Fabrication of mini UB_2 ingots via Arc melt synthesis using a customized copper hearth

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Abstract

As growing efforts take place to enhance the operational safety of nuclear reactors, fuel composites have been explored as replacement to the traditionally used Uranium dioxide (UO_2). One potential candidate that has been gaining momentum as a fuel composite additive is Uranium diboride. UB_2 is known to have a higher uranium density and higher thermal conductivity than UO_2, properties that would allow for a lower enrichment of the fuel pellets as well as improve the temperature gradient across the pellet during reactor operation. While various challenges arise when considering UB_2 as a drop-in replacement to UO_2, UB_2 has shown much promise as a composite fuel when combined with other uranium compounds such as U_3Si_2.Through the use of an arc-melter system, 50-250 mg ingots of UB_2 were fabricated using the fragments of a larger 2-5 g ingot of UB_2. X-Ray diffraction analysis was performed to confirm the purity of the initial UB_2 ingot. Further, an infrared camera was used to monitor the temperature of the furnace chamber during the mini-UB_2 bead fabrication. The purpose of this project is to understand the fabrication process of UB_2 and characterize the micro-structure of the as-fabricated mini fuel beads. We wish to better understand the viability of UB_2 as a potential fuel composite additive.

Background

- It has been well established by the literature that Uranium dioxide has a thermal conductivity of 6.5 W m^{-1} K^{-1} at 300 °C [1]. This value decreases with temperature increase which exacerbates thermal transport during an accident.
- The low thermal conductivity of UO_2 has been observed to cause a non-uniform temperature gradient across fuel pellets during reactor operation.
- This non-uniformity in temperature presents itself mainly through heat retention in the centerline of the UO_2 fuel pellets that causes fracturing and fragment dispersal.
- UB_2 has a higher thermal conductivity of 25 W m^{-1} K^{-1} at 300 °C and a higher uranium density of 11.7 g-U cm^{-3} [1].
- UB_2 while a promising ATF candidate, still has its own challenges to consider.

Material Properties	UO_2	UB_2	U_3Si_2
Uranium density (g-U/cm³)	9.6	11.7	11.34
Thermal Conductivity (W/m K at 300 °C)	6.5 (95% TD)	25 (100% TD)	14.7 (98% TD)
Melting point (C)	2840	2385	1665

Fig. 1 A table showing the properties of different ATF candidates as compared to those of traditional Uranium dioxide. [1]

- One of the greatest obstacles to its widespread adoption for fuel composites is its fabricability.
- Arc-melting is the only effective method of fabricating UB_2.

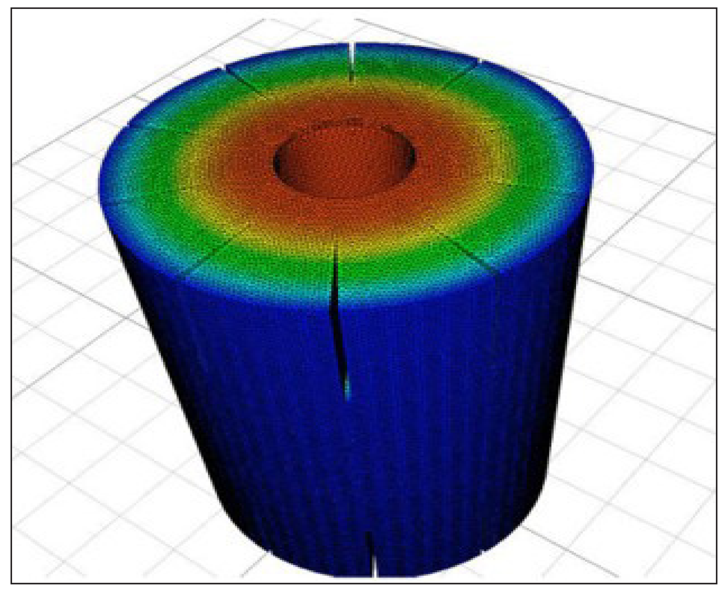

Fig. 2 An image showing the heat retention in the centerline of a UO_2 fuel pellet [2].

