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J. M. Wight
G. A. Moore
S. C. Taylor
N. E. Woolstenhulme
S. T. McCormick

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TESTING AND ACCEPTANCE OF FUEL PLATES FOR RERTR FUEL DEVELOPMENT EXPERIMENTS

J.M. Wight, G.A. Moore, S.C. Taylor, N.E. Woolstenhulme, and S.T. McCormick
Fuel Fabrication
Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID – USA

ABSTRACT

This paper discusses how candidate fuel plates for RERTR Fuel Development experiments are examined and tested for acceptance prior to reactor insertion. These tests include destructive and nondestructive examinations (DE and NDE). The DE includes blister annealing for dispersion fuel plates, bend testing of adjacent cladding, and microscopic examination of archive fuel plates. The NDE includes Ultrasonic (UT) scanning and radiography. UT tests include an ultrasonic scan for areas of "debonds" and a high frequency ultrasonic scan to determine the "minimum cladding" over the fuel. Radiography inspections include identifying fuel outside of the maximum fuel zone and measurements and calculations for fuel density. Details of each test are provided and acceptance criteria are defined. These tests help to provide a high level of confidence that the fuel plate will perform in the reactor without a breach in the cladding.

1. Introduction

The US RERTR Fuel Development program has been irradiating UMo fuel plates in the Advanced Test Reactor (ATR) since the 1990's. During this time many techniques have been developed to test and accept the fuel plates prior to irradiation. Because the plates are in direct contact with the primary coolant system, the examinations of the fuel plates must provide assurance that a cladding breach during irradiation is a low probability event.

Prior to reactor insertion, candidate RERTR fuel plates must undergo several nondestructive examinations which are specifically formulated to inspect cladding thickness, bond quality, and fuel zone/loading conformity. Candidate fuel plates are examined by UT scanning for the purpose of establishing minimum cladding thicknesses, hereafter referred to as "minclad" thicknesses. Furthermore, UT examinations are used to map any poorly bonded areas, hereafter referred to as "debonds". Several radiograph tests are also performed on each plate for the purpose of finding stray fuel particles external to the maximum fuel zone, hereafter referred to as fuel out of zone (FOZ), and for characterizing fuel loading densities.

Additionally, several destructive examinations are also performed. Blister annealing is performed on plates with dispersion fuels. Adjacent cladding trimmings are examined by mechanical bend testing. Lastly, archived plates are sectioned and evaluated by microscopy. Often, microscopy is performed on plates which are also evaluated by UT; authenticating UT as a method whereby minclad thicknesses may be obtained. These tests, along with material certifications, quality inspections, and other appropriate measures, help to ensure that RERTR experimental fuel plates are qualified and suitable for reactor insertion and irradiation.

2. Examinations

Dispersion type fuels are encapsulated in aluminum cladding by the roll bonding method whereas monolithic type fuels are encapsulated in cladding by either friction bonding (FB) or hot isostatic pressing (HIP). NDE techniques are identical for all RERTR fuel plates regardless of fuel type or cladding method. Dispersion type fuel plates receive the blister anneal DE, while monolithic plates do not. All NDE and DE are performed following the bonding operation.

Fuel Out of Zone (FOZ) Radiographs

FOZ radiographs are exposed such that the fuel zone is readily visible to the eye. However, FOZ radiographs are often performed with increased density (darker image) to better represent stray fuel particles. FOZ radiographs are visually inspected for fuel particles using an overlay template of the fuel plate drawing which includes the fuel zone boundary [1]. Stray fuel particles are allowed if they fit in a square 0.5 mm X 0.5 mm and are no closer than 2 mm to any other particle square (edge to edge) and are no closer to the plate edge than the major dimension of the particle. All other stray fuel particles are cause for rejection [2]. Figure 1 displays a FOZ radiograph of a monolithic mini-plate with a stray fuel particle.

