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Summary of Post Irradiation Examination Results of the AFIP-6 Failure

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Summary of Post Irradiation Examination Results of the AFIP-6 Failure

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ABSTRACT

The AFIP-6 test assembly was irradiated for one cycle in the Advanced Test Reactor at Idaho National Laboratory. The experiment was designed to test two monolithic fuel plates at power and burn-ups which bounded the operating conditions of both ATR and HFIR driver fuel. Both plates contain a solid U-Mo fuel foil with a zirconium diffusion barrier between 6061-aluminum cladding plates bonded by hot isostatic pressing.

The experiment was designed with an orifice to restrict the coolant flow in order to obtain prototypic coolant temperature conditions. While these coolant temperatures were obtained, flow restriction resulted in low heat transfer coefficients and the failure of the fuel plates.

The results from the post irradiation examinations and some observations of the failure mechanisms are outlined herein.

BACKGROUND

The AFIP-6 experiment was designed to test monolithic uranium-molybdenum fuel plates with a zirconium diffusion barrier at bounding ATR conditions[1]. The experiment consisted of two fueled plates both fabricated using hot isostatic pressing (HIP) with nominal fuel zones of 570 mm long by 35 mm wide and 0.33 mm thick. The plates were swaged into the rails of the fuel

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[1] Wachs, D.M. PLN-3222 "Experiment Control Plan for the AFIP-6 Fuel Irradiation in the ATR" November, 2009

assembly. The fuel foils consisted of U-10Mo with 40% U-235 enrichment in order to achieve desired heat fluxes of 500 W/cm^2.

Subsequent detailed thermal hydraulic analysis of the experiment indicated that the combination of the high operating power and test vehicle configuration led to high nominal operating temperatures for the fuel plates. This elevated temperature accelerated surface corrosion and eventually led to spallation of the fuel plate cladding. The thermal insulating nature of this corrosion layer led to significantly elevated fuel meat temperatures that are assumed to have induced blistering. Figure 1 shows the calculated surface temperature of the oxide layer as a function of axial location down the plates[2]. Calculations also indicate BOL peak heat fluxes were 525 W/cm^2.