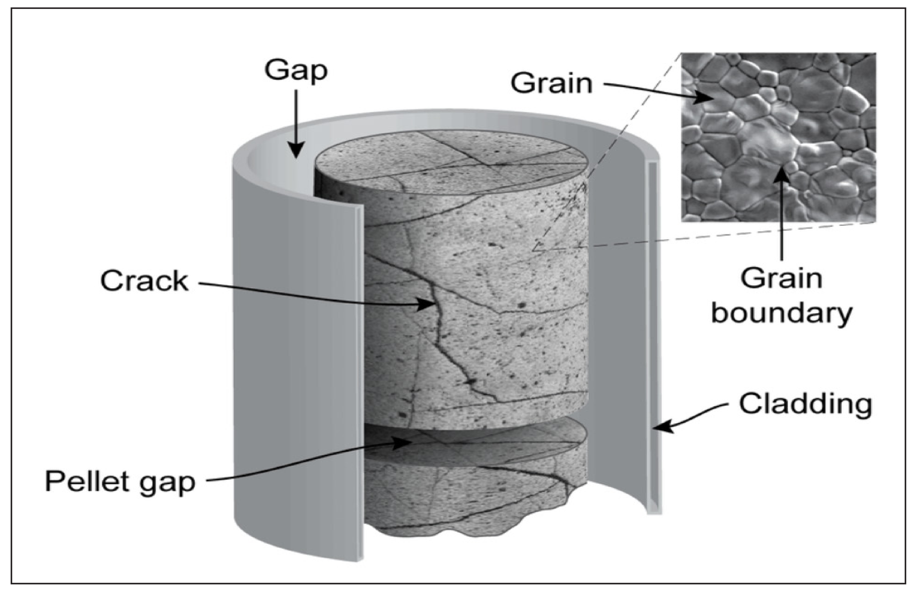

Fig. 3 An image showing the cracking of a UO_2 fuel pellet [3].

- New methods of fabrication must be investigated to allow for mass production of UB_2.
- UB_2 has not been well investigated and its full properties have not been mapped out in their entirety. As-fabricated UB_2 via arc-melting has shown to develop impurity phases that are not desirable for reactor operation.

Methods

The initial UB_2 ingot was fabricated by consolidating a 2.5477g piece of depleted uranium and 0.2315g of elemental boron powder via a Centorr Tri-Arc melt furnace. The furnace was kept in an inert atmosphere with Ar gas. A total of 5 melts were conducted on the initial ingot to homogenize the sample. The same process was performed to remelt the large UB_2 ingot into smaller 50-250 mg ingots using a customized copper hearth. A Bruker D2 Phaser XRD was used as well as a FLIR X-Series science camera.

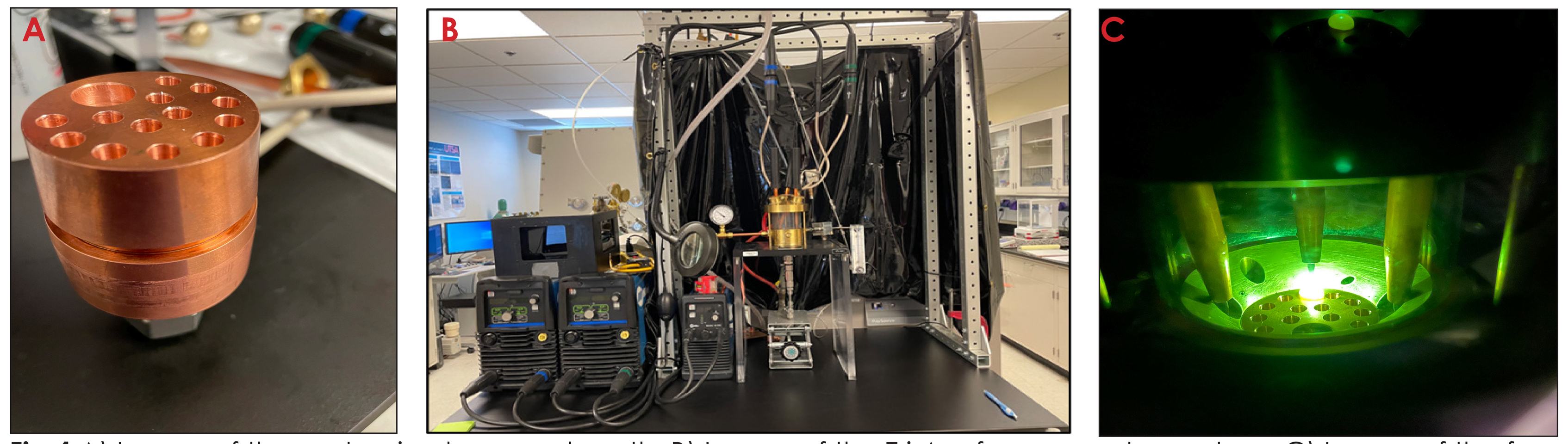

Fig.4 A) Image of the customized copper hearth. B) Image of the Tri-Arc furnace system set-up. C) Image of the furnace chamber during operation.