Figure 1: FOZ Radiograph

Density Radiographs

Unlike FOZ radiographs, density radiographs are much darker and are imaged alongside step-wedge density standards (see Figure 2). These density radiographs are used to calculate an equivalent fuel loading. Density standards are selected to envelope the density range of the fuel zone. Film densities are such that densitometer readings from the density standard are obtained between 1.0 and 4.0 [2]. Since density standard thicknesses are known, it is possible to correlate material thickness with densitometer readings from the standard. This correlation is typically found to be a 2nd order polynomial curve fit with a correlation of determination between 1.00 and 0.98. This curve fit is then applied to several densitometer readings from the fuel zone such that an equivalent fuel zone thickness is calculated using the appropriate mass absorption coefficient. The average and maximum fuel zone thickness are then compared to the allowable peaking factors analyzed for the specific experiment. Certain experiments on surrogate foils have demonstrated an average difference of 11.4 microns between radiography and micrometer thickness measurements [3]; confirming the accuracy of the densitometry to thickness correlation. Since excessive fuel loading may cause unwarranted power peaking and "hot spots" during irradiation, fuel plates which do not conform to loading specifications are rejected. These loading specifications are determined for each experiment based on thermal modeling. Example fuel loading specifications are found in Table 1.

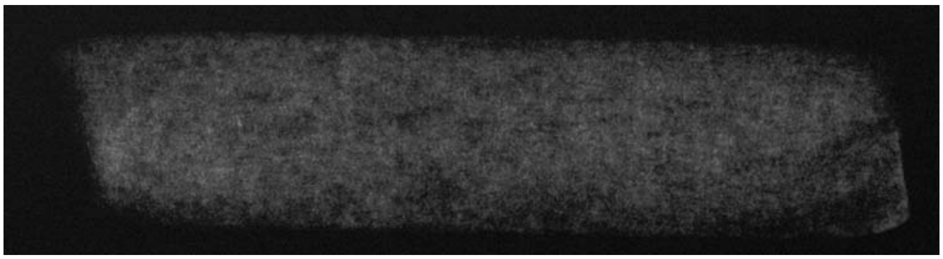


Figure 2: Density Radiograph

Table 1: Example Fuel Loading Specifications

Maximum Allowable Calculated Thickness Nominal Fuel Meat: U-10Mo, 66% U-235, 0.010" thick	0.0116"
Maximum Allowable Average Calculated Thickness Nominal Fuel Meat: U-10Mo, 66% U-235, 0.010" thick	0.011"
Maximum Allowable Calculated Thickness Nominal Fuel Meat: U-10Mo, 33% U-235, 0.020" thick	0.0231"
Maximum Allowable Average Calculated Thickness Nominal Fuel Meat: U-10Mo, 33% U-235, 0.020" thick	0.022"

UT Characterization

UT signals, which are nothing more than high frequency mechanical waves, differ from sound waves only in frequency and behave quite similarly. Like sound waves, UT signals transmit through different media with different speeds and impedances. Furthermore, UT signals may be reflected, scattered, and absorbed. The UT signals are emitted and received by piezoelectric transducers. The current UT characterization system employs four transducers, two for each characterization: debond and minclad. This configuration is shown in schematically in Figure 3.

