RERTR 2011 — 33rd INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 23-27, 2011
Marriott Santiago Hotel
Santiago, Chile

Update on Uranium-Molybdenum Foil Fabrication Activities at the Y-12 National Security Complex

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ABSTRACT

The Y-12 National Security Complex (Y-12) is a participant in the NNSA NA-21 Convert Program, also known as RERTR. In 2011, Y-12 fabricated DU-Mo, LEU-Mo and HEU-Mo coupons and foils. These fabrications provided materials for key reactor experiments and for demonstrations of alternative processing techniques. The most challenging task has been the fabrication of the ATR size foils for the Full Element (FE) Reactor Experiment. These foils are approximately fifty inches in length and must meet a two percent tolerance on the U-235 fuel loading. The purpose of this report is to describe the FE foil fabrication process and update the RERTR audience on experiences gained and lessons learned during the fabrication.

1. Introduction

The Reduced Enrichment for Research and Test Reactors (RERTR) Program was initiated by the U.S. Department of Energy (DOE) to develop the technical means for the conversion of high powered research reactors (HPRRs) from HEU to LEU. The RERTR program cooperates with the research reactor community to achieve this goal of HEU to LEU conversion while maintaining reactor reliability and performance. The goal of the RERTR program is to complete the conversion of all HPRRs.

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2. Description of Full Element Production Requirements

As a fabrication facility, Y-12 strives to meet the customer requirements and specifications. Furthermore, in an effort to meet the requirements, Y-12 initially tried to adhere to the reference baseline process. Figure 1: Baseline Fuel Fabrication Process displays the initial baseline process used to fabricate the FE foils. As production continued, the process had to be modified to account for the high material attrition rate of the casting processes. Figure 2: Adjusted Casting Process displays the changes to the casting process that were implemented during the FE foil fabrication.

