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ADVANCED TEST REACTOR IN-CANAL ULTRASONIC SCANNER: EXPERIMENT DESIGN AND INITIAL RESULTS ON IRRADIATED PLATES

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ABSTRACT

An irradiation test device has been developed to support testing of prototypic scale plate type fuels in the Advanced Test Reactor. The experiment hardware and operating conditions were optimized to provide the irradiation conditions necessary to conduct performance and qualification tests on research reactor type fuels for the RERTR program. The device was designed to allow disassembly and reassembly in the ATR spent fuel canal so that interim inspections could be performed on the fuel plates. An ultrasonic scanner was developed to perform dimensional and transmission inspections during these interim investigations. Example results from the AFIP-2 experiment are presented.

1 Introduction

Prior to implementation of any new nuclear fuel design, the fuel must be tested under a wide range of irradiation conditions. These tests provide the basis for evaluating fuel performance and ultimately the data necessary for a regulator to license a reactor to operate with the fuel. In most cases, this testing envelope must meaningfully exceed the anticipated operating conditions to establish appropriate margins for safe operation. This envelope encompasses a number of key environmental variables that include the thermal, hydraulic, nuclear, and geometric conditions of the experiment. The Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL) was specifically designed for this purpose and provides the experimenter with the ability to control all of these variables over a wide range. The INL Nuclear Fuels and Materials (NFM) Division (through leadership of the Reduced Enrichment for Research and Test Reactor (RERTR) Fuel Development Program) is utilizing this key asset to develop the nuclear fuels necessary to support the NNSA Global Threat Reduction Initiative (GTR) Convert Program's high enriched uranium (HEU) minimization objectives.

The NFM Division has developed several experiment test trains to enable irradiation testing of nuclear fuel designs in the ATR. The RERTR program is focused on the development of research reactor fuels that operate under conditions that are very similar to the standard ATR coolant environment. Consequently all the RERTR irradiation test devices are immersed directly in the ATR coolant stream. The first experiments (RERTR-1, -2, and -3) were designed to test the behavior of very small fuel samples (dubbed nano- and micro-plates). The size of these samples allowed for testing of a large number of candidate materials and greatly simplified test sample fabrication. The post irradiation examination (PIE) results collected from these screening tests were used to select aluminum clad, uranium-molybdenum (U-Mo) alloys for further development. To further evaluate performance, an irradiation test device was developed to test slightly larger scale plates (mini-plates). This scale allowed the experimenter to account for fabrication variables that might appear at a more representative scale while still accommodating a fairly large number of test specimens at a low cost. The sensitivity of fuel performance to various variables was evaluated by testing multiple samples of each type under different irradiation conditions. After extensive testing at the 'mini-plate' scale a few fuel designs were deemed viable enough to justify testing at prototypic scale. Testing at this scale substantially reduced the number of samples that could be tested while simultaneously increasing the cost of testing for each sample. It was therefore desirable to develop an irradiation test device that maximized the amount of data that could be collected from each experiment.

The AFIP test assembly was specifically designed to serve this purpose by providing a versatile test-bed for plate-type fuel experiments. The hardware allows the experimenter to subject experiments of various scale to a broad range of nuclear and thermal-hydraulic conditions. The experiment is also designed to allow disassembly in the ATR canal between irradiation cycles. As a result the experiment behaviour can be routinely interrogated at various stages of irradiation. A complementary set of examination tools have also been developed to collect this data.

2 AFIP Test Hardware

A basic function of the AFIP test assembly is to enable testing of research reactor fuel designs at a prototypic scale and under prototypic irradiation conditions. The ATR operates a wide range of irradiation test positions capable of supporting all types of nuclear fuels and materials testing, however, only a few positions are appropriate for the type of testing required for this program (large openings with high neutron flux). The ATR center flux trap (CFT) offers a 3” diameter and 48” long cylindrical cavity with a peak (unperturbed) thermal neutron flux of approximately 4.4×10^{14} $n/cm^2/sec$ and was selected to house the AFIP experiment.