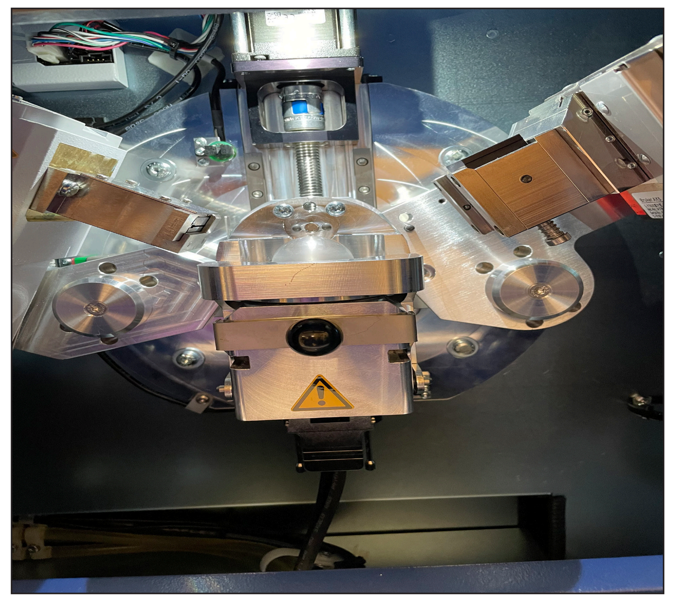

Fig.5 An image of the interior of the Bruker D2 Phaser XRD.

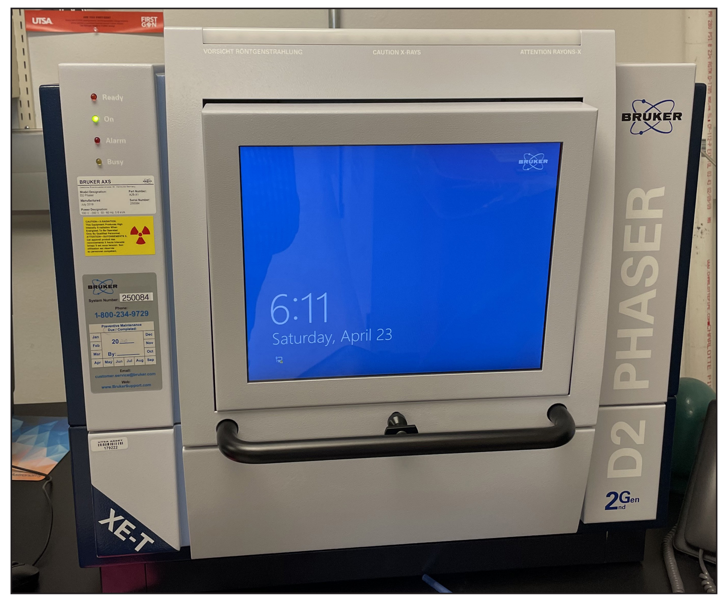

Fig.6 An image of the exterior of the Bruker D2 Phaser XRD.

