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AFIP-6 MKII First Cycle Report

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EXECUTIVE SUMMARY

The first fuel plate frame assembly of the AFIP-6 MKII experiment was irradiated as planned from December, 2011 through February, 2012 in the center flux trap of the Advanced Test Reactor during cycle 151A. Following irradiation in this cycle and while reconfiguring the experiment in the ATR canal, a non-fueled component (the bottom plate) of the first fuel plate frame assembly became separated from the rail sides. There is no evidence that the fueled region of the fuel plate frame assembly was compromised by this incident or the irradiation conditions.

The separation of this component was determined to have been caused by flow induced vibrations, where vortex shedding frequencies were resonant with a natural frequency of the bottom plate component. This gave way to amplification, fracture, and separation from the assembly. Parallel flow induced vibrations were identified and analyzed, however, vortex shedding flow induced vibrations, an unfamiliar failure mode, were not.

Both the once-irradiated first fuel plate and un-irradiated second fuel plate frame assemblies were planned for irradiation in the subsequent cycle 151B. The AFIP-6 MKII experiment was excluded from irradiation in cycle 151B because non-trivial design modifications would be needed to mitigate this type of incident during the second irradiation cycle. All items of the experiment hardware were accounted for and cycle 151B occurred with a non-fueled AFIP backup assembly in the center flux trap. Options for completion of the AFIP-6 MKII experiment campaign are presented and future preventative actions are recommended.

CONTENTS

ACRONYMS

AFIP	ATR Full Size In Flux Trap Position
ATR	Advanced Test Reactor
B&W	Babcock and Wilcox
CFT	Center Flux Trap
ESAP	Experiment Safety Assurance Package
HFEF	Hot Fuel Examination Facility
HFIR	High Flux Isotope Reactor
HIP	Hot Isostatic Pressing
HPRR	High Performance Research Reactor
GTRI	Global Threat Reduction Initiative
RERTR	Reduced Enrichment for Research and Test Reactors
SAR	Safety Analysis Report
SFT	South Flux Trap
SORC	Safety Oversight Review Committee
TEV	Technical Evaluation
TFR	Technical and Functional Requirements
UT	Ultrasonic Testing
U-Mo	Uranium-Molybdenum Alloy

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1. INTRODUCTION

The original AFIP-6 irradiation, which started in early 2010, did not complete irradiation as planned due to fission gas release during irradiation [1]. Consequently, a second irradiation of identical plates was necessary to meet program objectives. This irradiation was named AFIP-6 MKII and was purposed to evaluate high-power, large-scale performance of monolithic uranium-molybdenum (U-Mo) fuels [2] using the base monolithic fuel design.

The experiment was designed to allow the fuel plates to be tested in the Center Flux Trap (CFT) of the Advanced Test Reactor (ATR) using a modified AFIP-6 irradiation hardware design. This modified irradiation hardware design was identical to the original AFIP-6 irradiation hardware design, except that it allowed additional cooling of the fuel plates by resizing of the plate holder orifice [2]. Unlike the original AFIP-6 experiment, AFIP-6 MKII was orientated with the fuel plates running east-west as seen in Figure 1 in order to reduce the power gradient across the plate due to planned power splits between the north and south lobes. [3]

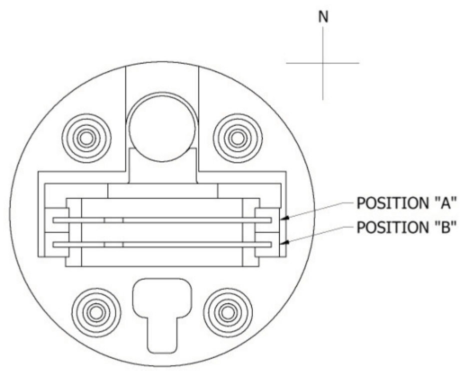


Figure 1: AFIP-6 MKII Orientation

The irradiation assembly was planned for 2 fuel plates, both fabricated by the Hot Isostatic Press (HIP) process. A sketch of the fuel plate's critical dimensions is seen in Figure 2. [2]

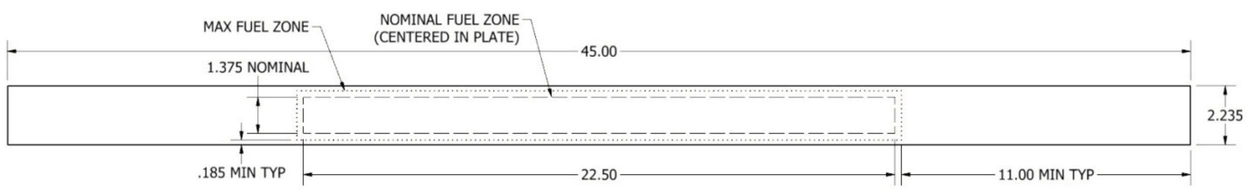


Figure 2: AFIP-6 MKII Fuel Plate Sketch

The fuel phase in AFIP-6 MKII fuel plates was uranium 10wt% molybdenum (U-10Mo) alloy at 40% U-235 enrichment. The enrichment was selected to achieve surface heat flux of approximately 450-500 W/cm^2. A zirconium interlayer was applied to the fuel material. Nominal U-Mo thickness was 0.013" with a 0.001" zirconium interlayer on each side and nominal fuel plate thickness of 0.050" as seen in Figure 3. [2]

