U.S. High Performance Research Reactor Project

Characterization Report for the MP-1 Experiment Fabrication Campaign

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R Kalsar
FG DeLemma
T Trowbridge
EL Tegtmeier
R McCabe
R Prabhakaran
NR Overman
DL Blanchard
J Schulthess
C Brizzee
K Bohn
J Lopez
B Alexander
C Miller
NJ Lombardo
VV Joshi

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Revision History

Revision Number	Revision Date	Description of Change
0		Initial Release

Executive Summary

This report covers the results of MP-1 fuel characterization analysis to provide a detailed understanding of the as-fabricated fuel that would be irradiated in the MP-1 (Mini-Plate 1) experiment. The work was performed at Pacific Northwest National Laboratory (PNNL), Idaho National Laboratory (INL), and Los Alamos National Laboratory (LANL).

Characterization of the as-fabricated fuel was performed in accordance with *Characterization Plan for the Fabrication of U-10Mo for the MP-1 Experiment*, hereinafter the MP-1 Characterization Plan (PLN-5380). Under the MP-1 Characterization Plan, fuel foils at different points in the foil fabrication process (e.g., hot rolled annealed, cold rolled annealed) were studied to understand the effect of various thermomechanical processes on the fuel microstructure. Samples were sent to each of the three organizations so that testing and analysis could be performed independently using similar equipment and a standardized set of measurement and analysis procedures. The MP-1 fabrication campaign will provide an opportunity to understand the effects of processing conditions on the final fuel microstructure, to compare independently obtained results, and achieve a three-way validation.

PNNL characterized 28 uranium–10 wt% molybdenum (U-10Mo) samples. Six pieces/specimens from each sample/foil were sectioned, in accordance with the MP-1 Characterization Plan. Similarly, INL and LANL also examined 24 and 17 U-10Mo specimens, respectively. These total 69 samples consist of six types of MP-1 characterization foils fabricated by Babcock and Wilcox Technologies (BWXT) from ingots produced by the Y-12 National Security Complex:

- 0.047 in.-thick hot-rolled and annealed samples with and without Zr layers
- 0.02 in.-thick cold-rolled and annealed samples with and without Zr layers
- 0.01 in.-thick cold-rolled and annealed samples with and without Zr layers.

Microstructure, chemical composition, carbide morphology, U-10Mo foil thickness, Zr thickness, mechanical properties (microhardness), and density were evaluated in both longitudinal and transverse directions for foils of the three different thicknesses.

The U-10Mo average grain size decreased as the foil thickness decreased. This is the effect of thickness reduction: more thickness reduction introduces more nucleation sites for new recrystallized grains. The average grain sizes observed in U-10Mo samples without Zr were 13.6 μm for 0.01 in. thickness, 18 μm for 0.025 in. thickness, and 26 μm for 0.047 in. thickness. The average grain sizes observed in U-10Mo samples with Zr were 15.3 μm for 0.01 in. thickness, 18.8 μm for 0.025 in. thickness and 28 μm for 0.047 in. thickness. Orientation-based imaging using EBSD was carried out to examine the microstructural state (deformed or recrystallized) and calculate grain size. The grains were equiaxed and fully recrystallized. No abnormal grain growth was observed. The microstructures of all samples showed nearly homogeneous Mo distribution and no chemical banding. In all U-10Mo samples, the average carbide fraction was under 1.0% (carbon under 400 ppm), and certain specimens had less than 1.5% (carbon under 570 ppm). Thickness variation of U-10Mo foils decreased with thickness reduction. The U-10Mo foil thickness distribution becomes narrower with thickness reduction. The average Zr thicknesses (top and bottom) were about 54 μm (0.0021 in.), 38 μm (0.0015 in.), and 38 μm (0.0015 in.) for U-10Mo specimens of thicknesses 0.047 in., 0.025 in., and 0.010 in., respectively. Zr thickness variation decreased with foil thickness reduction.

Acronyms and Abbreviations

BSE	backscattered electron
BWXT	Babcock and Wilcox Technologies
EBSD	electron backscatter diffraction
EDS	energy-dispersive x-ray spectroscopy
INL	Idaho National Laboratory
LABE	low-angle backscattered electron
LANL	Los Alamos National Laboratory
LEI	lower electron image
LEU	low-enriched uranium
MP-1	Mini-Plate-1
PNNL	Pacific Northwest National Laboratory
SD	standard deviation
SEM	scanning electron microscopy
UC	uranium carbide
U-10Mo	uranium alloyed with 10 wt% molybdenum

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1.0 Introduction

The purpose of the Mini-Plate 1 (MP-1) experiment is to evaluate the in-reactor performance of uranium–10 wt% molybdenum (U-10Mo) monolithic fuel. The fuel was produced by commercial fabricators using a fabrication process defined in (MAQP 2016). This assessment is one of several performed on the fuel and fuel fabrication processes.

In the MP-1 test, 56 mini-plates will be irradiated at various locations in Idaho National Laboratory's (INL's) Advanced Test Reactor. Smaller numbers of samples were irradiated in previous irradiation campaigns. The MP-1 irradiation experiment differs because the fuel fabrication was performed by a commercial manufacturer using a fabrication process that being optimized for the steady-state production of U-10Mo fuel Fabrication of the U-10Mo involves material processes such as casting, thermal annealing, hot and cold rolling, co-rolling, and hot isostatic pressing, and it is very important to correlate processing with structure and properties. Thus, the fuel microstructure and processing data can be studied to better understand the U-10Mo monolithic fuel and its fabrication process. The MP-1 experiment presents the first opportunity to investigate the microstructure evolution throughout a commercial fabrication process (INL 2018).

Characterization of the as-fabricated fuel was performed at Pacific Northwest National Laboratory (PNNL) according to *Characterization Plan for the Fabrication of U-10Mo for the MP-1 Experiment*, hereinafter the MP-1 Characterization Plan (INL 2018). Similar characterization work was also performed at INL and Los Alamos National Laboratory (LANL) to provide a detailed understanding of the as-fabricated fuel that would be irradiated in the MP-1 experiment. In accordance with the MP-1 Characterization Plan, fuel samples were taken from different stages of processing to better understand the evolution of both microstructures and properties.. Similar samples from foils were sent to the above three organizations, so that testing and analysis could be performed independently using similar equipment and a standardized set of measurement and analysis procedures. The MP-1 experiment will provide an opportunity to understand the effect of processing conditions on the fuel microstructure, compare results obtained independently, and achieve a three-way validation.

In accordance with the MP-1 Characterization Plan (INL 2018), PNNL, INL, and LANL analyzed the microstructure, chemical composition, carbide fraction and morphology, U-10Mo foil thickness, Zr layer thickness, mechanical properties (microhardness), and density of U-10Mo MP-1 foils received from Babcock and Wilcox Technologies (BWXT). Information on foil Mo content, U-10Mo foil thickness, and Zr thickness supported the qualification of MP-1 foils by addressing the fuel specification requirements 4.2.1 (bulk Mo content), 4.2.2 (physical requirements), and 4.2.6 (Zr thickness), respectively (INL 2019)

The MP-1 experiment presents the first opportunity to investigate the microstructure evolution throughout the fabrication process. This work will provide critical insights into the variation in the fuel microstructure and processing data. Findings from this study may be used to refine specification limits and/or identify opportunities for process improvement (to reduce variability of intermediate products and reduce the number of non-conformances).

2.0 Fabrication Process and Sample Materials

To properly interpret the characterization results presented in this study, it is important to understand the thermomechanical processes used to fabricate the fuel as well as the source of the materials characterized. The fabrication process and a description of the sample materials used in the characterization of MP-1 foils is presented below.

2.1 MP-1 Fabrication Process Overview

The MP-1 fabrication process produced low and medium power fuel; the target foil thickness was for the low and medium power foils was 0.025 in. and 0.0085 in., respectively. An identical fabrication process was used in the two foils (except for the extra rolling needed for the medium power foils). A detailed summary of the foil fabrication process can be found (Hubbard et al. 2017). An overview of the process is illustrated in Figure 2-1. An illustration of the intermediate and final products produced from the eight MP-1 castings in support the medium and low power MP-experiment is provided in Figure 2-2.

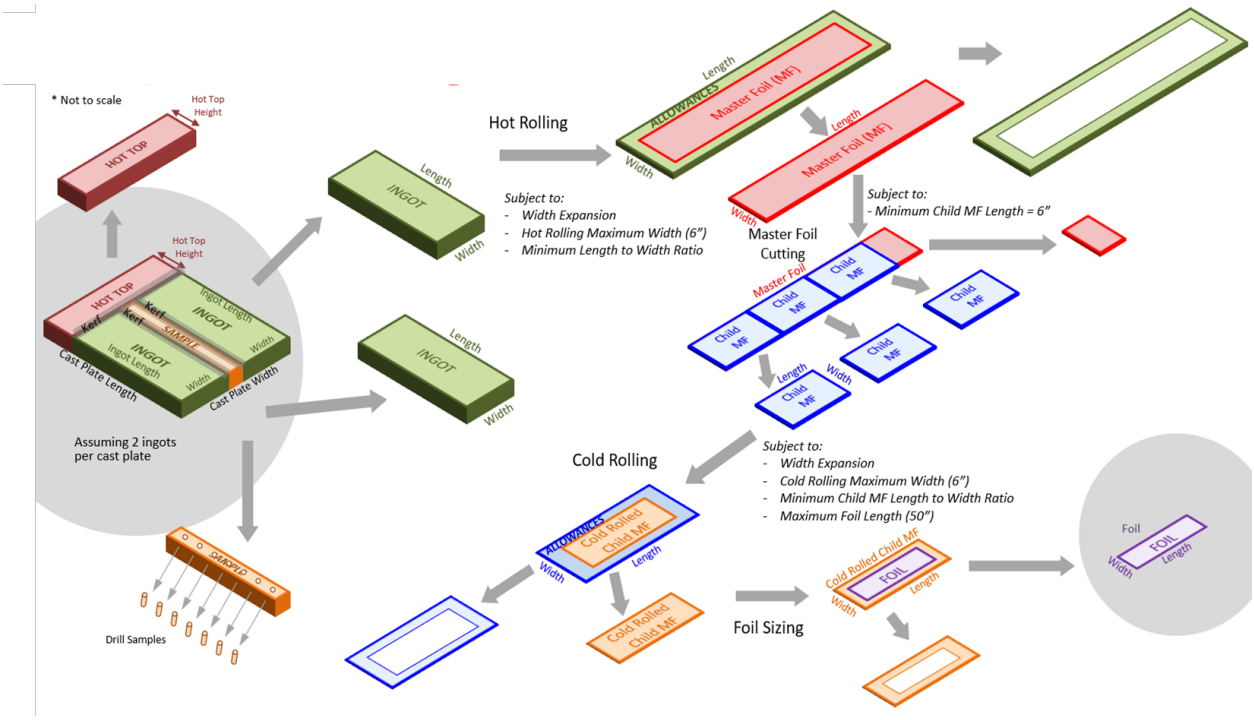

Figure 2-1. Overview of MP-1 fabrication process

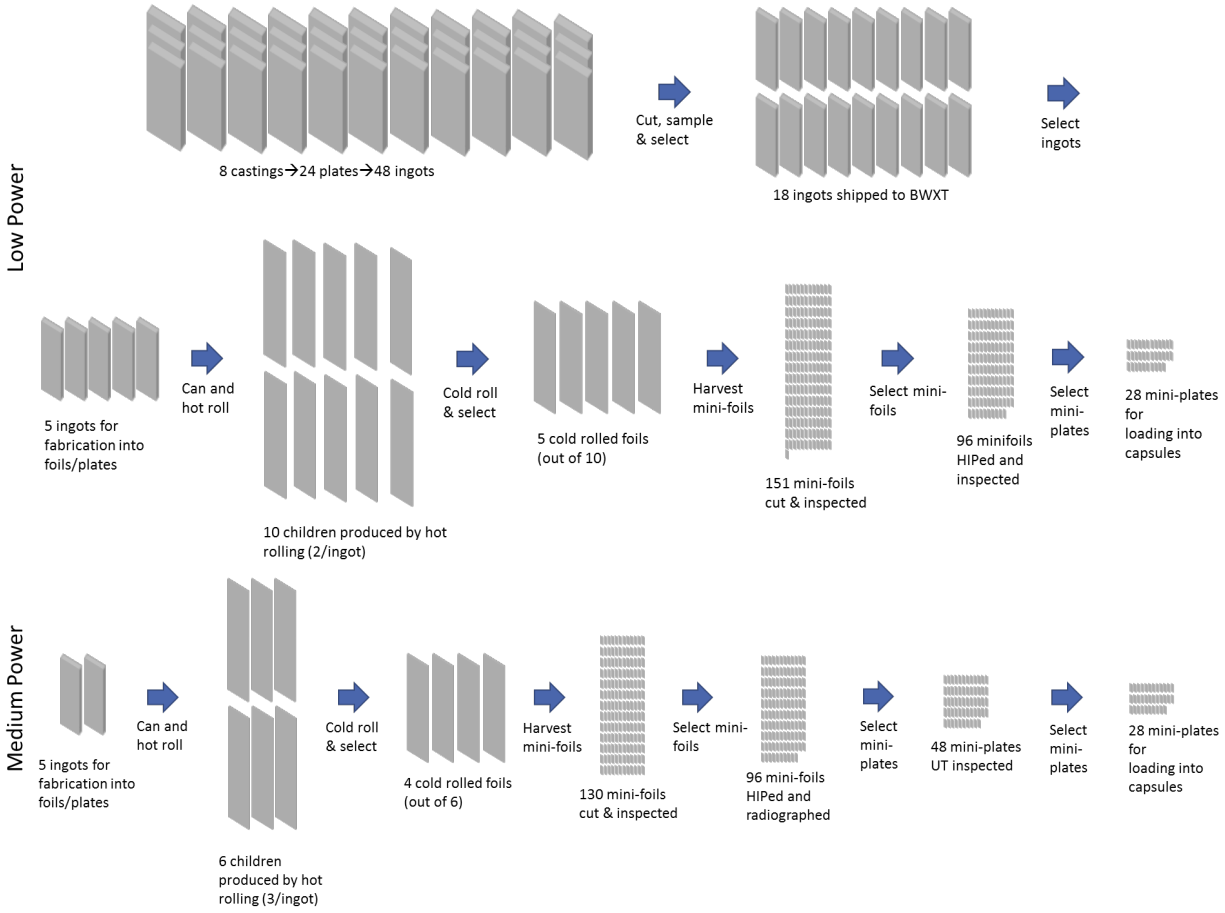

Figure 2-2. Overview of intermediate and final products produced for mp-1 medium and low power experiments

A total of twelve castings were produced at Y-12 in support of MP-1 fuel fabrication; eight of these were considered "MP-1 castings" and four were considered "contingency castings." The feedstock for the MP-1 castings utilized a master alloy (0.2 wt% ^{235}U and 12.6 wt% Mo) and high enriched uranium (~93.1 wt% ^{235}U). The feedstock was melted in a vacuum induction melter and cast into a three-plate vertical mold. After casting, the U-10Mo alloy was broken out of the graphite mold. Holes were drilled in specified locations in a center vertical strip on each plate and the sample turnings analyzed for isotopics and chemistry. The hot top on each plate was removed and a one-inch wide sample strip was cut from the center of the plate leaving two ingots per plate. Thus, each casting produced six ingots. A total of 66 ingots measuring approximately 9.5 inches in length by 3.5 inches in width by 0.2 inches thick were produced for MP-1; each underwent the appropriate quality control (QC) checks to assess compliance with the fuel spec (one casting was a "short pour" and was not cut into ingots).

Eighteen of the 66 ingots cast for the MP-1 fabrication campaign were accepted "as is" and shipped to BWXT for potential fabrication into min-foils and mini-plates. Out of the 18 ingots, two were selected to produce medium power min-plates and five were selected to produce low power mini-plates. Each ingot was placed in a can with Zr foil on each side of the ingot and hot rolled to a target thickness of 0.048 inches; this resulted in a "master foil" approximately 36 inches in length. The medium power masterfoils were cut into three equal sections and cold rolled to a final thickness of 0.0085 inches while the low power masterfoils were cut into two equal sections and cold rolled to a final thickness of 0.025 inches.

The cold rolled masterfoils were cut into "children," samples removed from the leading edge, center, and trailing edge of the foil for subsequent analysis, and then hand sheared into 3.75 in. long by 0.75 in. wide mini-foils. An illustration of how foil samples were obtained from a masterfoil is presented in Figure 2-1 (medium power foil samples).

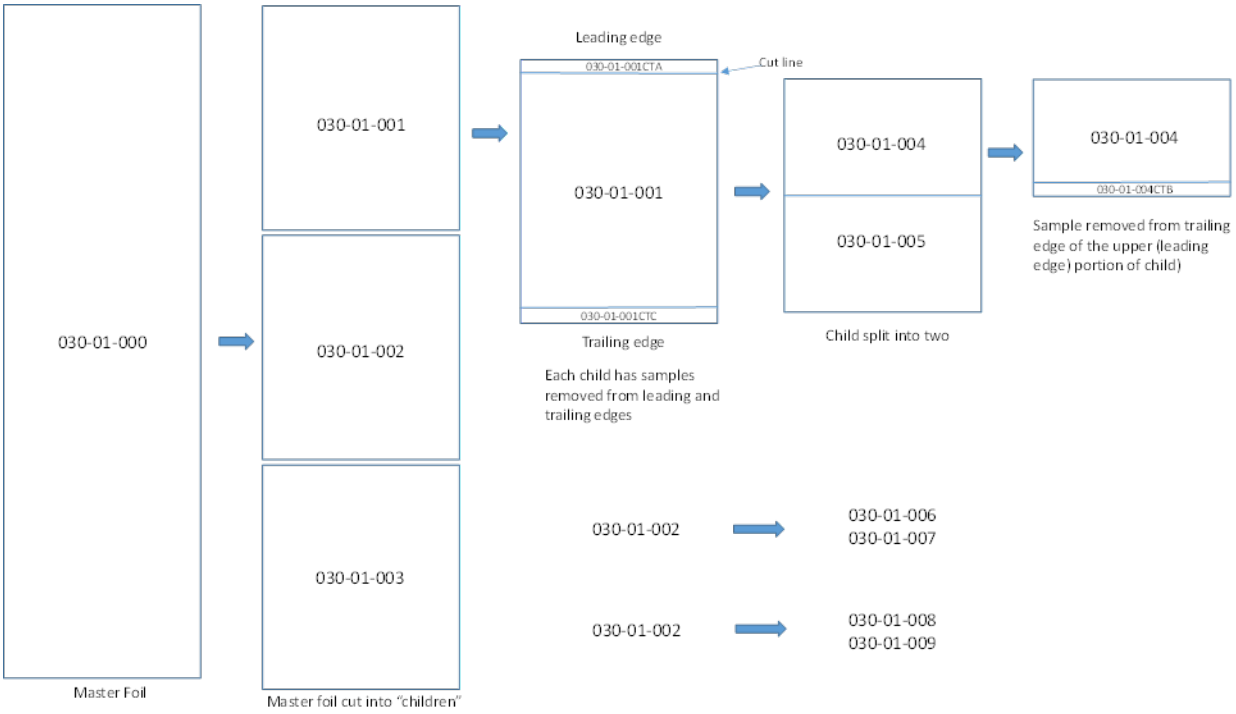

Figure 2-3. Illustration of foil sample locations for medium power foils

A total of 283 in. of medium power foils and a total of 297 in. of low power foils were rolled. When cutting mini-foils, operators avoided areas of the cold rolled foils that exhibited irregularities. A total of 130 medium power and 151 low power mini-foils were cut from the foils. The mini-foils then underwent QC inspection. Ninety-six of the medium and low power mini-foils were selected for fabrication into mini-plates. Four mini foils were placed in the pockets of Al "composite" plates; the composite plates along with strongbacks were loaded into steel cans, evacuated, and welded shut. The cans then underwent a hot isostatic pressing (HIP) process to clad the mini-foil with Al. The cans were cut open and the composite plates removed. The composite plates were placed under a fluoroscope to locate the foil and punch locating (alignment) holes. The mini-plates were then punched from the composite plate using the fluoroscope system. The mini-plates were again radiographed to determine foil location (e.g., edge- and end-clad) and the cladding thickness and the cladding-cladding and cladding-fuel bonds were evaluated by ultrasonic testing (UT).

It is important to note the many "culling" opportunities were exploited during the MP-1 fabrication. Of the 66 ingots produced, 27% (18 of 66) were selected for shipping to BWXT; of the ingots received by BWXT, 39% (7 of 18) were selected for fabrication into foils. Of the masterfoils rolled from the 7 ingots, cut into children, and cold rolled into foils, 3 were fully used and 3 were partially used for mini-foil harvesting (one was not used at all). The harvest operation in itself was process by which operators subjectively selected areas where mini-foils would be cut (in the case of medium power foils fabricated from a single ingot, as much as one-third of the foil remained unharvested). The mini-foils harvested were further culled as to which ones would move on to HIPing—this included the selection of mini-foils that had failed the QC inspection for Zr thickness (e.g., surface irregularities). Forty-four of the 96 medium power mini-plates and 96 of the low power mini-plates would complete the spectrum of plate QC inspections. The final culling came from the selection of mini-plates that would be loaded into capsules for irradiation testing: 28 of the 44 medium power mini-plates and 28 of the 96 low power mini-plates that were inspected were selected for loading into an experimental capsule.

2.2 Sample Material Summary

PNNL, INL, and LANL received six types of MP-1 characterization foils from BWXT, as shown in **Table 2-**–**Table 2-**:

- 0.047 in. hot-rolled and annealed samples with and without Zr layers.
- 0.025 in. cold-rolled and annealed samples with and without Zr layers, and
- 0.0085 in. cold-rolled and annealed samples with and without Zr layers.

Sample IDs ending in DTA, DTB, and DTC originated from masterfoils after the completion of the hot rolling step, but before the beginning of the cold rolling step. and sample IDs ending in CTA, CTB, and CTC were harvested after the completion of the cold rolling step. The final letter A and C denote the leading and trailing edge, respectively; the "B" samples are taken from the middle of the masterfoil/foil.

Extensive studies were performed on 28 U-10Mo samples in accordance with the MP-1 Characterization Plan (INL 2018). Additional information about each sample and its condition are also shown in **Table 2-**–**Table 2-**.

Samples were taken from five MP-1 castings. Each casting was done in the same furnace and had the same hold temperature. One casting, AHTD, had a hold time of 25 minutes whereas the other castings were held at the hold temperature for 30 minutes. The average vacuum levels for the castings ranged from 19 to 34 microns; the average pressure for the castings was 26.7 microns. The small differences observed in the casting process conditions are not expected to influence the microstructure and chemical composition of the castings.

Isotopics and chemistry associated with each ingot was determined by the average of three samples taken from the sample strip. Samples were taken from foils fabricated from MP-1 castings AE1K, AHTD, AMF9, AMFA, and C4DX (MP-1 castings 2, 3, 5, 6, and 7)[1]. From these castings, ingots from plates 1, 2, and 3 were fabricated into foils (the right and left plates are assumed to be chemically and isotopically identical). Plate 2 was the center plate and was flanked by plates 2 and 3. No documentation is available to determine the orientation of plates 1 and 3. An illustration summarizing the ingots selected from plates selected from castings that supplied the feedstock materials for masterfoils (designated by "M") and foils (designated by "F") is provided in Figure 2-4. Four distinct castings were used to provide feedstock materials for masterfoil samples (castings AE1K, AHTD, AMFA, and C4DX) while five castings provided materials for foil samples (castings AE1K, AHTD, AMF9, AMFA, and C4DX).

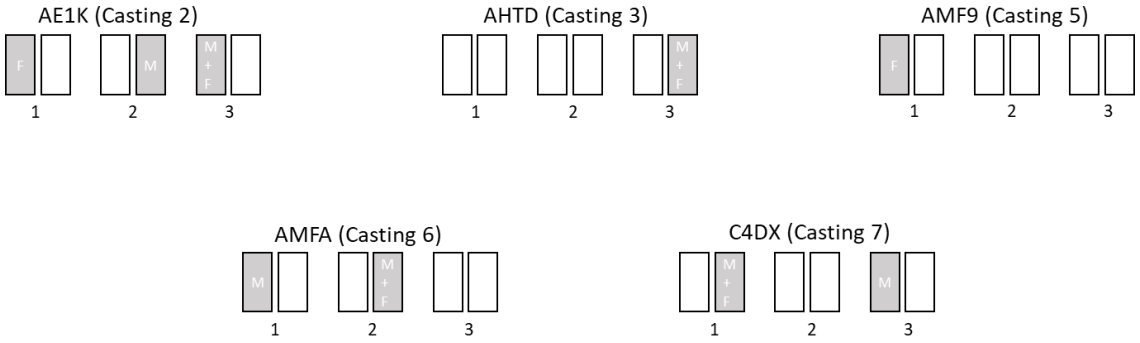

Figure 2-4. Source of feedstock materials for masterfoils ("M") and foils ("F"). Numbers refer to plate number.

Because carbon is an important impurity in the fabrication of ingots to foils, the average carbon content for the plate (ingot) castings and the average carbon content for the plates used in this characterization study is provided in Table 2-. As noted in the table, the range of carbon seen in the feedstock was from 253 ppm to 456 ppm. Furthermore, there's a bi-modal distribution of carbon impurities among the casting: the average carbon content for castings AHTD, AMF9, AMFA, and C4DX is 270 ppm while the carbon content from casting AE1K was 433 ppm.

Table 2-1. Plate Carbon Levels by Casting

[1] MP-1 castings have a 10-digit ID; the ID has been shortened to the identifying 4 digits for this report.

Casting ID	Casting No.	Plate	Plate Average Carbon (ppm)	Casting Average Carbon (ppm)
AE1K	2	1	427	
AE1K	2	2	456	433
AE1K	2	3	416	
AHTD	3	3	253	253
AMF9	5	1	271	271
AMFA	6	1	262	258
AMFA	6	2	253	
C4DX	7	1	291	290
C4DX	7	3	288	

Statistical analysis was performed separately in different feedstock samples to examine the variability in microstructural parameters at different locations in the rolled foil. Variability or non-uniformity was examined for foil thickness, Zr thickness, Mo content, Grain size and carbide fraction at different locations (such as leading and trailing) and data will be published separately.

Upon receipt of each sample, an entry was made in the Sample Log. The Sample Log contains the sample identification number, sample description, and other relevant information to support positive sample identification and traceability.

Table 2-2. U-10Mo bare, hot-rolled, and annealed MP-1 samples from Lot 027 and Lot 28

No.	Y-12 Casting Info	Ingot	Master Foil	Foil Sample Source	Grain Direction	Foil Area Sample Region	Sample ID	Thickness (in.)
1	Casting 2 right plate 2	3K74-2R-AE1K	027-04-000	027-04-000	Transverse	Leading edge	027-04-000DTA	0.047
2	Casting 2 right plate 2	3K74-2R-AE1K	027-04-000	027-04-002	Transverse	Leading edge	027-04-002DTB	0.047
3	Casting 2 right plate 2	3K74-2R-AE1K	027-04-000	027-04-000	Transverse	Trailing edge	027-04-000DTC	0.047
4	Casting 2 left plate 3	3K74-3L-AE1K	027-05-000	027-05-000	Transverse	Leading edge	027-05-000DTA	0.047
5	Casting 2 left plate 3	3K74-3L-AE1K	027-05-000	027-05-002	Transverse	Leading edge	027-05-002DTB	0.047
6	Casting 2 left plate 3	3K74-3L-AE1K	027-05-000	027-05-000	Transverse	Trailing edge	027-05-000DTC	0.047
7	Casting 6 plate 1 left	3K74-1L-AMFA	028-01-000	028-01-000	Transverse	Leading edge	028-01-000DTA	0.047
8	Casting 6 plate 1 left	3K74-1L-AMFA	028-01-000	028-01-002	Transverse	Leading edge	028-01-002DTB	0.047
9	Casting 6 plate 1 left	3K74-1L-AMFA	028-01-000	028-01-000	Transverse	Trailing edge	028-01-000DTC	0.047
10	Casting 3 plate 3 right	3K74-3R-AHTD	028-05-000	028-05-000	Transverse	Leading edge	028-05-000DTA	0.047
11	Casting 3 plate 3 right	3K74-3R-AHTD	028-05-000	028-05-002	Transverse	Leading edge	028-05-002DTB	0.047
12	Casting 3 plate 3 right	3K74-3R-AHTD	028-05-000	028-05-000	Transverse	Trailing edge	028-05-000DTC	0.047

Table 2-3 U-10Mo hot-rolled and annealed, co-rolled with Zr MP-1 samples from Lot 029 and Lot 030

No.	Y-12 Casting Info	Ingot	Master Foil	Foil Sample Source	Grain Direction	Foil Area Sample Region	Sample ID	Thickness (in.)
1	Casting 6 plate 2 right	3K74-2R-AMFA	029-01-000	029-01-000	Transverse	Leading edge	029-01-000DTA	0.047
2	Casting 6 plate 2 right	3K74-2R-AMFA	029-01-000	029-01-002	Transverse	Leading edge	029-01-002DTB	0.047
3	Casting 6 plate 2 right	3K74-2R-AMFA	029-01-000	029-01-000	Transverse	Trailing edge	029-01-000DTC	0.047
4	Casting 7 plate 3 left	3K74-3L-C4DX	030-01-000	030-01-000	Transverse	Leading edge	030-01-000DTA	0.047
5	Casting 6 plate 1 left	3K74-1L-AMFA	029-02-000	029-02-000	Transverse	Leading edge	029-02-000DTA	0.047
6	Casting 6 plate 1 left	3K74-1L-AMFA	029-02-000	029-02-002	Transverse	Leading edge	029-02-002DTB	0.047
7	Casting 6 plate 1 left	3K74-1L-AMFA	029-02-000	029-02-000	Transverse	Trailing edge	029-02-000DTC	0.047
8	Casting 7 plate 1 right	3K74-1R-C4DX	029-05-000	029-05-000	Transverse	Leading edge	029-05-000DTA	0.047
9	Casting 7 plate 1 right	3K74-1R-C4DX	029-05-000	029-05-002	Transverse	Leading edge	029-05-002DTB	0.047
10	Casting 7 plate 1 right	3K74-1R-C4DX	029-05-000	029-05-000	Transverse	Trailing edge	029-05-000DTC	0.047
11	Casting 7 plate 3 left	3K74-3L-C4DX	030-01-000	030-01-000	Transverse	Leading edge	030-01-000DTA	0.047

Table 2-4. U-10Mo cold-rolled and annealed; MP-1 samples from Lot 028 and 027

No.	Y-12 Casting Info	Ingot	Master Foil	Foil Sample Source	Grain Direction	Foil Area Sample Region	Sample ID	Thickness (in.)
1	3K74-1L-AMFA	028-01-000	028-01-001	028-01-001	Transverse	Leading edge	028-01-001CTA	0.0245
2	3K74-1L-AMFA	028-01-000	028-01-001	028-01-001	Transverse	Middle edge	028-01-001CTB	0.0245
3	3K74-1L-AMFA	028-01-000	028-01-001	028-01-001	Transverse	Trailing edge	028-01-001CTC	0.0245
4	3K74-1L-AMFA	028-01-000	028-01-002	028-01-002	Transverse	Leading edge	028-01-002CTA	0.0245
5	3K74-1L-AMFA	028-01-000	028-01-002	028-01-002	Transverse	Middle edge	028-01-002CTB	0.0245
6	3K74-1L-AMFA	028-01-000	028-01-002	028-01-002	Transverse	Trailing edge	028-01-002CTC	0.0245
7	3K74-3R-AHTD	028-05-000	028-05-001	028-05-001	Transverse	Leading edge	028-05-001CTA	0.0245
8	3K74-3R-AHTD	028-05-000	028-05-001	028-05-001	Transverse	Middle edge	028-05-001CTB	0.0245
9	3K74-3R-AHTD	028-05-000	028-05-001	028-05-001	Transverse	Trailing edge	028-05-001CTC	0.0245
10	3K74-3R-AHTD	028-05-000	028-05-002	028-05-002	Transverse	Leading edge	028-05-002CTA	0.0245
11	3K74-3R-AHTD	028-05-000	028-05-002	028-05-002	Transverse	Middle edge	028-05-002CTB	0.0245
12	3K74-3R-AHTD	028-05-000	028-05-002	028-05-002	Transverse	Trailing edge	028-05-002CTC	0.0245

13	3K74-3L-AE1K	027-05-000	027-05-002	027-05-002	Transverse	Leading edge	027-05-002CTA	0.0235
14	3K74-3L-AE1K	027-05-000	027-05-002	027-05-002	Transverse	Middle edge	027-05-002CTB	0.0235
15	3K74-3L-AE1K	027-05-000	027-05-002	027-05-002	Transverse	Trailing edge	027-05-002CTC	0.0235
16	3K74-1L-AE1K	027-01-000	027-01-001	027-01-001	Transverse	Leading edge	027-01-001CTA	0.0235
17	3K74-1L-AE1K	027-01-000	027-01-001	027-01-001	Transverse	Middle edge	027-05-001CTB	0.0235
18	3K74-1L-AE1K	027-01-000	027-01-001	027-01-001	Transverse	Trailing edge	027-05-001CTC	0.0235

Table 2-5. U-10Mo cold-rolled and annealed, co-rolled with Zr; MP-1 samples from Lot 029

No.	Y-12 Casting Info	Ingot	Master Foil	Foil Sample Source	Grain Direction	Foil Area Sample Region	Sample ID	Thickness (in.)
1	3K74-2R-AMFA	029-01-000	029-01-001	029-01-001	Transverse	Leading edge	029-01-001CTA	0.0269
2	3K74-2R-AMFA	029-01-000	029-01-001	029-01-004	Transverse	Leading edge	029-01-004CTB	0.0269
3	3K74-2R-AMFA	029-01-000	029-01-001	029-01-001	Transverse	Trailing edge	029-01-001CTC	0.0269
4	3K74-2R-AMFA	029-01-000	029-01-002	029-01-002	Transverse	Leading edge	029-01-002CTA	0.0273
5	3K74-2R-AMFA	029-01-000	029-01-002	029-01-006	Transverse	Leading edge	029-01-006CTB	0.0273
6	3K74-2R-AMFA	029-01-000	029-01-002	029-01-002	Transverse	Trailing edge	029-01-002CTC	0.0273
7	3K74-1L-AMF9	029-02-000	029-02-001	029-02-001	Transverse	Leading edge	029-02-001CTA	0.0259
8	3K74-1L-AMF9	029-02-000	029-02-001	029-02-004	Transverse	Leading edge	029-02-004CTB	0.0259
9	3K74-1L-AMF9	029-02-000	029-02-001	029-02-001	Transverse	Trailing edge	029-02-001CTC	0.0259
10	3K74-1L-AMF9	029-02-000	029-02-002	029-02-002	Transverse	Leading edge	029-02-002CTA	0.0262
11	3K74-1L-AMF9	029-02-000	029-02-002	029-02-006	Transverse	Leading edge	029-02-006CTB	0.0262
12	3K74-1L-AMF9	029-02-000	029-02-002	029-02-002	Transverse	Trailing edge	029-02-002CTC	0.0262
13	3K74-1R-C4DX	029-05-000	029-05-001	029-05-001	Transverse	Leading edge	029-05-001CTA	0.0262
14	3K74-1R-C4DX	029-05-000	029-05-001	029-05-004	Transverse	Leading edge	029-05-004CTB	0.0262
15	3K74-1R-C4DX	029-05-000	029-05-001	029-05-001	Transverse	Trailing edge	029-05-001CTC	0.0262
16	3K74-1R-C4DX	029-05-000	029-05-002	029-05-002	Transverse	Leading edge	029-05-002CTA	0.0278
18	3K74-1R-C4DX	029-05-000	029-05-002	029-05-006	Transverse	Leading edge	029-05-006CTB	0.0278
18	3K74-1R-C4DX	029-05-000	029-05-002	029-05-002	Transverse	Trailing edge	029-05-002CTC	0.0278

Table 2-6. U-10Mo cold-rolled and annealed MP-1 samples from Lot 027

No.	Y-12 Casting Info	Ingot	Master Foil	Foil Sample Source	Grain Direction	Foil Area Sample Region	Sample ID	Thickness (in.)
1	3K74-2R-AE1K	027-04-000	027-04-001	027-04-003	Transverse	Leading edge	027-04-003CTA	0.009
2	3K74-2R-AE1K	027-04-000	027-04-001	027-04-003	Transverse	Trailing edge	027-04-003CTB	0.009
3	3K74-2R-AE1K	027-04-000	027-04-001	027-04-004	Transverse	Trailing edge	027-04-004CTC	0.009
4	3K74-2R-AE1K	027-04-000	027-04-002	027-04-005	Transverse	Leading edge	027-04-005CTA	0.009
5	3K74-2R-AE1K	027-04-000	027-04-002	027-04-005	Transverse	Leading edge	027-04-005CTA	0.009
6	3K74-2R-AE1K	027-04-000	027-04-002	027-04-005	Transverse	Trailing edge	027-04-005CTA	0.009

Table 2-7. U-10Mo cold-rolled and annealed, co-rolled with Zr, MP-1 samples from Lot 030

No.	Y-12 Casting Info	Ingot	Master Foil	Foil Sample Source	Grain Direction	Foil Area Sample Region	Sample ID	Thickness (in.)
1	3K74-3L-C4DX	030-01-000	030-01-001	030-01-001	Transverse	Leading edge	030-01-001CTA	0.0104
2	3K74-3L-C4DX	030-01-000	030-01-001	030-01-004	Transverse	Trailing edge	030-01-004CTB	0.0104
3	3K74-3L-C4DX	030-01-000	030-01-001	030-01-001	Transverse	Trailing edge	030-01-001CTC	0.0104
4	3K74-3L-C4DX	030-01-000	030-01-002	030-01-002	Transverse	Leading Edge	030-01-002CTA	0.0119
5	3K74-3L-C4DX	030-01-000	030-01-002	030-01-002	Transverse	Trailing edge	030-01-002CTA	0.0119
6	3K74-3L-C4DX	030-01-000	030-01-002	030-01-002	Transverse	Trailing edge	030-01-002CTA	0.0119
7	3K74-3L-C4DX	030-01-000	030-01-003	030-01-003	Transverse	Leading Edge	030-01-003CTA	0.0121
8	3K74-3L-C4DX	030-01-000	030-01-003	030-01-008	Transverse	Trailing edge	030-01-008CTB	0.0121
9	3K74-3L-C4DX	030-01-000	030-01-003	030-01-003	Transverse	Trailing edge	030-01-003CTC	0.0121

3.0 Specimen Preparation

3.1 Specimen Sectioning

Specimen sectioning from U-10Mo samples listed in **Table 2-**–**Table 2-** was performed in accordance with the MP-1 Characterization Plan (INL 2018) and Characterization Working Group (CWG)-approved procedure for specimen sectioning and preparation (Prabhakaran et al. 2016b). Samples were taken from the leading and trailing edge and the center masterfoils and foils (note that the leading and trailing edges of the masterfoils and foils were squared before samples were cut). Six specimens from each sample were sectioned as follows: two specimens (longitudinal, referred to as L; and transverse, referred to as T with respect to rolling direction) from each location (left edge, center, and right edge), as shown in Figure 3-1. Upon sectioning each sample, an entry was made in the Sample Log. The Sample Log contains the specimen identification number, sample number, sample description, and other relevant information to support positive specimen identification and traceability.

