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Assembly of MiniFuel Targets for Irradiation of U-Mo Fuel Specimens in the High Flux Isotope Reactor

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Nuclear Energy and Fuel Cycle Division

ASSEMBLY OF MINIFUEL TARGETS FOR IRRADIATION OF U-MO FUEL SPECIMENS IN THE HIGH FLUX ISOTOPE REACTOR

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ABBREVIATIONS

ALEU	advanced low-enriched uranium
EABD	experiment authorization bases document
EB	electron beam
EDM	electro-discharge machining
FE	finite element
HFIR	High Flux Isotope Reactor
HGR	heat generation rate
LEU	low-enriched uranium
ORNL	Oak Ridge National Laboratory
PIE	post-irradiation examination
PWR	pressurized-water reactor
QA	quality assurance
RA	radial-axial
SiC	silicon carbide
TM	thermometry
VXF	vertical experiment facility

ABSTRACT

To support the development of advanced low-enriched uranium for use in nuclear reactors, irradiation testing of U-Mo disk specimens was performed at the Oak Ridge National Laboratory (ORNL) High Flux Isotope Reactor (HFIR) to collect experimental irradiation data on this type of fuel at pressurized water reactor–relevant temperatures. U-Mo is a uranium alloy that has superior dimensional stability relative to alpha-phase uranium metal and has a substantially higher uranium density compared to UO_2. U-Mo disks specimens were fabricated at Idaho National Laboratory and inserted into MiniFuel targets for HFIR irradiation. Three MiniFuel targets were successfully assembled, welded, tested, and delivered to HFIR, along with their quality assurance documentation. The targets were inserted into HFIR's inner vertical experiment facility within the permanent beryllium reflector. Each target contains six disk specimens and will be irradiated in HFIR for three, four, and eight cycles, with target temperatures between 250 and 500°C. This report summarizes the experiment design, test matrix, pre-characterization of specimens, and experiment assembly.

1. INTRODUCTION

For nonproliferation purposes, research and development work has been performed on low-enriched uranium (LEU) fuel for use in nuclear reactors. The use of LEU requires much larger uranium densities compared to the fuel currently used in nuclear reactors. The Advanced LEU (ALEU) fuel program has identified a range of nuclear fuels and other fabrication technologies that could offer solutions to achieve this goal. U-Mo, which has a dimensional stability superior to that of alpha-phase uranium metal and a substantially higher uranium density than UO_2, is a fuel form candidate for this type of application. Because U-Mo alloys have been studied for application in fast reactors, its irradiation properties at high temperature are available. However, irradiation data for U-Mo at temperatures relevant for pressurized water reactors (PWRs) are limited and need to be collected for PWR applications [1].

Irradiation testing is being performed at Oak Ridge National Laboratory (ORNL) in the High Flux Isotope Reactor (HFIR) to collect experimental data on two different U-Mo fuel compositions: U-10Mo and U-16.7Mo (wt.%). This testing is being conducted at temperatures between 250 and 500°C. ORNL's MiniFuel experiment design [2] is being used to (1) explore the swelling transition fission density of U-Mo at PWR conditions, (2) collect data to validate existing models, and (3) define the operational constraints for using U-Mo fuel in nuclear reactors. The irradiation data will also be compared to results from previous irradiations [3]. This report summarizes the experiment design, test matrix, specimens pre-characterization, and experiment assembly for the HFIR U-Mo experiments.

2. DESIGN OF U-MO FUEL IRRADIATION EXPERIMENT

2.1 DESIGN AND ANALYSIS METHODS

2.1.1 Experiment Geometry

Figure 1 illustrates the components of the MiniFuel experiment design [2]. The experiment facility consists of an aluminum basket with three radial positions (R = 1, 2, 3) and three axial positions (A = 1, 2, 3), for a total of 9 positions. Two of the radial positions face the core (R = 2 and 3), and the middle axial position (A =2) is located around the core's mid-plane. MiniFuel targets can be inserted into each radial position and stacked at each axial position. A MiniFuel target is made of a stainless-steel tube, sealed on both ends, which contains a stack of six individually sealed subcapsules. The positions of the subcapsules in the target are referred to as $S = 1$ (bottom position) through $S = 6$ (top position). Centering thimbles made of titanium alloy are placed at each end of the subcapsules to ensure that the gas gap between the target tube and the subcapsule is radially uniform and cannot be displaced during irradiation. The target irradiation temperature of the fuel specimens is controlled by the size of the gas gap and the fill gas thermal conductivity, which is a mixture of helium and argon gas. The subcapsule is composed of Mo and contains the U-Mo disk fuel specimen, a Mo cup, a Mo insert tube, SiC passive thermometry (TM), and grafoil insulator disks. A Mo end cap is welded to the holder to seal the subcapsule. All subcapsules are sealed with pure helium backfill gas. This experiment is similar to previous miniature fuel experiments in which bare fuel kernels, fuel disks, and fully ceramic encapsulated coated particles with slight modifications to the size of the components inside the subcapsule were irradiated. More details on the MiniFuel facility are available in the literature [2][4].

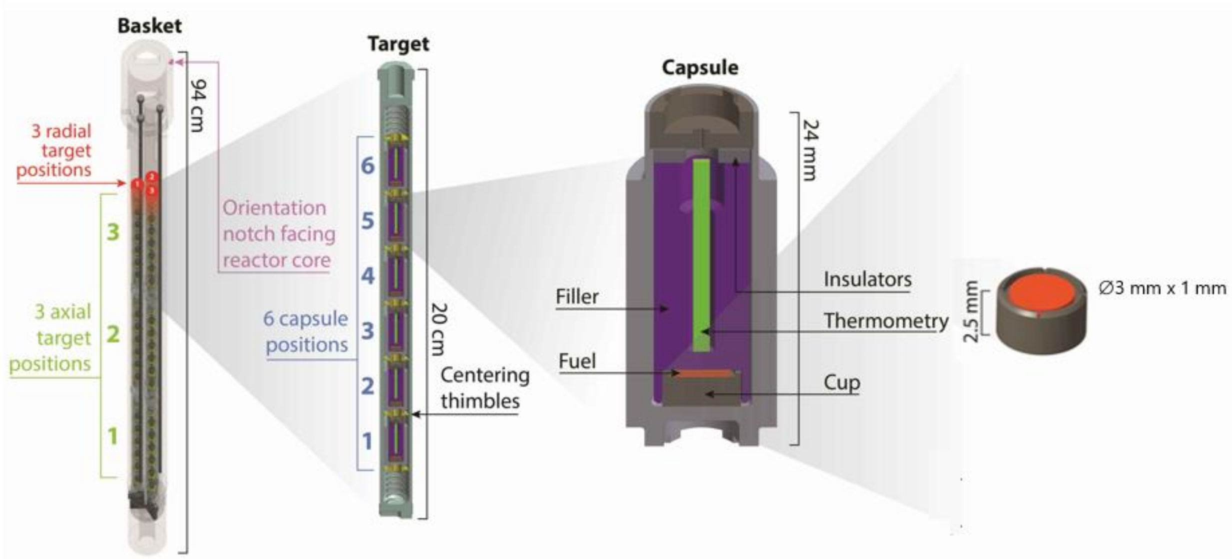


Figure 1. MiniFuel experiment design for irradiation of U-Mo disk specimens.

2.1.2 Experiment Test Matrix

Table 1 provides details of the experiment irradiation test matrix, the irradiation conditions, and the specimens inserted into the targets. Each of the 3 ALEU targets contains 6 U-Mo disk specimens with a composition of either U-10Mo or U-16.7Mo (wt.%) (see Section 3). The targets are planned to be irradiated for 3, 4, and 8 HFIR cycles, corresponding to a burnup of 0.5, 1, and 2% fission per initial heavy metal atom and 2.1×10^{20}, 4.2×10^{20}, and 8.3×10^{20} fissions/cm^3, respectively.

