Post Irradiation Examination of Monolithic Mini fuel Plates from RERTR-6[1]

by

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ABSTRACT

The requirement to convert the high power research reactors cannot be achieved with standard dispersion fuels. It is only possible to achieve the necessary power densities by the replacement of the traditional fuel/dispersant meat with a solid fuel. The solid fuel in the form of a foil has come to be known as 'monolithic fuel'. The idea to use a solid foil was based, at least in part, on the extensive reaction that occurs between UMo fuel and the aluminium matrix which plagued the early UMo irradiation tests.

A monolithic fuel, in the form of a 12 mm diameter UMo disk was first irradiated in RERTR-4 with promising results. Based on that success and the requirements of the high power reactors, significant effort has been devoted to the development of fabrication of mini-plates containing foils. The RERTR-6 experiment was the first irradiation of monolithic fuel where the foil occupied the full fuel meat volume in the mini-plate. RERTR-6 contained 10 monolithic mini-plates fabricated by Friction Stir Welding (FSW), that were irradiated at moderate power density to moderate burn-up.

In this paper non-destructive and destructive post-irradiation examination results of those monolithic mini-plates are presented. The results are encouraging and suggest that the qualification of this type of fuel is possible.

1. Introduction

The idea of a monolithic fuel first arose in the period before the RERTR-4 & 5 experiments began in August 2000. From the post-irradiation exams of RERTR-3 it was obvious the significant reaction that occurred between the fuel and the aluminium matrix had potential implications for the performance of the fuel plate. While the consequence of porosity formation in the reaction layer was not evident or foreseen at that time, it was clear that the reaction layer resulted in increased swelling of the fuel plate and its poor thermal properties affected heat transfer [1].

A solid fuel eliminated the matrix and significantly reduced the surface area for reaction between the fuel and the clad. The initial trial of this concept occurred in the RERTR-4 experiment. A thin disk ~12 mm diameter, 0.3 mm thick was incorporated into a standard 4" long RERTR mini-plate by hot rolling. The low ductility of the UMo alloy relative to the 6061 Al Alloy cladding at the rolling temperature led to fracture of the disks before the desired elongation was achieved. Despite the fractures, the irradiation behaviour of the UMo foils was excellent (Figure 1). The plate swelling and fuel swelling was consistent with other plates irradiated in RERTR-4 [2].

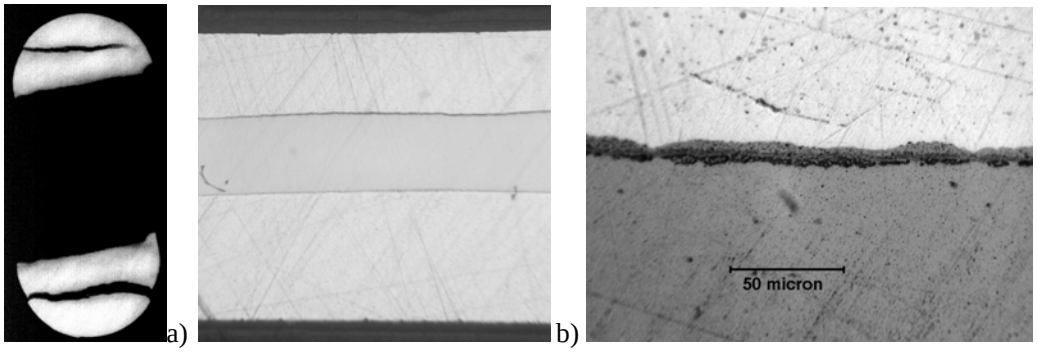

Figure 1. a) Radiograph of U-10Mo foil after hot rolling. b) Cross Section of plate showing top and bottom clad and fuel. c) Micrograph of fuel/clad interface at ~ 80% ^{235}U burn-up showing reaction layer (fuel is the medium contrast phase).

On the basis of the successful irradiation in RERTR-4 and the requirements for conversion of the high power reactors, an aggressive program to fabricate, irradiate and qualify the monolithic fuel has been developed and pursued [3]. The development of fabrication techniques for monolithic fuel has received considerable attention since 2004 and is reported elsewhere [4,5]. The RERTR-6 experiment was the first irradiation of true monolithic mini-plates. Surface photographs of a U-10Mo mini-plate and the radiograph of the foil are shown in Figure 2.

