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MICROSTRUCTURAL DEVELOPMENT DURING IRRADIATION OF AFIP-1 FUEL PLATES

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ABSTRACT

The growth of fuel/matrix interaction layers during irradiation of U-Mo dispersion fuels can be affected by many different variables related to the characteristics of the as-fabricated fuel plate (e.g., the amount of Si in the fuel meat matrix) and the parameters used during the reactor test (e.g., the irradiation temperature, power density, fission density, fission rate). Recently, the microstructures of irradiated full-size AFIP-1 fuel plates have been characterized along with as-fabricated AFIP-1 archives, allowing for the comparison of microstructures before and after irradiation. This paper reports the changes in microstructure that occurred during irradiation of AFIP-1 fuel plates with Al-2Si and AA4043 matrix.

1. Introduction

Interaction of the fuel and matrix during irradiation can have a profound effect on the overall performance of a fuel plate. For a fuel plate with pure Al as the matrix, this interaction product has been observed to be unstable [1]. This has led to the identification of elements that could be added to the U-Mo alloy or the Al matrix to stabilize the interaction product that forms during irradiation [2]. One addition that is being evaluated is Si, which is added to the Al matrix. Starting with the RERTR-6 experiment, dispersion fuel mini-plates with Si additions have been irradiated in the Advanced Test Reactor. In both RERTR-6 and RERTR-7, fuel plates with Al-0.2 wt.% Si (Al-0.2Si), Al-2Si, AA6061 (0.8 wt.% Si), or AA4043 (4.8 wt.% Si) alloy as the matrix were tested [3, 4]. In RERTR-8, fuel plates with U-7Mo, U-7Mo-1Ti or U-7Mo-2Zr fuel particles dispersed in AA4043 matrix were tested [5]. The RERTR-9 experiment was a very aggressive experiment that tested dispersion fuel plates with Al-2Si, Al-3.5Si, or AA4043 matrix [6]. Recently, the reactor experiment AFIP-1 was completed, which tested larger scale dispersion fuel plates, fabricated by Babcock and Wilcox [7], with either Al-2Si or AA4043 as the matrix [8,9]. Preliminary calculations show that the average fission density for AFIP-1 fuel plates was ~4.0 x 10^{21} fissions/cm^3, the peak heat flux was ~325 W/m^2, and the peak centerline temperature was ~150˚C [9]. In order to improve the understanding of the AFIP-1 PIE metallography results, the starting fuel plate microstructures have been determined by characterizing the archive fuel plates using scanning electron microscopy (SEM), which were then compared to the optical image generated for the irradiated fuel plates. This paper describes the results of the archive fuel plate characterization, along with how these as-fabricated microstructures compared to those that developed during irradiation.

2. Experimental

2.1 SEM Analysis of AFIP-1 Archive Plates

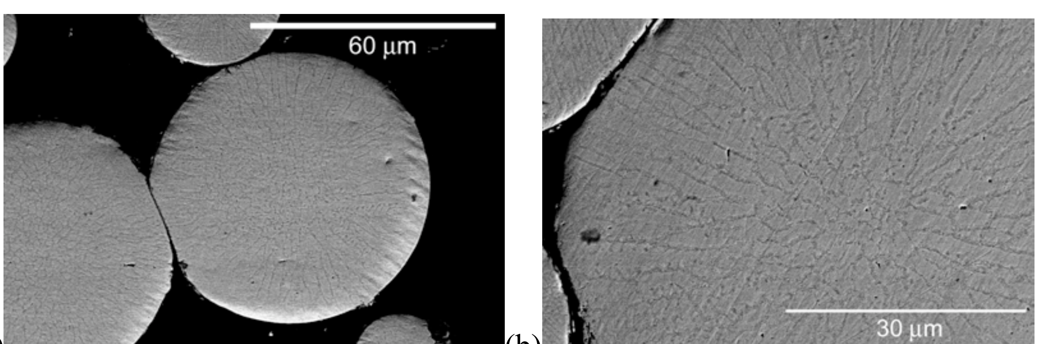
SEM analysis, combined with energy-dispersive and wavelength-dispersive spectroscopy (EDS/WDS), was performed on a cross-section of archive fuel plates 1T2 (Al-2Si) and 1B5 (AA4043). Backscattered and secondary electron images were taken to reveal the microstructure, Si x-ray maps were generated to show how Si partitioned between the various phases, and point-to-point composition analysis was performed to determine compositions of different phases.

3. SEM Results

3.1 Fuel Plate 1T2 (Al-2Si Matrix)

In Fig. 1, backscattered electron images of the microstructure observed for the U-7Mo particles are shown. These microstructures are typical of what is observed for KAERI powders [10], where an equiaxed cellular structure exists towards the center of the particles and a more columnar grain structure extends to the surface of the particles.

Backscattered electron images of the fuel meat microstructure are presented in Fig. 2. A uniform distribution of U-7Mo particles is observed for this fuel plate with 8.0 g U/cc fuel density. The higher magnification images show that relatively large pores were observed in the Al-2Si matrix (see Figs 2b and 2c). With respect to the fuel/matrix interaction that was observed around the fuel particles, only localized regions of interaction could be observed in the BSE images (see Fig. 3). Si x-ray maps indicated that the localized interaction layers that formed were Si-rich (see Fig. 4). The results of point-to-point composition analysis that was performed on the interaction layers shown in Fig. 3b are listed in Table 1. Uniform interaction layers were not observed around the fuel particles.

(a) (b)