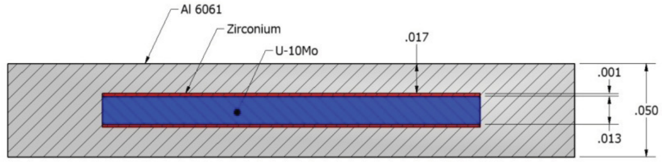


Figure 3: Nominal Fuel Plate Cross Section

During cycle 151A the 1st fuel plate (6II-1) and a dummy plate were irradiated in the “A” and “B” positions of the experiment hardware, respectively (see Figure 1). The partially irradiated 1st fuel plate (6II-1) and an unirradiated 2nd fuel plate (6II-2) were planned for irradiation in the “A” and “B” positions of the experiment hardware, respectively, during cycle 151B [2]. The original AFIP-6 configuration irradiated both fuel plate frame assemblies concurrently during the first ATR cycle. This change in experiment configuration (i.e. one fueled plate for the 1st cycle) was used to offset the cycle 151A power reduction in the ATR North-East lobe in order to achieve the desired peak heat flux. [4]

1.1 Experiment Design

The original AFIP design was developed for use in the AFIP-1 through -3 campaigns. Irradiation of these campaigns occurred from February of 2008 to April of 2009 [5][6]. This design consisted of two fuel plates (each ~22” long), which were butted end-to-end and welded to aluminum rails on both sides. A handle and bottom plate were also welded to the rails and were spaced 0.50” from the top and bottom fuel plates, respectively, as seen in Figure 4. The fuel plate frame assembly produced a geometry which could be handled in the ATR spent fuel storage canal and ultrasonically (UT) characterized in the in-canal flat plate scanner. During irradiation, two such fuel plate frame assemblies were housed in the “holder” assembly and were constrained within the inner cavity with a ram and ramrod as seen in Figure 5. Four holes existed for flux monitor wires and a removable “retriever” assembly latched to the top of the holder assembly to give an interface for handling the irradiation assembly as seen in Figure 6.

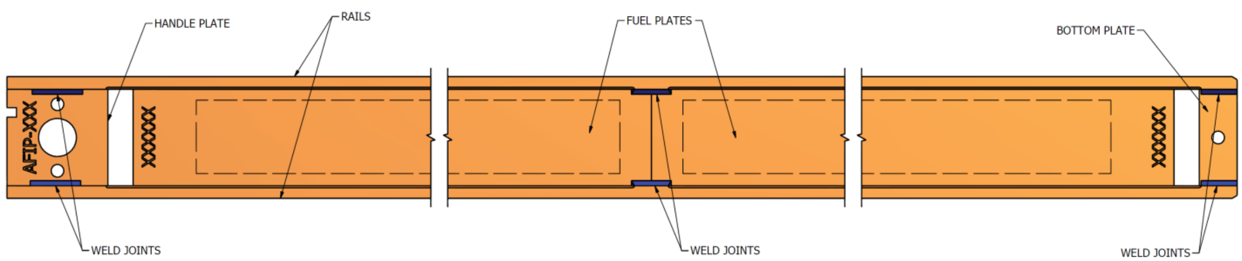


Figure 4: AFIP-1 through -3 Fuel Plate Frame Assembly

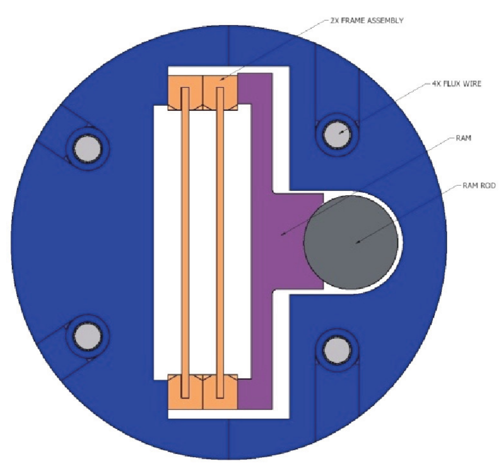


Figure 5: AFIP-1 through -3 Frame Assemblies in Holder Assembly

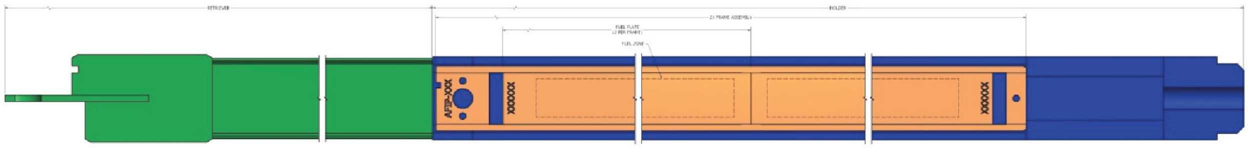


Figure 6: AFIP-1 through -3 Irradiation Assembly

Several small design changes were implemented during these and subsequent campaigns such as a more robust lifting bail on the retriever [7], slightly reduced diameter on the ramrod [8], and shortening of the fuel plates to accommodate six per frame assembly (i.e. AFIP-4) [9]. AFIP-1 through -4 saw irradiation of fuel plates, which were attached to the frame assembly via welding, with a fuel enrichment of 20%. In order to demonstrate the fuel at higher fission rates, the AFIP-6 experiment was designed with a fuel enrichment of 40%. Had the AFIP-6 frame assembly accommodated 2 fuel plates each (4 plates total), the increase in U-235 enrichment would have resulted in frame assemblies which could not be shipped within standard drum limits and its reactivity worth in the ATR CFT could not have been bounded by a non-fuel backup design. Consequently, the AFIP-6 design was changed to accommodate one fuel plate per frame where the fuel length was 22.50", centered within a plate where the total length was 45.00" as seen previously in Figure 2.

