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DEVELOPMENT AND PROCESSING OF LEU TARGETS FOR ^{99}Mo PRODUCTION

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Abstract

Most of the world's supply of $^{99\text{m}}\text{Tc}$ for medical purposes is currently produced from the decay of ^{99}Mo derived from the fissioning of high-enriched uranium (HEU). Substantial progress has been made in developing targets and chemical processes for producing ^{99}Mo using low-enriched uranium (LEU). Target development has been focused on a uranium-metal foil target as a replacement for the coated- UO_2 Cintichem-type target. Although the first designs were not successful because of ion mixing-induced bonding of the uranium foil to the target tubes, recent irradiations of modified targets have proven successful. Only minor modifications of the Cintichem chemical process are required for the uranium-metal foil targets. A demonstration using prototypically irradiated targets is anticipated in February 1997. Progress has also been made in basic dissolution of both uranium-metal foil and aluminum-clad U_3Si_2 dispersion fuel targets.

Introduction

Technetium-99m, the daughter of ^{99}Mo , is the most commonly used medical radioisotope. It is relied upon for over nine million medical procedures each year in the U.S. alone, comprising over 70% of all nuclear medicine procedures. Most ^{99}Mo is produced in research and test reactors by the irradiation of targets containing high-enriched uranium (HEU). Because the worldwide effort to fuel research and test reactors with low-enriched uranium (LEU) instead of with HEU has been so successful, HEU is now used only for ^{99}Mo production in some countries. In addition, while there are only a few major producers of ^{99}Mo , many nations with developing nuclear programs are seeking to become producers of ^{99}Mo , both for domestic and foreign consumption. Therefore, an important component of the U.S. Reduced Enrichment for Research and Test Reactors (RERTR) program's goal of reducing world commerce in HEU is the development of means to produce ^{99}Mo using LEU.

Substituting LEU for HEU in targets for the production of fission-product ^{99}Mo will require, in most cases, changes in both target design and chemical processing. Three major challenges have been identified: (1) to modify targets and processing as little as possible, (2) to assure continued high yield and purity of the ^{99}Mo product, and (3) to limit economic disadvantage. Keeping the

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target geometry the same, thereby minimizing the effects of LEU substitution on target irradiation, necessitates modifying the form of uranium used. Changing the amount and form of the uranium in the target necessitates modifying at least one or, possibly, two target processing steps--dissolution and initial molybdenum recovery. Our progress in target and process development is summarized in this paper.

One of the issues always raised in connection with using LEU to produce ^{99}Mo is the effect on product purity of the ~30 times greater amount of ^{239}Pu generated through neutron capture by the ^{238}U of an LEU target yielding the same amount of ^{99}Mo as the HEU target it replaces. However, because significantly more ^{234}U is present in HEU than in LEU as a consequence of the enrichment process, total alpha contamination of an irradiated LEU target is less than 20% higher than that of an equivalent HEU target.

Target Development and Testing

One way to categorize the world's ^{99}Mo -production is by the type of target used. We know of only one producer of fission product molybdenum that does not use an HEU target--the Australian Nuclear Science and Technology Organization (ANSTO); their target consists of slightly enriched UO_2 pellets. Targets for the production of ^{99}Mo from HEU are generally either (1) miniature Al-clad fuel plates containing U-Al alloy or UAl_x dispersion fuel [Argentine National Atomic Energy Commission (CNEA), the Atomic Energy Corporation of South Africa Limited (South African AEC), National Institute of Radioelements (IRE) of Belgium, and Mallinckrodt in the Netherlands]¹⁻⁹, (2) pins containing U-Al alloy [Atomic Energy of Canada, Limited (AECL)]^{10,11}, or (3) a thin film of UO_2 coated on the inside of a stainless steel tube [the National Atomic Energy Agency (BATAN) of Indonesia, and, in the near future, the U.S. Department of Energy's Sandia National Laboratories (SNL)]. Use of an electrodeposited UO_2 layer on the inner surface of a stainless steel cylinder, which is used as both a target and a dissolver, is part of the so-called Cintichem process developed by Union Carbide^{12,13}.

