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NON-DESTRUCTIVE EXAMINATION OF FUEL PLATES FOR THE RERTR FUEL DEVELOPMENT EXPERIMENTS

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Idaho National Laboratory

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CONTENTS

Abstract

Nuclear fuel is the core component of reactors that is used to produce the neutron flux required for irradiation research purposes as well as commercial power generation. The development of nuclear fuels with low enrichments of uranium is a major endeavor of the RERTR program. In the development of these fuels, the RERTR program uses nondestructive examination (NDE) techniques for the purpose of determining the properties of nuclear fuel plate experiments without imparting damage or altering the fuel specimens before they are irradiated in a reactor. The vast range of properties and information about the fuel plates that can be characterized using NDE makes them highly useful for quality assurance and for analyses used in modeling the behavior of the fuel while undergoing irradiation. NDE is also particularly useful for creating a control group for post-irradiation examination comparison. The two major categories of NDE discussed in this paper are X-ray radiography and ultrasonic testing (UT) inspection/evaluation. The radiographic scans are used for the characterization of fuel meat density and homogeneity as well as the determination of fuel location within the cladding. The UT scans are able to characterize indications such as voids, delaminations, inclusions, and other abnormalities in the fuel plates which are generally referred to as debonds as well as to determine the thickness of the cladding using ultrasonic acoustic microscopy methods. Additionally, the UT techniques are now also being applied to in-canal interim examination of fuel experiments undergoing irradiation and the mapping of the fuel plate surface profile to determine fuel swelling. The methods used to carry out these NDE techniques, as well as how they operate and function, are described along with a description of which properties are characterized.

NON-DESTRUCTIVE EXAMINATION OF FUEL PLATES FOR THE RERTR FUEL DEVELOPMENT EXPERIMENTS

1. Introduction

Nuclear fuel, which generally contains uranium-235 or an equivalent fissile isotope, is vital to the production of neutron fluxes necessary for power generation in modern reactors. Fuel plate experiments designed for the Reduced Enrichment for Research and Test Reactors (RERTR) program are a step toward replacing highly enriched fuel elements with ones that can produce the compulsory flux required by many reactors at a much lower and safer level of uranium enrichment. Before any of these fuel plate experiments for the RERTR program at the Idaho National Laboratory (INL) can be irradiated, a progression of examinations for an assurance of quality must be performed. Due to the demanding irradiation conditions often imposed on the fuel plates and the direct contact between the plate cladding and coolant flow, it is essential that thorough examinations are conducted as outlined to minimize the possibility that fission products from the fuel experiments are released. Candidate fuel plates for the RERTR program experiments must undergo a series of distinct groups of examinations prior to their insertion into the reactor for irradiation. Destructive examination (DE) involves tests that significantly alter the specimen. Conversely, nondestructive examination (NDE) involves methods of examination that have minimal impact on the structure and form of the experiment specimen. NDE techniques can provide numerous useful properties for study, such as density, void locations, and cladding thickness, while requiring fewer test fuel plates to be manufactured.

The two primary types of pre-irradiation NDE implemented at the INL for many of the RERTR program experiments before reactor insertion are conventional X-ray radiography and ultrasonic testing (UT) inspection. Certain other types of microscopy, such as scanning and transmission electron microscopy, are another type of NDE used at the INL; however, scanning and transmission electron microscopy are not a major focus of this paper and will not be discussed in detail. The radiography and UT scans are highly useful in the measurement of data relating to a number of properties of the fuel specimens, specifically the location of the fuel material, the density of the fuel sample and consequently the fuel loading, the detection of locations of poorly bonded areas known as debonds, the determination of cladding thickness, and fuel swelling detection. This paper describes the techniques and methodology behind the radiography and UT scan types of NDE as well as the beneficial properties that can be ascertained through the implementation of these inspections/examinations on RERTR fuel experiments.