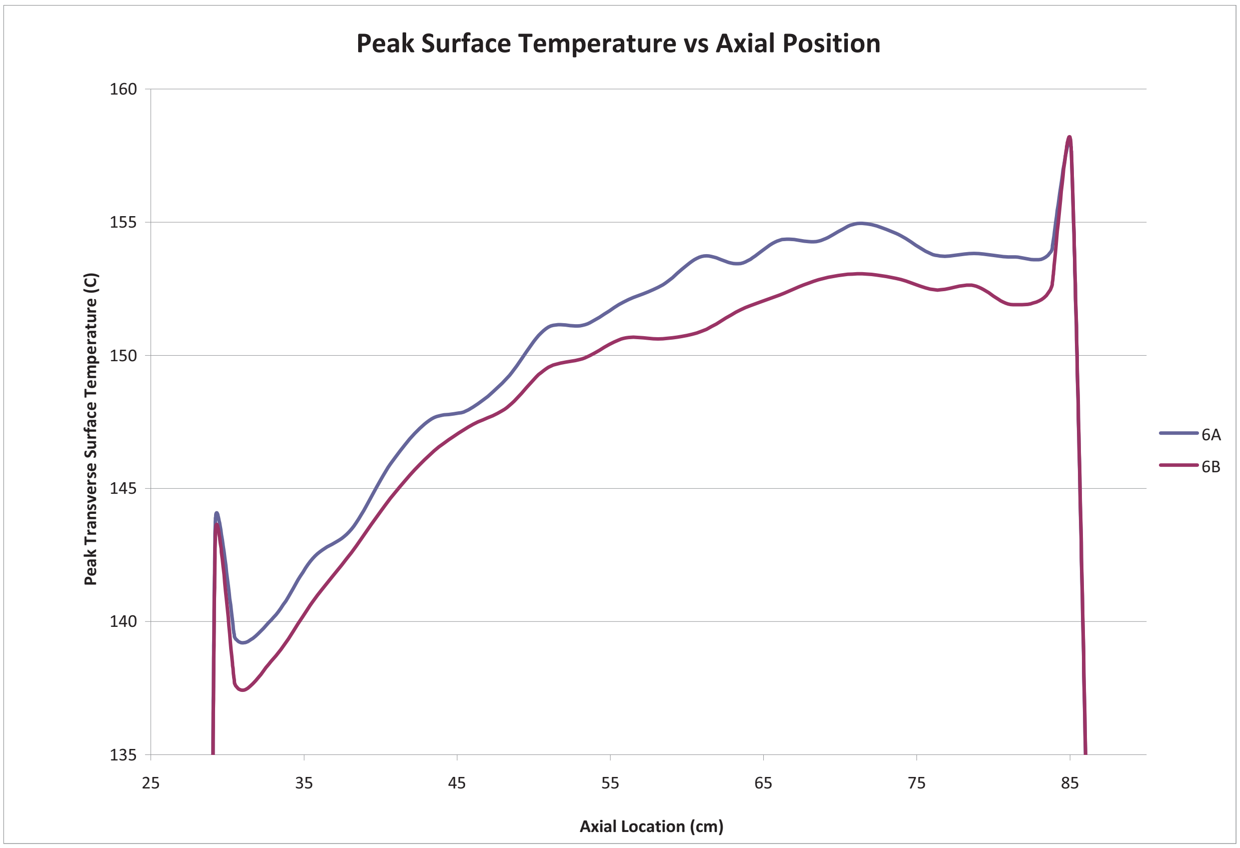

Figure 1 Peak surface temperature of the oxide layer as a function of axial location

[2] Perez, D.M. et al, INL/EXT-11-23296 "AFIP-6 Irradiation Summary Report", August 2011

VISUAL EXAMINATIONS

Visual examinations of the plates showed abnormal oxide formation, regions with pronounced blisters, and locations where spallation of the oxide had clearly occurred. Figure 2 and Figure 3 show samples of the images collected of the surface of the plates and the neutron radiograph images.