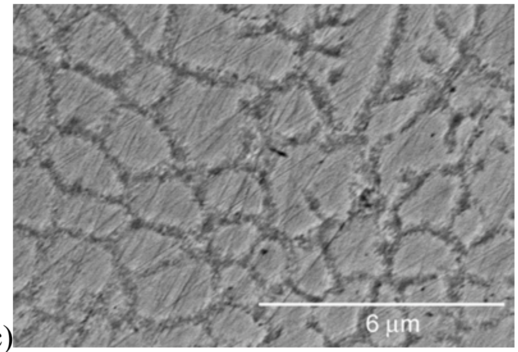
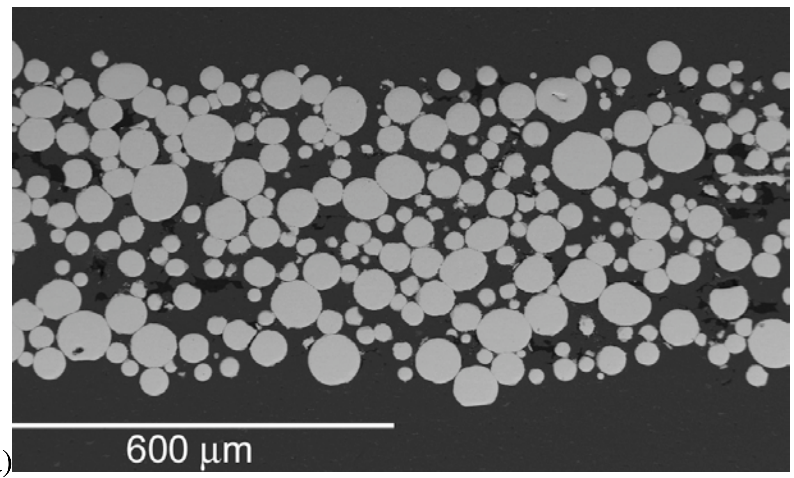
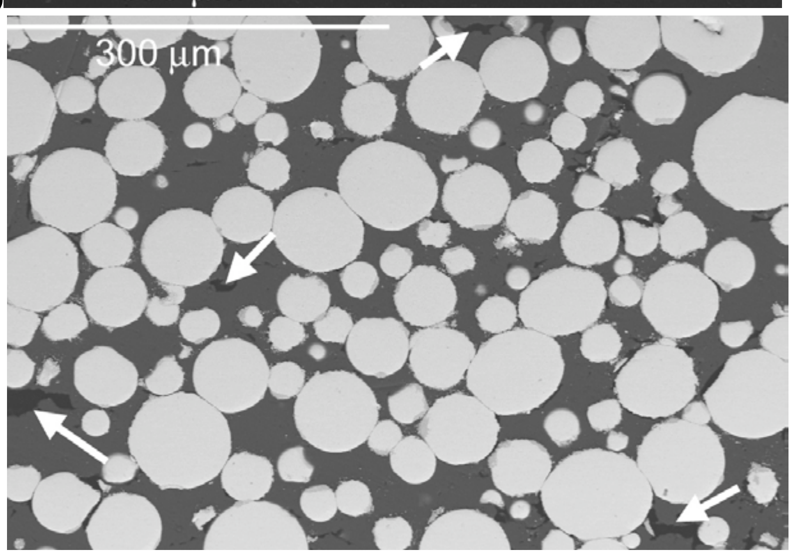
(c) 

Fig. 1. Backscattered electron images (a,b) of the microstructure observed for the U-7Mo particles in the as-fabricated AFIP-1 fuel plate 1T2. (b) is a higher magnification image of the microstructure observed at the center of a fuel particle.



(a)

(b) 

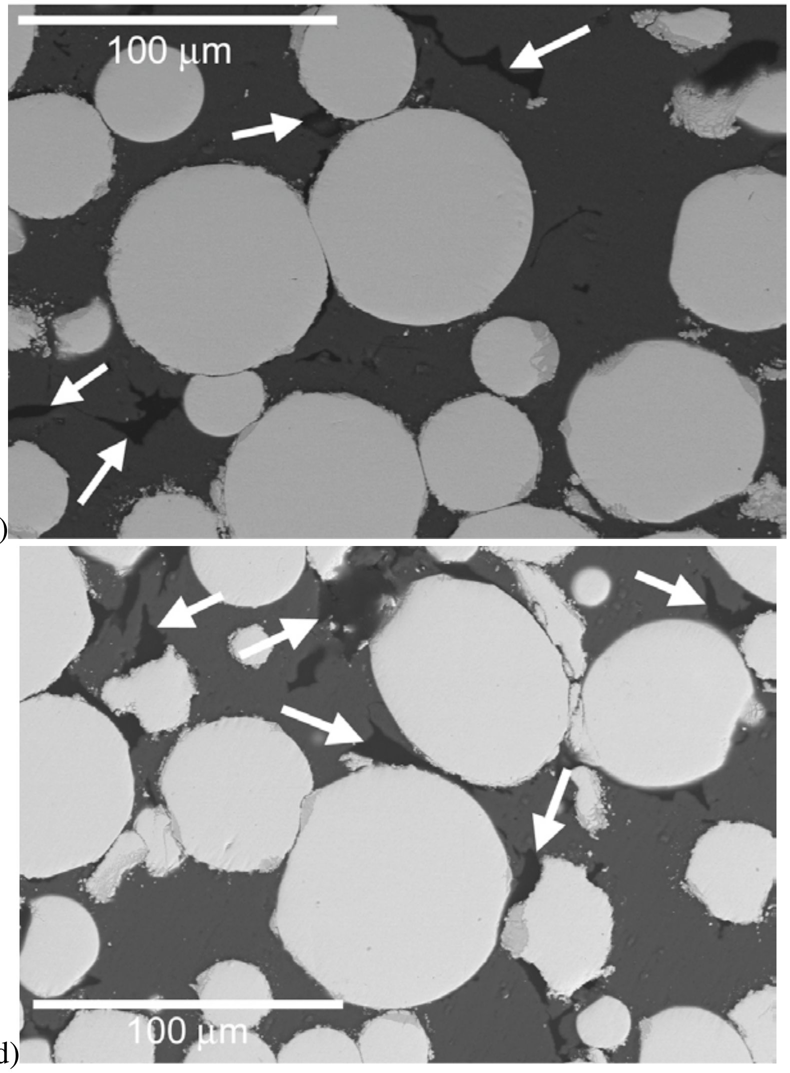
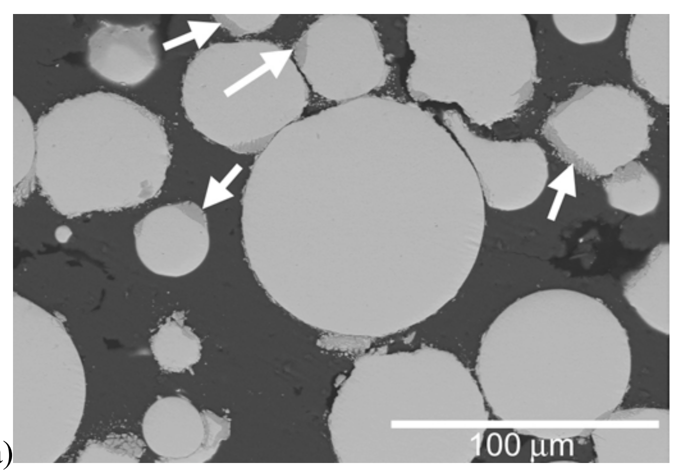


Fig. 2. Backscattered electron images (a-c) of the fuel meat in fuel plate 1T2. The arrows in (b-d) identify porosity that was observed in the Al-2Si alloy matrix.