Table 1. Irradiation test matrix

Target ID	Number of irradiation cycles	Target temperature (°C)	Fuel disks	Irradiation location (R-A)	Target fill gas
ALEU-1	3	250 350 340 450 500 250	U-10Mo U-10Mo U-10Mo U-10Mo U-16.7Mo U-16.7Mo	2-3	94% He / Ar bal.
ALEU-2	4	250 350 340 450 500 250	U-10Mo U-10Mo U-10Mo U-10Mo U-16.7Mo U-16.7Mo	3-3	94% He / Ar bal
ALEU-3	8	250 500 450 340 350 250	U-16.7Mo U-16.7Mo U-10Mo U-10Mo U-10Mo U-10Mo	2-1	98% He / Ar bal

2.1.3 Neutronic Analysis

Neutronic calculations were performed to determine heat generation rates (HGRs) in the fuel and target structures that result from neutron and gamma interactions. These HGRs were provided as inputs for the thermal finite element models to predict burnup during the irradiation. The neutronic calculations were performed using a version of the Monte Carlo N-Particle, Version 5 (MCNP5) neutronics code [5], the SCALE software package [6], and the ADVANTG [7] variance-reduction tool that are merged together using a wrapper code called HFIRCON [8]. The MCNP HFIR Cycle 400 model was modified to include the irradiation experiments described in this report. The model was also used to calculate the neutron and photon heating, fission rate, and fuel burnup as a function of irradiation time in HFIR [9]. The HFIRCON wrapper automates a five-step process that calculates heat generation from fission neutrons (prompt and delayed), prompt fission photons, delayed photons from fission product decay, α and β decay heat, and photon heating from local activation product decay. The methodology is also described in works by Petrie et al. [2] and Chandler [10]. This calculation procedure is consistent with those used to analyze MiniFuel experiments [2][4].

In this experiment, two separate cases were evaluated. One case considered targets containing U-10Mo fuel disks with 1.2% ^{235}U enrichment, and the other case considered U-16.7Mo with 1.2% ^{235}U enrichment. The analysis considered five HFIR cycles, each 26 days in length, with 15 days of downtime assumed between cycles. Heating rates in W/g were calculated for all target and sub-capsule components for all 9 target positions.

2.1.4 Finite Element Analysis

Finite element (FE) thermal analysis was performed using a quarter-symmetry model of a single MiniFuel target developed in the commercial FE software package ANSYS. The target model was adapted from ANSYS models that had been used in previous MiniFuel analyses [2][11][12], and custom macro programs were used to calculate thermal contact conductance through variable gas gaps [13]. Temperature-dependent material properties were implemented for each nonfuel component. The thermal property files are maintained internally and have been reviewed for quality assurance. The properties implemented for the U-Mo disk specimens are from the U-Mo Fuel Handbook, Ver. 1.0 [1]. The fuel burnup was predicted using HFIRCON, and a Python script was used to read the predicted fuel burnup into ANSYS. The Python script was also used to read HGRs for each target component based on the number of days and position in HFIR and to set the internal heat generation in each component in the ANSYS model [4]. Convective boundary conditions on the target housing have been calculated in RELAP5 for previous MiniFuel irradiations in the inner small vertical experiment facility (VXF). The heat transfer coefficient used was 44.8 kW/m^{2}K, and the water temperature was calculated as 58°C [2][14].

2.2 RESULTS

2.2.1 Neutronic Results

The HFIRCON simulations included days 0, 1, 3, 5, 10, 15, 20, 22, 24, and 26 of the cycle. The HGRs in all materials from photons vary with respect to time into the cycle. These variations result from movement of the control element, resulting in an increase in HGRs near the end of the cycle. However, the gamma heating rates vary minimally from cycle to cycle. The fuel fission heating is also affected by the control element movement, as shown in Figure 2**.** The legend on the figure indicates the radial and axial (RA) position of the target and subcapsule.

The overall trend for the fuel HGR considered in this experiment is decreasing with respect to time as the fissile material burns up and the fission rates decrease. The positions near the HFIR axial midplane also experience higher HGRs from both gamma and neutrons. Figure 2 shows the predicted burnup and HGR in the fuel for ALEU-1 (RA:23) for the U-10Mo fuel (top) and the U-16.7Mo fuel (bottom). ALEU-2 and ALEU-3 were simulated at positions RA:33 and RA:21, respectively, and are located at the same radial distance from the HFIR core centerline. Therefore, the performance of ALEU-2 will be nearly identical to that of ALEU-1. ALEU-3 will also have similar performance because the specimen stack within the target mirrors ALEU-1 relative to the HFIR axial midplane. This accounts for the reactor's Gaussian flux profile. The simulations did not incorporate data from the final 3 cycles to reach the 8 total cycles planned for ALEU. However, extrapolation can be used to estimate the HGRs and the eventual burnup.

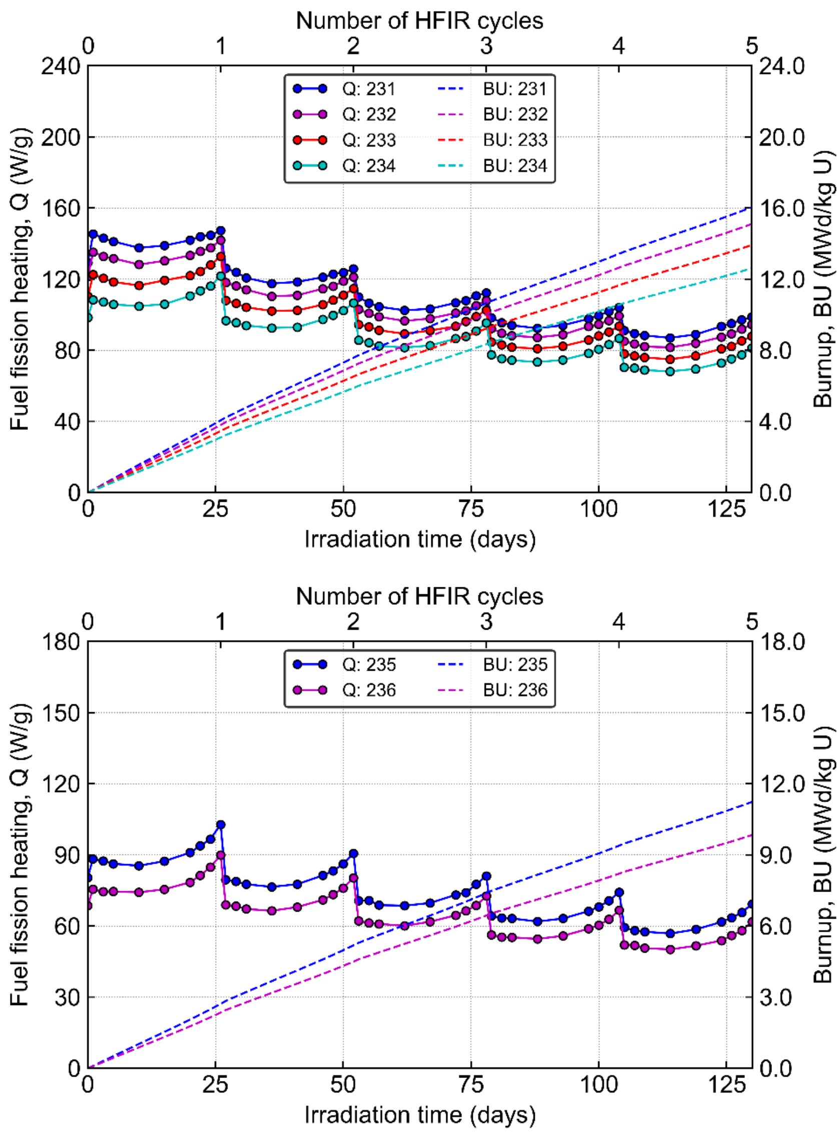


Figure 2. The burnup and fission HGRs for fuel disks at the RA:23 positions for the U-10Mo specimens (top) and the U-16.7Mo specimens (bottom).

2.2.2 Thermal Analysis Results

The design temperature for each fuel specimen was targeted by modifying the size of the gas gap between the subcapsule's outer diameter and the target's inner diameter. The design temperature metric used herein was the fuel disk temperature averaged over both time and volume. Table 2 summarizes the time-averaged and volume-averaged temperatures of the specimens and TM for each target. Figure 3 presents the fuel average temperatures for each subcapsule and each target as a function of irradiation time. The legend on the figure specifies the subcapsule position (S) and the end of the corresponding specimen ID in parentheses. The maximum spatial temperature gradients in the specimens ranged from ~20-40°C, depending on the position. Positions closer to the reactor mid-plane have higher fission rates, resulting higher heat generation rates in the fuel and larger temperature gradients compared to specimens located closer to the periphery. It can be seen on Figure 3 that by the fifth irradiation cycle, the temperature variation from fuel burnup is minimal. Therefore, the average temperature for ALEU-3 cycles 6 ,7 and 8 (not simulated in HFIRCON) assumed the same thermal history as cycle 5 when computing the time-averaged temperatures.