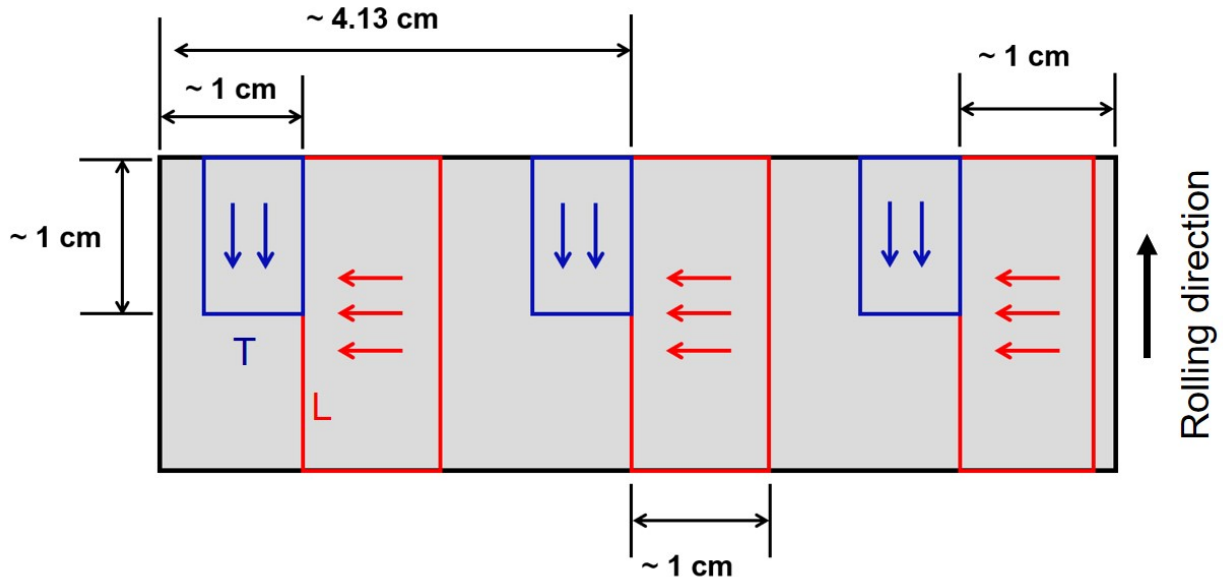

Figure 3-1. Example sectioning diagram according to the MP-1 Characterization Plan (INL 2018)

3.2 Specimen Mounting, Grinding, and Polishing

After sectioning, specimens were mounted using glass slides and epoxy resin for grinding and polishing in order to expose the specimen's surface for observation (optical and scanning electron microscopy [SEM]), and in accordance with the CWG-approved procedure (Prabhakaran et al. 2016b). Among the main objectives of a mounting operation are protecting the sample edge and maintaining the integrity of the specimen's surface features. Mounted specimens (longitudinal and transverse) were polished to a 1,200-grit finish using silicon carbide grinding paper, followed by polishing using 9 µm and 3 µm diamond suspensions. Final polishing using a vibratory polisher was performed using 1 µm diamond suspension and 0.08 µm colloidal silica suspension. Additional details about specimen mounting, grinding, and polishing can be found in the sample preparation and examination report (Prabhakaran et al. 2016b).

4.0 Equipment Used for Analysis

4.1 Optical Microscope

After the final polishing, the mounted specimens were stored for at least 48 hours prior to examination using an optical microscope. Typically, the grains show up much better in the polarized mode when samples such as these have been oxidized in air for at least 48 hours.

Optical metallography was performed using an Olympus BX61M optical microscope with a three-axis automated stage and digital charge-coupled device camera. The objective lenses used for this study have magnifications of 2.5×, 5×, 10×, 20×, and 50×. Good quality images were obtained by using the polarized light filter. A stage micrometer was periodically employed to verify the functioning of the objective lenses and software.

Olympus Stream Motion software was used to obtain and record individual and montage images. Using the software along with the automated stage enables the user to define top-left and bottom-right corners of the specimen after choosing a magnification. Once the border is set, the software automatically calculates the number of individual images required to obtain a montage of the entire specimen. After recording the first image, the automated stage moves slightly to capture the second image at a different location, and this process continues to document the required number of images. Once the individual images are obtained, the software automatically stitches the images to form a single montage image of the entire specimen.

For each specimen, an overview montage image was captured at 2.5× or 5× magnification (based on foil thickness). Additional images at magnifications 10×, 20×, and 50× were captured at two to three locations (left and right; or left, center, and right) for each specimen, depending on its size. The Olympus Stream Motion software was also used to adjust contrast and other settings to enhance image quality to that suitable for grain size analysis.

Specimens subjected to each set of processing conditions were studied at various magnifications to identify their basic microstructural features, including phases present, degree of homogeneity, orientation, Zr thickness, foil thickness, and extent of banding.

The grain sizes of U-10Mo specimens were calculated using images obtained from the optical microscope, using ImageJ software. For each specimen, two to three images (50×; left, center, and right; depending upon the specimen size) were used. A target of 150–200 grains per specimen were used for the measurement of average grain size and standard deviation. The grain diameter was measured across one axis or two axes (major [longer] and minor [shorter]) of a grain, depending upon the material's microstructure. Measurements were done manually.

The optical microscope used at INL is different from PNNL. Samples were analyzed by optical microscopy using Zeiss Axio Pro 10 mm. Calibration of the optical microscope is performed every 12 months by manufacturer's field engineer during the preventive maintenance. Furthermore, calibration was checked regularly using a NIST approved stage micrometer (2 mm) at all magnifications of interest. Images were collected in the bright field mode for the 2.5, 5, 10x objective and in the polarized mode for 10, 20x. Areas of interest were also observed with the 50x objective when possible. Montages were performed for the samples at 2.5, 5, 10x and/ or 20x, as the full length of the samples were analyzed. Photoshop software was also used to enhance images to obtain the best contrast for grain size determination.

4.2 Scanning Electron Microscope

4.2.1 Microstructural and Elemental Analyses

Prior to performing SEM imaging, the mounted and polished U-10Mo specimens were cleaned using a Fischione plasma cleaner, and then coated with ~10 nm gold in an SPI-Module sputter coater. The gold-coated specimens were again cleaned using the plasma cleaner.

SEM was employed to provide information needed to evaluate the effect of fabrication parameters on U-10Mo. Microstructural and elemental analyses were carried out using a JEOL JSM-7600F SEM equipped with an Oxford Instruments AZtec X-Max 80 mm^2 energy-dispersive x-ray spectroscopy (EDS) detector and INCA Microanalysis Suite software. The JEOL JSM-7600F system has the following components: (1) in-lens secondary electron detector (SEI); (2) Everhart-Thornley detector (lower electron image, LEI); (3) low-angle backscattered electron detector (LABE or LBE); (4) silicon drift (SDD) EDS detector; (5) wavelength-dispersive x-ray spectroscopy (WDS) detector; and (6) electron backscatter diffraction (EBSD) detector. The Oxford Instruments AZtec system's components are (1) An X-Max 80 mm^2 SDD (item 4 above); (2) WDS detector (item 5 above); (3) HKL Nordlys EBSD camera (item 6 above); and (4) AZtec software.

Typical microscope settings are the following: 30 keV, 15 mm working distance,110 µm aperture, and beam current of ~6×10^{-9} A or higher. Higher beam currents allow faster EDS data acquisition. On the JSM 7600F, in SEM mode, images are available from the SEI, LEI, and LABE detectors, whereas Low Mag mode only offers LEI and LABE images. Additional details about the SEM setup can be found in the sample preparation and examination report (Prabhakaran et al. 2016b).

SEM was performed to analyze carbide size and volume fraction , Zr thickness, the U-10Mo-Zr interaction layer, amount of uranium phase transformation, chemical banding, phase, homogeneity, and defects. For U-10Mo specimens without Zr, the following images were taken:

- LEI and LABE images of the U-10Mo at 250× and 500× (left, center, and right);
- LEI and LABE montage image of U-10Mo at 250× (center only; covering entire thickness; 8–10 images to create a center-montage image, as shown in Figure 4-1).

For U-10Mo specimens with Zr, the following images focusing on the Zr layer were taken in addition to those mentioned above: LEI and LABE images at 250×/500× (Zr layer - top center and Zr-layer - bottom center; 10–12 images each to create a montage image of a Zr layer). Other magnifications were used as needed to observe specific features.

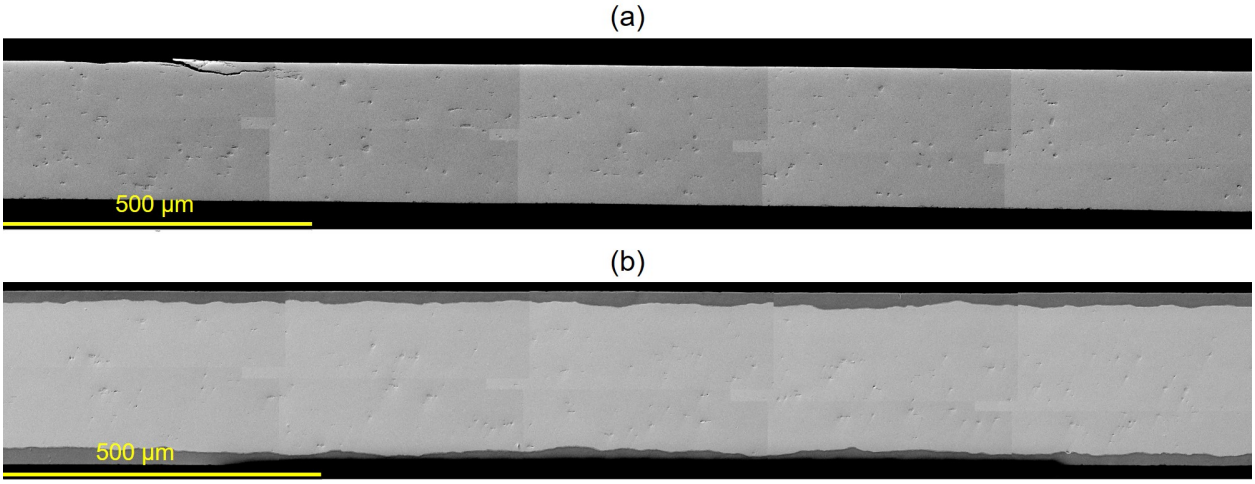

Figure 4-1. Representative center-montage images of U-10Mo specimens of thickness 0.01 in.: (a) 027-04-003CTA (T) and (b) 030-01-004CTB (T). ('T' stands for Transverse direction)

Quantitative chemical analysis was performed using EDS. Spectra were collected at a working distance of 15 mm and a voltage of 30 keV. The EDS analyses were performed using three line scans (200–300 microns each, depending upon thickness) at the center of the fuel for each specimen to evaluate the Mo distribution across the specimen thickness at a magnification of 250× and step size of 1 µm, in accordance with the MP-1 Characterization Plan (INL 2018). An average of three line scans for each specimen was used to document Mo weight percent (wt%). During EDS line scanning, x-ray spectra come from U-10Mo matrix and carbide particles. To avoid carbide particles in evaluating overall Mo concentration, data points were filtered according to Mo concentration (from 7 to

12 wt%). Data points under 7 wt% Mo were ignored because the spectra included emissions from carbide particles. The carbon concentration in the alloy was not considered during Mo concentration evaluation. (Quantitative carbon analysis using EDS is not reliable because carbon has a low atomic number). Finally, the filtered data points were used to estimate average Mo concentration.

4.2.2 Electron Backscatter Diffraction

EBSD analyses were carried out using a JEOL JSM-7600 field emission SEM, an HKL Nordlys EBSD camera, and an Oxford Instruments AZtec NanoAnalysis software package. EBSD analyses were performed on a few selected specimens to corroborate the grain size measurements obtained optically. Additional analysis, such as of misorientation and texture, will be performed later.

EBSD mapping was performed at a working distance of ~24 mm using an accelerating voltage of 20 kV and probe current setting of 16. Camera binning was set to 2 × 2 with a 3.7 Hz acquisition speed and two-frame averaging. Individual maps were recorded at 250× magnification, and step sizes ranged from 2.25 µm to 2.5 µm. Indexing of the uranium and uranium carbide (UC) phases was performed using cubic crystal symmetry, and phase details are included in Table 4-1 below.

Table 4-1. EBSD phase details used for phase indexing

Phase	Lattice Parameter	Angles	Space/Laue Group
Gamma uranium	$a = b = c = 3.41$ Å	$\alpha = \beta = \gamma = 90°$	229/11
Uranium carbide	$a = b = c = 4.96$ Å	$\alpha = \beta = \gamma = 90°$	225/11

Post-processing of the acquired data was performed using the HKL Tango software package by removing wild spikes and performing an iterative zero-solution extrapolation to a medium level. Grain size analysis was performed using a 10° critical misorientation to define boundaries. Boundary completion down to 2° was applied in addition to a four-pixel minimum area grain filter. The carbide phases were excluded from the grain size analysis of the specimen matrix. Border grains located on the edge of the map were included in the grain size determination and weighted according to the number of borders with which any given grain is in contact. (A 2× multiplier is used when a grain is in contact with a single border, whereas a 4× multiplier is used if a single grain is in contact with two borders.)

4.3 Vickers Microhardness Tester

Vickers microhardness testing was performed using a Future Tech FM-7 Hardness Tester to study the effect of fabrication parameters on U-10Mo alloy in accordance with ASTM Standard E384 (ASTM 2017). Prior to U-10Mo specimen testing, a calibration block was used on a daily basis to verify the operation of the Vickers microhardness tester at 500 gram force (gf) with a dwell time of 12 seconds. After successful verification, Vickers microhardness testing was performed on U-10Mo specimens using a 300 gf load and dwell time of 15 seconds. For each specimen, four indents were made, and the average and standard deviation were calculated. The indent size was less than one-third of the foil thickness.

4.4 Density Measurement Setup

A mass balance, a solid density determination kit, and a liquid (distilled water) of known density were employed to determine the density of U-10Mo specimens using Archimedes' principle in accordance with the PNNL-developed procedure (Prabhakaran et al. 2016a). Archimedes' principle states that the apparent weight of an object immersed in a liquid decreases by an amount equal to the weight of the volume of the liquid that it displaces. Because 1 mL of water has a mass almost exactly equal to 1 g the difference between the two masses (in grams) will equal (almost

exactly) the volume (in mL) of the object weighed. When the mass and the volume of an object are known, its density can be calculated.

The density of each specimen was measured using an analytical mass balance (Mettler AE200) and a Mettler Density Determination Kit for Solids (Part #33360). The kit was used to measure the mass of the solids in air and in water. The analytical mass balance was supported in a manner that eliminated mechanical vibrations and could be shielded from air drafts. A glass beaker was used to contain the liquid (distilled water) so the presence of air bubbles could be easily discerned.

Prior to measuring the density of U-10Mo specimens, a density standard (with a known density) was used daily to verify the operation of the density measurement system. Additional details about the density measurement setup and procedure can be found in the associated procedure for determining uranium-molybdenum density and porosity (Prabhakaran et al. 2016a).

5.0 Results and Discussion

This section presents a summary of the multi-lab results, a discussion, and representative microstructural features observed in U-10Mo specimens.

5.1 Grain Size

Grain size measurements were obtained using an optical microscope and EBSD. The results of each are discussed below.

5.1.1 Grain Size Measurement Using Optical Microscope

A summary of the grain size results obtained for various U-10Mo specimens from all three labs, without and with the Zr interlayer, is presented in **Table A.1** to **Table A.6**.

Representative microstructures of specimens (without Zr) with different foil thicknesses used for grain size measurement are shown in Figure 5-1. Optical metallography typically displayed fully recrystallized, equiaxed grain structures in the U-10Mo specimens. However, elongated grains were also observed in a few specimens. Discontinuous UC phase was observed in the U-10Mo specimens' microstructures.

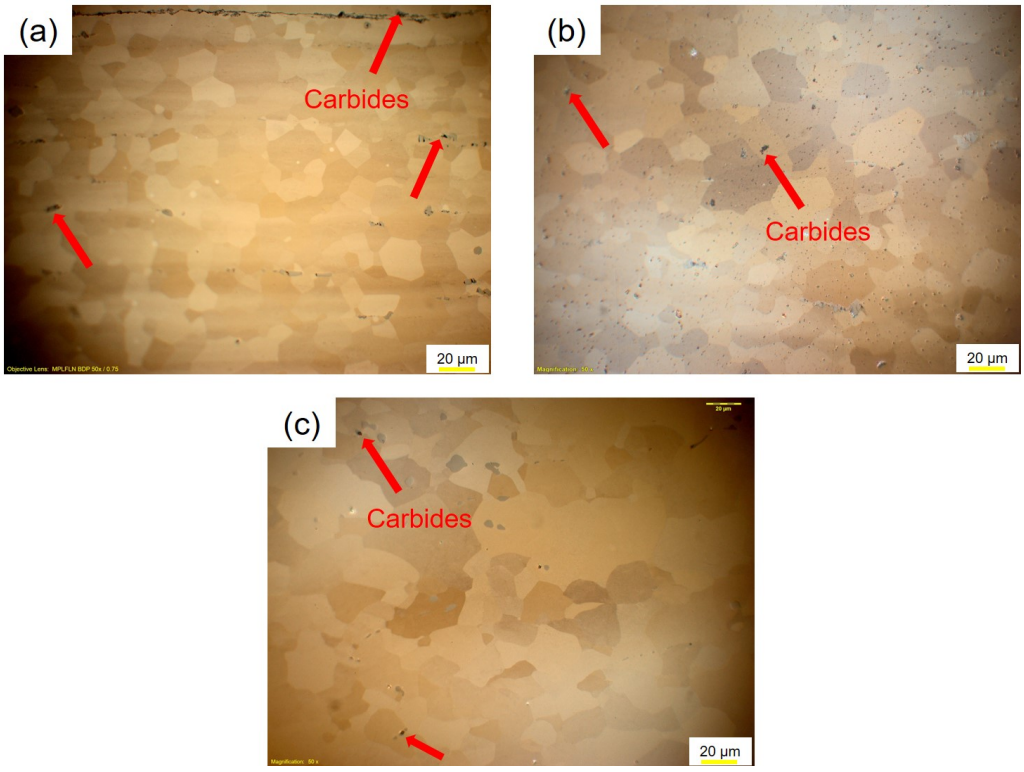

Figure 5-1. Representative microstructure of specimens (without Zr) with different thicknesses: (a) 027-04-003CTA (L) from 0.01 in. foil, (b) 028-01-001CTA (L) from 0.025 in. foil, and (c) 027-04-000DTC (L) from 0.047 in. masterfoil. Carbide particles are indicated by red arrows. ('L' stands for Longitudinal direction)

Different grain sizes were expected to depend on the U-10Mo foil fabrication history. The U-10Mo specimens with different thicknesses indicated that the average grain size decreased as the foil thickness decreased. The 0.01 in.-

thick U-10Mo foil specimens (without Zr) exhibited smaller grain sizes, whereas the 0.047 in.-thick masterfoil specimens showed larger grain sizes (Figure 5-2a). Similarly, 0.01 in.-thick U-10Mo foil specimens (with Zr) exhibited smaller grain sizes, whereas the 0.047 in.-thick masterfoil specimens showed larger grain sizes (Figure 5-2a). This is the result of thickness reduction; greater thickness reductions introduce more nucleation sites for new recrystallized grains. Unrecrystallized, elongated grains were observed in a few foil and masterfoil specimens (028-01-002CTB (L), 027-04-000DTC (L), 027-04-002DTB (L), 027-05-000DTA (L)). Grain size decreased with thickness reduction in all four different feedstock materials, as shown in Figure 5-2b. Grain size and variation were greater for 3K74-C4DX feedstock material. Similarly, grain size variation with thickness reduction is shown in Figure 5-2c for both leading- and trailing-edge samples. The data show grain size and variation are very similar in both leading- and trailing-edge samples.

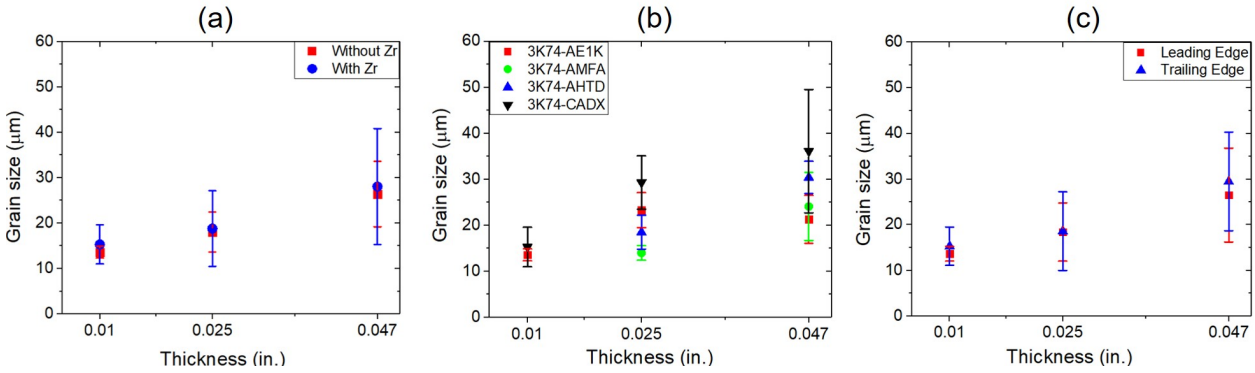

Figure 5-2. (a) Grain size with and without Zr layer with thickness reduction, (b) Grain size for different feedstock materials with thickness reduction and (c) Grain size for leading and trailing edges with thickness reduction

Grain size data separated in terms of feedstock materials is shown in Figure 5-3. All the feedstock materials follow a very similar trend: with thickness reduction, grain sizes decrease. Grain size and variation were greatest for C4DX feedstock material.

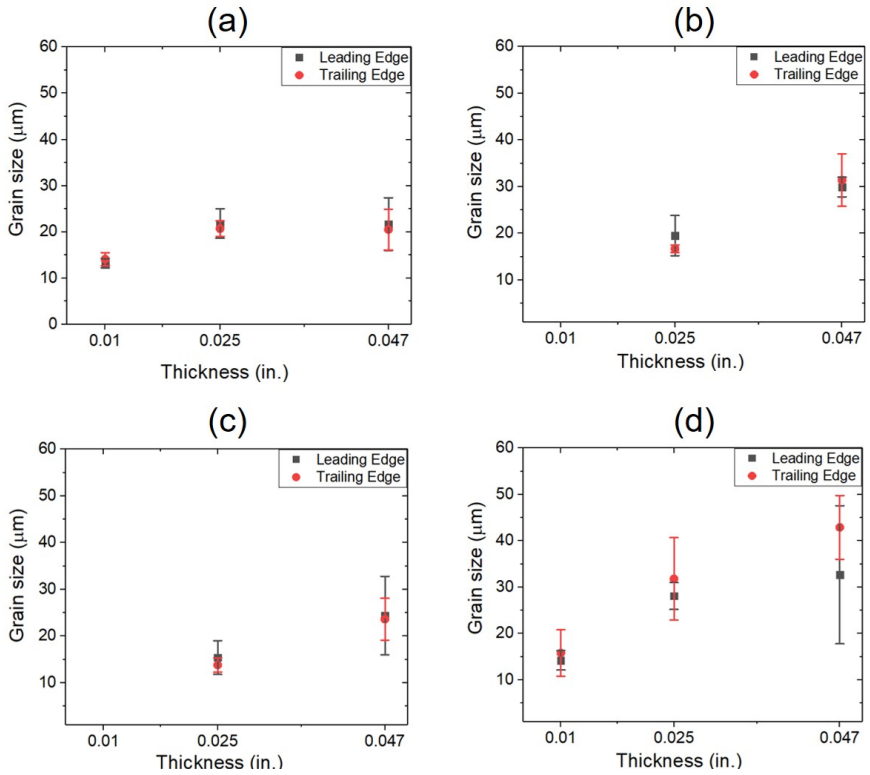

Figure 5-3. Grain size for different feedstock materials (a) AE1K, (b) AMFA, (c) AHTD and (d) C4DX

5.1.2 Grain Size Measurements Using EBSD

Orientation-based imaging was carried out to study the microstructural state (deformed or recrystallized) and perform grain size calculation. This report includes results of recent orientation-based microstructural characterization performed using EBSD on two samples of different thicknesses: 027-05-000DTC (L) (0.047 in., masterfoil without Zr); and 029-01-001CTA (L) (0.025 in, cold-rolled, annealed U-10Mo foil co-rolled with Zr). The microstructures of these two specimens are shown in Figure 5-4. The grains were equiaxed and fully recrystallized. No abnormal grain growth was observed.

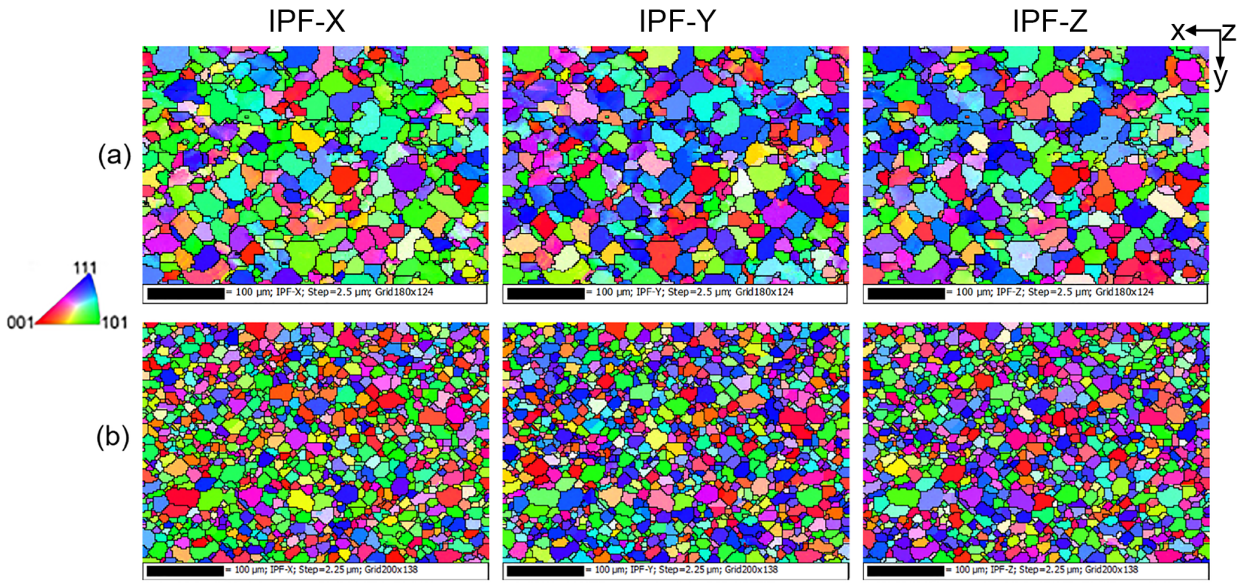

Figure 5-4. EBSD-generated microstructure of U-10Mo specimens: (a) 027-05-000DTC (L) (0.047 in masterfoil without Zr) and (b) 029-01-001CTA (L) (0.02 in. foil with Zr). ('L' stands for Longitudinal direction)

The grain size distributions calculated from EBSD microstructures are shown in Figure 5-5. The total number of grains considered for average grain size and size distribution were 467 and 1,177 for the 027-05-000DTC (L) and 029-01-001CTA (L) samples, respectively. The total area and step size used for the EBSD measurements are shown in the respective figures. Grain sizes measured from optical microstructure and EBSD are consistent.

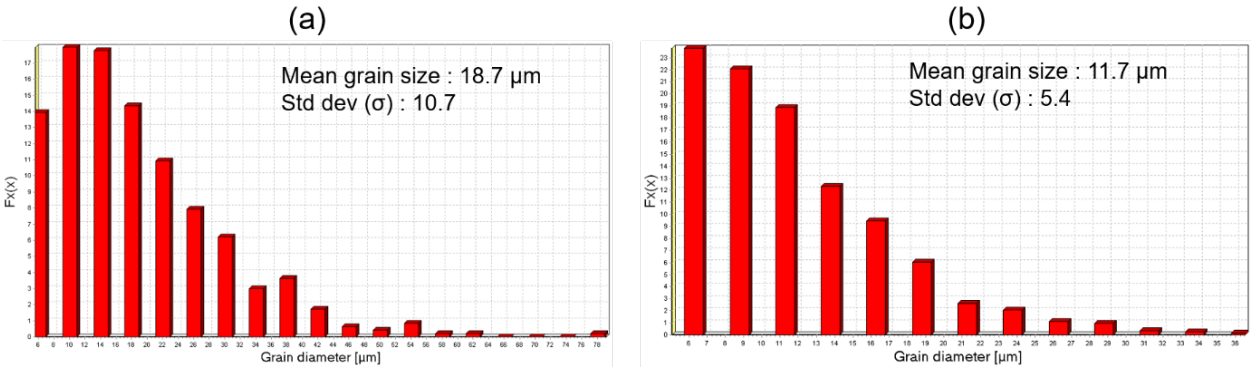

Figure 5-5. Grain size distribution calculated from EBSD microstructure for (a) 027-05-000DTC (L) and (b) 029-01-001CTA (L) specimens. ('L' stands for Longitudinal direction)

5.2 Molybdenum Distribution and Chemical Banding

The U-10Mo as-cast microstructure is an inhomogeneous, dendritic structure with Mo-rich and Mo-lean regions (Nyberg et al. 2013; Nyberg et al. 2014; Joshi et al. 2015). Mo segregation during the casting process is detrimental because it may affect the γ-phase stability, and it could lead to formation of an α-phase, along with a phase transition from γ to α + γ′ during thermal annealing (Jana et al. 2017).

A homogenization process is needed to reduce Mo segregation and to produce the desired microstructure with uniformly distributed Mo. Homogenization of U-10Mo is performed in the γ-phase field (above 560°C) for 48–144 hours, depending upon the temperature (Burkes et al. 2010; Nyberg et al. 2014; Joshi et al. 2015; Bostrom

and Halteman 1956). Experiments had been performed earlier to determine the optimum homogenization temperature and time for the U-10Mo alloy. All MP-1ingots were homogenized (at 900°C for 144 hours) prior to thermomechanical processing.

Quantitative chemical analysis was performed using EDS. The EDS analyses were performed on each specimen to evaluate the Mo distribution through the specimen thickness. The average Mo present was about 10 wt% in most of the specimens, with a standard deviation of less than 0.7% for all specimens. These results confirm the effectiveness of the homogenization process and support the assessment that the MP-1 materials met the specification for Mo uniformity (10 wt% ± 1 wt%)[2].

A representative Mo distribution (a line scan through the specimen thickness) is shown in Figure 5-6 for a 0.01 in. thick U-10Mo specimen without Zr (LEU-53-L). The microstructure of all specimens showed nearly homogeneous Mo distribution and no chemical banding. The Mo distributions obtained from the EDS line analyses for U-10Mo specimens without and with Zr are shown in **Table A.7** to **Table A.13**. The tables show average Mo concentration, standard deviation (SD), and variation (minimum to maximum) of Mo in U-10Mo specimens. While imaging for Mo concentration, efforts were made to avoid UC regions.[3] As expected, no noticeable differences in Mo concentration were observed between specimens with and without a Zr layer (Figure 5-7a). The Mo concentration as a function of thickness for the different feedstock materials is shown in Figure 5-7b. Relatively higher Mo concentration and variation observed for 3K74-AHTD and 3K74-AE1K feedstock materials. Mo concentration variation with thickness reduction shown in Figure 5-7c for both leading- and trailing-edge samples. No noticeable Mo variation was observed based on the location of the samples.

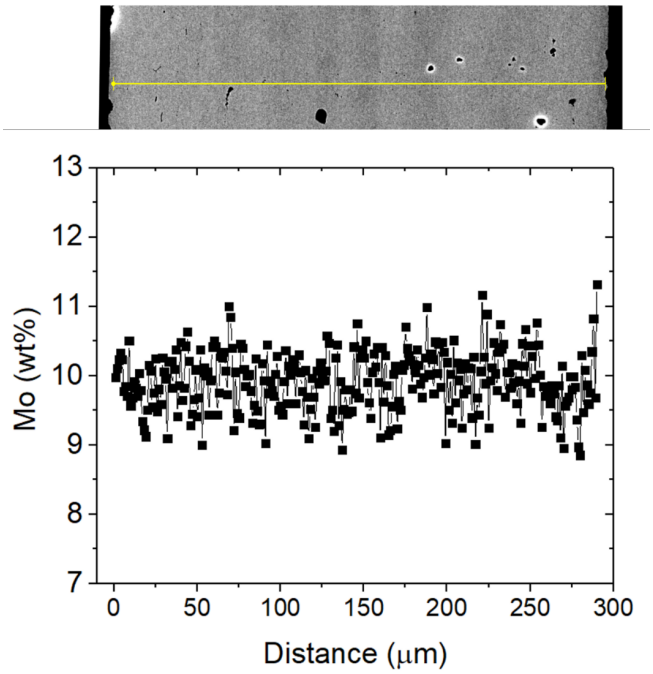

Figure 5-6. Mo distribution (a line scan through the specimen thickness) for a U-10Mo specimen of thickness 0.01 in. without Zr 027-04-003CTA (L). ('L' stands for Longitudinal direction)

[2] The specification for Mo uniformity requires a 95% confidence level; this assessment has not been performed.
[3] Limited distribution document, PNNL-27814, Pacific Northwest National Laboratory, Richland, WA.

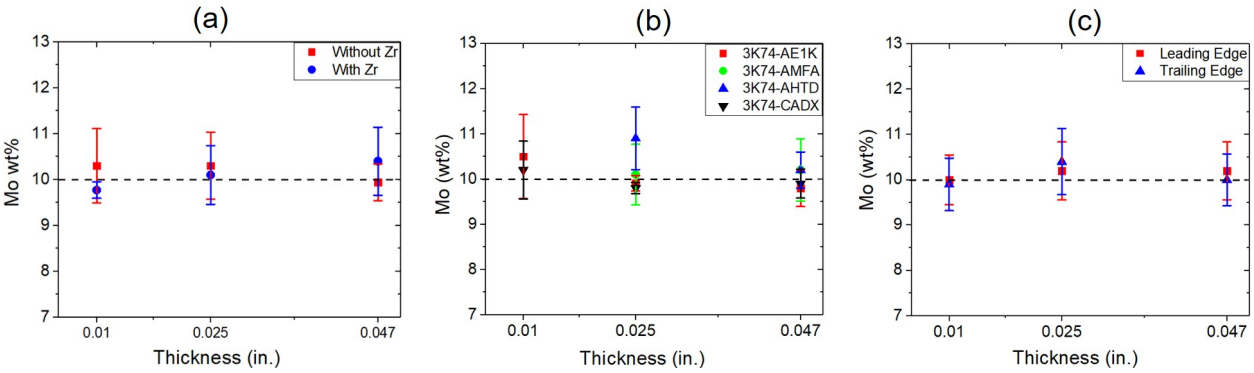

Figure 5-7. Mo concentration through sample thickness. (a) Mo concentration with and without Zr layer with thickness reduction; (b) Mo concentration for different feedstock materials with thickness reduction; (c) Mo concentration for leading and trailing edges with thickness reduction

Mo concentration as a function of thickness for the leading and trailing edge specimens is shown in Figure 5.8 for the different feedstock materials. Higher variation was observed for 3K74-AE1K feedstock at 0.01 in. thickness (Figure 5-8a). In samples made from other feedstock materials, Mo concentration was very similar for leading- and trailing-edge specimens (Figure 5-8c).

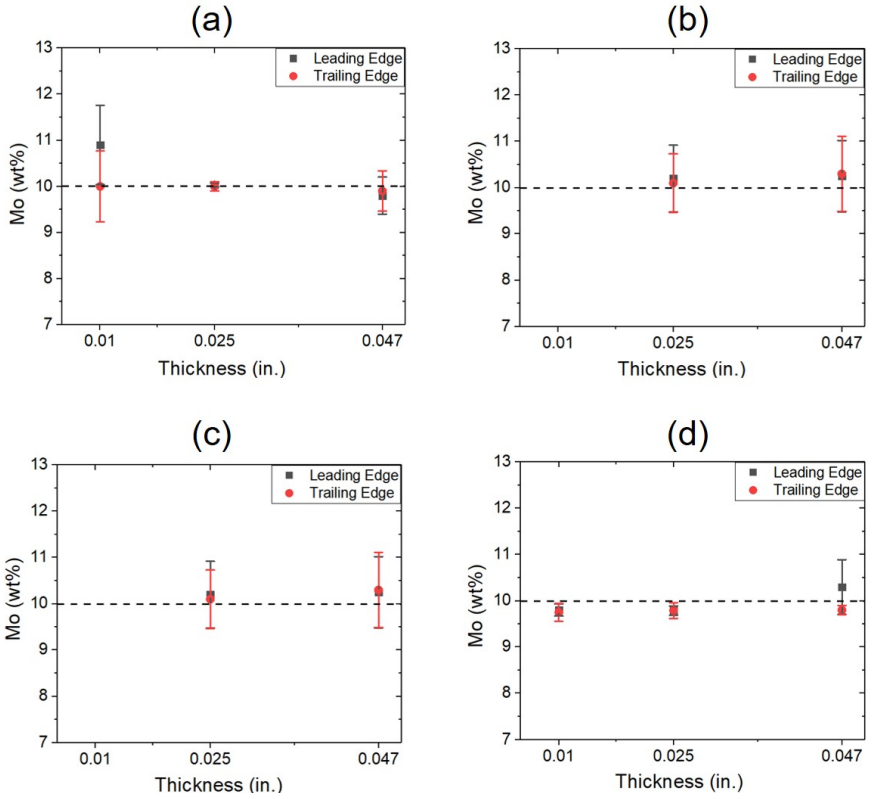

Figure 5-8. Mo concentration as a function of foil thickness for different feedstock materials: (a) AE1K, (b) AMFA, (c) AHTD, and (d) C4DX

5.3 Carbide Volume Fraction Evaluation

It is important to evaluate the carbide volume fraction and distribution because they have a strong influence on the mechanical behavior and grain size of the U-10Mo.

