

Enhancing isotope mixing in U-10Mo downblend castings with electromagnetic stirring

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ARTICLE INFO

Article history:

Received 7 May 2021

Revised 21 June 2021

Accepted 22 June 2021

Available online 25 June 2021

Keywords:

U-10Mo

Uranium, Downblending

Casting

Electromagnetic stirring

EMS

Isotopes

ABSTRACT

Uranium alloyed with 10 wt percent molybdenum (U-10Mo) is the proposed fuel for use in the United States' high-performance research reactors. The U-10Mo fuel is fabricated by a two-step casting process that downblends highly enriched uranium with depleted uranium (DU) and/or natural uranium (NU) and subsequently alloys the resulting high-assay low-enriched uranium (HALEU) with Mo. Currently, a two-step casting process is needed to meet the ingots' U-235 enrichment homogeneity specifications.

This work demonstrates the ability to provide more homogeneous U-235 distributions during downblend casting by using zirconia for crucibles rather than graphite. When graphite is used as a crucible, the electromagnetic field produced by the induction heater couples directly with the graphite. Zirconia is nonconducting in this study, and therefore does not couple with the field. The induction field couples directly with the metal, and causes electromagnetic stirring (EMS) in the molten metal pool.

Eight downblend casting experiments were carried out in this work. Four were performed with zirconia crucibles and four with graphite crucibles. The U-235 enrichment was measured at nine discrete points in each casting using laser ablation multi-collector inductively coupled mass spectrometry (LA-MC-ICP-MS). The enrichment homogeneity was approximately eight times better in zirconia crucible castings than in graphite crucible castings as measured by the plate enrichment range and enrichment coefficient of variation. The results show a single casting step could be used to meet USHPRR enrichment specifications if electromagnetic stirring is present during casting.

A related investigation was carried out to determine whether it is appropriate to measure enrichment on as-cast ingots or whether heat treated specimens should be used to accurately characterize enrichment. The results show that the as-cast microstructure plays a significant role in enrichment homogeneity. It is recommended that all enrichment measurements be done after the homogenization heat treatment typical of U-10Mo processing.

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1. Introduction

Currently, the United States High Performance Research Reactors (USHPRRs) are using highly enriched uranium (HEU). Because there is an inherent nuclear proliferation risk, these HEU reactors are being converted to use a high-assay, low-enriched uranium (HALEU) fuel. The National Nuclear Security Administration's Material Management and Minimization (M3) program is working to convert the USHPRRs to a monolithic nuclear fuel of HALEU alloyed with 10 wt.% Mo (U-10Mo). The higher density metallic U-10Mo fuel gives the needed fissile U-235 quantities while reducing enrichment to a nominal 19.75% [1–3]

The current USHPRR method for producing the HALEU is to mix metallic HEU and depleted uranium (DU) and/or natural uranium (NU) in specific ratios to meet the U-235 enrichment required. Transforming fuel for the USHPRR program from feedstock into alloyed U-10Mo currently requires double casting. The first casting downblends the HEU with DU or NU. After the first casting, the unalloyed HALEU is now called “logs.” The logs are then broken up to make up the feedstock for the second casting [4,5]. During the second melt the Mo is added and cast into the final ingot. This U-10Mo ingot is then processed into the final fuel geometry. High performance reactors typically require a homogeneous U-235 isotope content. This is important to reduce heterogeneous distributions of fission gas bubbles and provide stable reactor performance [6,7]. During the first production of mini-plates for irradiation (MP-1), measurements of the U-235 enrichment during

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the casting campaign demonstrated that a single downblend casting did not produce a homogeneous enrichment. Although the Mo dissolution into the uranium matrix only takes one casting to meet Mo homogeneity specifications, U isotopes (specifically U-235) require two castings to be within the enrichment homogeneity specifications, as demonstrated in the Optimization (OPT) casting campaign [4,5]. Double casting adds cost, reduces yield, and increases the likelihood that additional impurities would be picked up that can affect downstream processing, such as rolling or forging [8,9]. Therefore, the conversion program would benefit from a method that reduces the number of castings needed to meet enrichment specifications while avoiding adding additional impurities.

This work proposes to alleviate the isotopic inhomogeneity experienced in single castings by increasing mechanical mixing in the U melt. Unlike Mo, which diffuses in response to a chemical concentration gradient between the U and Mo, there is little chemical difference between U-235 and U-238, and therefore, the two isotopes mix extremely slowly without external forces [4,10]. The proposed method to increase mechanical mixing is to couple the induction field in a vacuum induction melter (VIM) casting system directly to the metal. Historical methods generally rely on coupling the induction field to a graphite or an electrical conducting crucible and indirectly heating the metal [11–13]. The use of graphite crucibles is the current USHPRR program method [5]. Mechanical mixing can be accomplished using any of several mechanisms, such as electromagnetic stirring (EMS), turbulence during pouring, and convective currents. The use of EMS in casting and metallurgy is well known and thoroughly studied [14–19]. Despite this, the authors are not aware of any work using EMS homogenize isotope distribution during casting. This is likely due to the rare nature of such a need.