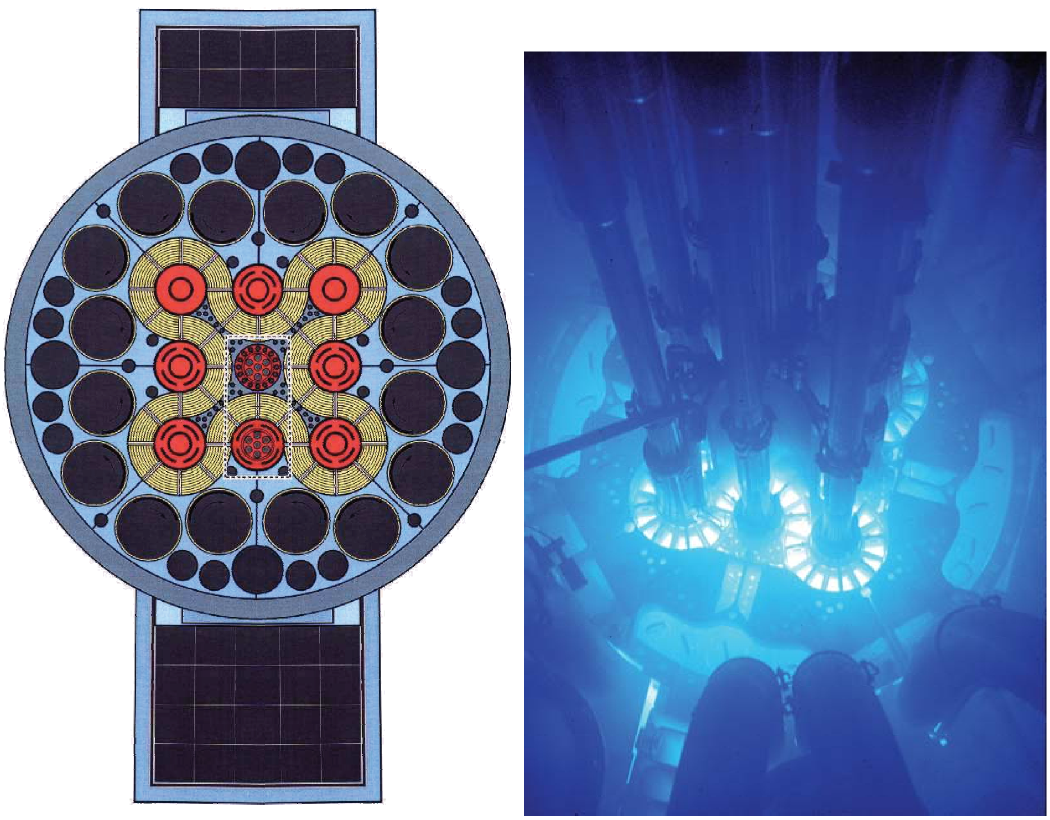

Figure 1. ATR cross section image

An insert was necessary to convert the circular opening into a square channel large enough to accommodate a fuel plate at least 2” wide. The hardware also provides the structure necessary to control the experiment configuration during testing (i.e prevent movement, vibration, etc.) and handling (pre and post irradiation). The hardware must completely constrain the fuel plates during irradiation (without removable screws, bolts, pins, etc.) while still allowing operators to disassemble the experiment (which is submerged under 20’ of water). A schematic of the experiment cross-section showing the key components of the hardware is provided in Figure 2. Photographs of the hardware components are shown in Figure 3. The experiment can accommodate two fuel plate assemblies with a plate width of 2.25”. The plate assemblies can accommodate single plates up to 48” long or several plates adding up to that total length. The plate assemblies (Figure 4) are held together by a thin rail piece on both sides that extends the full length of the plate assembly. The rail also assures that the coolant channel gap width is maintained during irradiation. The fuel plate assemblies are held in position by a ‘ram’ that is pinned in place by a tapered ‘ram-rod’. Four flux monitor wires are also included in the experiment to baseline nuclear analysis. The experiment is inserted into the ATR CFT through a long ‘in-pile’ tube that extends above the reactor core. An extension piece is attached to the top of the experiment hardware to allow loading and unloading of the experiment. The extension also pins the experiment components in place during irradiation.