Research Reactor Fuel-Type Targets

The first two types of targets listed above, U-Al alloy and UAl_x dispersion, are the fuels which were being used in the reactors at the time ^{99}Mo production was begun. These targets are miniature versions of the reactor fuel plates or pins and are fabricated in the same manner by "commercial" fuel fabricators. The U_3Si_2 -Al dispersion fuel already developed for reactor conversion by the RERTR program¹⁴ offers, from the fabrication and irradiation performance points of view, a suitable high-density alternative for the research reactor fuel-type targets mentioned above. Since the fabricability and irradiation behavior of this fuel are well known, no target development work is needed. The presence of silicon presents a challenge in the chemical processing, however, so other fuel materials are also being considered, e.g., UO_2 dispersed in aluminum (for which considerable irradiation data is also available) and the uranium-metal foils discussed below.

Replacement for Cintichem Targets

The UO_2 -coated target was used in the U.S. by Cintichem until 1989, when a reactor problem forced a halt in production. As mentioned above, this process is currently being used in Indonesia by BATAN. During the late 1980s we had shown that the UO_2 coating thickness could not be increased nearly enough to produce an LEU target with an equivalent ^{235}U content, and we had begun to develop electrodeposited metallic uranium targets¹⁵. However, since we were seeking a target which could be fabricated in developing countries using "low-tech" methods, we have developed a concept using uranium metal foils^{16,17}. We have concentrated on the design illustrated in Fig. 1, where a thin (~125- μm -thick) uranium metal foil is sandwiched between slightly tapered inner and outer tubes. In our preferred design the inner tube is made of a material with a larger thermal expansion coefficient than that of the outer tube material in order for differential thermal expansion to assist in maintaining good thermal contact between the foil and the tubes. The taper and the greater shrinking of the inner tube upon cooling after irradiation facilitate disassembly. We would like to separate the irradiated foil from the tubes, so that only the foil need be dissolved to recover the molybdenum, thereby minimizing waste volume. In our first test targets thin oxide layers were produced on the inner and outer tubes to serve as diffusion barriers to inhibit diffusion bonding of the uranium to the tubes. As will be discussed later, we have added fission-fragment-absorbing barriers between the uranium foil and the target tubes. Several targets of this type have been irradiated in the Indonesian RSG-GAS reactor operating at 22.5 MW, and postirradiation examinations have been performed in the adjacent BATAN hot cell facility, under a cooperative research agreement between BATAN and Argonne National Laboratory.

One such target, with a zirconium outer tube and an aluminum inner tube, was irradiated and examined during the summer of 1995. In spite of a thin aluminum oxide barrier between the

