery processing software program was developed using the National Instruments LabVIEW.[3] This system can be operated in a semi-automated or manual mode. The user has complete control over the system when in manual mode. While in the semi-automated mode, a user is required to press the "next step" button in order to continue at certain steps in the process. Parameters such as temperatures, conductivity, pH, turbidity, mass, and pressure are recorded and time-stamped by the program. Another useful feature of the program includes comment boxes for the user to document observations and other pertinent information.

In order to test the completed system (Figure 1), a 5 L solution of $NaHSO_4$ (0.55 M, pH = 1) was spiked with 2 – 10 mCi of ^{99}Mo and Na_2MoO_4 (3 µM) carrier and irradiated. This solution was circulated for two or more hours prior to irradiation. During irradiation, samples were remotely collected hourly. Physical collection of these samples occurred ~12 hours after irradiation. Directly following irradiation, the solution was remotely processed with the LabVIEW program. Molybdenum was sorbed on a titania column, washed with acid and then water, and eluted with base into a transfer cask (Figure 2).[4-6]
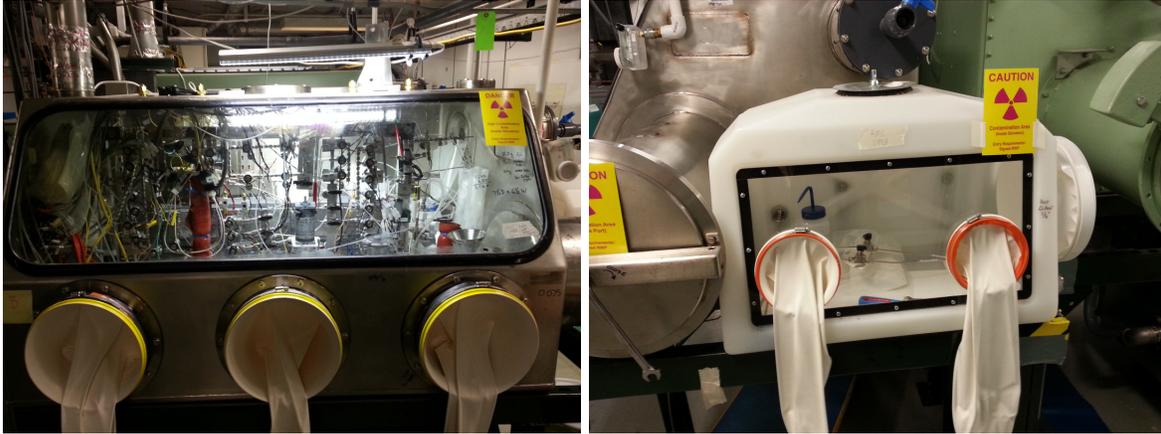
Figure 1. Recovery glove box (left) and white intermediate transfer glove box (right).

2.2. Concentration column

Due to the high dose rate in the target room from high-energy-photon activation of the surrounding materials, the transfer cask holding the molybdenum strip solution from the column was not accessible until ~12 hr post irradiation. The cask was connected to the Recovery Glove Box through a smaller white glove box. An identical system was setup at the hot cell (dubbed "Bigfoot", Figure 2) where the final processing occurred.

Figure 2. Image of Bigfoot hot cell used during concentration column, evaporation, and LEU-Modified Cintichem processing. The identical white intermediate transfer glove box and transfer cask are also shown.

After the allotted time, stainless steel Swagelock® connections were disengaged, capped, and the cask transferred to an adjacent room for further processing. A positive displacement pump was then used to syphon the solution from the cask into 1 L vessel where it was

acidified with HNO_3 (8 M, 20-30 mL) to pH 2. This solution was concentrated from ~1 L to ~36 mL using another titania column. A block diagram of the system is shown in Figure 3.
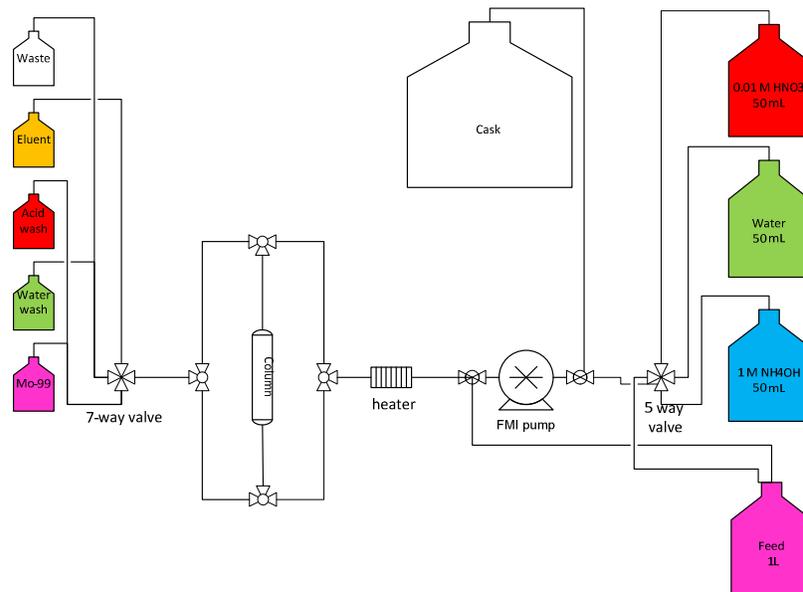
Figure 3. Block diagram of [99]Mo concentration column