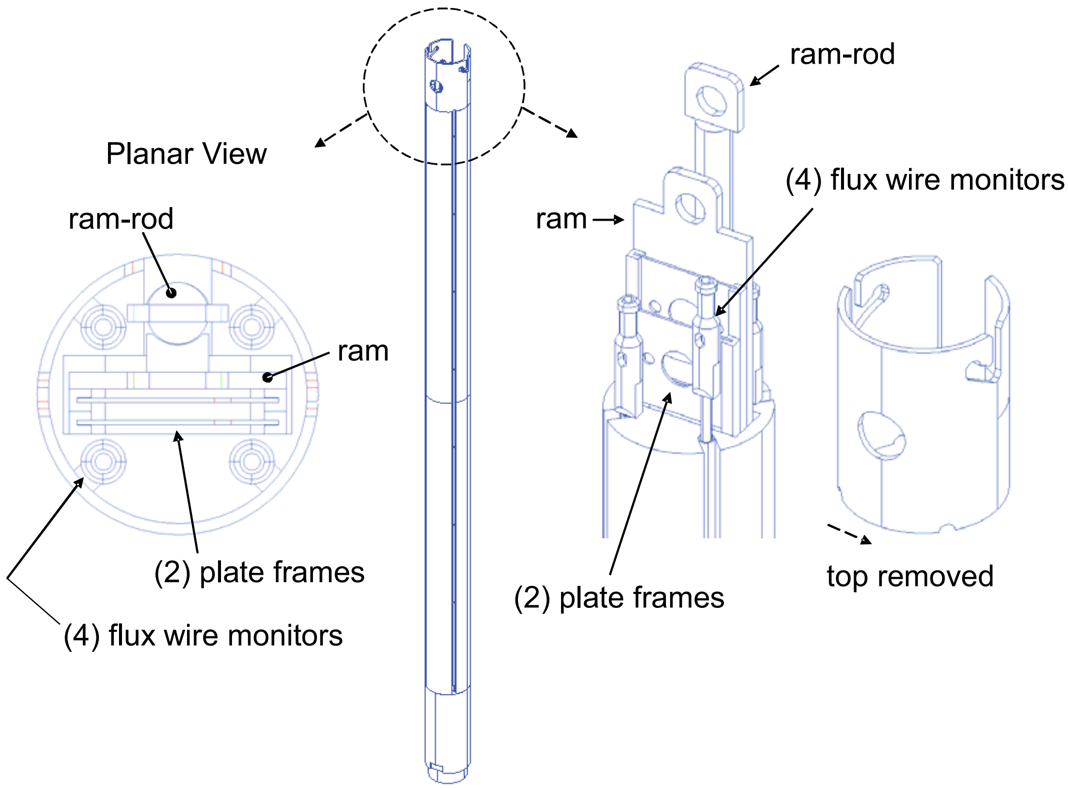

Figure 2. AFIP test assembly

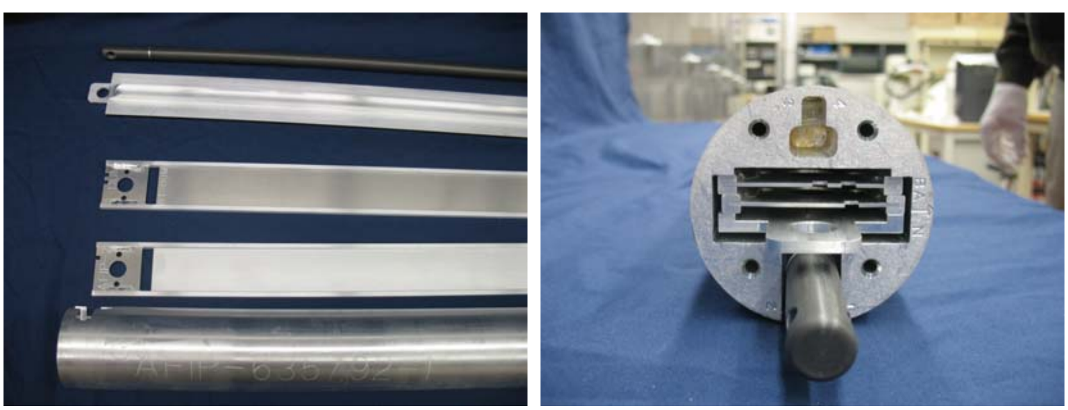

Figure 3. Test hardware photographs

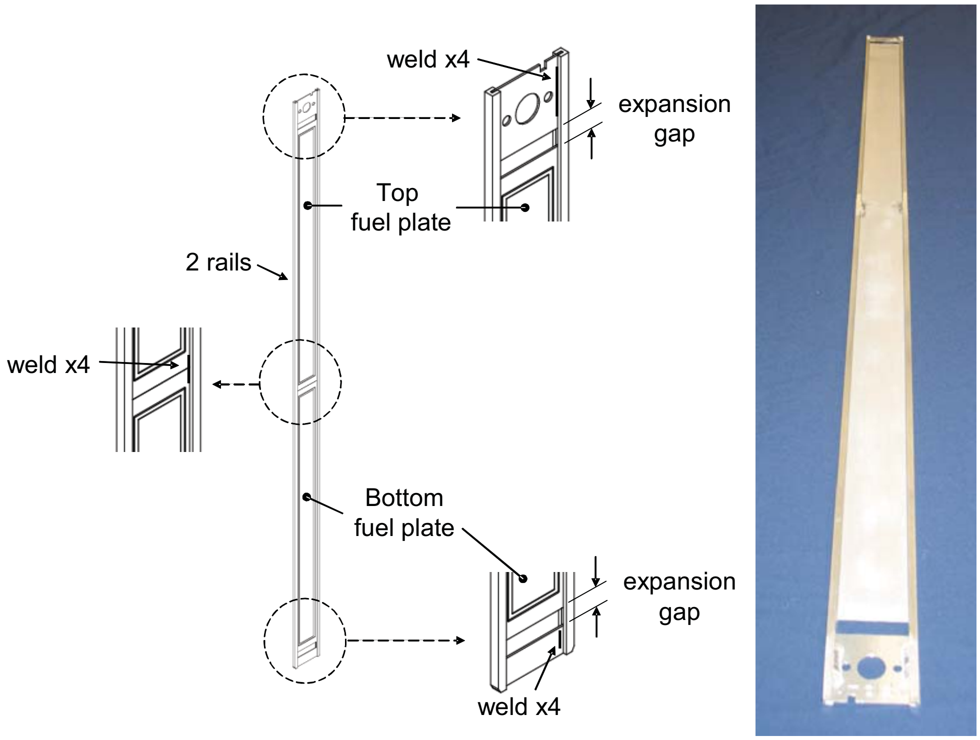

Figure 4. AFIP fuel plate

3 Irradiation Conditions

The experiment operating conditions are constrained by the allowable ATR coolant conditions. For ATR experiments, the flow instability (FIR) and departure from nucleate boiling (DNBR) ratios must be larger than 2.0. Hydraulic tests and high fidelity thermal models were developed to clearly establish the experiment operating envelope. A mock-up of the hardware (including non-fueled dummy plates) was fabricated for the hydraulic tests. The ATR is typically operated with a core pressure drop of 77 psi (2 pump mode). In two pump mode the coolant velocity in the fuel plate channels is roughly 17.4 m/s. The coolant velocity can be increased or decreased, respectively, by operating in the 3 pump mode (100 psi pressure drop) or by inserting an orifice plate at the exit. Thermal analysis was performed to confirm that the experiment could operate at a peak surface heat flux of at least 500 W/cm^2 without exceeding the FIR or DNBR limits. The fuel plate portion of the thermal model is shown in Figure 5.