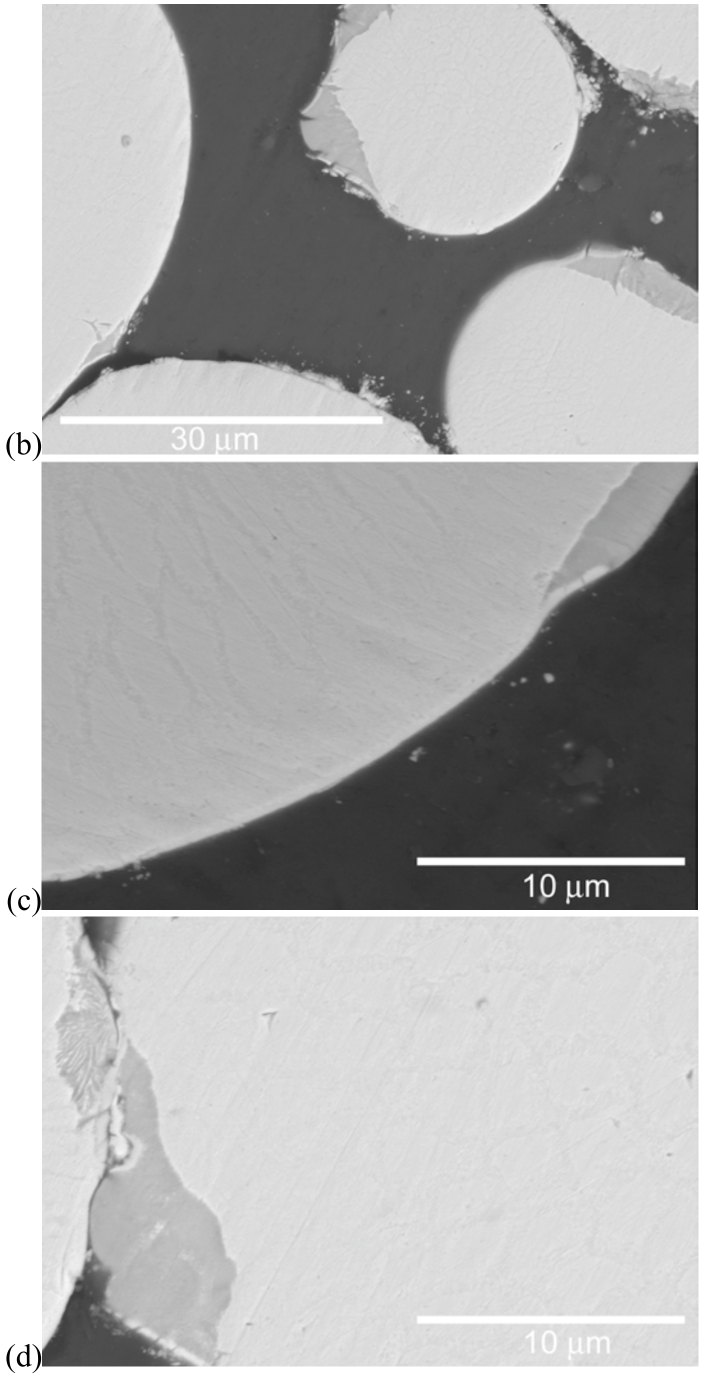


Fig. 3. Backscattered electron images (a-d) of the fuel/matrix interaction layers in fuel plate 1T2. The arrows in (a) identify some of the observable, localized regions where interaction had occurred.

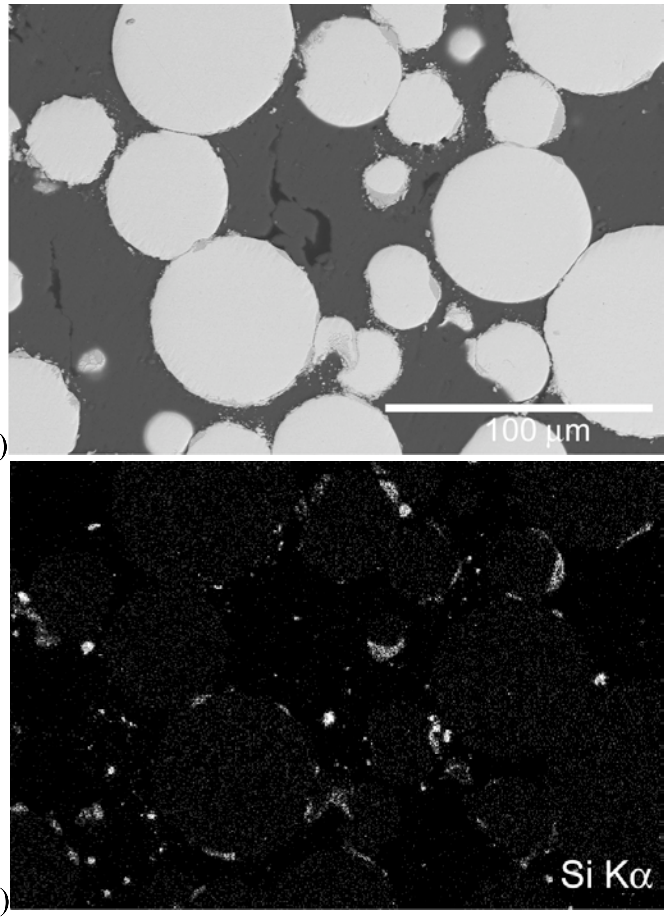
(a)
(b)


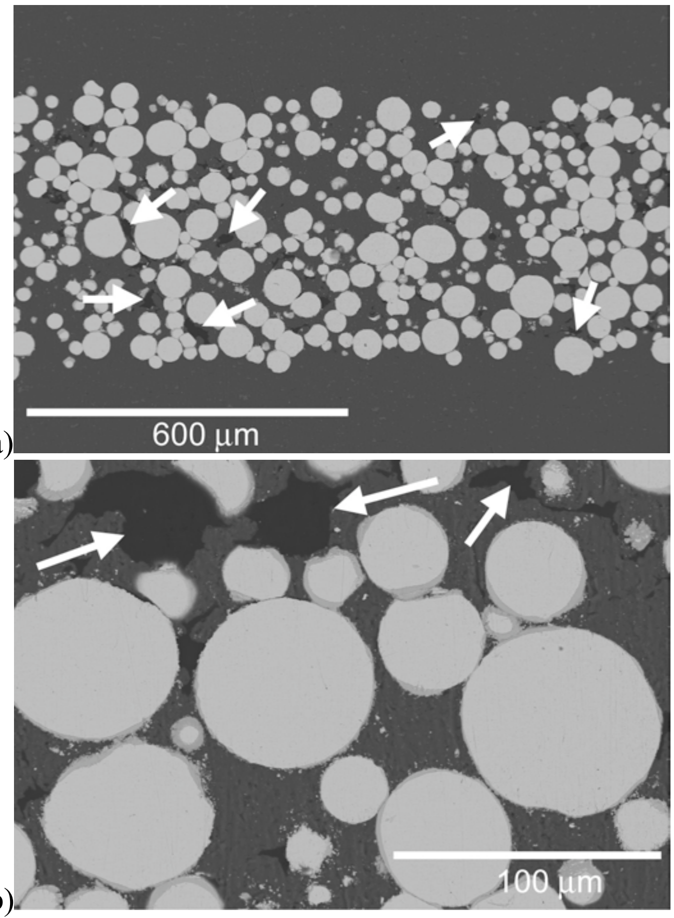
Fig. 4. Backscattered electron image (a) and Si x-ray map (b) showing observable fuel/matrix interaction layers in fuel plate 1T2.