Carbides are easily identified based upon their darker contrast with respect to the U-10Mo matrix while using the backscattered electron (BSE) detector, as shown in Figure 5-9. The carbide area fraction in U-10Mo specimens was evaluated using SEM images obtained with a BSE detector at 250× magnification. A montage image (area 2,000 µm × 200 µm) consisting of 8–10 individual images, at 250× magnification, covering the entire fuel thickness at the specimen center was used, because a larger sample yields better statistics than a single image. The carbide particle size/area analysis was performed using 3–5 individual SEM images (at different locations) obtained with a BSE detector at 250× magnification. Average carbide particle size (cross-sectional area) ranged from 0.3 to 30 µm^2.

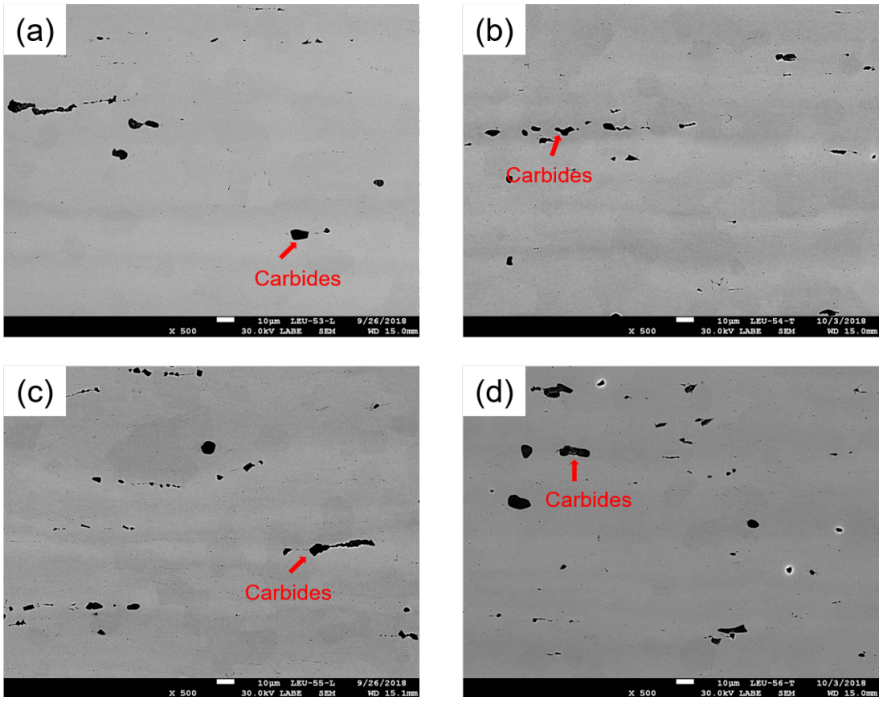

Figure 5-9. BSE-SEM microstructures of U-10Mo specimens of thickness 0.01 in.: (a) 027-04-003CTA (L); (b) 027-04-003CTA (T); (c) 027-04-003CTB (L); and (d) 027-04-003CTB (T). ('L' and 'T' stands for Longitudinal and Transverse direction)

ImageJ software was employed for calculating area fraction and for particle area analysis. A sequential procedure for the ImageJ analysis method is given in Figure 5-10. A thresholding method was used to distinguish carbide particles from the matrix. Representative microstructures after ImageJ thresholding are shown in Figure 5-11. ImageJ-thresholded images were used for the calculation of carbide area fractions and their distributions.

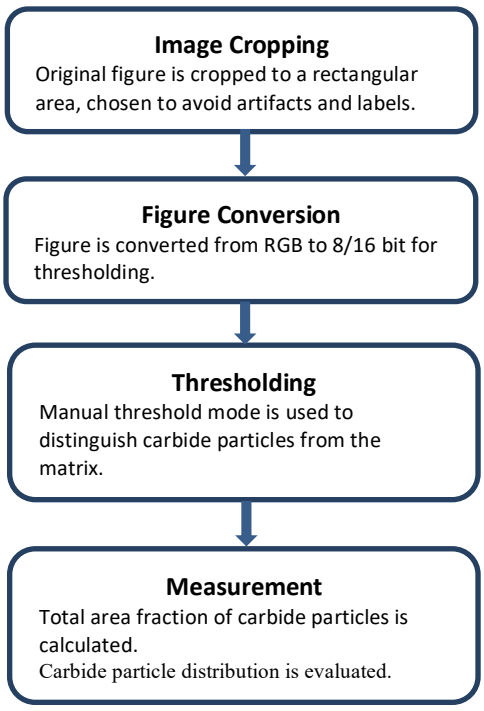

Figure 5-10. Schematic illustration of steps performed while using ImageJ analysis software

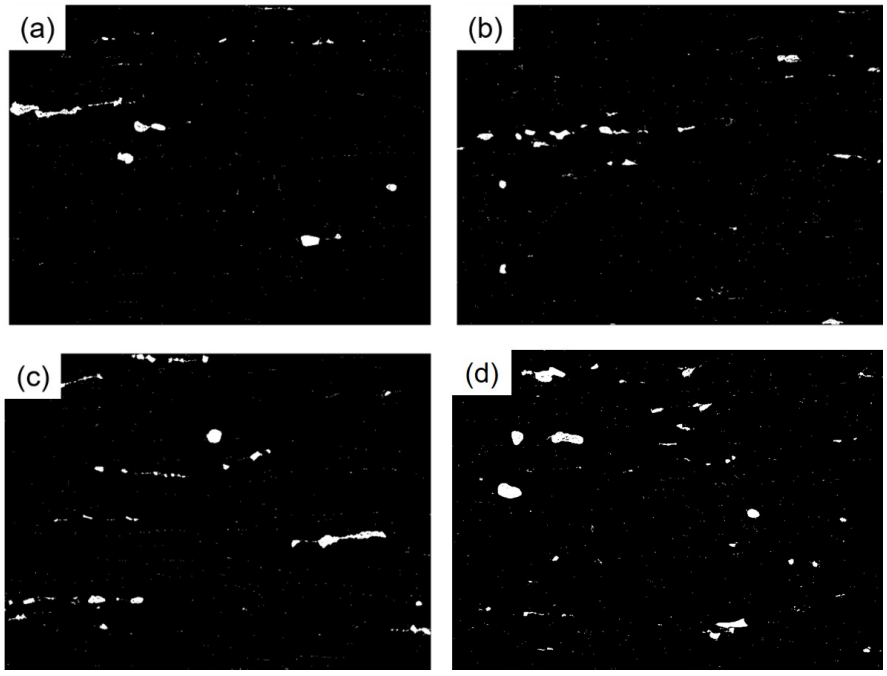

Figure 5-11. BSE-SEM microstructures of U-10Mo specimens of thickness 0.01 in. after ImageJ thresholding: (a) 027-04-003CTA (L), (b) 027-04-003CTA (T), (c) 027-04-003CTB (L) and (d) 027-04-003CTB (T). ('L' and 'T' stands for Longitudinal and Transverse direction)

A summary of carbide area fractions in U-10Mo specimens, without and with Zr, is provided in **Table A.13**–**Error! Reference source not found.**. All U-10Mo specimens have low carbide content (under 1.5% area fraction, carbon content under 570 ppm). Any submicron- and nanometer-size particles present in the microstructure that were not resolved by SEM might have been excluded from the area fraction calculation. Figure 5-12a shows the carbide

fraction for specimens with and without a Zr layer. Higher carbide fraction was observed for samples without Zr. Carbide fraction variations with thickness reduction for four different feedstock materials are shown in Figure 5-12b. Higher carbide fraction was observed for 3K74-AE1K feedstock material, consistent with the higher carbon levels of this casting and the bi-modal distribution of feedstock materials discussed in Section 2.1. Similarly, carbide fraction variation with thickness reduction is shown in Figure 5-12c for both leading- and trailing-edge samples.

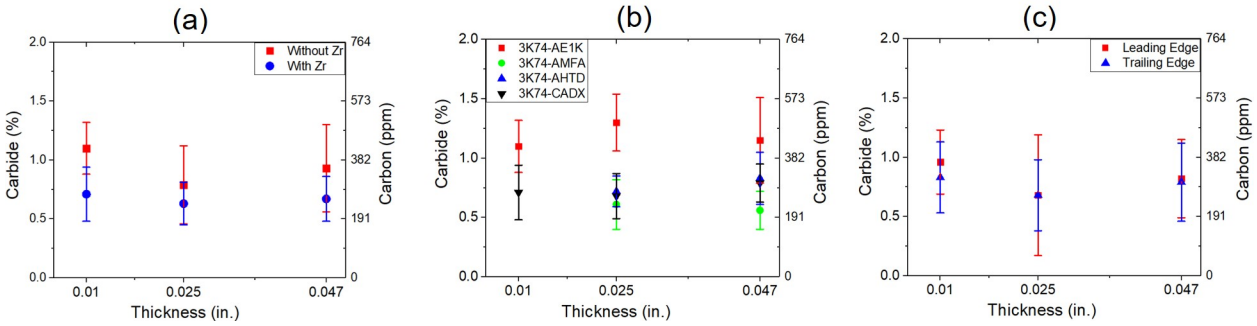

Figure 5-12. (a) Carbide percentage with and without Zr layer with thickness reduction, (b) Carbide percentage for different feedstock materials with thickness reduction and (c) Carbide percentage for leading and trailing edges with thickness reduction. Carbon content (in ppm) shown in secondary Y-axis.

No noticeable difference was observed between leading- and trailing-edge specimens (Figure 5.13). Carbide fraction also differed among feedstock materials. Higher carbide fraction was observed for the 3K74-AE1K sample at greater foil thickness (Figure 5-13a). In the rest of the feedstock materials, carbide fraction was very similar for leading- and trailing-edge specimens (Figure 5-13b-d). Carbon content (in ppm) also shown along with carbide fraction.

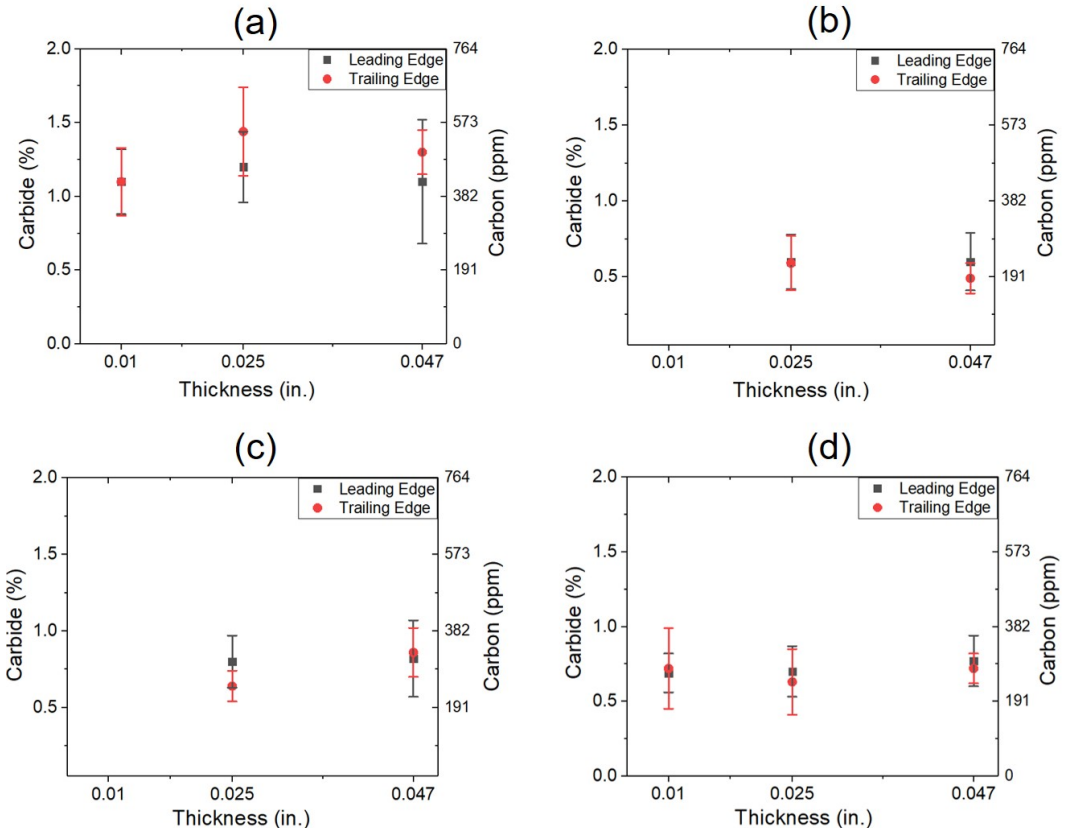

Figure 5-13. Carbide fraction for different feedstock materials: (a) AE1K, (b) AMFA, (c) AHTD and (d) C4DX. Carbon content (in ppm) also shown in secondary Y-axis.

Elongated carbides were observed in U-10Mo specimens. The thickness reduction during rolling reduction and annealing processes will redistribute the carbides, during which they tend to form stringers (Cheng et al. 2018; Hu et al. 2018). Carbide stringers with a typical length of 10 to 20 µm (maximum of about 160 µm) were observed in U-10Mo specimens. A summary of the carbide particle size distribution in U-10Mo specimens, without and with Zr, is provided in Table A.19 and A.25. Figure 5.14 is a box plot of carbide particle size for samples with and without a Zr layer. Result shows higher particle size for higher thickness and gradually decreases with thickness reduction.

Further analysis is needed to isolate other potential precipitates from carbides to determine the exact chemistry and correlate with the wet chemistry results.

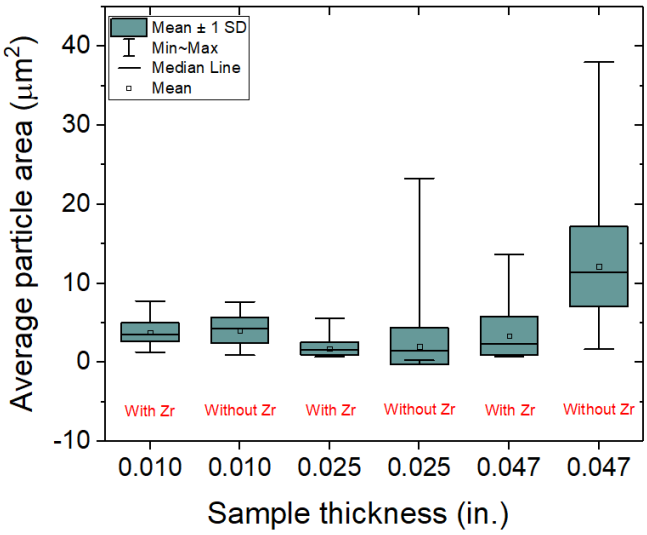

Figure 5-14. Box plot of average carbide particle size for samples with different thicknesses (PNNL data)

5.4 Gamma Phase Decomposition

No gamma phase decomposition was observed in any U-10Mo samples that were characterized using optical and scanning electron microscopes. If a minor decomposition of gamma phase in the submicron or nanometer size range is suspected, then transmission electron microscopy could be used for confirmation.

5.5 Fuel Meat Thickness

The U-10Mo monolithic fuel fabrication process involves several complex material processing techniques such as casting, thermal annealing, hot and cold rolling, and hot isostatic pressing. The manufacturing process should consistently produce fuel with acceptable quality (i.e., that meets or exceeds design requirements) (Senor and Burkes 2014). Hence, it is important to verify the consistency of the fuel thickness produced during a typical fabrication process to support adequate irradiation performance.

The U-10Mo fuel thickness was measured using two to three images (left, center, and right) obtained from an optical microscope at 5–20× magnification for each specimen. At least five measurements per image were made using ImageJ software, so the average thickness of the fuel was calculated from 10 to 15 measurements per specimen, in accordance with the MP-1 Characterization Plan (INL 2018). Summaries of the fuel foil thickness for specimens without and with Zr are presented in Table A.26 to Table A.31. Figure 5-15a shows the measured U-10Mo foil thickness for specimens with and without a Zr layer. U-10Mo foil thickness variations with thickness reduction in four different feedstock materials are shown in Figure 5-15b. Similarly, U-10Mo foil thickness variations with thickness reduction for leading and trailing edges are shown in Figure 5-15c. There is no effect of Zr interlaryer, material feedstock, or specimen location (e.g., leading or trailing edge) on the uniformity of the U-10Mo.

Average thicknesses are very similar in leading- and trailing-edge specimens. U-10Mo foil thickness data in leading- and trailing-edge specimens, separated for different feedstock materials are shown in Figure 5-16. For better understanding, histograms of U-10Mo foil thickness distribution are shown in Figure 5-17. Deviation of U-10Mo foil thickness gradually decreases with thickness reduction. This is an indication of good foil uniformity with thickness reduction.

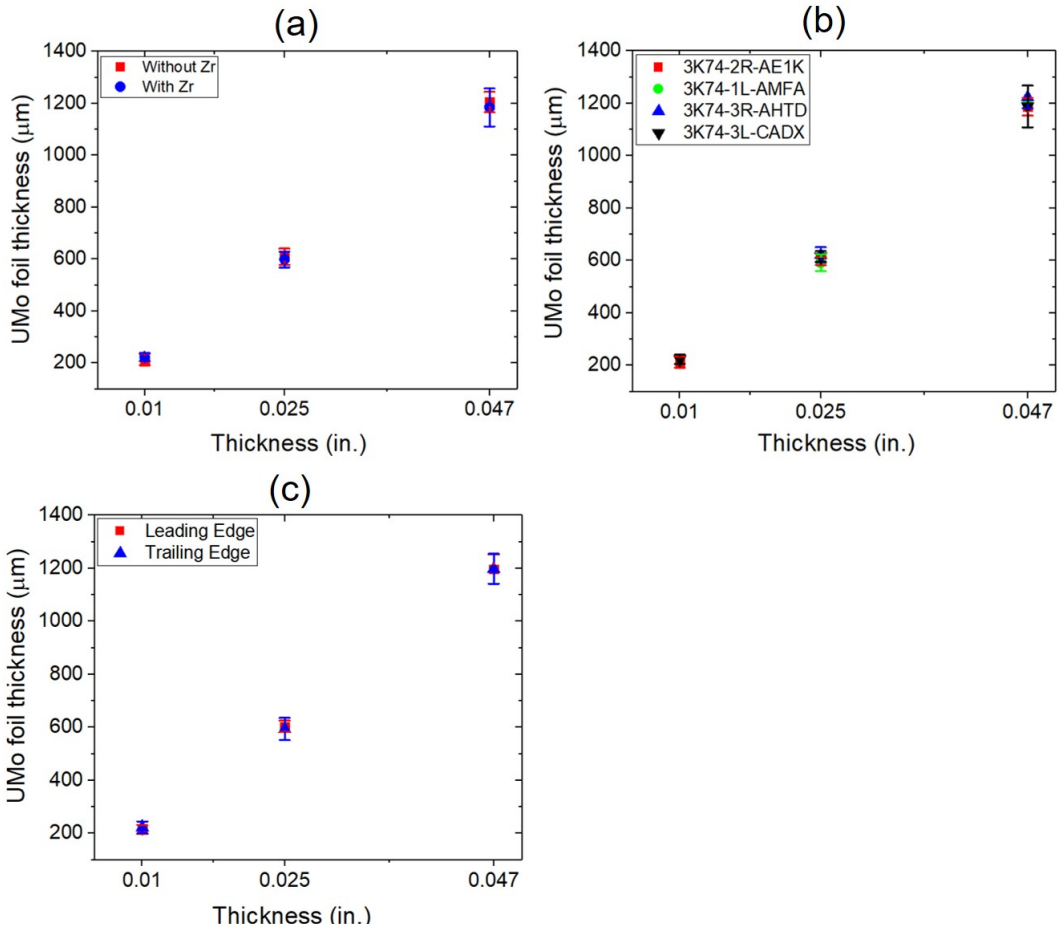

Figure 5-15. Average U-10Mo foil thicknesses after thickness reduction: (a) with and without Zr layer, (b) for different feedstock materials, and (c) for leading and trailing edges

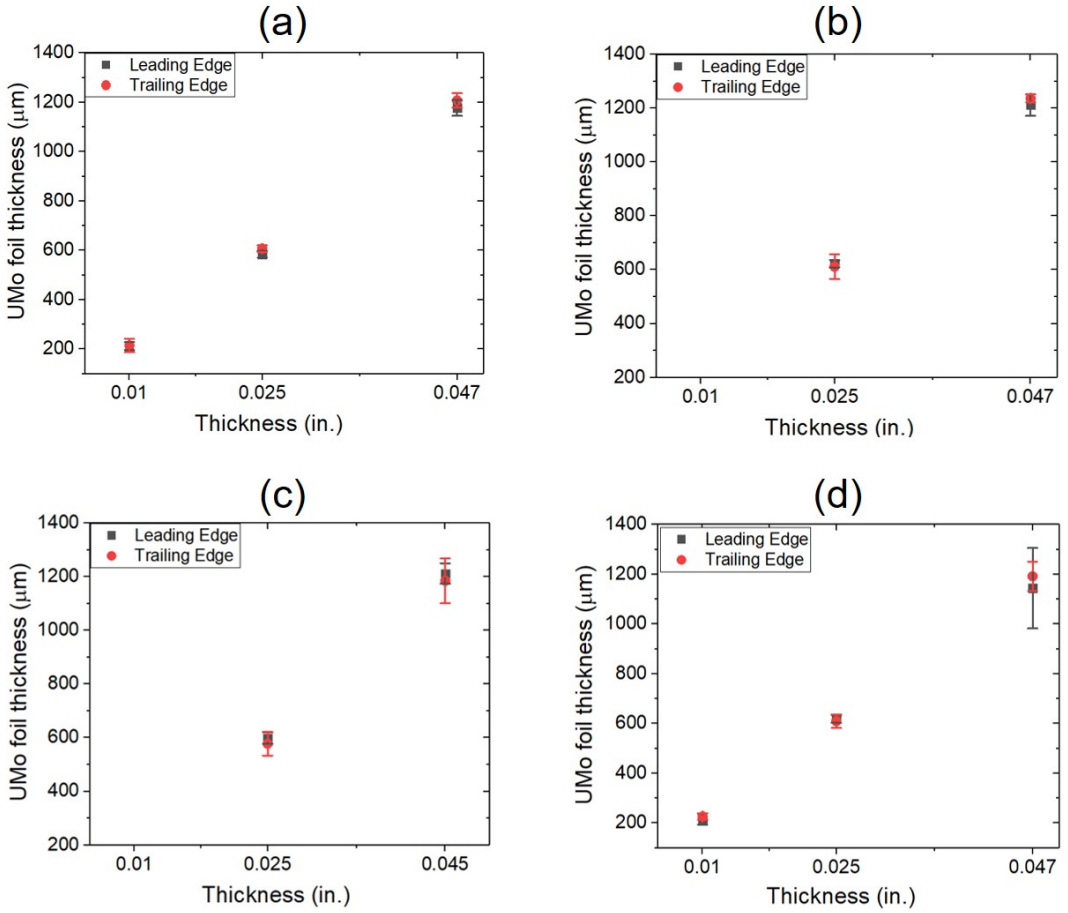

Figure 5-16. U-10Mo foil thickness for different feedstock materials: (a) AE1K, (b) AMFA, (c) AHTD, and (d) C4DX

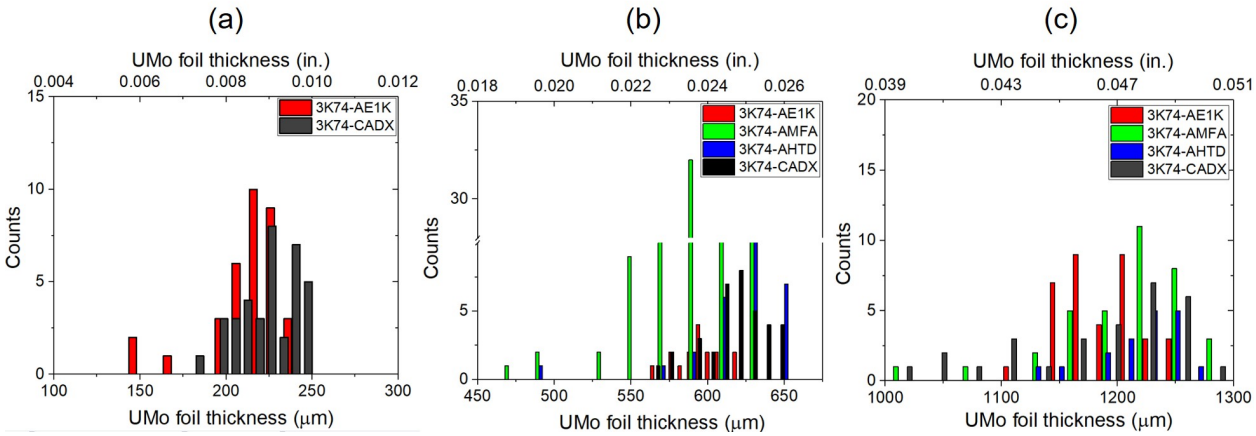

Figure 5-17. U-10Mo foil thickness distribution (a) 0.010 in. (AE1K and C4DX feedstock), (b) 0.025 in. (AE1K, AMFA, AHTD and C4DX feedstocks), and (c) 0.047 in. (AE1K, AMFA, AHTD and C4DX feedstocks)

5.6 Zr Layer Thickness

There is a need to minimize the interaction between the U-10Mo fuel foil and the cladding by introducing a Zr interlayer. A barrier thickness of 25 µm was selected to exceed the maximum fission fragment recoil range (about 9 µm in Zr) and to allow for the inherent thickness variability resulting from the U-10Mo fuel fabrication process (Meyer et al. 2014). The starting microstructure and processing parameters must be optimized properly to achieve the desired uniform Zr layers on the top and bottom of the U-10Mo fuel foil.

The Zr thickness in U-10Mo specimens was measured by using two to three images (left, center, and right) obtained from an optical microscope. At least 25 measurements per specimen were made, using ImageJ software, of the thicknesses of the top and bottom Zr layers. Thus, 50 measurements were made for any given U-10Mo specimen. Figure 5-18 shows typical Zr layers (top and bottom) observed in U-10Mo specimens of 0.0104 in. thickness.

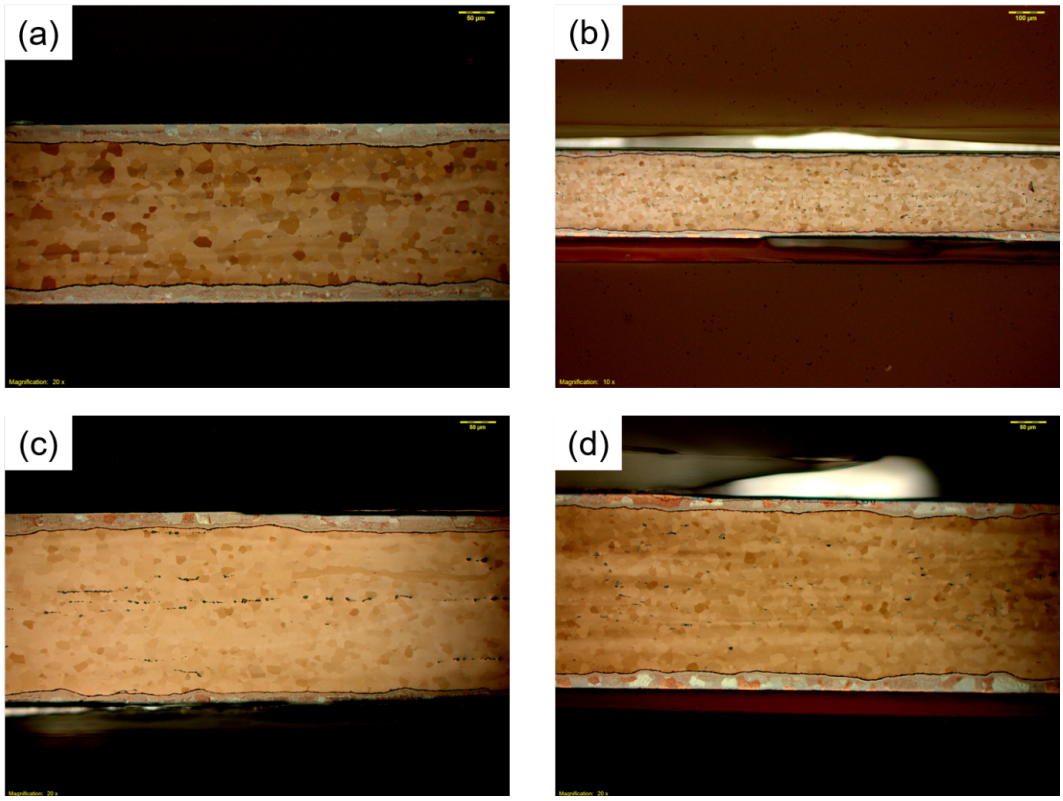

Figure 5-18. Typical Zr layers observed in U-10Mo specimens of 0.0104 in. thickness: (a) 030-01-001CTA (L), (b) 030-01-001CTA (T), (c) 030-01-004CTB (L), and (d) 030-01-004CTB (T). ('L' and 'T' stands for Longitudinal and Transverse direction)

A summary of the Zr layer (top and bottom) thicknesses for U-10Mo specimens of different thicknesses is presented in **Table A.32** to **Table A.34**. The average Zr thicknesses (top/bottom) were about 54 µm, 38 µm, and 38 µm for U-10Mo specimens of 0.047 in., 0.025 in., and 0.010 in. thicknesses, respectively (Figure 5-19a). Changes in Zr layer thickness and its variation with thickness reduction in four different feedstock materials are shown in Figure 5-19b. Greater Zr layer thickness and variation were observed for 3K74-CADX feedstock material in the 0.047 in.-thick specimen. Average Zr layer thickness variation with thickness reduction is shown in Figure 5-19c for leading- and trailing-edge specimens. Average Zr layer thickness and deviation are very similar between leading- and trailing-edge specimens.

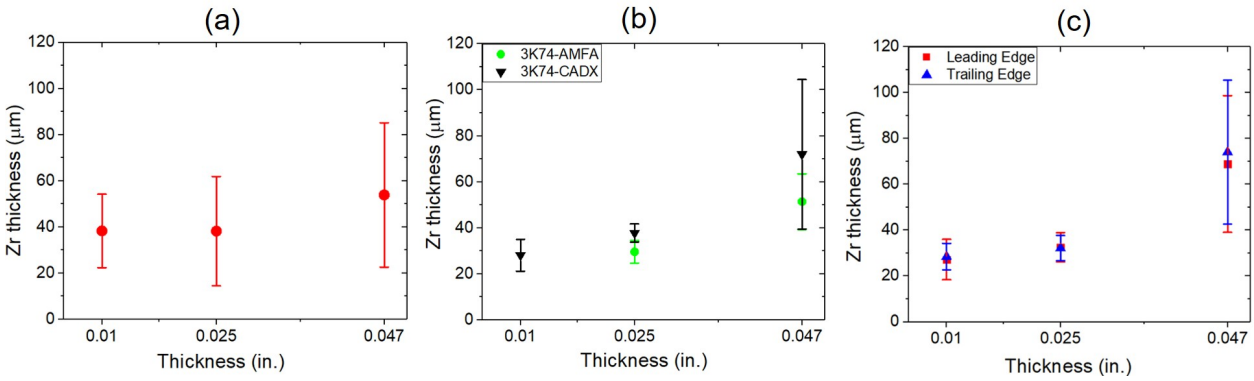

Figure 5-19. (a) Zr layer thickness with thickness reduction, (b) Zr thickness for different feedstock materials with thickness reduction, and (c) Zr thickness for leading and trailing edges with thickness reduction

Average Zr thickness also differed among feedstock materials (Figure 5-20). All the feedstock materials follow a similar trend: with thickness reduction, Zr layer thickness decreases. More variation was observed in 0.047 in.-thick specimens, irrespective of feedstock material. For better understanding, histograms of Zr layer thickness are shown in Figure 5-21. Deviation of Zr layer thickness gradually decreases with thickness reduction. This is a good indication of Zr layer uniformity in thinner specimens. For understanding the Zr layer uniformity in top and bottom layers, thickness data have been separated by layer (Figure 5-22). At 0.047 in. fuel thickness, top and bottom Zr layer thicknesses are clearly different but gradually become uniform with thickness reduction.

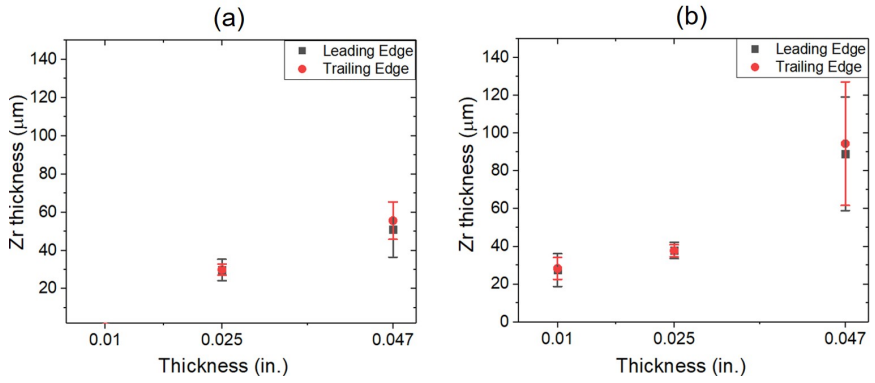

Figure 5-20. Zr thickness for leading and trailing edges with thickness reduction for different materials: (a) 3K74-AMFA and (b) 3K74-CADX feedstock

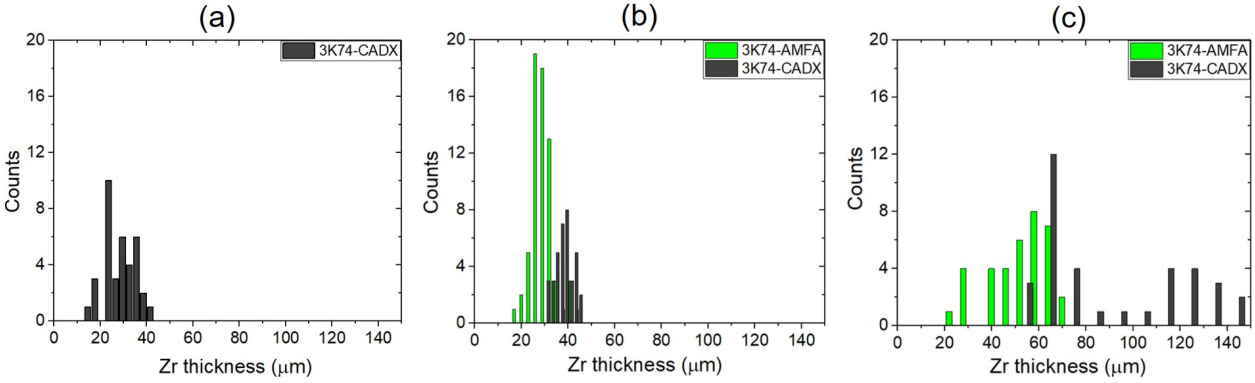

Figure 5-21. Zr thickness distributions: (a) C4DX feedstock (0.010 in.), (b) AMFA and C4DX feedstocks (0.025 in.), and (c) AMFA and C4DX feedstocks (0.047 in.)

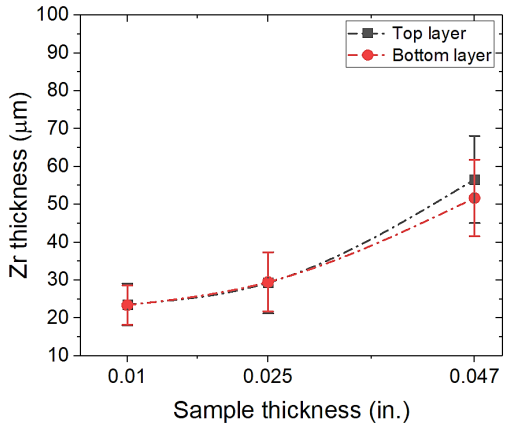

Figure 5-22. Zr thickness variation for three different sample thicknesses (PNNL data)

Typical interactions between U-10Mo and Zr layers observed in U-10Mo specimens are shown in Figure 5-23. The average thickness of the interaction layer was approximately 1–1.5 µm. The interaction layer is basically a U-Zr intermetallic phase. Single or multiple phases could be present in the interaction layer. The interaction layer was wavy, and its thickness varied throughout the same specimen. Any interactions that do occur between the Zr, U-10Mo fuel, and AA6061 aluminum cladding during fabrication and irradiation have been observed to be very slow, and more importantly, any interaction products that were formed appeared to be stable during irradiation (Perez et al. 2010; Robinson et al. 2008).