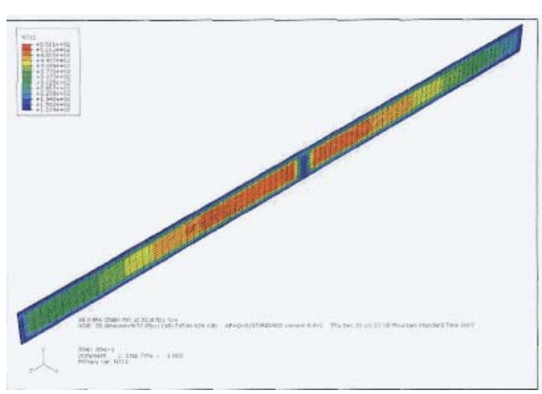

Figure 5. Fuel surface temperature estimates from thermal analysis

4 In-Canal Examination

The most critical performance measure for nuclear fuels is its ability to maintain a stable geometry during irradiation. The conversion of fissile atoms (typically U^{235}) into two fission fragments inevitably leads to growth of the fuel material during irradiation. All nuclear fuels experience this type of behavior on a microscopic scale. The primary challenge of the fuel developer is to identify materials that accommodate fission fragments in a manner that minimizes swelling and that are geometrically stable at the macroscopic scale during irradiation. This swelling is typically manifest by growth in the plate thickness as a function of fission density. It is also possible that local differences in fission density (and thus local swelling) could lead to the formation of significant non-uniformities in stress throughout the plate. These stresses could result in overall plate distortion or even delamination of the interface between the fuel and cladding.