Table 1. Results of point-to-point composition analysis, in at%, conducted at specific locations in the interaction zones shown in Fig. 3b.

Spectrum No.	**Al**	**Si**	**Mo**	**U**
1	30	41	5	25
2	38	36	4	23
3	18	49	5	28
4	23	47	5	25
5	29	43	5	23
6	25	45	4	26
7	54	26	4	17
Mean	31	41	4	24

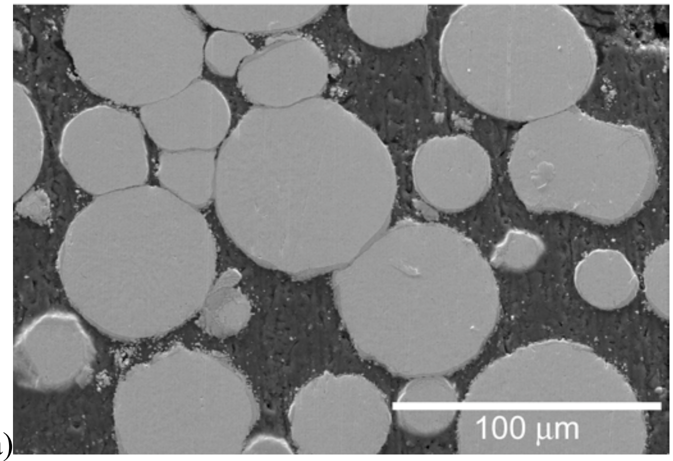
3.2 Fuel Plate 1B5 (AA4043 Matrix)

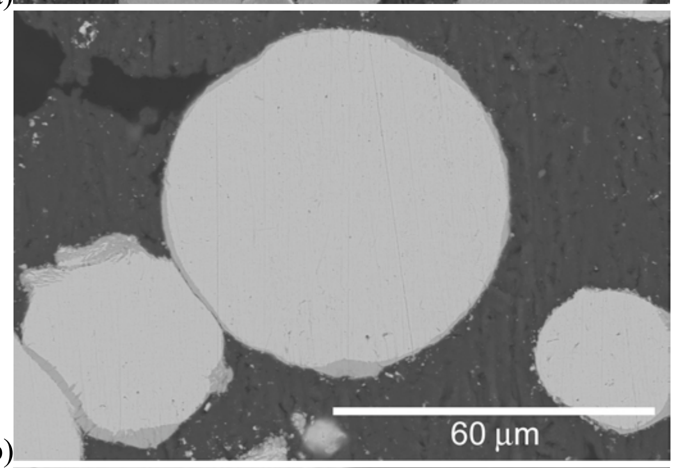
Backscattered electron images of the fuel meat microstructure observed for fuel plate 1B5 are shown in Fig. 5. As was the case for fuel plate 1T2, porosity was observed in the Al alloy matrix. The fuel/matrix interaction layers that were present around the fuel particles are shown in Fig. 6. X-ray mapping of the fuel meat microstructure (see Fig. 7) showed that thin Si-rich interaction layers were present at many locations around the U-7Mo fuel particles. However, there were some regions along the interface where there was negligible Si-rich interaction layer.



(a) (b)

Fig. 5. Backscattered electron images (a,b) of the fuel meat microstructure observed for fuel plate 1B5. The arrows indicated regions of porosity.

(a)


(b)


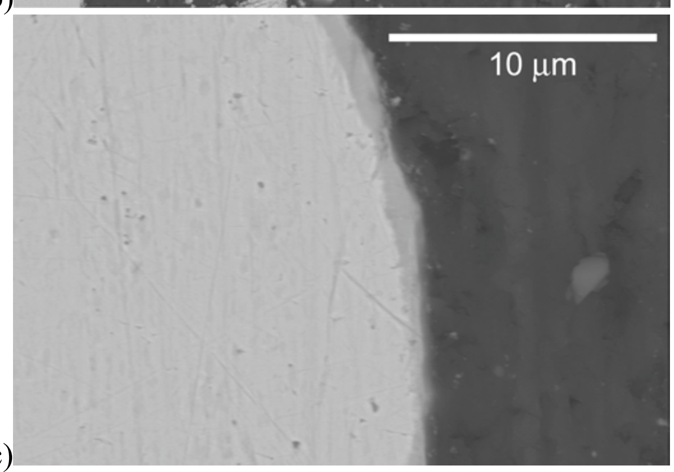
(c)


Fig. 6. Backscattered electron images (a-c) of the fuel/matrix interaction layers observed in the fuel meat of fuel plate 1B5.

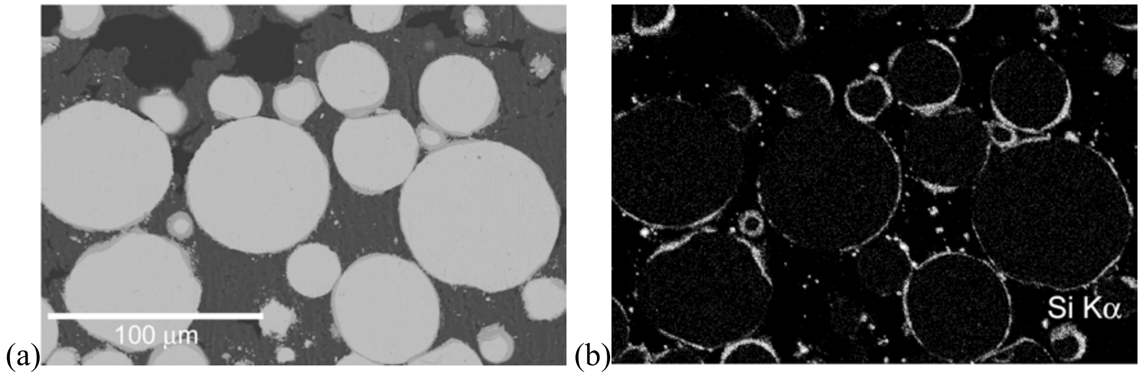


Fig. 7. Backscattered electron image (a) and Si x-ray map (b) showing the presence of Si-rich interaction layers around the U-7Mo fuel particles.

4. Results of Irradiated AFIP-1 Fuel Plate Characterization

4.1 Gamma Scanning Results

Gamma scanning results can be used to identify whether there were any significant burnup differences at different locations along the length of fuel plate 1T2 compared to 1B5. Figure 8 shows the results of gamma scanning analysis overlaid with the results of chemical analysis. The gamma scan spectrum indicates relative fission density over the entire experiment, which is plotted to correspond with the results of fission density calculations based on the chemical analysis samples taken at the four identified locations. The results presented in Fig. 8 indicate that the burnup is very similar for each plate at the high power ends. However, at the low power ends there is a slight difference. The low power end of fuel plate 1T2 had lower burnup than the low power end of fuel plate 1B5. The burnup differences at the low power ends of the fuel plates should be kept in mind when comparing the optical images.