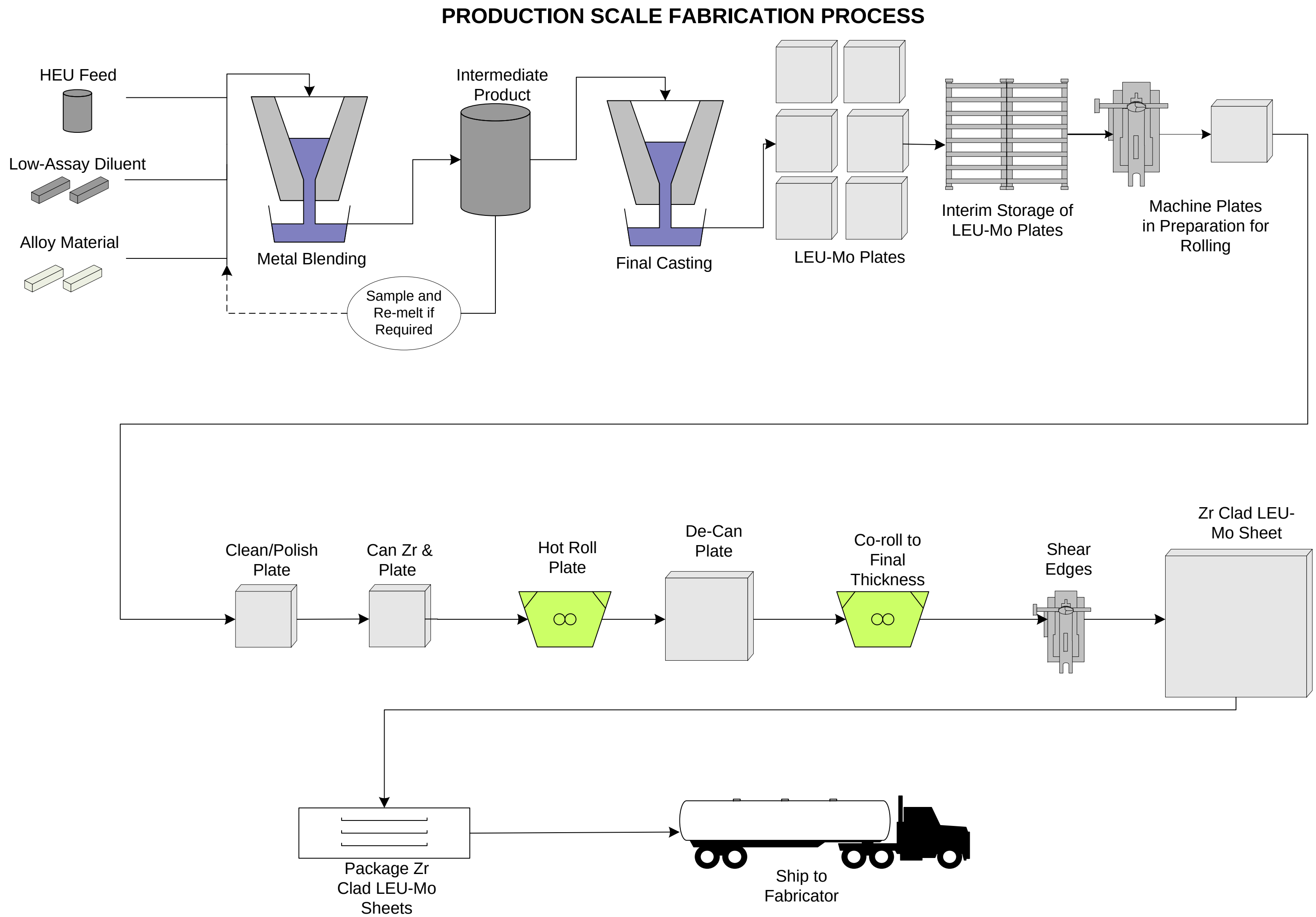


Figure 1: Baseline Fuel Fabrication Process

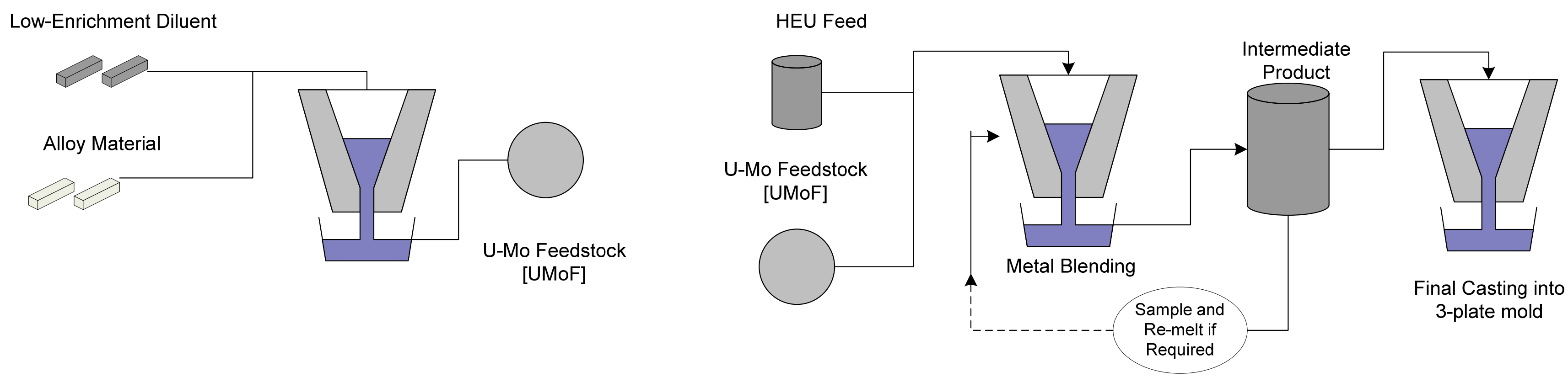


Figure 2: Adjusted Casting Process

2.1 Specification

The FE foil fabrication requirements are specified by SPC-1167, *Specification for U-Mo Monolithic Foils*. This specification defines the isotopic and chemical compositional requirements, the equivalent boron content requirements, the chemical requirements of the zirconium, the U-235 foil loading requirements, the dimensional evaluation and the radiographical/metallographic requirements.

The FE experiment consists of eleven full sized ATR plates, plate 5 through plate 15. In addition, an archive plate is required. The dimensional guidelines are listed in Table 1: Full Element Dimensional Requirements. The nominal length of the foils is set at 50 inches ± 0.125 inches. This added length allows for sampling by the final fabricator.

	Fuel Foil Width (in) (± 0.060")	Nominal U-235 Mass (g)	Minimum U-235 Mass (g)	Maximum U-235 Mass (g)
Plate-5	2.163	66.35	65.02	67.68
Plate-6	2.264	69.45	68.06	70.84
Plate-7	2.364	72.52	71.07	73.97
Plate-8	2.465	75.62	74.11	77.13
Plate-9	2.565	78.69	77.12	80.26
Plate-10	2.666	81.78	80.14	83.42
Plate-11	2.766	84.85	83.15	86.55
Plate-12	2.867	87.95	86.19	89.71
Plate-13	2.967	91.02	89.20	92.84
Plate-14	3.068	94.12	92.24	96.00
Plate-15	3.168	97.18	95.24	99.12

Table 1: Full Element Dimensional Requirements

2.2 Casting/Machining

Casting activities were initially performed in a two stage process, shown in Figure 1: Baseline Fuel Fabrication Process. In the first casting step, highly enriched uranium (HEU), a diluent of depleted uranium (DU) or natural uranium (NU), and molybdenum (Mo) were combined to fabricate a cylindrical casting of low enriched uranium (LEU)-Mo alloy in a vacuum induction melter (VIM). This casting was sampled in three locations, top, middle and bottom, to ensure the enrichment, Mo content and homogeneity of the casting. Once accepted, the cylindrical casting was broken and recast into a plate like shape in the VIM. The plate is sampled to provide the chemical certification used for shipment.