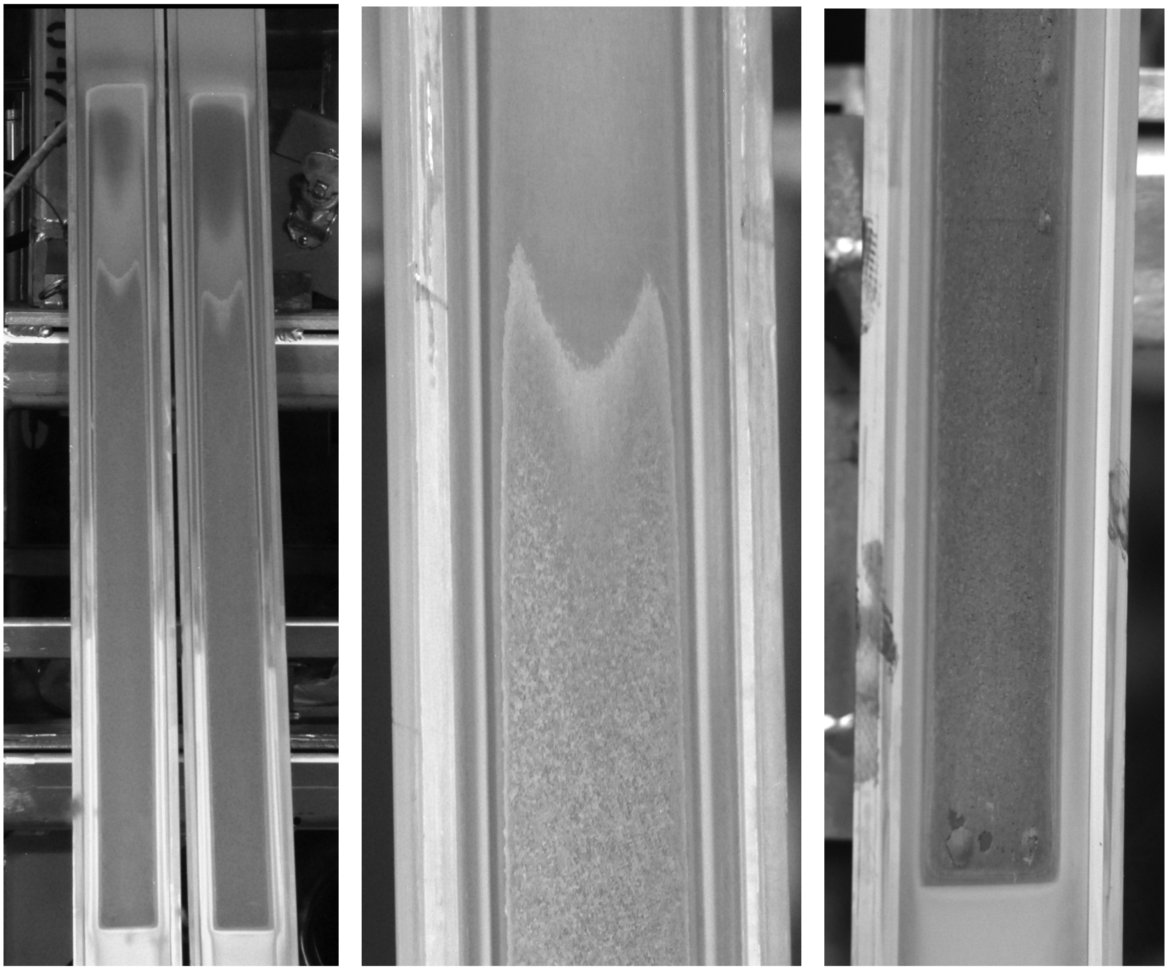

Figure 2 Visual examination photographs of AFIP-6 plates

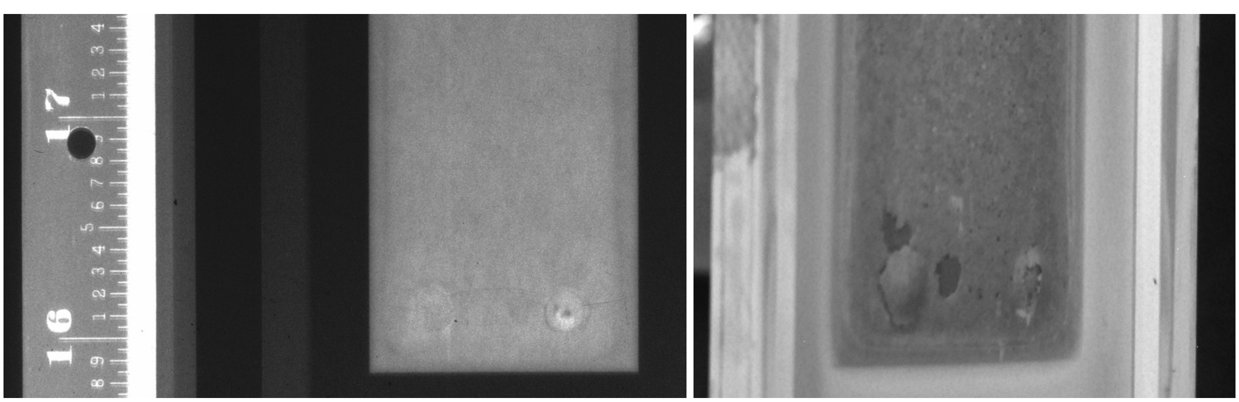

Figure 3 Comparison of neutron radiograph (left) and visual exam (right)

EDDY CURRENT & PROFILOMETRY

Eddy current testing was performed at 4 equi-spaced points across the width of the plate and every half inch down the length of the plate. This thickness typically represents the boehmite oxide that has formed on the surface of the fuel plate. In the case of the AFIP-6 experiment where the cladding has failed and heavily oxidized, there are additional factors that influence the measurement. The measurement values accurately describe the thickness of compromised cladding, but much of this value is a thick degraded region of aluminum that was seen in the destructive examinations and does not reflect traditional 'oxide thickness'.

The results show a small increase at 30 cm's where the fuel zone begins, and then a drastic increase at approximately 42 cm's where the oxide begins to grow to an unstable value. Variations can be seen down the length of the 6A plate with peaks occurring at approximately 75 cm's and 86 cm's where visually observable blisters had occurred.