This work proposes using a zirconia (ZrO_2) crucible to enable the coupling of the induction field directly to the metal. Because the zirconia is nonconducting under the conditions used for U-10Mo melting, it is essentially invisible to the magnetic field produced by the induction currents. The eddy currents induced in the metal are expected to provide EMS along with the heat needed for melting. Direct comparisons of the isotopic homogeneity are made between downblended U-10Mo castings done with zirconia and the traditional graphite crucible.

2. Materials and methodology

Eight castings were completed for this study. The castings were produced using a tilt-pour VIM. The crucibles used were made from either graphite or zirconia. The U feedstock consisted of HALEU alloyed with Mo at nominally 10 wt.% and unalloyed DU. The HALEU was used as a surrogate for the HEU to conform with facility controls as well as being more readily available. The HALEU to DU ratio was kept similar to that used for a typical downblending of >90%-enriched HEU with DU (approximately 1:4). Enrichment data was obtained using laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) with working reference materials (WRMs) to correct for mass fractionation in the LA-MC-ICP-MS. The following subsections will describe each aspect in more depth.

2.1. Casting system

The castings were made using an Indutherm VTC 200 V Ti tilt-pour VIM operating at approximately 15 kHz frequency. The induction heater in this system can achieve a maximum power of 15 kW. The VIM induction coil has 10 turns of copper piping, an outer diameter of 82.6 mm, an inner diameter of 69.9 mm, and a height of 69.9 mm. The copper coil is cooled internally by flowing chilled

glycol. The temperature of the melt is measured by an optical pyrometer with a minimum readable temperature of 1073 K.

The graphite crucible was made from isomolded graphite obtained from GraphiteStore.com in grade GR001CC. The zirconia crucible was magnesia stabilized and purchased from Zircoa Inc. Each of the crucibles had a 50.8 mm inner diameter with an inner opening length of 130 mm. The graphite crucible had a wall thickness of 4.06 mm and the zirconia crucible had a wall thickness of 5.08 mm. The bottom of both crucibles was aligned with the bottom turn of the induction coil. This put the melt 4.06 mm (graphite) or 5.08 mm (zirconia) above the bottom turn of the induction coil and the full height of the melt was within the induction coil. The graphite mold used for the castings was made from the same stock as the graphite crucible and formed a plate with maximum dimensions of 91 mm wide by 5.1 mm thick and 203 mm tall.

2.2. Casting materials and preparation

The casting feedstock consisted of pre-alloyed HALEU U-10Mo (nominally 10 wt.% Mo and 19.75% enriched) and unalloyed DU (0.2% enriched) acquired from Materials Sciences Corp. To increase the charge mass concentration to 10 wt.% Mo (to account for unalloyed DU feedstock), additional Mo was added in the form of 0.040" diameter wire obtained from Elmet Technologies. A nominal target proportion of 210 g HALEU mixed with 790 g DU was targeted. Because the DU and HALEU feedstock sizes differed, the charge masses varied from 1099 g to 1187 g.

Before the crucible was loaded, the HALEU and DU were both etched in 8 M nitric acid for 10 minutes to remove the surface oxide layer, rinsed with deionized water, and finally rinsed with ethanol to dry. The additional Mo needed was sheared into approximately 12 mm long pieces and then rinsed with ethanol to remove surface contamination from shearing. The material was melted within 1 hour of etching and cleaning. The mold and crucible surfaces were coated with 3 thin layers of yttria aerosol to reduce interactions between the molten U and crucible materials. Each layer was baked in air at 373 K for 1 hour to dry. The crucibles were loaded with the charge metals in an alternating arrangement as shown in Fig. 1. For USHPRR downblend castings, the castings are done in a bottom pour system with Mo rod laid out concentric to the pour hole and U chunks stacked on top of the Mo.

2.3. Casting parameters

The casting parameters used for all melts can be seen in Table 1. Four castings were melted in graphite crucibles ("G" samples) and four melted in zirconia crucibles ("Z" samples). The first two castings (Z1 and G1) were melted in the VIM but not poured into the plate mold to investigate the difference in the stirring induced by turbulent pouring of molten metal into a mold.