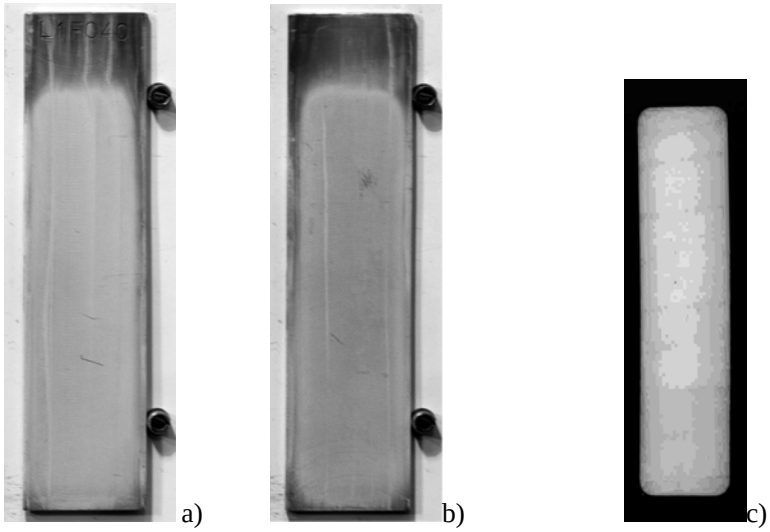

Figure 2. Photograph of the a) front and b) back side of L1F040 (post-irradiation) and c) radiograph of foil (pre-irradiation). Plate length 10cm, foil length ~ 8 cm.

2. Irradiation Details

RERTR-6 was a scoping test designed to evaluate the performance of a range of modified matrix dispersion fuels and irradiate the first monolithic fuels. The experiment was loaded into the Advanced Test Reactor (ATR) in May 2005 in experimental position B-12. It remained in the ATR for three cycles for a total of 135 EFPD. Average burn-up of the 19.7% enriched fuel was 35-49% depending on the location in the experiment. BOL fuel temperatures were < 200°C and peak heat flux was 140W/cm^2 (170 W/cm^2 for the 500 μm foil). Three different monolithic fuel variations were irradiated: U-7Mo and U-10Mo, 250-μm-thick foils, and U-10Mo 500-μm-thick foils. The position of each plate within the experiment basket is shown in Figure 3. The RERTR-6 experiment consisted of four capsules A-D, each containing eight plates. More information on experiment design is reported in [6,[7]]. The power history of plates from RERTR-4, 5 & 6 is shown in Figure 4. The experiment basket is positioned so that one edge of the mini-plates faces the core. A strong neutron flux exists across the width of the plates and

hence one edge ran at ~ 35% higher power than the other. In previous RERTR experiments the basket was rotated 180° between cycles to obtain uniform burn-up across the plate. Figure 4 shows the difference in fission rate and burn-up between the core edge and outer edge of L1F100.

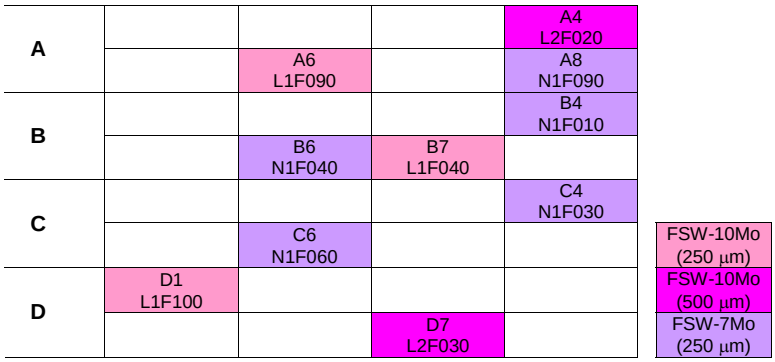

Figure 3. Schematic diagram of the RERTR-6 experiment showing location, composition and foil thickness of the monolithic mini-plates in RERTR-6.