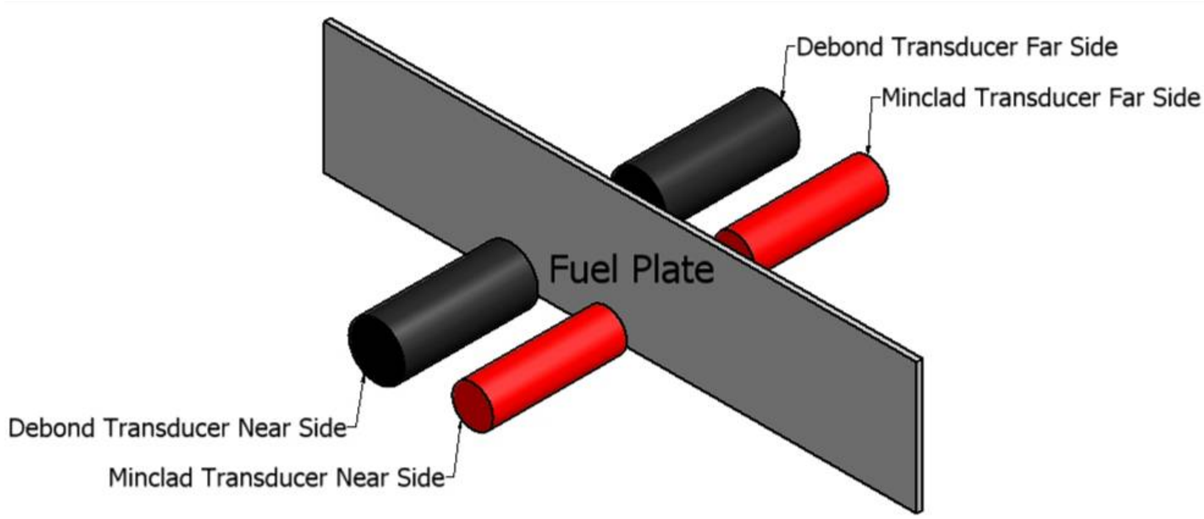


Figure 3: UT Transducer Configuration

The transducer assembly scans candidate fuel plates in a computer numeric controlled pattern which provides a 100% raster scan of each fuel plate with scan/step increments of 0.003". Debond and min-clad transducers use beam sizes diameter at 0.010" and 0.006" to 0.008", respectively. This provides greater than 300% and 250% over scan for debond and min-clad scans, respectively. The fuel plate and transducer assembly are totally immersed in water during operation. Debond and min-clad inspection systems operate at frequencies of 15 MHz and 40 MHz, respectively. This enables signal differentiation such that both systems may operate concurrently. Before and after the fuel plate is characterized, reference standards are used to verify both debond and min-clad system calibrations. The debond standard is an Al-6061 plate having engineered voids with inspected depths and diameters while the min-clad standard is an aluminum step wedge plate with known thicknesses [2].

Debond UT

Debond UT operates in though transmission mode and utilizes the amplitude of received signals to characterize debonds. Through transmission mode examines specimens simply by measuring signal attenuation through the specimen. The debond UT signal is emitted by one transducer and received by another. Signal attenuation through dense materials is minimal while attenuation though less dense materials, specifically gases, is significant. Consequently, debonds within fuel plates attenuate UT signals to noticeably low levels. The debond UT system characterizes the entire fuel plate by this method and renders an image of the plate. Often, this image is a simple grayscale representation where white represents no signal attenuation (100% signal) and black represents those signals below a determined value. Figure 4 displays a UT debond signal and a rendering of a plate after a full scan, where black represents those areas of less than 10% signal. The signal seen in the upper portion of the figure is an example characterization of a specific debond location (within the red circle). Debond locations are characterized individually by analyzing the signal to determine the amount of attenuation.