4.2 Optical Micrographs of Irradiated Fuel Plates

Optical images of the microstructure observed in transverse cross sections taken from the low and high power regions of fuel plate 1T2 (Al-2Si matrix) are presented in Figs. 9 and 10, respectively. Interaction layers are observed around the fuel particles that are a few microns thick. Relatively large pores can be observed that look very similar to those that were observed in the as-fabricated fuel plate. Unreacted Al-2Si matrix can be observed at the low power region of the fuel plate, and at the high power region the original Al-2Si matrix has been mostly consumed.

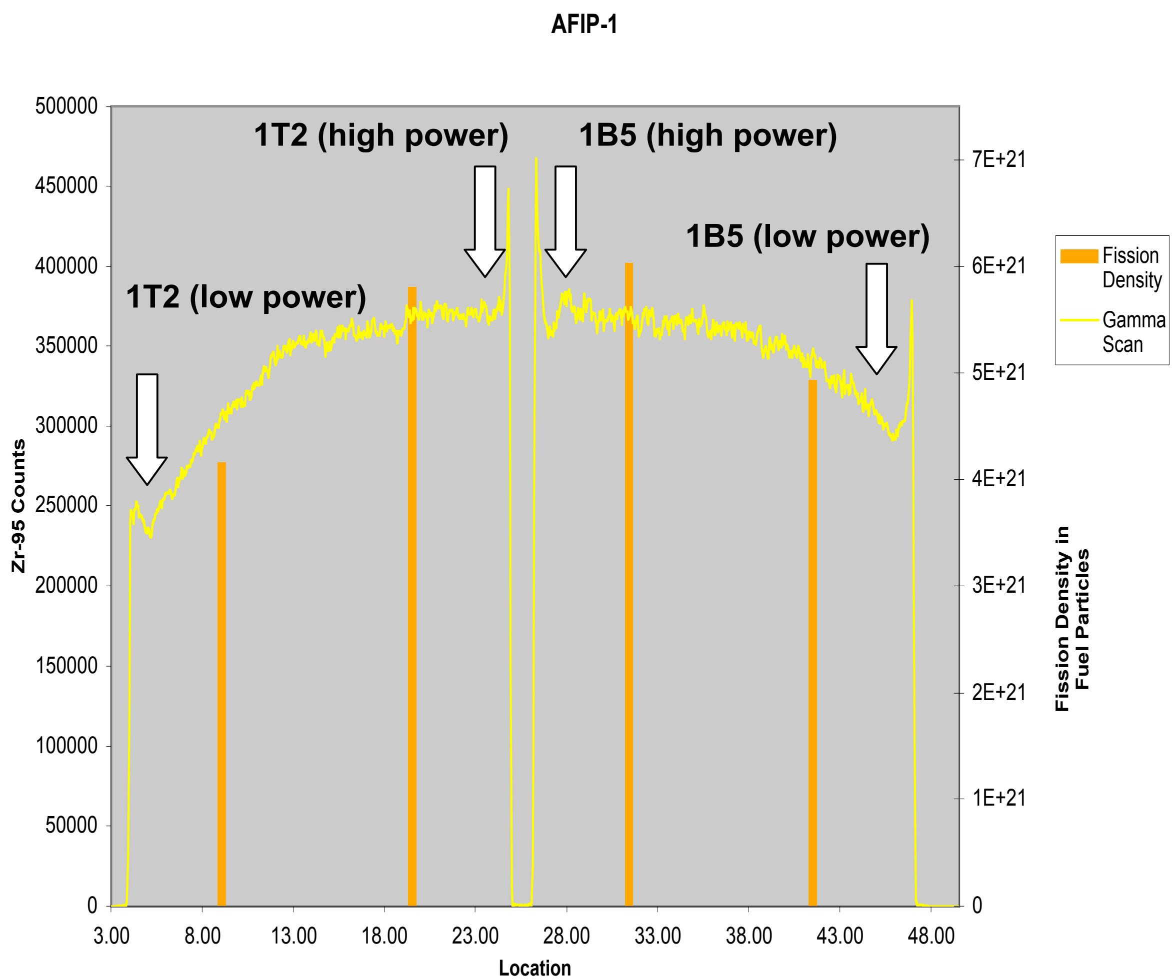
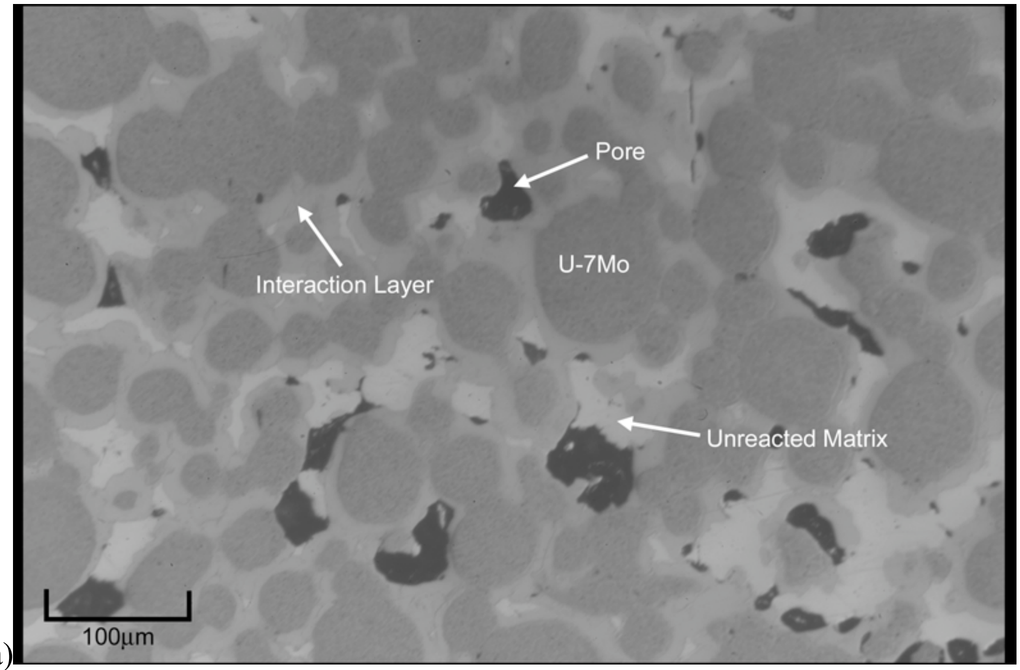
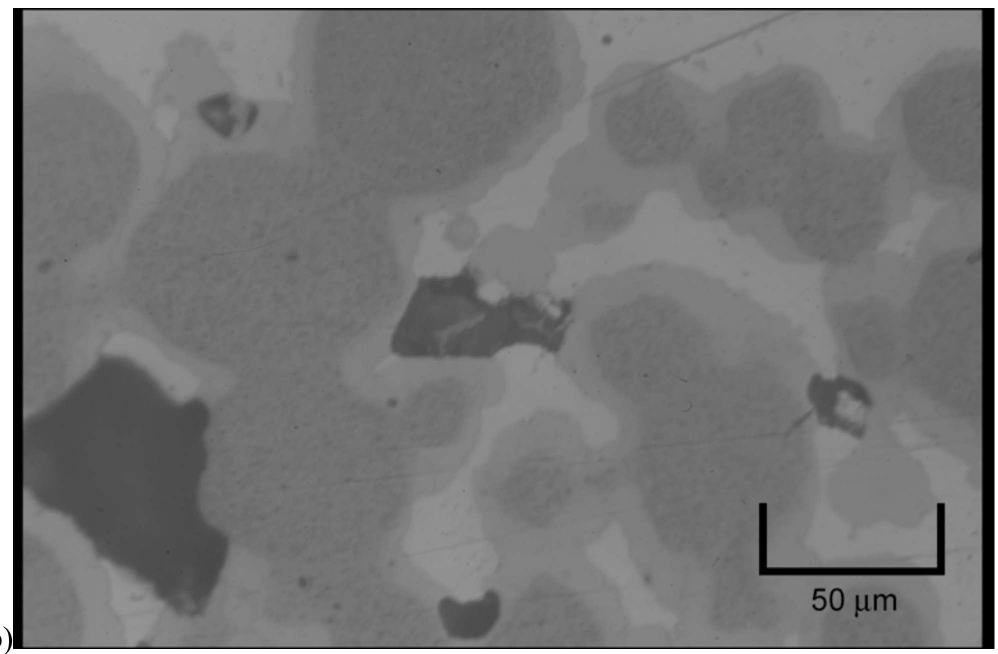