Results

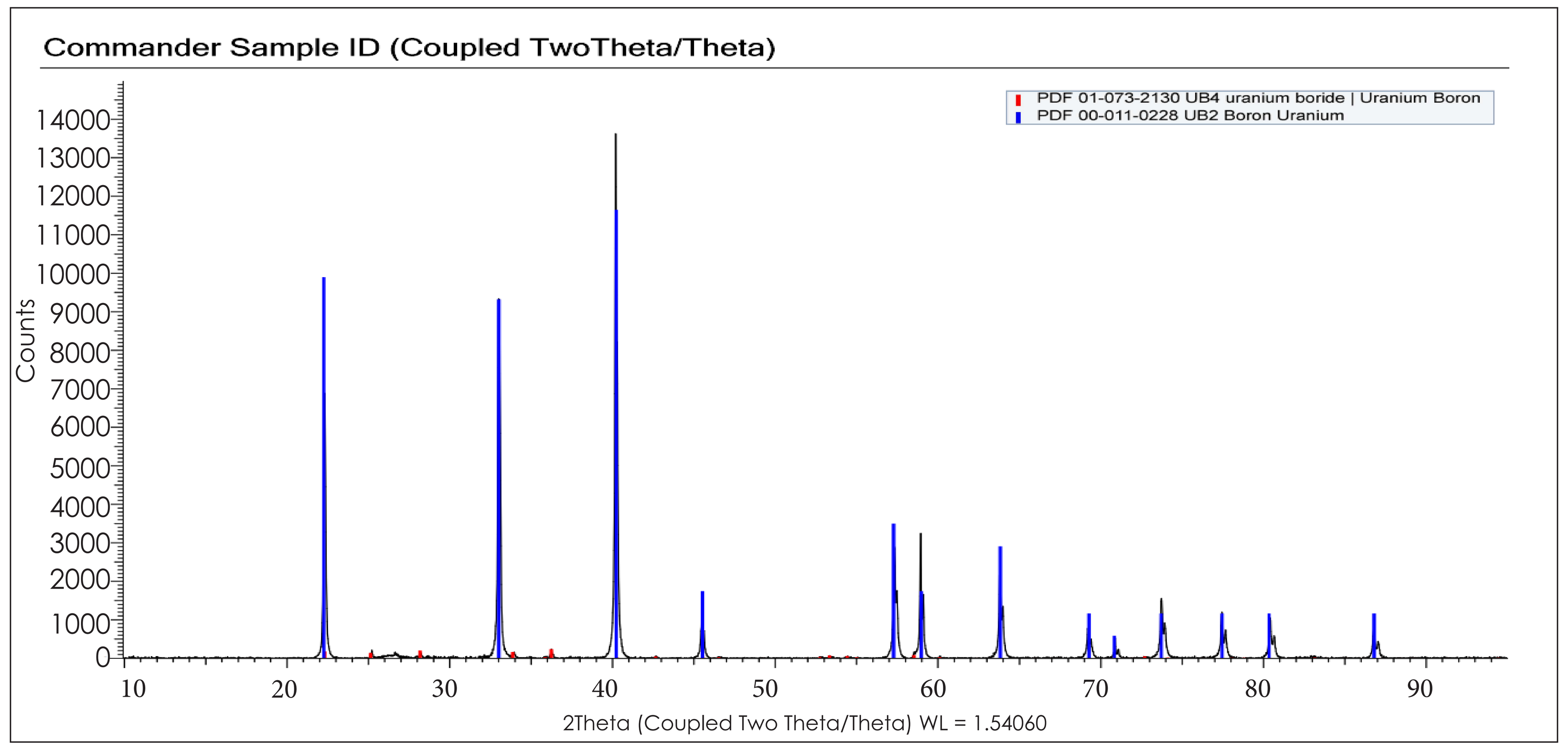

Fig.7 Image of the initial XRD results of the large UB_2 ingot confirming a majority pure UB_2 phase

Following the fabrication of the large UB_2 ingot, X-ray diffraction (XRD) analysis was performed to confirm the purity of the sample. The bench-top Bruker D2 Phaser XRD was run from 10 to 95° 2 theta with a 0.1 step and dwell time of 1second. XRD results confirmed the dominant presence of UB_2 and low trace amounts of UB_4; these results are outlined in figures 7 and 8.

A FLIR X-series infrared camera was used during the fabrication of the mini-UB_2 beads to monitor the temperature inside the furnace chamber.