The original AFIP-6 design was also changed in order to attach the fuel plates to the rails by swaging. This was necessary in order to demonstrate irradiation of large scale monolithic fuel plates which were constrained by the swaging method used in assembly of ATR driver fuel elements. This design change effectively affixed the fuel plates throughout the entire length of the plate; making the handle and bottom plates unnecessary structural components. However, the handle and bottom plates were included in the design in order to maintain geometric compatibility with existing AFIP infrastructure including irradiation housing, canal tooling, UT in-canal flat plate scanner, and hot-cell fixturing. The AFIP-6 fuel plate assembly was designed for fabrication at Babcock & Wilcox (B&W). Swaging was also used to attach the handle and bottom plates in lieu of welding because the welding of thin plates to the rails posed some risk of "burn-through" and the weld's heat affected zone reduced the structural robustness of the frame assembly in static loading. Swaging, in lieu of welding, was recommended by B&W engineers, viewed as a design improvement, and verified by way of structural analysis [10]. The handle and bottom plate components were specified to be annealed in order to facilitate swaging [9].

The AFIP-7 experiment design represented a large departure from the frame assembly specimen geometry, required substantial redesign of the irradiation hardware (except the retriever assembly), and is discussed elsewhere [11][12]. The failure of a retriever assembly during AFIP-7 irradiation was caused by a fabrication issue and was not related to a design problem [13].

1.2 Experiment Analysis

The AFIP-6 MKII experiment was the first irradiation conducted by the Global Threat Reduction Initiative (GTRI) fuel development team which was initiated, designed, and executed, entirely within the framework of the INL's newly implemented procedure for irradiation experiment life cycle [14]. The overall project execution was set forth in the AFIP-6 MKII Project Execution Plan [15]. Three sets of analyses were performed and documented as inputs to the Experiment Safety Analysis Package (ESAP) regarding neutronic, thermal-hydraulic, and structural considerations [16][17][18]. This ESAP was reviewed and found to be in compliance with the ATR Safety Analysis Report (SAR) requirements by the Safety and Operations Review Committee (SORC). These were performed in compliance with the INL's procedure for calculations and analyses [19], underwent technical checking, and were considered engineering deliverables which were validated against the experiment Technical and Functional

Requirements (TFR) [20] by way of design verification [21]. Design activities were controlled and documented in an Engineering Job package per the INL's procedure for design control [22].

Additionally, a Technical Evaluation (TEV) was performed in order to assess the AFIP-6 MKII irradiation against the experiment objectives and to explicitly evaluate the experiment for failure modes which are not routinely considered [4] such as margin to blister threshold [23] and breakaway oxidation of aluminum cladding [24]. This TEV received independent reviews from members the Nuclear Safety Oversight Committee and was determined to be properly engineered for irradiation in the ATR [25]. All of the aforementioned analyses, documentation, and reviews were completed with comment resolution in a timely manner. Analyses were accomplished in accordance the level of rigor (quality level 2) as identified in applicable quality level determinations.

1.3 Experiment Fabrication

The AFIP-6 MKII experiment hardware (e.g. ramrod, retriever assembly, holder assembly), were fabricated and inspected at INL machine shops by the R&D Manufacturing and Technical Services Organization. The AFIP-6 MKII fuel plates were fabricated as described in the Fabrication Control Plan [26] and were found to be in compliance with the requirements of TFR-662 "Specification for AFIP Fuel Plates and Assemblies for Irradiation in the ATR" [27]. Uranium feedstocks were downblended to 40% enrichment, alloyed with 10 wt% molybdenum, cast, and machined into rectangular coupons at the Y-12 national security complex. These were rolled to final thickness, laminated with a thin zirconium interlayers, and sheared to final foil geometry at the INL Material and Fuel Complex. These foils were then shipped to B&W where they were bonded between sheets of aluminum 6061 via the HIP process, machined to final dimensions, and received final inspection.

Both AFIP-6 MKII fuel plates which were selected for irradiation were found to be in compliance with all specification requirements including bonding quality and minimum cladding thickness criteria (inspected via UT) as well as fuel location and homogeneity criteria (inspected via radiography). These were assembled into fuel plate frame assemblies by swaging and received boehmite prefilm prior to shipment to the ATR complex.

The process for swaging the plates into the frame was developed and validated at B&W. Three inch swage specimens were swaged intermittently so that they were produced before, in-between, and after the swaging of the actual AFIP-6 MKII frame assemblies. These swage specimens were constructed from representative materials and were positioned at the handle end, middle, and bottom plate end of the swage fixturing "bed". These swage specimens were sequenced and positioned strategically in order to best envelope the chronologic and fixture location swaging parameters. These specimens were tensile tested and found to be greater than the minimum pullout strength criteria of 150 lbs per linear inch; giving a high level of confidence that the swage joints on the actual AFIP-6 MKII frame assemblies were at least as strong as specified.

Two non-conformances were identified during the fabrication campaign. First, the rail material used for the fuel plate frame assemblies was purchased at a lower than specified quality level. This material was found to be in conformance with material specification via independent chemical analysis and documented in a non-conformance report [28]. Second, welds on the holder assembly were found to violate drawing porosity requirements. This non-conformance was found acceptable via structural analysis and documented in a non-conformance report [29].

2. IN-CANAL FINDINGS FOLLOWING CYCLE 151A

The first fuel plate (6II-1) of the AFIP-6 MKII experiment was inserted into the ATR CFT and irradiated for 56.1 effective full power days during cycle 151A. The ATR came to full power on December 14th, 2011 and completed cycle 151A with shutdown on February 11th, 2012. The average center lobe power during this cycle was 22.0 MW. Preliminary as-run calculations show that this fuel plate achieved average and peak fission density of 3.96 E21 and 4.14 E21 fission/cc, respectively [30].

During the outage prior to ATR cycle 151B, the AFIP-6 MKII irradiation assembly was disassembled at the working tray in the ATR canal area on February 20th, 2012. This work was conducted in order to extract the 6II-1 fuel plate frame assembly from holder assembly, UT characterize the 6II-1 fuel plate frame assembly via the in-canal UT flat plate scanner, and load the once-irradiated 6II-1 and unirradiated 6II-2 fuel plate frame assemblies into the irradiation assembly for insertion in cycle 151B. These evolutions were captured with an underwater canal camera.