Table 2. Thermal results for each target: disk specimens and TM temperatures

	Subcapsule position					
	S=1	**S=2**	**S=3**	**S=4**	**S=5**	**S=6**
Target ID	**ALEU-1**					
	ALEU-10Mo				***ALEU-15Mo***	
Specimen ID	2002-N	2003-J	2002-F	2002-A	2004-G	2004-D
Specimen avg. temp. (°C)	287	511	471	371	376	276
TM avg. temp. (°C)	156	389	347	262	289	194
Target ID	**ALEU-2**					
	ALEU-10Mo				***ALEU-15Mo***	
Specimen ID	2002-D	2003-A	2002-B	2003-K	2004-E	2004-H
Specimen avg. temp. (°C)	261	482	446	358	360	261
TM avg. temp. (°C)	153	378	339	256	280	188
Target ID	**ALEU-3**					
	ALEU-15Mo		***ALEU-10Mo***			
Specimen ID	2004-A	2005-H	2003-G	2003-B	2003-F	2002-I
Specimen avg. temp. (°C)	260	364	361	463	497	258
TM avg. temp. (°C)	197	296	273	368	382	147

Note that even though the Mo content for the U-16.7Mo batches is indeed 16.7%, the batch names (*ALEU-15Mo-*) do *not* reflect the actual fuel composition.

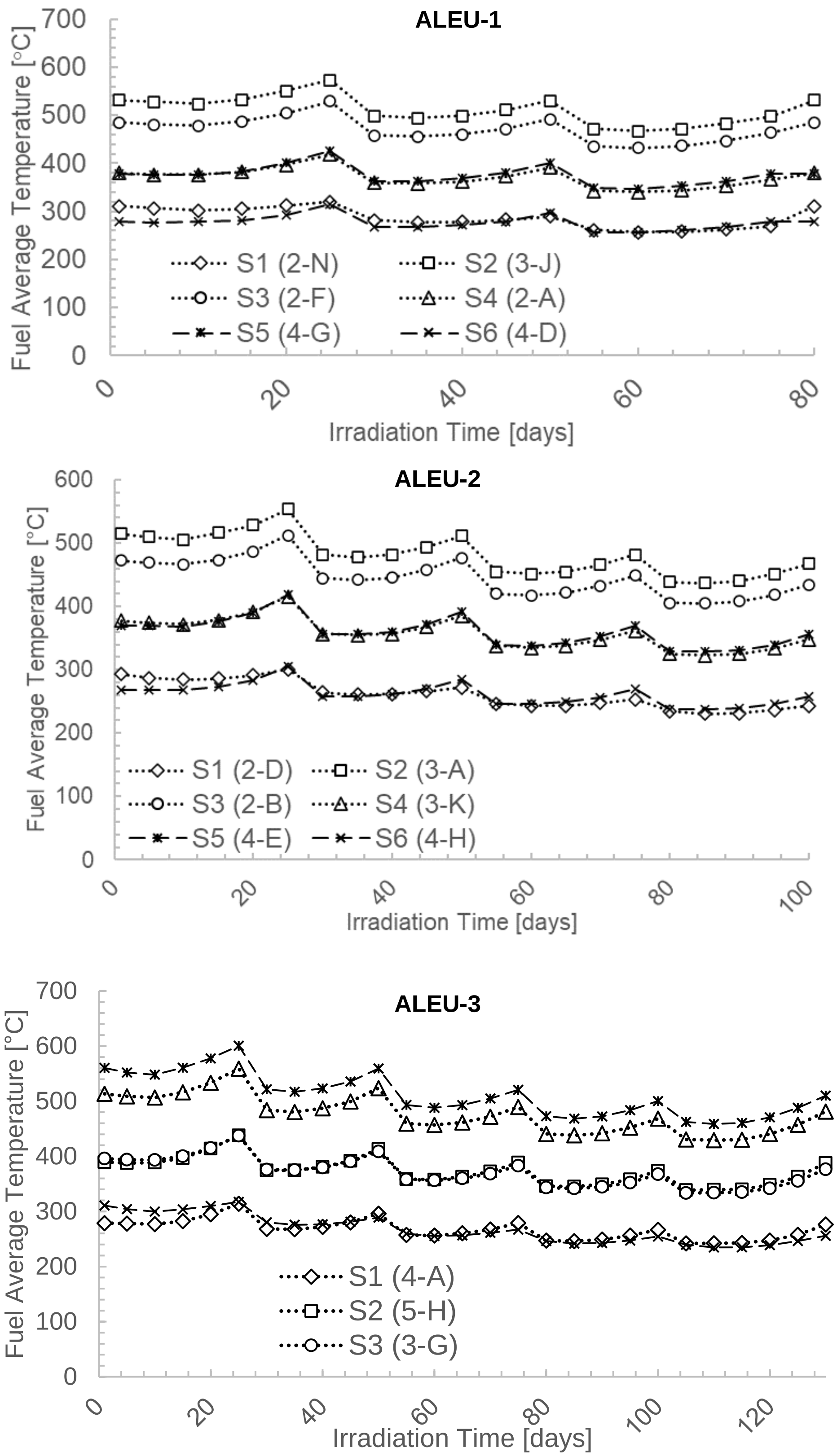


Figure 3. Disk fuel specimen temperature for each subcapsule and each target as a function of irradiation time.

3. SPECIMENS FABRICATION AND PRE-CHARACTERIZATION

3.1 SPECIMENS FABRICATION

The U-Mo disk specimens were fabricated at Idaho National Laboratory by casting charge input of depleted uranium (0.22% ^{235}U), highly enriched uranium (69.5% ^{235}U), and Mo foil (99.95% pure). The casting charge was arc melted three times to ensure alloy homogeneity. After the third alloying cycle, the charge was heated one more time and was then arc cast into a 5 mm rod. The rod was then machined on a lathe to a diameter of 3 mm, and disk specimens were cut using wire electro-discharge machining (EDM). Finally, to remove the contamination and burr caused by the EDM, disk specimens were hand polished on SiC sandpaper.

Disk specimens of two different compositions—U-10Mo and U-16.7Mo (U_2Mo phase)—were fabricated. Table 3 presents the characteristics of each batch of fuel disks (two batches for each composition). Note that even though the Mo content for the U-16.7Mo batches is indeed 16.7%, the batch names do *not* reflect the actual fuel composition.

Table 3. Characteristics of the fuel for each type of disks

Disk type	Batch #	Enrichment	U mass per disk (g)	^{235}U mass per compact (g)	Mo content (wt.%)
U-10Mo	ALEU-10Mo-2002	1.24%	0.0804	0.0010	10.00
	ALEU-10Mo-2003	1.23%	0.0872	0.0011	9.99
U-16.7Mo	ALEU-15Mo-2004	1.22%	0.0800	0.0010	16.75
	ALEU-15Mo-2005	1.23%	0.0794	0.0010	16.76

3.2 PRE-CHARACTERIZATION OF SPECIMENS

Pre-irradiation measurements of the disk specimens included mass and dimensional inspection (thickness and diameter) and volume measurement. The volume of the specimens was calculated from the dimensional measurements and was measured via digital microscopy and pycnometry. The instruments used to pre-characterize the specimens are specified below:

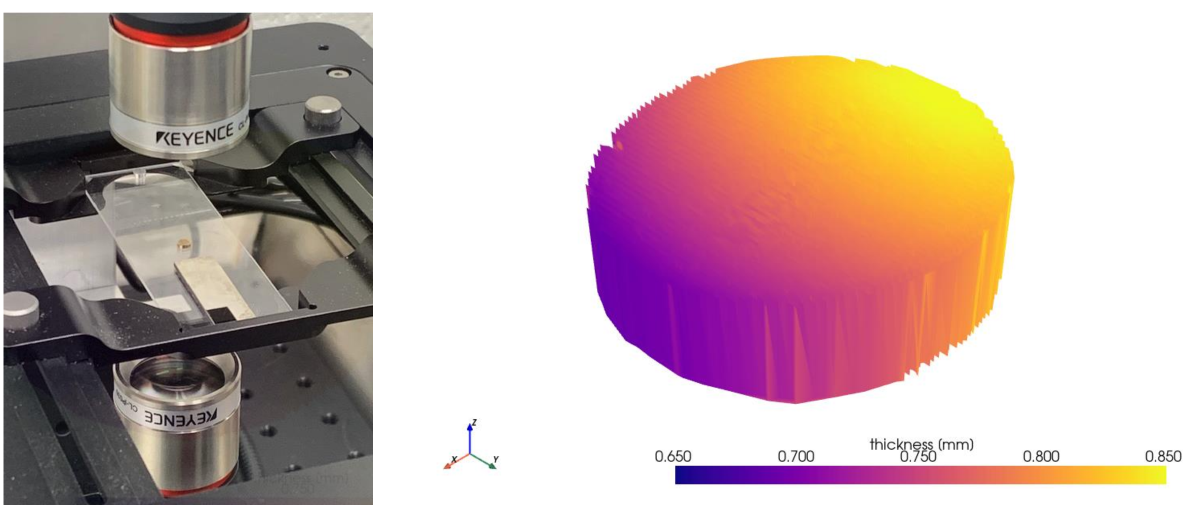
- Mass: Mettler Toledo XP504 balance
- Thickness measurements: Starrett Digital Indicator F2720-0
- Diameter measurements: Mitotuyo CD-6"PMX Digital Caliper
- Volume measurements: Keyence VR-5000 Wide-Area 3D Measurement System and Micromeritics AccuPyc II Pycnometer

The pre-irradiation measurements results are presented in Table 4.The dimensional inspection, Keyence instrument, and pycnometer show consistent volume results. Images of the specimens were also collected using the Keyence digital microscope (see APPENDIX A).