Macroscopic shifts in fuel geometry are routinely evaluated after irradiation. However, the value of an individual experiment can be substantially enhanced through periodic non-destructive examination (NDE) that allows this data to be collected several times during the experiment. This effectively allows the experimenter to transform a single experiment into the equivalent of several experiments. This translates into massive time and money savings for large experiments.

Ultrasonic (UT) scanning has long been used to inspect fresh fuel plates prior to irradiation and, thus, techniques to determine both the cladding thickness and level of contact (bonding) between fuel and clad layers have been well established. It is also possible to use UT technology to map the surface profile of the plates. Since the UT technique requires that the fuel plates be submersed in water in the first place, implementation of the technique for use on irradiated fuel plates in the ATR spent fuel canal is ideal for interim examination. A UT test stand that can be operated remotely with radiation hardened detectors was developed at INL for this purpose (Figure 6).

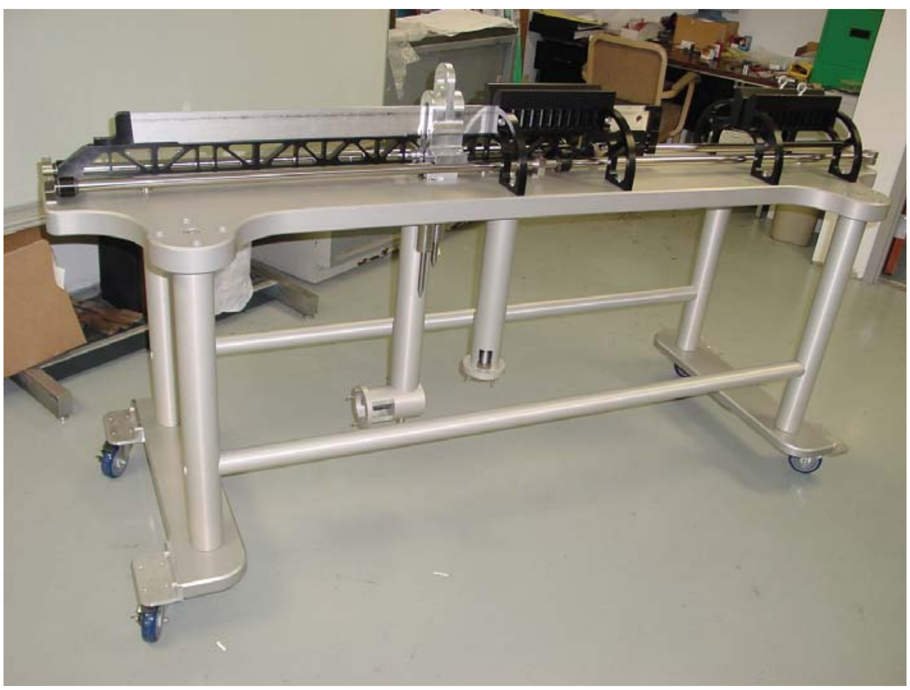

Figure 6. ATR in-canal UT scanner (prior to installation).

The in-canal UT scanner was first demonstrated as an integral part of the AFIP-2 experiment on full-size monolithic fuel plates. Although significant work had been successfully performed at the mini-plates scale, the experiment was the first opportunity to evaluate the performance of prototypic scale monolithic U-Mo fuel plates. The examinations yielded unprecedented dimensional resolution for irradiated fuel. Examinations were conducted at four points (prior to irradiation, after 35, 77, and 133 days of irradiation). The results clearly show the relationship between swelling and fission density as the plate thickness mirrors the plate power profile (as shown in Figure 7). The measurements (Figure 8) showed that the plate contours remain relatively unchanged during the irradiation (i.e. plate buckling or warping does not occur). Transmission scans were also completed to reveal the formation of any delaminations (Figure 9).. However, the scans did identify small regions where void densities were large enough to diminish sound transmission in one of the fuel designs. These indications will be an area of focus during destructive examination in the hot cell.