Before power was applied to the induction coil, the system was evacuated then purged with argon. This was repeated three times and then vacuum was applied for the remainder of the casting. The VIM was set to run at 9 kW until maximum temperature was reached, after which the power was modulated by the VIM system to maintain the hold temperature. All experiments heated the material to 1673 K and held for 30 min at temperature until pouring occurred. All operations were done in a vacuum less than 8 mtorr. For Z1 and G1, melts that did not pour the molten metal, the 1673 K hold temperature was gradually lowered by controlling the coil power with a target of 373 K cooling per minute. Once the temperature dropped below 1073 K, the system was shut off and automatically purged with argon.



Fig. 1. Loading sequence, shown from left to right. A layer of smaller pieces of LEU-10Mo and DU are loaded first, the additional Mo is then added, and finally the larger LEU-10Mo and DU pieces.

Table 1

Casting parameters for all downblends. The Casting ID indicates whether it was cast in a zirconia (Z) or graphite (G) crucible. Z1 and G1 were melted and cooled without being poured into a mold.

Casting ID	DU Mass (g)	LEU-Mo Mass (g)	DU:LEU Ratio	Mo Charge	Casting Mass (g)
Z1	840	219	4.29	10.04%	1151
Z2	842	249	3.80	10.40%	1187
Z3	783	241	3.64	10.00%	1108
Z4	787	231	3.83	10.18%	1105
G1	834	217	4.31	9.97%	1142
G2	790	247	3.60	10.00%	1122
G3	782	231	3.81	10.24%	1099
G4	847	234	4.06	9.97%	1173

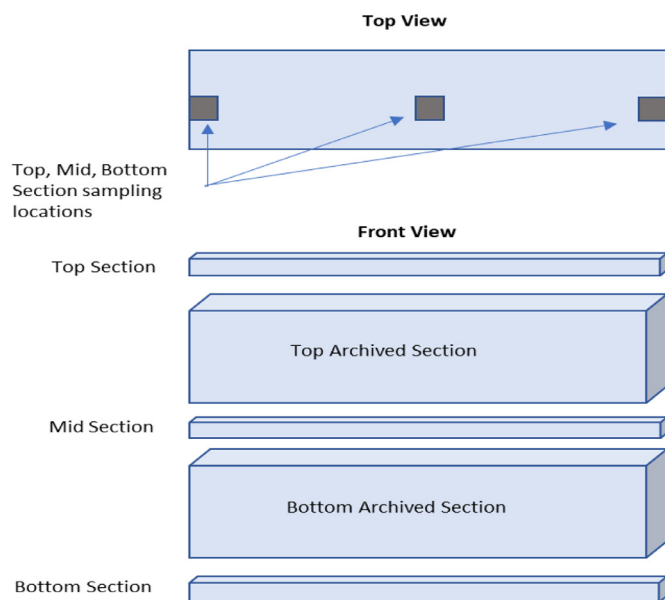


Fig. 2. Locations of each of the nine samples that were cut from each casting and used for enrichment analysis.

2.4. Enrichment analysis

After casting, nine samples were cut from each plate for determining enrichment. A 0.125" tall section was cut from the top, middle, and bottom of each plate. The top, middle, and bottom sections were then subsampled in the middle and at the two short edges. The sampling schematic can be seen in Fig. 2. Each sample was approximately 0.5 g.

The samples were homogenized in a vacuum furnace for 144 hours at 1173 K. This Mo homogenization heat treatment changes the microstructure from a typical as-cast dendritic structure to a more uniform, homogeneous structure [20]. The homogenization aimed to replicate the same step used in the USHPRR program.

For the first casting (Z1), a set of as-cast samples were taken pre-heat treatment from next to the homogenized samples location for a separate analysis.

The enrichment of the plates was determined by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) using an Elemental Scientific NWR213 laser ablation system, which uses a 213 nm Nd:YAG nanosecond laser, coupled with a Nu Plasma 3. Laser ablation parameters included a laser output of 1% power at 2 Hz, a 10 μm spot size, and rastering at 5 $\mu\text{m/s}$. A 500 mL/minute flow of argon was used as a carrier gas.

This was coupled with a Nu Instruments Plasma 3 was outfitted with 16 Faraday cups and five ion counters and was operated in static multicollection mode for laser ablation. U-238 and U-235 were measured on Faraday cups with $10^{11} \Omega$ resistors. Initial tuning parameters for the source lens voltages were set up with the instrument in solution mode. Tuning the plasma parameters (torch position and gas flow) was done by optimizing the observed background Kr-84 signal and peak shape with the laser online (the krypton being present mainly in gas flow from the laser chamber). On-peak zeros were used to obtain baselines, and no system memory was observed for samples with washout times of 1 min. Each sample (9 samples per casting) was analyzed for 150 s in triplicate at random locations on the sample, with U-238 signal intensity typically ranging between 1 and 10 Vs.