2. RERTR Fuel Experiments

The most promising fissile phase currently pursued by the RERTR fuel development program is a binary alloy consisting of uranium alloyed with 10 wt% molybdenum (hereafter referred to as U-Mo). While other fuel forms have been tested, the United States portion of the RERTR fuel development program is primarily focused on development of a plate type fuel where the U-Mo takes the form of a single continuous monolith. Reactor core analysis shows that this fuel system has a sufficient uranium density to enable low enriched uranium (LEU) conversion of high performance research reactors, which currently utilize highly enriched uranium (HEU) [1]. The cladding for these fuel plates is nearly always made from aluminum 6061, due to the fact that the research reactors for which this fuel is being developed currently use aluminum based cladding [2]. Interlayer materials are often added to the system in order to limit the reaction of the U-Mo alloy and the aluminum.

Experimental fuel plate specimens undergo irradiation primarily in the Advanced Test Reactor (ATR) where the experiment is designed to achieve target burnup and irradiation conditions (e.g. fission rate, constituent temperatures). Testing of the U-Mo fuel is intended to produce a data set that will be used in regulatory qualification of the fuel system as well as analytic design/safety-bases modeling of those reactors for which the fuel is intended. While much of this data is obtained via Post Irradiation Examination (PIE), characterization of unirradiated samples, which includes both DE of representative sample and NDE of pre-irradiated specimens, is essential to serve as the control group for comparison to PIE results.

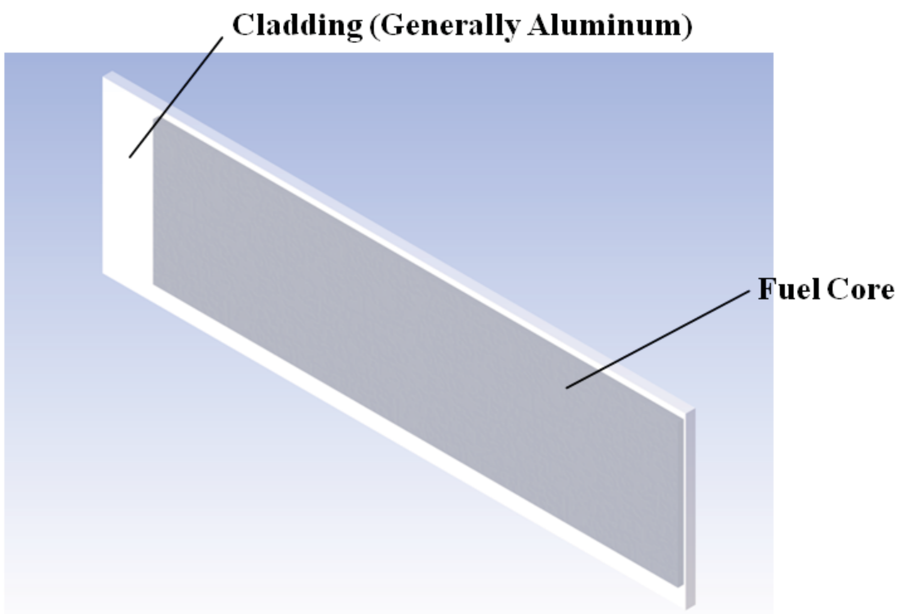

Figure 1: Typical RERTR Fuel Plate (Cladding Transparent to Reveal Fuel Core)