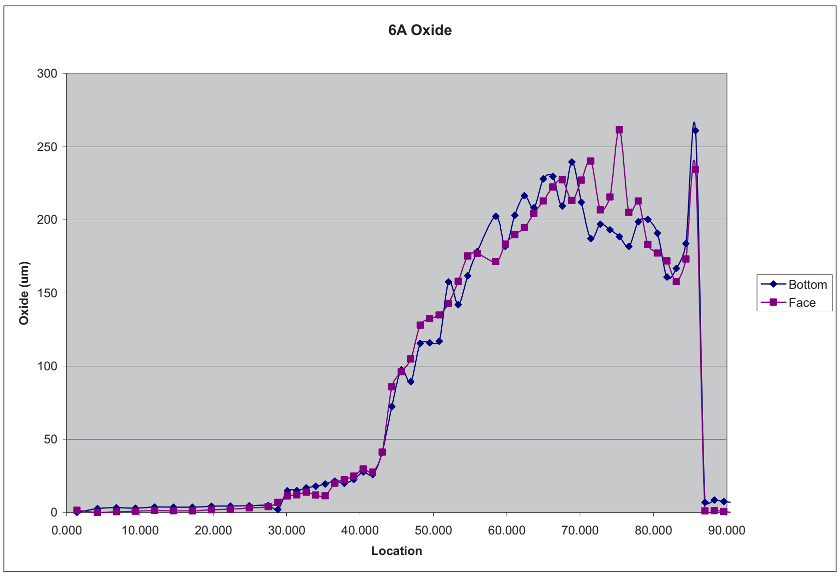

Figure 4 Eddy current results from plate 6A

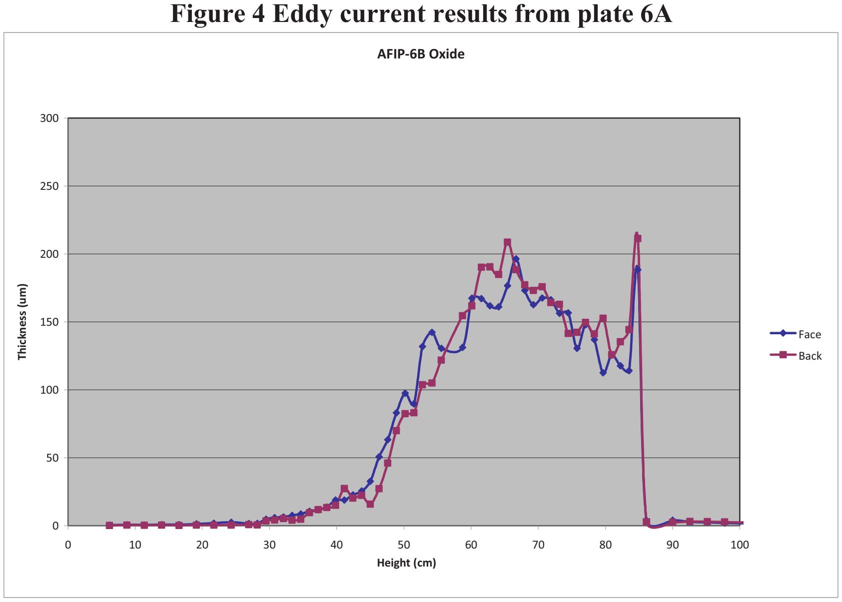

Figure 5 Eddy current results from plate 6B

Profilometry of the AFIP-6 experiment was performed on the plate and rodlet checker. Because the unit is only capable of handling the half sized AFIP experiments or smaller plates, it was required to section the plates in half in order to obtain measurements. Once sectioned, measurements were taken on a 0.3175 cm by 0.3175 cm grid over the entire area of the plates.

Because large blisters exaggerate the thickness data, swelling values will need to be determined using optical metallography. However, the thickness data gives an idea of the location of failures and defects over the surface of the plate. Plate 6A suffered two large blisters at the bottom region of the plate as well as smaller defects predominantly down one edge of the plate with an additional large blister towards the top of the fuel zone. Plate 6B had significantly fewer large defects as can be seen from the profiles in Figure 6 and Figure 7.