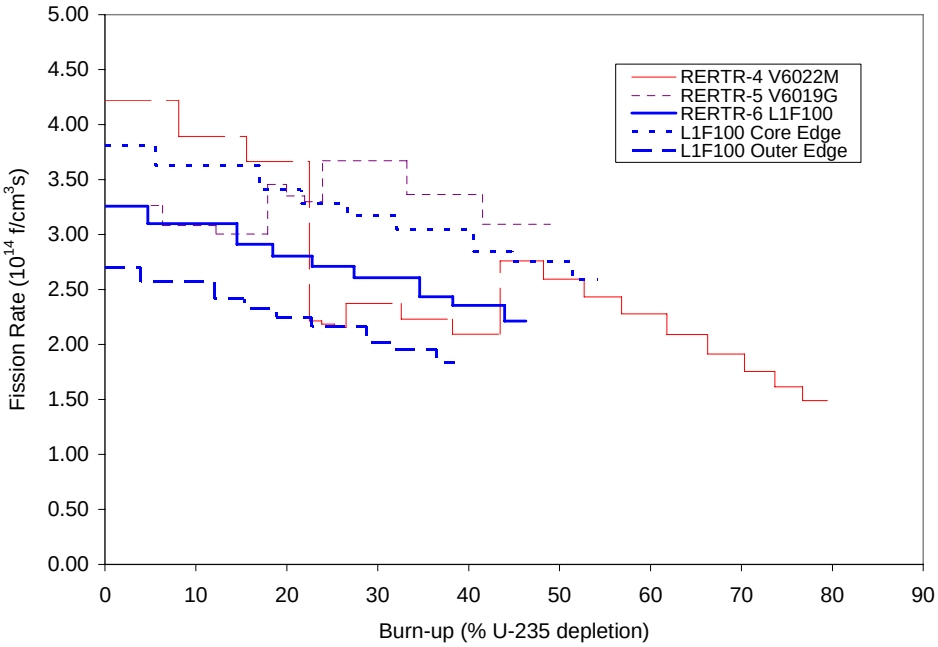

Figure 4. Power History of selected mini-plates from RERTR-4, 5 & 6.

3. Non-Destructive Examination

The swelling behaviour of the monolithic fuel plates is calculated from thickness measurements taken at 15 locations over the plate surface and is shown in Figure 5. The data is consistent and reveals clearly the effects of composition, axial power profile and foil thickness. The axial power profile increases to a peak in the B and C capsules. That trend is illustrated for both the 7Mo and 10Mo plates. The 7Mo wt% plates swell more than the 10Mo wt% plates which is consistent with the knowledge that a larger concentration of Mo provides increased resistance to swelling. Presumably, this difference will be more pronounced at higher fission rates and higher burn-ups.

Plate swelling of the modified matrix dispersion and monolithic mini-plates is shown in Figure 6. The U-10Mo monolithic miniplates, clad in 6061 Al Alloy, exhibit comparable swelling to the dispersion mini-plates using a 6061 matrix. The dispersion plates with the higher silicon content, (i.e. greater than 2wt%) modified matrix show reduced swelling but the difference is not significant. The 500 µm foils show an increase in plate swelling compared to 250 µm foils. The difference might be expected to be

greater but the low power positions and self shielding mean that the burn-up is considerably lower than the mini-plates in the higher power positions.

The pre-irradiation plate thickness measurements illustrate that the FSW process does not generate a flat, smooth surface when compared to the hot rolled dispersion plates as revealed by the considerable scatter (Figure 7).