Table 4. Pre-irradiation measurements on the U-Mo disk specimens

Specimen ID	Mass (g)	Thickness (mm)	Diameter (mm)	Volume (mm^3)		
				Dimensional	Keyence	Pycnometer
ALEU-10Mo-2002-A	0.0944	0.80	2.99	5.617	5.593 (σ=0.009)	5.6
ALEU-10Mo-2002-B	0.0878	0.77	2.93	5.183	5.161 (σ=0.008)	5.0
ALEU-10Mo-2002-D	0.0833	0.73	2.96	5.019	4.886 (σ=0.000)	4.7
ALEU-10Mo-2002-F	0.0919	0.80	2.98	5.577	5.443 (σ=0.000)	5.4
ALEU-10Mo-2002-I	0.0880	0.76	2.97	5.242	5.188 (σ=0.010)	5.2
ALEU-10Mo-2002-N	0.0956	0.81	2.95	5.526	5.634 (σ=0.008)	5.5
ALEU-10Mo-2003-A	0.0924	0.751	3.00	5.320	5.430 (σ=0.013)	5.3
ALEU-10Mo-2003-B	0.1037	0.866	2.99	6.067	6.129 (σ=0.002)	6.0
ALEU-10Mo-2003-F	0.1028	0.852	3.00	6.007	6.069 (σ=0.007)	5.9
ALEU-10Mo-2003-G	0.1070	0.876	2.98	6.107	6.305 (σ=0.007)	6.2
ALEU-10Mo-2003-J	0.0990	0.811	3.00	5.748	5.809 (σ=0.002)	5.7
ALEU-10Mo-2003-K	0.0963	0.793	3.01	5.658	5.683 (σ=0.005)	5.6
ALEU-15Mo-2004-A	0.1072	0.940	3.02	6.716	6.603 (σ=0.010)	6.6
ALEU-15Mo-2004-D	0.1047	0.896	3.03	6.461	6.423 (σ=0.001)	6.4
ALEU-15Mo-2004-E	0.0898	0.790	3.02	5.661	5.539 (σ=0.007)	5.5
ALEU-15Mo-2004-G	0.0974	0.836	3.01	5.951	6.009 (σ=0.008)	6.0
ALEU-15Mo-2004-H	0.0951	0.836	3.01	5.938	5.929 (σ=0.006)	5.8
ALEU-15Mo-2005-H	0.1022	0.896	3.02	6.421	6.427 (σ=0.001)	6.4

The Keyence system presented in Figure 4a was used to collect profilometry data on the disk specimens. Profilometry captures thickness variation of the specimens. Figure 4b shows an example of a 3D volume of a disk specimen that was collected via profilometry. The thickness variation for all the specimens is presented in Figure 5: the thickness overall ranges from 0.5 to 1 mm. Additional information on the specimens' pre-characterization is available in the pre-characterization report by Massey [15].



(a) (b)

Figure 4. Profilometry measurement system (a) and 3D volume from profilometers for specimen ALEU-10Mo-2002A (b).

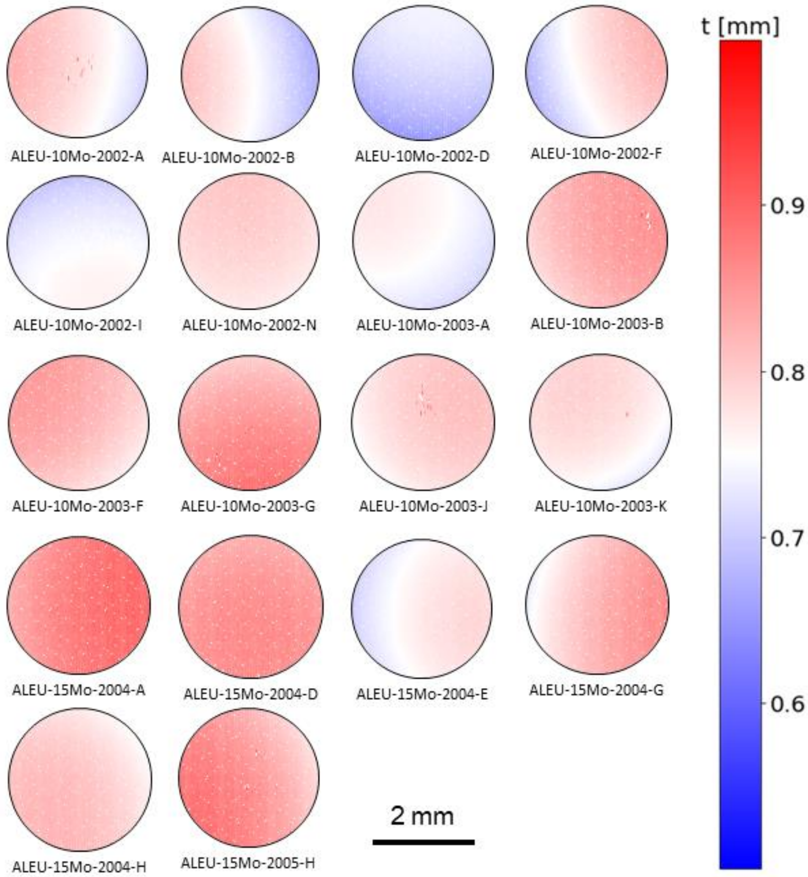


Figure 5. Thickness variations of the U-Mo disk specimens.

4. EXPERIMENT FABRICATION AND HFIR DELIVERY

4.1 SUBCAPSULES ASSEMBLY

Figure 6 shows the parts layout for one subcapsule: 18 subcapsules were assembled (see Figure 7). The signed subassembly fabrication request forms are provided in APPENDIX B.

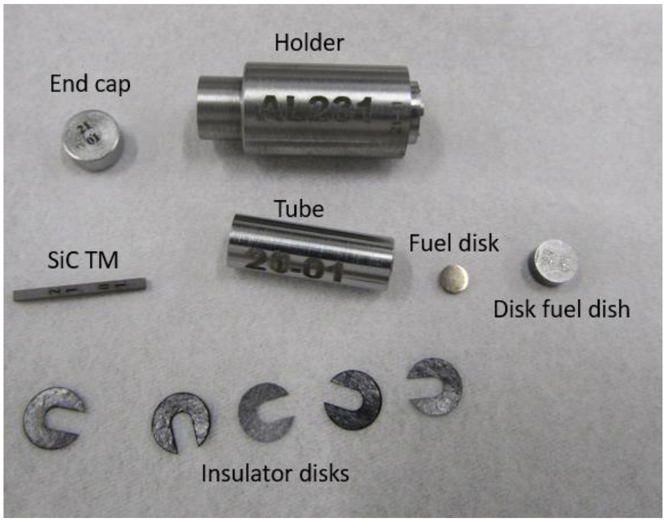


Figure 6. Subcapsule parts layout (Credit: ORNL, US Department of Energy).

Figure 7. Subcapsules assembled for ALEU MiniFuel targets (Credit: ORNL, US Department of Energy).

All subcapsule components were dimensionally inspected and cleaned according to HFIR-approved procedures, drawings, and sketches. After the internal components were assembled, the subcapsule end caps were welded to the subcapsule bodies using an electron beam (EB) weld. Figure 8 shows the subcapsules after EB welding. The subcapsule assemblies were then placed inside sealed containers that were evacuated and backfilled with ultra-high purity helium three times to ensure a pure environment. The containers were placed inside a glovebox, which was also evacuated and backfilled with the same gas that was used in the sealed containers, to a pressure equivalent to local atmospheric pressure. A small hole was seal-welded in each subcapsule end cap using a gas tungsten arc welding procedure. All welds passed visual examination. Each subcapsule was then sent for nondestructive examination, which included a bubble test and a helium leak test. All assemblies passed the nondestructive examination.