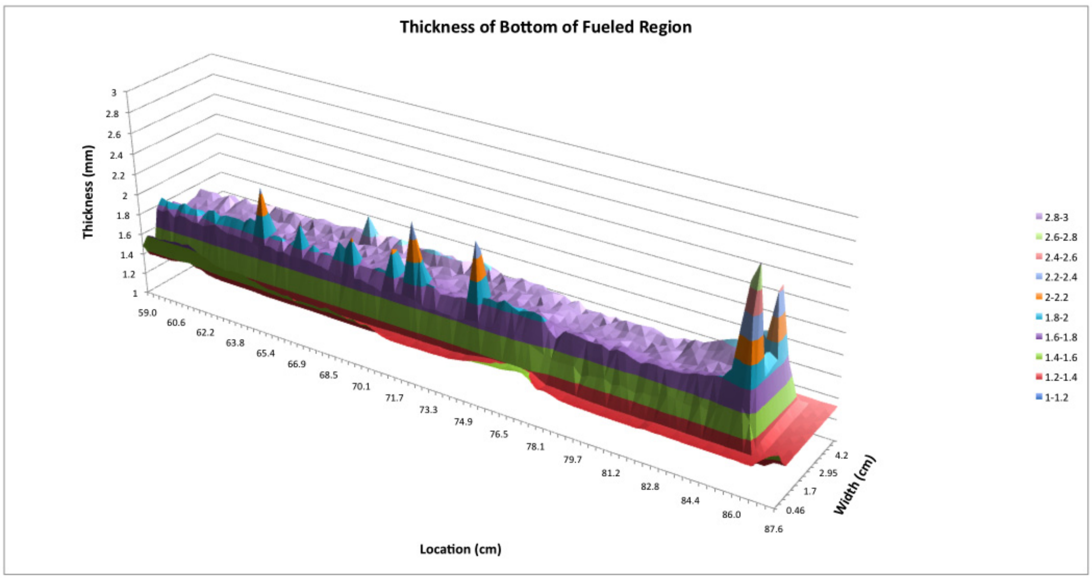

Figure 6 Thickness profile of fueled region of AFIP-6A plate

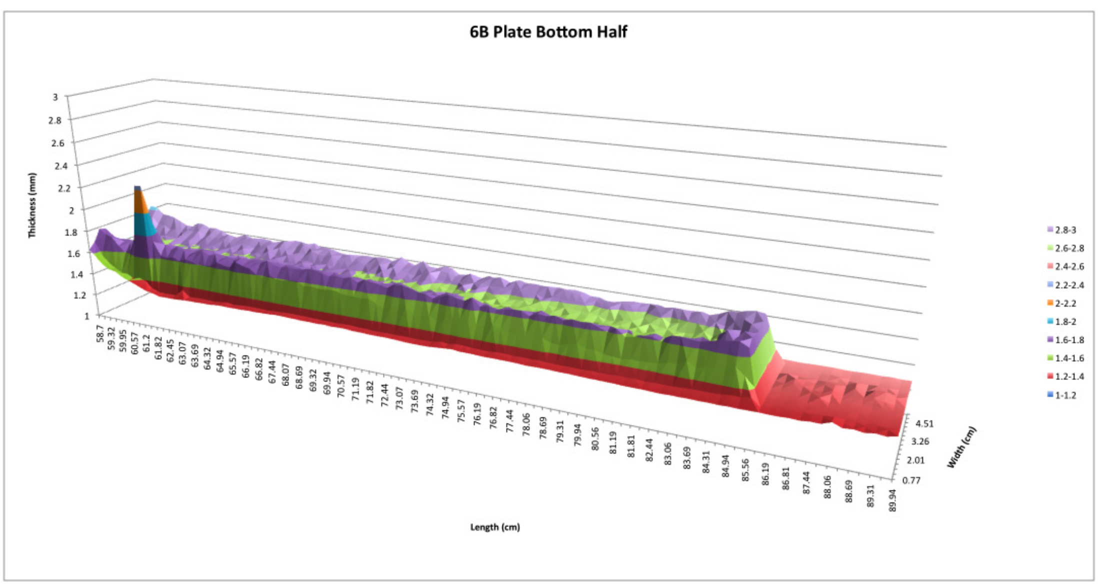

Figure 7 Thickness profile of fueled region of AFIP-6B plate

METALLOGRAPHY

Samples taken from the top regions of the fuel plates indicate typical behavior of the fuel, cladding, and diffusion barrier. Examination showed behavior that has been seen in previous experiments. The oxide layer is thin (5-10 µm) Figure 8 (right), the cladding is uniform, there is little to no reaction between the fuel/zirconium/cladding, Figure 8 (left), and at this burnup no visible porosity can be seen.