The repeatability of the casting process described in Figure 1 was challenging due to the amount of variables being controlled in one unit operation. Major factors affecting cast product quality are:

Feed material geometry/surface area
Melting point of constituents/non-eutectic behavior
Mold coating break-down/adhesion
Amount of oxidation
Impurity content of batch constituents
Mold stack temperature profile gradient/location with respect to induction coil
Amount of stock for machining
Melt pool size/geometry impact on inductive stirring potential
Pouring rate/flow continuity
Temperature limit of equipment
Carbon pick-up

These variables can result in the product exhibiting: large uranium carbides, undissolved molybdenum, oxide stringers, shrinkage voids, hot tears, alloy non-uniformity, isotopic non-uniformity, etc. Since improvement in one variable can negatively impact another variable, the challenge has been to find (and control within) a process “sweet spot”. Multiple casting attempts are required to zero in on the optimum scheme.

To reduce the variability, improve the metal integrity, and meet the chemistry and isotopic requirements the casting process was altered to perform a pre-alloy of material, shown in Figure 2. The diluent material, in this case NU, was alloyed with the Mo using an arc melting process. This process provides a high reliability of the amount of NU and Mo in the melt. Furthermore, this process does not increase the carbon content of the material. The NU-Mo alloy was then added to HEU to downblend into an LEU-Mo alloy. This change ensured that the Mo was in the mixture and atomically adhered to the uranium particles. While data is being collected for presentation in the future, preliminary results indicate that the change has allowed the casting process to achieve a tighter tolerance on the Mo and U235. Also, solidification issues in the plate castings are being addressed by run profile adjustments.

Once plates are cast and the chemistries are acceptable, the plates are cut into coupons, usually 4 inches by 6.25 inches. These coupons are machined to remove the cast surface, to provide a smooth surface for the zirconium to adhere, and to provide a parallel surface to ensure a uniform zirconium layer across the area of the foil. Also, the coupons are radiographed to ensure that the metal integrity is acceptable prior to rolling.

2.3 Rolling and Shearing Activities

The rolling and shearing activities are critical, not only due to the dimensional requirements, but to determine if the U-235 loading is correct for the monolithic foil. The current process is an iterative process. Data from the coupon, such as weight, dimensions, and density are factored to determine a target thickness for the foil. An example of this is shown in Table 2: Initial Targets for Foil Fabrication.

		Zr Foil Attributes		Coupon Attributes			
Select Coupon & Input Zr Foil Attributes ->	Coupon ID	Zr Foil Thickness (in)	Zr Foil Density (g/cc)	Molybdenum Wt%	U-235 Enrichment (%)	Avg Coupon Thickness (in)	Coupon Density (g/cc)
	3E67-K1-RC89	0.01	6.49	9.78%	19.83%	0.12911111	17.08

Select Foil/Plate Type ->	Foil/Plate Type	Plate-10

Fuel Foil Specification Requirements											
Plate Type	Minimum Mo Content (%)	Maximum Mo Content (%)	Minimum U-235 Enrichment (%)	Minimum U-235 Enrichment (%)	Fuel Foil Length nominal (in)	Fuel Foil Length minimum (in)	Fuel Meat Length maximum(in)	Fuel Foil Width (in) (± 0.060")	Nominal U-235 Mass (g)	Minimum U-235 Mass (g)	Maximum U-235 Mass (g)
Plate-10	9%	11%	19.45%	19.95%	48	47.26	48.76	2.666	81.78	80.1444	83.4156

Roll Foil to Thickness Target ->	Max U Mass (g)	Max UMo Mass (g)	Max UMo Thick (in)	**Maximum Avg Foil Thick (mils)**	Max mass & Min size	**Nominal Average Foil Thick (mils)**
	420.63	466.23	0.01322	15.27		14.75
	Minimum U Mass (g)	Min UMo Mass (g)	Min UMo Thick (in)	**Minimum Avg Foil Thick (mils)**	Min mass & Max size	
	404.14	447.95	0.01231	14.22		

Shear Foil(s) To Width & Length ->	Fuel Foil Width (in) (± 0.060")	Final Foil Desired Length (in) (± 0.125")
	2.666	50.000

The maximum and minimum average foil thicknesses are for a guide only. Foils may have spots which are higher or lower than the max or min. This is acceptable, **IF** the average of all the measurements of the foil meets the max and min average foil thickness.