Using a laser as a sample introduction system introduces several complications to highly accurate and precise isotopic analyses. The matrix of the sample has a strong effect on the observed results; for example, overloading the plasma with the bulk matrix can occur when trying to analyze low-concentration isotopes, and polyatomic interference at masses of interest may form [21]. However, in this case, neither of these are of concern given that the analyte of interest is also the bulk content of the sample. Instead, the principal issue is how the sample ablates strongly affects the instrumental mass bias, causing variation between samples of different matrices (such as glass standard reference materials versus uranium metal alloys). Hence, it was deemed preferable to use

Table 2

²³⁵U enrichment measurement average, range and COV for each casting and for each crucible type. Z1* is the measurements of the as-cast Z1 samples whereas all others are for homogenized samples. The average Z row does not include the as-cast Z1 sample values.

Casting ID	Average% Enrichment	Range of% Enrichment	COV of% Enrichment
Z1	3.858	0.0089	0.0006
Z1*	3.835	0.0443	0.0044
Z2	4.321	0.0388	0.0020
Z3	4.420	0.0325	0.0017
Z4	4.218	0.0452	0.0023
G1	3.887	0.2487	0.0143
G2	4.383	0.5337	0.0376
G3	4.238	0.0764	0.0043
G4	4.063	0.0133	0.0009
Average Z	4.204	0.0313	0.0017
Average G	4.143	0.2181	0.0143

WRMs to keep track of instrumental mass bias, accuracy, and precision.

The homogenized WRMs (samples from Z1 top, middle, and bottom edge) isotope composition were characterized by TIMS and solution ICP-MS and analyzed every three samples to determine the LA-MC-ICP-MS instrumental mass bias and to correct for drifts in ion counter efficiencies on minor isotopes. Although not reported in the results, the accurate measure of the minor isotopes is important for calculating total U-235 enrichment. A NIST certified U030A and U500 standard were used to verify the ICP-MS analyses, and a U200 standard was used to verify the TIMS analyses during the WRM production.

3. Results and discussion

This work aimed to determine whether induction fields could adequately mix uranium isotopes when coupled directly to the melt constituents. The induction field coupling directly to the melt was assured by use of a zirconia crucible. The varying electromagnetic field, when coupled directly to the melt, causes EMS while it directly heats the metal. With a graphite crucible, the inductive currents could potentially penetrate the graphite wall and couple to the metal, producing EMS. The coupling is directly related to the coil diameter and the inductor frequency [22]. The induction field penetration is out of the scope of this work; it is mentioned because of the potential for systems of other designs to experience different amounts of electromagnetic coupling when using graphite crucibles. In the induction system used for this work, melts carried out in graphite crucibles do not experience appreciable EMS. This is evident by the difference in viewing the melt when using zirconia and graphite crucibles.

Table 2 shows each casting's average enrichment, range, and coefficient of variation (COV). The range and COV are used as metrics for homogeneity in this work. An attempt at defining homogeneous enrichment is not made in this work, rather the metrics are used to determine a relative homogeneity between graphite and zirconia crucibles. Based on our defined metrics, the zirconia crucible yielded a more homogeneous enrichment. In zirconia crucible castings, the average range is seven times smaller and the average COV is eight times lower. This difference in homogeneity is due to the mechanical mixing induced by EMS. The EMS mixes the different isotopic composition U constituents in the molten state thereby overcoming the considerably slower diffusion of U isotopes as compared to the Mo diffusion in the melt. Without EMS, the melt can be pictured as regions of high and low enrichment with little net mass transport of total U, and localized differences (10's to 100's of micron scale) in enrichment with no driving force to mix on a smaller scale and some mixing at the sampling scale. The physical mixing caused by EMS is used to homogenize the regions where localized atoms of U-235 and U-238 have exchanged places

as happens frequently at these temperatures, but the microscale enrichment has not fully homogenized because of too few atoms exchanging places due to the sluggish diffusion between different U isotopes. This is evident by the lack of finding regions of pure DU at 0.2% enrichment and HALEU at 19.75% enrichment in the worst case scenario, G1, where there is no external mixing force and no turbulence during pouring. Despite no external mixing force, sluggish diffusion mechanisms, and lack of turbulence from pouring, the enrichment still only has a range of 0.25%. An important note here is that EMS only changes the state of the melt (isotope homogeneity) prior to pouring. With the same mold and crucible designs and pouring parameters, it is expected that similar amounts of isotope mixing occurs after discharge from the crucible. The mixing during pour occurs as a function of residence time in the mold before solidification as new material enters the pool of molten material and causes a localized turbulent region similar to pouring water from one cup into another.