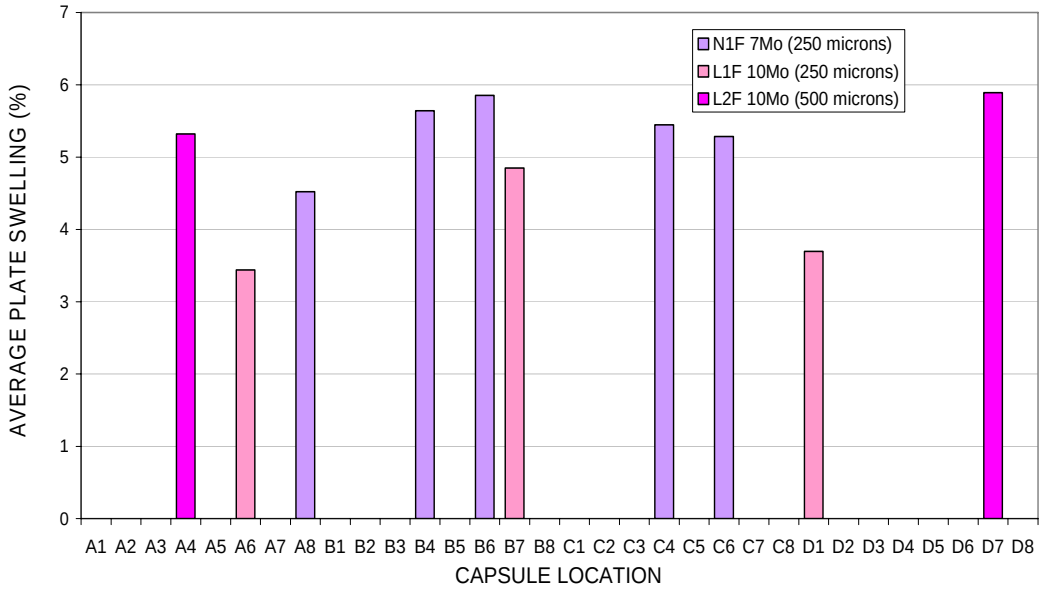

Figure 5. Plate swelling of monolithic fuel plates in the RERTR-6 experiment as a function of location in the experiment

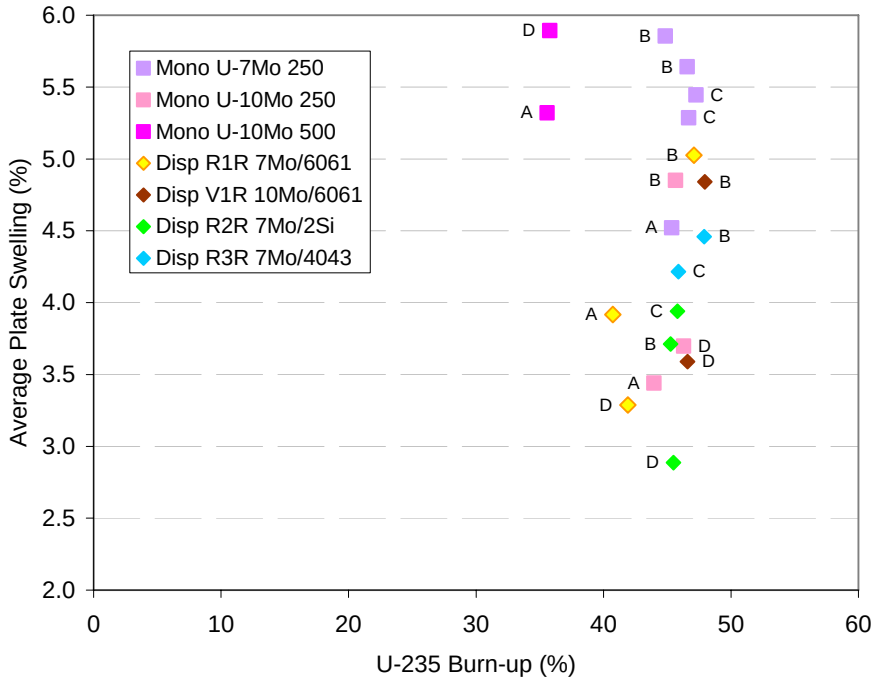

Figure 6. Plot of average plate swelling versus burn-up for monolithic mini-plates compared against modified matrix dispersion plates. The data labels indicate capsule location of plate.

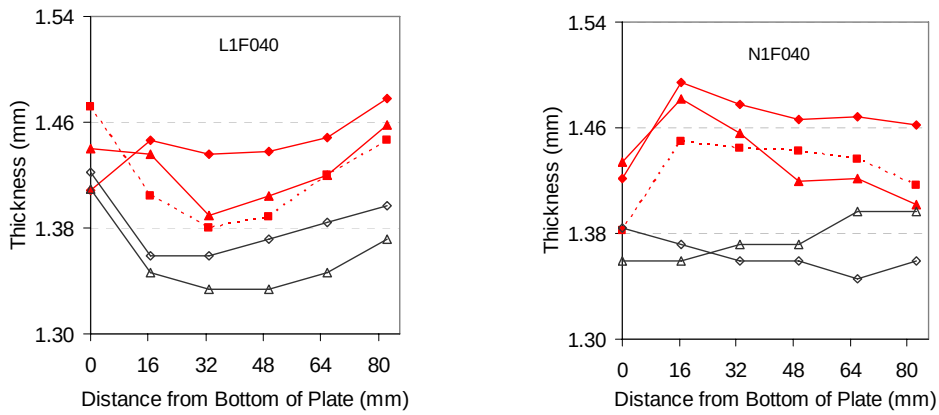

Figure 7. Individual plate thickness measurements of two monolithic plates. L1F040 (B7) and N1F040 (B6). Each line represents six data measurements in the axial direction over the length of the plate. The red lines are post-irradiation data and the grey is pre-irradiation data.