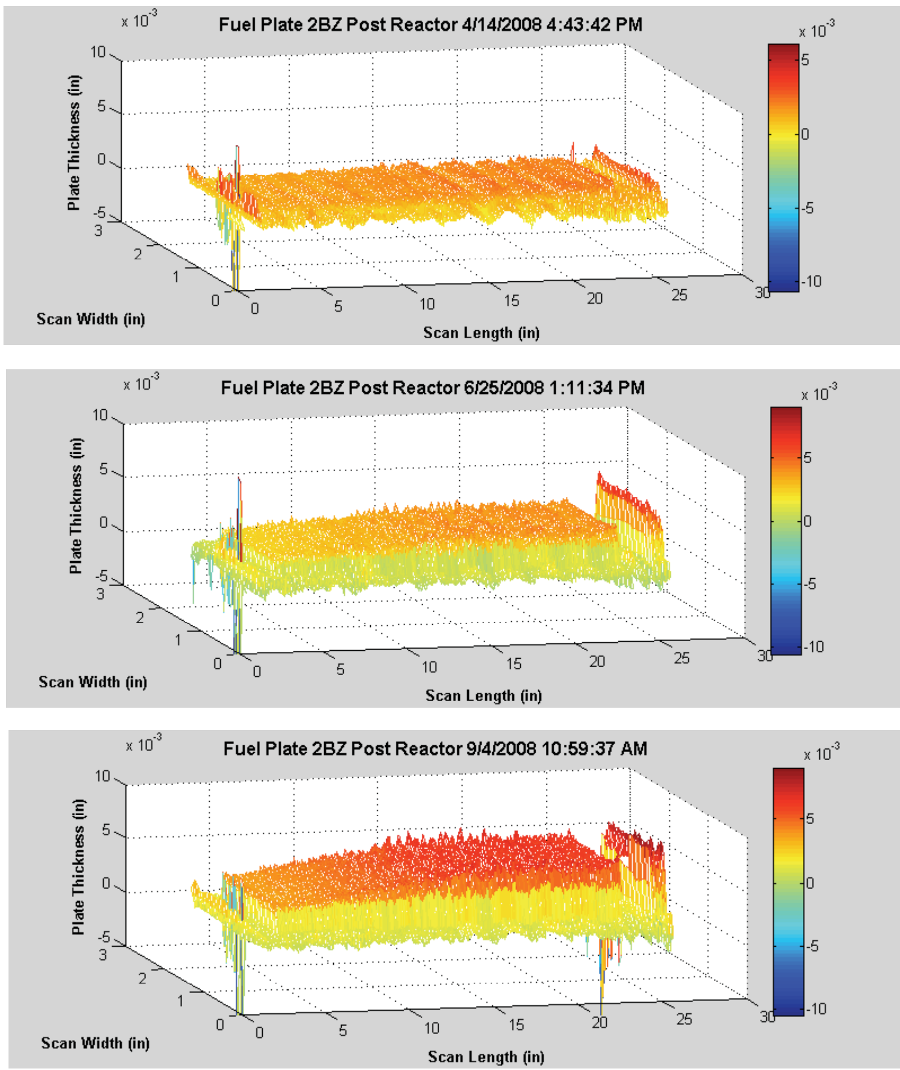

Figure 7. Thickness change of one AFIP-2 plate after each irradiation cycle. The right edge of the plate was located at the reactor core centerline and was therefore at the highest power/fission density. This location is where the maximum swelling condition occurs. (The highest peak on the far right is from the upper plate.)