With an average enrichment of 19.75% and an assumed allowable deviation of $\pm 0.20\%$ enrichment to meet fuel specifications, all the zirconia specimens would be within the specification limits, while only two of the graphite castings would be within the limits (Table 3). The average of the graphite castings would not meet the specification limit. Fig. 3 shows the location-based measurements from samples for each of the crucible types. The enrichment measurement by location is normalized to the plate mean. This allows for direct comparison of discrete locations within all plates. There appears to be no biasing in any particular location. The graphite crucible castings' larger deviation from centerline is indicative of the higher COV observed.

One significant finding that corroborates the likelihood of EMS increasing isotopic mixing is that the melts not poured (Z1 and G1) had vastly different homogeneity from each other. Z1 was the most homogeneous of all downblends, and G1 had the second-worst homogeneity of the downblends. Omitting the mixing induced by turbulent pouring is likely to result in a less homogeneous casting. Specifically, the lack of EMS in the G1 melt clearly leaves residual isotopic amplitude and distance between the different isotope amplitude starting materials. This effect is evident in the vast differences observed in Z1 and G1. Obtaining high U-235 homogeneity without the turbulent pour induced mixing demonstrates that the zirconia crucible results in substantially better isotope mixing. This mixing is almost surely related to the in-crucible melt turbulence induced by direct coupling of a varying electromagnetic field to the metallic U and Mo melt constituents. This comparison of melt in place (not poured) enrichment homogeneity defines the difference EMS has on the isotope distribution while the poured melts provide the practical comparisons relevant to industrial operations. During casting, it is often a goal to reduce as much turbulence in the melt as possible because a turbulent pour generally results in entrained oxide [23]. If the turbulence during pouring was reduced

Table 3

Maximum and minimum enrichment values to be expected based on COV if the average enrichment of the castings is 19.75% ^{235}U and the specification allows for $\pm 0.2\%$.

Casting ID	Average Enrichment \times COV	Maximum Enrichment (%)	Minimum Enrichment (%)	Meets Specification (19.55%–19.95%)
Z1	0.0117	19.76	19.74	YES
Z2	0.0399	19.79	19.71	YES
Z3	0.0340	19.78	19.72	YES
Z4	0.0455	19.80	19.70	YES
G1	0.2826	20.03	19.47	NO
G2	0.7427	20.49	19.01	NO
G3	0.0845	19.83	19.67	YES
G4	0.0176	19.77	19.73	YES
Z Average	0.0328	19.78	19.72	YES
G Average	0.2819	20.03	19.47	NO

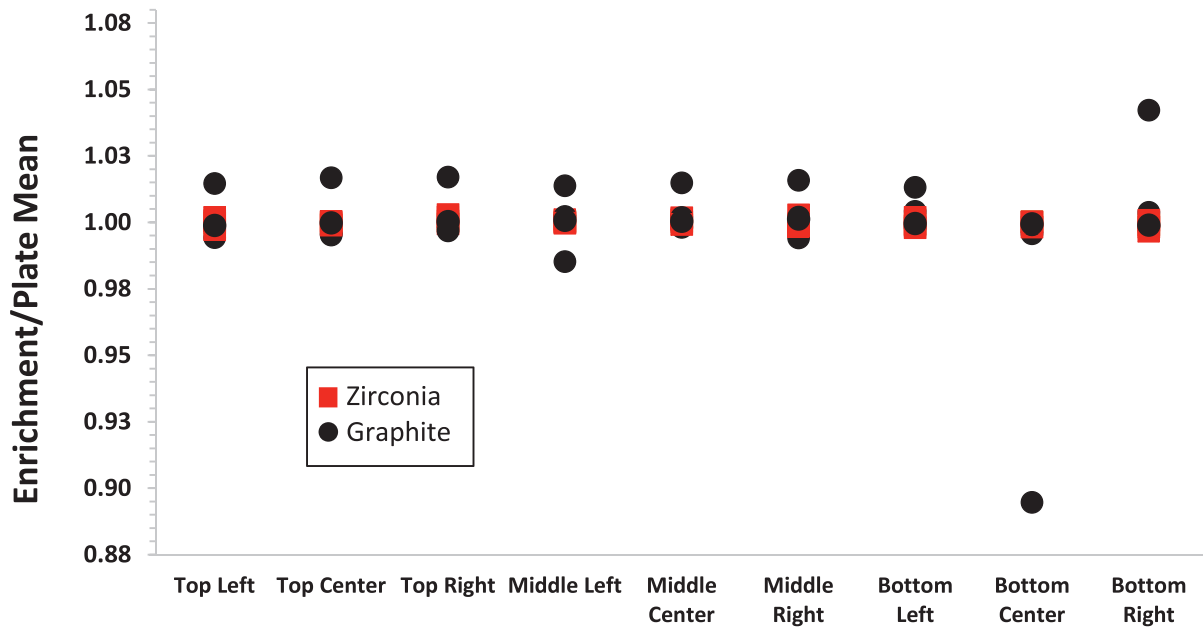


Fig. 3. Normalized enrichments by location. The graphite series that are higher than 1.00 are offset by the low value at less than 0.90.