3. Radiography

In the preliminary stages of pre-irradiation testing, the fuel plates are characterized using a series of radiographic examinations. Radiography is a highly useful NDE for gathering data to measure a number of properties that can subsequently be used in the analytic design of the RERTR experimental specimens. For fresh fuel plates, conventional X-ray radiography is used prior to experiment capsule loading. In the process of radiography, X-rays are passed through the target, which in this case are the experiment fuel plate samples. Depending on the mass absorption coefficient (MAC) of the materials that the X-rays are passing through, differing intensities of the X-rays are allowed to pass through the fuel plate sample and into a radiographic film. To ensure accurate results, the film used for radiography is a fine grain, high contrast, double emulsion type of X-ray film equivalent to the film grade often used in industry [3]. After the X-rays pass through the target fuel plates, they darken the film, while the most intense or least attenuated signals produce the darkest areas on the film. In this way, the intensities of the X-rays that pass through the plate samples can be observed and certain properties of the material through which the X-rays passed can be ascertained based on the relative lightness and darkness of the film and consequently the signal strength of the X-rays. Recently, the INL has started to implement the use of digital radiography, which uses a digital array to capture the radiograph as opposed to the traditional film technique. Digital radiography is expected to make the radiographic process more efficient and cost effective by eliminating the need for new film for each radiograph that is created and putting the radiographic scans into the more versatile digital format. The two most useful properties that can be determined using the radiographic method are the location of the fuel in the plate relative to the aluminum cladding, as well as the density throughout the sample by which the thickness of the fuel core and fuel loading can also be determined.

3.1 Fuel Location Radiography

If the fuel plate core contained within the aluminum cladding has shifted or a fuel particle is out of place or has broken off from the meat, this abnormality can be detected through the use of fuel location radiographs. For these types of radiographs, a lower intensity of X-rays are passed through the fuel sample creating a much lighter image on the film. Because the area containing the aluminum cladding has relatively low absorption, this area appears much darker on the film as opposed to the area containing the dense fuel meat which appears much lighter. Consequently, the location of the fuel core can be clearly differentiated relative to the aluminum cladding as is shown in Figure 2, where the cladding is the black area and the fuel meat is within the lighter white area.

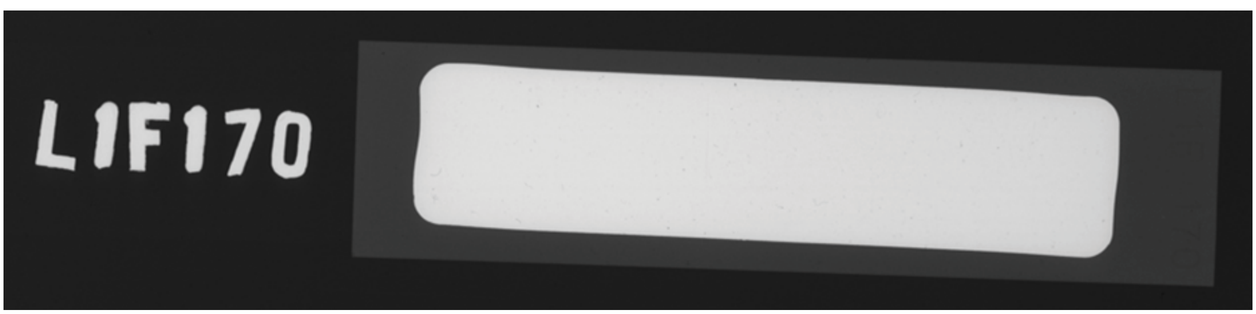

Figure 2: Fuel Location Radiograph

Fuel location radiographs are visually inspected using an overlay template of the fuel plate drawing that includes a precise location of the fuel plate boundary [4]. A comparison between the overlay template and the fuel plate radiograph can then be conducted to ensure that the fuel core is in the proper location as outlined by the template. From these radiographs, the final shearing can be determined and the unwanted fuel particles that must be eliminated during final shearing can be identified [3]. In the event that the fuel core has significantly shifted, there may be cause for rejection depending on the substantiality of this shift.

3.2 Density Radiography

Density radiographs are characterized by passing much higher intensity X-ray beams through the fuel plates and into a film. This higher intensity beam produces an image on the film that appears significantly darker than the radiographs used for fuel location radiography as can be seen in Figure 3 [4]. After the radiographic image is developed on the film, a densitometer is used to take readings of the film based on a density standard, and this standard, along with the fuel plate identification and the orientation or step numbers, are generally included on the film [5]. The densitometer operates by passing light through the film in areas over the regions of the sample containing the fuel core. Depending on the relative lightness and darkness of the film, a detector placed on the opposite side of the film as that of the light source will measure the light intensity and assign it a value between 1.0 and 4.0 on the density standard. A lighter area on the film implies a higher density point of the fuel plate.