Enter Foil ID(s)	**Foil #1 ID**	**Foil #2 ID**
	3E67-K5-RC89	**N/A**

Enter N/A if only 1 foil is sheared

Table 2: Initial Targets for Foil Fabrication

The coupons are cleaned using an electropolishing process. Zirconium is placed on the top and bottom surface of the coupon and the materials are welded into a steel can assembly. The foil is hot rolled using a salt bath and a 2 high rolling mill. Prior to proceeding to cold rolling, the foil is examined for debonding, cracks or other defects. After cold rolling, final dimensional measurements are taken on the foil, as shown in Table 3: Example of Foil Dimensional Analysis.

Foil #1 ID: 3E67-K5-RC89

Input Final Foil Attributes ->

Foil Thickness Measurements (mils)	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	Avg Thick
Row #1	15.00	15.05	15.10	15.10	15.15	15.05	15.15	15.05	15.10	15.15	15.1
Row #2	15.05	14.90	14.85	14.65	14.75	14.75	14.60	14.75	14.90	14.90	14.81

Width Measurements (in)									
#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
2.654	2.654	2.654	2.655	2.654	2.652	2.648	2.645	2.641	2.639

Fuel Foil Length (in)	Actual Foil Mass (g)	Average Fuel Foil Width (in)	Average Fuel Foil Thickness (mils)
50	502.20	2.649	15.0

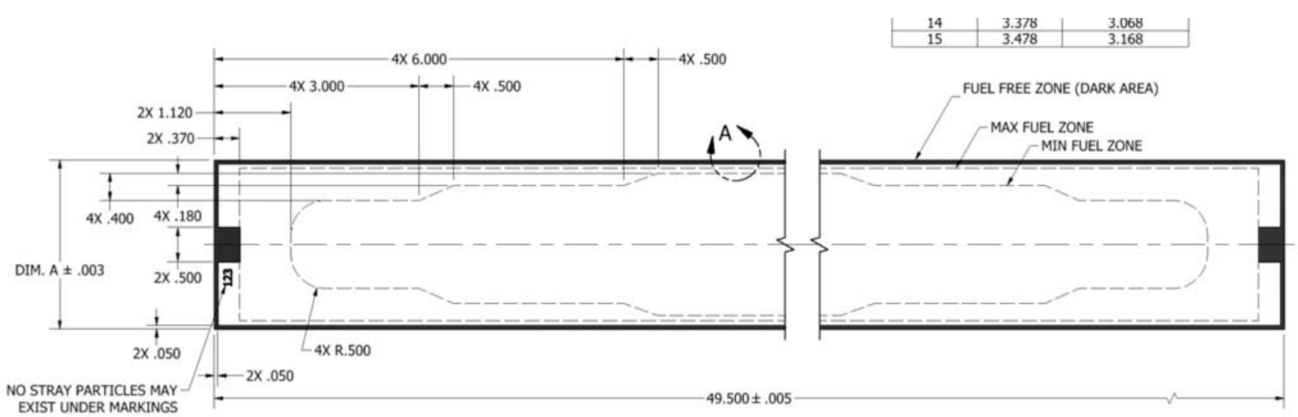
Check Foil Mass ->

Foil Acceptance Check				
Est. Foil Mass at current size (g)	Est. U-235 Mass at Final Max size	Est. U-235 Mass at Final Nominal size	Est. U-235 Mass at Final Min size(trim length only)	Est. U-235 Mass at Final Min size (Theo)
508.09	83.72	82.42	81.15	59.50
↑ Just for a check		↑ Best effort is to have the Nominal Size "green" or acceptable		

Table 3: Example of Foil Dimensional Analysis

This type of dimensional inspection allows for the estimation of the U-235 loading and helps determine if additional work is needed. For example, based on chemistry, the spreadsheet will set a target thickness. After rolling, the spreadsheet may indicate that the foil is too thick; thus requiring additional rolling or shearing.

Due to the length of the FE foils, shearing proved to be a challenging task. The shear used for this experiment is a foot shear that cuts from one end of the foil to the opposite end. The initial challenge was related to the clamping force of the shear. The force should be sufficient to maintain control of the foil throughout the cut, but also not damage the shear. The existing shear was modified to increase the clamping force. An additional challenge to shearing was the material properties. The material tended to initially bow, sometimes requiring additional cuts. To allow for sufficient material, the coupon size was increased to provide the greatest opportunity of success for the foil.