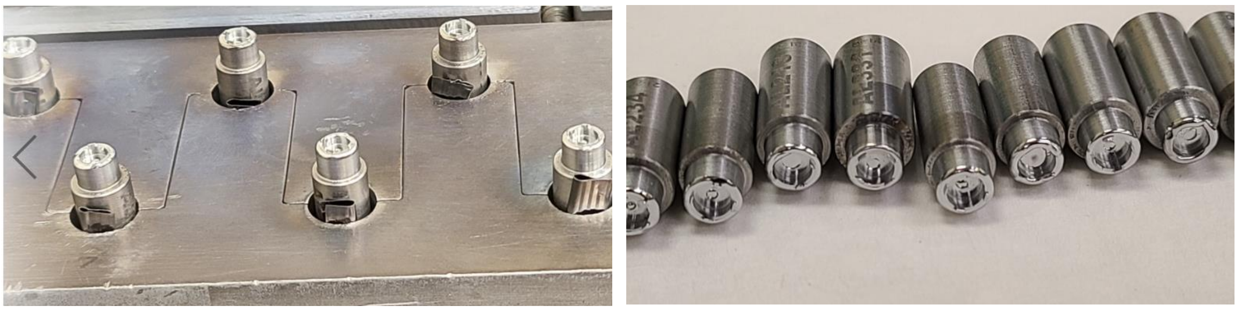


Figure 8. Subcapsules after EB welding (Credit: ORNL, US Department of Energy).

4.2 TARGET ASSEMBLY

Three targets were assembled, each containing 6 subcapsules. The parts layout for one target assembly is shown in Figure 9. As can be seen in this figure, the target's bottom end cap was welded to the target housing before the subcapsules were loaded. The signed target fabrication request forms are provided in APPENDIX B.

Figure 9. Parts layout of one target assembly: individual parts layout (top) and final target assembly (bottom) (Credit: ORNL, US Department of Energy).

All target components were dimensionally inspected and cleaned according to HFIR-approved procedures, drawings, and sketches. After the subcapsules, centering thimbles, and compression springs were loaded, the target top end caps were orbital-welded to the target housings. The targets were then placed inside a sealed container that was evacuated and backfilled with an ultra-high-purity helium/argon mixture (see fill gas in Table 1) three times to ensure a pure environment. The containers were placed inside a glovebox which was also evacuated and backfilled with the same gas that was used in the sealed container to a pressure equivalent to local atmospheric pressure. A small hole was seal-welded in each target assembly’s top end cap using a gas tungsten arc welding procedure. All welds passed visual examination. Each target was then sent for nondestructive examination, which included a helium leak test, hydrostatic compression at a pressure of 7.1 MPa (1,035 psi), mass comparisons before and after hydrostatic compression to ensure that no water penetrated the target assembly, another post-compression helium leak test, dye penetrant inspection, and radiographic inspection. Figure 10 shows a fully welded target, along with a radiographic image of the welds. All target assemblies passed the nondestructive examination.

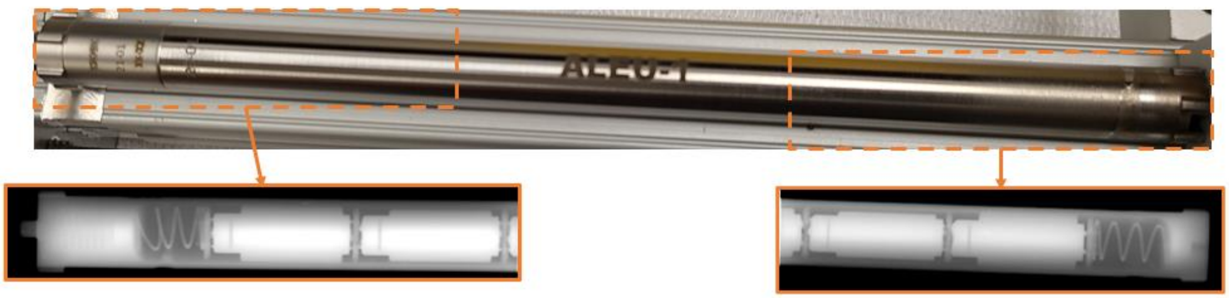


Figure 10. Final target fully welded (top), and radiography of the welds (bottom left and right) (Credit: ORNL, US Department of Energy).

4.3 LOADING IN THE MINIFUEL BASKET

The irradiation targets must be loaded into a basket assembly (see Figure 1) to keep the targets centered within the flow channel in HFIR’s small VXF. The 3 ALEU targets were loaded in a MiniFuel basket (ID MFA) in the irradiation locations shown in Table 1.

4.4 FABRICATION PACKAGE AND DELIVERY TO HFIR

A fabrication package must be developed for each irradiation experiment. The package must be reviewed by an independent design engineer, a lead quality assurance (QA) representative, and a HFIR QA representative before the experiment can be accepted for insertion into HFIR. The fabrication package must satisfy the requirements of the experiment authorization bases document (EABD). The irradiation of miniature fuel specimen experiments falls under HFIR QA document EABD-HFIR-2018-001, Rev. 2, which specifies requirements for the rabbits in the following areas:

- thermal safety analyses,
- material certification,
- dimensional inspection,
- cleaning,
- assembly procedure,
- sample loading,
- fill gas,
- welding, and
- nondestructive evaluation.

The fabrication package for the ALEU targets was reviewed and approved by all parties and was accepted by HFIR on July 28, 2021. The final signed acceptance page of the EABD is provided in APPENDIX C. The loaded MFA basket containing the ALEU targets was inserted into HFIR's small VXF-9 position to start irradiation of these targets in cycle 494 (August 2021).

5. SUMMARY AND CONCLUSIONS

Three MiniFuel targets containing U-Mo disk specimens were inserted in HFIR to start irradiation in cycle 494 (commencing on August 10, 2021); the irradiation of the three targets will be completed after 3, 4, and 8 HFIR cycles, respectively. Two different fuel compositions, U-10Mo and U-16.7Mo, are part of this irradiation testing. Pre-characterization of the fuel specimens included mass and dimensional measurements, volume measurements, and profilometry. Ultimately, post-irradiation examination will focus on fission gas release measurements and swelling of the specimens. The measured swelling will be compared to that predicted by BISON as described in Greenquist et al. [16]. Microstructure and detailed transmission electron microscopy to analyze the location of fission gas bubbles in the fuel will also provide useful information before comparison with existing data.