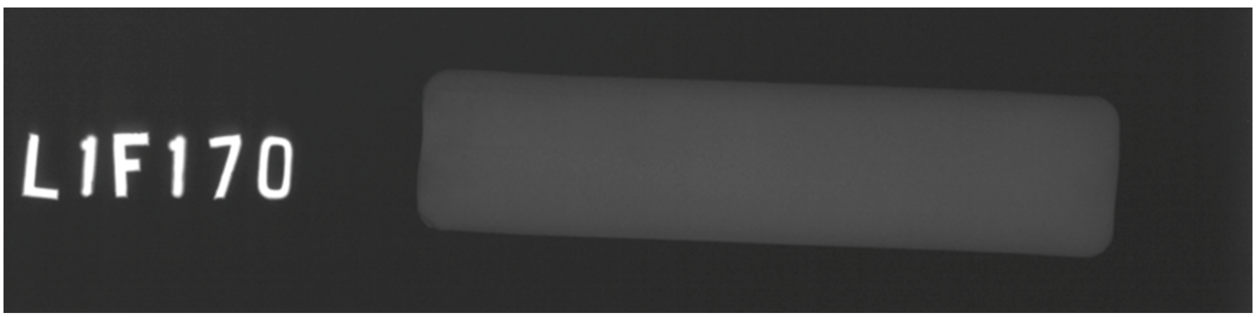

Figure 3: Density Radiograph

The density of the fuel meat and its thickness can then be correlated to a mathematical function based on pre-measured density standard thicknesses. This correlation is generally found to be a 2^{nd} order polynomial curve fit with a coefficient of determination somewhere between 1.00 and 0.98, implying a high level of accuracy between the two [4]. This curve fit can also be applied to many of the densitometer measurements from the zone containing the fuel. With this information, an equivalent thickness of the fuel core can then be calculated using the U-Mo MAC standard. The accuracy of this method has been demonstrated by a comparison of the calculated thickness of the fuel plates to micrometer thickness measurements conducted on surrogate foils with an average difference of around 11.4 microns between the two measurement types [6].

The radiographic technique for performing density measurements and thickness correlation of the samples is also useful for determining fuel loading based on the data obtained from calculating the thickness. By calculating the fuel loading using the nominal fuel area and thickness from the correlated density data, neutronic and thermal analyses can then be conducted on the fuel plates to determine the manner in which the fuel will behave when irradiated [5]. In cases in which fuel loading is found to be above the desirable limit, “hot spots” and unwarranted power peaking may occur leading to local regions of unacceptable thermal hydraulic conditions. Thermal modeling is used to determine these loading specifications and ensure that these “hot spots” do not occur by setting guidelines for rejecting fuel plates based on fuel loadings that exceed these specified limits [4]. Therefore, the data obtained from the density radiographs is essential for helping to ensure that these experiments are conducted safely and with minimal risk.