The system was closed to atmosphere; a positive displacement pump was used to transfer solution through the system. The system was controlled remotely with manipulators by a valve board shown in Figure 4. The acidified solution was then passed through an HNO_3 – equilibrated titania column. The Mo-loaded column was washed with HNO_3 (0.01 M), water, and then stripped with NH_4OH (30%). Volumes of each wash and elution were measured by flow rates. Samples of the solution were collected from the 1 L vessel prior to acidification and after acidification. The HNO_3 wash, water wash, effluent, and final product were also sampled for later testing.
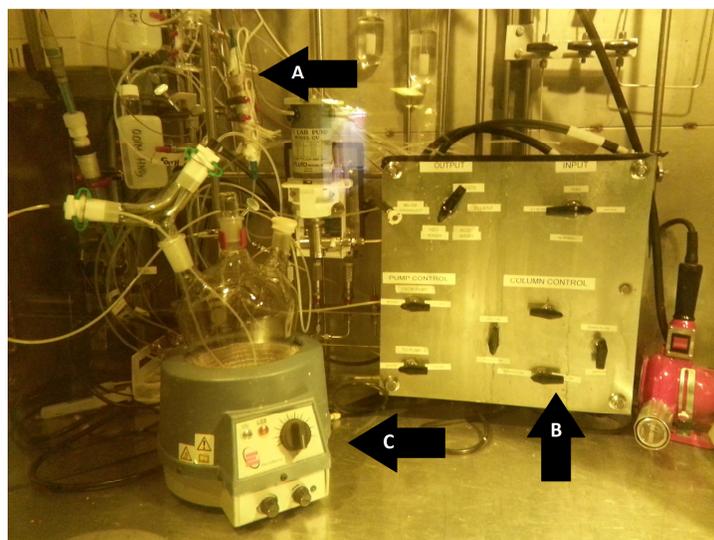
Figure 4. Image of mini-SHINE concentration column (A), column control board (B), and acidification vessel (C) inside of Bigfoot.

2.3. Evaporation

After the product was eluted from the column and sampled, the solution was transferred to an evaporation apparatus (Figure 5) while observing inert atmosphere techniques (i.e. no exposure to atmosphere). The solution was evaporated to dryness while being stirred and heated under vacuum. Once the solution was evaporated, the solid was dissolved in HNO_3 (1 M, 30 mL) and evaporated again. The solid was again dissolved in HNO_3 (1 M, 60 mL) and transferred to the Raw Fission 1 (RF1) bottle for LEU-Modified Cintichem processing. The RF1 bottle and evaporation collection vessel were sampled for later testing.

Figure 5. Evaporation apparatus: Collection flask (left) water cooled condenser (middle), insulating tape-wrapped adapter (right), evaporation vessel (right), heating/stirring mantel (right). Septa were used to allow for addition of solvents and removal of solution via needles and cannulas. Quick-connect valves were utilized for the water lines.

2.4. LEU-Modified Cintichem

LEU-Modified Cintichem bottles were prepared on bench top prior to being brought into Bigfoot. A 51 mm fritted-glass column was loaded with wetted glass beads. Activated charcoal (AC), silver charcoal (AgC), and ZrO resin were washed with NaOH (4 M) prior to use. All other reagents were loaded into appropriately sized syringes equipped with 18 gauge needles. Filter disks must be pre-wetted prior use. Eighteen gauge double-ended needles were used in all transfer steps except during ABO precipitation when 16 gauge needles were used.