6. REFERENCES

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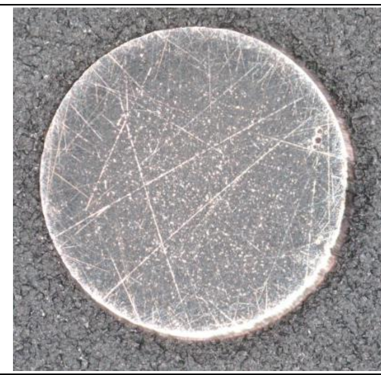
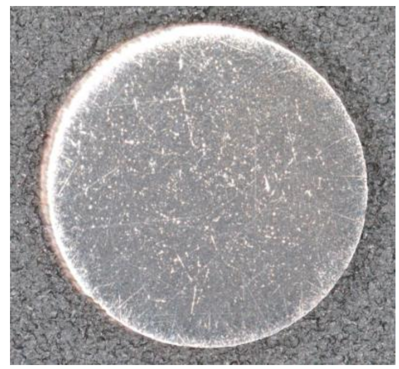
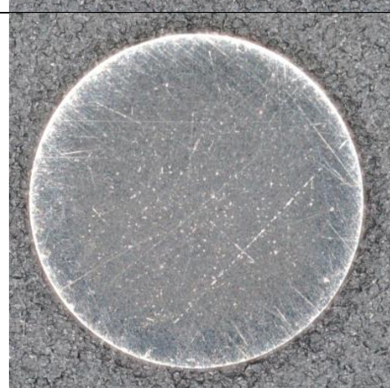
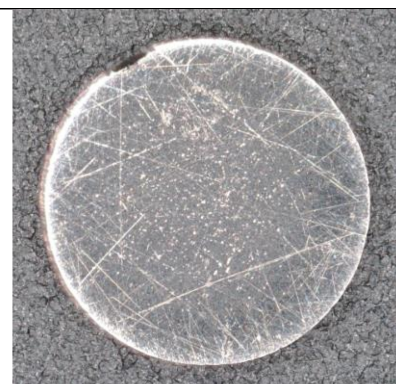
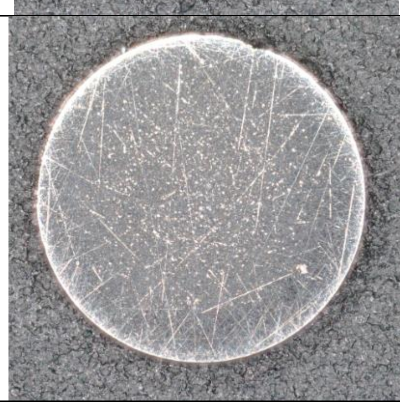
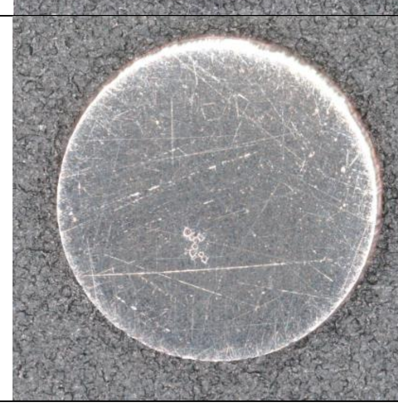
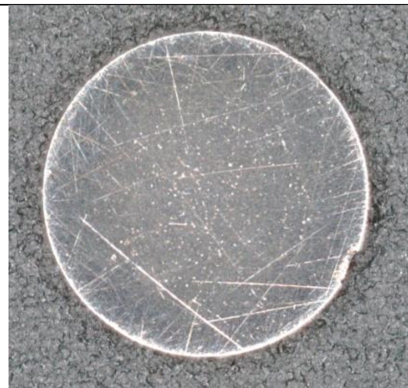
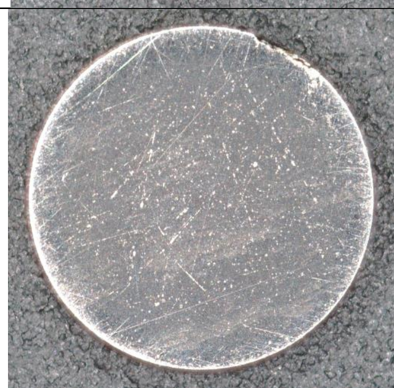
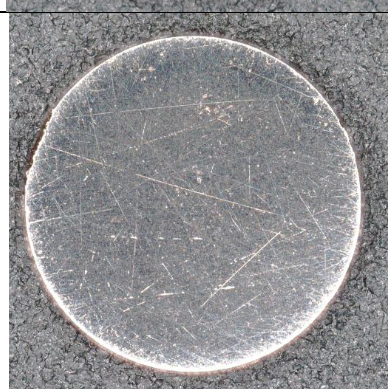
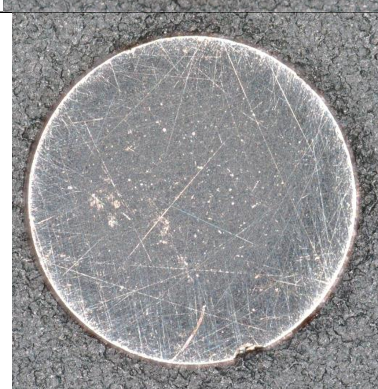
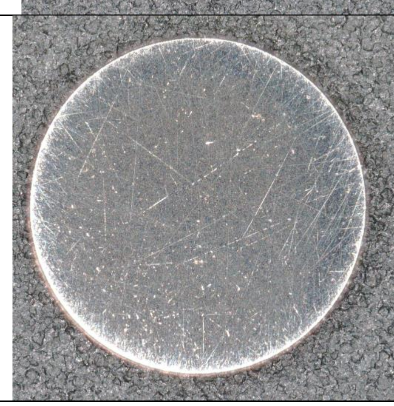
APPENDIX A. IMAGES OF THE DISK SPECIMENS

APPENDIX A. IMAGES OF THE DISK SPECIMENS

Specimen ID	Side 1	Side 2
ALEU-10Mo-2002-A		
ALEU-10Mo-2002-B		
ALEU-10Mo-2002-D		
ALEU-10Mo-2002-F		

Specimen ID	**Side 1**	**Side 2**
ALEU-10Mo-2002-I		
ALEU-10Mo-2002-N		
ALEU-10Mo-2003-A		
ALEU-10Mo-2003-B		

Specimen ID	**Side 1**	**Side 2**
ALEU-10Mo-2003-F		
ALEU-10Mo-2003-G		
ALEU-10Mo-2003-J		
ALEU-10Mo-2003-K		

Specimen ID	Side 1	Side 2
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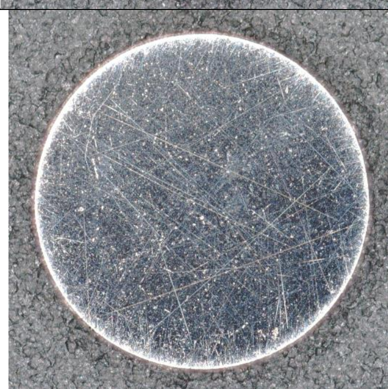
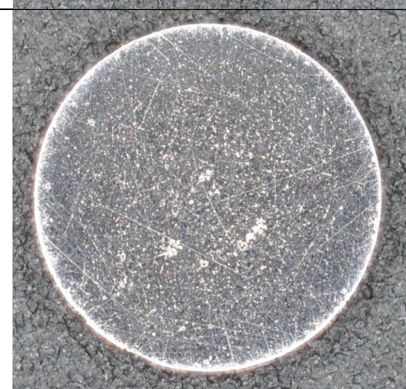
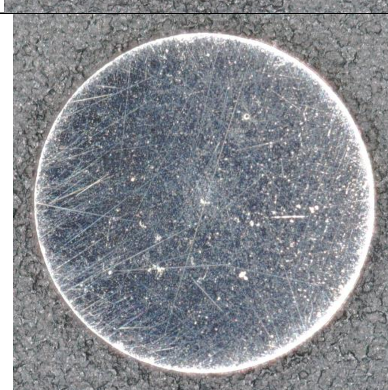
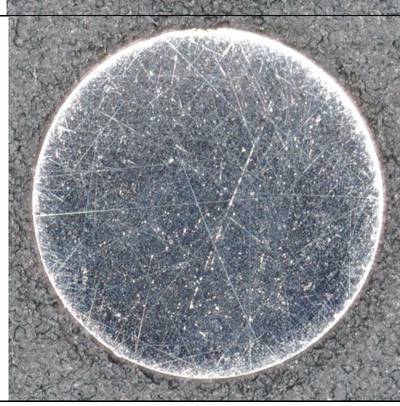
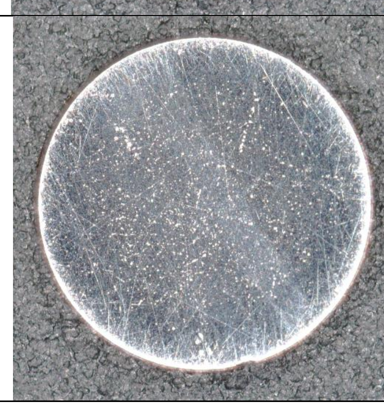
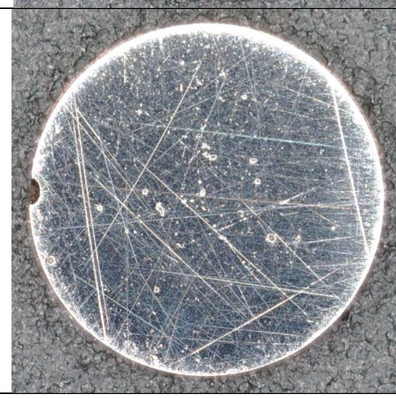
ALEU-15Mo-2004-D		
ALEU-15Mo-2004-E		
ALEU-15Mo-2004-G		

Specimen ID	Side 1	Side 2
ALEU-15Mo-2004-H		
ALEU-15Mo-2005-H		

APPENDIX B. FABRICATION REQUEST SHEETS

Target ID:	ALEU_1
Irradiation Conditions	
Irradiation Location (R, A)	2 3
Number cycles	2
First Cycle Goal	494
Fill Gas	94%He/Ar bal.
Irradiation Temperature	350°C
Holder assembly drawing	HS-2020-004 Rev. 0
Holder assembly welding drawing	HS-2020-003 Rev. 0

Approvals

	Request	Build
Performed by:	Annabelle Le Coq Digitally signed by Annabelle Le Coq Date: 2021.07.23 10:36:47 -04'00'	Christopher Hobbs Digitally signed by Christopher Hobbs Date: 2021.07.23 12:23:06 -04'00'
Checked by:	Ryan C. Gallagher Digitally signed by Ryan C. Gallagher Date: 2021.07.23 11:10:43 -04'00'	David Bryant Digitally signed by David Bryant Date: 2021.07.23 11:16:30 -04'00'