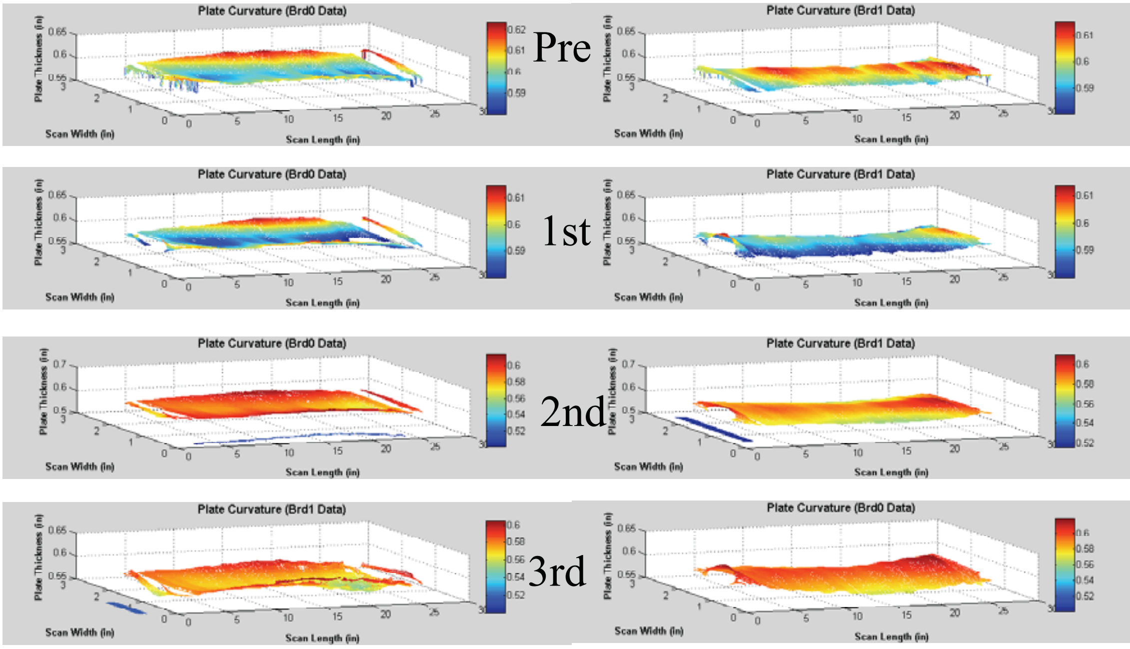

Figure 8. Surface profiles for one AFIP-2 plate after each irradiation cycle. The images show that the general shape of the plates remained relatively unchanged during irradiation.

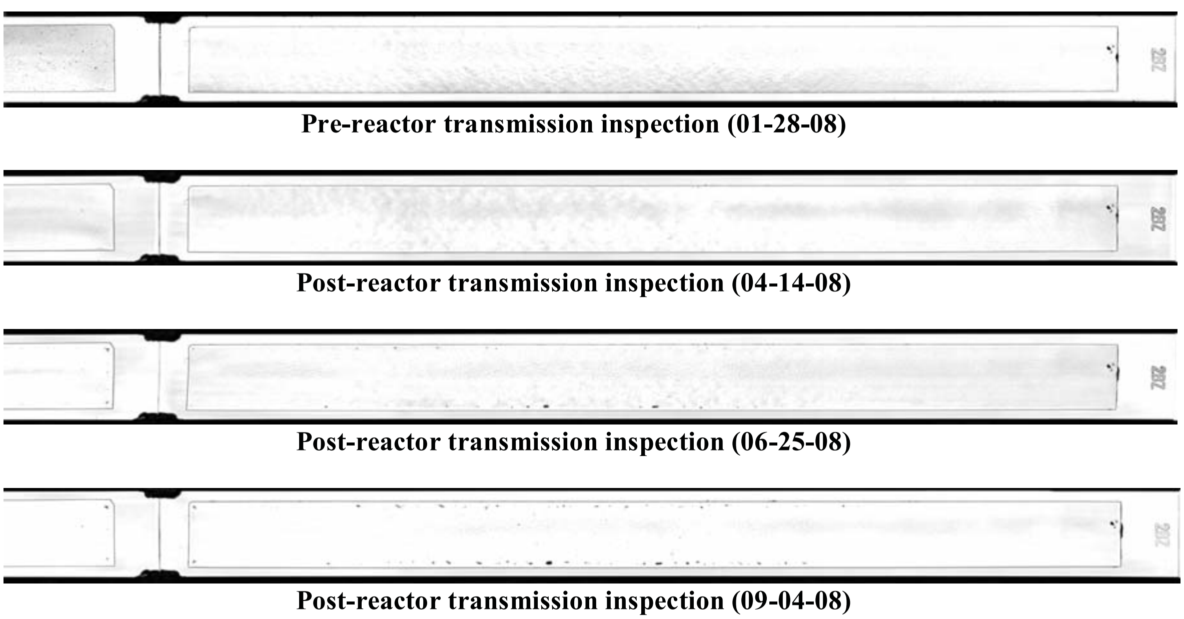

Figure 9. UT transmission images of one AFIP-2 plate taken from each irradiation cycle. The images show the formation of several small indications in the final cycle.

5 Conclusions

The AFIP experiment hardware was designed to enable detailed testing of prototypic scale research reactor fuels designs. The flexible design of the experiment hardware allows the experimenter to configure the test to achieve a wide range of desired irradiation conditions (nuclear, thermal-hydraulic, and geometric). The test apparatus also enables collection of a substantial amount of performance data previously unavailable to the experimenter, substantially reducing the cost and length of time required to conduct a fuels development program. Ultimately, this experiment design will be the workhorse capability that enables qualification of new research reactor fuel designs.

Acknowledgements

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