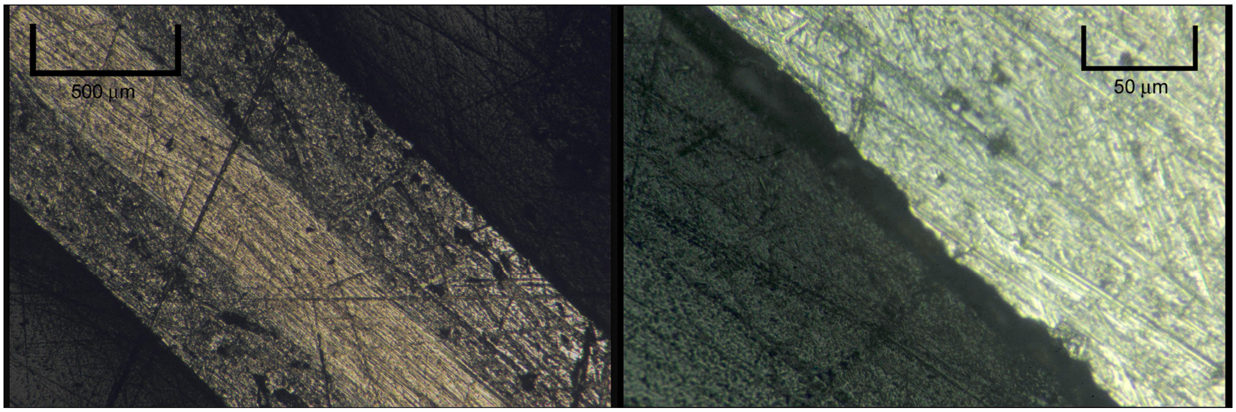

Figure 8 Optical images from the top of plate 6A including

As the temperature increased down the length of the fuel plates, abnormal behavior was seen. Dramatic increases in plate surface oxide thickness were observed, which further increase the temperature of the fuel. Figure 11 shows one side of the cladding from plate 6A. Approximately half of the cladding thickness has been degraded by corrosion. The traditional oxide layer has spalled off and grain boundary attack of the aluminum has occurred resulting in compromised cladding properties, both thermal and mechanical. Similar results were seen in tests performed on aluminum at Oak Ridge National Laboratory by Selby et al[3]. Figure 9 shows a region where spallation has occurred.

At locations near the mid plate of the fuel plate, fission gas bubbles began to form throughout the fuel and preferentially along the periphery of the fuel meat. This is similar to features that have been seen in U-Mo monolithic fuel at very high burn-ups (>100% LEU burn-up) where it is believed that the fission gas lattice structure has decomposed and fission gas migration is prevalent[4]. This behavior would indicate that the elevated temperature of the fuel has accelerated the decomposition of this stable fission gas lattice.

Figure 10 shows this large amount of porosity that was beginning to form within the fuel with emphasis given to the periphery regions of the fuel zone. Porosity did not appear to preferentially form along the fuel to zirconium bond line but rather 5-10 micrometers into the fuel. This indicates good stability of the fuel/zirconium/clad bond.

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[3] D.L. Selby, R.M. Harrington, ORNL—6574 "Advanced Neutron Source Project Progress Report", April 1990

[4] Keiser, D.D. et al, "Results of SEM and TEM Characterization of a Dispersion Fuel Plate with Al-2Si Matrix Tested in the RERTR-7 Experiment", Proceedings of the 32nd International Meeting on Reduced Enrichment for Research and Test Reactors, October 2010.