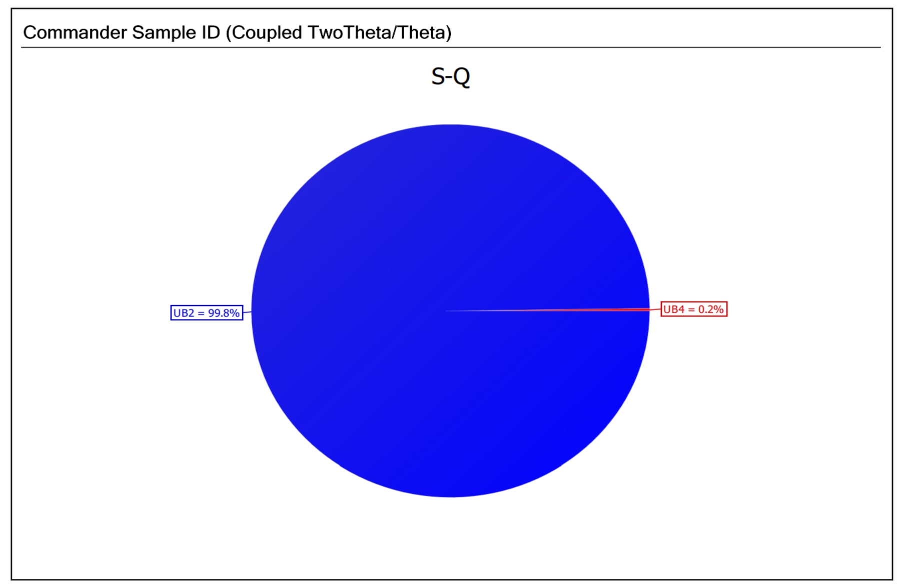

Fig.8 Image of the initial XRD results of the large UB_2 ingot confirming a majority pure UB_2 phase and trace amounts of UB_2

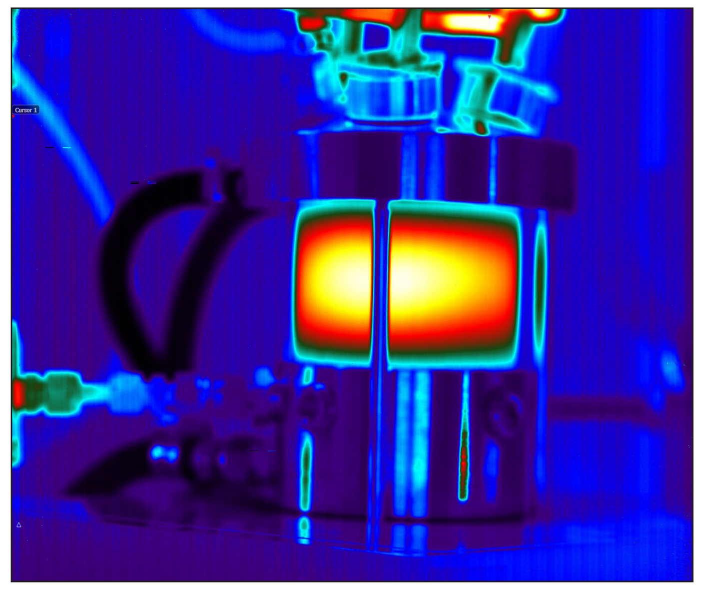

Fig.9 IR image of the furnace chamber during mini-UB_2 bead fabrication.

Unfortunately, the IR camera lens used was not calibrated for temperatures above 350 °C resulting in inaccurate temperature readings. Despite the incorrect calibration, using control IR images, we approximated the temperature inside the furnace chamber during the melt to reach ~1900 °C at the highest amperage setting used on the stingers.

Conclusion

- Fabrication of the mini-UB_2 beads via arc-melting proved satisfactory as sufficient UB_2 purity was confirmed by XRD analysis.
- The temperature at which the melt was performed is still unclear as the IR camera used to monitor it was not correctly calibrated.
- Further monitoring and investigation of the temperatures within the furnace chambers is needed to inform on melt performance.
- To better understand th viability of UB_2 as a fuel additive, oxidation testing is needed to inform on its performance under off-normal reactor conditions.
- Characterization of the as-fabricated as well as heat treated UB_2 sample is needed to understand the different phases present. This is to be carried out via Scanning Electron Microscopy.
- Overall, arc-melting was proved a reliable method of producing UB_2 as confirmed by XRD analysis. As arc-melting is not a effective method for mass producing UB_2, additional study is needed to look into more efficient methods to accomplish this.

References

[1] Jennifer K. Watkins, Adrian R. Wagner, Adrian Gonzales, Brian J. Jaques, Elizabeth S. Sooby, Challenges and opportunities to alloyed and composite fuel architectures to mitigate high uranium density fuel oxidation: Uranium diboride and uranium carbide

[2] Piro, Markus (2011) et al, Computation of Thermodynamic Equilibria Pertinent to Nuclear Materials in Multi-Physics Codes.

[3] Fors, Patrik. (2009). The effect of dissolved hydrogen on spent nuclear fuel corrosion.. 10.13140/RG.2.1.5125.4244.

Acknowledegements

This project was carried out for and supported by the CONsortium on Nuclear sECurity Technologies (CONNECT) in collaboration with The University of Texas at San Antonio and the Extreme Environment Materials Lab. (EEML). Funding for this project was provided by the National Nuclear Security Administration Minority Serving Institution Partnership Program.