4. Destructive Examination

Plate Swelling

Several mini-plates were sectioned for examination in the metallograph. All plates were sectioned in the transverse direction at the mid-plane of the mini-plate. The foil irradiation behaviour was consistent with previous knowledge and understanding of UMo fuel. No unstable behaviour was observed and no large fission gas bubbles were detected in the fuel phase.

It was not possible to accurately quantify swelling of the foils because of the relatively small amount of foil swelling, the variation in the as-fabricated foil thickness of up to 25 μm, and the non-uniform swelling. From Figure 8 the difference in fuel swelling between U-7Mo and U-10Mo is apparent, even if a quantitative assessment of that difference is not possible. A flux gradient of ~35% exists from the outer edge of the plate to the edge closest to the core of the reactor. As a result the burn-up varies from ~ 37% ^{235}U at the outer edge to ~ 52% ^{235}U at the core edge. This is the driving force for the differential swelling across the plate.

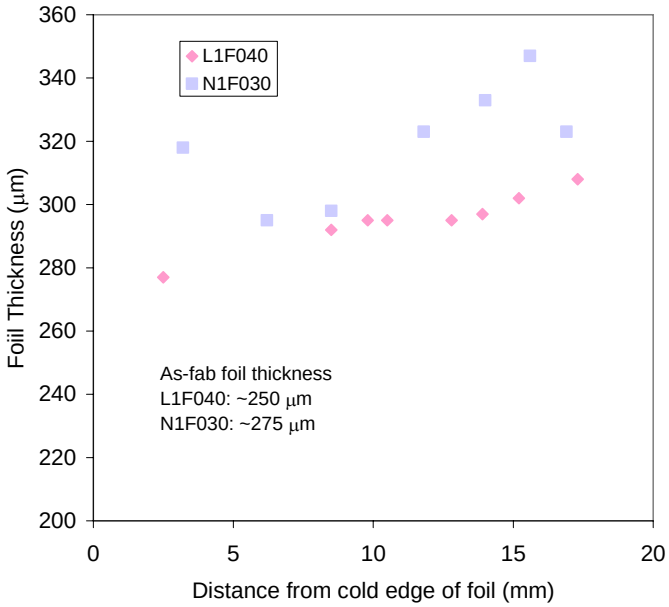

Figure 8. Thickness of the foil measured from the cold edge of plate to the hot edge. Measurements were made for U-7Mo and U-10Mo compostions.

Previous work on RERTR-4 & 5 found that up to the point of recrystallisation which is ~ 50% ^{235}U depletion, the rate of fuel swelling is ~ 0.5% per % burn-up [2]. That is, in a plate with 50% ^{235}U burn-up the fuel swelling is ~25%. In RERTR-6 this statement appears to hold true. In Figure 9 fuel swelling is shown based on plate thickness measurements. Swelling calculations are made from pre and post-irradiation thickness measurements using nominal foil thickness. Based on these measurements, the fuel swelling is consistent with UMo fuel in other experiments.