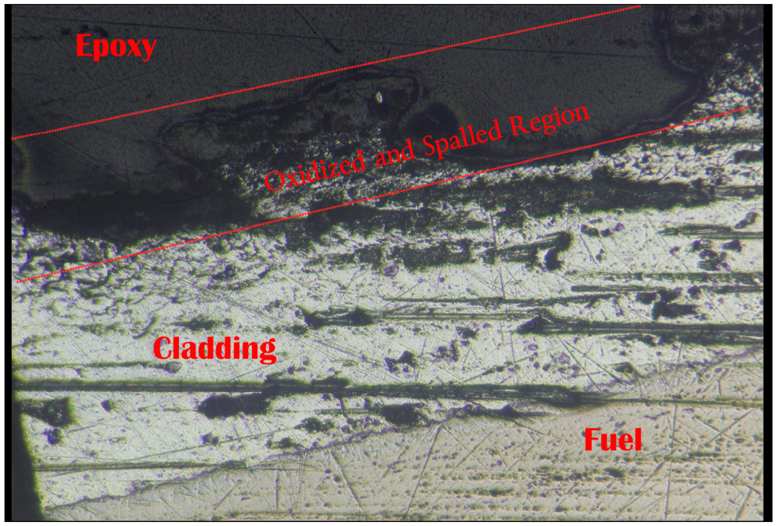

Figure 9: Image showing oxidation/spallation region

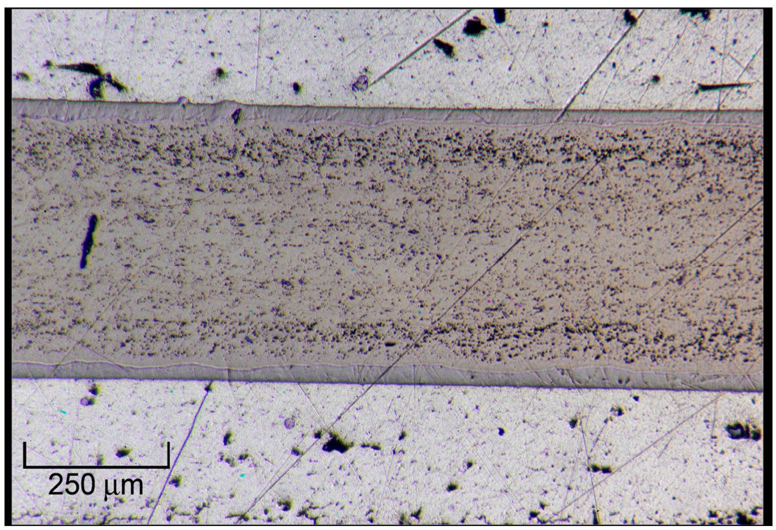

Figure 10: Porosity beginning to form in the fuel foil

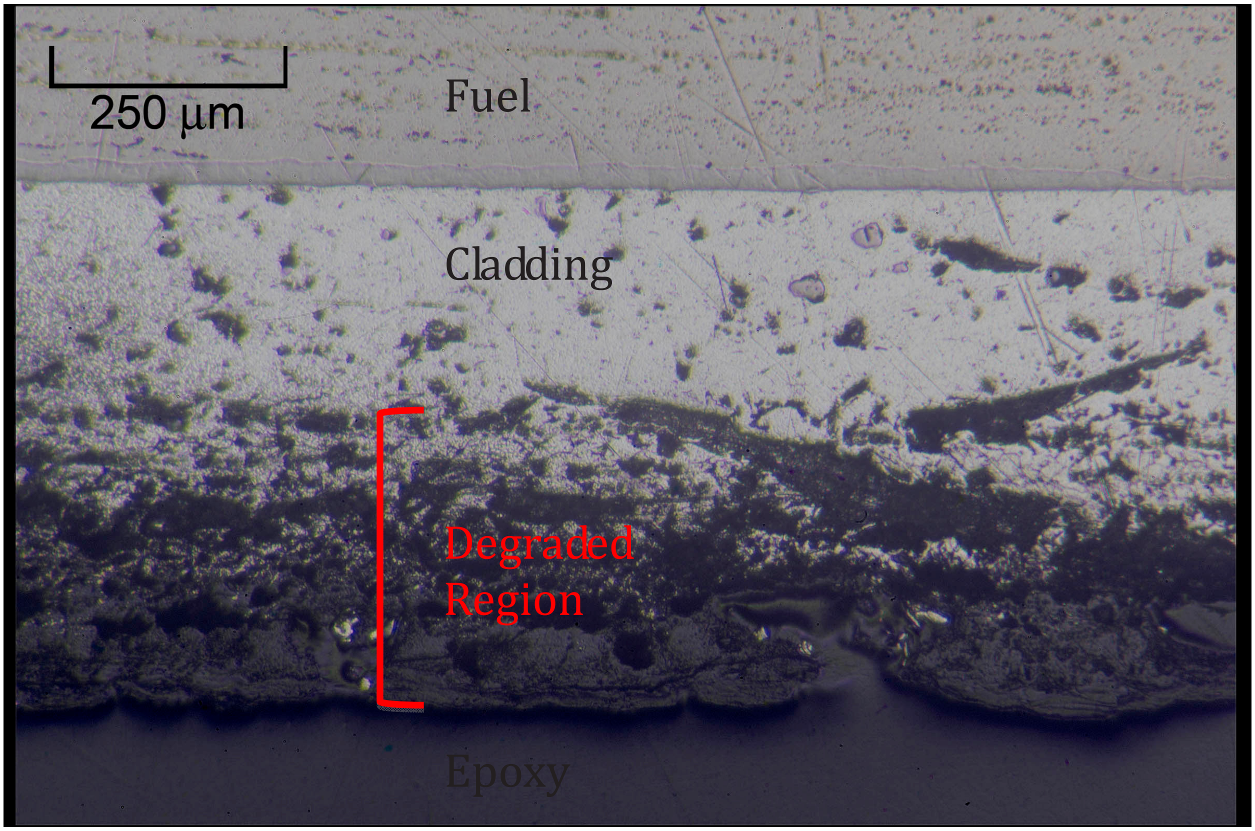

Figure 11: Image of plate surface at the mid plate of the AFIP-6A plate

Moving axially down the fuel plates, the resulting decrease in the thermal conductivity of the cladding has further increased the fuel temperature and again changed the fission gas retention properties of the U-Mo fuel foil. The small, dispersed fission gas bubbles seen in cooler locations of the experiment are no longer visible within the fuel. Large voids have now formed in locations where fission gas bubbles were seen previously in cooler parts of the plate, i.e. Figure 10. Figure 12, an axial section, shows examples of two void regions that have formed within the fuel meat very near the rail region. Again, these voids have formed a small distance into the fuel and away from the interface. It is anticipated that these defects have become 'sinks' for fission gases and will ultimately become large enough to cause blisters like those observed in hotter regions of the plate. UT images indicate that these voids continue to appear down the length of the fuel plate as shown in Figure 13.

A cross section was taken through the blistered region at the bottom of plate 6A, which corresponded to the highest temperature region during the test. Figure 14 shows the fuel through the blister and as expected, significant damage to the fuel has occurred. A large void has formed near the centerline of the fuel foil and cracking is evident in the fuel around the void. It is anticipated that cracks in the cladding over this blister resulted in the release of fission gases to the primary coolant.