Solutions received from the evaporation vessel were mixed with NaI carrier (4.0 mL, 1 mg/mL). The solution was shaken and $AgNO_3$ (0.5 mL, 10%) in HNO_3 (0.1 M) was added. A white solid immediately precipitated from solution. The vessel was shaken for ~2 minutes. Hydrochloric acid (1 mL, 1.0 M) was added to give more precipitate. The vessel was shaken for ~2 minutes. This mixture was passed through a 0.2 μm filter into another bottle marked Raw Fission 2 (RF2). RF1, the original bottle was rinsed with HNO_3 (11 mL, 4 M) and passed through the filter into RF2. Molybdenum carrier (0.5 mL, 10 mg/mL) was added to RF2 and the vessel shaken. $KMnO_4$ (8 mg/mL, 2.5%) was added drop-wise until a deep pink color held for ~30 seconds. Rhodium (1.5 mL, 8 mg/mL) and ruthenium carrier (2.0 mL, 5 mg/mL) were added and the solution shaken. Molybdenum was precipitated with fresh alpha-

benzoin-oxime (ABO, 25 mL, 2%) in NaOH (0.4 M). The vessel was shaken for 5 minutes, and the solid was isolated on a fritted-glass column (51 mm), the filtrate was isolated in a bottle marked Raw Fission Waste (RFW). This bottle was set to the side and observed for further solid formation. If solid formation occurred, the solution was passed through the fritted-funnel again and collected in a new bottle marked Acid Wash (AW). RF2 was rinsed with HNO_3 (20 mL, 0.1 M) onto the fritted-funnel and into AW. This process was repeated twice more. The solid on the frit was washed five times with HNO_3 (10 mL each wash, 0.1 M). The frit was shaken with each wash to ensure good mixing prior to draining the solution into AW. The solid was then dissolved with H_2O_2 (~1%) in NaOH (10 mL, 0.4 M). A charcoal filter was attached to the top of the fritted-funnel for venting and the mixture was heated with a heat gun. Heat was removed after the solution reached a boil. At this point the vessel was shaken for five minutes and then drained into bottle 1-A. The dissolution process was repeated with H_2O_2 (~1%) in NaOH (10 mL, 0.2 M). The solution was then passed through an AgC column into the 2-A bottle by gravity. The column was then rinsed with NaOH (10 mL, 0.2 M). Sodium iodide (4 mL, 1 mg/mL) was added to the 2-A and the vessel shaken. Silver nitrate (0.5 mL, 10%) in HNO_3 (0.1 M) was added and the vessel shaken for 5 minutes. The slurry was passed through a 3-phase combination column (AgC/ZrO/AC) into the final product vessel, 1-B, by gravity. A-2 was rinsed with NaOH (10 mL, 0.2 M) and the solution passed through the combination column into 1-B. This bottle, which contained the purified molybdenum, was sampled for later testing.

3. Results and Discussion

3.1. Recovery Glove Box

After irradiation, the $NaHSO_4$ solution, spiked with ^{99}Mo and natural Mo carrier, was purified using a titania column. The processing time was 2 hours. During these trials, 80% of ^{99}Mo was recovered. This yield was consistent over several trials. In order to determine where the 20% was being lost, the column sorbent, column components, and all column washes were gamma counted. Negligible amounts of ^{99}Mo were observed for these items. The system is currently being tested to determine if any material is being lost in the lines or in the many connections of the system.

During initial cold testing, it was found that $NaHSO_4$ is corrosive to stainless steel. Solutions that were passed through the system had turned blue and intensified during "at temperature" runs (80 °C). Corrosion tests were performed and reported elsewhere.[7] In short, the corrosion rates of solutions this system will be exposed to are as follows $NaHSO_4 > H_2SO_4 > UO_2SO_4$. All solutions demonstrated a high initial corrosion rate that tapered off after a passivation barrier was formed. It is possible that the missing Mo may be plating out or adsorbed somewhere in the system. This is currently under investigation.[7]

Phantom tests, where a column was loaded with glass beads and ^{99}Mo spiked solutions were ran through the system using standard procedures were performed. These trials determined that a minimum of 2 hrs is required for adequate mixing to obtain a homogenously ^{99}Mo-spiked solution, 95% of ^{99}Mo was recovered from the system, and >99% was recovered from the column spike solution. This suggests that corrosion of the system is not affecting ^{99}Mo recovery.