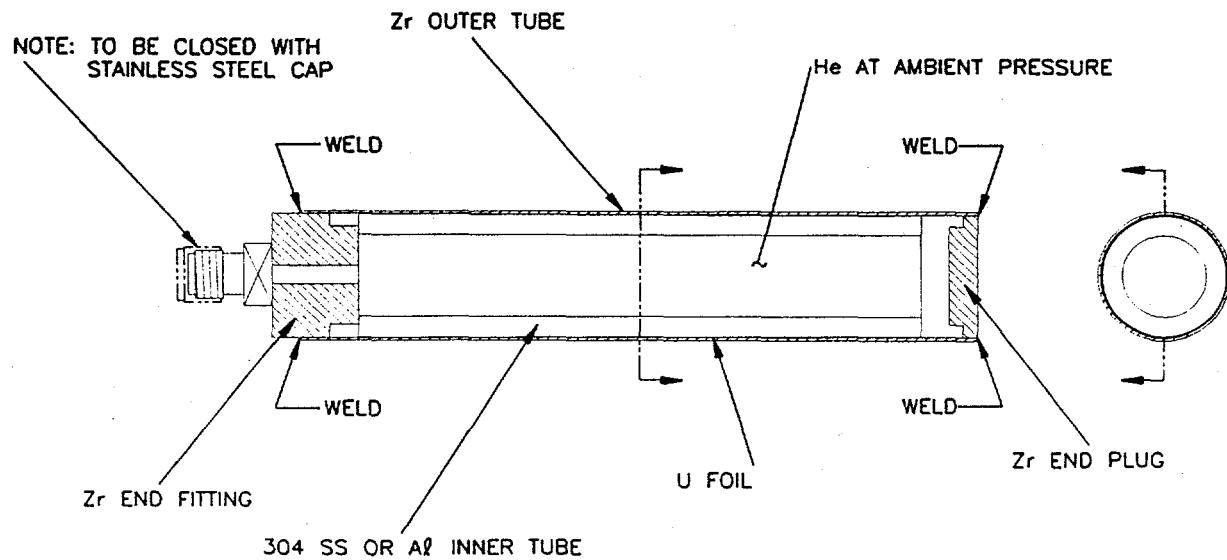


Fig. 1. Drawing of U-Metal Foil Target Being Tested in Indonesia

uranium foil and the inner tube, which had proven to be sufficient to prevent reaction during thermal testing at elevated temperature, the uranium reacted with the aluminum during irradiation and could not be removed from the inner tube. Metallography showed no apparent interaction of the uranium with the zirconium outer tube, on which a thin zirconium oxide barrier had been placed. Therefore, zirconium appeared to be a suitable target tube material.

Three additional test targets were irradiated between November 1995 and March 1996 to explore different materials for the inner tube of the target. In one we coated the aluminum with zirconium by flame spraying, thereby retaining all the features of the first design while adding a zirconium layer between the uranium and aluminum to prevent interaction. In a second target the inner tube was made from magnesium, which also has a larger expansion coefficient than zirconium but forms no compounds with uranium. The third target had a zirconium inner tube. Obviously, the thermal expansion difference feature was not present in this combination; however, we believed that adequate thermal contact was assured by the assembly process with the tapered tubes. This test was added to verify the apparent nonbonding of uranium foil and zirconium.

Postirradiation examinations performed during April and May of 1996 showed that the uranium foil was bonded to the inner tube of each of these targets also. The tentative explanation is that the high fission rate in the uranium and correspondingly high recoil atom flux at the uranium-target tube interface leads to an efficient atomic intermixing at the interface. It appears that bonding by this mechanism will occur with any material.

Based on the experience gained thus far, a third set of irradiations was performed during August 1996. We irradiated four targets to test two basic concepts:

1. The inner tube material of one target was changed to austenitic stainless steel. This material was chosen because it will not dissolve in the acid used to dissolve the uranium and because its use will retain the thermal expansion difference feature since 300 series stainless steel has 2 to 2.5 times the expansion coefficient of zirconium. We expected the uranium foil to bond to the stainless steel inner tube and to be pulled loose from the zirconium outer tube during cooling and disassembly (as was the case for the targets with aluminum and magnesium inner tubes), so that the uranium could be dissolved off the inner tube by placing the entire inner tube into the dissolver. However, the inner tube and foil could not be extracted from the outer tube, indicating some amount of bonding of the uranium foil to the zirconium outer tube.
2. Thin recoil-absorbing barrier foils of ~10- μm thickness were placed between the uranium and one or both target tubes. We expected these barrier foils to bond to the uranium by recoil mixing but not to the target tubes, since the fission fragments will not penetrate the barrier. Since the barrier foils must be dissolved with the uranium foil, only certain materials such as nickel, copper, iron, and zinc are allowed. We tested both nickel and copper. In one target an aluminum tube with unoxidized surfaces was used, and nickel foils were placed on both sides of the uranium foil. The inner tube with foils was easily extracted, but the foils could not be removed, indicating bonding, presumably by diffusion, of the nickel to the aluminum. We think that introduction of an aluminum oxide layer will

prevent such bonding. The other two targets used a stainless steel inner tube. In one a nickel barrier foil was introduced only between the uranium and the zirconium outer tube. The inner tube with foils was easily extractable, and, as expected, the uranium bonded to the inner tube. The uranium and nickel could be dissolved as described above. The final target contained copper barrier foils placed on both sides of the uranium foil. The inner tube with foils was easily extracted, and the foil sandwich was easily removed from the inner tube.