in the casting of U-10Mo, an alternative method of homogenizing the enrichment would be needed. These results demonstrate that the switching of crucible materials can result in improved homogeneity without the mixing caused by turbulent pouring.

During each of the castings, the EMS was also clearly visible when observing the melt pool in the crucible. In the case of zirconia, there is a periodic pulse sloshing the molten pool back and forth and an evident convex shape in the top of the pool that indicates electromagnetic levitation. In a graphite crucible, the molten pool does not visually appear to move or take on a convex shape like that of the melt in a zirconia crucible.

A second thrust of this work was to determine if Mo homogenization affected enrichment measurements. This is an important determination as it can be used to inform fuel fabricators of when the most reliable measurements can be made during fuel processing. The as-cast microstructure of the U-Mo metal is a dendritic structure often with macro-sized dendrites [24,25]. The homogenization treatment results in an equiaxed, granular structure. The change in microstructure after homogenization will likely simplify the ingot sampling and therefore enrichment measurement.

Enrichment was analyzed for the as-cast and homogenized Z1 samples with the same LA-MC-ICP-MS method. Due to the differences between the turbulence induced by bottom pouring, as is done for the USHPRR program, and the tilt-pour VIM used in this work, the melt in place samples were chosen to better represent pre and post-homogenization enrichment measurements. Addition-

ally, since Z1 had a more homogeneous enrichment than G1, it was determined it would represent the difference between as-cast and homogenized sufficiently. It is expected that the enrichment differences in G1 would be greater than Z1. The as-cast sample sizes were approximately the same as the homogenized samples. The enrichment comparison between as-cast and Mo homogenized samples shows a distinct difference. It appears the Mo homogenization treatment also redistributed the U-235 substantially more homogeneously throughout each sample. The enrichment measurements at specific locations on the Z1 samples can be seen in Fig. 4 and are reported in Table 2 as “Z1 – As Cast”. The enrichment range of the as-cast samples is on average six times larger as that of the homogenized samples, and the average COV is seven times higher.

Additionally, the homogenized samples all indicated increased U-235 content, as shown in Fig. 4. Since the homogenization treatment does not add more U-235 atoms and the measurement technique was the same, the observed increase in enrichment must be a function of material sampling. One likely possibility is that thermally activating the entire matrix results in some self-diffusion of U isotopes which will move through vacancy and grain boundary diffusion mechanisms. In this case, it was a coincidence that the as-cast samples were in a lower enriched region and the homogenization treatment corrected this issue. Another possibility is the enrichment is tied to the inhomogeneous dendritic structure of the as-cast material where the movement of Mo atoms during the heat