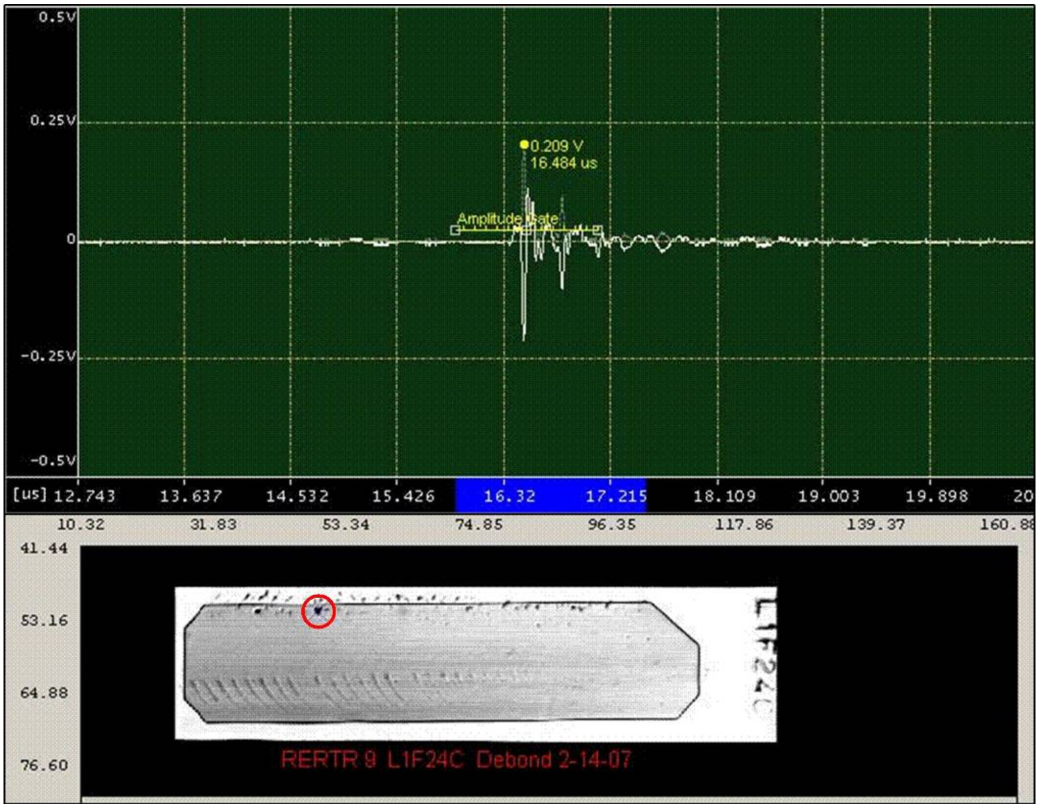


Figure 4: UT Debond Signal

Areas of less than 50% signal are cause for plate rejection if they occur in the Al-Al cladding region. Due to the lack of a complete data set for U-Mo fuel, there are currently no accept/reject criteria for UT debond indications over the fuel core [2]. Debond UT data must be examined carefully as certain phenomena, such as signal scattering, often cause signal loss where there is no debond. Signal loss due to scattering is often seen at the edge of monolithic foils and is referred to as the “edge effect”. Additionally, surface defects, such as FB stir marks and fuel plate identification stamps, can cause signal scattering and may be misinterpreted as debonds. Consequently, all debond indications are meticulously examined by subject matter experts.

<u>Minclad UT</u>

Minclad UT, unlike the debond system, operates in pulse echo mode. Pulse echo differs from through transmission in that “time of flight” must be utilized in characterizing the specimen. Time of flight is defined as the time required for a signal to travel a certain distance in a given medium. In pulse echo mode, each transducer emits a brief signal, receives reflections of that signal, and produces an amplitude vs. time waveform. This mode of scanning is analogous to sonar and is often referred to as A-scan. By nature, a portion of the UT signal will be reflected whenever it encounters an interface such as the plate surface or fuel zone. Using the time difference between the plate surface and the fuel zone indications, it is possible to calculate the cladding thickness since the speed at which UT signals travel through the cladding material is known. Figure 5 displays a schematic minclad waveform (A-scan).

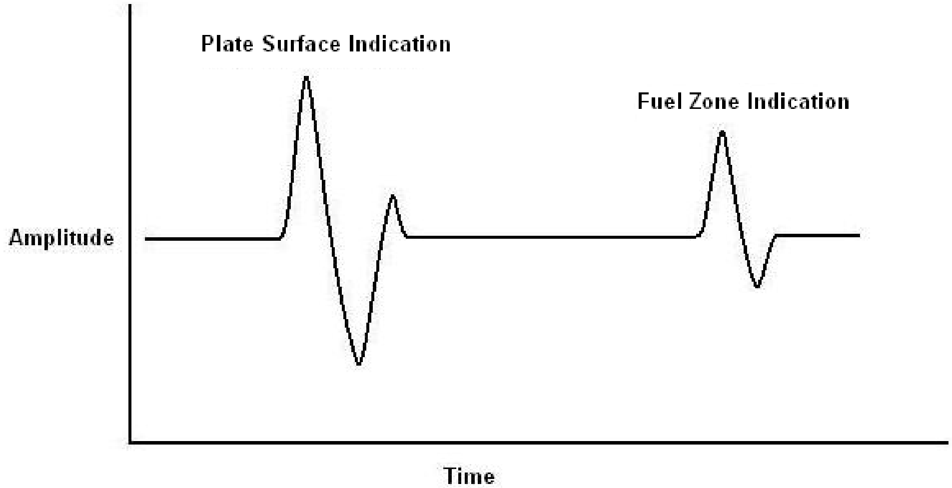


Figure 5: Schematic Waveform (A-scan)

Since the UT minclad system measures time of flight between the plate surface and fuel zone, rather than between the transducer and either of those interfaces, the system is somewhat impervious to the plate not being perpendicular to the transducer's signal; although severe misalignments may create scattering issues similar to those discussed earlier. Furthermore, each A-scan can be "sliced" at a given point in time, relative to the plate surface indication, and the associated amplitude recorded. Since the speed of sound in aluminum is known, each "time" or slice correlates to an internal cladding thickness. In order to characterize minclad thickness, images are rendered from several A-scan "slices" such that the entire plate is represented at a given depth from the surface. This mode is referred to as C-scan.

Minclad thicknesses are analyzed in C-scan mode. These images are created starting at 0.005" below the plate surface and continuing at each 0.001" increment until a fuel zone indication is located. When a fuel zone indication is found, the depth of the previous image is recorded as the minimum cladding thickness (minclad thickness). Figure 6 displays representative UT minclad images. In this example, the near and far side minclad thickness were found to be 0.021" and 0.016", respectively. The RERTR minclad thickness is specified as 0.006" or greater.