The retriever, ramrod, ram, and frame assembly 6II-1 were removed without event. No unexpected phenomena were observed in the fuel region of the 6II-1 fuel plate frame assembly. The fuel region exhibited oxidation whose coloration was consistent throughout and showed no evidence of spallation or blistering as seen on the original AFIP-6 fuel plates. This is seen in Figure 7. (Note that the horizontal banding seen in some figures is a product of the image rendering process and is not present on the fuel plate). The integrity of the fuel region was further verified on March 13th, 2012 by ultrasonic characterization with the in-canal flat plate scanner as seen in Figure 8.

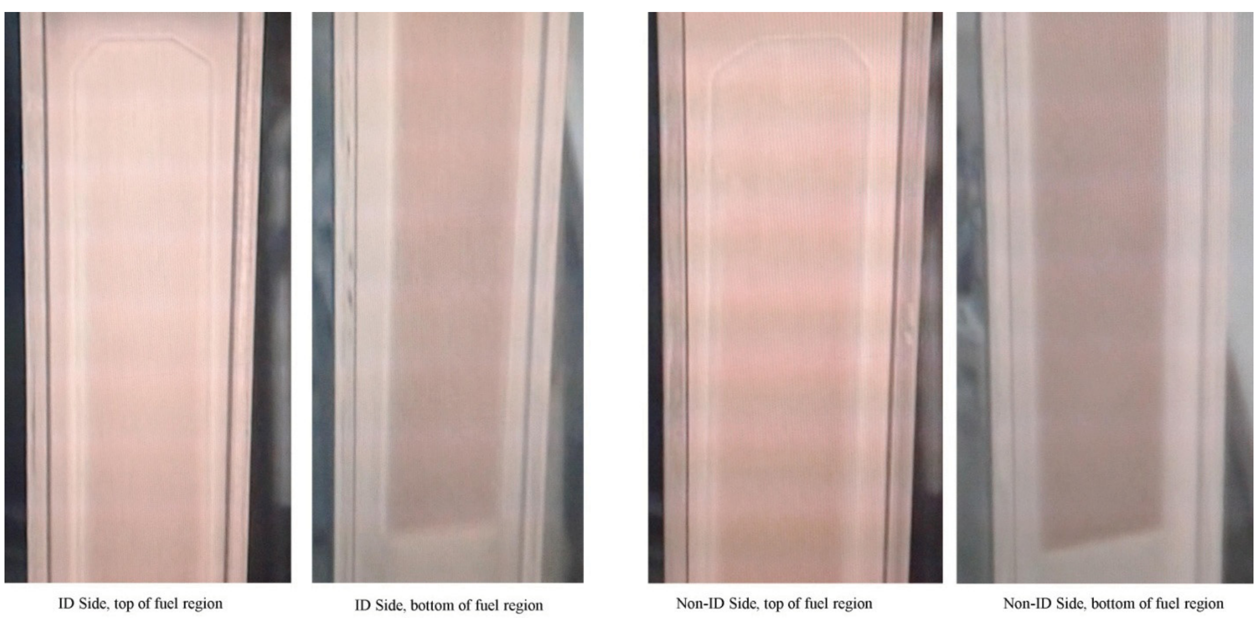


Figure 7: 6II-1 Fuel Regions Post 151A

Plate 6II-1 top of fuel region

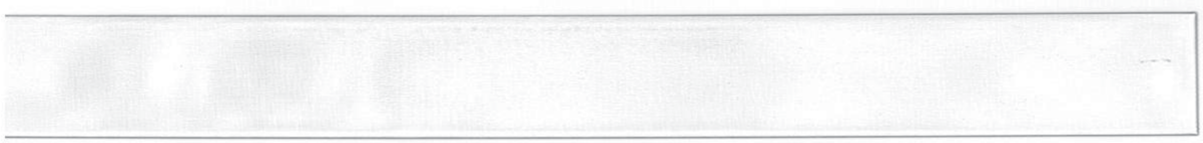


Plate 6II-1 bottom of fuel region

Figure 8: Plate 6II-1 UT Debond Image Following Irradiation in 151A

Immediately following removal from the irradiation assembly the bottom plate component of the 6II-1 frame assembly was observed to be present in its intended axial location within the frame assembly. However, it was also observed that the bottom plate exhibited some slight deformation (bowing) and was precariously held between the flats of the frame rails as seen in Figure 9. Note that the bottom plate has shifted out of the plane of the rail-grooves/fuel-plate. The underwater canal footage demonstrated that the bottom plate was visible in this state until the camera panned up so that the bottom plate was out of the field of view. After the whole frame assembly swung slightly to the side and tapped the retriever assembly (which was lying on the working tray) the camera panned down and the bottom plate was no longer between the rails. The bottom plate was found lying on the working tray. Assumedly this small impact dislodged the item. The manner of handling did not appear to be rough or negligent. The fuel plate frame was placed in approved storage and plans to UT scan the plate were suspended. The state of the 6II-1 frame following this event can be seen in Figure 10.

The separated bottom plate was also further examined from multiple camera angles. This gave visual evidence of fracture surfaces on both short edges of the bottom plate. One edge exhibited a small "V-shaped" recess near the center of the short edge. The dummy frame assembly was positioned near the separated bottom plate to give a reference for dimensional scale. This showed that the width of the remaining bottom plate was equivalent to the distance between the inner rail edges of the frame assembly. This suggested that the bottom plate had fractured on both sides near the swage joints. See Figure 11.

Non-ID Side, bottom of frame (canal footage)

Non-ID Side, bottom of frame (CAD rendering)

Figure 9: Frame 6II-1 Immediately Following Removal from Irradiation Assembly

Figure 10: Frame 6II-1 Immediately Following Bottom Plate Separation

Figure 11: Fractured Edge of Failed Bottom Plate

The fuel plate frame assembly 6II-1 was further examined on February 28th, 2012. This showed that the remnants of the edges of the separated bottom plate were captive within the groove of the rails; suggesting that the swage joints are intact. The inverse of the fractured V-shape seen in Figure 11 was also observed on one of the bottom plate edge remnants. These can be seen in Figure 12 and Figure 13.