3.2. Concentration column

Solutions were received from the recovery glove box in a transfer cask. The solution was found to precipitate an orange solid when left in the cask for >24 hrs. (Figure 6). The solid was determined to consist mostly of iron but silicon, titanium, chromium, manganese, and nickel were also found (typical corrosion products). Despite any solid formation, column yields were consistently >95%. This process, from cask retrieval to isolation of purified ^{99}Mo product, took 4 hours.
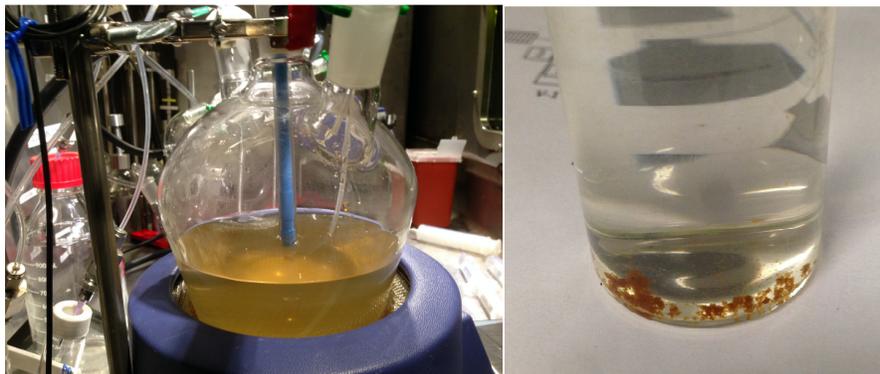
Figure 6. Image of solution prior to acidification (left) left in cask for >24 hrs and isolated solid collected (right).

3.3. Evaporation

Evaporation under vacuum has certain difficulties associated with it, such as "bumping", this is a phenomenon familiar to chemist in which solutions are heated and nucleation (bubble formation) does not occur, instead a large vapor bubble forms and violently spatters liquid throughout the vessel. Spatter that comes into contact with the walls of the vessel can then dry and material can be lost. Depending on the apparatus being used, the large vapor bubble has the capability of forcing liquid into inaccessible parts of the apparatus, thus loss of material occurs. Lowering the pressure of a solution lowers the boiling point and thus bumping becomes more common during these procedures. This was observed during several trial runs. Solution bumped and spattered onto areas of the apparatus that were incapable of being washed clean. Yields from the evaporation step averaged 70% with 30% being left behind in the evaporation vessel.

This problem was solved by making small modification to the evaporation apparatus. A longer neck was added between the evaporation flask and the condenser. The long neck stopped the spattered solution from reaching the condenser and allowed the material trapped in the neck to be washed back into the vessel prior to transfer to RF1. The neck was also wrapped with insulating tape to decrease evaporation times. Another modification was to the evaporation vessel itself. Instead of using a standard round bottom flask with two 24/40 (standard taper) ground-glass joints, a pear-shaped vessel with one 24/40 joint and another 14/20 joint was made (Figure 7). The second joint is needed for the transfer of solution to RF1 by cannula transfer. The slender neck associated with the second joint helps to minimize the amount of spatter that will strike the underside of the rubber septum (a hard to wash area). The conical bottom allows for easier transfer via needle or cannula. This new modification is expected to increase recovery of ^{99}Mo. Acidification and concentration of the purified product took 3 hours.

Figure 7. Image of pear-shaped evaporation flask with central 24/40 and side 14/20 standard taper ground-glass joint.

3.4. LEU-Modified Cintichem

The original Cintichem process has been utilized since the 1980's and has demonstrated excellent purification of Mo-99 from fission by-products and consistent recovery (>85%) of Mo-99. The most challenging aspect of the labor intensive Cintichem process was the necessity to constantly rearrange vessels, with the low headspace and inadequate manipulators in the this shielded cell. Solutions and mixtures were transferred from vessel to vessel with needles inserted through rubber septum. The filtration step shown in Figure 8 demonstrates how the vessels are stacked upon one another. Special needle guards were designed to ensure needles would not plunge too deeply into vessels, bypassing solution, thus loosing yield. It was observed that if a septum was pierced with a needle too many times, that septum would start to leak, therefor small gauge (18) needles were employed. Larger gauged (16) needles were used during the ABO precipitation step to avoid clogging.

Figure 8. Image of Cintichem filtration step (left) and non-modified fritted vessel (right).

On several occasions, the fritted bottle designed (Figure 8) to isolate the ABO precipitate slipped and broke. The bottle was small and difficult to handle despite the rubber grips on the

manipulators in Bigfoot. Therefore, to increase the ease of handling, the bottle was elongated by two inches. Cintichem processing usually took 4-5 hours to complete.

4. Conclusion

Progress towards irradiation of $UO_2SO_{4(aq)}$ has been made. Automation of processes allows for purification of irradiated solutions prior to safe entry conditions, streamlining processing. The use of corrosive $NaHSO_4$ to verify safety protocols has caused unforeseen complications and thus delays. Steps are being made to correct these issues. Modifications to processes have been made in efforts to optimize yields and processing times. Post irradiation processing time is currently 12 hrs.

5. Acknowledgments

6. References

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