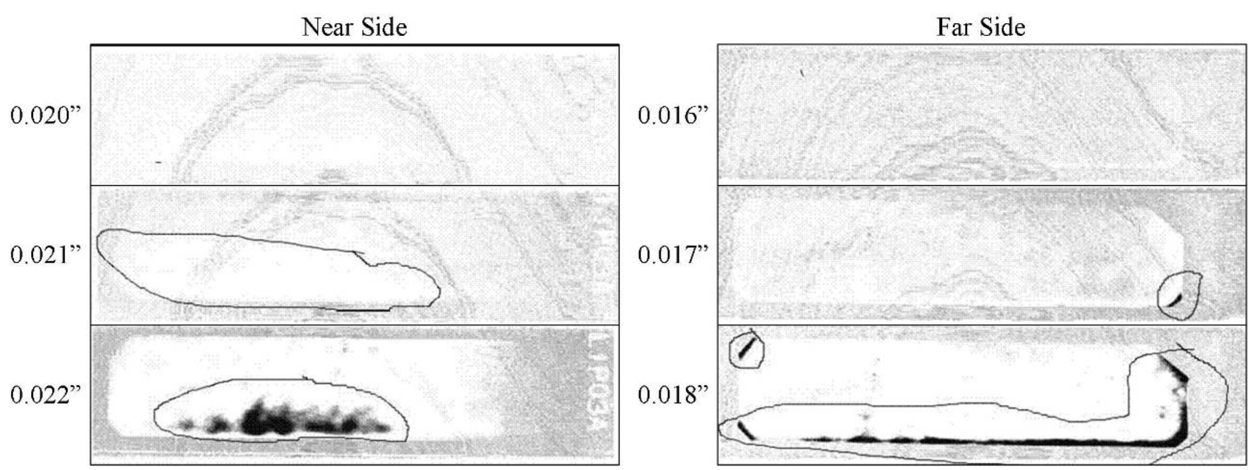
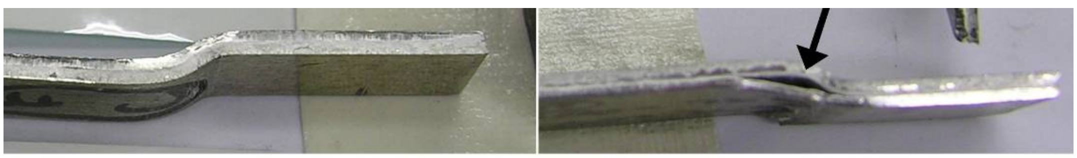


Figure 6: UT Minclad Scans (C-scans)

Bend Tests

Subsequent to radiography examinations, excess cladding is trimmed from the edges of the fuel plate using a shear. While this operation is performed primarily to obtain the necessary plate size, leftover trimmings of the aluminum cladding, directly adjacent to the final plate, are subjected to bend tests as a means of evaluating bond quality. Bend test samples are taken from all four sides of each plate. Each sample is clamped in a test fixture and bent around a mandrel 90 degrees in one direction, returned to 0 degrees, bent 90 degrees in the other direction, and returned to 0 degrees. The edges which were adjacent to the final plate of the bend test specimen are then visually examined for delamination as shown in Figure 7. Any strip showing delamination of the cladding layers is determined to be unbonded and the associated plate is rejected. At least six bend samples from each miniplate (including two from each long side and one from each short side) are tested [2].



Bend test sample without delamination | Bend test sample with delamination

Figure 7: Bend Test Examples

Blister Annealing

Blister annealing and subsequent inspections are performed on all dispersion fuel plates immediately after the rolling operation. Rolled plates are heated in a furnace to 485°C and held for 30 minutes for the purpose of forming blisters (raised areas in the plate). After heating, the plates are removed from the furnace, allowed to air cool, and examined for blister formation. Both sides of each plate are inspected at ~ 5 X magnification. Any blister larger than 1.5 mm in diameter (directly over the fuel zone) or 3 mm in diameter (non-fuel zone) is an indication of poor bonding and is cause for plate rejection. A maximum of two blisters in the fuel zone is allowed as long as they are at least 6 mm apart from each other [4].