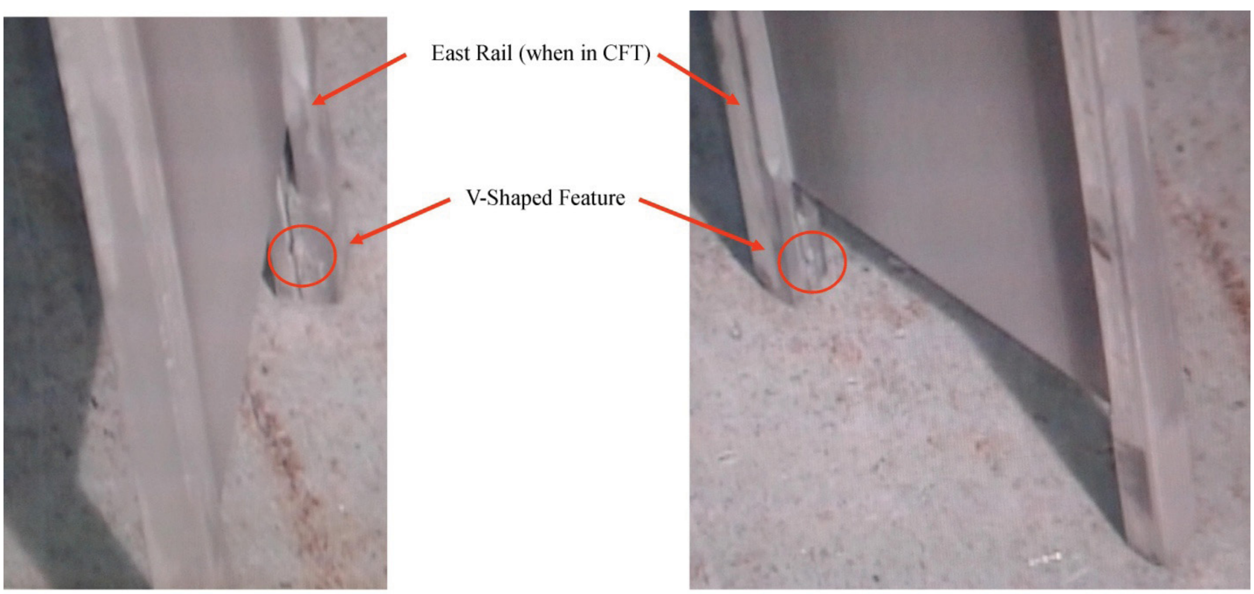


Figure 12: Bottom Plate Edge Remnants in “East” Rail Groove

ID Side Visible

Non-ID Side Visible

Figure 13: Bottom Plate Edge Remnants in “West” Rail Groove

The dummy plate frame assembly was irradiated alongside fuel plate frame assembly 6II-1 during cycle 151A. In terms of external geometry, the dummy frame was identical to that of the fuel plate frame 6II-1, except that dummy frame contained two half-length mock fuel plates, and that all plate components (i.e. handle, fuel plates, bottom plate) were attached to the rails by welding. The dummy frame was made to match the design of the original AFIP-1 through -3 design [31] and has been irradiated in previous AFIP irradiation campaigns without event. The dummy plate was visually examined at the canal working tray on February 23, 2012, and found to be entirely intact. No fractures or other evidences of structural degradation were ascertained within the capabilities of the underwater canal camera. The dummy frame assembly can be seen in Figure 14.

Dummy Frame, Handle
Plate Weld Joints

Dummy Frame, Mock Fuel
Plate Weld Joints

Dummy Frame, Bottom
Plate Weld Joints

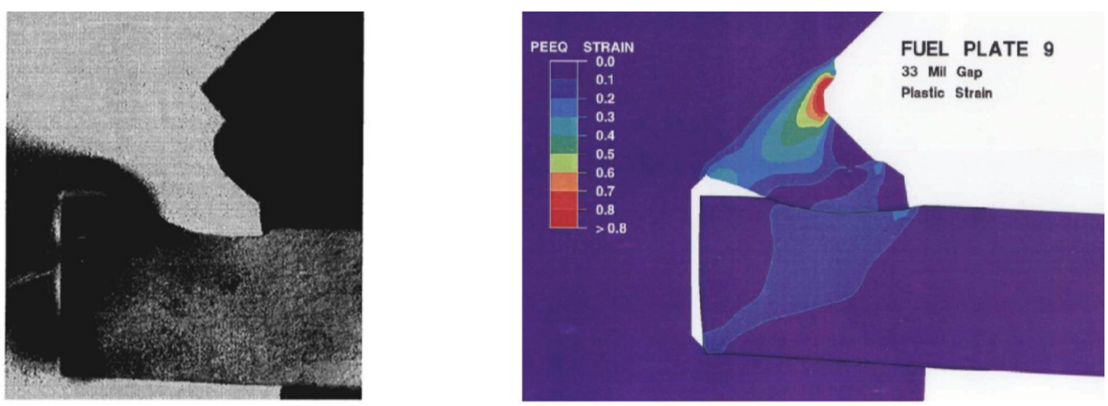
Figure 14: Dummy Frame Assembly

3. ROOT CAUSE ANALYSIS

3.1 Failure Mode

Review of the as-built fabrication documentation [32] gave no reason to believe that the materials of construction (i.e. rails and bottom plate) were of poor quality, that the swage joints were of inadequate strength, or that the fabrication process had damaged the bottom plate component. While the rails were fabricated from material which was purchased at a lower-than-specified quality level, the material was traceable to vendor certifications, verified by independent laboratory analysis, and dispositioned by way of non-conformance report [28]. Consequently, there was a high level of confidence that the rail material was Al-6061-T6 per ASTM B221 as specified by the frame assembly drawing [33]. It is unlikely that the non-conformances discussed in section 1.3 contributed to this incident.