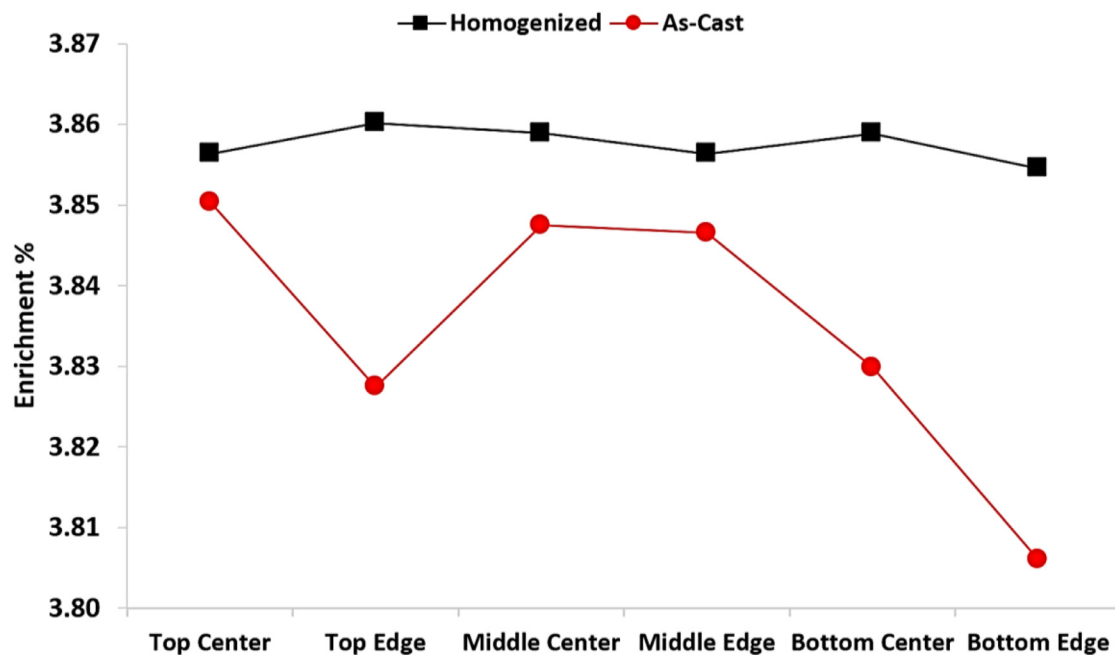


Fig. 4. As-cast and homogenized enrichment variation based on location of sample for casting Z1. The line connecting data points is used to guide the eye.

treatment helps to rearrange the U atoms. In both cases, larger sampling sizes would likely yield more homogeneous results.

Sampling more material, and therefore losing more fuel-capable material, is not recommended because of the precious nature of enriched uranium. These findings indicate that measuring enrichment of the U-Mo alloy in the as-cast state would produce unreliable data. Because the final fuel form is a Mo homogenized foil, the enrichment should be measured after the Mo homogenization heat treatment for the most accurate representation of U-235 enrichment. Overall, the Mo homogenization heat treatment seems to be critically important in measurement of both Mo content and enrichment in the U-10Mo system.

4. Conclusion

This work demonstrated that zirconia crucibles enable better mixing of the U-235 isotope than graphite crucibles in downblend castings of U-10Mo. The downblend ratio (of DU to EU) was nominally the same as the USHPRR ratio, but this work used HALEU and DU, whereas the USHPRR program uses HEU and DU. The observed improvement in enrichment homogeneity in zirconia crucibles is attributed to direct coupling of the induction field to the metal melt constituents that is present in ceramic, but not graphite, crucibles. This direct coupling to the metal constituents results in EMS. In multiple castings, the average enrichment COV was eight times lower in zirconia crucibles and the enrichment range was seven times smaller. Assuming $\pm 0.2\%$ enrichment specification with an average of 19.75% enrichment, the zirconia crucible castings would have met that specification for all four experiments. The graphite crucible castings would only have met the assumed specification in two of the four experiments.

While all enrichment measurements were performed on homogenized specimens using LA-MC-ICP-MS, a separate investigation measured enrichment on as-cast samples to assess the need for homogenization before enrichment measurement. The as-cast specimens showed more variation in enrichment than the homogenized specimens. This is attributed to the inhomogeneous dendritic structure present in as-cast U-10Mo. Because more accurate values can be expected from homogenized samples, it is recommended

that all enrichment measurements be carried out on homogenized samples.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Zachary Huber: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Matthew Athon:** Methodology, Investigation, Writing – review & editing. **Steve Shen:** Formal analysis, Investigation, Writing – review & editing. **Elise Conte:** Formal analysis, Investigation, Writing – review & editing. **Kaylyn McCoy:** Conceptualization, Methodology, Investigation. **Curt Lavender:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

Acknowledgement

The current work was supported by the U.S. Department of Energy, National Nuclear Security Administration under Contract [DE-AC05-76RL01830](#).

References

- [1] T. Nelson, B.G. Eddy, Foreign Research Reactor Uranium Supply Program: the Y-12 National Security Complex Process, Babcock & Wilcox Technical Services Y12 LLC, Oak Ridge, Tennessee, 2010 INIS-BE-10K0001.
- [2] D.M. Wachs, C.R. Clark, R.J. Dunavant, Conceptual Process Description for the Manufacture of Low-Enriched Uranium-Molybdenum Fuel, Idaho National Laboratory, Idaho Falls, Idaho, 2008 INL/EXT0813840.
- [3] E.H. Wilson, D. Jaluvka, A. Hebden, J. Stillman, L.M. Jamison, US High-Performance Research Reactor Preliminary Design Milestone for Conversion to Low Enriched Uranium Fuel, Argonne National Laboratory, Argonne, Illinois, 2019.
- [4] C.A. Lavender, M.A. Catalan, V.V. Joshi, in: Molybdenum Alloying in Uranium for the U.S. High Performance Research Reactor Conversion Program, PNNL30287, Pacific Northwest National Laboratory, Richland, WA, 2020, p. 2020.
- [5] D. Turpin, J. Henkel, LEU-Mo Casting Update, Y12 National Security Complex, Oak Ridge, Tennessee, 2019 IROS12723.