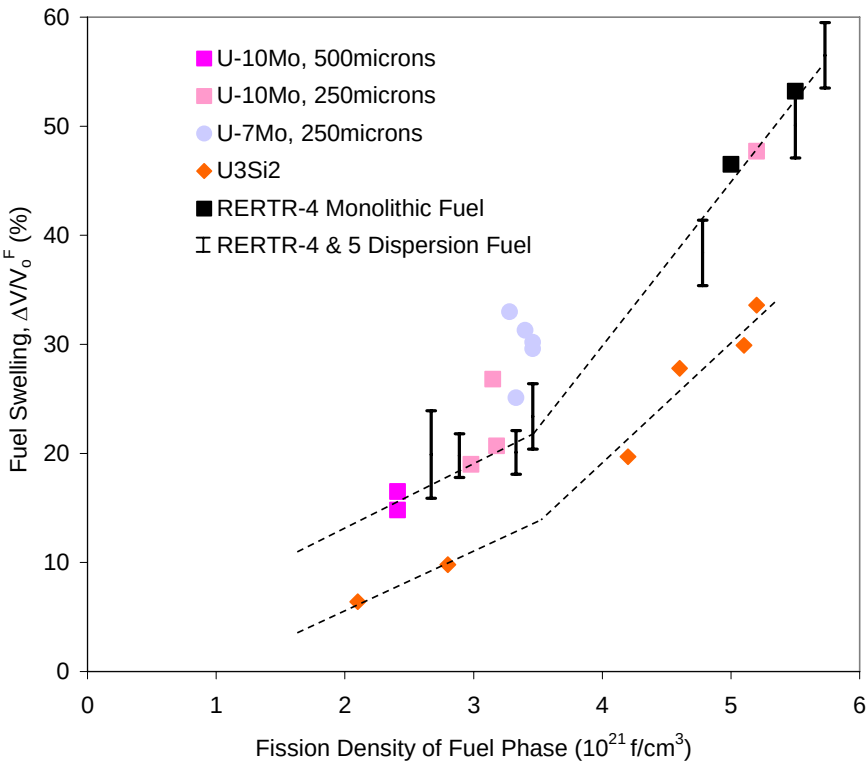

Figure 9. Fuel Swelling of U-Mo foils compared against dispersion fuels from RERTR-4 & 5.

Metallography

Given the propensity of the fuel and matrix to react extensively in dispersion fuels there is considerable interest in the reaction layer, developed either during fabrication and/or irradiation between the foil and the clad in the monolithic mini-plates. Of equal interest is the bond achieved by the joining process, in this case FSW. Considerable effort is being devoted to the question of 'what is an acceptable bond' and how to determine it.

In RERTR-6 the reaction layer was generally thin, uniform and adherent. The extent of reaction was less in the U-10Mo mini-plates (~ 3 μm) than the U-7Mo (4-6 μm) as shown in Figure 10 and Figure 11. There were departures from this behaviour and some examples are provided below. In all cases the bond between the fuel and clad was retained during the irradiation.

In Figure 11, there appear indications of the phenomenon that beset the U-Mo dispersion fuels. Small voids are apparent in the reaction layer that are consistent with the voids that form in the reaction layer of the dispersion fuels. They have a viscous like appearance and the voids close together appear to be linking up to form larger voids. Close inspection also shows the voids initiating at the reaction/clad interface which is consistent with the fission gas bubbles seen in the dispersion fuels. Since the burn-up is moderate at ~50% ^{235}U, only the earliest signs of the phenomenon might be expected. The high fission rates and burn-up of RERTR-7 should indicate whether fission gas bubbles are to be encountered and problematic in monolithic fuel.

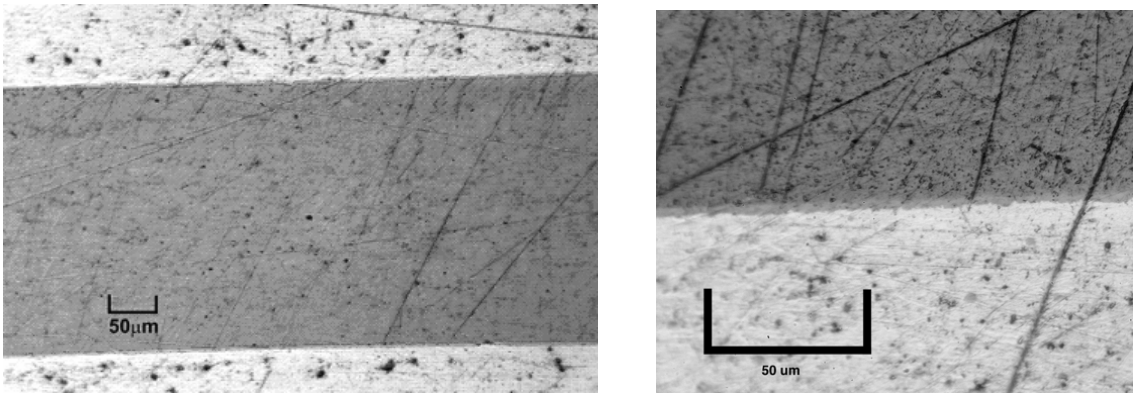

Figure 10. Optical micrographs of L1F040 (U-10Mo) showing the full thickness of the foil and a higher magnification image of the interface and the reaction layer that formed. Reaction layer ~ 3 μm.