The bottom plate material was fabricated from end croppings of ATR fuel plates and is traceable to qualified lot material [34]. These same materials were used for the swage tensile test specimens. Furthermore, in-canal observations show that the bottom plate remnants remained captive within the rail grooves. This suggested that the swage joints were still intact and that the bottom plate fractured instead. The swage process, unlike the welding process used for assembly of the dummy frame, imparted strain, cold work, and stress concentrations in the plate components. Local deformation on the surface of the plate components is essential in establishing an acceptable swage joint as seen in Figure 15 and Figure 16.



B&W Photograph of Typical Swage Joint | Swage Joint FEA Model

Figure 15: Images of ATR Swage Joints [35]

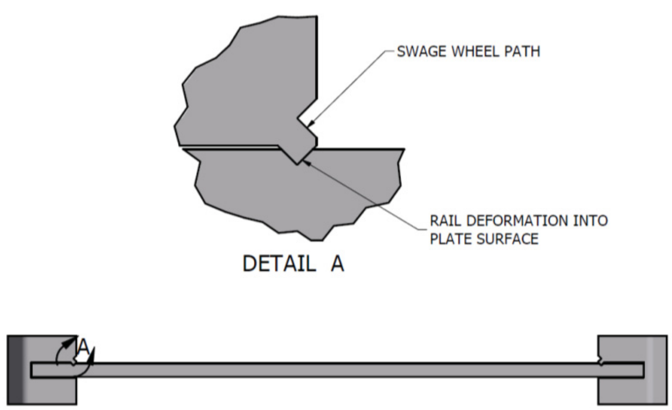


Figure 16: Schematic Rendering of AFIP-6 MKII Swage Joints

The fractures which occurred on both of the short sides of the bottom plate, along with the remnants which remained captive under the rail, demonstrated that the bottom plate fractured at or very near to the swage joint. This was likely due to the stress concentrator and local deformation on the plate surface caused by swaging. While other loading modes were hypothesized, (e.g. differential channel to channel pressures and/or thermal expansion gradients), the most likely failure mode was determined to have been flow induced vibrations and resonance with the bottom plate; giving way to amplification and fracture [36]. Note that an increase in flow velocity was the principal design change for AFIP-6 MKII. The AFIP-6 MKII fuel plate channel flow rate was calculated to be 18.2 m/s and represented a significant increase from 10.4 m/s for the original AFIP-6 [4].

The design structural analysis [18] included an evaluation of the fuel plate for parallel flow-induced vibrations. The results showed that the maximum amplitude of vibration under parallel flow conditions was acceptably small. These calculations for parallel flow were judged applicable (and conservative) to the top handle and bottom plate. This design analysis did not address resonance of components due to vortex shedding. The design structural analysis has been supplemented [36] with stress calculations which showed that the resulting maximum stresses in the fuel plate due to parallel flow-induced vibrations were below the fatigue endurance limit for the material. Additionally, critical flow velocity calculations were included in the supplemental analysis which showed that the ATR flow conditions were well below the critical velocity for fuel plate collapse [38]. Thus, parallel flow-induced vibrations were judged to be acceptable.

The supplemental calculations [36] also considered loadings from vortex shedding. These showed that as the flow passes over the handle, vortices formed at its leading and trailing edges. Additional vortices formed at the leading and trailing edges of the fuel plate and the bottom plate. Holes in the handle and bottom plate further perturbed the flow. These vortices applied cyclically-varying loads to the handle, fuel plate, and bottom plate.

In the supplemental analysis [36], a calculation of the bottom plate natural frequencies showed that mode no. 2 was a close match to the frequencies of vortex shedding for normal conditions 2 pump (within 10%) and 3 pump (within 3%) flows. Also, mode no. 2 was shown to be a twisting motion (from top-to-bottom, see Figure 17) that would increase the incident angle of the bottom plate to the flow. The frequency matches of the bottom plate and coolant vortex shedding, with the compounding twisting mode no. 2, were shown to make adverse resonance conditions likely. Therefore, damaging vibrations of the bottom plate were predicted to occur under normal operations. Damage was predicted to be due to high stresses with a resulting reduced fatigue life. Failure under this scenario was expected to have progressed as follows: 1) further work hardening along the clamped edges; 2) fatigue cracking at the front and rear of the clamped edges; 3) progression aft and forward (respectively) until the material holding the piece in place was limited to a small band of material at the axis of rotation; 4) failure in shear. The V-shaped features of Figure 11 and Figure 12 are consistent with this progression. The swage joint likely compounded the issue by creating a stress concentration on the bottom plate clamped edges where the stresses would be largest under mode no. 2 resonant vibration.

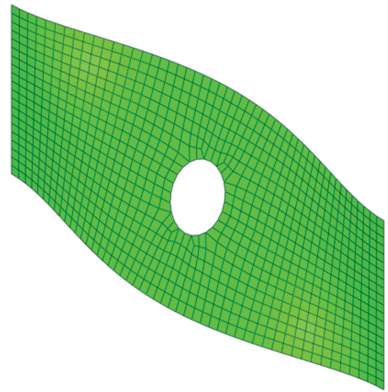


Figure 17: Bottom Plate Natural Frequency Mode No. 2 (at 3234 Hz.)