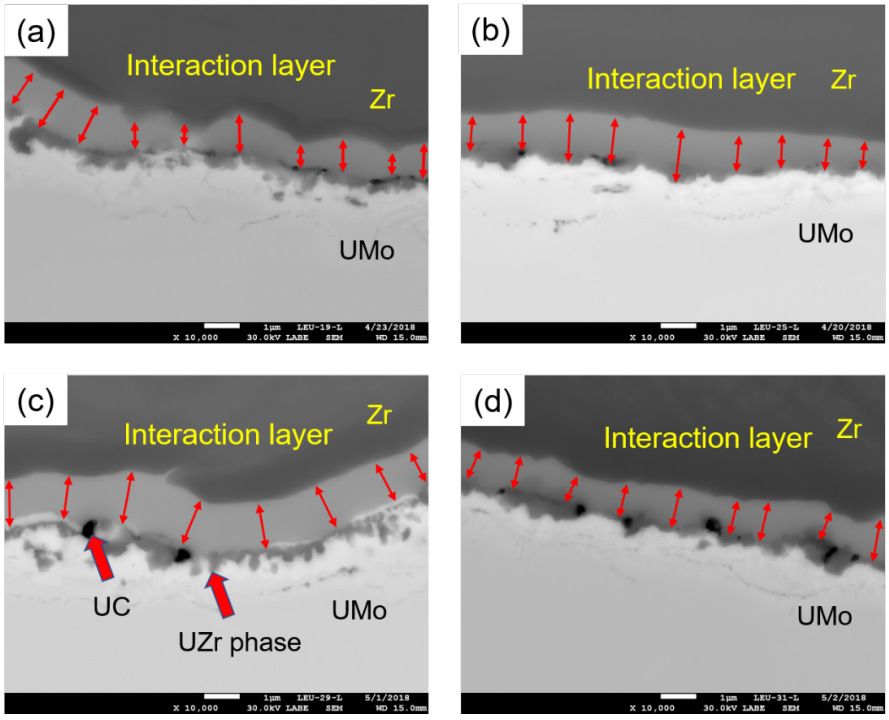

Figure 5-23. Interaction layers observed in U-10Mo specimens of 0.027 in. thickness: (a) 029-01-001CTC (L), (b) 029-01-001CTA (L), (c) 029-01-002CTA (L), and (d) 029-01-006CTB (L). ('L' stands for Longitudinal direction)

5.7 Vickers Microhardness

Hardness of U-10Mo specimens with and without Zr was evaluated using a Vickers microhardness tester. Microhardness testing is a quick way to study the effect on mechanical properties of fabrication parameters such as hot rolling, cold rolling, co-rolling, and annealing. It can also be employed to correlate the presence of carbide and lamellar phases and their distribution in the microstructure.

Table A.35 and **Table A.36** present Vickers microhardness data obtained from U-10Mo specimens without and with Zr, respectively. The U-10Mo specimens (with and without Zr) that were hot-rolled and annealed (0.047 in. thick) exhibited hardness similar that had been cold-rolled and annealed (0.025 in. and 0.010 in. thick). Average hardness values for specimens with and without Zr layers with thickness reduction are shown in Figure 5-24.Hardness with different thickness are statistically very similar for both with and without Zr layer foils.

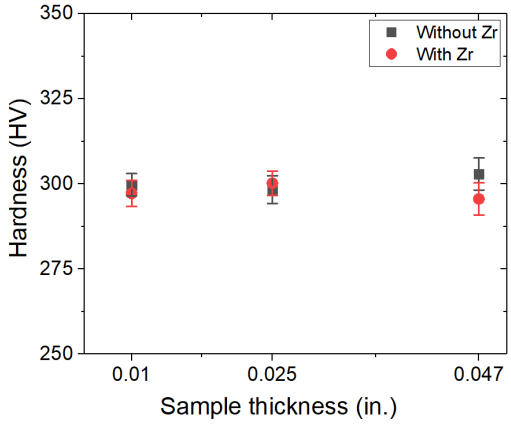

Figure 5-24. Vickers microhardness for samples with and without Zr layers (PNNL data)

5.8 Density

The densities of U-10Mo specimens were measured using Archimedes' principle in accordance with the PNNL-developed procedure (Prabhakaran et al. 2016a). The density was measured in deionized water using the same apparatus described in the PNNL report (Prabhakaran et al. 2016a). A total of six pieces/sections of each foil were taken for density measurements. The theoretical density of the U-10Mo alloy was calculated, based on the crystal structure, to be 17.3 g/cm^3 (Devaraj et al. 2016b). The density of an actual foil is affected by impurities, and any changes to the chemistry affect the measured results (Devaraj et al. 2016b; Devaraj et al. 2016a).

The measured density of the 0.009 in.-thick LEU-Mo foil was 17.15 ± 0.03 g/cm^3, and that of the 0.025 in.-thick foil was 17.14 ± 0.03 g/cm^3. Table 5-1 presents the densities of the measured specimens. Average measured density for specimens of two different thicknesses is shown in Figure 5-25. Measured density was very similar to the theoretically calculated density (17.3 g/cm^3).

Table 5-1. Density of U-10Mo samples: 027-04-003CTA (0.009 in.) and 028-01-001CTA (0.025 in.)

Sample ID	Reading No.	Weight in Air (g)	Buoyancy (g)	Weight in Air ÷ Buoyancy	Temperature of Distilled Water (°C)	Density of Distilled Water (g/cc)	Density of Specimen (g/cc)
027-04-003CTA (0.009 in.)	1	0.5594	0.0326	17.159	23.2	0.99752	17.117
	2	0.6876	0.0400	17.190	23.2	0.99752	17.147
	3	0.6114	0.0355	17.222	23.1	0.99754	17.180

Sample ID	Reading No.	Weight in Air (g)	Buoyancy (g)	Weight in Air ÷ Buoyancy	Temperature of Distilled Water (°C)	Density of Distilled Water (g/cc)	Density of Specimen (g/cc)
	4	0.5671	0.0329	17.237	23.1	0.99754	17.194
	5	0.7111	0.0414	17.176	23.1	0.99754	17.134
	6	0.8639	0.0505	17.106	23.1	0.99754	17.064
						Average	17.140
						Standard Deviation	0.047
028-01-001CTA (0.025 in.)	1	1.1975	0.0700	17.1071	23.0	0.99756	17.065
	2	1.3227	0.0772	17.1334	23.1	0.99754	17.091
	3	1.3972	0.0816	17.1225	23.1	0.99754	17.080
	4	1.1224	0.0652	17.2147	23.1	0.99754	17.172
	5	1.3169	0.0767	17.1695	23.1	0.99754	17.127
	6	1.4210	0.0820	17.3293	23.1	0.99754	17.287
						Average	17.137
						Standard Deviation	0.083

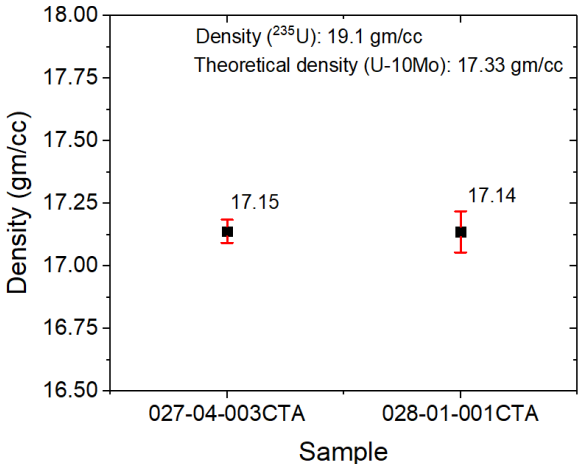

Figure 5-25. Density of specimens for two different thicknesses: 27-04-003CTA (0.009 in.) and 028-01-001CTA (0.025 in.) (PNNL data)

6.0 Conclusions

An analysis of the feedstock material that supplied the samples for analysis indicated the following:

- The casting process used to fabricate ingots was nearly identical for the 5 castings that were the source of the samples analyzed. The small differences noted (a 5-minute shorter hold time and a 7.5-micron average variation in the crucible vacuum levels) were not expected to result in different casting products.

- Feedstock materials used to make the foils that were sampled had carbon impurities levels of in the range of 290 ppm or 433 ppm. Four of the castings used in this analysis had an average carbon level of 270 ppm while the 5th casting (AE1K) had a carbon level of 433 ppm.

PNNL, INL, and LANL each received six types of MP-1 characterization foils from BWXT:

- 0.047 in.-thick hot-rolled and annealed samples with and without Zr
- 0.025 in.-thick cold-rolled and annealed samples with and without Zr
- 0.0085 in.-thick cold-rolled and annealed samples with and without Zr.

Microstructure, chemical composition, carbide morphology, U-10Mo foil thickness, Zr thickness, mechanical properties (microhardness), and density were evaluated in both the longitudinal and transverse directions for foils of the three different thicknesses.

The following conclusions were drawn based on the investigations:

- The U-10Mo average grain size decreased as the foil thickness decreased. This is the effect of thickness reduction: more thickness reduction introduces more nucleation sites for new recrystallized grains. The average grain sizes observed in U-10Mo samples without Zr were 13.6 μm for 0.01 in. thickness, 18 μm for 0.025 in. thickness, and 26 μm for 0.047 in. thickness. The average grain sizes observed in U-10Mo samples with Zr were 15.3 μm for 0.01 in. thickness, 18.8 μm for 0.025 in. thickness and 28 μm for 0.047 in. thickness.
- Orientation-based imaging using EBSD was carried out to examine the microstructural state (deformed or recrystallized) and calculate grain size. The grains were equiaxed and fully recrystallized. No abnormal grain growth was observed. Grain sizes calculated from EBSD and optical methods are consistent.
- The microstructures of all samples showed nearly homogeneous Mo distribution and no chemical banding.
- In all U-10Mo samples, the average carbide fraction was under 1.0% (carbon under 400 ppm), and certain specimens had less than 1.5% (carbon under 570 ppm). The irregularities in carbide fraction are due to different regions in the castings with different carbon impurities. Average carbide particle area observed in the microstructures ranged from 0.2 to 30 μm^2. Carbide stringers with typical lengths of 10–20 μm (maximum about 160 μm) were observed in U-10Mo specimens. The increased carbon levels noted in casting AE1K were reflected in the carbon fraction data.
- No gamma phase decomposition was observed in any samples that were characterized using optical and scanning electron microscopes.
- Thickness variation of U-10Mo foils decreased with thickness reduction. The U-10Mo foil thickness distribution becomes narrower with thickness reduction.
- The average Zr thicknesses (top and bottom) were about 54 μm (0.0021 in.), 38 μm (0.0015 in.), and 38 μm (0.0015 in.) for U-10Mo specimens of thicknesses 0.047 in., 0.025 in., and 0.010 in., respectively. Zr thickness variation decreased with foil thickness reduction.
- No microstructural differences were noted between specimens taken from the leading or trailing edge of foils.

- The average thickness of the interaction layer in U-10Mo specimens was approximately 1–1.5 μm. The interaction layer is basically a U-Zr intermetallic phase. Single or multiple phases could be present in the interaction layer. The interaction layer was wavy, and it thickness varied throughout individual specimens.
- The average hardness of the foils was 297–302 HV.
- Measured density (17.14 g/cm^3) is very close to the theoretically calculated density (17.33 g/cm^3).

As per specification requirement, the U-10Mo loading of each fuel plate shall be within ±15% of the nominal loading. The nominal loading shall be defined by the nominal U-10Mo thickness of the applicable foil. Similarly, the thickness requirement of Zr barrier layer applied to each of the in-plane surfaces of foils shall have a thickness of 0.001 ± 0.0005 in. (25 ± 12 μm). In this experiment, only 0.01 in. thick samples showed close to the thickness specification requirement for U-10Mo foil and Zr barrier layer.

7.0 Quality Assurance

Work performed at PNNL was in accordance with the PNNL Nuclear Quality Assurance Program (NQAP). The NQAP complies with the United States Department of Energy Order 414.1D, *Quality Assurance*. The NQAP uses NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Application* as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality.

This work emphasized acquiring new theoretical or experimental knowledge. The information associated with this report should not be used as design input or operating parameters without additional qualification.

Work performed at INL and LANL was in accordance with their respective DOE-approved quality programs.

8.0 References

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Appendix

Measurement Data

Appendix
Measurement Data

A.1 Grain Size

Table A.1. Grain size of U-10Mo specimens (without Zr) obtained by optical microscopy (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
0.01	027-04-003CTA	LEU-53-L	15.2	5.9
		LEU-54-T	15.6	6.0
		LEU-85-LE1	12.3	5.4
		LEU-86-TE1	12.0	5.0
		LEU-87-LE2	12.5	5.4
		LEU-88-TE2	13.0	5.6
	027-04-003CTB	LEU-55-L	16.3	5.9
		LEU-56-T	15.1	5.4
		LEU-97-LE1	13.2	6.2
		LEU-98-TE1		
		LEU-99-LE2	12.1	5.1
		LEU-100-TE2	12.4	5.6
	027-04-004CTC	LEU-57-L	14.9	4.4
		LEU-58-T	13.9	4.7
		LEU-109-LE1	13.1	5.9
		LEU-110-TE1		
		LEU-111-LE2	12.7	4.9
		LEU-112-TE2	11.6	5.2
0.025	028-01-001CTA	LEU-59-L	16.8	7.2
		LEU-60-T	18.3	6.7
		LEU-91-LE1	13.3	5.7
		LEU-92-TE1	14.1	5.6
		LEU-93-LE2	13.1	5.3
		LEU-94-TE2	15.9	6.3
	028-01-001CTB	LEU-61-L	17.2	6.7
		LEU-62-T	15.3	5.8
		LEU-101-LE1	13.8	5.7
		LEU-102-TE1	12.7	5.9
		LEU-103-LE2		
		LEU-104-TE2	13.7	6.2
	028-01-001CTC	LEU-63-L	16.3	6.9
		LEU-64-T	16.4	6.2
		LEU-137-LE1	13.7	6.4

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
		LEU-138-TE1	13.2	6.1
		LEU-139-LE2	13.0	5.2
		LEU-140-TE2	13.6	5.8
	028-01-002CTA	LEU-65-L	17.3	6.6
		LEU-66-L	16.1	5.8
		LEU-141-LE1	14.9	8.1
		LEU-142-TE1	14.0	6.5
		LEU-143-LE2	14.1	6.0
		LEU-144-TE2	14.1	6.7
	028-01-002CTB	LEU-67-L	17.2	7.0
		LEU-68-T	17.4	5.8
		LEU-175-TE-A	14.5	6.2
		LEU-176-LE-A	15.1	5.4
		LEU-177-TE-B	14.3	6.4
		LEU-178-LE-B	12.8	5.1
	028-01-002CTC	LEU-69-L	16.9	6.6
		LEU-70-T	16.0	5.9
		LEU-179-TE-A	13.5	4.9
		LEU-180-LE-A	13.5	4.9
		LEU-181-TE-B	14.1	6.4
		LEU-182-LE-B	12.5	5.2
0.047	027-04-000DTA	LEU-05-L	27.9	12.2
		LEU-04-T	30.2	14.7
		LEU-71-LE	20.4	10.3
		LEU-72-TE	20.9	10.4
		LEU-73-LC	16.0	9.3
		LEU-74-TC	18.2	10.2
	027-04-002DTB	LEU-08-L	27.5	10.4
		LEU-07-T	31.2	15.5
		LEU-75-LE	18.6	9.3
		LEU-76-TE	18.6	8.7
		LEU-77-LC	18.2	9.4
		LEU-78-TC	17.1	10.5
	027-04-000DTC	LEU-02-L	24.1	10.4
		LEU-01-T	27.2	11.9
		LEU-117-LE	17.4	8.7
		LEU-118-TE	17.1	8.8
		LEU-119-LC	18.7	9.7
		LEU-120-TC	16.8	8.9
	027-05-000DTA	LEU-11-L	28.4	12.9
		LEU-10-T	33.8	14.5

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
		LEU-79-LE	17.7	8.7
		LEU-80-TE	17.7	8.8
		LEU-81-LC	15.9	8.7
		LEU-82-TC	16.6	8.7
	027-05-002DTB	LEU-14-L	27.7	13.1
		LEU-13-T	26.7	12.7
		LEU-113-LE	18.8	9.2
		LEU-114-TE	18.2	10.1
		LEU-115-LC	16.5	7.1
		LEU-116-TC	17.8	9.3
	027-05-000DTC	LEU-17-L	27.8	13.1
		LEU-16-T	26.1	11.2
		LEU-105-LE1	17.0	9.0
		LEU-106-TE1	17.7	9.3
		LEU-107-LC	18.0	9.2
		LEU-108-TC	18.5	8.9

Table A.2. Grain size of U-10Mo specimens without Zr (INL data)

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
0.0235	027-05-002CTA	met 1 trans	15.92	1.38
		met 1 long	21.69	1.30
		met 2 trans	23.30	1.68
		met 2 long	20.73	1.16
		met 3 trans	23.98	1.93
		met 3 long	24.97	1.57
	027-05-002CTB	met 1 trans	28.44	1.06
		met 1 long	28.81	1.57
		met 2 trans	26.37	1.40
		met 2 long	28.14	0.82
		met 3 trans	27.45	1.52
		met 3 long	26.67	1.49
	027-05-002CTC	met 1 trans	20.49	1.76
		met 1 long	21.33	1.47
		met 2 trans	22.06	2.84
		met 2 long	22.68	1.30
		met 3 trans	19.10	2.07
		met 3 long	18.34	1.25
0.0245	028-05-001CTA	met 1 trans	21.78	0.94
		met 1 long	22.81	1.11

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
		met 2 trans	24.58	1.15
		met 2 long	24.68	1.16
		met 3 trans	23.42	0.90
		met 3 long	23.88	2.32
	028-05-001CTB	met 1 trans	21.84	1.33
		met 1 long	22.71	0.99
		met 2 trans	25.74	1.78
		met 2 long	22.70	1.27
		met 3 trans	24.79	1.58
		met 3 long	23.22	1.83
0.047	028-01-000DTA	met 1 trans	36.09	3.98
		met 1 long	45.46	6.60
		met 2 trans	36.35	5.40
		met 2 long	34.26	4.68
		met 3 trans	26.46	3.11
		met 3 long	47.38	6.72
	028-01-002DTB	met 1 trans	29.51	2.44
		met 1 long	28.85	1.76
		met 2 trans	34.50	3.90
		met 2 long	31.17	3.58
		met 3 trans	30.97	2.86
		met 3 long	28.73	2.98
	028-01-000DTC	met 1 trans	27.47	2.29
		met 1 long	28.01	1.50
		met 2 trans	29.44	2.53
		met 2 long	30.69	1.34
		met 3 trans	30.41	1.59
		met 3 long	29.69	2.14
	028-05-000DTA	met 1 trans	31.28	1.60
		met 1 long	29.40	3.54
		met 2 trans	29.61	2.43
		met 2 long	30.65	4.08
		met 3 trans	27.72	3.56
		met 3 long	28.40	3.18
	028-05-002DTB	met 1 trans	34.45	1.97
		met 1 long	31.80	3.43
		met 2 trans	31.01	2.97
		met 2 long	29.13	3.71
		met 3 trans	27.25	2.55
		met 3 long	27.83	3.40
	028-05-000DTC	met 1 trans	29.00	1.92

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
		met 1 long	33.25	2.53
		met 2 trans	31.49	2.16
		met 2 long	40.99	3.41
		met 3 trans	24.48	2.39
		met 3 long	29.02	2.89

Table A.3. Grain size of U-10Mo specimens without Zr (LANL data)

Thickness (in.)	Sample ID	Specimen ID	Average Grain Diameter (µm)	Standard Deviation (µm)
0.01	027-04-005CTA	13365-5A (T)	13.1	0.6
		13365-5B (L)	13.0	0.8
		13365-5C (T)	12.7	0.7
		13365-5D (L)	12.9	0.7
		13365-5E (T)	12.8	0.3
		13365-5F (L)	13.2	0.8
	027-04-006CTB	13365-6A (T)	13.3	0.3
		13365-6B (L)	13.8	0.6
		13365-6C (T)	11.8	0.6
		13365-6D (L)	13.4	0.5
		13365-6E (T)	13.9	0.7
		13365-6F (L)	13.0	0.5
	027-04-006CTC	13365-7A (T)	15.0	1.4
		13365-7B (L)	14.4	1.9
		13365-7C (T)	15.1	0.8
		13365-7D (L)	15.9	0.6
		13365-7E (T)	15.8	0.9
		13365-7F (L)	14.7	0.5
0.025	028-05-001CTC	13365-8A (T)	15.4	0.1
		13365-8B (L)	16.2	0.2
		13365-8C (T)	16.3	0.2
		13365-8D (L)	18.4	2.0
		13365-8E (T)	17.2	0.6
		13365-8F (L)	16.4	0.4
	028-05-002CTA	13365-9A (T)	14.6	0.2
		13365-9B (L)	15.3	0.4
		13365-9C (T)	15.0	0.5
		13365-9D (L)	15.9	0.7
		13365-9E (T)	15.9	0.4
		13365-9F (L)	16.3	0.8
	028-05-002CTB	13365-10A (T)	14.9	0.7

Thickness (in.)	Sample ID	Specimen ID	Average Grain Diameter (µm)	Standard Deviation (µm)
		13365-10B (L)	14.8	0.4
		13365-10C (T)	15.2	0.3
		13365-10D (L)	15.1	0.8
		13365-10E (T)	15.7	0.3
		13365-10F (L)	16.0	0.8
	28-05-002CTC	13365-11A (T)	16.8	0.6
		13365-11B (L)	17.1	0.5
		13365-11C (T)	16.1	0.6
		13365-11D (L)	17.5	0.7
		13365-11E (T)	16.2	0.4
		13365-11F (L)	16.4	0.2

Table A.4. Grain size of U-10Mo specimens (with Zr) obtained by optical microscopy (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
0.01	030-01-001CTA	LEU-37-L	15.3	6.9
		LEU-38-T	13.9	6.4
		LEU-167-TE-A	12.6	5.3
		LEU-168-LE-A	13.3	5.6
		LEU-169-TE-B	11.0	4.4
		LEU-170-LE-B	10.8	3.9
	030-01-004CTB	LEU-39-L	13.4	4.9
		LEU-40-T	12.7	5.1
		LEU-125-LE1	9.9	4.3
		LEU-126-TE1	10.4	3.8
		LEU-127-LE2	11.9	4.5
		LEU-128-TE2	11.2	4.6
	030-01-001CTC	LEU-41-L	11.7	4.7
		LEU-42-T	11.8	5.0
		LEU-121-LE1	10.3	3.9
		LEU-122-TE1	9.2	3.5
		LEU-123-LE2	10.3	4.2
		LEU-124-TE2	10.0	4.0
0.027	029-01-001CTA	LEU-25-L	15.3	6.9
		LEU-26-T	15.3	6.9
		LEU-159-TE-A	11.2	4.7
		LEU-160-LE-A	11.5	4.7
		LEU-161-TE-B	11.4	4.2
		LEU-162-LE-B	11.6	5.2
	029-01-004CTB	LEU-23-L	14.7	5.8

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
		LEU-24-T	17.8	7.2
		LEU-133-LE1	12.2	5.6
		LEU-134-TE1	12.6	4.8
		LEU-135-LE2	11.6	5.1
		LEU-136-TE2	11.4	4.2
	029-01-001CTC	LEU-19-L	14.1	5.7
		LEU-20-T	13.2	5.0
		LEU-129-LE1	13.1	5.8
		LEU-130-TE1	11.3	4.9
		LEU-131-LE2	11.0	5.1
		LEU-132-TE2	11.3	4.7
	029-01-002CTA	LEU-29-L	15.7	6.1
		LEU-30-T	15.7	5.3
		LEU-163-TE-A	12.3	5.2
		LEU-164-LE-A	11.8	5.9
		LEU-165-TE-B	11.7	4.8
		LEU-166-LE-B	11.5	5.9
	029-01-006CTB	LEU-31-L	15.5	5.8
		LEU-32-T	16.1	5.5
		LEU-183-TE-A	11.5	4.5
		LEU-184-LE-A	13.3	6.4
		LEU-185-TE-B	12.2	4.5
		LEU-186-LE-B	12.7	5.2
	029-01-002CTC	LEU-33-L	15.6	5.7
		LEU-34-T	16.6	6.5
		LEU-187-TE-A	14.3	5.7
		LEU-188-LE-A	11.7	4.4
		LEU-189-TE-B	12.7	5.4
		LEU-190-LE-B	12.1	4.9
0.047	029-01-000DTA	LEU-43-L	22.2	8.2
		LEU-44-T	19.5	8.8
		LEU-145-LE-A	16.8	9.5
		LEU-146-TE-A	15.4	7.4
		LEU-147-LE-B	15.9	7.5
		LEU-148-TE-B	14.8	8.2
	029-01-002DTB	LEU-45-L	22.7	9.2
		LEU-46-T	20.3	8.6
		LEU-149-LE-A	17.5	7.4
		LEU-150-TE-A	16.5	7.8
		LEU-151-LE-B	16.4	7.8
		LEU-152-TE-B	17.3	7.9

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
	029-01-000DTC	LEU-49-L	21.3	11.1
		LEU-50-T	23.4	10.4
		LEU-153-LE-A	15.9	7.6
		LEU-154-TE-A	16.8	8.1
		LEU-157-TE-B	18.2	9.1
		LEU-158-LE-B	17.0	9.4
	030-01-000DTA	LEU-51-L	16.3	7.1
		LEU-52-T	19.8	9.2
		LEU-171-TE-A	14.6	6.8
		LEU-172-LE-A	16.2	8.2
		LEU-173-TE-B	16.7	7.9
		LEU-174-LE-B	16.5	7.4

Table A.5. Grain size of U-10Mo specimens with Zr (INL data)

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
0.0121	030-01-003CTA	met 1 trans	15.08	1.18
		met 1 long	14.27	0.82
		met 2 trans	15.57	0.92
		met 2 long	16.05	0.51
		met 3 trans	15.08	1.34
		met 3 long	18.06	1.70
	030-01-008CTB	met 1 trans	21.02	1.80
		met 1 long	18.60	1.67
		met 2 trans	18.98	1.36
		met 2 long	20.11	1.04
		met 3 trans	21.59	1.47
		met 3 long	20.06	0.80
	030-01-003CTC	met 1 trans	24.04	1.24
		met 1 long	19.32	1.37
		met 2 trans	20.03	1.41
		met 2 long	18.79	0.77
		met 3 trans	21.50	1.50
		met 3 long	21.74	1.41
0.0262	029-05-001CTA	met 1 trans	33.61	2.45
		met 1 long	31.71	2.40
		met 2 trans	31.56	2.96
		met 2 long	32.64	3.04
		met 3 trans	28.84	1.41
		met 3 long	32.25	2.43

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
	029-05-004CTB	met 1 trans	26.35	1.62
		met 1 long	24.52	2.23
		met 2 trans	28.73	1.42
		met 2 long	28.81	1.95
		met 3 trans	30.28	2.19
		met 3 long	29.92	1.21
	029-05-001CTC	met 1 trans	19.46	1.30
		met 1 long	37.71	3.48
		met 2 trans	46.26	3.43
		met 2 long	44.71	4.2
		met 3 trans	41.07	1.99
		met 3 long	36.34	3.99
0.0278	029-05-002CTA	met 1 trans	24.33	2.43
		met 1 long	25.87	2.20
		met 2 trans	28.82	3.14
		met 2 long	25.57	2.19
		met 3 trans	24.99	0.77
		met 3 long	24.47	1.91
	029-05-006CTB	met 1 trans	25.62	2.41
		met 1 long	25.78	2.99
		met 2 trans	27.19	1.13
		met 2 long	25.40	1.85
		met 3 trans	29.53	2.50
		met 3 long	27.67	1.29
	029-05-002CTC	met 1 trans	26.10	1.04
		met 1 long	23.80	1.22
		met 2 trans	23.73	1.83
		met 2 long	26.69	1.93
		met 3 trans	28.00	2.60
		met 3 long	28.51	2.20
0.047	029-05-000DTA	met 1 trans	40.19	3.52
		met 1 long	37.71	3.48
		met 2 trans	42.26	3.42
		met 2 long	44.71	4.22
		met 3 trans	41.07	1.99
		met 3 long	36.34	3.99
	029-05-002DTB	met 1 trans	47.94	4.31
		met 1 long	47.54	3.38
		met 2 trans	50.78	5.40
		met 2 long	42.27	6.67
		met 3 trans	62.40	3.80

Thickness (in.)	Sample ID	Specimen ID	Average grain diameter (µm)	Standard deviation (µm)
		met 3 long	58.92	4.33
	029-05-000DTC	met 1 trans	41.65	2.44
		met 1 long	41.35	4.10
		met 2 trans	41.65	4.32
		met 2 long	32.62	3.55
		met 3 trans	33.35	2.75
		met 3 long	32.85	2.75
	030-01-000DTC	met 1 trans	46.88	2.81
		met 1 long	49.32	4.41
		met 2 trans	46.82	2.69
		met 2 long	51.65	5.51
		met 3 trans	49.91	4.29
		met 3 long	47.54	5.62

Table A.6. Grain size of U-10Mo specimens with Zr (LANL data)

Thickness (in.)	Sample ID	Specimen ID	Average Grain Diameter (µm)	Standard Deviation (µm)
0.047	029-02-000DTA	13365-1A (T)	17.4	N/A
		13365-1B (L)	17.1	N/A
		13365-1C (T)	17.5	N/A
		13365-1D (L)	16.1	N/A
		13365-1A (T)	21.5	N/A
		13365-1A (L)	20.3	N/A
	029-02-002DTB	13365-2A (T)	21.6	N/A
		13365-2B (L)	22.4	N/A
		13365-2C (T)	23.0	N/A
		13365-2D (L)	29.8	N/A
		13365-2A (T)	24.0	0.9
		13365-2A (L)	22.7	N/A
	029-02-000DTC	13365-3A (T)	20.3	N/A
		13365-3B (L)	24.4	N/A
		13365-3C (T)	25.8	N/A
		13365-3D (L)	22.8	N/A
		13365-3E (T)	21.6	N/A
		13365-3F (L)	22.2	N/A
	030-01-002DTB	13365-4A (T)	21.4	0.39
		13365-4B (L)	20.1	1.4
		13365-4C (T)	21.0	N/A
		13365-4D (L)	21.5	N/A
		13365-4E (T)	22.2	2.47

Thickness (in.)	Sample ID	Specimen ID	Average Grain Diameter (µm)	Standard Deviation (µm)
		13365-4F (L)	26.5	4.89
0.025	029-02-001CTA	13365-12A (T)	14.4	0.8
		13365-12B (L)	14.5	1.0
		13365-12C (T)	13.8	0.6
		13365-12D (L)	14.6	0.2
		13365-12E (T)	14.1	0.5
		13365-12F (L)	13.6	1.3
	029-02-004CTB	13365-13A (T)	13.4	0.5
		13365-13B (L)	12.9	0.4
		13365-13C (T)	13.9	0.1
		13365-13D (L)	14.6	0.7
		13365-13E (T)	15.1	0.7
		13365-13F (L)	14.8	0.2
	029-02-001CTC	13365-14A (T)	14.2	0.5
		13365-14B (L)	13.6	0.8
		13365-14C (T)	14.4	0.3
		13365-14D (L)	14.5	0.6
		13365-14E (T)	14.0	0.4
		13365-14F (L)	14.6	0.5
	029-02-002CTA	13365-15A (T)	12.7	0.5
		13365-15B (L)	13.1	0.4
		13365-15C (T)	12.7	0.1
		13365-15D (L)	13.6	0.5
		13365-15E (T)	13.2	0.7
		13365-15F (L)	12.7	0.5
	029-02-006CTB	13365-16A (T)	13.6	0.5
		13365-16B (L)	14.5	0.8
		13365-16C (T)	14.9	0.9
		13365-16D (L)	15.6	0.8
		13365-16E (T)	14.7	0.6
		13365-16F (L)	15.2	1.3
	029-02-002CTC	13365-17A (T)	13.2	0.6
		13365-17B (L)	13.0	0.5
		13365-17C (T)	14.5	0.6
		13365-17D (L)	13.7	0.3
		13365-17E (T)	14.5	0.4
		13365-17F (L)	13.6	0.6

A.2 Mo Concentration

Table A.7. Mo distribution (EDS measurements) in U-10Mo specimens without Zr (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
0.01	027-04-003CTA	LEU-53-L	10.0	0.50	8.8–11.7	866	No
		LEU-54-T	10.0	0.49	7.1–11.8	865	No
		LEU-85-LE1	10.1	0.48	7.0–11.8	870	No
		LEU-86-TE1	10.1	0.49	7.7–11.4	858	No
		LEU-87-LE2	9.5	0.52	7.0–11.5	868	No
		LEU-88-TE2	9.3	0.55	7.0–11.5	865	No
	027-04-003CTB	LEU-55-L	9.9	0.47	7.8–11.5	867	No
		LEU-56-T	9.9	0.47	8.1–11.8	865	No
		LEU-97-LE1	9.7	0.48	8.1–11.2	863	No
		LEU-98-TE1	9.8	0.46	7.4–11.1	870	No
		LEU-99-LE2	9.7	0.50	7.4–11.4	859	No
		LEU-100-TE2	9.8	0.51	7.1–11.5	865	No
	027-04-004CTC	LEU-57-L	10.0	0.45	8.4–11.4	870	No
		LEU-58-T	8.8	0.40	7.1–10.2	864	No
		LEU-109-LE1	9.5	0.56	7.3–11.5	869	No
		LEU-110-TE1	9.4	0.56	7.6–11.1	868	No
		LEU-111-LE2	9.4	0.69	7.0–11.7	870	No
		LEU-112-TE2	9.4	0.58	7.6–11.4	869	No
0.025	028-01-001CTA	LEU-59-L	9.9	0.51	8.2–11.6	870	No
		LEU-60-T	10.1	0.49	7.8–11.6	870	No
		LEU-91-LE1	10.2	0.47	7.2–11.6	868	No
		LEU-92-TE1	10.1	0.46	7.8–11.5	864	No
		LEU-93-LE2	9.4	0.44	7.5–10.8	870	No
		LEU-94-TE2	9.4	0.44	8.2–10.8	870	No
	028-01-001CTB	LEU-61-L	10.0	0.48	7.9–11.4	870	No
		LEU-62-T	9.9	0.45	8.6–11.3	870	No
		LEU-101-LE1	9.7	0.46	8.3–11.2	870	No
		LEU-102-TE1	9.7	0.45	7.6–11.2	870	No
		LEU-103-LE2	9.7	0.50	8.3–11.4	870	No
		LEU-104-TE2	9.6	0.46	7.2–11.2	869	No
	028-01-001CTC	LEU-63-L	10.0	0.46	8.4–11.6	870	No
		LEU-64-T	9.9	0.48	7.3–11.4	870	No
		LEU-137-LE1	9.7	0.46	8.1–11.4	869	No
		LEU-138-TE1	9.5	0.47	7.6–10.7	868	No
		LEU-139-LE2	9.6	0.41	8.4–10.9	866	No
		LEU-140-TE2	9.6	0.43	8.2–11.0	870	No

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
	028-01-002CTA	LEU-65-L	10.0	0.46	8.4–11.6	869	No
		LEU-66-T	10.8	0.53	7.3–12.0	862	No
		LEU-141-LE1	9.6	0.44	7.9–11.0	870	No
		LEU-142-TE1	9.6	0.46	7.0–11.3	867	No
		LEU-143-LE2	9.5	0.45	8.0–10.9	868	No
		LEU-144-TE2	9.6	0.45	7.9–11.6	870	No
	028-01-002CTB	LEU-67-L	9.7	0.45	7.1–10.9	868	No
		LEU-68-T	9.5	0.42	8.2–10.9	870	No
		LEU-175-TE-A	9.6	0.45	8.1–11.3	868	No
		LEU-176-LE-A	9.8	0.48	7.1–11.2	870	No
		LEU-177-TE-B	9.6	0.43	8.3–10.8	870	No
		LEU-178-LE-B	9.7	0.45	8.2–11.1	870	No
	028-01-002CTC	LEU-69-L	10.8	0.50	8.3–12.0	857	No
		LEU-70-T	10.8	0.52	9.0–12.0	861	No
		LEU-179-TE-A	9.6	0.44	7.9–11.0	870	No
		LEU-180-LE-A	9.6	0.43	7.1–10.9	869	No
		LEU-181-TE-B	9.6	0.44	7.3–10.8	870	No
		LEU-182-LE-B	9.6	0.42	7.9–10.9	870	No
0.047	027-04-000DTA	LEU-04-T	9.9	0.42	8.1–11.1	854	No
		LEU-05-L	9.9	0.34	8.2–10.8	867	No
		LEU-71-LE	9.5	0.43	8.2–10.8	869	No
		LEU-72-TE	9.4	0.47	7.2–11.0	867	No
		LEU-73-LC	10.1	0.5	7.6–11.6	868	No
		LEU-74-TC	9.9	1.1	7.0–12.0	821	No
	027-04-002DTB	LEU-07-T	10.0	0.45	8.2–11.4	870	No
		LEU-08-L	9.1	0.35	7.1–10.0	856	No
		LEU-75-LE	9.7	0.45	7.9–11.2	870	No
		LEU-76-TE	9.7	0.45	8.1–11.2	869	No
		LEU-77-LC	10.2	0.53	7.2–11.6	864	No
		LEU-78-TC	10.1	0.46	8.7–11.9	866	No
	027-04-000DTC	LEU-01-T	10.1	0.50	8.4–11.6	865	No
		LEU-02-L	10.0	0.50	7.0–11.6	866	No
		LEU-117-LE	9.7	0.56	8.0–11.7	870	No
		LEU-118-TE	9.5	0.53	7.2–11.4	864	No
		LEU-119-LC	9.7	0.51	7.8–12.0	868	No
		LEU-120-TC	9.6	0.52	8.0–11.2	869	No
	027-05-000DTA	LEU-10-T	10.8	0.48	7.2–11.9	862	No
		LEU-11-L	9.1	0.33	7.6–10.0	857	No
		LEU-79-LE	9.6	0.43	7.1–10.8	870	No
		LEU-80-TE	9.5	0.44	8.2–10.9	864	No

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		LEU-81-LC	10.2	0.45	8.4–11.8	867	No
		LEU-82-TC	10.2	0.44	7.9–11.5	860	No
	027-05-002DTB	LEU-13-T	9.5	0.43	8.1–10.8	870	No
		LEU-14-L	9.3	0.36	7.2–10.2	864	No
		LEU-113-LE	9.7	0.45	8.2–11.4	870	No
		LEU-114-TE	9.7	0.46	7.6–11.3	867	No
		LEU-115-LC	9.6	0.46	8.0–11.5	870	No
		LEU-116-TC	9.6	0.45	7.5–10.9	870	No
	027-05-000DTC	LEU-16-T	9.9	0.51	7.2–11.9	870	No
		LEU-17-L	11.2	0.45	9.6–12.0	798	No
		LEU-105-LE1	9.9	0.50	7.1–11.2	870	No
		LEU-106-TE1	9.8	0.50	7.8–11.5	869	No
		LEU-107-LC	9.8	0.48	8.4–11.3	868	No
		LEU-108-TC	9.7	0.47	8.0–11.2	869	No