4. Ultrasonic Testing

The technique of ultrasonic testing (UT) on the fuel plates makes use of mechanical pressure waves with a higher frequency than audible sound waves. The two main properties characterized using ultrasonic signals, debonds and minimum cladding (min-clad) thickness, are found by use of separate methods. However, the basic principles of each UT method, including the in-canal UT technique, are similar. A piezoelectric UT emitter passes ultrasonic waves through a target. A piezoelectric transducer then receives a signal that can be measured, through which properties of the target may be determined. Ultrasonic waves travel at different speeds through different media which is dependent upon the medium's impedance as well as the ability of the wave to be reflected, scattered, or absorbed as it passes through the media of different densities [4]. After an ultrasonic wave passes through its target and is reflected or attenuated, it is received by a piezoelectric transducer. This creates a temporary deformation in the transducer leading to a voltage change equivalent to the strength of the reflected or attenuated ultrasonic wave. This voltage change can then be measured and the relative strength of the reflected or attenuated ultrasonic signal may be determined by plotting the data. A plot of this data is known as an A-scan and a compilation of A-scan data is referred to as a C-scan. At the INL, UT scan experiments are conducted underwater with both the transducer and experimental fuel plate fully submersed in a specialized water tank due to the ability of the UT waves to travel more easily through a liquid medium rather than a gas, such as air. The ultrasonic waves that are used for debond scans operate at a frequency of 15 MHz as opposed to the 40 MHz frequency and above used for the min-clad scans. This difference in frequencies between the debond and min-clad scans allows for signal differentiation, thus, both transducer systems may operate in tandem and do not interfere with the other's signal [4]. The transducer configuration for UT scans is shown in Figure 4 [4].

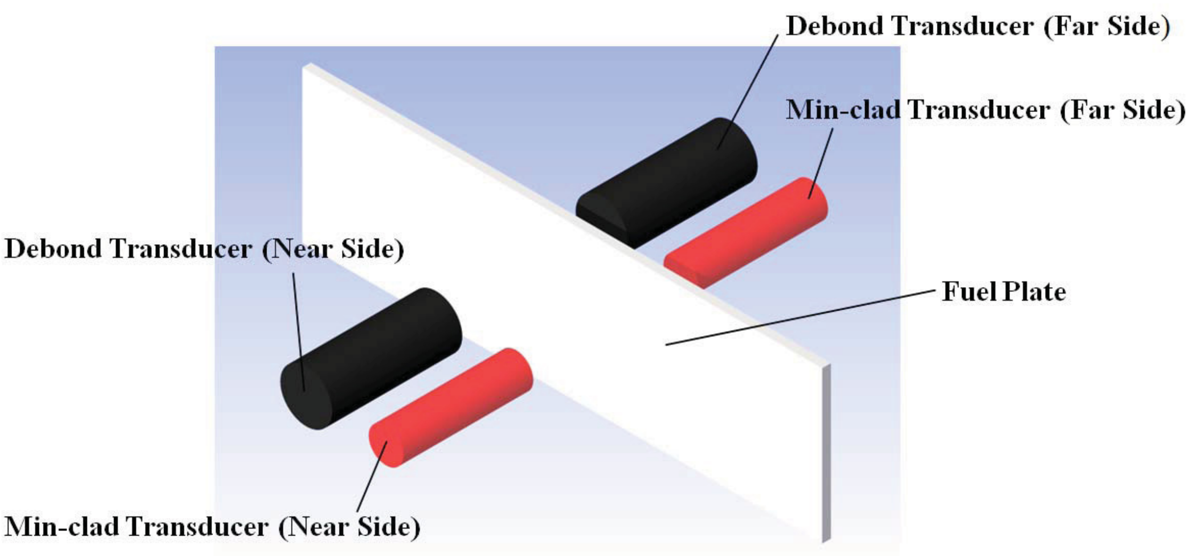

Figure 4: UT Transducer Configuration [4]

4.1 Debond UT

The debond UT scans are used to detect areas containing manufactured voids or abnormalities in the fuel plates. These scans make use of through transmission beams of 15 MHz frequency ultrasonic waves. Through transmission simply means that the ultrasonic signal is transmitted through the plate to a second receiving transducer on the opposite side [3]. In the event that one of these through transmissions is interrupted by a significant void in the fuel plate, a disruption in the ultrasonic signal will occur. This disruption in the ultrasonic signal will cause a subsequent disruption in voltage across the receiving transducer that can be clearly observed on an A-scan plot of the piezoelectric voltage. An A-scan plot showing a void disruption voltage change in the piezoelectric transducer versus the time since the ultrasonic wave was emitted for an area containing a debond can be observed in the top left and right sides of Figure 5 [7], along with a C-scan image created of the fuel plate locating the area of the debond at the bottom left and right sides.