During the forensic investigation, it was noted that the dummy plate frame assembly remained intact. This was likely due to the fact that the bottom plate of the dummy plate frame assembly was welded to the rail sides. In this type of loading, the weld joint was likely to be more robust as it would avoid stress concentrations due to swaging, stiffen the bottom plate by shortening its length between the welds (resulting in somewhat higher plate natural frequencies), and contribute to system damping. These differences in the bottom plate design in the dummy plate frame assembly likely prolonged its fatigue life compared to that of the swaged fuel plate frame assembly. While the bottom plates of the original AFIP-6 fuel plate frame assemblies were also assembled by swaging, they did not fracture or separate from the rails likely because they were cooled by slower velocity coolant (lower vortex shedding frequencies) and experienced less residence time in this environment (39.2 full power days [37]).

The supplemental analysis [36] also included an investigation of the resonant propensity of the other components of the fuel plate frame assembly including the handle and fuel plate. A calculation of the handle's natural frequencies showed that mode no. 7 was a close match to the frequency of vortex shedding for normal operations – 2 pump flow (within 3%). However, mode no. 7 was an axially twisting pattern of the handle that would not synchronize as well with coherent vortex shedding as more fundamental vibrational modes. Therefore, the handle was not expected to experience damage as soon as the bottom plate, but could eventually be damaged under this flow condition. A detailed analytical evaluation of the handle fatigue life under the specified flow conditions was not performed because handle reconfiguration was recommended.

The fuel plate was also considered in the supplemental analysis [36]. A calculation of the fuel plate natural frequencies showed that mode numbers 22 through 29, which were high order modes of vibration, were close matches to the frequencies of vortex shedding. These fuel plate high order frequency modes would be associated with lower amplitudes of vibration, lower stresses, with non-uniform distributions. Therefore, the fuel plate was not expected to experience damage as soon as the bottom plate, but could eventually be damaged under these flow conditions. No calculations were performed to estimate the number of cycles until onset of damage for the fuel plate in the current configuration as reconfiguration was recommended to address the handle and bottom plate issues. However, as mentioned previously, the critical flow velocity for the current geometry was calculated and showed that the experiment flow velocities were adequately below the critical flow velocity.

3.2 Engineering Process

The technical and functional requirements for the AFP-6 MKII experiment stated "Design analysis shall present evidence that any flow induced vibrations will not mechanically wear or damage the irradiation assembly or supporting structures in a manner that would adversely affect their reliability or the safe operation of the reactor. [20]" This requirement was explicitly identified as an input to the AFIP-6 MKII structural evaluation, flow induced vibration loading modes were analyzed for the entire frame assembly structure, and were found to be sufficiently small [18]. These were in analyzed in terms of parallel flow induced vibrations. The specific phenomenon of shedding vortices and their impact on smaller components, such as the bottom plate, were not identified in this analysis. This was not intentionally ignored or disregarding. Rather, it was not identified as a failure mode because it was an unfamiliar phenomenon which was difficult to recognize.

It is worth noting that this same group of analysts and calculation tools successfully identified a flow induced resonant mode in the preceding AFIP-7 design. This resulted in a minor design change which successfully mitigated the phenomenon [12]. The AFIP-6 MKII structural analysis was considered an engineering deliverable and was validated against the experiment technical and functional requirements via design review. The engineering process for this experiment is discussed in greater detail in section 1.2 of this document. The root cause of this incident does not stand out as a failure to execute the engineering or experiment life cycle processes correctly. However, some proposals for making the existing process more robust are discussed in section 4 of this document.

4. RECOMMENDATIONS AND PATH FORWARD

4.1 Further Root Cause Evaluation

The root cause of this incident was an unexpected phenomena and merits further investigation in order to better understand it and preclude future occurrences. Consequently, it is recommended that the separated bottom plate be retrieved from the ATR canal and be shipped to the Hot Fuel Examination Facility (HFEF) for further evaluation of fracture surfaces (e.g. more resolved optical evaluation). This should be accomplished in concert with one of the upcoming RERTR post irradiation shipments.

Furthermore, flow testing of mock-up assemblies is recommended using the Hydro-Mechanical Fuel Testing Facility and/or Flow Visualization Laboratory at Oregon State University. This work would enable measurement of the dynamic response of plate to plate natural frequency in fluid medium [39]; further clarifying the phenomena believed to have caused the bottom plate failure. This work would also help develop the testing methodology needed to identify these phenomena in future experiment designs.

4.2 Continuation of Irradiation

Several options which may have enabled irradiation of AFIP-6 MKII as planned during cycle 151A were seriously considered (e.g. removal of the bottom plate from frame assembly 6II-2). However, the decision was eventually made to exclude AFIP-6 MKII from cycle 151B based primarily on analytic evidence that the handle and fuel plates also posed some risk for flow induced failure [36] and non-trivial hardware modifications would be needed to mitigate both the initiators and potential severity of this failure mode. Since all items of the experiment hardware could be accounted for, cycle 151B startup occurred without delay relating to this incident with a non-fueled AFIP backup assembly in the CFT.

Further irradiation of 6II-1 is not recommended due to the unknown structural and dimensional fidelity as a result of flow induced vibration. It is recommended that plate 6II-1 be shipped to HFEF for post irradiation examination in concert with one of the upcoming RERTR post irradiation shipments.

The AFIP-6 MKII campaign was originally planned to irradiate two large-scale fuel plate specimens at intermediate and bounding fission rates applicable to all U.S. High Performance Research Reactors (HPRR). The irradiation conditions are most pertinent to the ATR operating envelope. The ATR conversion team is currently working to produce a point design for low enriched uranium ATR fuel elements, fuel cycle projection, and expected end of life peak fission density. While these designs may include burnable absorber "complex" designs in the exterior plates, it is likely that the plates achieving these fission rates and densities will contain the non-borated base fuel design in the interior plates of element [40]. Apart from the ATR, the High Flux Isotope Reactor (HFIR) is the only other HPRR which requires demonstration of this fuel at high fission rates. HFIR will require separate development of a "complex" fuel system and will not require high fission densities. HPRR's which achieve the highest fission densities are projected to do so at considerably slower fission rates (e.g. National Bureau of Standards Reactor).