Fig. 8. Gamma scanning profiles of Zr-95 for the two fuel plates that comprised the AFIP-1 experiment, and fission density values based on chemical analysis of discrete fuel plate samples.



(a)



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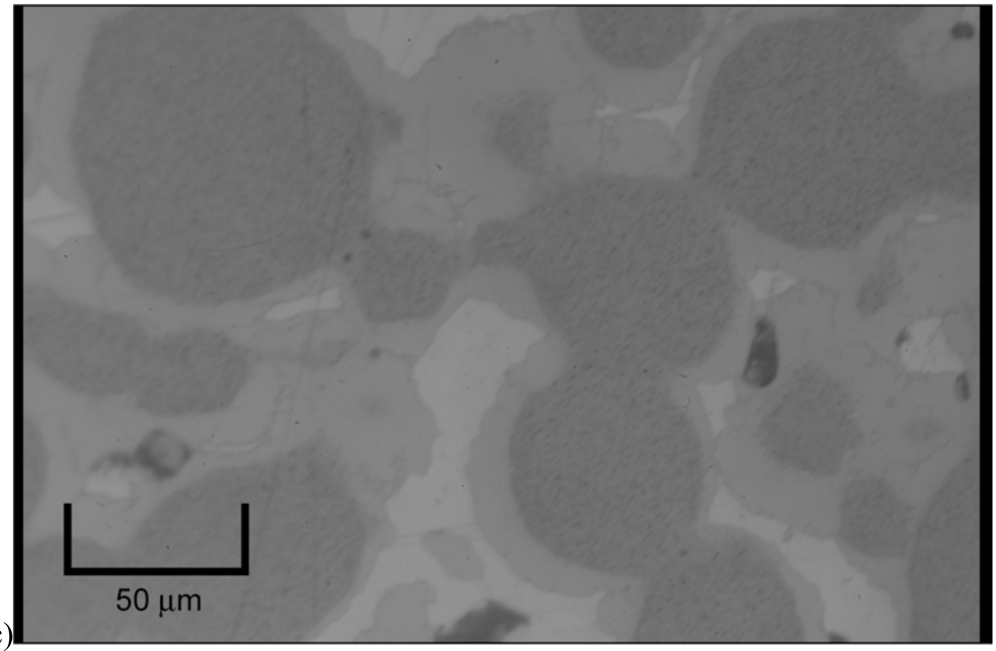
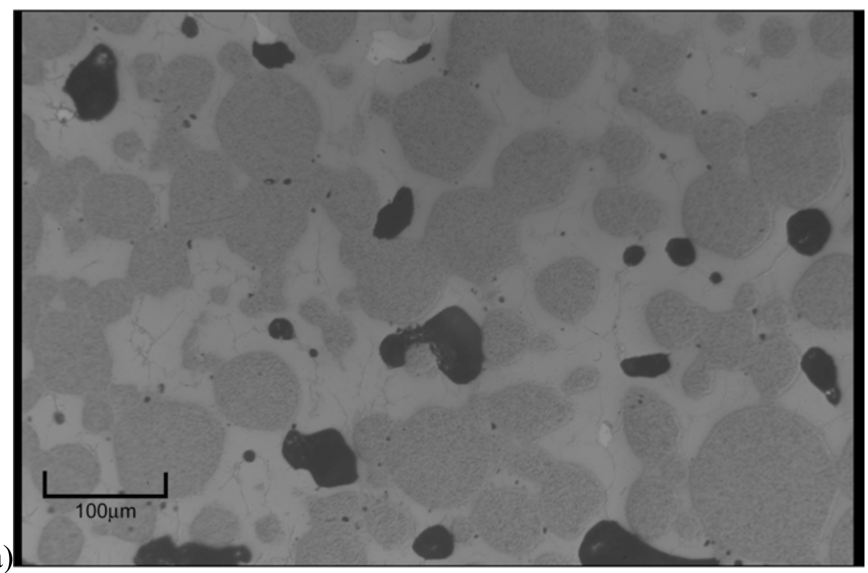


Fig. 9. Optical micrographs (a-c) of the microstructure observed at the low power region of the irradiated 1T2 fuel plate with Al-2Si matrix. The black regions are pores, the dark contrast phase is U-7Mo alloy, the medium contrast phase is interaction layer, and the brightest phase is unreacted Al-2Si matrix.