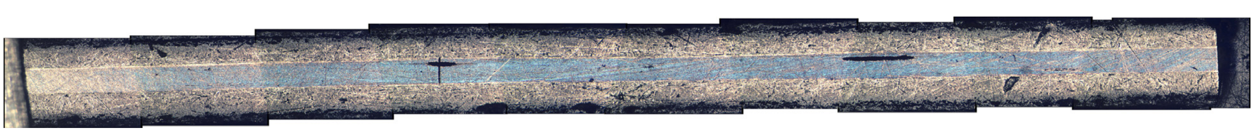

Figure 12: Cross section through the AFIP-6A plate showing typical porosity location

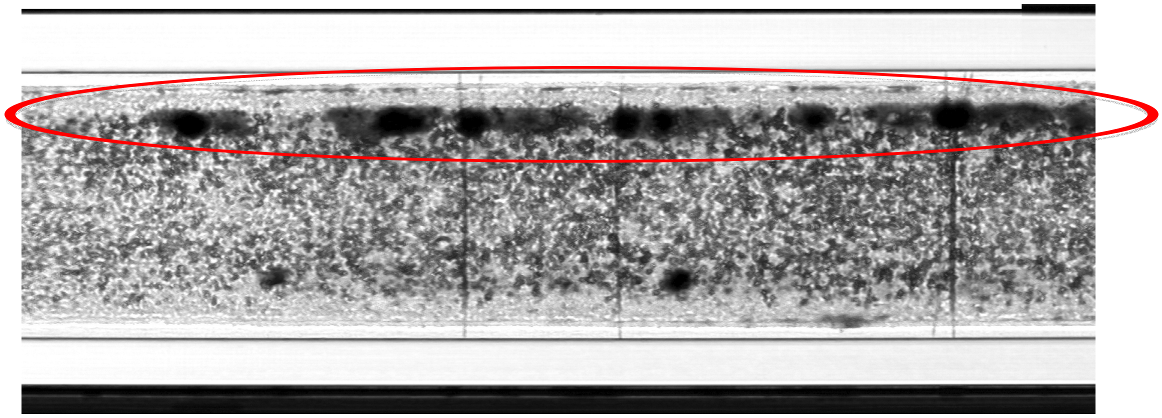

Figure 13: UT scan indicating the location of large porosity in the fuel along the rail

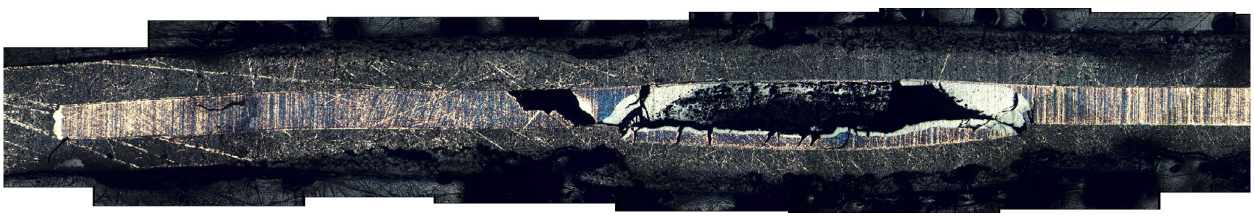

Figure 14: Cross section through blistered region of 6A plate

Conclusions

The AFIP-6 test experiment breached during irradiation. It is now understood that the increased size of the coolant channels and a test train flow restriction added to minimize coolant flow through the center flux trap led to a convective heat transfer coefficient that was lower than necessary to cool the experiment. The overall fuel plate operating thermal conditions were subsequently outside the intended conditions resulting in severe oxidation of the aluminum cladding. The high surface temperature accelerated oxide growth until the spallation threshold was reached leading to significant degradation of the cladding surface. The degraded cladding led to further increases in fuel temperature which resulted in the formation of small surface blisters in the peak temperature regions of the fuel plates.

As the temperature increased down the length of the experiment, behavior of the U-Mo fuel, specifically regarding fission gas retention changed. The upper regions of the experiment that operated near the intended temperature range behaved normally. Regions of higher temperature experienced severe oxidation and unstable fission gas behavior. The hottest regions of the plate experienced blistering and localized severe fuel degredation. Not all regions of the fuel, even at the highest temperatures showed signs of degradation, but failures appear to have occurred at locations that were acting as sinks. The locations of these sinks within the fuel are likely determined by mechanical stresses within the fuel meat.