Table A.8. Mo distribution (EDS measurements) in U-10Mo specimens without Zr (INL data)

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
0.0235	027-05-002CTA	met 1 trans	10.05	0.11	9.51-10.28	89	
		met 1 long	10.09	0.23	9.62-10.47	91	
		met 2 trans	10.01	0.14	9.34-10.24	90	
		met 2 long	10.02	0.21	9.54-10.43	91	
		met 3 trans	10.04	0.11	9.77-10.30	85	
		met 3 long	9.97	0.11	9.70-10.20	85	
	027-05-002CTB	met 1 trans	9.65	0.11	9.42-9.89	85	
		met 1 long	9.95	0.12	9.72-10.20	85	
		met 2 trans	9.81	0.20	9.53-10.25	85	
		met 2 long	9.61	0.13	9.38-9.90	85	
		met 3 trans	9.75	0.16	9.40-10.10	85	
		met 3 long	9.55	0.09	9.32-9.77	85	
	027-05-002CTC	met 1 trans	10.03	0.16	9.44-10.42	90	
		met 1 long	10.06	0.16	9.68-10.35	89	
		met 2 trans	10.03	0.35	9.61-11.33	82	
		met 2 long	9.86	0.12	9.64-10.13	82	
		met 3 trans	9.97	0.22	9.63-10.45	83	
		met 3 long	10.00	0.15	9.66-10.37	83	
0.0245	028-05-001CTA	met 1 trans	10.64	0.14	10.27-10.91	84	
		met 1 long	10.38	0.47	9.58-11.14	85	
		met 2 trans	10.58	0.14	10.16-10.98	85	

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		met 2 long	10.51	0.18	10.10-10.97	85	
		met 3 trans	9.93	0.19	9.57-10.34	85	
		met 3 long	10.74	0.14	10.36-11.17	85	
	028-05-001CTB	met 1 trans	9.84	0.11	9.60-10.06	85	
		met 1 long	9.76	0.19	9.36-10.21	89	
		met 2 trans	9.93	0.14	9.61-10.21	85	
		met 2 long	10.32	0.35	9.66-10.97	84	
		met 3 trans	9.68	0.15	9.34-9.93	85	
		met 3 long	9.81	0.19	9.30-10.15	85	
0.047	028-01-000DTA	met 1 trans	10.00	0.09	9.73-10.20	90	
		met 1 long	10.08	0.18	9.68-10.34	91	
		met 2 trans	9.96	0.12	9.15-10.22	91	
		met 2 long	9.85	0.17	9.10-10.11	90	
		met 3 trans	9.72	0.22	9.03-10.06	91	
		met 3 long	9.45	0.09	9.22-9.65	77	
	028-01-002DTB	met 1 trans	9.90	0.08	9.60-10.06	89	
		met 1 long	9.94	0.08	9.76-10.23	80	
		met 2 trans	9.83	0.08	9.44-10	91	
		met 2 long	9.78	0.08	9.54-9.96	91	
		met 3 trans	9.84	0.08	9.65-10.05	82	
		met 3 long	10.54	0.30	8.20-10.98	91	
	028-01-000DTC	met 1 trans	10.04	0.17	9.52-10.54	91	
		met 1 long	9.89	0.19	8.94-10.27	91	
		met 2 trans	9.92	0.14	9.57-10.19	90	
		met 2 long	9.90	0.10	9.64-10.14	91	
		met 3 trans	10.01	0.10	9.79-10.27	90	
		met 3 long	9.94	0.12	9.43-10.16	91	
	028-05-000DTA	met 1 trans	10.57	0.45	7.21-11.49	81	
		met 1 long	10.23	0.21	9.78-10.82	89	
		met 2 trans	10.90	0.14	10.55-11.17	87	
		met 2 long	10.31	0.13	9.87-10.80	76	
		met 3 trans	10.69	0.14	10.11-10.96	90	
		met 3 long	10.55	0.23	10.10-11.05	89	
	028-05-002DTB	met 1 trans	10.57	0.12	10.19-10.82	90	
		met 1 long	10.49	0.15	10.00-10.91	88	
		met 2 trans	9.78	0.07	9.61-10.00	90	
		met 2 long	9.78	0.10	9.59-10.04	90	
		met 3 trans	10.56	0.15	10.08-10.98	89	
		met 3 long	10.35	0.13	10.03-10.69	88	
	028-05-000DTC	met 1 trans	9.61	0.17	8.47-9.89	91	

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		met 1 long	9.92	0.12	9.64-10.15	91	
		met 2 trans	10.02	0.10	9.52-10.21	91	
		met 2 long	10.15	0.11	9.92-10.40	90	
		met 3 trans	9.69	0.23	7.79-9.95	91	
		met 3 long	9.61	0.08	9.42-9.80	91	

Table A.9. Mo distribution (EDS measurements) in U-10Mo specimens without Zr (LANL data)

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No of points	Banding
0.01	027-04-005CTA	13365-5A (T)	11.65	0.24	10.8–12.0	167	No
		13365-5B (L)	11.60	0.27	10.1–12.0	140	No
		13365-5C (T)	11.6	0.24	10.9–12.0	148	No
		13365-5D (L)	11.6	0.28	10.7–12.0	162	No
		13365-5E (T)	11.6	0.46	7.6–12.0	160	No
		13365-5F (L)	11.9	0.28	11.3–12.0	143	No
	027-04-006CTB	13365-6A (T)	11.6	0.25	10.8–12.0	206	No
		13365-6B (L)	11.4	0.36	10.0–12.0	217	No
		13365-6C (T)	11.5	0.33	9.3–11.9	207	No
		13365-6D (L)	11.6	0.28	10.2–12.0	206	No
		13365-6E (T)	11.4	0.35	8.5–12.0	217	No
		13365-6F (L)	11.3	0.4	9.4–12.0	223	No
	027-04-006CTC	13365-7A (T)	10.5	1.1	7.5–11.9	193	No
		13365-7B (L)	10.6	1.0	7.3–12.0	198	No
		13365-7C (T)	11.4	0.4	10.3-12.0	193	No
		13365-7D (L)	11.3	0.34	10.1–12.0	232	No
		13365-7E (T)	11.6	0.28	10.4–12.0	203	No
		13365-7F (L)	10.6	1.0	7.0–12.0	198	No
0.025	028-05-001CTC	13365-8A (T)	10.7	0.87	7.7–12.0	253	No
		13365-8B (L)	10.8	0.92	7.4–12.0	252	No
		13365-8C (T)	11.1	0.32	9.2–11.8	288	No
		13365-8D (L)	10.8	0.30	9.8–11.6	309	No
		13365-8E (T)	11	0.28	10.2–11.9	305	No
		13365-8F (L)	10.5	1.0	7.4–12.0	287	No
	028-05-002CTA	13365-9A (T)	11.7	0.25	10.2–12.0	142	No
		13365-9B (L)	10.5	1.2	7.2–12.0	172	No
		13365-9C (T)	10.6	1.1	7.5–12.0	166	No
		13365-9D (L)	11.6	0.33	9.2–12.0	166	No
		13365-9E (T)	10.5	1.1	7.7–12.0	170	No
		13365-9F (L)	11.5	0.42	7.2–12.0	162	No

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No of points	Banding
	028-05-002CTB	13365-10A (T)	11.6	0.25	9.9–12.0	178	No
		13365-10B (L)	11.6	0.30	9.8–12.0	131	No
		13365-10C (T)	11.6	0.25	10.6–12.0	192	No
		13365-10D (L)	11.6	0.46	7.9–12.0	159	No
		13365-10E (T)	11.7	0.20	10.5–12.0	161	No
		13365-10F (L)	11.7	0.34	8.5–12.0	123	No
	28-05-002CTC	13365-11A (T)	11.7	0.20	10.9–12.0	170	No
		13365-11B (L)	11.6	0.20	10.7–12.0	142	No
		13365-11C (T)	11.6	0.33	8.0–12.0	180	No
		13365-11D (L)	11.7	0.21	10.8–12.0	181	No
		13365-11E (T)	11.7	0.20	10.7–12.0	177	No
		13365-11F (L)	11.7	0.32	8.5–12.0	175	No

Table A.10. Mo distribution (EDS measurements) in U-10Mo specimens with Zr (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
0.01	030-01-001CTA	LEU-37-L	10.0	0.50	7.5–11.9	728	No
		LEU-38-T	10.0	0.57	7.2–12.0	816	No
		LEU-167-TE-A	9.7	0.55	7.3–11.6	726	No
		LEU-168-LE-A	9.7	0.53	7.2–12.0	774	No
		LEU-169-TE-B	9.7	0.50	7.0–11.7	702	No
		LEU-170-LE-B	9.8	0.54	7.0–11.7	775	No
	030-01-004CTB	LEU-39-L	9.9	0.48	8.4–11.5	864	No
		LEU-40-T	10.2	0.58	7.0–11.8	708	No
		LEU-125-LE1	9.6	0.57	7.0–11.1	696	No
		LEU-126-TE1	9.6	0.55	7.0–11.5	714	No
		LEU-127-LE2	9.5	0.58	7.0–11.3	719	No
		LEU-128-TE2	9.5	0.55	7.4–11.3	692	No
	030-01-001CTC	LEU-41-L	10.2	0.57	7.4–11.7	471	No
		LEU-42-T	10.0	0.55	7.3–11.7	707	No
		LEU-121-LE1	9.6	0.50	7.8–11.0	484	No
		LEU-122-TE1	9.6	0.56	7.6–11.7	742	No
		LEU-123-LE2	9.6	0.54	7.2–11.7	742	No
		LEU-124-TE2	9.5	0.51	7.5–11.4	701	No
0.027	029-01-001CTA	LEU-25-L	9.8	0.50	7.2–11.4	870	No
		LEU-26-T	10.0	0.52	7.9–11.7	870	No
		LEU-159-TE-A	9.4	0.56	7.6–11.1	868	No
		LEU-160-LE-A	9.4	0.56	7.3–11.5	869	No
		LEU-161-TE-B	9.4	0.58	7.6–11.4	869	No

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		LEU-162-LE-B	9.4	0.70	7.0–11.7	870	No
	029-01-004CTB	LEU-23-L	10.0	0.50	8.2–11.6	869	No
		LEU-24-T	10.0	0.47	8.2–11.5	870	No
		LEU-133-LE1	9.6	0.46	7.7–11.0	869	No
		LEU-134-TE1	9.6	0.44	8.5–11.3	870	No
		LEU-135-LE2	9.6	0.46	7.0–10.9	870	No
		LEU-136-TE2	9.6	0.44	7.9–10.9	870	No
	029-01-001CTC	LEU-19-L	10.0	0.47	8.6–11.8	866	No
		LEU-20-T	9.9	0.45	7.8–11.4	866	No
		LEU-129-LE1	9.5	0.43	8.2–11.4	870	No
		LEU-130-TE1	9.6	0.46	7.5–11.1	870	No
		LEU-131-LE2	9.5	0.61	7.4–11.5	869	No
		LEU-132-TE2	9.5	0.60	7.3–11.6	868	No
	029-01-002CTA	LEU-29-L	9.8	0.45	7.2–11.2	857	No
		LEU-30-T	9.9	0.48	7.7–11.3	869	No
		LEU-163-TE-A	9.5	0.47	7.7–11.1	870	No
		LEU-164-LE-A	9.4	0.47	7.7–10.9	866	No
		LEU-165-TE-B	9.5	0.46	8.1–11.0	869	No
		LEU-166-LE-B	9.5	0.49	7.3–11.1	870	No
	029-01-006CTB	LEU-31-L	9.9	0.45	7.7–11.3	867	No
		LEU-32-T	9.9	0.48	7.4–11.5	867	No
		LEU-183-TE-A	9.5	0.46	8.2–10.9	870	No
		LEU-184-LE-A	9.5	0.46	8.0–10.8	868	No
		LEU-185-TE-B	9.4	0.49	7.1–10.9	869	No
		LEU-186-LE-B	9.5	0.45	8.0–10.9	870	No
	029-01-002CTC	LEU-33-L	9.9	0.41	8.4–11.4	870	No
		LEU-34-T	9.9	0.42	8.5–11.3	868	No
		LEU-187-TE-A	9.6	0.40	7.8–11.0	870	No
		LEU-188-LE-A	9.4	0.45	7.4–10.7	868	No
		LEU-189-TE-B	9.6	0.45	7.8–10.8	869	No
		LEU-190-LE-B	9.6	0.44	8.0–10.9	869	No
0.047	029-01-000DTA	LEU-43-L	10.2	0.41	8.8–11.4	870	No
		LEU-44-T	10.1	0.49	8.5–11.6	867	No
		LEU-145-LE-A	9.4	0.53	7.7–11.2	870	No
		LEU-146-TE-A	9.5	0.49	8.0–10.8	870	No
		LEU-147-LE-B	9.4	0.51	7.4–11.0	867	No
		LEU-148-TE-B	9.5	0.49	8.0–11.2	870	No
	029-01-002DTB	LEU-45-L	9.8	0.48	7.0–11.5	862	No
		LEU-46-T	10.0	0.47	8.3–11.7	864	No
		LEU-149-LE-A	9.5	0.43	8.2–10.8	870	No

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		LEU-150-TE-A	9.5	0.50	7.2–10.8	869	No
		LEU-151-LE-B	9.4	0.47	7.9–10.7	870	No
		LEU-152-TE-B	9.5	0.48	7.1–10.8	870	No
	029-01-000DTC	LEU-49-L	9.9	0.42	7.2–11.2	866	No
		LEU-50-T	9.9	0.42	8.6–11.0	870	No
		LEU-153-LE-A	9.4	0.48	8.1–11.1	580	No
		LEU-154-TE-A	9.4	0.49	7.1–11.7	867	No
		LEU-157-TE-B	9.4	0.53	7.2–11.4	870	No
		LEU-158-LE-B	9.4	0.52	7.4–10.9	868	No
	030-01-000DTA	LEU-51-L	10.3	0.52	7.0–11.8	870	No
		LEU-52-T	10.1	0.54	7.3–12.0	870	No
		LEU-171-TE-A	9.8	0.46	8.1–11.4	870	No
		LEU-172-LE-A	10.0	0.51	8.1–11.7	869	No
		LEU-173-TE-B	9.8	0.44	8.1–11.3	866	No
		LEU-174-LE-B	9.7	0.47	8.1–11.5	868	No

Table A.11. Mo distribution (EDS measurements) in U-10Mo specimens with Zr (INL data)

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
0.0121	030-01-003CTA	met 1 trans	9.98	0.16	9.59-10.37	100	
		met 1 long	9.93	0.15	9.61-10.52	100	
		met 2 trans	9.74	0.10	9.55-10.01	100	
		met 2 long	9.66	0.09	9.44-9.89	100	
		met 3 trans	9.74	0.10	9.37-9.99	100	
		met 3 long	9.70	0.09	9.51-9.93	100	
	030-01-008CTB	met 1 trans	9.69	0.19	9.24-10.21	100	
		met 1 long	9.71	0.12	9.39-9.96	100	
		met 2 trans	9.81	0.18	9.38-10.33	100	
		met 2 long	9.89	0.25	9.37-10.83	100	
		met 3 trans	9.74	0.18	9.36-10.17	100	
		met 3 long	9.72	0.21	9.14-10.32	100	
	030-01-003CTC	met 1 trans	9.70	0.14	9.38-10.06	84	
		met 1 long	9.67	0.20	9.03-10.01	99	
		met 2 trans	9.82	0.21	9.35-10.36	100	
		met 2 long	9.82	0.23	9.29-10.34	100	
		met 3 trans	9.86	0.20	9.53-10.54	99	
		met 3 long	9.92	0.17	9.41-10.35	100	
0.0262	029-05-001CTA	met 1 trans	9.78	0.28	9.10-10.60	100	
		met 1 long	9.78	0.28	9.10-10.39	100	

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		met 2 trans	9.66	0.14	9.38-10.08	100	
		met 2 long	9.73	0.17	9.38-10.12	100	
		met 3 trans	9.75	0.21	9.35-10.19	100	
		met 3 long	9.78	0.26	8.95-10.42	100	
	029-05-004CTB	met 1 trans	9.88	0.21	9.40-10.44	100	
		met 1 long	9.76	0.15	9.46-10.15	100	
		met 2 trans	9.79	0.27	9.21-10.40	100	
		met 2 long	9.96	0.26	9.37-10.56	100	
		met 3 trans	9.73	0.21	9.21-10.15	100	
		met 3 long	9.86	0.20	9.42-10.36	100	
	029-05-001CTC	met 1 trans	10.20	0.19	9.46-10.58	100	
		met 1 long	10.07	0.17	9.64-10.41	100	
		met 2 trans	9.66	0.14	9.38-10.08	100	
		met 2 long	9.73	0.17	9.38-10.12	100	
		met 3 trans	9.75	0.21	9.35-10.20	100	
		met 3 long	9.78	0.26	8.95-10.42	100	
0.0278	029-05-002CTA	met 1 trans	9.76	0.22	9.19-10.38	100	
		met 1 long	9.83	0.21	9.31-10.59	100	
		met 2 trans					
		met 2 long	9.83	0.26	9.29-10.50	100	
		met 3 trans	9.69	0.17	9.34-10.16	100	
		met 3 long	9.74	0.18	9.39-10.36	101	
	029-05-006CTB	met 1 trans	9.89	0.21	9.42-10.40	100	
		met 1 long	9.86	0.20	9.30-10.41	100	
		met 2 trans	9.85	0.25	9.38-10.53	100	
		met 2 long	9.93	0.20	9.34-10.31	100	
		met 3 trans	9.73	0.24	8.56-10.30	100	
		met 3 long	9.74	0.18	9.23-10.17	100	
	029-05-002CTC	met 1 trans	9.77	0.10	9.37-10.05	100	
		met 1 long	9.72	0.14	8.76-10.05	100	
		met 2 trans	9.75	0.11	9.56-10.20	100	
		met 2 long	9.78	0.11	9.59-10.30	100	
		met 3 trans	9.78	0.12	9.50-10.44	100	
		met 3 long	9.54	0.08	9.38-9.77	100	
0.047	029-05-000DTA	met 1 trans	9.64	0.09	9.39-9.82	100	
		met 1 long	9.94	0.12	9.56-10.39	100	
		met 2 trans	10.72	0.16	10.36-11.10	100	
		met 2 long	9.51	0.35	8.93-10.07	100	
		met 3 trans	9.88	0.25	9.36-10.38	119	
		met 3 long	9.97	0.16	9.38-10.48	105	

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
	029-05-002DTB	met 1 trans	9.88	0.16	9.55-10.20	100	
		met 1 long	10.00	0.18	9.66-10.34	100	
		met 2 trans	10.58	0.16	10.28-10.97	120	
		met 2 long	10.98	0.21	10.59-11.51	84	
		met 3 trans	10.07	0.11	9.51-10.31	100	
		met 3 long	9.79	0.18	9.48-10.04	100	
	029-05-000DTC	met 1 trans	9.64	0.07	9.39-9.92	100	
		met 1 long	9.75	0.09	9.49-9.98	105	
		met 2 trans	9.76	0.08	9.6-10.03	107	
		met 2 long	9.79	0.08	9.54-9.98	108	
		met 3 trans	9.74	0.08	9.46-9.99	107	
		met 3 long	9.73	0.08	9.52-9.97	110	
	030-01-000DTC	met 1 trans	9.85	0.09	9.67-10.10	100	
		met 1 long	9.76	0.09	9.56-10.04	100	
		met 2 trans	9.92	0.08	9.75-10.11	105	
		met 2 long	9.92	0.11	9.57-10.31	107	
		met 3 trans	9.91	0.11	9.44-10.16	105	
		met 3 long	9.87	0.09	9.66-10.14	102	

Table A.12. Mo distribution (EDS measurements) in U-10Mo specimens with Zr (LANL data)

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
0.047	029-02-000DTA	13365-1A (T)	10.9	0.38	7.9-11.9	427	No
		13365-1B (L)	10.8	0.36	9.1-11.8	390	No
		13365-1C (T)	11.1	0.34	9.8-12.0	454	No
		13365-1D (L)	10.9	0.42	8.8-11.9	428	No
		13365-1E (T)	11.1	0.37	8.3-12.0	485	No
		13365-1F (L)	11.3	0.32	10.1-12.0	427	No
	029-02-002DTB	13365-2A (T)	11.0	0.87	8.0-12.0	215	No
		13365-2B (L)	11.3	0.7	8.1-12.0	164	No
		13365-2C (T)	11.6	0.26	10.1-12.0	192	No
		13365-2D (L)	11.6	0.31	9.3-12.0	226	No
		13365-2E (T)	11.6	0.3	8.7-12.0	195	No
		13365-2F (L)	11.6	0.34	8.5-12.0	207	No
	029-02-000DTC	13365-3A (T)	11.6	0.20	10.9-12.0	205	No
		13365-3B (L)	10.6	1.0	7.5-12.0	218	No
		13365-3C (T)	10.6	1.1	7.4-12.0	224	No
		13365-3D (L)	11.6	0.22	10.7-12.0	236	No
		13365-3E (T)	11.6	0.17	11.1-12.0	206	No

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		13365-3F (L)	11.6	0.24	9.9-12.0	224	No
	030-01-002DTB	13365-4A (T)	11.1	0.22	10.4-11.9	212	No
		13365-4B (L)	11.2	0.27	10.3-11.8	218	No
		13365-4C (T)	11.2	0.27	10.4-11.8	209	No
		13365-4D (L)	11.1	0.40	7.5-12.0	219	No
		13365-4E (T)	11.2	0.27	10.3-11.9	193	No
		13365-4F (L)	11.2	0.32	9.6-11.9	238	No
0.025	029-02-001CTA	13365-12A (T)	11.4	0.34	10.1-12.0	387	No
		13365-12B (L)	11.5	0.29	9.9-12.0	336	No
		13365-12C (T)	10.8	0.35	9.5-11.9	233	No
		13365-12D (L)	10.9	0.34	9.5-11.8	236	No
		13365-12E (T)	11.5	0.42	7.8-12.0	371	No
		13365-12F (L)	10.7	0.45	8.8-11.7	224	No
	029-02-004CTB	13365-13A (T)	11.0	0.27	10.3-11.5	114	No
		13365-13B (L)	11.3	0.33	9.8-11.9	112	No
		13365-13C (T)	10.9	0.28	9.9-11.7	227	No
		13365-13D (L)	10.9	0.33	9.5-11.6	234	No
		13365-13E (T)	11.1	0.35	9.2-12.0	240	No
		13365-13F (L)	11.0	0.31	10-11.8	114	No
	029-02-001CTC	13365-14A (T)	-	-	-	-	-
		13365-14B (L)	10.9	0.51	7.3-11.6	115	No
		13365-14C (T)	11.0	0.32	9.2-11.7	113	No
		13365-14D (L)	11.1	0.42	7.6-12.0	236	No
		13365-14E (T)	10.9	0.28	10.1-11.6	219	No
		13365-14F (L)	10.6	0.38	8.3-11.5	288	No
	029-02-002CTA	13365-15A (T)	11.1	0.38	8.1-11.8	234	No
		13365-15B (L)	10.4	0.38	7.1-11.1	293	No
		13365-15C (T)	10.9	0.32	9.7-11.8	239	No
		13365-15D (L)	10.9	0.34	9.2-11.6	229	No
		13365-15E (T)	10.9	0.35	9.2-11.6	229	No
		13365-15F (L)	11.0	0.42	7.6-11.7	231	No
	029-02-006CTB	13365-16A (T)	11.0	0.31	10-11.8	236	No
		13365-16B (L)	11.2	0.31	10.4-12.0	229	No
		13365-16C (T)	11.1	0.30	9.4-11.8	242	No
		13365-16D (L)	11.2	0.30	10.2-11.8	233	No
		13365-16E (T)	11.2	0.34	9.1-11.9	246	No
		13365-16F (L)	11.0	0.33	8-11.7	235	No
	029-02-002CTC	13365-17A (T)	11.0	0.31	10-11.8	237	No
		13365-17B (L)	10.9	0.30	9.2-11.7	218	No
		13365-17C (T)	11.1	0.30	10.2-11.7	225	No
		13365-17D (L)	11.0	0.30	9.2-11.6	224	No
		13365-17E (T)	10.9	0.34	8.5-11.6	221	No

Thickness (in.)	Sample ID	Specimen ID	Average Mo (wt%)	Standard deviation (wt%)	Mo variation (wt%)	No. of points	Banding
		13365-17F (L)	10.9	0.26	9.4-11.4	277	No
0.010 (R)	030-01-002CTA	13365-18A (T)	11.0	0.26	10.1-11.8	220	No
		13365-18B (L)	11.1	0.24	10.2-11.8	230	No
		13365-18C (T)	10.9	0.31	9.9-11.9	251	No
		13365-18D (L)	11.1	0.32	7.9-11.9	241	No
		13365-18E (T)	11.2	0.39	8.1-12.0	210	No
		13365-18F (L)	11.0	0.31	9.8-11.9	232	No
	030-01-006CTB	13365-19A (T)	11.2	0.26	9.9-11.8	225	No
		13365-19B (L)	10.9	0.50	9.2-12.0	217	No
		13365-19C (T)	11.7	0.29	9.5-12.0	202	No
		13365-19D (L)	11.7	0.27	10.0-12.0	167	No
		13365-19E (T)	11.7	0.21	10.9-12.0	85	No
		13365-19F (L)	11.0	0.28	9.9-11.8	233	No
	030-02-002CTC	13365-20A (T)	10.6	0.35	9.5-11.3	241	No
		13365-20B (L)	10.6	0.41	9.4-11.4	246	No
		13365-20C (T)	10.7	0.34	9.1-11.4	246	No
		13365-20D (L)	10.7	0.48	8.5-11.8	248	No
		13365-20E (T)	10.7	0.36	8.5-11.4	236	No
		13365-20F (L)	10.4	0.40	8.5-11.0	234	No

A.3 Carbide Fraction

Table A.13. Carbide area fraction in U-10Mo specimens without Zr (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
0.01	027-04-003CTA	LEU-53-L	1.21	0.20	462
		LEU-54-T	1.15	0.40	439
		LEU-85-LE1	1.20	0.10	458
		LEU-86-TE1	1.19	0.06	454
		LEU-87-LE2	0.42	0.12	160
		LEU-88-TE2	1.0	0.10	382
	027-04-003CTB	LEU-55-L	0.98	0.22	374
		LEU-56-T	1.12	0.38	427
		LEU-97-LE1	1.15	0.06	439
		LEU-98-TE1	1.6	0.08	611
		LEU-99-LE2	1.12	0.02	427
		LEU-100-TE2	1.17	0.15	447
	027-04-004CTC	LEU-57-L	0.92	0.30	351
		LEU-58-T	1.00	0.42	382

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
		LEU-109-LE1	1.0	0.10	382
		LEU-110-TE1	1.1	0.08	420
		LEU-111-LE2	0.49	0.17	187
		LEU-112-TE2	1.2	0.12	458
0.025	028-01-001CTA	LEU-59-L	0.51	0.08	195
		LEU-60-T	0.45	0.06	172
		LEU-91-LE1	0.75	0.1	286
		LEU-92-TE1	0.62	0.18	237
		LEU-93-LE2	1.18	0.18	450
		LEU-94-TE2	0.54	0.11	206
	028-01-001CTB	LEU-61-L	0.49	0.11	187
		LEU-62-T	0.36	0.05	137
		LEU-101-LE1	0.44	0.14	168
		LEU-102-TE1	0.54	0.10	206
		LEU-103-LE2	1.0	0.10	382
		LEU-104-TE2	0.58	0.20	221
	028-01-001CTC	LEU-63-L	0.52	0.06	198
		LEU-64-T	0.21	0.03	80
		LEU-137-LE1	0.73	0.1	279
		LEU-138-TE1	1.13	0.08	431
		LEU-139-LE2	0.46	0.05	176
		LEU-140-TE2	0.64	0.11	244
	028-01-002CTA	LEU-65-L	0.38	0.05	145
		LEU-66-T	0.44	0.07	168
		LEU-141-LE1	0.87	0.19	332
		LEU-142-TE1	0.96	0.18	366
		LEU-143-LE2	0.63	0.10	240
		LEU-144-TE2	0.61	0.05	233
	028-01-002CTB	LEU-67-L	0.44	0.08	168
		LEU-68-T	0.41	0.17	156
		LEU-175-TE-A	0.78	0.08	298
		LEU-176-LE-A	0.72	0.25	275
		LEU-177-TE-B	0.58	0.19	221
		LEU-178-LE-B	0.43	0.14	164
	028-01-002CTC	LEU-69-L	0.39	0.13	149
		LEU-70-T	0.40	0.07	153
		LEU-179-TE-A	0.49	0.13	187
		LEU-180-LE-A	0.74	0.11	282
		LEU-181-TE-B	0.66	0.12	252
		LEU-182-LE-B	0.78	0.10	298
0.047		LEU-04-T	0.74	0.17	282

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
	027-04-000DTA	LEU-05-L	1.07	0.18	408
		LEU-71-LE	1.19	0.11	454
		LEU-72-TE	1.12	0.11	427
		LEU-73-LC	2.24	0.05	855
		LEU-74-TC	2.35		897
	027-04-002DTB	LEU-07-T	0.82	0.20	313
		LEU-08-L	0.76	0.14	290
		LEU-75-LE	0.98	0.12	374
		LEU-76-TE	0.98	0.06	374
		LEU-77-LC	1.07	0.17	408
		LEU-78-TC	1.07	0.06	408
	027-04-000DTC	LEU-01-T	0.92	0.27	351
		LEU-02-L	1.23	0.22	469
		LEU-117-LE	1.4	0.15	534
		LEU-118-TE	1.4	0.06	534
		LEU-119-LC	1.41	0.15	538
		LEU-120-TC	1.07	0.09	408
	027-05-000DTA	LEU-10-T	0.86	0.16	328
		LEU-11-L	0.73	0.12	279
		LEU-79-LE	0.72	0.05	275
		LEU-80-TE	0.74	0.07	282
		LEU-81-LC	0.82	0.10	313
		LEU-82-TC	1.23	0.11	469
	027-05-002DTB	LEU-13-T	0.82	0.17	313
		LEU-14-L	0.91	0.17	347
		LEU-113-LE	1.4	0.16	534
		LEU-114-TE	1.3	0.41	496
		LEU-115-LC	1.1	0.14	420
		LEU-116-TC	0.98	0.06	374
	027-05-000DTC	LEU-16-T	1.30	0.33	496
		LEU-17-L	1.17	0.26	447
		LEU-105-LE1	1.4	0.14	534
		LEU-106-TE1	1.4	0.05	534
		LEU-107-LC	1.3	0.18	496
		LEU-108-TC	1.35	0.05	515

Table A.14. Carbide area fraction in U-10Mo specimens (without Zr) (INL data)

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
0.0235	027-05-002CTA	met 1 trans	1.22	0.27	466

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
		met 1 long	1.29	0.28	492
		met 2 trans	1.37	0.49	523
		met 2 long	0.83	0.38	317
		met 3 trans	1.47	0.13	561
		met 3 long	1.00	0.42	382
	027-05-002CTB	met 1 trans	1.43	0.16	546
		met 1 long	1.52	0.40	580
		met 2 trans	1.33	0.20	508
		met 2 long	1.28	0.41	489
		met 3 trans	1.38	0.24	527
		met 3 long	1.33	0.37	508
	027-05-002CTC	met 1 trans	1.66	0.51	634
		met 1 long	1.73	0.43	660
		met 2 trans	1.51	0.19	576
		met 2 long	0.90	1.17	344
		met 3 trans	1.33	0.11	508
		met 3 long	1.50	0.51	573
0.0245	028-05-001CTA	met 1 trans	0.91	0.16	347
		met 1 long	0.84	0.55	321
		met 2 trans	0.77	0.16	294
		met 2 long	0.91	0.66	347
		met 3 trans	0.75	0.14	286
		met 3 long	0.61	0.17	233
	028-05-001CTB	met 1 trans	0.79	0.15	302
		met 1 long	0.76	0.18	290
		met 2 trans	0.68	0.09	260
		met 2 long	0.82	0.23	313
		met 3 trans	0.87	0.43	332
		met 3 long	0.67	0.20	256
0.047	028-01-000DTA	met 1 trans	0.45	0.12	172
		met 1 long	0.48	0.13	183
		met 2 trans	0.85	0.45	324
		met 2 long	1.01	1.01	385
		met 3 trans	0.57	0.14	218
		met 3 long	0.66	0.13	252
	028-01-002DTB	met 1 trans	0.58	0.24	221
		met 1 long	0.62	0.08	237
		met 2 trans	0.56	0.12	214
		met 2 long	0.47	0.06	179
		met 3 trans	0.46	0.13	176
		met 3 long	0.56	0.11	214

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
	028-01-000DTC	met 1 trans	0.49	0.13	187
		met 1 long	0.52	0.17	198
		met 2 trans	0.48	0.22	183
		met 2 long	0.54	0.19	206
		met 3 trans	0.52	0.25	198
		met 3 long	0.57	0.22	218
	028-05-000DTA	met 1 trans	1.36	0.50	519
		met 1 long	1.21	0.34	462
		met 2 trans	0.58	0.16	221
		met 2 long	0.57	0.33	218
		met 3 trans	1.04	0.51	397
		met 3 long	0.65	0.38	248
	028-05-002DTB	met 1 trans	0.81	0.17	309
		met 1 long	0.82	0.28	313
		met 2 trans	0.71	0.15	271
		met 2 long	0.65	0.28	248
		met 3 trans	0.80	0.13	305
		met 3 long	0.63	0.13	240
	028-05-000DTC	met 1 trans	1.05	0.28	401
		met 1 long	0.90	0.22	344
		met 2 trans	0.78	0.30	298
		met 2 long	0.87	0.31	332
		met 3 trans	0.59	0.18	225
		met 3 long	0.99	0.45	378

Table A.15. Carbide area fraction in U-10Mo specimens (without Zr) (LANL data)

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation	Carbon (ppm)
0.01	027-04-005CTA	13365-5A (T)	1.16	0.09	443
		13365-5B (L)	0.97	0.04	370
		13365-5C (T)	0.96	0.02	366
		13365-5D (L)	0.94	0.02	359
		13365-5E (T)	1.12	0.29	427
		13365-5F (L)	0.77	0.07	294
	027-04-006CTB	13365-6A (T)	1.00	0.02	382
		13365-6B (L)	1.30	0.03	496
		13365-6C (T)	1.34	0.26	511
		13365-6D (L)	1.13	0.10	431
		13365-6E (T)	1.28	0.10	489
		13365-6F (L)	1.03	0.29	393

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation	Carbon (ppm)
	027-04-006CTC	13365-7A (T)	1.10	0.09	420
		13365-7B (L)	1.04	0.12	397
		13365-7C (T)	1.28	0.04	489
		13365-7D (L)	1.40	0.04	534
		13365-7E (T)	1.25	0.30	477
		13365-7F (L)	0.85	0.01	324
0.25	028-05-001CTC	13365-8A (T)	0.74	0.06	282
		13365-8B (L)	0.56	0.07	214
		13365-8C (T)	0.65	0.05	248
		13365-8D (L)	0.68	0.10	260
		13365-8E (T)	0.68	0.09	260
		13365-8F (L)	0.52	0.08	198
	028-05-002CTA	13365-9A (T)	0.62	0.04	237
		13365-9B (L)	0.99	0.52	378
		13365-9C (T)	0.67	0.01	256
		13365-9D (L)	1.17	0.06	447
		13365-9E (T)	0.77	0.14	294
		13365-9F (L)	0.67	0.04	256
	028-05-002CTB	13365-10A(T)	0.60	0.01	229
		13365-10B(L)	0.69	0.12	263
		13365-10C(T)	0.65	0.02	248
		13365-10D(L)	0.73	0.04	279
		13365-10E (T)	0.53	0.07	202
		13365-10F (L)	0.68	0.07	260
	28-05-002CTC	13365-11A(T)	0.62	0.03	237
		13365-11B(L)	0.60	0.04	229
		13365-11C(T)	0.66	0.03	252
		13365-11D(L)	0.72	0.06	275
		13365-11E (T)	0.69	0.03	263
		13365-11F (L)	0.62	0.11	237

Table A.16. Carbide area fraction in U-10Mo specimens with Zr (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
0.01	030-01-001CTA	LEU-37-L	0.57	0.22	218
		LEU-38-T	0.66	0.24	252
		LEU-167-TE-A	0.77	0.12	294
		LEU-168-LE-A	0.81	0.1	309
		LEU-169-TE-B	0.79	0.10	302
		LEU-170-LE-B	0.76	0.03	290

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
	030-01-004CTB	LEU-39-L	0.35	0.04	134
		LEU-40-T	0.29	0.12	111
		LEU-125-LE1	0.6	0.1	229
		LEU-126-TE1	0.58	0.05	221
		LEU-127-LE2	0.82	0.22	313
		LEU-128-TE2	0.88	0.11	336
	030-01-001CTC	LEU-41-L	0.56	0.21	214
		LEU-42-T	0.59	0.29	225
		LEU-121-LE1	0.81	0.16	309
		LEU-122-TE1	0.79	0.19	302
		LEU-123-LE2	0.79	0.12	302
		LEU-124-TE2	1.4	0.08	534
0.027	029-01-001CTA	LEU-25-L	0.24	0.06	92
		LEU-26-T	0.30	0.12	115
		LEU-159-TE-A	0.88	0.10	336
		LEU-160-LE-A	0.85	0.15	324
		LEU-161-TE-B	0.64	0.10	244
		LEU-162-LE-B	0.88	0.11	336
	029-01-004CTB	LEU-23-L	0.27	0.17	103
		LEU-24-T	0.45	0.11	172
		LEU-133-LE1	0.67	0.02	256
		LEU-134-TE1	0.63	0.07	240
		LEU-135-LE2	0.59	0.05	225
		LEU-136-TE2	0.61	0.21	233
	029-01-001CTC	LEU-19-L	0.43	0.11	164
		LEU-20-T	0.28	0.15	107
		LEU-129-LE1	0.75	0.14	286
		LEU-130-TE1	0.82	0.1	313
		LEU-131-LE2	0.58	0.08	221
		LEU-132-TE2	0.72	0.12	175
	029-01-002CTA	LEU-29-L	0.50	0.13	191
		LEU-30-T	0.50	0.08	191
		LEU-163-TE-A	0.82	0.10	313
		LEU-164-LE-A	0.71	0.11	271
		LEU-165-TE-B	0.72	0.10	275
		LEU-166-LE-B	0.96	0.14	366
	029-01-006CTB	LEU-31-L	0.40	0.10	153
		LEU-32-T	0.37	0.10	141
		LEU-183-TE-A	0.59	0.10	225
		LEU-184-LE-A	0.57	0.18	218
		LEU-185-TE-B	0.80	0.29	305