(a)


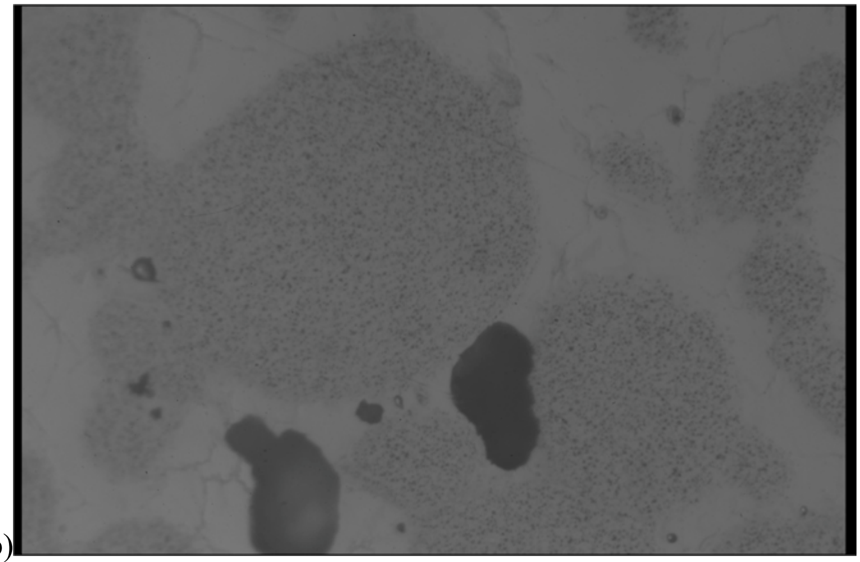
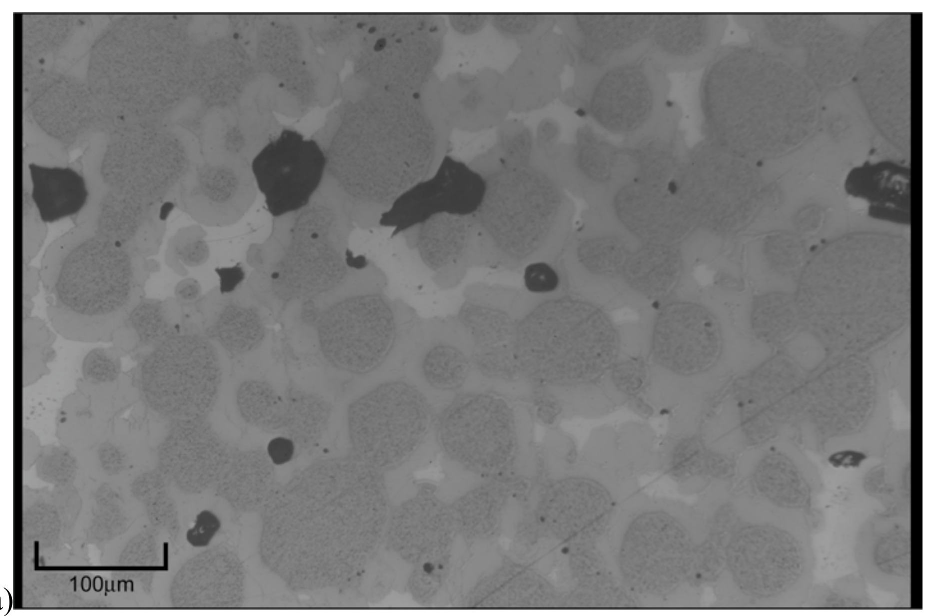
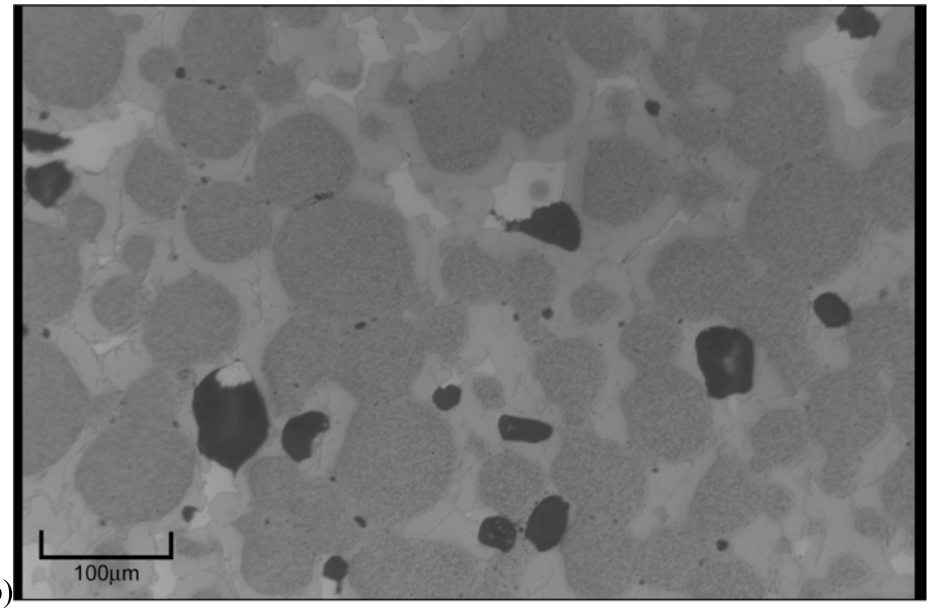

(b)

Fig. 10. Optical micrographs (a,b) of the microstructure observed at the high power region of the irradiated 1T2 fuel plate with Al-2Si matrix. The black regions are porosity. The dark phase is U-7Mo alloy, the medium contrast phase is interaction layer, and the brightest phase is unreacted Al-2Si matrix.

Optical images of the microstructure observed in transverse cross sections taken from the low and high power regions of fuel plate 1B5 (AA4043 matrix) are presented in Figs. 11 and 12, respectively. Interaction layers are observed around the fuel particles that are a few microns thick. Relatively large pores can be observed that look very similar to those that were observed in the as-fabricated fuel plate. Unreacted AA4043 matrix can be observed in both the low and high power regions of the fuel plate.

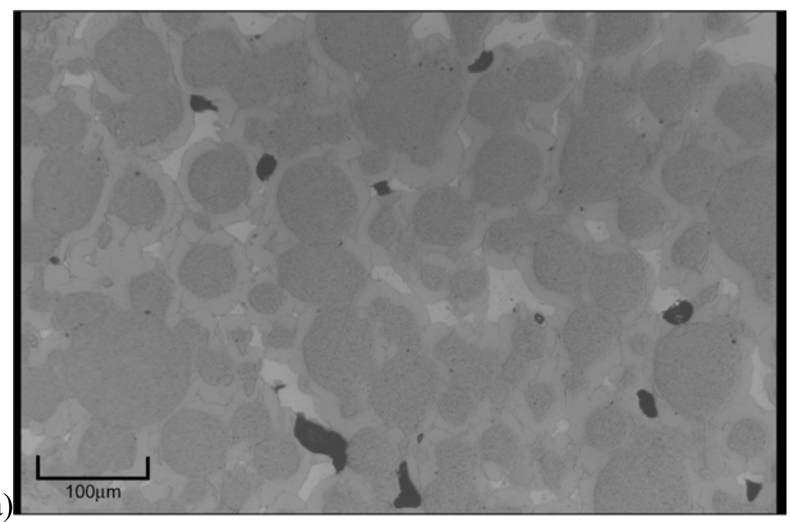


(a)