The latter two targets demonstrated the viability of the fission-fragment barrier concept. Another series of tests in Indonesia is planned for February 1997 to test additional barrier material/target tube material combinations. In all of these tests, an oxide diffusion barrier will be placed on the target tube surfaces. We have also begun to optimize the target. We will be studying the use of aluminum or other low-neutron-absorbing materials for the inner tube in order to decrease the reactivity penalty of the target, minimizing the thicknesses of the target tubes in order to minimize waste, and deposition of barrier materials rather than using foils in order to minimize fabrication costs.

Chemical Processing Development and Testing

Processing of irradiated uranium targets for ^{99}Mo can be divided into two broad areas by the target dissolution method. Acid dissolution is currently practiced by AECL, BATAN, and SNL. Dissolution by strong base is practiced by the CNEA, South African AEC, IRE, and Mallinckrodt. We are pursuing LEU options for both types of processes. The ultimate goal of our work is to obtain the data which would be needed by a producer to obtain regulatory (e.g., FDA) approval to supply ^{99}Mo produced using LEU.

Processing LEU Targets Using Strong Base

The ^{99}Mo is extracted from the current HEU targets by first dissolving the entire Al-clad fuel plate and then performing a series of extraction and purification steps. As discussed previously, we have pursued the substitution of LEU for HEU in plate-type targets by the use of U_3Si_2 dispersed in aluminum. However, the U_3Si_2 is far more difficult to dissolve, and the silicon in the target complicates molybdenum recovery steps. Our development has been centered on this dissolution step^{18,19}.

We have developed a two-step process for dissolving the target to recover the ^{99}Mo . The first step is dissolving the aluminum-alloy cladding and the matrix aluminum by a solution of NaOH and NaNO_3 . The second step is U_3Si_2 dissolution by NaOH and hydrogen peroxide. Enough ^{99}Mo is lost to the matrix by fission recoil that it must be recovered from both solutions. We foresee dissolution being carried out in a plug flow reactor and have developed a model for predicting the rate of dissolution under a variety of conditions. This model is being used to design a dissolver. Once dissolution is developed, we will turn to optimizing ^{99}Mo recovery from the dissolver solution. Because $\text{U}(\text{VI})$ precipitates from the dissolver solution, only the effects of silicate on the primary recovery step must be analyzed. We must also assure that decontamination from plutonium is sufficient to meet product purity requirements. Future work on this process will concentrate on developing improved mechanical means to break up the fuel meat wafer and, perhaps, more powerful dissolution agents. However, we are seriously

considering abandoning research in this area and concentrating on metal foil targets, as discussed below.

Because of the difficulties associated with dissolving and processing the uranium silicide targets, we have also pursued an alternative--alkaline-peroxide dissolution of an LEU metal-foil target¹⁹. Although the target design would need to be altered from that currently used with reactor-type fuels, the uranium metal foil can be dissolved using alkaline hydrogen peroxide in a manner similar to that used for the U₃Si₂ fuel plates. Use of the uranium metal foil eliminates the problems associated with silicon. We have also modeled the dissolution of this material and are currently in the process of designing a dissolver for it. We have completed a preliminary study of possible fission-fragment barrier materials and have selected zinc for further study.

Modified Cintichem Processing of LEU-Metal Targets

To replace the HEU-oxide target, we are also planning to use an LEU foil target. The LEU foil can be dissolved using a cocktail of HNO₃ and H₂SO₄, much like that now being used to dissolve the HEU oxide^{20,21}. We have recently developed the dissolution using nitric acid alone. This innovation should significantly improve waste treatment and disposal over that currently used. The products of the nitric-acid dissolution of UO₂ and uranium metal are the same: UO₂²⁺, NO gas, and water. However, because (1) dissolution of uranium metal requires a six-electron oxidation rather than a two-electron oxidation for UO₂ and (2) approximately five times more uranium is required for an LEU target, considerably more gas is formed during LEU target dissolution. Also, the LEU foil will be removed from the target following irradiation for dissolution in separate piece of equipment. Design of a closed dissolver system, which includes off-gas collection, is part of our conversion development.