Plate 6II-1 achieved an estimated peak fission density of 4.14E21 fissions/cc [30]. A comprehensive evaluation of current program requirements for this irradiation will be performed to determine whether AFIP-6 MKII will provide the data necessary for base fuel qualification. This determination will be made in the framework of a formalized requirements based engineering process. If this determination finds that the AFIP-6 MKII irradiation campaign should continue, several options for irradiation have been identified.

The first such option is to irradiate the existing 6II-2 plate frame (currently unirradiated) in the South Flux Trap (SFT) of the ATR for two cycles. The SFT typically operates at lobe powers consistent with that of the CFT and the irradiation condition would likely be very similar to those originally planned for AFIP-6 MKII. Preliminary discussion with key stakeholders show that the SFT may be available for this purpose beginning in July of 2013 during the transition from the SPICE-9 to SPICE-10 irradiation facilities [42]. This may require minor modifications to the frame assembly. Such could likely be accomplished in the ATR "green room" machine shop. The SFT has a different geometry than the CFT and would require some additional redesign work (in addition to those modifications needed to mitigate flow vibration failures). It would also be recommended that some of the handling interfaces of this design, including the retriever and ramrod, be modified to facilitate reconfiguration in the ATR canal Conceptual designs for AFIP-6 MKII irradiation in the SFT can be seen in Figure 18.

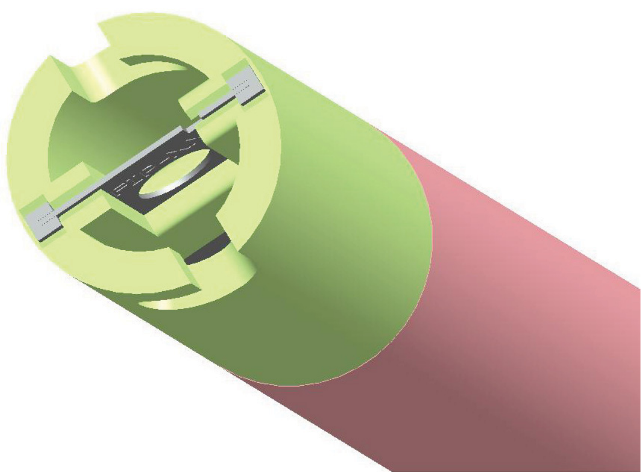


Figure 18: AFIP-6 MKII SFT Concept [41]

The second option for completion of the AFIP-6 MKII technical scope would be to accomplish irradiation of the base fuel design in the Belgium Reactor 2 using the existing E-FUTURE irradiation housing. The E-FUTURE fuel plate specimen geometry is comparable to that of the AFIP series irradiations (30" fuel length). This option would require fabrication of new 20% monolithic fuel plates at B&W. However, much of the infrastructure needed for this campaign has been previously established for the FUTURE-MONO campaign (e.g. planning, contracting, and specifications). This plate design would likely be identical to plate type "A" which has already been specified for the FUTURE-MONO campaign [43].

The CFT is scheduled to have a loop facility (loop 2A) installed immediately following cycle 151A; rendering the CFT unusable for further irradiation of AFIP plates. INL management has affirmed that installation of loop 2A will proceed as scheduled; making the CFT unlikely to be available in a timeframe which supports completion of AFIP-6 MKII.

4.3 Design Process Improvements

The irradiation of AFIP-6 MKII revealed a failure mode which was not considered in the otherwise comprehensive suite of design and safety analyses. The original AFIP-6 incident resulted in implementation of new analytic tools in order to evaluate the potential for cladding oxidation/spallation type failures [44]. As a result of the AFIP-6 MKII incident, the GTRI fuel development team will ensure that additional vibrational modes are evaluated relative to structural natural frequencies as part of the standard structural analysis. This may also be augmented with experimental verification accomplished by instrumented flow testing or similar experimentation.

It is relatively straightforward to mandate mitigating actions for a specific failure mode once its root cause has been identified and the appropriate evaluation tools have been established. However, the more difficult challenge lies in establishing a process where the expertise, knowledge base, and sequencing facilitate anticipation of unfamiliar failure modes. The risk of the unknown can never be completely eliminated from any research project, but reasonable processes can be established which increase the likelihood of anticipating an atypical failure mode or design issue. While the INL's process for executing irradiation experiments is based on sound principles, opportunities for improvement can always be collected from these types of experiences. The AFIP-6 MKII incident has revealed that some process improvements including:

- Establishing a committee of analysis and design experts to conduct a review focused on unusual failure modes
- Establishing a succinct volume of design failures, best practices, and successful remedies relating to ATR experiments
- Mandating that all GTRI experiment designs be reviewed by the appropriate members of the above mentioned committee at an intermittent design review (e.g. 60% design review) [45]

The objective of above mentioned review will not be to approve analysis that has been completed, but to identify potential failure modes. The review committee will be chartered to ensure that the objectives for each experiment review are consistent and are being met. All reviews will be documented as part of the experiment design review and all issues or questions will be resolved prior to completion of the design.

Conceptually, this process improvement is similar to the established approach where the SORC evaluates the ESAP against the ATR SAR requirements concurrent to final design completion; except that here the committee of analysis and design experts will evaluate the experiment design, rather than its safety bases, in the context of their own expertise and the above mentioned database (rather than the ATR SAR), at an intermittent design review (rather than a final design review) in order to facilitate an environment where that facilitates imagining of unfamiliar failure modes. To further facilitate this process enhancement, the GTRI fuel development team will continue to develop and implement the framework of a more formalized requirements-based engineering process. This will ensure that mature conceptual designs, with appropriate documentation, are provided in a timely manner to facilitate ample review by the committee of analysis and design experts.

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