Holder Assembly

							S = Sub-assembly position												
							1	2	3	4	5	6	1	2	3	4	5	6	
							Component IDs for each holder ID						Component mass (g) for each holder ID						
Component	**Drawing**	**Rev.**	**Part**	**Material**	**MAT IR**	**FAB IR**	**AL231**	**AL232**	**AL233**	**AL234**	**AL235**	**AL236**	**AL231**	**AL232**	**AL233**	**AL234**	**AL235**	**AL236**	**All**
Holder	S17-14-CER_FUEL	2	1	Moly	21174	21182	21-41	21-04	21-19	21-27	21-15	21-38	9.6146	5.5494	6.9254	8.1366	6.5640	8.6528	45.4428
End cap	S17-14-CER_FUEL	2	2	Moly	21174	21181	21-01	21-02	21-03	21-04	21-05	21-06	0.5211	0.5227	0.5228	0.5191	0.5212	0.5193	3.1262
Tube	HS-2020-004	0	2	Moly	20868	21178	20-01	20-02	20-03	20-04	20-05	20-06	3.3441	3.3177	3.3224	3.3599	3.3426	3.3264	20.0131
Thermometry	HS-2020-004	0	3	SiC	20863	21184	21-01	21-02	21-03	21-04	21-05	21-06	0.0445	0.0440	0.0441	0.0450	0.0444	0.0450	0.2670
Insulator disk (list total # and mass)	HS-2020-004	0	4	Grafoil	19812	19812	5	5	5	5	5	5	0.0145	0.0145	0.0145	0.0145	0.0145	0.0145	0.0870
Disk Fuel Dish	HS-2020-004	0	5	Moly	21174	21200	21-01	21-02	21-03	21-04	21-05	21-06	0.2763	0.2785	0.2564	0.2662	0.2667	0.2792	1.6233
Disk Fuel Specimen	HS-2020-004	0	6	UMo	21241	21241	ALEU-10Mo-2002-N	ALEU-10Mo-2003-J	ALEU-10Mo-2002-F	ALEU-10Mo-2002-A	ALEU-15Mo-2004-G	ALEU-15Mo-2004-D	0.0956	0.0990	0.0919	0.0944	0.0974	0.1047	0.5830
												Total	13.9107	9.8258	11.1775	12.4357	10.8508	12.9419	71.1424
												Fuel	0.0956	0.0990	0.0919	0.0944	0.0974	0.1047	0.5830

Target ID: ALEU_1

Irradiation Conditions

Irradiation Location (R, A)	2 3
Number cycles	2
First Cycle Goal	494
Fill Gas	94% He/Ar bal.
Irradiation Temperature	350°C
Assembly drawing	HS-2020-003 Rev. 0
Welding drawing	HD-2020-007 Rev. 1

Approvals

	Request	Build
Performed by:	Annabelle Le Coq	David Bryant
Checked by:	Ryan C. Gallagher	Christopher Hobbs

Capsule Fabrication

Component	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Capsule outer tube	X3E020977A520	B	2	304 SS	1		21198	21198	21-01	54.0850
Capsule bottom end cap	X3E020977A520	B	3	304 SS	1		21179	21179	21-01	8.4487
Capsule top end cap	X3E020977A520	B	4	304 SS	1		21150	21205	20-03	15.9800
Spring	HS-2020-003	0	3	304 SS	2		20810	21197	011	0.2560
									012	0.2610
Centering thimble	HS-2020-003	0	4	Grade 5 Ti	14		21204	21204	20-01	0.1361
									20-02	0.1357
									20-03	0.1380
									20-04	0.1347
									20-05	0.1377
									20-06	0.1349
									20-07	0.1309
									20-08	0.1377
									20-09	0.1359
									20-10	0.1343
									20-11	0.1341
									20-12	0.1357
									20-13	0.1388
									20-14	0.1364
Subcapsule assembly	HS-2020-004	0	1	N/A	6		N/A	21225	AL236	12.9419
									AL235	10.8508
									AL234	12.4357
									AL233	11.1775
									AL232	9.8258
									AL231	13.9107
									Total Mass	152.0740

Holder Sub-Assemblies

Holder ID	S = Sub-Assem Position	R-A-S (R = Radial target position, A = Axial target position)	Holder diameter (mm)	Initial
AL236	6	2-3-6	9.60	DB
AL235	5	2-3-5	8.80	DB
AL234	4	2-3-4	9.45	DB
AL233	3	2-3-3	8.95	DB
AL232	2	2-3-2	8.35	DB
AL231	1	2-3-1	9.97	DB

Target ID: ALEU_2

Irradiation Conditions

Irradiation Location (R, A)	3 3
Number cycles	4
First Cycle Goal	494
Fill Gas	94%He/Ar bal.
Irradiation Temperature	350°C
Holder assembly drawing	HS-2020-004 Rev. 0
Holder assembly welding drawing	HS-2020-003 Rev. 0

Approvals

	Request	Build
Performed by:	Annabelle Le Coq Digitally signed by Annabelle Le Coq Date: 2021.07.23 10:39:08 -04'00'	Christopher Hobbs Digitally signed by Christopher Hobbs Date: 2021.07.23 12:23:45 -04'00'
Checked by:	Ryan C. Gallagher Digitally signed by Ryan C. Gallagher Date: 2021.07.23 11:12:49 -04'00'	David Bryant Digitally signed by David Bryant Date: 2021.07.23 11:17:11 -04'00'

Holder Assembly

							S = Sub-assembly position												
							1	2	3	4	5	6	1	2	3	4	5	6	
							Component IDs for each holder ID						Component mass (g) for each holder ID						
Component	Drawing	Rev.	Part	Material	MAT IR	FAB IR	AL331	AL332	AL333	AL334	AL335	AL336	AL331	AL332	AL333	AL334	AL335	AL336	All
Holder	S17-14-CER_FUEL	2	1	Moly	21174	21182	21-42	21-05	21-20	21-29	21-16	21-40	9.6478	5.5477	6.9135	8.1655	6.6075	8.5978	45.4798
End cap	S17-14-CER_FUEL	2	2	Moly	21174	21181	21-07	21-08	21-09	21-19	21-11	21-12	0.5178	0.5217	0.5218	0.5219	0.5223	0.5225	3.1280
Tube	HS-2020-004	0	2	Moly	20868	21178	20-07	20-08	20-09	20-10	20-11	20-12	3.3356	3.3448	3.3387	3.3710	3.3311	3.3492	20.0704
Thermometry	HS-2020-004	0	3	SiC	20863	21184	21-07	21-08	21-09	21-10	21-11	21-12	0.0444	0.0449	0.0445	0.0445	0.0442	0.0445	0.2670
Insulator disk (list total # and mass)	HS-2020-004	0	4	Grafoil	19812	19812	5	5	5	5	5	5	0.0145	0.0145	0.0145	0.0145	0.0145	0.0145	0.0870
Disk Fuel Dish	HS-2020-004	0	5	Moly	21174	21200	21-07	21-08	21-09	21-10	21-11	21-12	0.2693	0.2684	0.2651	0.2831	0.2707	0.2693	1.6259
Disk Fuel Specimen	HS-2020-004	0	6	UMo	21241	21241	ALEU-10Mo-2002-D	ALEU-10Mo-2003-A	ALEU-10Mo-2002-B	ALEU-10Mo-2003-K	ALEU-15Mo-2004-E	ALEU-15Mo-2004-H	0.0833	0.0924	0.0878	0.0963	0.0898	0.0951	0.5447
												Total	13.9127	9.8344	11.1859	12.4968	10.8801	12.8929	71.2028
												Fuel	0.0833	0.0924	0.0878	0.0963	0.0898	0.0951	0.5447

Target ID: ALEU_2

Irradiation Conditions

Irradiation Location (R, A)	3 3
Number cycles	4
First Cycle Goal	494
Fill Gas	94%He/Ar bal.
Irradiation Temperature	350°C
Assembly drawing	HS-2020-003 Rev. 0
Welding drawing	HD-2020-007 Rev. 1

Approvals

	Request	Build
Performed by:	Annabelle Le Coq	David Bryant
Checked by:	Ryan C. Gallagher	Christopher Hobbs

Capsule Fabrication

Component	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Capsule outer tube	X3E020977A520	B	2	304 SS	1		21198	21198	21-02	54.0930
Capsule bottom end cap	X3E020977A520	B	3	304 SS	1		21179	21179	21-02	8.4407
Capsule top end cap	X3E020977A520	B	4	304 SS	1		21150	21205	20-07	15.8995
Spring	HS-2020-003	0	3	304 SS	2		20810	21197	016	0.2570
									017	0.2580
Centering thimble	HS-2020-003	0	4	Grade 5 Ti	14		21204	21204	20-15	0.1355
									20-16	0.1407
									20-17	0.1337
									20-18	0.1316
									20-19	0.1352
									20-20	0.1370
									20-21	0.1339
									20-22	0.1337
									20-23	0.1358
									20-24	0.1342
									20-25	0.1269
									20-26	0.1359
									20-27	0.1357
									20-28	0.1271
Subcapsule assembly	HS-2020-004	0	1	N/A	6		N/A	21225	AL336	12.8929
									AL335	10.8801
									AL334	12.4968
									AL333	11.1859
									AL332	9.8344
									AL331	13.9127
									Total Mass	152.0279