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
		LEU-186-LE-B	0.73	0.12	279
	029-01-002CTC	LEU-33-L	0.32	0.12	122
		LEU-34-T	0.38	0.10	145
		LEU-187-TE-A	0.78	0.06	298
		LEU-188-LE-A	0.65	0.08	248
		LEU-189-TE-B	0.64	0.11	244
		LEU-190-LE-B	0.92	0.20	351
0.047	029-01-000DTA	LEU-43-L	0.45	0.10	172
		LEU-44-T	0.30	0.06	115
		LEU-145-LE-A			
		LEU-146-TE-A	0.80	0.13	305
		LEU-147-LE-B	0.51	0.05	195
		LEU-148-TE-B	0.60	0.16	229
	029-01-002DTB	LEU-45-L	0.43	0.07	164
		LEU-46-T	0.24	0.06	92
		LEU-149-LE-A	0.74	0.10	282
		LEU-150-TE-A	0.89	0.10	340
		LEU-151-LE-B	0.92	0.25	351
		LEU-152-TE-B	0.90	0.20	344
	029-01-000DTC	LEU-49-L	0.32	0.12	122
		LEU-50-T	0.37	0.08	141
		LEU-153-LE-A	0.45	0.12	172
		LEU-154-TE-A	0.47	0.15	179
		LEU-157-TE-B	0.53	0.10	202
		LEU-158-LE-B	0.38	0.04	145
	030-01-000DTA	LEU-51-L	1.19	0.34	454
		LEU-52-T	0.65	0.14	248
		LEU-171-TE-A	0.48	0.03	183
		LEU-172-LE-A	0.61	0.06	233
		LEU-173-TE-B	0.87	0.20	332
		LEU-174-LE-B	0.53	0.08	202

Table A.17. Carbide area fraction in U-10Mo specimens (with Zr) (INL data)

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
0.0121	030-01-003CTA	met 1 trans	0.32	0.15	122
		met 1 long	0.65	0.15	248
		met 2 trans	0.66	0.29	252
		met 2 long	0.74	0.13	282
		met 3 trans	0.76	0.14	290

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
		met 3 long	0.75	0.13	286
	030-01-008CTB	met 1 trans	0.80	0.18	305
		met 1 long	0.66	0.16	252
		met 2 trans	0.94	0.39	359
		met 2 long	0.84	0.18	321
		met 3 trans	0.94	0.20	359
		met 3 long	0.90	0.19	344
	030-01-003CTC	met 1 trans	1.06	0.54	405
		met 1 long	0.30	0.13	115
		met 2 trans	0.96	0.36	366
		met 2 long	0.80	0.17	305
		met 3 trans	0.29	0.05	111
		met 3 long	0.44	0.12	168
0.0262	029-05-001CTA	met 1 trans	0.59	0.34	225
		met 1 long	0.61	0.11	233
		met 2 trans	1.01	0.38	385
		met 2 long	0.74	0.28	282
		met 3 trans	0.70	0.33	267
		met 3 long	0.67	0.22	256
	029-05-004CTB	met 1 trans	0.58	0.15	221
		met 1 long	0.72	0.13	275
		met 2 trans	0.40	0.21	153
		met 2 long	0.73	0.12	279
		met 3 trans	0.84	0.32	321
		met 3 long	0.84	0.16	321
	029-05-001CTC	met 1 trans	0.20	0.11	76
		met 1 long	0.40	0.27	153
		met 2 trans	0.64	0.35	244
		met 2 long	0.92	0.24	351
		met 3 trans	0.64	0.33	244
		met 3 long	0.27	0.07	103
0.0278	029-05-002CTA	met 1 trans	0.71	0.11	271
		met 1 long	0.68	0.08	260
		met 2 trans	0.93	0.28	355
		met 2 long	0.73	0.15	279
		met 3 trans	0.46	0.17	176
		met 3 long	0.72	0.19	275
	029-05-006CTB	met 1 trans	0.59	0.28	225
		met 1 long	0.55	0.35	210
		met 2 trans	1.10	0.28	420
		met 2 long	0.77	0.22	294

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation (%)	Carbon (ppm)
		met 3 trans	0.43	0.23	164
		met 3 long	0.79	0.23	302
	029-05-002CTC	met 1 trans	0.81	0.20	309
		met 1 long	0.69	0.25	263
		met 2 trans	0.76	0.12	290
		met 2 long	0.80	0.18	305
		met 3 trans	0.70	0.17	267
		met 3 long	0.77	0.13	294
0.047	029-05-000DTA	met 1 trans	0.93	0.46	355
		met 1 long	0.66	0.24	252
		met 2 trans	0.83	0.20	317
		met 2 long	0.64	0.24	244
		met 3 trans	0.82	0.25	313
		met 3 long	0.85	0.29	324
	029-05-002DTB	met 1 trans	0.82	0.20	313
		met 1 long	1.00	0.44	382
		met 2 trans	0.64	0.19	244
		met 2 long	0.91	0.32	347
		met 3 trans	0.90	0.32	344
		met 3 long	0.89	0.20	340
	029-05-000DTC	met 1 trans	0.65	0.07	248
		met 1 long	0.72	0.11	275
		met 2 trans	0.72	0.09	275
		met 2 long	0.70	0.13	267
		met 3 trans	0.91	0.33	347
		met 3 long	0.74	0.14	282
	030-01-000DTC	met 1 trans	0.68	0.21	260
		met 1 long	0.68	0.14	260
		met 2 trans	0.77	0.16	294
		met 2 long	0.70	0.17	267
		met 3 trans	0.72	0.13	275
		met 3 long	0.69	0.13	263

Table A.18. Carbide area fraction in U-10Mo specimens (with Zr) (LANL data)

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation	Carbon (ppm)
0.047	029-02-000DTA	13365-1A (T)	0.74	0.26	282
		13365-1B (L)	0.45	0.03	172
		13365-1C (T)	0.46	0.03	176
		13365-1D (L)	0.84	0.00	321

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation	Carbon (ppm)
		13365-1E (T)	0.52	0.00	198
		13365-1F (L)	0.52	0.01	198
	029-02-002DTB	13365-2A (T)	0.62	0.00	237
		13365-2B (L)	0.45	0.03	172
		13365-2C (T)	0.64	0.09	244
		13365-2D (L)	0.38	0.08	145
		13365-2E (T)	0.44	0.04	168
		13365-2F (L)	0.76	0.01	290
	029-02-000DTC	13365-3A (T)	0.49	0.07	187
		13365-3B (L)	0.50	0.06	191
		13365-3C (T)	0.48	0.20	183
		13365-3D (L)	0.50	0.01	191
		13365-3E (T)	0.50	0.04	191
		13365-3F (L)	0.64	0.04	144
	030-01-002DTB	13365-4A (T)	0.80	0.19	305
		13365-4B (L)	0.78	0.27	298
		13365-4C (T)	0.57	0.11	218
		13365-4D (L)	0.71	0.02	271
		13365-4E (T)	0.78	0.02	298
		13365-4F (L)	0.57	0.10	218
0.025	029-02-001CTA	13365-12A (T)	0.52	0.04	198
		13365-12B (L)	0.45	0.00	172
		13365-12C (T)	0.58	0.08	221
		13365-12D (L)	0.49	0.04	187
		13365-12E (T)	0.43	0.03	164
		13365-12F (L)	0.44	0.02	168
	029-02-004CTB	13365-13A (T)	0.45	0.09	172
		13365-13B (L)	0.52	0.00	198
		13365-13C (T)	0.55	0.00	210
		13365-13D (L)	0.61	0.06	233
		13365-13E (T)	0.60	0.04	229
		13365-13F (L)	0.40	0.00	153
	029-02-001CTC	13365-14A (T)	0.51	0.00	195
		13365-14B (L)	0.43	0.05	164
		13365-14C (T)	0.60	0.06	229
		13365-14D (L)	0.49	0.05	187
		13365-14E (T)	0.65	0.01	248
		13365-14F (L)	0.64	0.05	244
	029-02-002CTA	13365-15A (T)	0.53	0.06	202
		13365-15B (L)	0.51	0.10	195
		13365-15C (T)	0.63	0.13	240

Thickness (in.)	Sample ID	Specimen ID	Carbide area fraction (%)	Standard deviation	Carbon (ppm)
		13365-15D (L)	0.82	0.06	313
		13365-15E (T)	0.50	0.08	191
		13365-15F (L)	0.61	0.11	233
	029-02-006CTB	13365-16A (T)	0.56	0.05	214
		13365-16B (L)	0.65	0.03	248
		13365-16C (T)	0.72	0.07	275
		13365-16D (L)	0.68	0.15	260
		13365-16E (T)	0.55	0.04	210
		13365-16F (L)	0.44	0.09	168
	029-02-002CTC	13365-17A (T)	0.62	0.03	237
		13365-17B (L)	0.50	0.07	191
		13365-17C (T)	0.64	0.01	244
		13365-17D (L)	0.65	0.08	248
		13365-17E (T)	0.55	0.04	210
		13365-17F (L)	0.54	0.09	206
0.047	030-01-002CTA	13365-18A (T)	0.89	0.09	340
		13365-18B (L)	0.61	0.07	233
		13365-18C (T)	0.80	0.05	305
		13365-18D (L)	0.51	0.03	195
		13365-18E (T)	0.57	0.17	218
		13365-18F (L)	0.40	0.04	153
	030-01-006CTB	13365-19A (T)	0.73	0.02	279
		13365-19B (L)	0.59	0.14	225
		13365-19C (T)	0.91	0.23	347
		13365-19D (L)	0.51	0.11	195
		13365-19E (T)	0.57	0.03	218
		13365-19F (L)	0.41	0.01	156
	030-02-002CTC	13365-20A (T)	0.93	0.04	355
		13365-20B (L)	0.88	0.17	336
		13365-20C (T)	0.81	0.12	309
		13365-20D (L)	0.72	0.03	275
		13365-20E (T)	1.10	0.04	420
		13365-20F (L)	1.09	0.08	416

A.4 Carbide Size

Table A.19. Carbide particle size distribution in U-Mo specimens without Zr (0.010 in.)

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
027-04-003CTA	LEU-53-L	4.2	8.1	0.206/59.8
		4.1	10.9	0.203/75.34
		4.4	14.4	0.203/80.7
	LEU-54-T	3.8	8.2	0.203/39.9
		5.6	13.7	0.203/92.8
		4.7	21.3	0.202/255.5
	LEU-85-LE1	4.2	10.9	0.207/81.8
		5.1	13.8	0.209/102.1
		5.0	12.3	0.207/86.7
	LEU-86-TE1	2.9	7.7	0.208/65.7
		2.9	5.9	0.207/39.5
		3.6	10.3	0.209/91.3
	LEU-87-LE2	2.1	4.5	0.216/28.1
		1.1	2.0	0.225/11.3
		2.1	4.7	0.216/32.5
	LEU-88-TE2	3.4	6.4	0.208/35.6
		7.1	11.8	0.211/60.5
		7.7	28.3	0.206/285.2
027-04-003CTB	LEU-55-L	4.5	8.9	0.204/59.9
		4.8	10.9	0.203/90.0
		3.8	7.8	0.203/40.5
	LEU-56-T	5.0	15.4	0.204/97.2
		4.7	10.3	0.202/56.9
		5.7	14.9	0.203/155.2
	LEU-97-LE1	3.8	8.7	0.207/72.9
		4.2	13.6	0.207/130.6
		3.9	6.2	0.207/31.1
	LEU-98-TE1	7.1	17.4	0.208/125.1
		6.0	11.3	0.206/54.6
		1.8	2.6	0.206/14.3
	LEU-99-LE2	5.1	8.2	0.207/54.7
		4.3	8.9	0.206/61.2
		5.9	12.4	0.208/85.2
	LEU-100-TE2	4.9	9.9	0.216/55.1
		5.5	9.2	0.208/47.1
		4.9	9.4	0.208/46.6
027-04-004CTC	LEU-57-L	6.6	38.8	0.202/377.4

Sample ID	Specimen ID	Average area (μm²)	Standard deviation (μm²)	Min/Max area (μm²)
		3.8	7.3	0.03/37.8
		4.9	12.6	0.202/92.1
	LEU-58-T	2.5	5.2	0.203/78.9
		4.9	17.4	0.202/173.5
		4.4	10.8	0.202/64.0
	LEU-109-LE1	3.6	6.9	0.208/31.1
		1.5	2.1	0.207/9.5
		2.5	9.2	0.208/64.1
	LEU-110-TE1	1.1	2.1	0.208/11.4
		4.1	7.9	0.207/40.3
		4.6	11.7	0.211/132.4
		5.8	11.1	0.208/68.9
	LEU-111-LE2	1.1	2.6	0.211/14.7
		1.7	3.7	0.207/16.2
		2.2	3.8	0.208/21.1
		0.9	3.4	0.212/30.2
		2.3	7.4	0.208/28.9
	LEU-112-TE2	3.8	8.5	0.211/82.6
		4.4	8.1	0.207/49.3
		4.4	8.9	0.212/83.5
		5.9	10.6	0.208/52.3

Table A.20. Carbide particle size distribution in U Mo specimens without Zr (0.02 in.)

Sample ID	Specimen ID	Average area (μm²)	Standard deviation(μm²)	Min/Max area (μm²)
028-01-001CTA	LEU-59-L	7.3	16.3	0.823/106.9
		6.5	17.2	0.83/129.4
		17.7	34.4	1.1/270.3
		9.5	13.1	1.2/69.9
		23.3	58.3	1.2/406.6
	LEU-60-T	1.4	7.4	0.217/151.5
		1.1	6.4	0.202/160.2
		1.4	5.5	0.204/77.6
		1.9	10.4	0.206/208.4
		1.2	5.8	0.205/113.4
	LEU-91-LE1	1.4	7.7	0.206/124.6
		1.5	8.5	0.283/196.2
		3.4	9.7	0.229/79.2
		4.0	13.4	0.227/151.2
		4.1	11.3	0.226/90.9
	LEU-92-TE1	0.8	3.3	0.207/47.7

Sample ID	Specimen ID	Average area (μm²)	Standard deviation(μm²)	Min/Max area (μm²)
		1.2	5.4	0.282/124.6
		1.0	4.0	0.209/46.9
		1.9	8.3	0.226/111.0
		1.7	6.9	0.227/96.1
	LEU-93-LE2	1.1	4.8	0.209/84.1
		1.1	5.6	0.284/81.3
		0.9	5.7	0.206/86.7
		1.4	11.6	0.285/363.8
		1.0	5.1	0.205/86.5
	LEU-94-TE2	0.7	2.5	0.208/32.8
		1.6	7.6	0.283/161.8
		1.3	7.2	0.210/112.5
		0.7	1.8	0.208/15.8
		5.3	13.7	0.228/73.1
028-01-001CTB	LEU-61-L	1.4	7.5	0.217/179.6
		1.4	9.3	0.204/184.5
		1.1	4.4	0.206/72.3
		1.1	6.5	0.205/175.2
		1.1	5.2	0.206/86.8
	LEU-62-T	0.8	3.2	0.203/56.4
		1.4	7.1	0.219/152.7
		1.1	4.3	0.204/73.4
		1.5	7.7	0.205/147.9
		1.1	4.5	0.205/63.2
	LEU-101-LE1	1.4	6.1	0.211/62.7
		1.8	6.9	0.208/65.8
		1.1	5.0	0.207/59.5
		2.0	6.4	0.233/46.0
		1.9	6.1	0.232/47.6
	LEU-102-TE1	1.5	5.6	0.211/50.6
		1.0	4.5	0.208/57.0
		1.4	4.6	0.211/53.2
		1.8	6.3	0.206/61.6
		2.2	7.3	0.233/88.7
	LEU-103-LE2	0.9	2.2	0.208/21.4
		1.7	10.9	0.211/222.7
		1.5	7.3	0.232/108.8
		4.1	21.2	0.232/239.7
		3.2	14.5	0.233/183.2
	LEU-104-TE2	1.3	7.1	0.212/141.3
		2.5	13.6	0.206/160.8
		1.3	4.5	0.211/64.2

Sample ID	Specimen ID	Average area (μm²)	Standard deviation(μm²)	Min/Max area (μm²)
		1.4	5.2	0.208/62.8
		2.4	8.6	0.232/110.7
028-01-001CTC	LEU-63-L	1.3	7.1	0.219/110.9
		1.2	7.5	0.204/118.7
		0.9	5.1	0.204/99.6
		1.4	7.5	0.204/113.1
		2.1	9.3	0.206/150.3
	LEU-64-T	2.0	10.7	0.205/115.8
		1.3	4.2	0.23/42.2
		0.8	3.1	0.205/42.8
		1.5	6.3	0.205/85.5
	LEU-137-LE1	2.7	8.3	0.211/89.6
		1.3	5.2	0.207/52.7
		2.8	9.1	0.233/100.5
		3.1	9.0	0.233/69.5
		2.2	7.2	0.231/98.0
	LEU-138-TE1	2.4	10.1	0.211/117.2
		1.0	5.3	0.206/75.5
		5.2	14.5	0.232/159.2
		1.8	7.6	0.232/102.5
		1.5	6.3	0.234/83.3
	LEU-139-LE2	1.1	5.3	0.206/73.3
		1.2	4.8	0.212/71.9
		1.4	5.6	0.211/66.4
		2.6	6.4	0.232/44.7
		1.9	5.7	0.232/52.1
	LEU-140-TE2	2.1	7.3	0.231/84.2
		1.6	5.5	0.233/59.2
		1.9	5.7	0.233/59.2
028-01-002CTA	LEU-65-L	1.0	4.6	0.247/95.7
		0.6	2.7	0.205/41.4
		2.6	11.9	0.205/157.6
		1.4	8.4	0.204/172.7
		1.9	8.9	0.204/121.3
	LEU-66-T	1.3	5.3	0.202/69.6
		1.0	4.2	0.23/84.0
		1.0	4.9	0.202/90.0
		1.4	6.5	0.205/105.8
		0.8	3.7	0.205/77.6
	LEU-141-LE1	1.1	4.0	0.212/61.9
		0.9	4.6	0.207/70.0
		1.7	5.6	0.233/81.8

Sample ID	Specimen ID	Average area (μm²)	Standard deviation(μm²)	Min/Max area (μm²)
		3.9	8.6	0.233/57.5
		1.6	5.8	0.232/76.3
	LEU-142-TE1	2.1	10.3	0.213/183.9
		3.6	11.8	0.208/104.5
		2.2	9	0.212/125.9
		3.3	11.1	0.234/109.8
		1.5	5.3	0.232/67.9
	LEU-143-LE2	1.1	7.2	0.212/157.8
		2.0	11.5	0.206/177.3
		2.7	11.4	0.232/122.7
		1.7	8.3	0.233/124.9
		2.1	5.6	0.232/100.1
	LEU-144-TE2	1.8	7.8	0.207/93.5
		1.0	4.3	0.211/69.7
		2.5	8.2	0.232/55.9
		1.5	6.1	0.232/98.4
		2.1	7.4	0.233/70.7
028-01-002CTB	LEU-67-L	1.3	5.5	0.247/80.7
		2.1	10.2	0.203/134.7
		1.2	6.1	0.205/85.7
		1.1	4.9	0.206/73.0
		1.1	5.8	0.205/115.0
	LEU-68-T	1.7	8.4	0.202/100.9
		1.2	5.4	0.202/71.3
		1.3	6.3	0.202/67.1
		1.1	5.3	0.205/112.2
	LEU-175-TE-A	1.4	6.9	0.211/117.6
		1.4	7.6	0.208/110.4
		1.9	6.4	0.232/60.4
		1.9	7.6	0.233/105.5
		2.6	8.9	0.232/73.9
	LEU-176-LE-A	1.2	4.8	0.211/70.5
		1.1	3.8	0.206/40.2
		1.3	4.1	0.232/49.1
		1.3	4.2	0.232/57.1
		1.6	7.0	0.232/109.1
	LEU-177-TE-B	3.4	12.1	0.211/126.2
		2.6	12.1	0.207/144.2
		0.8	3.0	0.232/40.1
		0.8	3.4	0.233/42.4
		0.7	2.9	0.233/64.7
	LEU-178-LE-B	5.8	18.2	0.214/187.5

Sample ID	Specimen ID	Average area (μm²)	Standard deviation(μm²)	Min/Max area (μm²)
		1.4	3.1	0.208/21.9
		2.2	5.4	0.232/35.2
		2.6	10.3	0.232/154.2
		4.8	20.3	0.233/252.8
028-01-002CTC	LEU-69-L	3.5	13.6	0.205/109.7
		1.2	5.2	0.246/84.3
		0.5	2.7	0.206/100.9
		0.3	1.6	0.205/73.5
		1.0	4.3	0.206/62.8
	LEU-70-T	1.3	5.2	0.247/78.5
		1.2	5.5	0.206/78.8
		1.1	3.80	0.204/53.9
		0.6	2.9	0.206/93.0
		1.2	5.9	0.206/111.5
	LEU-179-TE-A	1.6	5.6	0.212/78.9
		1.1	4.6	0.210/113.3
		2.0	5.9	0.233/68.6
		1.8	5.4	0.233/62.5
		1.8	5.6	0.232/51.3
	LEU-180-LE-A	1.7	4.8	0.211/47.2
		2.5	6.9	0.206/47.5
		1.8	13.6	0.233/341.8
		1.6	4.3	0.232/46.8
		1.5	4.9	0.233/65.0
	LEU-181-TE-B	2.5	6.5	0.208/46.8
		1.8	5.7	0.207/72.3
		1.8	5.7	0.233/56.4
		2.6	6.3	0.232/45.2
		2.2	4.6	0.233/47.9
	LEU-182-LE-B	1.5	4.2	0.211/61.8
		1.3	3.9	0.208/45.1
		2.3	15.7	0.232/376.3
		1.9	4.1	0.233/36.7
		2.7	8.4	0.232/142.1

Table A.21. Carbide particle size distribution in U-Mo specimens without Zr (0.02 in.)

Sample ID	Specimen ID	Average area (μm²)	Standard deviation(μm²)	Min/Max area (μm²)
028-01-001CTA	LEU-59-L	7.3	16.3	0.823/106.9
		6.5	17.2	0.83/129.4
		17.7	34.4	1.1/270.3

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation(μm^2)	Min/Max area (μm^2)
		9.5	13.1	1.2/69.9
		23.3	58.3	1.2/406.6
	LEU-60-T	1.4	7.4	0.217/151.5
		1.1	6.4	0.202/160.2
		1.4	5.5	0.204/77.6
		1.9	10.4	0.206/208.4
		1.2	5.8	0.205/113.4
	LEU-91-LE1	1.4	7.7	0.206/124.6
		1.5	8.5	0.283/196.2
		3.4	9.7	0.229/79.2
		4.0	13.4	0.227/151.2
		4.1	11.3	0.226/90.9
	LEU-92-TE1	0.8	3.3	0.207/47.7
		1.2	5.4	0.282/124.6
		1.0	4.0	0.209/46.9
		1.9	8.3	0.226/111.0
		1.7	6.9	0.227/96.1
	LEU-93-LE2	1.1	4.8	0.209/84.1
		1.1	5.6	0.284/81.3
		0.9	5.7	0.206/86.7
		1.4	11.6	0.285/363.8
		1.0	5.1	0.205/86.5
	LEU-94-TE2	0.7	2.5	0.208/32.8
		1.6	7.6	0.283/161.8
		1.3	7.2	0.210/112.5
		0.7	1.8	0.208/15.8
		5.3	13.7	0.228/73.1
028-01-001CTB	LEU-61-L	1.4	7.5	0.217/179.6
		1.4	9.3	0.204/184.5
		1.1	4.4	0.206/72.3
		1.1	6.5	0.205/175.2
		1.1	5.2	0.206/86.8
	LEU-62-T	0.8	3.2	0.203/56.4
		1.4	7.1	0.219/152.7
		1.1	4.3	0.204/73.4
		1.5	7.7	0.205/147.9
		1.1	4.5	0.205/63.2
	LEU-101-LE1	1.4	6.1	0.211/62.7
		1.8	6.9	0.208/65.8
		1.1	5.0	0.207/59.5
		2.0	6.4	0.233/46.0

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation(μm^2)	Min/Max area (μm^2)
		1.9	6.1	0.232/47.6
	LEU-102-TE1	1.5	5.6	0.211/50.6
		1.0	4.5	0.208/57.0
		1.4	4.6	0.211/53.2
		1.8	6.3	0.206/61.6
		2.2	7.3	0.233/88.7
	LEU-103-LE2	0.9	2.2	0.208/21.4
		1.7	10.9	0.211/222.7
		1.5	7.3	0.232/108.8
		4.1	21.2	0.232/239.7
		3.2	14.5	0.233/183.2
	LEU-104-TE2	1.3	7.1	0.212/141.3
		2.5	13.6	0.206/160.8
		1.3	4.5	0.211/64.2
		1.4	5.2	0.208/62.8
		2.4	8.6	0.232/110.7
028-01-001CTC	LEU-63-L	1.3	7.1	0.219/110.9
		1.2	7.5	0.204/118.7
		0.9	5.1	0.204/99.6
		1.4	7.5	0.204/113.1
		2.1	9.3	0.206/150.3
	LEU-64-T	2.0	10.7	0.205/115.8
		1.3	4.2	0.23/42.2
		0.8	3.1	0.205/42.8
		1.5	6.3	0.205/85.5
	LEU-137-LE1	2.7	8.3	0.211/89.6
		1.3	5.2	0.207/52.7
		2.8	9.1	0.233/100.5
		3.1	9.0	0.233/69.5
		2.2	7.2	0.231/98.0
	LEU-138-TE1	2.4	10.1	0.211/117.2
		1.0	5.3	0.206/75.5
		5.2	14.5	0.232/159.2
		1.8	7.6	0.232/102.5
		1.5	6.3	0.234/83.3
	LEU-139-LE2	1.1	5.3	0.206/73.3
		1.2	4.8	0.212/71.9
		1.4	5.6	0.211/66.4
		2.6	6.4	0.232/44.7
		1.9	5.7	0.232/52.1
	LEU-140-TE2	2.1	7.3	0.231/84.2

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation(μm^2)	Min/Max area (μm^2)
		1.6	5.5	0.233/59.2
		1.9	5.7	0.233/59.2
028-01-002CTA	LEU-65-L	1.0	4.6	0.247/95.7
		0.6	2.7	0.205/41.4
		2.6	11.9	0.205/157.6
		1.4	8.4	0.204/172.7
		1.9	8.9	0.204/121.3
	LEU-66-T	1.3	5.3	0.202/69.6
		1.0	4.2	0.23/84.0
		1.0	4.9	0.202/90.0
		1.4	6.5	0.205/105.8
		0.8	3.7	0.205/77.6
	LEU-141-LE1	1.1	4.0	0.212/61.9
		0.9	4.6	0.207/70.0
		1.7	5.6	0.233/81.8
		3.9	8.6	0.233/57.5
		1.6	5.8	0.232/76.3
	LEU-142-TE1	2.1	10.3	0.213/183.9
		3.6	11.8	0.208/104.5
		2.2	9	0.212/125.9
		3.3	11.1	0.234/109.8
		1.5	5.3	0.232/67.9
	LEU-143-LE2	1.1	7.2	0.212/157.8
		2.0	11.5	0.206/177.3
		2.7	11.4	0.232/122.7
		1.7	8.3	0.233/124.9
		2.1	5.6	0.232/100.1
	LEU-144-TE2	1.8	7.8	0.207/93.5
		1.0	4.3	0.211/69.7
		2.5	8.2	0.232/55.9
		1.5	6.1	0.232/98.4
		2.1	7.4	0.233/70.7
028-01-002CTB	LEU-67-L	1.3	5.5	0.247/80.7
		2.1	10.2	0.203/134.7
		1.2	6.1	0.205/85.7
		1.1	4.9	0.206/73.0
		1.1	5.8	0.205/115.0
	LEU-68-T	1.7	8.4	0.202/100.9
		1.2	5.4	0.202/71.3
		1.3	6.3	0.202/67.1
		1.1	5.3	0.205/112.2

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation(μm^2)	Min/Max area (μm^2)
	LEU-175-TE-A	1.4	6.9	0.211/117.6
		1.4	7.6	0.208/110.4
		1.9	6.4	0.232/60.4
		1.9	7.6	0.233/105.5
		2.6	8.9	0.232/73.9
	LEU-176-LE-A	1.2	4.8	0.211/70.5
		1.1	3.8	0.206/40.2
		1.3	4.1	0.232/49.1
		1.3	4.2	0.232/57.1
		1.6	7.0	0.232/109.1
	LEU-177-TE-B	3.4	12.1	0.211/126.2
		2.6	12.1	0.207/144.2
		0.8	3.0	0.232/40.1
		0.8	3.4	0.233/42.4
		0.7	2.9	0.233/64.7
	LEU-178-LE-B	5.8	18.2	0.214/187.5
		1.4	3.1	0.208/21.9
		2.2	5.4	0.232/35.2
		2.6	10.3	0.232/154.2
		4.8	20.3	0.233/252.8
028-01-002CTC	LEU-69-L	3.5	13.6	0.205/109.7
		1.2	5.2	0.246/84.3
		0.5	2.7	0.206/100.9
		0.3	1.6	0.205/73.5
		1.0	4.3	0.206/62.8
	LEU-70-T	1.3	5.2	0.247/78.5
		1.2	5.5	0.206/78.8
		1.1	3.80	0.204/53.9
		0.6	2.9	0.206/93.0
		1.2	5.9	0.206/111.5
	LEU-179-TE-A	1.6	5.6	0.212/78.9
		1.1	4.6	0.210/113.3
		2.0	5.9	0.233/68.6
		1.8	5.4	0.233/62.5
		1.8	5.6	0.232/51.3
	LEU-180-LE-A	1.7	4.8	0.211/47.2
		2.5	6.9	0.206/47.5
		1.8	13.6	0.233/341.8
		1.6	4.3	0.232/46.8
		1.5	4.9	0.233/65.0
	LEU-181-TE-B	2.5	6.5	0.208/46.8

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation(μm^2)	Min/Max area (μm^2)
		1.8	5.7	0.207/72.3
		1.8	5.7	0.233/56.4
		2.6	6.3	0.232/45.2
		2.2	4.6	0.233/47.9
	LEU-182-LE-B	1.5	4.2	0.211/61.8
		1.3	3.9	0.208/45.1
		2.3	15.7	0.232/376.3
		1.9	4.1	0.233/36.7
		2.7	8.4	0.232/142.1

Table A.22. Carbide particle size distribution in U-Mo specimens without Zr (0.047 in.)

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
027-04-000DTA	LEU-05-L	6.3	19.5	0.229/136.7
		5.5	17.4	0.23/136.3
		7.3	19.8	0.229/111.8
		11.9	25.7	0.206/186.2
		17.3	33.2	0.205/190.5
	LEU-04-T	8.9	19.8	0.229/97.9
		9.6	18.5	0.202/74.1
		8.7	21.5	0.228/140.6
		14.9	22.4	0.204/101.7
		14.4	23.8	0.206/135.9
	LEU-71-LE	5.6	15.9	0.208/102.2
		13.2	27	0.213/182.7
		11.6	17.7	0.215/61.9
		8.9	17.1	0.208/73.7
	LEU-72-TE	14.9	25.8	0.211/176.8
		13.4	32.6	0.206/203.1
		9.7	18.1	0.227/139.9
		10.1	19.0	0.228/116.2
		14.4	24.0	0.227/137.9
	LEU-73-LC	13.1	33.2	0.211/352.5
		21.6	36.2	0.227/265.0
		21.2	36.4	0.226/291.4
		16.6	22.2	0.273/118.9
		16.6	26.8	0.273/138.2
	LEU-74-TC	11.1	21.7	0.211/160.6
		10.5	14.5	0.228/78.0
		11.3	18.8	0.228/154.1

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
		14.4	22.2	0.228/136.1
		12.6	17.4	0.227/99.6
027-04-002DTB	LEU-08-L	24.0	39.8	0.23/213.5
		8.4	18.3	0.205/101.3
		8.5	19.2	0.205/125.4
		12.2	28.6	0.206/189.3
		9.5	18.6	0.206/96.4
	LEU-07-T	5.9	15.6	0.229/105.9
		15.0	25.5	0.253/194.8
		19.6	33.4	0.254/234.5
		16.3	35.8	0.255/233.6
		11.8	18.3	0.254/88.2
	LEU-75-LE	13.8	34.1	0.212/233.0
		11.9	21.7	0.225/160.4
		11.2	16.5	0.228/73.5
		16.7	28.8	0.227/172.6
		13.1	21.4	0.227/132.6
	LEU-76-TE	10.0	16.5	0.211/84.5
		8.9	20	0.207/98.2
		11.2	18.8	0.228/108.9
		10.4	14.6	0.228/108.2
		11.1	14.7	0.226/63.7
	LEU-77-LC	21.3	41.8	0.211/340.9
		12.7	15.9	0.227/72.5
		16.6	24.2	0.227/138.7
		17.1	27	0.228/145.9
		29.3	32.2	0.275/125.5
	LEU-78-TC	8.1	18.5	0.285/202.5
		8.5	13.6	0.207/66.5
		15.1	25.5	0.228/156.8
		9.8	16.8	0.228/118.4
		11.3	18.9	0.228/162.5
027-04-000DTC	LEU-02-L	15.4	26.4	0.247/186.7
		15.2	26.4	0.202/162.1
		16.0	25.5	0.203/112.1
		16.0	31.9	0.206/242.0
		19.9	37.6	0.204/308.7
	LEU-01-T	9.7	25.2	0.247/240.4
		3.2	13.9	0.247/211.8
		1.7	9.4	0.247/185.1
		1.8	8.6	0.246/161.5

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
	LEU-117-LE	15.1	27.9	0.233/156.1
		11.3	16.4	0.232/104.1
		12.4	19.5	0.233/138.9
		11.8	14.4	0.232/77.1
		13.6	24.8	0.233/139.8
	LEU-118-TE	6.1	10.7	0.232/80.1
		10.2	18.4	0.232/142.1
		7.8	14.1	0.233/123.5
		9.8	17.4	0.232/134.9
		10.5	17.9	0.233/119.6
	LEU-119-LC	12.9	31.4	0.211/245.4
		16.5	22.7	0.233/111.0
		15.3	20.3	0.232/134.5
		12.7	21.9	0.232/194.5
		13.5	17.2	0.233/79.2
	LEU-120-TC	7.5	13.1	0.233/102.5
		11.9	19.4	0.233/118.3
		10.2	21.1	0.232/209.1
		8.4	12.4	0.232/65.4
		7.7	12.6	0.233/106.2
027-05-000DTA	LEU-11-L	14.4	22.7	0.229/129.5
		9.0	26.5	0.205/181.0
		7.9	22.2	0.254/210.0
		10.3	22.9	0.255/121.5
		13.0	33.1	0.253/255.3
	LEU-10-T	8.5	19.7	0.254/122.6
		12.3	29.7	0.253/263.6
		8.2	25.4	0.255/256.6
		5.0	15.8	0.255/208.7
		4.1	13.3	0.254/114.8
	LEU-79-LE	9.8	26.5	0.211/294.1
		19.5	40.7	0.206/239.2
		12.9	32.2	0.227/243.4
		12.5	22.7	0.227/127.7
		15.1	29.5	0.228/226.5
	LEU-80-TE	7.8	17.7	0.213/126.4
		12.1	25	0.208/122.3
		9.3	16.2	0.229/85.3
		13.8	19.8	0.227/99.1
		11.0	17.2	0.227/78.9
	LEU-81-LC	38.0	30.6	1.125/95.9

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
		6.7	19.1	0.208/90.0
		34.3	40.8	0.567/202.8
		10.6	38.2	0.209/241.0
		1.8	6.2	0.209/47.7
	LEU-82-TC	7.7	13.4	0.227/76.6
		11.5	18.7	0.228/115.0
		12.7	20.8	0.228/98.2
		13.6	20.6	0.227/98.7
		8.6	12.8	0.229/69.8
027-05-002DTB	LEU-14-L	9.8	21.5	0.255/151.3
		9.3	19.4	0.253/148.6
		14.2	24.1	0.254/154.0
		19.4	34.7	0.254/180.7
		14.8	34.8	0.255/253.9
	LEU-13-T	11.8	22.3	0.205/190.1
		13.4	24.2	0.205/134.6
		10.8	20.0	0.204/132.5
		5.0	13.5	0.204/112.7
		11.2	26.6	0.205/272.5
	LEU-113-LE	7.7	16.8	0.233/108.1
		9.9	18.9	0.233/146.4
		10.5	24.1	0.232/183.7
		13.3	24.2	0.232/159.7
		13.6	19.9	0.233/95.8
	LEU-114-TE	9.5	13.3	0.232/94.5
		7.3	12.9	0.233/88.6
		8.1	16.2	0.233/126.9
		7.7	15.3	0.233/97.9
		9.6	16.8	0.233/92.7
	LEU-115-LC	11.8	24.4	0.233/165.5
		12.6	23.2	0.233/116.5
		14.5	24.5	0.233/147.6
		10.1	29.9	0.233/235.4
		14.4	24.3	0.233/136.2
	LEU-116-TC	9.1	13.7	0.232/74.2
		7.2	17.9	0.233/148.6
		10.7	22.6	0.233/188.7
		9.4	16.6	0.233/108.4
		9.9	15.6	0.232/70.5
027-05-000DTC	LEU-17-L	10.0	27.3	0.229/223.7
		12.4	21.8	0.237/128.5

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
		14.6	33.3	0.238/230.8
		8.2	19.5	0.237/121.1
		12.2	24.8	0.236/174.8
	LEU-16-T	13.5	20.0	0.207/83.1
		15.3	23.4	0.206/108.9
		19.7	28.6	0.229/140.2
		31.0	38.0	0.213/159.3
		22.2	32.6	0.205/244.8
	LEU-105-LE1	11.9	26.4	0.211/212.4
		14.2	27.2	0.207/157.1
		20.1	38.6	0.233/366.3
		6.7	12.3	0.233/86.5
		9.8	13.3	0.233/61.3
	LEU-106-TE1	9.7	23	0.232/178.2
		11.0	22.9	0.234/173.4
		15.4	52.3	0.233/547.0
		10.7	58.3	0.232/908.3
		10.6	17.4	0.233/122.5
	LEU-107-LC	13.6	23.8	0.232/144.8
		10.7	18.3	0.232/106.3
		14.8	31.3	0.232/260.3
		13.6	26.2	0.232/257.8
		6.8	12.7	0.233/85.2
	LEU-108-TC	8.8	13.1	0.233/76.0
		14.1	23.9	0.233/199.3
		8.5	14.1	0.232/104.7
		9.3	15.1	0.232/116.2
		11.8	25	0.233/205.3

Table A.23. Carbide particle size distribution in U-Mo specimens with Zr (0.047 in.)