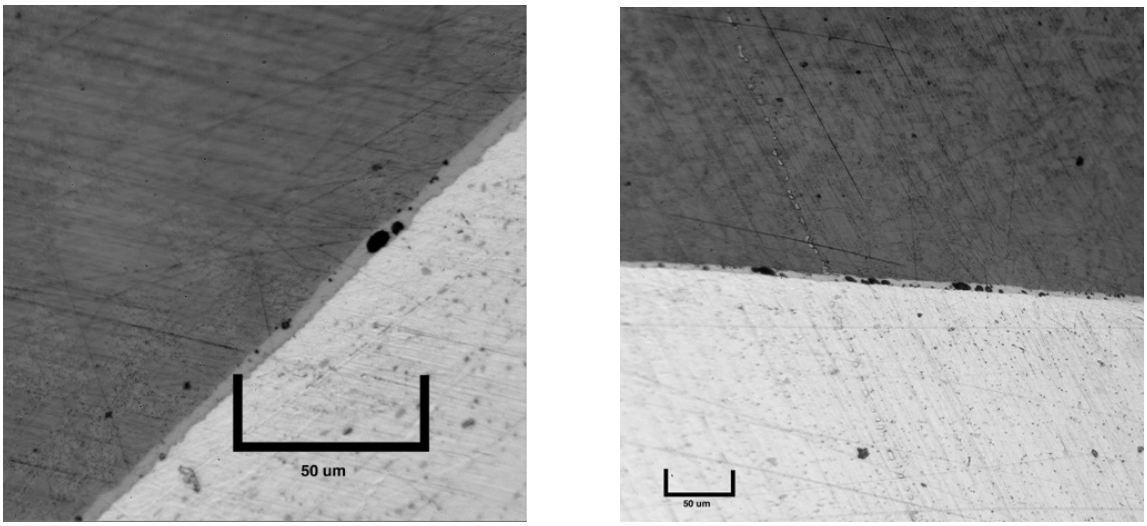

Figure 11. N1F030 (U-7Mo) Voids apparent in the reaction layer. Reaction ~ 4-6 μm.

Figure 12 shows a transverse section of the foil which revealed a few issues that are largely the result of fabrication. The foil does not appear to be flat within the clad. This is the result of numerous passes and the raster pattern employed to lay down those passes.

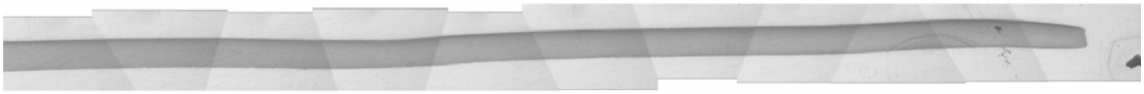

Figure 12. A transverse section of the half of the foil width in L1F100 at the midplane. The foil is ~ 300 μm thick.

Early attempts to fabricate mini-plates by FSW led to warping and poor surface finish. In an effort to obtain a flat plate and soften the surface to permit improved surface finish the mini-plates were annealed at 500°C for 30 minutes under a uniaxial press. Scotchbrite was used to improve the surface finish. This process provided the driving force for excessive reaction between the foil and the clad prior to irradiation as shown in Figure 13. The islands of fuel in the reaction layer are typical of very rapid diffusion, and consistent with the view that the reaction occurred during fabrication. This is further supported by SEM observations of mini-plates that did not undergo irradiation. Despite the non-ideal condition of this plate it demonstrated acceptable behaviour under irradiation. Swelling did not appear any worse than the other U-7Mo plates and no de-bond was discovered.

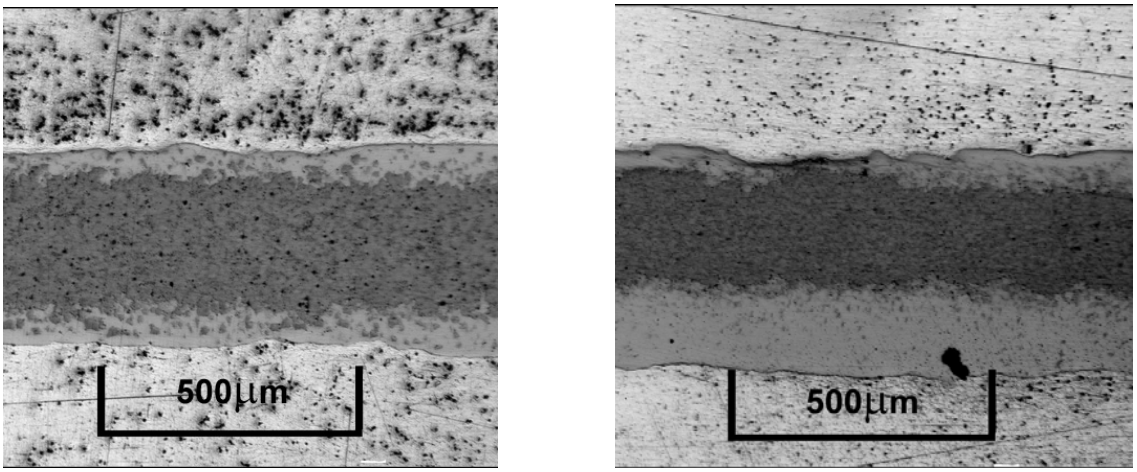

Figure 13. N1F090 (U-7Mo) Excessive reaction that occurred prior to irradiation due to the anneal applied during fabrication. Reaction 100 - 250 mm.