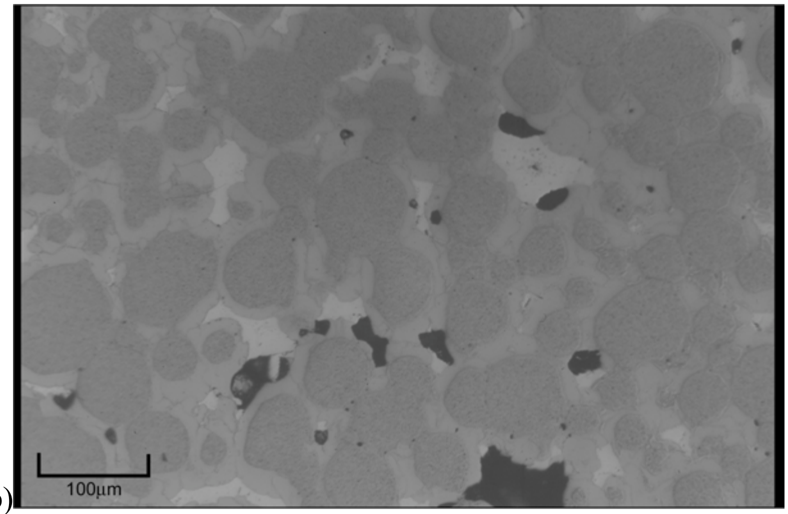


(b)

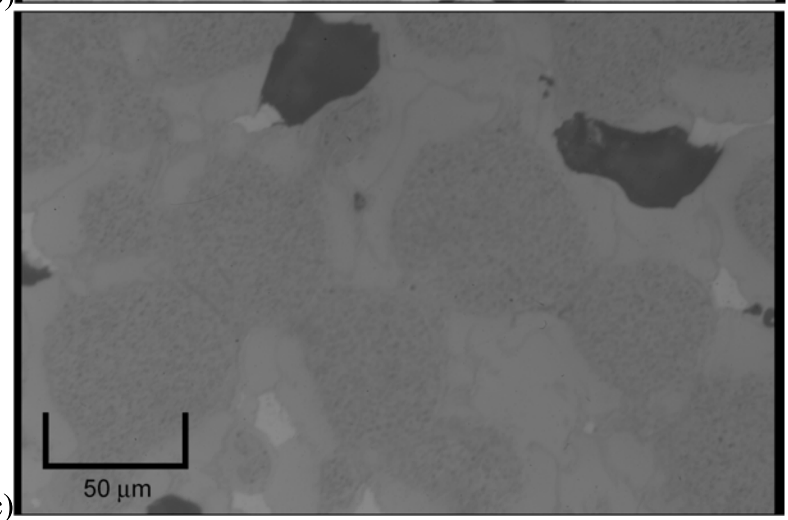
Fig. 11. Optical micrographs (a,b) of the microstructure observed at the low power region of the irradiated 1B5 fuel plate with AA4043 matrix. The black regions are porosity. The dark phase is U-7Mo alloy, the medium contrast phase is interaction layer, and the brightest phase is unreacted AA4043 matrix.



(a)



(b)



(c)

Fig. 12. Optical micrographs (a-c) of the microstructure observed at the high power region of the irradiated 1B5 fuel plate with AA4043 matrix. The black regions are porosity. The dark phase is U-7Mo alloy, the medium contrast phase is interaction layer, and the brightest phase is unreacted AA4043 matrix.

4. Discussion

After fabrication of the AFIP-1 fuel plates with Al-2Si and AA4043 fuel plates, relatively large pores remained in the matrix of both fuel plates. During fabrication, some interaction occurred between the U-7Mo particles and the Si-containing matrix for both fuel plates, resulting in the development of Si-rich interaction layers. These layers were more uniform around the U-7Mo particles for the fuel plate with AA4043 matrix, but even for this plate there were regions around the particles where negligible interaction layer had formed. Possible factors that could have affected the development of the fuel/matrix interaction layers could have been the presence of oxide layers around the original U-7Mo powders, and the amount of Si in the fuel meat matrix that would have affected the amount of Si available for the interaction. How the fuel plates were manufactured (e.g., number of rolling passes, parameters employed for blister annealing, etc.) would have also impacted the development of the fuel/matrix interaction layers.

By comparing the archive characterization results with the optical images generated for irradiated fuel plates 1T2 and 1B5, one can see that changes in the original as-fabricated microstructure occurred during irradiation in ATR. The main change was the growth of fuel/matrix interaction layers. For fuel plate 1T2, the layers consumed almost all the original Al-2Si matrix at the high power region of the fuel plate. For fuel plate 1B5, there was some original AA4043 matrix remaining in both the low and high power regions. It appears that original as-fabricated porosity remained after irradiation, and many of the original relatively large pores seemed to maintain their size and shape. With respect to the stability of the interaction product, there was little evidence of porosity forming at the interface between the interaction layer and the unreacted matrix that showed a tendency to the interlinking that might cause fuel plate failures, as was the case for fuel plates with pure Al matrix. If some of the larger pores actually formed due to fission gas generation, and were not already present in the as-fabricated fuel, there still was no indication that pores were linking up such that eventual fuel plate failure may result. Overall, both fuel plates exhibited acceptable irradiation performance, in terms of the overall fuel plate swelling behavior.

5. Conclusions

Based on the SEM characterization of AFIP-1 archive fuel plates with Al-2Si and AA4043 matrix and a comparison of these results to those produced during microstructural characterization of irradiated fuel plates, it can be concluded that in a full-sized fuel plate the fuel/matrix interaction layers can grow under the irradiation conditions of the AFIP-1 experiment such that in the high power region of a fuel plate with Al-2Si matrix the original matrix will be mainly consumed, and for a fuel plate with AA4043 matrix some original matrix will remain in both the low and high power regions of the fuel plate. The fuel/matrix interaction layers that form exhibit stable behavior in terms of the lack of development of large areas of fission gas porosity that show a tendency to interlinking. For a case where there is a relatively large amount of porosity in an as-fabricated fuel plate, pores remain in the irradiated fuel plate that seem to have changed little in size or shape from what was observed after fabrication.

Acknowledgments

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References

[1] A. Leenaers et al., J. Nucl. Mater. 335 (2004) 39-47.

[2] Y. S. Kim et al., Proc. of the RERTR-2005 International Meeting, Boston, MA, 2005.
[3] G. L. Hofman et al., Proc. of the RRFM 2007 Conference, Lyon, France, 2007.
[4] D. M. Wachs et al., Proc. of the RERTR-2006 International Meeting, Capetown, South Africa, 2006.
[5] G. L. Hofman et al., Proc. of the RRFM 2008 Conference, Hamburg, Germany, 2008.
[6] A. B. Robinson et al., Proc. of the RERTR-2008 International Meeting, Washington, D. C., 2008.
[7] M. J. Nilles et al., Proc. of the RERTR-2008 International Meeting, Washington, D. C., 2008.
[8] A. B. Robinson et al., Proc. of the RRFM 2010 Conference, Marrakech, Morocco, 2010.
[9] A. B. Robinson et al., AFIP Summary Report, Idaho National Laboratory Report, INL/EXT-10-18497 (2010).
[10] Jong Man Park et al., J. Nucl. Mater. 397 (2010) 27-30.