Archive Plate Microscopic Examinations

After UT characterization, at least one archive plate of each type of fuel plate is sectioned with a high speed saw and then chemically etched. Samples are mounted, polished, and measured visually with the aid of an optical microscope to obtain a series of cladding thickness measurements. These measurements have been used as a verification of the UT minclad system. Additionally, sectioning enables some degree of analysis regarding grain size/shape, microscopic defects, and debond regions [1]. Figure 8 and Figure 9 display section images of monolithic and dispersion fuel plates, respectively.

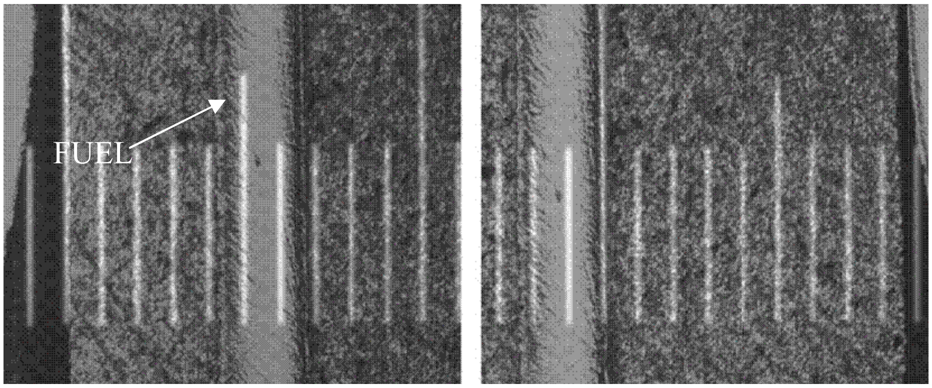


Figure 8: Monolithic Fuel Plate Section

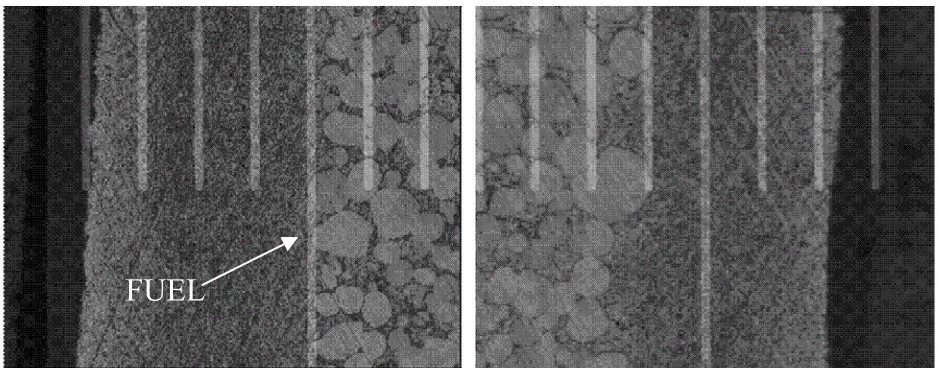


Figure 9: Dispersion Fuel Plate Section

4. Summary

Radiography has proven to be a capable method of characterizing both fuel location and density. Candidate fuel plates which pass radiographic tests must comply with specifications that ensure reliable irradiation behavior. Specifically, candidate fuel plates that meet fuel density specifications can be irradiated with little risk of power peaking and hot spots. Since cladding breaches may cause reactor coolant contamination, it is also critical to adequately characterize and qualify fuel plate cladding. Consequently, bend testing and UT examinations provide redundancy in examining cladding integrity. Bend testing is a dependable way of testing bond strength while UT examinations qualify both bonding homogeneity and minimum thickness of that cladding. Additionally, blister annealing further verifies cladding quality of dispersion fuel plates. Lastly, archive plate microscopy further supports the veracity of the UT characterization method. These tests provide a high level of confidence that qualifying RERTR experimental fuel plates are suitable for irradiation.

5. Acknowledgements

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6. References

[1] C.R. Clark, J.M. Wight, "RERTR Monolithic Fuel Plate Fabrication Report", May 13, 2008, INL Internal Document.

[2] J.M. Wight, "Fuel Plate Specification for the RERTR-10 Fuel Irradiation in the ATR," June 9, 2008, INL Internal Document.

[3] N.E. Woolstenhulme, G.A. Moore, W.D. Swank, and D.C. Haggard, "Fabrication of Contoured Monolithic Foils," August 14, 2008, INL Internal Report.

[4] J.M. Wight, "Fuel Plate Specification for the AFIP-1 Fuel Irradiation in the ATR Fabricated at BWXT," April 16, 2008, INL Internal Document.