2.4 Radiography

Once the dimensional inspections are complete, the foil is examined using radiography, as seen in Figure 3: Section of FE Foil. This tool is used to identify areas of high density or low density.

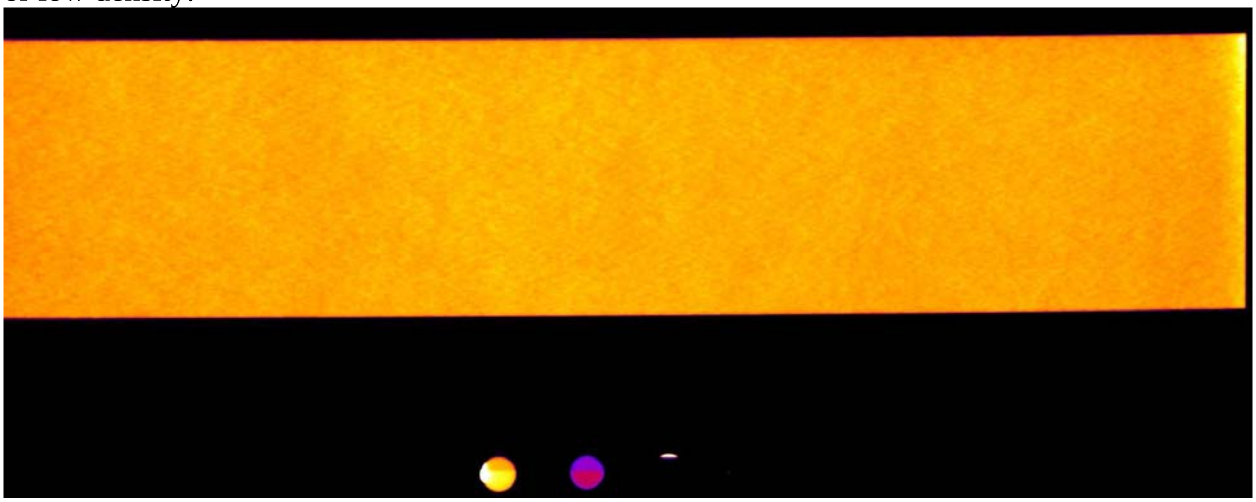


Figure 3: Section of FE Foil

2.5 Shipping

For this activity, the program initially tried to ship the material in an ES-3100 container, which was the only container available for use at the time. This required the foil to be coiled into a less than four inch diameter. Ultimately, the foil cracked due to the stresses applied, as displayed in Figure 4: Coiled Foil.

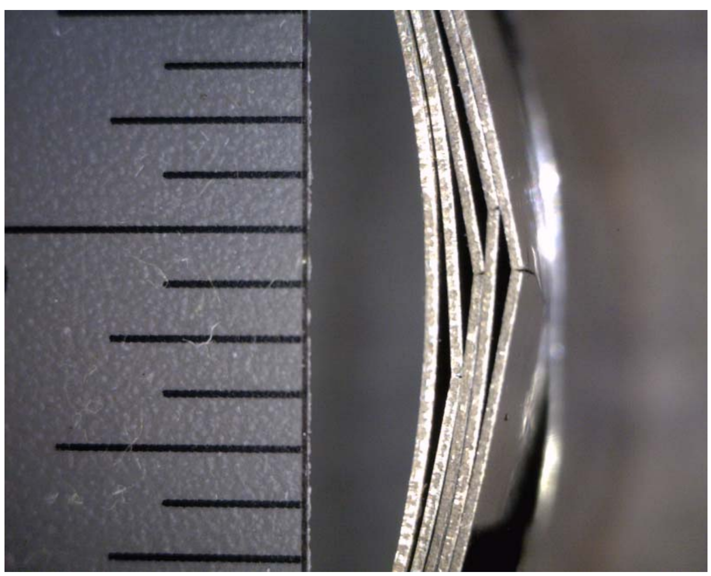


Figure 4: Coiled Foil

Due to this cracking issue, the ATR Fresh Fuel Shipping Container (FFSC) was used for all subsequent shipments.

3. Summary

In FY11, the most challenging task has been the fabrication of the ATR size foils for the Full Element (FE) Reactor Experiment. The size, tolerance limitations and fuel loading requirements led to unique opportunities and challenges. The challenges associated with this production have required adjustments in casting, machining, and rolling. The lessons learned during this task are expected to drive increased efficiency and ultimately process optimization.