The principal recovery and decontamination step of the Cintichem process is precipitation of molybdenum from the spent dissolver solution by α -benzoin oxime. This is a standard analytical method for molybdenum and, therefore, has essentially 100% Mo recovery and a molybdenum precipitate with very little impurities. Results from tracer demonstrations run at the University of Illinois at Urbana/Champaign (UIUC) and in Indonesia have shown that the additional uranium mass and the higher concentration of ²³⁹Pu in the irradiated target should not affect product purity. With the exception of ¹⁰³Ru, the purity requirements for gamma-emitting isotopes in the ⁹⁹Mo product, <0.1 μ Ci/mCi-⁹⁹Mo, are easily met for the LEU process. The alpha contamination level of <10⁻⁷ μ Ci/mCi-⁹⁹Mo was also met in tracer-level experiments. Table 1 shows typical decontamination factors for the recovery and two proprietary purification steps. In addition, we have shown that the introduction of the barrier materials does not interfere with molybdenum recovery and that they should be adequately removed without further changes to the process.

Both the dissolution and processing of uranium-metal foils have been developed to the point of demonstration using slightly irradiated LEU targets²²⁻²⁴. We are planning a full-scale demonstration in Indonesia in February 1997.

Table 1. Decontamination of the ^{99}Mo Product During Tracer-Level Demonstration of Modified Cintichem Processing of an LEU-Metal Target

Nuclide	Predicted Activity ^a (Ci)	DF Values			Impurity Level $\mu\text{Ci}/\text{mCi-}^{99}\text{Mo}$
		a-BO Ppt. ^b	Purification 1	Purification 2	
Ba-140	292	>516	>162	>165	<3.6E-05
Ce-141	121	>1116	328	419	<1.3E-06
Ce-143	685	>3354	313	641	<1.7E-06
I-131	186	51	28	41	5.3E-03
I-133	628	91	36	51	6.3E-03
I-135	104	121	38	43	8.8E-04
La-140	224	>2409	>104	>149	<1.0E-05
Mo-99	697	1.04	1.05	1.08	---
Nb-95	4.7	4	>13	>9.5	<1.6E-02
Nb/Zr-97	480	11	56	1410	9.2E-04
Nd-147	119	208	>62	>59	<2.6E-04
Np-239	1610	>1770	>247	>333	<1.9E-05
Pm-151	45	103	>16	>22	<2.1E-03
Rh-105	102	>276	>34	>46	<4.0E-04
Ru-103	54	113	1.3	3.7	1.7E-01
Sb-127	13.6	>41	1.3	>10.0	<4.3E-02
Sr-89 ^c	65.7	-	-	-	<2.3E-07
Sr-90 ^c	0.39	-	-	-	<1.4E-09
Sr-91	209	>3452	235	>586	<7.4E-07
Sr-92	2.65	>2101	>71	>63	<4.7E-07
Te-132	464	>5083	327	657	<7.1E-07
Zr-95	70	13	27	>49	<6.8E-03
Zr-97	447	17	23	>41	<4.6E-02

^aPredicted from an ORIGEN2 code calculation for an 18-g target 24-hours after removal from the Indonesian RSG-GAS reactor following a 120-h irradiation at full power.

^b α -benzoin oxime precipitation.

^cPredicted from Sr-91 behavior.

Standard Cintichem Processing of LEU UO_2 Targets

Even though the UO_2 layer cannot be increased sufficiently to accommodate the 18 g ^{235}U contained in an HEU Cintichem target, it appears that ^{235}U loadings in the range of 4 to 5 g may be possible with improved coating techniques being developed at Los Alamos National Laboratory²⁵. Since such loadings may be adequate for some applications, we are considering testing such targets. Currently, we are exploring the possibility of collaborating with SNL to include LEU Cintichem targets in their test matrix for obtaining FDA approval as a ^{99}Mo supplier.

Summary and Conclusions

We have made significant progress in developing targets and chemical processes for the production of ^{99}Mo using LEU. Target development has been concentrated on a uranium-metal foil target as a replacement for the coated- UO_2 Cintichem-type target. Although the first designs were not successful because of ion mixing-induced bonding of the uranium foil to the target tubes, recent irradiations of modified targets have proven successful. We have shown that only minor modifications of the Cintichem chemical process are required for the uranium-metal foil targets. A demonstration using prototypically irradiated targets is anticipated in February 1997. Progress has also been made in basic dissolution of both uranium-metal foil and aluminum-clad U_3Si_2 dispersion fuel targets; work in this area is also continuing.

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