Holder Sub-Assemblies

Holder ID	S = Sub-Assem Position	R-A-S (R = Radial target position, A = Axial target position)	Holder diameter (mm)	Initial
AL336	6	3-3-6	9.60	DB
AL335	5	3-3-5	8.80	DB
AL334	4	3-3-4	9.45	DB
AL333	3	3-3-3	8.95	DB
AL332	2	3-3-2	8.35	DB
AL331	1	3-3-1	9.97	DB

Target ID:	ALEU_3

Irradiation Conditions

Irradiation Location (R, A)	2 1
Number cycles	8
First Cycle Goal	494
Fill Gas	98%He/Ar bal.
Irradiation Temperature	350°C
Holder assembly drawing	HS-2020-004 Rev. 0
Holder assembly welding drawing	HS-2020-003 Rev. 0

Approvals

	Request		Build	
Performed by:	Annabelle Le Coq	Digitally signed by Annabelle Le Coq Date: 2021.07.23 10:40:50 -04'00'	Christopher Hobbs	Digitally signed by Christopher Hobbs Date: 2021.07.23 12:24:22 -04'00'
Checked by:	Ryan C. Gallagher	Digitally signed by Ryan C. Gallagher Date: 2021.07.23 11:18:10 -04'00'	David Bryant	Digitally signed by David Bryant Date: 2021.07.23 11:17:42 -04'00'

Holder Assembly

							S = Sub-assembly position					
							1	2	3	4	5	6
							Component IDs for each holder ID					
Component	Drawing	Rev.	Part	Material	MAT IR	FAB IR	AL211	AL212	AL213	AL214	AL215	AL216
Holder	S17-14-CER_FUEL	2	1	Moly	21174	21182	21-33	21-09	21-24	21-12	21-03	21-43
End cap	S17-14-CER_FUEL	2	2	Moly	21174	21181	21-13	21-14	21-15	21-16	21-17	21-18
Tube	HS-2020-004	0	2	Moly	20868	21178	20-13	20-14	20-15	20-16	20-17	20-18
Thermometry	HS-2020-004	0	3	SiC	20863	21184	21-13	21-14	21-15	21-16	21-17	21-18
Insulator disk (list total # and mass)	HS-2020-004	0	4	Grafoil	19612	19612	5	5	5	5	5	5
Disk Fuel Dish	HS-2020-004	0	5	Moly	21174	21200	21-13	21-14	21-15	21-16	21-17	21-18
Disk Fuel Specimen	HS-2020-004	0	6	UMo	21241	21241	ALEU-15Mo-2004-A	ALEU-15Mo-2005-H	ALEU-10Mo-2003-G	ALEU-10Mo-2003-B	ALEU-10Mo-2003-F	ALEU-10Mo-2002-I

	S = Sub-assembly position						
	1	2	3	4	5	6	
	Component mass (g) for each holder ID						
Component	AL211	AL212	AL213	AL214	AL215	AL216	All
Holder	8.3383	5.6605	7.8419	5.8796	4.3222	9.6378	41.6803
End cap	0.5267	0.5230	0.5228	0.5110	0.5198	0.5262	3.1295
Tube	3.3364	3.3149	3.3523	3.3523	3.3047	3.3239	19.9845
Thermometry	0.0442	0.0442	0.0439	0.0446	0.0445	0.0441	0.2655
Insulator disk (list total # and mass)	0.0145	0.0145	0.0145	0.0145	0.0145	0.0145	0.0870
Disk Fuel Dish	0.2698	0.2764	0.2675	0.2760	0.2703	0.2776	1.6376
Disk Fuel Specimen	0.1072	0.1022	0.107	0.1037	0.1028	0.0880	0.6109
Total	12.6371	9.9357	12.1499	10.1817	8.5788	13.9121	67.3953
Fuel	0.1072	0.1022	0.1070	0.1037	0.1028	0.0880	0.6109

Target ID: ALEU_3

Irradiation Conditions

Irradiation Location (R, A)	2 1
Number cycles	8
First Cycle Goal	494
Fill Gas	98% He/Ar bal.
Irradiation Temperature	350°C
Assembly drawing	HS-2020-003 Rev. 0
Welding drawing	HD-2020-007 Rev. 1

Approvals

	Request	Build
Performed by:	Annabelle Le Coq	David Bryant Digitally signed by David Bryant Date: 2021.07.23 11:17:30 -04'00'
Checked by:	Ryan C. Gallagher	Christopher Hobbs Digitally signed by Christopher Hobbs Date: 2021.07.23 12:24:05 -04'00'

Capsule Fabrication

Component	Drawing	Rev.	Part	Material	Count	Comment	MAT IR	FAB IR	ID	Mass (g)
Capsule outer tube	X3E020977A520	B	2	304 SS	1		21198	21198	21-03	54.0917
Capsule bottom end cap	X3E020977A520	B	3	304 SS	1		21179	21179	21-03	8.4420
Capsule top end cap	X3E020977A520	B	4	304 SS	1		21150	21205	20-08	15.9351
Spring	HS-2020-003	0	3	304 SS	2		20810	21197	018	0.2590
									019	0.2500
Centering thimble	HS-2020-003	0	4	Grade 5 Ti	14		21204	21204	20-29	0.1347
									20-30	0.1354
									20-31	0.1350
									20-32	0.1348
									20-33	0.1342
									20-34	0.1350
									20-35	0.1394
									20-36	0.1340
									20-37	0.1371
									20-38	0.1335
									20-39	0.1335
									20-40	0.1360
									20-41	0.1326
									20-42	0.1379
Subcapsule assembly	HS-2020-004	0	1	N/A	6		N/A	21225	AL216	13.9121
									AL215	8.5788
									AL214	10.1817
									AL213	12.1499
									AL212	9.9357
									AL211	12.6371
									Total Mass	148.2662

Holder Sub-Assemblies

Holder ID	S = Sub-Assem Position	R-A-S (R = Radial target position, A = Axial target position)	Holder diameter (mm)	Initial
AL216	6	2-1-6	9.97	DB
AL215	5	2-1-5	7.80	DB
AL214	4	2-1-4	8.50	DB
AL213	3	2-1-3	9.30	DB
AL212	2	2-1-2	8.40	DB
AL211	1	2-1-1	9.50	DB

APPENDIX C. EXPERIMENT AUTHORIZATION BASES DOCUMENT

APPENDIX C. EXPERIMENT AUTHORIZATION BASES DOCUMENT

Section 6: Acceptance for Use of As-Built Experiment Capsule

Note: This section is used to document acceptance of the as-built experiment for reactor installation and irradiation. This section is completed **after** completion of Section 2. See notes for explanation of signatures.

1. List Applicable Component Identifications:

Basket ID: MFA
Flux monitor IDs for Basket: 01,02,03

Target I.D. (as marked)	Dummy target
ALEU-1	☐
ALEU-2	☐
ALEU-3	☐
	☐
	☐
	☐
	☐
	☐
	☐

2. Approvals (see notes for explanation of signature responsibilities)

R.C. Gallagher Lead Experimenter	Ryan C. Gallagher (Digitally signed by Ryan C. Gallagher Date: 2021.07.23 15:21:27 -04'00') Lead Experimenter (signature)	Date
M.C. Vance Lead QA DLK 7/27/21	M. C. Vance (Digitally signed by M. C. Vance Date: 2021.07.23 15:39:56 -04'00') Lead QA (signature)	Date
~~A. Ross~~ D. KOZLOWSKY RRD NQR	[signature] RRD QA (signature)	7/27/21 Date
G.J. Hirtz E&FI Staff	[signature] E&FI Staff (signature)	7/27/21 Date
B. L. Lee RRD Criticality Safety Officer	[signature] RRD Criticality Safety Officer (signature)	7/28/21 Date
D.C. Stanley HFIR MBA Representative	[signature] HFIR MBA Representative (signature)	7/28/21 Date
D.C. Stanley HFIR Operations (print name)	[signature] HFIR Operations (signature)	7/28/21 Date

* RRD Criticality Safety Office item is pre-signed on the basis that the design content will not deviate and conforms to the specifications contained in this EABD. If Att B identifies a NCR or Deviation then the CSO shall be included as party to the specific document or shall acknowledge the change by initial and date in the above signature block.