- [6] T.D. Ippolito, Effects of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design, Diss. Massachusetts Institute of Technology, 1990.
- [7] C.-K. Kim, et al., Improvement of the Homogeneity of Atomized Particles Dispersed in High Uranium Density Research Reactor Fuels, 1998.
- [8] K.S. Choi, C. Wang, C. Lavender, V.V. Joshi, Carbide Particle Redistribution in U10Mo Alloy During Hot Rolling Process, Pacific Northwest National Laboratory, Richland, Washington, 2018 PNNL28383.
- [9] X. Hu, X. Wang, V.V. Joshi, C.A. Lavender, The effect of thermomechanical processing on second phase particle redistribution in U10 wt% Mo, *Journal of Nuclear Materials* 500 (2018) 270–279.
- [10] T.C. Kaspar, C.A. Lavender, M.W. Dibert, Evaluation of Uranium-235 Measurement Techniques, Pacific Northwest National Laboratory, Richland, Washington, 2017 PNNL26490.
- [11] C.E. Holcombe, R.H. Reiner, N.L. Dykes, Use of Tribocor 532N for a carbon-free induction furnace for vacuum-induction melting and casting of uranium and its alloys, *J. Mater. Sci. Lett.* 6 (11) (1987) 1353–1355.
- [12] B.R. Westphal, et al., Experience of Graphite Crucibles During the Pyrometallurgical Processing of Uranium, Idaho National Lab.(INL), Idaho Falls, 2017 No. INL/CON-17-41015ID (United States).
- [13] J. Sure, et al., Evaluation of plasma sprayed alumina–40 wt% titania and partially stabilized zirconia coatings on high density graphite for uranium melting application, *Ceram. Int.* 40 (5) (2014) 6509–6523.
- [14] S. Nafisi, et al., Effects of electromagnetic stirring and superheat on the microstructural characteristics of Al–Si–Fe alloy, *Mater. Sci. Eng.* 432 (1–2) (2006) 71–83.
- [15] L.B. Trindade, et al., Modeling of solidification in continuous casting round billet with mold electromagnetic stirring (M-EMS), *Steel Res. Int.* 88 (4) (2017) 1600319.
- [16] S. Agrawal, A.K. Ghose, I. Chakrabarty, Effect of rotary electromagnetic stirring during solidification of in-situ Al–TiB₂ composites, *Mater. Des.* 113 (2017) 195–206.
- [17] H. An, et al., Effects of electromagnetic stirring on fluid flow and temperature distribution in billet continuous casting mould and solidification structure of 55SiCr, *Metall. Res. Technol.* 115 (1) (2018) 103.
- [18] K.-H. Spitzer, M. Dubke, K. Schwerdtfeger, Rotational electromagnetic stirring in continuous casting of round strands, *Metall. Trans. B* 17 (1) (1986) 119–131.
- [19] Y. Yin, et al., Numerical study on the capture of large inclusion in slab continuous casting with the effect of in-mold electromagnetic stirring, *ISIJ Int.* (2017) ISIJINT-2017.
- [20] S. Jana, A. Schemer-Kohrn, N. Overman, L. Sweet, E. Kautz, C. Lavender, V. Joshi, Eutectoid “Transformation in U10Mo Alloy: Effect of Deformation History and Homogenization Heat Treatment.”, Pacific Northwest National Laboratory, Richland, Washington, 2019 PNNL28519.
- [21] J. Fietzke, M. Frische, Experimental evaluation of elemental behavior during LA-ICP-MS: influences of plasma conditions and limits of plasma robustness, *J. Anal. At. Spectrom.* 31 (1) (2016) 234–244.
- [22] R.M. Baker, Design and calculation of induction-heating coils, *Trans. Am. Inst. Electr. Eng. Part II* 76 (1) (1957) 31–40.
- [23] J. Campbell, *Complete Casting Handbook: Metal Casting Processes, Metallurgy, Techniques and Design*, Butterworth-Heinemann, 2015.
- [24] G.F. Nielsen, N.W.S. Morais, N.B. Lima, Crystallographic texture of hot rolled uranium-molybdenum alloys, *Braz. J. Radiat. Sci.* 8 (3A) (2020).
- [25] R. Prabhakaran, et al., U-10mo Sample Preparation and Examination Using Optical and Scanning Electron microscopy, Pacific Northwest National Lab.(PNNL), Richland, WA United States, 2016 No. PNNL-25308 Rev. 1.