The debond scan transducer beam size is approximately 254 µm in diameter with scan and step increments of approximately 80 µm. With such small step size in relation to the beam diameter, there is an over scan greater than 300%, which ensures that no area of the fuel plate is overlooked [5]. Because this method makes use of through transmission, the measurements obtained from this examination are based purely on the attenuation of the ultrasonic signal. However, due to the geometry of the monolithic fuel core within the fuel plate, scattering of the signal near the borders of the fuel core may occur to produce edge effect indications in the data, which are not debonds. The edge effect occurs when the ultrasonic beam is dispersed, reflected, or attenuated in some way that indicates that there is a boundary between the edges of the fuel core material and aluminum cladding [3]. The right side of Figure 5 [7] shows the signal plot of the edge effect and shows the location along the fuel core edge at which it occurs. Other indications may also arise from signal scattering due to defects in the surface of the cladding that can also be mistakenly classified as debonds [4].

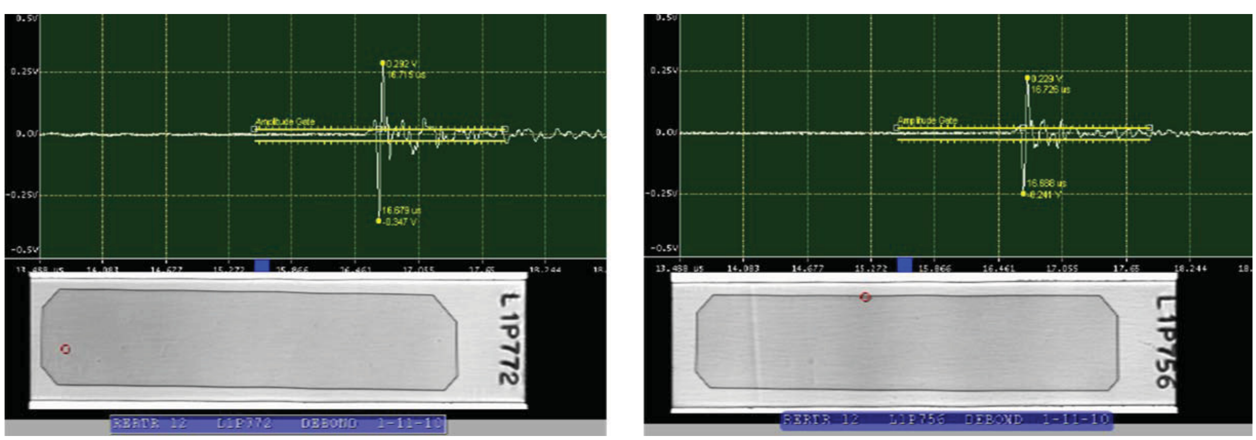

Figure 5: UT A-scan signal and C-scan image of debond (left) and UT A-scan signal and C-scan image of the edge effect (right)

4.2 Min-clad Thickness UT

Minimum cladding (min-clad) thickness testing is essential for ensuring that the minimum cladding thickness safety criterion is met to decrease the likelihood of a cladding breach. Rather than utilizing through transmission, min-clad UT makes use of a technique known as pulse echo mode. Pulse echo mode operates by the emission of brief ultrasonic signals from each of the transducers at high frequencies, approximately 40 MHz and above. These same transducers then receive the reflections or echoes of these signals to produce an amplitude versus time waveform for the received reflections [4]. The signal is most strongly reflected back to the transducer when these ultrasonic pulses encounter a boundary or interface between two different media, which can be distinctly observed in the waveform signal. In the case of the fuel plates, there are two interfaces for each side half. The first interface is between the water and the cladding material. The second interface boundary occurs between the cladding material and the fuel core. The time interval taken for the transducer to receive each of these interface reflections can be measured and plotted to create an A-scan. Figure 6 [8] shows a simplified schematic of a UT Deep-Focus beam and the reflected signals from the edges of the fuel plate as well as the reflected signal from a fuel core boundary indication or flaw that can be picked up by the transducer.