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
030-01-001CTA	LEU-37-L	5.4	13.5	0.229/142.3
		5.5	11.3	0.202/65.4
		3.5	9.9	0.229/77.6
		5.0	13.7	0.201/89.5
		4.0	12.9	0.202/112.9
	LEU-38-T	3.5	12.8	0.203/118.9
		4.7	15.4	0.202/148.7
		5.9	14.1	0.201/102.3

	LEU-167-TE-A	3.5	9.7	0.207/65.2
		4.3	10.5	0.207/68.0
		4.5	9.2	0.208/83.3
	LEU-168-LE-A	1.3	4.2	0.208/23.5
		2.2	3.7	0.206/19.3
		3.2	5.2	0.208/20.5
	LEU-169-TE-B	1.8	7.8	0.206/49.7
		3.6	8.6	0.208/46.5
		3.9	9.4	0.206/64.9
	LEU-170-LE-B	3.0	6.4	0.207/36.8
		3.0	7.0	0.207/45.2
030-01-004CTB	LEU-39-L	2.5	6.8	0.202/57.4
		3.4	8.7	0.229/71.1
		4.5	12.6	0.201/83.4
		4.2	10.5	0.229/110.0
		5.0	11.2	0.213/66.1
	LEU-40-T	7.8	25.5	0.216/209.4
		2.8	6.6	0.202/42.8
		4.9	14.5	0.201/115.3
	LEU-125-LE1	3.4	7.4	0.207/48.9
		3.0	4.4	0.207/16.0
		1.8	3.6	0.207/18.4
	LEU-126-TE1	2.6	4.2	0.207/15.5
		4.2	12.2	0.207/91.9
		6.0	14.1	0.216/96.9
	LEU-127-LE2	3.5	6.4	0.209/42.6
		3.1	7.0	0.207/52.9
		4.7	12.2	0.206/79.7
	LEU-128-TE2	4.6	16.7	0.208/117.4
		5.1	12.2	0.206/75.5
		3.8	9.4	0.206/50.7
030-01-001CTC	LEU-41-L	5.2	15.8	0.201/142.4
		2.9	14.9	0.202/176.0
		3.8	10.4	0.202/109.4
	LEU-42-T	3.2	6.7	0.201/32.0
	LEU-121-LE1	2.2	4.0	0.207/19.4
		3.9	7.9	0.207/41.4
		3.6	8.1	0.208/55.7
	LEU-122-TE1	2.5	4.3	0.207/20.9
		4.3	14.2	0.208/127.5
		5.1	12.2	0.206/99.1
	LEU-123-LE2	3.1	5.8	0.208/36.3
		4.0	8.6	0.207/53.3

		3.4	7.3	0.209/46.2
	LEU-124-TE2	2.6	5.0	0.206/24.3
		3.6	6.5	0.206/34.2
		4.3	10.4	0.208/66.7

Table A.24. Carbide particle size distribution in U-10Mo specimens with Zr (0.02 in.)

Sample ID	Specimen ID	Average area (μm²)	Standard deviation (μm²)	Min/Max area (μm²)
029-01-001CTA	LEU-25-L	2.1	9.2	0.228/120.0
		3.0	11.7	0.202/92.4
		1.1	6.3	0.229/127.9
		1.7	10.2	0.201/138.9
		1.3	7.4	0.23/155.2
	LEU-26-T	1.5	7.8	0.23/129.6
		1.7	10.6	0.202/148.1
		1.1	5.5	0.231/121.7
		1.2	7.6	0.202/140.2
		1.6	6.5	0.202/107.7
	LEU-159-TE-A	1.5	7	0.211/130.0
		1.6	6.1	0.207/55.6
		4.2	10.2	0.232/74.6
		3.8	9.4	0.232/90.3
		2.5	6.7	0.233/50.6
	LEU-160-LE-A	2.5	11.5	0.207/118.0
		2.2	11.7	0.211/298.4
		2.2	7.9	0.232/90.3
		1.7	5.2	0.233/50.0
		2.4	7.1	0.233/85.7
	LEU-161-TE-B	1.4	4.5	0.212/51.9
		1.8	6.1	0.211/61.4
		1.9	6.5	0.233/75.6
		2.0	4.9	0.232/42.1
		1.7	5.6	0.233/46.8
	LEU-162-LE-B	1.6	4.9	0.208/36.0
		5.6	18.5	0.211/138.8
		2.9	8.4	0.233/80.0
		3.3	13.5	0.232/132.9
		1.9	5.9	0.233/62.2
029-01-004CTB	LEU-23-L	1.2	4.5	0.201/54.1
		1.2	4.7	0.228/60.2
		1.0	4.1	0.202/62.6
		1.5	8.6	0.23/147.9
		1.2	9.3	0.202/171.9
	LEU-24-T	1.2	6.5	0.23/148.0
		1.2	5.2	0.202/72.1
		1.3	7.8	0.227/205.3
		1.2	7.5	0.201/107.9
		2.0	10.1	0.202/106.3
	LEU-133-LE1	1.2	4.7	0.212/82.3

Sample ID	Specimen ID	Average area (μm²)	Standard deviation (μm²)	Min/Max area (μm²)
		1.0	4.3	0.207/45.1
		2.8	8.3	0.232/78.9
		2.3	5.5	0.232/47.2
		2.4	6.5	0.233/45.9
	LEU-134-TE1	1.4	6.4	0.213/83.1
		1.5	7.2	0.207/88.4
		1.7	6.9	0.232/68.7
		2.8	8.8	0.232/82.2
		2.5	8.1	0.233/85.3
	LEU-135-LE2	1.5	4.8	0.208/40.2
		2.8	9.7	0.212/131.1
		1.1	3.3	0.233/32.4
		2.0	5.9	0.233/56.6
		3.8	14.1	0.233/168.0
	LEU-136-TE2	2.1	6.8	0.211/54.2
		1.1	4.9	0.207/66.7
		1.5	6.7	0.208/79.4
		1.8	5.7	0.233/50.3
029-01-001CTC	LEU-19-L	1.0	4.5	0.229/92.1
		1.0	3.5	0.201/52.4
		1.0	6.9	0.228/210.5
		1.5	8.1	0.229/171.9
		1.4	5.7	0.203/52.3
	LEU-20-T	0.9	3.8	0.201/46.3
		1.0	4.4	0.23/94.8
		0.9	4.6	0.203/85.9
		0.9	4.5	0.229/117.2
		0.8	4.3	0.201/57.4
	LEU-129-LE1	2.2	8.2	0.212/130.5
		1.8	6.2	0.207/45.1
		1.8	5.2	0.231/56.0
		2.2	7.6	0.232/107.1
		2.2	7.2	0.232/68.8
	LEU-130-TE1	2.1	7.7	0.210/117.8
		1.9	5.7	0.208/53.4
		1.9	7.9	0.206/74.8
		5.3	33.7	0.233/619.2
		3.5	8.8	0.233/87.4
	LEU-131-LE2	1.5	6.7	0.212/113.6
		1.3	3.3	0.207/29.0
		2.1	6.1	0.233/79.7
		2.2	6.6	0.232/54.7

Sample ID	Specimen ID	Average area (μm²)	Standard deviation (μm²)	Min/Max area (μm²)
		3.1	6.4	0.233/44.6
	LEU-132-TE2	3.1	9.4	0.232/100.7
		2.0	4.8	0.233/39.0
029-01-002CTA	LEU-29-L	1.5	8.8	0.229/143.3
		2.0	13.4	0.202/164.1
		1.3	6.9	0.229/128.0
		1.2	7.3	0.229/154.8
		1.3	7.2	0.202/120.0
	LEU-30-T	0.9	3.4	0.229/56.6
		0.9	4.2	0.202/57.3
		1.8	6.6	0.229/65.5
		1.1	4.9	0202/61.3
		1.1	5.7	0.202/70.1
	LEU-163-TE-A	1.6	8.4	0.211/166.2
		2.0	8.5	0.207/90.7
		2.0	6.7	0.232/68.5
		1.6	7.6	0.233/136.4
		1.7	5.9	0.232/55.3
	LEU-164-LE-A	0.8	2.5	0.206/28.9
		1.1	5.2	0.211/99.1
		1.4	5.5	0.233/78.9
		1.4	5.7	0.233/77.5
		1.7	5.2	0.233/50.3
	LEU-165-TE-B	1.5	5.9	0.211/69.1
		1.2	5.5	0.212/90.9
		1.8	4.8	0.232/42.0
		2.0	6.3	0.233/58.7
		2.1	7.1	0.233/53.5
	LEU-166-LE-B	2.1	6.3	0.206/43.6
		1.8	6.8	0.213/89.1
		4.3	11.1	0.232/85.9
		3.6	9.7	0.233/90.1
		2.2	6.0	0.233/53.8
029-01-006CTB	LEU-31-L	1.1	5.7	0.228/120.4
		1.0	4.4	0.201/67.5
		1.0	3.6	0.229/78.1
		1.0	4.1	0202/62.6
		1.2	5.7	0.23/128.8
	LEU-32-T	1.0	5.5	0.23/146.0
		1.6	5.2	0.231/67.9
		1.0	4.3	0.202/58.2
		1.2	5.7	0.229/135.0

Sample ID	Specimen ID	Average area (μm²)	Standard deviation (μm²)	Min/Max area (μm²)
		1.3	8.0	0.202/151.0
	LEU-183-TE-A	0.8	2.7	0.208/39.5
		0.8	3.3	0.208/49.4
		1.3	4.3	0.234/58.8
		3.1	29.8	0.232/592.3
		1.8	12.6	0.233/303.9
	LEU-184-LE-A	1.3	6.5	0.206/95.6
		3.3	24.4	0.211/469.5
		0.9	3.3	0.232/48.6
		2.2	5.3	0.233/36.1
		2.9	9.3	0.233/118.4
	LEU-185-TE-B	0.9	3.4	0.211/63.6
		1.2	4.46	0.208/72.9
		1.6	6.4	0.233/108.1
		1.4	4.1	0.233/55.1
		1.3	3.1	0.233/33.2
	LEU-186-LE-B	2.3	7	0.211/112.1
		1.7	6.6	0.233/130.8
		2.2	6.2	0.233/91.5
		1.8	5.4	0.233/71.9
029-01-002CTC	LEU-33-L	1.8	6.9	0.203/56.8
		1.8	8.7	0.229/164.4
		1.4	5.4	0.201/66.7
		1.1	5.2	0.228/101.2
		0.9	4.8	0.201/95.7
	LEU-34-T	1.4	8.4	0.202/130.5
		1.1	4.1	0.229/55.6
		1.1	4.3	0.202/43.8
		1.0	3.5	0.23/56.3
		0.7	1.7	0.201/18.6
	LEU-187-TE-A	1.7	5.8	0.209/48.1
		1.6	4.3	0.284/57.8
		1.7	4.3	0.206/31.9
		3.2	5.3	0.233/35.2
		3.2	5.4	0.234/38.5
	LEU-188-LE-A	3.7	7.3	0.285/56.8
		0.9	3.2	0.207/41.7
		2.7	6.9	0.233/96.3
		2.1	4.8	0.233/42.1
		2.4	5	0.233/40.2
	LEU-189-TE-B	0.8	3.2	0.207/35.1
		0.9	3.4	0.212/65.9

Sample ID	Specimen ID	Average area (μm²)	Standard deviation (μm²)	Min/Max area (μm²)
		1.9	5.7	0.233/65.8
		1.4	4.2	0.233/52.8
		1.6	4.8	0.233/52.9
	LEU-190-LE-B	1.0	3.4	0.211/64.4
		0.8	3.1	0.207/42.9
		2.2	5.3	0.233/47.1
		2.2	6.1	0.232/70.6
		3.0	5.7	0.232/37.4

Table A.25. Carbide particle size distribution in U-10Mo specimens with Zr (0.047 in.)

Sample ID	Specimen ID	Average area (μm²)	Standard deviation (μm²)	Min/Max area (μm²)
029-01-000DTA	LEU-43-L	1.2	5.2	0.23/72.3
		1.2	7.7	0.205/114.7
		1.9	9.5	0.202/99.3
		1.8	10.1	0.206/152.3
		2.3	11.8	0.204/159.5
	LEU-44-T	0.8	6.6	0.202/109.8
		1.4	9.1	0.226/174.4
		1.0	6.0	0.228/112.3
		1.0	7.2	0.202/133.3
		1.9	8.5	0.253/112.2
	LEU-145-LE-A	2.1	8.2	0.212/82.9
		1.6	7.3	0.207/63.4
		1.6	6.9	0.211/81.2
		2.1	8.1	0.207/62.1
	LEU-146-TE-A	4.4	11.4	0.211/78.4
		3.5	11.5	0.233/99.4
		5.3	12.5	0.233/90.6
		5.8	11.5	0.233/55.5
	LEU-147-LE-B	0.9	3.8	0.209/44.6
		1.2	4.8	0.233/52.0
		5.6	9.7	0.234/38.2
		1.1	3.8	0.233/35.5
		1.6	5.4	0.233/52.3
	LEU-148-TE-B	3.0	8.8	0.232/77.3
		4.4	11.2	0.232/74.1
		2.2	7.3	0.234/61.3
		6.7	18.7	0.233/139.9
		3.3	9.8	0.233/56.6
029-01-002DTB	LEU-45-L	2.3	10.2	0.202/81.0

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
		1.3	8.0	0.211/124.3
		2.1	11.6	0.228/189.6
		1.8	13.9	0.201/167.5
		3.5	16.5	0.205/174.3
	LEU-46-T	1.4	8.3	0.228/138.9
		1.4	7.1	0.202/86.5
	LEU-149-LE-A	0.7	2	0.207/34.4
		1.7	8.3	0.234/106.8
		1.5	9.5	0.233/169.1
		1.8	6.8	0.233/67.5
		2.0	8.4	0.233/88.1
	LEU-150-TE-A	1.5	5.3	0.208/46.6
		1.5	6.4	0.207/74.4
		2.3	7.4	0.233/77.6
		1.3	5.5	0.232/59.9
		1.8	5.4	0.233/41.9
	LEU-151-LE-B			
	LEU-152-TE-B			
029-01-000DTC	LEU-49-L	4.1	17.7	0.202/167.0
		2.4	8.8	0.229/82.4
		1.4	6.5	0.201/60.4
		2.6	10.4	0.228/101.1
		1.7	7.4	0.201/59.7
	LEU-50-T	1.7	6.9	0.229/90.1
		1.1	5.0	0.202/55.0
		2.4	7.9	0.228/95.0
		1.4	5.4	0.202/51.2
		2.6	8.7	0.228/70.1
	LEU-153-LE-A	2.1	6.4	0.213/61.3
		2.4	5.4	0.232/29.8
		3.6	9.3	0.233/63.4
		1.6	4	0.233/28.9
		2.2	5.3	0.233/30.6
	LEU-154-TE-A	0.9	3.3	0.208/27.7
		1.3	5.4	0.231/66.3
		1.3	5	0.233/50.1
		3.9	10.3	0.232/106.1
		4.3	10.8	0.233/85.8
	LEU-157-TE-B	2.5	6.1	0.233/41.2
		2.7	6.3	0.232/52.7
		2.7	6	0.233/49.9

Sample ID	Specimen ID	Average area (μm^2)	Standard deviation (μm^2)	Min/Max area (μm^2)
		2.2	4.2	0.233/24.9
		2.7	6.3	0.232/48.7
	LEU-158-LE-B	1.1	3.5	0.208/26.8
		4.7	10	0.232/52.8
		1.9	4.7	0.233/44.0
		3.3	6.9	0.232/41.7
		2.9	7.1	0.233/37.9
030-01-000DTA	LEU-51-L	5.2	20.3	0.213/231.0
		2.6	9.1	0.208/79.9
	LEU-52-T	13.7	29.4	0.202/120.8
		4.6	15.9	0.228/145.2
		9.5	22.8	0.201/120.7
		6.3	12.7	0.201/63.7
		5.7	13.5	0.235/101.7
	LEU-171-TE-A	5.8	22.1	0.233/196.1
		4.3	13.8	0.233/88.4
		5.7	19.3	0.234/184.8
		6.4	15.1	0.232/79.8
		6.4	17.5	0.232/105.0
	LEU-172-LE-A	4.4	12.1	0.233/78.7
		10.8	34	0.233/319.5
		6.2	28.6	0.233/313.2
		8.8	22.8	0.232/144.7
		4.9	11.9	0.232/68.5
	LEU-173-TE-B	7.7	16.9	0.233/69.4
		4.7	13.8	0.233/83.3
		7.4	18	0.232/88.0
		6.5	21.4	0.232/207.3
		7.4	17.6	0.232/122.5
	LEU-174-LE-B	6.0	17.2	0.233/154.2
		4.9	18.8	0.232/168.9
		6.0	12.9	0.233/75.4
		4.9	8.9	0.233/57.6
		5.6	14.6	0.233/138.0

A.5 Fuel Meat Thickness

Table A.26. Fuel meat thickness of U-10Mo specimens without Zr (PNNL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
0.009 (229 µm)	027-04-003CTA	LEU-53-L	223.5	6.2	214.2/231.3
		LEU-54-T	219.9	4.2	209.8/224.6
		LEU-85-LE1	201.6	3.2	194.7/206.1
		LEU-86-TE1	197.8	3.1	191.3/204.9
		LEU-87-LE2	166.1	3.8	157.8/172.7
		LEU-88-TE2	199.6	3.1	194.2/204.1
	027-04-003CTB	LEU-55-L	216.8	4.6	207.3/222.0
		LEU-56-T	222.9	1.7	219.4/225.8
		LEU-97-LE1	211.1	1.2	208.7/213.1
		LEU-98-TE1			
		LEU-99-LE2	218.8	1.7	213.7/221.2
		LEU-100-TE2	218.6	2.7	212.8/223.2
	027-04-004CTC	LEU-57-L	222.0	6.9	212.4/231.1
		LEU-58-T	224.4	2.0	220.4/228.3
		LEU-109-LE1	150.4	7.9	132.1/161.3
		LEU-110-TE1			
		LEU-111-LE2	144.1	7.5	132.2/155.2
		LEU-112-TE2	207.7	11.3	183.5/219.9
0.0245 (622 µm)	028-01-001CTA	LEU-59-L	621.5	2.7	614.1/624.5
		LEU-60-T	621.2	2.5	616.8/624.3
		LEU-91-LE1	600.2	6.2	581.5/608.7
		LEU-92-TE1	581.1	12.8	563.1/598.3
		LEU-93-LE2	589.6	2.7	583.3/593.4
		LEU-94-TE2	594.5	8.7	565.4/604.1
	028-01-001CTB	LEU-61-L	599.1	3.2	595.3/605.6
		LEU-62-T	604.3	2.2	601.6/608.8
		LEU-101-LE1	544.8	2.5	539.9/550.0
		LEU-102-TE1	560.2	11.5	531.1/574.7
		LEU-103-LE2			
		LEU-104-TE2	540.7	13.7	517.2/556.0
	028-01-001CTC	LEU-63-L	621.2	3.9	615.3/628.3
		LEU-64-T	617.2	3.7	611.3/624.5
		LEU-137-LE1	626.5	2.2	619.5/629.3
		LEU-138-TE1	627.1	1.7	624.4/630.4
		LEU-139-LE2	626.6	2.8	622.5/632.6
		LEU-140-TE2	619.4	6.2	604.1/630.2

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
	028-01-002CTA	LEU-65-L	631.3	3.5	626.4/637.7
		LEU-66-L	628.5	1.6	624.4/630.5
		LEU-141-LE1	622.9	5.2	612.1/630.7
		LEU-142-TE1	627.2	3.0	622.1/635.8
		LEU-143-LE2	630.1	2.1	627.7/634.2
		LEU-144-TE2	615.4	7.5	601.1/625.0
	028-01-002CTB	LEU-67-L	628.0	2.9	622.6/632.5
		LEU-68-T	630.8	3.5	624.7/635.3
		LEU-175-TE-A	641.2	2.7	636.7/644.9
		LEU-176-LE-A	613.6	5.5	596.9/620.7
		LEU-177-TE-B	558.3	6.2	535.9/568.9
		LEU-178-LE-B	593.2	13.8	564.0/609.9
	028-01-002CTC	LEU-69-L	605.3	10.9	588.1/620.0
		LEU-70-T	620.7	3.5	612.9/627.0
		LEU-179-TE-A	583.1	8.0	557.2/593.2
		LEU-180-LE-A	542.7	14.1	515.3/562.2
		LEU-181-TE-B	588.5	7.6	580.4/602.2
		LEU-182-LE-B	472.9	26.5	418.5/515.6
0.047 (1194 µm)	027-04-000DTA	LEU-04-T	1153.0	26.9	1099.5/1209.9
		LEU-05-L	1168.9	14.4	1148.5/1198.0
		LEU-71-LE	1171.3	11.3	1141.4/1188.9
		LEU-72-TE	1172.8	14.2	1134.6/1198.0
		LEU-73-LC	1201.2	20.8	1170.2/1245.7
		LEU-74-TC	1197.1	19.8	1162.6/1237.4
	027-04-002DTB	LEU-07-T	1105.4	23.1	1147.4/1134.4
		LEU-08-L	1152.5	23.5	1113.9/1203.5
		LEU-75-LE	1200.2	15.1	1183.3/1235.9
		LEU-76-TE	1250.9	23.9	1206.1/1302.7
		LEU-77-LC	1166.8	9.0	1153.9/1182.7
		LEU-78-TC	1210.9	31.5	1160.5/1267.1
	027-04-000DTC	LEU-01-T	1164.9	52.2	1042.5/1238.8
		LEU-02-L	1145.7	56.7	1075.9/1247.5
		LEU-117-LE	1209.6	19.9	1181.5/1252.5
		LEU-118-TE	1182.9	38.2	1085.2/1238.4
		LEU-119-LC	1211.9	17.9	1186.8/1250.0
		LEU-120-TC	1211.6	22.0	1165.0/1239.8
	027-05-000DTA	LEU-10-T	1167.6	24.1	1131.6/1204.3
		LEU-11-L	1154.1	22.3	1124.6/1186.2
		LEU-79-LE	1186.6	15.1	1145.3/1204.3
		LEU-80-TE	1155.7	21.0	1124.5/1200.0

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
		LEU-81-LC	1152.4	22.8	1128.4/1193.9
		LEU-82-TC	1167.2	29.0	1107.5/1205.3
	027-05-002DTB	LEU-13-T	1143.8	23.4	1111.6/1193.1
		LEU-14-L	1203.7	45.3	1128.7/1267.6
		LEU-113-LE	1168.2	18.4	1144.4/1204.0
		LEU-114-TE	1182.5	18.3	1149.0/1203.0
		LEU-115-LC	1245.1	10.1	1227.6/1264.4
		LEU-116-TC	1175.0	34.7	1128.1/1234.3
	027-05-000DTC	LEU-16-T	1214.5	46.4	1163.3/1308.4
		LEU-17-L	1226.5	43.1	1154.5/1314.5
		LEU-105-LE1	1221.7	19.6	1192.7/1257.9
		LEU-106-TE1	1217.6	17.1	1180.6/1245.3
		LEU-107-LC	1227.8	34.4	1172.9/1279.5
		LEU-108-TC	1251.9	34.4	1186.8/1299.6

Table A.27. Fuel meat thickness of U-10Mo specimens without Zr (INL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
0.0235 (597 µm)	027-05-002CTA	met 1 trans	564.8	10.4	543.1/578.9
		met 1 long	581.6	13.2	545.8/598.0
		met 2 trans	597.2	3.2	593.8/602.3
		met 2 long	599.2	15.3	572.7/621.3
		met 3 trans	582.8	6.5	571.7/594.5
		met 3 long	576.9	12.7	553.5/593.6
	027-05-002CTB	met 1 trans	590.5	6.0	581.2/598.0
		met 1 long	597.9	3.9	589.5/604.4
		met 2 trans	616.0	1.8	612.8/619.1
		met 2 long	600.2	4.9	591.9/608.7
		met 3 trans	612.5	3.8	604.4/619.1
		met 3 long	607.1	2.7	602.2/612.8
	027-05-002CTC	met 1 trans	589.7	9.0	575.3/602.1
		met 1 long	599.4	4.4	592.6/608.5
		met 2 trans	623.4	2.2	620.3/625.9
		met 2 long	622.1	8.8	606.5/633.0
		met 3 trans	607.3	4.7	600.5/613.2
		met 3 long	600.2	12.1	579.9/619.7

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
0.0245 (622 µm)	028-05-001CTA	met 1 trans	604.9	5.7	593.0/612.8
		met 1 long	616.7	4.7	606.5/625.8
		met 2 trans	632.7	2.5	627.6/636.1
		met 2 long	633.0	4.4	623.4/638.2
		met 3 trans	618.9	6.09	608.4/627.6
		met 3 long	593.4	7.2	579.8/604.5
	028-05-001CTB	met 1 trans	613.7	5.01	603.6/622.7
		met 1 long	618.5	2.3	614.7/621.1
		met 2 trans	635.1	4.6	629.1/642.1
		met 2 long	633.9	3.3	627.4/640.1
		met 3 trans	633.4	3.3	627.4/638.5
		met 3 long	625.4	4.1	616.4/633.8
0.047 (1194 µm)	028-01-000DTA	met 1 trans	1231.2	41.4	1170.6/1293.2
		met 1 long	1159.7	35.3	1124.2/1236.2
		met 2 trans	1223.2	31.1	1164.3/1274.2
		met 2 long	1233.7	29.9	1202.3/1299.5
		met 3 trans	1136.0	22.2	1097.0/1159.7
		met 3 long	1235.3	32.6	1170.6/1284.7
	028-01-002DTB	met 1 trans	1241.4	41.4	1177.1/1288.9
		met 1 long	1222.1	23.2	1181.3/1253.1
		met 2 trans	1252.6	35.2	1210.6/1319.8
		met 2 long	1265.1	37.7	1210.8/1323.1
		met 3 trans	1293.8	32.7	1259.4/1335.4
		met 3 long	1273.9	37.9	1223.5/1346.1
	028-01-000DTC	met 1 trans	1199.3	15.8	1175.6/1219.9
		met 1 long	1188.8	32.2	1145.6/1250.6
		met 2 trans	1232.7	23.1	1204.1/1277.1
		met 2 long	1215.2	30.2	1174.0/1274.0
		met 3 trans	1238.2	27.9	1207.4/1270.8
		met 3 long	1219.5	26.7	1193.1/1269.1
	028-05-000DTA	met 1 trans	1245.2	22.1	1208.9/1277.0
		met 1 long	1233.7	22.7	1200.9/1283.4
		met 2 trans	1261.1	29.9	1212.5/1303.9
		met 2 long	1255.6	44.4	1184.4/1315.3
		met 3 trans	1240.9	15.3	1207.3/1255.1
		met 3 long	1231.5	22.7	1200.9/1281.8
	028-05-002DTB	met 1 trans	1198.6	8.4	1185.2/1216.8
		met 1 long	1190.9	11.11	1174.2/1214.4
		met 2 trans	1202.8	11.5	1187.5/1225.2
		met 2 long	1201.6	13.9	1179.6/1233.2

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
		met 3 trans	1129.6	18.6	1093.7/1164.3
		met 3 long	1156.4	26.1	1098.1/1194.3
	028-05-000DTC	met 1 trans	1218.2	17.4	1197.8/1256.5
		met 1 long	1228.5	24.6	1193.1/1288.3
		met 2 trans	1235.7	20.7	1198.2/1257.35
		met 2 long	1229.9	25.1	1197.8/1281.8
		met 3 trans	1256.3	28.2	1208.9/1307.2
		met 3 long	1253.2	34.3	1190.1/1337.2

Table A.28. Fuel meat thickness of U-10Mo specimens without Zr (LANL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/ Max (µm)
0.009 (229 µm)	027-04-005CTA	13365-5A (T)	203.52	1.22	201.35/204.97
		13365-4B (L)	204.60	1.66	202.26/206.77
		13365-5C (T)	214.27	1.41	212.19/217.61
		13365-5D (L)	218.40	1.16	216.70/220.09
		13365-5E (T)	211.15	1.23	209.26/212.64
		13365-5F (L)	214.74	1.29	213.32/216.70
	027-04-006CTB	13365-6A (T)	205.40	6.24	201.35/222.81
		13365-6B (L)	219.68	2.67	214.67/222.12
		13365-6C (T)	235.80	0.83	234.31/237.02
		13365-6D (L)	232.48	0.78	231.60/233.63
		13365-6E (T)	224.70	1.38	222.80/226.86
		13365-6F (L)	223.81	1.64	220.09/225.51
	027-04-006CTC	13365-7A (T)	227.95	1.32	225.51/229.57
		13365-7B (L)	225.64	1.42	223.48/228.22
		13365-7C (T)	242.43	0.87	241.16/243.87
		13365-7D (L)	240.47	1.76	235.67/241.76
		13365-7E (T)	226.86	1.75	224.83/229.57
		13365-7F (L)	230.11	1.49	226.86/232.28
0.0245 (622 µm)	028-05-001CTC	13365-8A (T)	598.65	9.03	577.88/607.68
		13365-8B (L)	626.02	3.00	621.95/630.08
		13365-8C (T)	647.49	1.62	644.70/649.21
		13365-8D (L)	640.10	3.47	634.77/646.51
		13365-8E (T)	646.14	2.96	641.08/650.11

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/ Max (µm)
0.0245 (622 µm)		13365-8F (L)	643.70	0.99	642.89/645.60
	028-05-002CTA	13365-9A (T)	621.04	2.51	614.90/623.93
		13365-9B (L)	623.75	2.28	619.41/625.73
		13365-9C (T)	630.25	1.53	628.44/632.96
		13365-9D (L)	645.69	1.31	643.79/647.40
		13365-9E (T)	620.59	2.37	615.80/623.93
		13365-9F (L)	627.72	1.85	623.93/630.25
	028-05-002CTB	13365-10A (T)	634.01	2.89	630.08/639.57
		13365-10B (L)	634.85	1.88	632.05/637.47
		13365-10C (T)	649.21	1.35	646.50/651.02
		13365-10D (L)	649.93	1.19	648.31/651.92
		13365-10E (T)	630.79	1.91	628.44/633.86
		13365-10F (L)	632.24	0.99	631.22/634.62
	028-05-002CTC	13365-11A (T)	571.65	2.77	567.95/577.88
		13365-11B (L)	483.07	3.38	476.75/487.59
		13365-11C (T)	626.00	1.35	623.03/627.54
		13365-11D (L)	616.61	1.56	614.90/620.32
		13365-11E (T)	622.93	2.50	619.41/626.64
		13365-11F (T)	615.62	2.12	612.19/619.41

Table A.29. Fuel meat thickness of U-10Mo specimens with Zr (PNNL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
0.01 (254 µm)	030-01-001CTA	LEU-37-L	208.3	9.6	194.2/224.9
		LEU-38-T	201.8	8.5	185.8/219.3
		LEU-167-TE-A	196.2	13.0	173.4/219.3
		LEU-168-LE-A	179.3	14.0	146.8/199.7
		LEU-169-TE-B	195.7	10.6	175.2/214.9
		LEU-170-LE-B	196.7	12.3	178.5/219.8
	030-01-004CTB	LEU-39-L	221.9	6.9	207.3/234.8
		LEU-40-T	221.9	9.9	198.2/235.9
		LEU-125-LE1	202.4	5.4	191.3/218.2
		LEU-126-TE1	210.7	9.6	192.0/228.4
		LEU-127-LE2	210.5	6.5	200.7/223.3
		LEU-128-TE2	206.7	5.7	191.3/218.9
	030-01-001CTC	LEU-41-L	221.7	7.7	206.9/232.0

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
		LEU-42-T	220.6	6.6	209.8/238.8
		LEU-121-LE1	223.6	6.4	208.5/241.7
		LEU-122-TE1	217.7	7.4	200.7/235.2
		LEU-123-LE2	218.2	12.1	192.7/237.6
		LEU-124-TE2	210.4	7.7	188.4/223.7
0.027 (686 µm)	029-01-001CTA	LEU-25-L	581.7	17.7	546.8/606.5
		LEU-26-T	591.3	14.3	568.2/613.1
		LEU-159-TE-A	561.8	8.4	543.8/576.4
		LEU-160-LE-A	549.0	8.4	533.1/567.4
		LEU-161-TE-B	573.5	10.0	548.6/591.0
		LEU-162-LE-B	595.3	10.4	573.9/621.7
	029-01-004CTB	LEU-23-L	625.5	11.7	599.2/640.1
		LEU-24-T	612.1	6.7	599.2/622.1
		LEU-133-LE1	622.3	11.6	602.4/641.6
		LEU-134-TE1	613.0	8.4	595.1/627.6
		LEU-135-LE2	618.4	7.4	604.8/631.9
		LEU-136-TE2	623.5	8.9	605.7/643.1
	029-01-001CTC	LEU-19-L	533.9	16.3	499.3/556.4
		LEU-20-T	564.4	12.4	536.2/588.5
		LEU-129-LE1	524.7	15.0	481.5/540.2
		LEU-130-TE1	547.7	8.9	534.4/566.5
		LEU-131-LE2	495.1	25.9	446.1/541.6
		LEU-132-TE2	480.0	8.5	465.2/495.6
	029-01-002CTA	LEU-29-L	606.9	8.1	597.5/625.3
		LEU-30-T	612.7	9.4	601.6/635.9
		LEU-163-TE-A	595.6	10.9	573.9/619.6
		LEU-164-LE-A	575.4	13.0	548.6/594.3
		LEU-165-TE-B	597.5	8.3	580.4/611.9
		LEU-166-LE-B	585.9	10.3	565.7/603.3
	029-01-006CTB	LEU-31-L	627.2	10.0	611.4/640.9
		LEU-32-T	637.8	11.3	617.9/658.8
		LEU-183-TE-A	597.5	12.9	578.3/621.7
		LEU-184-LE-A	597.9	16.6	572.7/630.0
		LEU-185-TE-B	591.7	9.7	562.9/607.6
		LEU-186-LE-B	586.3	13.5	565.1/612.0
	029-01-002CTC	LEU-33-L	602.2	9.8	578.7/614.7
		LEU-34-T	597.9	9.8	581.9/611.4
		LEU-187-TE-A	551.2	12.4	529.1/570.4
		LEU-188-LE-A	556.8	17.4	524.4/591.4
		LEU-189-TE-B	562.1	14.9	535.2/592.4

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
		LEU-190-LE-B	563.5	12.6	534.5/581.9
0.047 (1194 µm)	029-01-000DTA	LEU-43-L	1259.3	54.1	1186.1/1328.2
		LEU-44-T	1248.6	35.8	1201.3/1280.5
		LEU-145-LE-A	1172.8	13.5	1154.8/1197.3
		LEU-146-TE-A	1191.2	11.8	1169.1/1211.1
		LEU-147-LE-B	1244.1	29.3	1211.4/1292.8
		LEU-148-TE-B	1185.6	27.6	1146.5/1224.1
	029-01-002DTB	LEU-45-L	1224.5	35.8	1165.0/1283.8
		LEU-46-T	1271.5	32.1	1234.7/1330.5
		LEU-149-LE-A	1219.5	35.8	1167.4/1284.8
		LEU-150-TE-A	1157.7	36.9	1086.9/1200
		LEU-151-LE-B	1198.7	22.2	1163.0/1236.9
		LEU-152-TE-B	1174.9	36.8	1121.2/1222.4
	029-01-000DTC	LEU-49-L	1245.6	23.6	1210.1/1289.3
		LEU-50-T	1216.4	30.4	1159.7/1245.6
		LEU-153-LE-A	1161.3	43.2	1076.1/1226.1
		LEU-154-TE-A	1118.5	8.8	1099.3/1129.8
		LEU-157-TE-B	998.5	40.3	944.7/1066.6
		LEU-158-LE-B	1060.3	33.5	1011.6/1119.5
	030-01-000DTA	LEU-51-L	1043.9	24.1	1001.1/1066.9
		LEU-52-T	1083.3	35.3	1036.7/1139.0
		LEU-171-TE-A	1022.6	29.4	970.6/1080.3
		LEU-172-LE-A	1037.8	26.2	1000.0/1071.8
		LEU-172-TE-B			
		LEU-173-LE-B	1121.9	20.6	1076.1/1147.8

Table A.30. Fuel meat thickness of U-10Mo specimens with Zr (INL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
0.0121 (307 µm)	030-01-003CTA	met 1 trans	231.62	7.31	220.24/240.85
		met 1 long	223.86	9.1	210.75/245.62
		met 2 trans	247.39	4.96	239.39/256.76
		met 2 long	244.77	6.28	236.07/259.88
		met 3 trans	227.86	7.13	210.95/241.59
		met 3 long	239.87	6.11	229.78/248.87
	030-01-008CTB	met 1 trans	238.48	6.02	225.02/250.35
		met 1 long	238.48	9.36	222.50/251.78