All mini-plates were given the flattening anneal, yet not all plates displayed the excessive reaction as shown in Figure 13. Some plates showed considerable variation in reaction layers as shown in Figure 14. The two micrographs are separated by less than 2mm. This indicates that there is considerable variation in the fabrication process since the operating conditions are the same in this region. Factors such as surface condition of the foil and temperature variations in different passes of the stirring tool are all possible contributors.

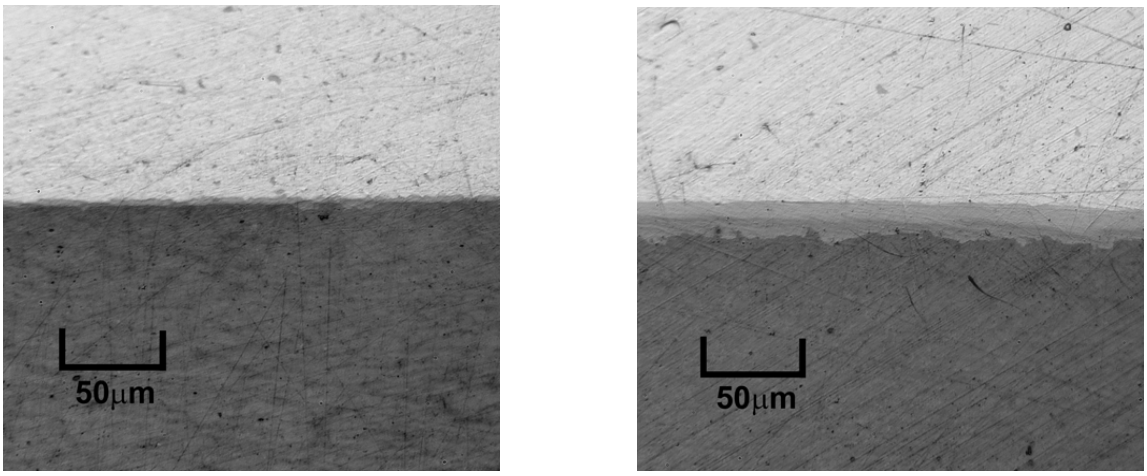

Figure 14. L1F100 (U-10Mo) showing significant variations in reaction layer at fuel/clad interface. Reaction ~3 μm (left image) Reaction ~ 18μm (right image).

One of the mini-plates containing a 500 μm thick foil delaminated upon sectioning in preparation for metallography (Figure 15). Plate thickness measurements prior to sectioning showed that the core edge of the mini-plate was marginally thicker than the outer edge. Examination of the post-sectioning images show clearly a significant bulge in the midpoint of the section. At this time the cause of the de-bond is not understood but residual compressive stress in the cladding is considered to be a factor. During sample preparation rounding of the metallographic specimen occurred because the hardness differences in the fuel and clad. At low magnification there is a shadow around the perimeter of the foil as a result. At higher magnification the bond is shown to be sound.

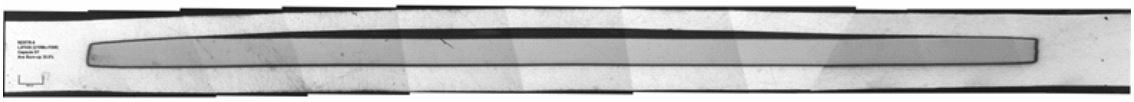

Figure 15. L2F030 (U-10Mo), 500 μm thick foil. Transverse cross section of the mini-plate which shows a de-lamination between the fuel and the cladding.

5. Summary

The first irradiation of monolithic fuel plates is considered to be a success and provide encouragement for more aggressive tests and further development of current and other monolithic fabrication techniques. There is evidence of uniform and stable reaction layer and low fuel swelling. The results indicate that there are issues that must be addressed, primarily bonding and the formation of the reaction layer.

6. Acknowledgements

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7. References

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