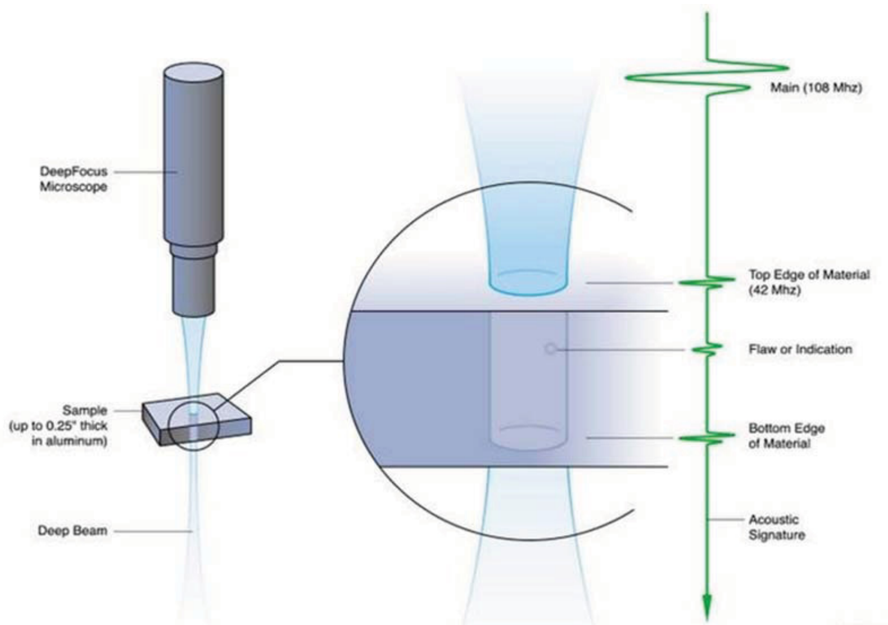

Figure 6: Schematic of UT beam and Reflected Signal from Material Boundaries [8]

With the data from the A-scan, the cladding thickness can then be calculated using a value known as the time of flight. The time of flight is the time necessary for a signal to travel a certain distance through a specific medium [4]. By knowing the time of flight for ultrasonic waves through aluminum, the thickness of the aluminum cladding can easily be calculated using the time interval between the boundary reflections. These calculations can then provide the location of the fuel boundary and the thickness of the cladding. By compiling a number of the individual A-scan "slices" that were produced, a C-scan rendering of the entire plate can created at any given depth from the surface of the fuel plate [4]. An example of a set of C-scan compilation layers used for min-clad determination can be observed in Figure 7 [7].

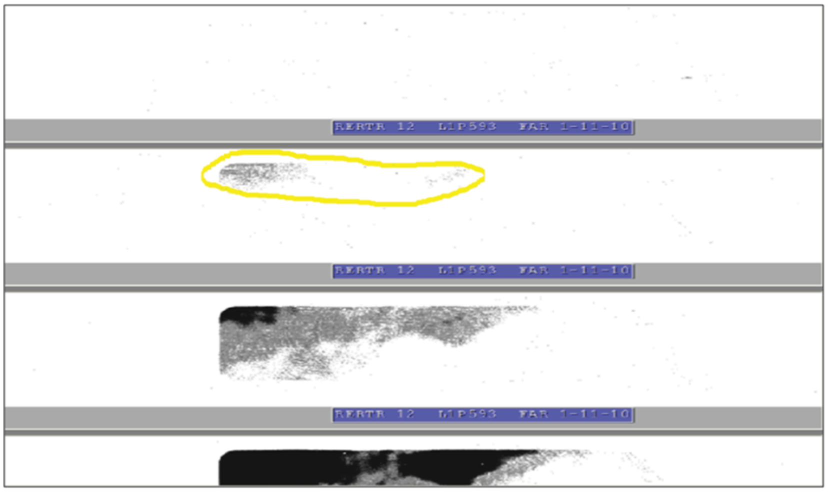

Figure 7: Typical UT Min-clad C-Scan [7]