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
		met 2 trans	244.41	6.43	229.84/252.01
		met 2 long	248.88	8.22	231.37/267.78
		met 3 trans	237.47	7.30	229.75/250.43
		met 3 long	237.35	4.35	229.78/244.25
	030-01-003CTC	met 1 trans	226.34	7.26	215.70/234.78
		met 1 long	223.12	8.52	200.84/234.64
		met 2 trans	247.09	5.25	239.34/256.76
		met 2 long	240.33	4.76	231.34/248.83
		met 3 trans	229.20	4.02	223.32/234.06
		met 3 long	238.92	10.18	215.58/253.60
0.0262 (665 µm)	029-05-001CTA	met 1 trans	592.06	10.75	576..93/608.75
		met 1 long	588.04	7.05	579.88/605.25
		met 2 trans	610.19	7.65	595.80/621.19
		met 2 long	616.29	10.23	598.97/635.39
		met 3 trans	600.34	10.80	575.06/611.63
		met 3 long	600.68	8.22	592.66/616.33
	029-05-004CTB	met 1 trans	623.87	5.37	613.19/632.33
		met 1 long	607.99	11.85	583.11/635.57
		met 2 trans	630.44	7.75	616.36/638.63
		met 2 long	634.80	5.94	625.87/648.18
		met 3 trans	615.19	10.57	598.94/635.40
		met 3 long	635.78	9.09	621.11/652.83
	029-05-001CTC	met 1 trans	627.23	4.79	619.73/636.96
		met 1 long	624.15	14.11	600.78/647.13
		met 2 trans	639.58	8.92	623.38/653.34
		met 2 long	644.16	9.14	621.26/655.08
		met 3 trans	618.14	9.88	604.36/638.42
		met 3 long	621.68	13.22	591.68/644.48
0.0278 (706 µm)	029-05-002CTA	met 1 trans	616.47	8.04	608.51/638.67
		met 1 long	608.09	14.61	579.99/626.03
		met 2 trans	647.74	9.15	667.07/633.80
		met 2 long	643.21	11.36	621.21/657.61
		met 3 trans	612.47	6.98	602.11/623.15
		met 3 long	618.90	13.88	602.60/654.73
	029-05-006CTB	met 1 trans	616.10	8.61	602.37/634.15
		met 1 long	623.16	12.27	594.44/641.87
		met 2 trans	635.40	9.03	624.29/649.64
		met 2 long	642.79	11.07	624.28/654.97
		met 3 trans	610.56	8.98	600.87/626.52
		met 3 long	621.85	11.87	603.78/644.89

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/Max (µm)
	029-05-002CTC	met 1 trans	566.70	19.82	544.70/601.26
		met 1 long	569.02	8.72	553.72/583.34
		met 2 trans	607.03	16.54	579.93/630.66
		met 2 long	607.17	12.59	579.90/625.99
		met 3 trans	573.31	7.58	563.05/586.06
		met 3 long	590.52	10.52	565.63/608.50
0.047 (1194 µm)	029-05-000DTA	met 1 trans	1216.78	46.86	1129.13/1263.08
		met 1 long	1186.63	51.15	1083.88/1243.86
		met 2 trans	1193.90	23.82	1153.76/1223.50
		met 2 long	1244.62	41.86	1157.96/1310.10
		met 3 trans	1117.74	25.46	1084.04/1150.35
		met 3 long	1196.60	36.45	1137.29/1271.80
	029-05-002DTB	met 1 trans	1235.94	23.98	1195.06/1282.16
		met 1 long	1238.80	35.84	1181.22/1305.94
		met 2 trans	1288.60	28.32	1256.24/1334.76
		met 2 long	1268.62	35.08	1225.68/1318.54
		met 3 trans	1254.92	19.42	1231.94/1284.78
		met 3 long	1250.64	28.32	1210.84/1282.74
	029-05-000DTC	met 1 trans	1160.44	29.14	1080.36/1229.34
		met 1 long	1184.54	35.98	1133.60/1244.46
		met 2 trans	1230.54	33.36	1193.17/1277.09
		met 2 long	1266.64	45.01	1200.04/1333.47
		met 3 trans	1256.55	28.38	1190.25/1283.43
		met 3 long	1235.92	45.85	1167.84/1343.61
	030-01-000DTC	met 1 trans	1097.36	33.96	1051.40/1160.76
		met 1 long	1092.90	54.66	1014.28/1213.16
		met 2 trans	1166.53	24.20	1125.09/1217.08
		met 2 long	1155.79	38.82	1074.23/1207.30
		met 3 trans	1220.57	27.47	1144.57/1242.23
		met 3 long	1236.32	42.50	1175.61/1328.01

Table A.31. Fuel meat thickness of U-10Mo specimens with Zr (LANL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/ Max (µm)
0.01 (254 µm)	029-02-000DTA	13365-1A (T)	203.52	1.22	201.35/204.97
		13365-1B (L)	204.60	1.66	202.26/206.77
		13365-1C (T)	214.27	1.41	212.19/217.61

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/ Max (µm)
		13365-1D (L)	218.40	1.16	216.70/220.09
		13365-1E (T)	211.15	1.23	209.26/212.64
		13365-1F (L)	214.74	1.29	213.32/216.70
	029-02-002DTB	13365-2A (T)	205.40	6.24	201.35/222.81
		13365-2B (L)	219.68	2.67	214.67/222.12
		13365-2C (T)	235.80	0.83	234.31/237.02
		13365-2D (L)	232.48	0.78	231.60/233.63
		13365-2E (T)	224.70	1.38	222.80/226.86
		13365-2F (L)	223.81	1.64	220.09/225.51
	029-02-000DTC	13365-3A (T)	227.95	1.32	225.51/229.57
		13365-3B (L)	225.64	1.42	223.48/228.22
		13365-3C (T)	242.43	0.87	241.16/243.87
		13365-3D (L)	240.47	1.76	235.67/241.76
		13365-3E (T)	226.86	1.75	224.83/229.57
		13365-3F (L)	230.11	1.49	226.86/232.28
0.027 (686 µm)	030-01-002DTB	13365-4A (T)	598.65	9.03	577.88/607.68
		13365-4B (L)	626.02	3.00	621.95/630.08
		13365-4C (T)	647.49	1.62	644.70/649.21
		13365-4D (L)	640.10	3.47	634.77/646.51
		13365-4E (T)	646.14	2.96	641.08/650.11
		13365-4F (L)	643.70	0.99	642.89/645.60
0.027 (686 µm)	029-02-001CTA	13365-12A (T)	618.67	9.49	604.44/638.89
		13365-12B (L)	589.56	5.24	580.00/596.67
		13365-12C (T)	597.56	8.91	583.71/612.67
		13365-12D (L)	613.57	5.79	601.81/623.53
		13365-12E (T)	598.67	11.83	580.00/616.67
		13365-12F (L)	583.80	6.33	575.57/592.76
	029-02-004CTB	13365-13A (T)	576.76	4.41	569.73/584.87
		13365-13B (L)	580.22	4.98	570.81/588.11
		13365-13C (T)	611.37	6.19	598.91/620.77
		13365-13D (L)	592.79	9.91	578.14/609.84
		13365-13E (T)	566.67	6.32	559.56/579.24
		13365-13F (L)	582.40	6.51	570.49/591.26
	029-01-002CTA	13365-14A (T)	541.42	6.56	533.33/557.38
		13365-14B (L)	576.83	3.93	571.59/581.42
		13365-14C (T)	592.79	12.15	578.14/616.39
		13365-14D (L)	586.56	5.06	578.14/594.54
		13365-14E (T)	585.79	3.62	579.24/591.26
		13365-14F (L)	578.58	3.66	571.59/584.70
	029-01-006CTB	13365-15A (T)	591.48	6.37	581.42/600.00

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured fuel thickness (µm)	Standard deviation (µm)	Min/ Max (µm)
		13365-15B (L)	579.67	7.53	565.03/590.16
		13365-15C (T)	609.40	5.13	600.00/619.67
		13365-15D (L)	612.24	6.22	600.00/619.67
		13365-15E (T)	595.19	10.91	575.96/613.12
		13365-15F (L)	610.16	11.27	586.89/629.51
	029-01-002CTC	13365-16A (T)	607.32	5.66	597.81/618.58
		13365-16B (L)	602.62	6.79	586.89/612.02
		13365-16C (T)	615.74	5.60	607.65/624.04
		13365-16D (L)	601.09	9.62	584.70/618.58
		13365-16E (T)	589.73	9.38	575.96/603.28
		13365-16F (L)	581.31	7.21	572.68/596.72
0.047 (1194 µm)	029-01-000DTA	13365-17A (T)	556.50	3.90	547.54/561.75
		13365-17B (L)	538.14	7.59	520.22/553.01
		13365-1 7C (T)	578.80	7.99	563.93/590.16
		13365-17D (L)	568.52	7.44	557.38/584.70
		13365-17E (T)	561.20	5.73	554.10/571.59
		13365-17F (L)	547.87	12.20	530.06/566.12
	029-01-002DTB	13365-18A (T)	231.92	7.05	221.27/245.70
		13365-18B (L)	234.98	4.73	228.05/245.02
		13365-18C (T)	241.09	7.42	231.45/253.17
		13365-18D (L)	236.88	7.06	221.27/245.70
		13365-18E (T)	231.92	7.05	221.27/245.70
		13365-18F (L)	231.92	7.05	221.27/245.70
	029-01-000DTC	13365-19A (T)	229.26	6.50	219.60/241.89
		13365-19B (L)	228.78	4.08	222.30/233.78
		13365-19C (T)	222.66	12.79	207.46/247.98
		13365-19D (L)	242.43	5.10	231.08/250.68
		13365-19E (T)	231.28	7.52	217.57/243.24
		13365-19F (L)	235.81	5.80	229.73/250.00
	030-01-000DTA	13365-20A (T)	226.89	6.69	215.30/234.97
		13365-20B (L)	213.88	5.08	205.46/221.86
		13365-20C (T)	235.08	4.52	228.42/240.44
		13365-20D (L)	229.29	6.54	219.67/239.34
		13365-20E (T)	209.95	7.47	198.91/225.14
		13365-20A (T)	213.80	6.38	204.85/225.34

A.6 Zr Thickness

Table A.32. Summary of the Zr layer (top and bottom) thicknesses for U-10Mo specimens (PNNL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Top Layer			Bottom Layer		
			Average Zr thickness (µm)	SD (µm)	Min/Max (µm)	Average Zr thickness (µm)	SD (µm)	Min/Max (µm)
0.01 (254 µm)	030-01-001CTA	LEU-37-L	32.4	6.6	21.6/46.0	26.6	6.3	12.3/37.9
		LEU-38-T	22.4	5.5	5.5/40.1	26.8	10.0	12.7/46.6
		LEU-167-TE-A	17.2	3.9	9.4/23.4	16.5	4.9	5.8/29.8
		LEU-168-LE-A	15.0	3.8	7.2/23.4	13.4	5.0	4.4/25.2
		LEU-169-TE-B	22.2	6.4	6.5/31.6	20.8	4.5	10.7/30.9
		LEU-170-LE-B	16.4	4.9	6.2/27.9	14.7	4.1	5.8/23.7
	030-01-004CTB	LEU-39-L	30	6.3	17/50.3	32.9	5.7	24.6/45.1
		LEU-40-T	28.6	8.5	13.7/47.3	30.4	6.1	19.6/46.6
		LEU-125-LE1	24.1	3.6	16.9/32.9	25.1	4.1	16.6/33.7
		LEU-126-TE1	23.2	6.4	11.4/38.5	22.8	4.1	16.1/31.9
		LEU-127-LE2	24.4	4.2	17.7/34.6	21.7	4	11.2/30.8
		LEU-128-TE2	22.1	3.6	14.4/29.0	23.2	2.5	19.0/29.9
	030-01-001CTC	LEU-41-L	27.4	11.4	3.3/47.3	35.5	6.9	23.9/52.9
		LEU-42-T	36.3	6.1	23.1/48.7	31.2	5.4	19.4/42.8
		LEU-121-LE1	17.4	5.6	8.7/31.5	21.9	4.8	8.2/34.1
		LEU-122-TE1	22	3.4	13.2/29.1	15.9	4.3	8.3/27.6
		LEU-123-LE2	22	4.8	12.8/34.0	21.3	6.1	10.5/31.3
		LEU-124-TE2	22.7	3.6	15.2/32.9	21.5	4.8	13.3/32.7
0.027 (686 µm)	029-01-001CTA	LEU-25-L	32.6	16.7	8.6/70.4	29.7	10.5	12.2/48.4
		LEU-26-T	28.2	12.2	6.6/52.5	33.6	14.4	8.3/60.4
		LEU-159-TE-A	27.3	4.8	15.2/38.5	25.4	6.1	11.2/36.6
		LEU-160-LE-A	18.9	6.8	5.4/31.5	24.0	4.4	15.5/32.6
		LEU-161-TE-B	21.3	4.2	13.6/30.5	31.5	9.0	11.6/49.8

Expected fuel thickness (in.)	Sample ID	Specimen ID	Top Layer			Bottom Layer		
			Average Zr thickness (µm)	SD (µm)	Min/Max (µm)	Average Zr thickness (µm)	SD (µm)	Min/Max (µm)
		LEU-162-LE-B	21.6	4.1	13.0/29.5	22.2	6.4	8.8/34.7
	029-01-004CTB	LEU-23-L	30.8	11.4	13.8/57.9	32.8	8.8	13.6/51.3
		LEU-24-T	42.5	10.9	29.2/63.7	39.7	11.7	22.5/63.6
		LEU-133-LE1	32.8	9.8	14.8/55.5	27.2	6.4	12.5/42.1
		LEU-134-TE1	31.2	4.7	21.4/43.7	37.0	9.8	14.1/56.0
		LEU-135-LE2	30.8	6.4	18.4/45.5	30.4	4.5	17.6/39.4
		LEU-136-TE2	32.0	7	14.1/45.6	25.9	6.5	12.3/41.6
	029-01-001CTC	LEU-19-L	32.1	9.5	12.2/49.6	30.8	11.3	14.3/55.2
		LEU-20-T	32.9	8.7	13.7/52.6	24.3	9.0	8.1/45.4
		LEU-129-LE1	22.8	6	11.9/37.7	24.5	5.7	10.6/39.7
		LEU-130-TE1	26.1	4.6	16.8/36.5	26.8	7.1	10.8/41.1
		LEU-131-LE2	29.4	5.9	15.5/43.1	24.4	8.4	8.9/39.9
		LEU-132-TE2	26.6	6.1	10.8/42.4	24.4	5.4	10.1/36.4
	029-01-002CTA	LEU-29-L	42.5	9.1	22.5/61.8	45.3	7.5	28.3/63.3
		LEU-30-T	34.7	9.8	12.9/55.5	45.2	9.2	24.5/60.4
		LEU-163-TE-A	27.4	7.7	6.5/40.0	22.9	6.1	11.4/36.7
		LEU-164-LE-A	29.3	7.9	16.7/49.5	26.6	6.0	15.4/38.1
		LEU-165-TE-B	25.1	7.9	12.3/41.3	27.2	7.1	11.9/39.8
		LEU-166-LE-B	22.2	7.2	5.2/35.8	27.8	5.4	13.9/38.0
	029-01-006CTB	LEU-31-L	29.8	16.6	7.9/60.2	35.2	10.7	16.7/57.9
		LEU-32-T	37.9	8.1	21.6/53.8	34.4	10.3	10.0/60.9
		LEU-183-TE-A	26.5	6.4	15.2/38.7	27.7	6.6	14.3/39.6
		LEU-184-LE-A	26.3	6.9	8.7/38.7	24.7	8.3	6.0/37.9
		LEU-185-TE-B	26.8	7.9	13.1/44.2	26.3	5.7	15.3/42.5
		LEU-186-LE-B	28.4	9.7	11.6/48.5	24.5	7.8	7.3/40.9
	029-01-002CTC	LEU-33-L	33.2	16.1	7.4/67.4	32.2	10.0	19.4/61.8
		LEU-34-T	31.9	7.6	13.3/47.7	38.7	9.4	19.5/57.4
		LEU-187-TE-A	28.5	5.6	17.7/45.2	31.7	7.7	14.8/48.3

Expected fuel thickness (in.)	Sample ID	Specimen ID	Top Layer			Bottom Layer		
			Average Zr thickness (µm)	SD (µm)	Min/Max (µm)	Average Zr thickness (µm)	SD (µm)	Min/Max (µm)
		LEU-188-LE-A	30.5	5.7	18.7/41.4	28.6	7.9	13.7/40.8
		LEU-189-TE-B	26.4	7.4	14.3/45.4	21.6	6.6	4.3/32.0
		LEU-190-LE-B	29.5	6.0	15.2/40.8	25.6	5.9	13.4/35.4
0.047 (1194 µm)	029-01-000DTA	LEU-43-L	67.3	6.6	55.3/80.4	61.7	10.0	41.5/81.7
		LEU-44-T	58.5	12.5	26.5/76.4	47.9	10.6	25.6/65.3
		LEU-145-LE-A	23.2	7.7	9.3/45.8	30.1	10.1	12.4/46.7
		LEU-146-TE-A	28.0	8.8	9.7/45.8	35.1	5.2	27.3/44.2
		LEU-147-LE-B	28.8	13.9	7.1/58.6	30.3	8.6	16.6/46.7
		LEU-148-TE-B	27.5	3.2	22.2/32.3	34.1	5.5	23.6/40.3
	029-01-002DTB	LEU-45-L	65.7	9.5	47.2/80.7	39.6	8.2	23.4/57.4
		LEU-46-T	53.8	24.5	15.5/99.9	64.2	9.2	43.7/79.0
		LEU-149-LE-A	43.7	11.9	9.8/61.6	33.2	6.3	17.9/43.5
		LEU-150-TE-A	27.7	11.6	9.4/44.2	43.9	7.1	23.4/53.3
		LEU-151-LE-B	43.8	10.0	28.3/60.6	31.0	6.9	21.7/45.6
		LEU-152-TE-B	52.6	15.6	29.4/74.2	36.7	6.5	24.7/47.9
	029-01-000DTC	LEU-49-L	59.7	12.2	36.4/77.0	51.7	8.5	36.5/67.7
		LEU-50-T	73.9	10.6	50.3/91.4	59.7	15.7	25.6/87.3
		LEU-153-LE-A	40.5	10.3	15.2/61.2	36.0	16.7	7.9/68.1
		LEU-154-TE-A	51.9	5.9	43.5/63.1	43.6	7.5	27.9/58.0
		LEU-157-TE-B	46.5	10.8	27.2/68.2	40.2	11.1	9.1/59.1
		LEU-158-LE-B	42.1	5.4	27.2/54.7	40.8	10.5	20.1/65.3
	030-01-000DTA	LEU-51-L	99.3	15.6	68.8/134.1	122.4	8.5	106.6/138.5
		LEU-52-T	118.5	16.4	95.8/158.9	100.4	21.7	72.4/139
		LEU-171-TE-A	102.3	20.9	66.7/124.8	61.8	20.5	20.9/110.5
		LEU-172-LE-A	64.3	10.5	50.3/81.2	54.7	12.4	32.2/83.3
		LEU-172-TE-B						
		LEU-173-LE-B	83.5	10.6	66.6/107.6	90.9	6.3	79.7/105.4

Table A.33. Summary of the Zr layer (top and bottom) thicknesses for U-10Mo specimens (INL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average Zr thickness (µm)	SD (µm)	Min/Max(µm)
0.0121 (307 µm)	030-01-003CTA	met 1 trans	31.46	8.08	15.75/43.37
		met 1 long	33.39	5.19	24.59/40.19
		met 2 trans	35.91	7.66	26.74/54.66
		met 2 long	36.73	8.68	22.22/49.12
		met 3 trans	26.85	6.50	17.60/36.31
		met 3 long	40.06	4.56	33.23/45.69
	030-01-008CTB	met 1 trans	34.33	7.24	25.70/47.90
		met 1 long	22.19	4.87	15.72/30.86
		met 2 trans	34.43	8.68	21.11/49.24
		met 2 long	30.72	8.67	19.93/44.50
		met 3 trans	30.80	7.45	21.91/37.47
		met 3 long	28.66	8.20	24.62/49.23
	030-01-003CTC	met 1 trans	39.41	9.22	28.00/57.59
		met 1 long	31.11	7.44	14.44/45.44
		met 2 trans	30.17	6.23	12.90/38.70
		met 2 long	34.50	7.42	28.04/42.12
		met 3 trans	38.05	10.55	25.70/57.24
		met 3 long	27.60	8.86	13.69/36.72
0.0262 (665 µm)	029-05-001CTA	met 1 trans	41.34	12.33	14.00/60.70
		met 1 long	35.11	8.75	21.95/50.06
		met 2 trans	42.38	7.53	30.56/55.22
		met 2 long	36.52	12.74	12.93/53.98
		met 3 trans	30.62	14.22	8.24/47.07
		met 3 long	40.02	10.78	21.09/59.94
	029-05-004CTB	met 1 trans	39.62	4.92	31.69/46.96
		met 1 long	44.87	11.55	31.64/67.21
		met 2 trans	43.25	11.10	22.40/60.96
		met 2 long	37.76	12.71	16.13/49.44

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average Zr thickness (µm)	SD (µm)	Min/Max(µm)
		met 3 trans	42.64	10.74	28.03/61.84
		met 3 long	38.42	14.44	17.19/68.79
	029-05-001CTC	met 1 trans	38.88	9.26	21.94/54.10
		met 1 long	36.38	12.14	12.51/50.53
		met 2 trans	38.48	7.28	25.23/51.86
		met 2 long	43.67	10.26	21.84/56.18
		met 3 trans	39.94	7.42	20.40/48.25
		met 3 long	37.33	12.21	25.08/58.01
0.0278 (706 µm)	029-05-002CTA	met 1 trans	44.03	11.64	19.89/62.06
		met 1 long	35.64	10.89	16.53/51.95
		met 2 trans	38.48	9.91	15.27/52.69
		met 2 long	38.83	10.67	15.25/52.64
		met 3 trans	32.15	8.91	16.32/44.53
		met 3 long	41.71	6.07	28.03/57.47
	029-05-006CTB	met 1 trans	36.66	9.18	26.08/50.29
		met 1 long	36.93	9.81	21.53/47.60
		met 2 trans	30.93	7.97	16.94/46.85
		met 2 long	38.41	6.74	31.84/47.08
		met 3 trans	30.98	4.39	15.63/37.13
		met 3 long	32.22	9.93	19.35/49.11
	029-05-002CTC	met 1 trans	34.37	9.98	15.96/44.27
		met 1 long	35.49	10.43	17.76/52.96
		met 2 trans	33.56	9.35	15.71/48.48
		met 2 long	34.55	11.42	15.93/50.00
		met 3 trans	42.89	9.53	28.64/63.88
		met 3 long	37.29	11.45	17.26/54.71
0.047 (1194 µm)	029-05-000DTA	met 1 trans	62.45	19.48	32.71/87.90
		met 1 long	71.70	19.88	34.35/99.97
		met 2 trans	58.40	19.33	26.72/79.69

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average Zr thickness (µm)	SD (µm)	Min/Max(µm)
		met 2 long	65.80	23.50	19.92/93.58
		met 3 trans	66.55	24.75	10.92/99.91
		met 3 long	66.71	24.81	10.94/100.15
	029-05-000DTA	met 1 trans	58.57	24.82	20.51/93.68
		met 1 long	78.48	24.55	34.51/122.22
		met 2 trans	57.19	19.62	21.16/78.90
		met 2 long	66.73	18.73	17.94/93.19
		met 3 trans	65.24	15.88	28.09/79.54
		met 3 long	75.00	21.70	38.23/133.28
	029-05-000DTC	met 1 trans	65.90	19.96	35.21/99.53
		met 1 long	60.44	23.69	18.76/90.71
		met 2 trans	60.88	22.85	22.14/85.98
		met 2 long	62.85	27.26	13.00/104.04
		met 3 trans	72.40	18.69	46.89/101.46
		met 3 long	62.31	24.43	34.04/114.50
	030-01-000DTC	met 1 trans	143.11	23.66	94.27/177.45
		met 1 long	130.77	29.75	74.02/188.45
		met 2 trans	124.42	31.06	58.80/160.70
		met 2 long	121.44	31.69	78.25/179.09
		met 3 trans	117.27	34.90	45.14/164.93
		met 3 long	112.19	23.72	65.22/147.14

Table A.34. Summary of the Zr layer (top and bottom) thicknesses for U-10Mo specimens (LANL data)

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured Zr thickness (µm)	Standard deviation (µm)	Min (µm)/ Max (µm)
(**0.047**) (1194 µm)	029-02-000DTA	13365-1A (T)	62.14	7.72	50.73/75.18
		13365-1B (L)	72.46	6.24	61.59/81.52
		13365-1C (T)	55.80	6.48	46.20/65.22

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured Zr thickness (µm)	Standard deviation (µm)	Min (µm)/ Max (µm)
		13365-1D (L)	51.81	12.87	28.99/67.94
		13365-1E (T)	55.33	10.21	40.98/69.67
		13365-1F (L)	61.50	3.20	56.16/67.94
	029-02-002DTB	13365-2A (T)	56.49	11.80	36.69/72.01
		13365-2B (L)	48.47	13.54	18.71/62.93
		13365-2C (T)	63.18	6.05	52.99/73.37
		13365-2D (L)	63.18	6.05	52.99/73.37
		13365-2E (T)	45.96	19.81	19.72/74.95
		13365-2F (L)	66.13	14.96	39.30/84.01
	029-02-000DTC	13365-3A (T)	57.47	21.14	24.46/78.80
		13365-3B (L)	63.59	9.28	39.40/72.01
		13365-3C (T)	60.73	4.84	52.99/66.58
		13365-3D (L)	49.46	5.13	38.04/57.07
		13365-3E (T)	60.19	9.67	42.12/78.80
		13365-3F (L)	61.03	7.61	47.55/73.37
0.027 (686 µm)	030-01-002DTB	13365-4A (T)	128.32	10.98	110.46/141.82
		13365-4B (L)	126.82	4.48	120.00/135.00
		13365-4C (T)	136.99	5.00	125.64/141.82
		13365-4D (L)	117.68	6.37	107.73/126.82
		13365-4E (T)	148.91	24.00	111.82/184.09
		13365-4F (L)	130.50	17.84	106.36/159.55
	029-02-001CTA	13365-12A (T)	32.22	5.26	22.22/37.78
		13365-12B (L)	41.56	4.72	34.44/48.89
		13365-12C (T)	32.31	4.56	26.24/40.72
		13365-12D (L)	32.58	5.35	26.24/46.15
		13365-12E (T)	30.56	6.93	16.67/41.11
		13365-12F (L)	24.07	3.80	18.10/29.86
	029-02-004CTB	13365-13A (T)	27.89	4.40	22.70/35.68

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured Zr thickness (µm)	Standard deviation (µm)	Min (µm)/ Max (µm)
		13365-13B (L)	23.78	2.37	20.54/27.03
		13365-13C (T)	22.51	1.97	19.67/26.23
		13365-13D (L)	44.70	5.98	34.97/54.65
		13365-13E (T)	26.89	4.48	17.49/33.88
		13365-13F (L)	28.31	4.10	22.95/34.97
	029-01-002CTA	13365-14A (T)	27.76	6.71	18.58/40.44
		13365-14B (L)	25.79	3.82	19.67/32.79
		13365-14C (T)	25.90	6.63	12.02/34.97
		13365-14D (L)	31.91	3.04	25.14/34.97
		13365-14E (T)	27.10	5.50	17.49/34.97
		13365-14F (L)	30.38	3.87	22.95/36.07
	029-01-006CTB	13365-15A (T)	30.27	5.64	24.04/40.44
		13365-15B (L)	28.63	3.12	21.86/32.79
		13365-15C (T)	26.67	9.42	9.84/40.44
		13365-15D (L)	35.19	4.08	28.42/41.53
		13365-15E (T)	34.86	8.92	18.58/49.18
		13365-15F (L)	30.38	8.82	15.30/42.62
	029-01-002CTC	13365-16A (T)	26.45	4.86	19.67/39.34
		13365-16B (L)	27.10	4.11	20.77/34.97
		13365-16C (T)	29.62	2.99	22.95/32.79
		13365-16D (L)	32.68	3.89	26.23/39.34
		13365-16E (T)	26.67	6.76	16.39/38.25
		13365-16F (L)	29.51	5.91	16.39/38.25
0.047 (1194 µm)	029-01-000DTA	13365-17A (T)	20.98	5.59	12.02/30.60
		13365-17B (L)	23.83	3.58	19.67/29.51
		13365-17C (T)	25.46	6.05	15.30/33.88
		13365-17D (L)	25.25	6.02	18.58/36.07
		13365-17E (T)	28.42	4.48	20.77/37.16

Expected fuel thickness (in.)	Sample ID	Specimen ID	Average measured Zr thickness (µm)	Standard deviation (µm)	Min (µm)/ Max (µm)
	029-01-002DTB	13365-17F (L)	26.67	6.60	20.77/38.25
		13365-18A (T)	23.56	4.50	14.93/29.19
		13365-18B (L)	24.23	3.15	19.68/31.90
		13365-18C (T)	22.47	5.32	14.93/29.86
		13365-18D (L)	28.30	6.46	21.72/40.05
		13365-18E (T)	23.56	4.50	14.93/29.19
		13365-18F (L)	23.56	4.50	14.93/29.19
	029-01-000DTC	13365-19A (T)	24.73	4.93	16.89/31.08
		13365-19B (L)	23.38	4.46	18.24/31.76
		13365-19C (T)	37.64	7.86	24.32/50.68
		13365-19D (L)	22.91	3.32	16.22/26.35
		13365-19E (T)	27.43	4.35	20.95/34.46
		13365-19F (L)	24.32	5.04	14.87/29.73
	030-01-000DTA	13365-20A (T)	23.06	2.95	17.49/28.42
		13365-20B (L)	26.45	3.48	21.86/31.69
		13365-20C (T)	20.66	3.07	14.21/24.04
		13365-20D (L)	25.03	5.99	14.21/32.79
		13365-20E (T)	25.25	3.86	20.77/30.60
		13365-20A (T)	25.12	2.64	21.56/31.27

A.7 Hardness

Table A.35. Vickers microhardness data obtained from U-10Mo specimens without Zr (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Average hardness (HV)	Standard deviation (HV)
0.01	027-04-003CTA	LEU-53-L	308.08	1.73
		LEU-54-T	308.10	4.28
		LEU-85-LE1	-	-
		LEU-86-TE1	293.93	3.55
		LEU-87-LE2	292.40	1.72
		LEU-88-TE2	292.97	3.95
	027-04-003CTB	LEU-55-L	311.88	4.63
		LEU-56-T	310.05	1.87
		LEU-97-LE1	288.60	2.37
		LEU-98-TE1	289.72	4.74
		LEU-99-LE2	294.05	2.24
		LEU-100-TE2	292.28	3.25
	027-04-004CTC	LEU-57-L	307.45	4.96
		LEU-58-T	307.55	3.66
		LEU-109-LE1	-	-
		LEU-110-TE1	-	-
		LEU-111-LE2	-	-
		LEU-112-TE2	-	-
0.025	028-01-001CTA	LEU-59-L	303.93	1.93
		LEU-60-T	304.23	1.86
		LEU-91-LE1	291.20	4.51
		LEU-92-TE1	292.81	5.67
		LEU-93-LE2	295.33	4.55
		LEU-94-TE2	293.43	4.96
	028-01-001CTB	LEU-61-L	304.50	4.11
		LEU-62-T	304.23	5.21
		LEU-101-LE1	291.98	3.97
		LEU-102-TE1	291.20	2.04
		LEU-103-LE2	293.26	4.70
		LEU-104-TE2	292.44	4.96
	028-01-001CTC	LEU-63-L	303.90	2.83
		LEU-64-T	306.93	2.97
		LEU-137-LE1	295.46	4.00
		LEU-138-TE1	296.03	4.56
		LEU-139-LE2	293.25	4.24
		LEU-140-TE2	293.07	5.46

Thickness (in.)	Sample ID	Specimen ID	Average hardness (HV)	Standard deviation (HV)
	028-01-002CTA	LEU-65-L	308.58	4.69
		LEU-66-L	306.40	5.38
		LEU-141-LE1	291.87	3.51
		LEU-142-TE1	294.20	3.15
		LEU-143-LE2	290.29	6.16
		LEU-144-TE2	291.86	2.64
	028-01-002CTB	LEU-67-L	309.48	4.71
		LEU-68-T	304.23	2.82
		LEU-175-TE-A	-	-
		LEU-176-LE-A	-	-
		LEU-177-TE-B	-	-
		LEU-178-LE-B	-	-
	028-01-002CTC	LEU-69-L	304.78	5.94
		LEU-70-T	302.95	2.02
		LEU-179-TE-A	-	-
		LEU-180-LE-A	-	-
		LEU-181-TE-B	-	-
		LEU-182-LE-B	-	-
0.047	027-04-000DTA	LEU-05-L	307.30	2.79
		LEU-04-T	309.38	2.13
		LEU-71-LE	295.34	3.56
		LEU-72-TE	293.59	4.79
		LEU-73-LC	296.43	3.81
		LEU-74-TC	296.60	5.30
	027-04-002DTB	LEU-08-L	313.85	5.51
		LEU-07-T	320.25	5.75
		LEU-75-LE	298.82	4.85
		LEU-76-TE	297.09	4.50
		LEU-77-LC	293.82	4.92
		LEU-78-TC	297.79	4.22
	027-04-000DTC	LEU-02-L	309.58	3.51
		LEU-01-T	312.23	6.96
		LEU-117-LE	296.26	5.70
		LEU-118-TE	297.16	4.87
		LEU-119-LC	297.21	4.63
		LEU-120-TC	293.37	2.94
	027-05-000DTA	LEU-11-L	314.20	4.45
		LEU-10-T	312.82	5.61
		LEU-79-LE	296.90	3.16
		LEU-80-TE	291.28	4.65
		LEU-81-LC	296.83	4.58

Thickness (in.)	Sample ID	Specimen ID	Average hardness (HV)	Standard deviation (HV)
		LEU-82-TC	297.20	5.05
	027-05-002DTB	LEU-14-L	313.33	4.68
		LEU-13-T	322.38	2.74
		LEU-113-LE	-	-
		LEU-114-TE	-	-
		LEU-115-LC	-	-
		LEU-116-TC	296.95	4.41
	027-05-000DTC	LEU-17-L	320.55	4.55
		LEU-16-T	314.75	5.42
		LEU-105-LE1	301.16	6.06
		LEU-106-TE1	296.21	5.73
		LEU-107-LC	295.13	3.22
		LEU-108-TC	300.97	9.24

Table A.36. Vickers microhardness data obtained from U-10Mo specimens with Zr (PNNL data)

Thickness (in.)	Sample ID	Specimen ID	Average hardness (HV)	Standard deviation (HV)
0.01	030-01-001CTA	LEU-37-L	310.7	4.9
		LEU-38-T	310.8	4.3
		LEU-167-TE-A	291.32	3.19
		LEU-168-LE-A	291.46	3.59
		LEU-169-TE-B	288.92	5.37
		LEU-170-LE-B	291.46	3.51
	030-01-004CTB	LEU-39-L	308.5	3.0
		LEU-40-T	306.5	3.8
		LEU-125-LE1	296.30	3.87
		LEU-126-TE1	290.24	3.62
		LEU-127-LE2	294.09	5.03
		LEU-128-TE2	290.52	4.46
	030-01-001CTC	LEU-41-L	307.8	3.4
		LEU-42-T	305.8	1.9
		LEU-121-LE1	291.73	3.45
		LEU-122-TE1	294.21	3.80
		LEU-123-LE2	289.14	2.23
		LEU-124-TE2	290.12	4.85
0.027	029-01-001CTA	LEU-25-L	308.2	4.5
		LEU-26-T	308.8	4.7
		LEU-159-TE-A	288.90	4.14
		LEU-160-LE-A	289.69	3.44
		LEU-161-TE-B	289.86	4.29
		LEU-162-LE-B	292.08	4.64

Thickness (in.)	Sample ID	Specimen ID	Average hardness (HV)	Standard deviation (HV)
	029-01-004CTB	LEU-23-L	309.2	3.1
		LEU-24-T	312.2	3.1
		LEU-133-LE1	293.95	4.87
		LEU-134-TE1	296.00	2.74
		LEU-135-LE2	292.04	1.83
		LEU-136-TE2	291.32	3.01
	029-01-001CTC	LEU-19-L	318.2	4.9
		LEU-20-T	309.5	3.7
		LEU-129-LE1	290.81	5.03
		LEU-130-TE1	291.38	4.77
		LEU-131-LE2	290.21	4.46
		LEU-132-TE2	288.88	2.99
	029-01-002CTA	LEU-29-L	309.8	2.7
		LEU-30-T	311.7	1.7
		LEU-163-TE-A	311.68	1.76
		LEU-164-LE-A	289.42	3.18
		LEU-165-TE-B	291.62	5.02
		LEU-166-LE-B	292.84	4.11
	029-01-006CTB	LEU-31-L	307.0	3.0
		LEU-32-T	312.9	3.8
		LEU-183-TE-A	-	-
		LEU-184-LE-A	-	-
		LEU-185-TE-B	-	-
		LEU-186-LE-B	-	-
	029-01-002CTC	LEU-33-L	310.4	2.1
		LEU-34-T	306.4	4.8
		LEU-187-TE-A	-	-
		LEU-188-LE-A	-	-
		LEU-189-TE-B	-	-
		LEU-190-LE-B	-	-
0.047	029-01-000DTA	LEU-43-L	306.8	3.1
		LEU-44-T	318.9	5.4
		LEU-145-LE-A	294.42	4.57
		LEU-146-TE-A	277.36	5.56
		LEU-147-LE-B	286.15	7.78
		LEU-148-TE-B	286.76	5.54
	029-01-002DTB	LEU-45-L	316.1	2.4
		LEU-46-T	310.7	5.4
		LEU-149-LE-A	292.95	5.21
		LEU-150-TE-A	286.87	5.51
		LEU-151-LE-B	-	-
		LEU-152-TE-B	-	-

Thickness (in.)	Sample ID	Specimen ID	Average hardness (HV)	Standard deviation (HV)
	029-01-000DTC	LEU-49-L	309.6	5.1
		LEU-50-T	315.1	2.3
		LEU-153-LE-A	281.53	5.34
		LEU-154-TE-A	287.48	5.28
		LEU-157-TE-B	294.35	3.72
		LEU-158-LE-B	286.22	3.87
	030-01-000DTA	LEU-51-L	312.1	3.2
		LEU-52-T	311.9	5.2
		LEU-171-TE-A	281.09	2.79
		LEU-172-LE-A	284.52	5.76
		LEU-173-TE-B	284.91	5.99
		LEU-174-LE-B	278.43	4.65

CONVERT, REMOVE, DISPOSE