A strong advantage of the Deep-Focus min-clad transducer is that it allows for fuel examinations that do not depend on the transducer focal distance from the actual fuel plate as long as it is within the depth-of-field. For min-clad UT scans, the size of the transducer beam is slightly smaller than that used to detect debonds, with a total beam diameter in the range of 152.4 to 203.2 µm. However, the raster scan and step sizes remain the same as those used for the debond UT, with an increment of approximately 80 µm for both. Due to the smaller diameter of the beam in comparison to the one used for debond UT, the over scan is reduced to around 250% [5]. However, 250% over scan is more than sufficient to ensure that the entire fuel plate is thoroughly examined.

4.3 UT During Irradiation

In more recent years, the INL has been using UT for the purpose of studying fuel swelling for fuel plates undergoing irradiation at the Advanced Test Reactor (ATR). These types of fuel plates are classified as ATR full-size plates in the center flux trap position (AFIP) experiments and are an integral part of the RERTR program. It is essential that these plates maintain a relatively stable geometry and that plate deformation is minimized. However, the fissioning of the uranium atoms during irradiation inevitably leads to the production of fission gases that have a tendency to expand the fuel meat leading to fuel swelling [9]. To monitor this phenomenon, two UT scanners have been installed directly into the ATR spent fuel canal, the area where hot fuels and experiments are stored during interim periods of reactor operation. Rather than determining the locations of debonds or determining cladding thickness, the UT for the in-canal measurements is primarily used to determine the total plate thickness to assess any fuel swelling that has occurred and to determine if any debonds have occurred or changed in size. The second scanner is used to measure water channel spacing between the fuel plates which also indicates, among other things, swelling of the plates. Significant fuel swelling has the potential to cause fuel plate delamination between the core and the cladding [9]. For this reason, the in-canal UT method is especially important for swelling detection during the interim periods of experiment irradiation.

In-canal UT is conducted by specially designed UT scanners located in the ATR canal. The UT inspections/evaluation systems are remotely operated and contain detectors that are radiation tolerant [9]. Due to the fact that UT scans are conducted in enclosed water tanks, the ATR canal is an ideal place to conduct these types of scans. Operating in much the same way as min-clad thickness UT scans, this method uses the piezoelectric transducer to emit ultrasonic waves in pulse echo mode and subsequently detect the boundary reflections from the interface between the outer fuel plate edge and the surrounding canal water, allowing the transducer to determine the distance to the fuel plate edge. Consolidating the beam signals from the raster scan enables the UT scanner technology to produce a mapped image of the fuel plate's surface profile [9]. With a mapped image of the fuel profile, a comparison can be made between the original thickness of the fuel plate and the thickness of the plate at intermittent periods of irradiation, allowing for detection of minor changes in plate thickness and the monitoring of fuel swelling.

5. Summary

The main purpose of conducting these nondestructive examinations is to gain an insight into the small scale structures of the fuel plates and to discover possible flaws in this structure that could pose hazards and be adequate cause for plate rejection, without altering the actual experiment plates. These types of inspections/examinations are also conducted to obtain data that can be used in the analysis of how the fuel plates will behave while being irradiated and to create a control group for a comparison during PIE of the fuel plates. It is essential that manufacturing flaws are detected before these experimental fuel plates are inserted into the reactor to ensure that they can withstand the rigors of irradiation successfully and with minimal disruption. It is also essential that a precise thermal and neutronic analysis are conducted to ensure that overheating and power peaking does not occur and that "hot spots" are kept to a minimum. These analyses can only be conducted accurately if precise data for the calculation of fuel loading is obtained, which is what these NDEs can supply. Overall, these methods are important to the development of new fuels. These NDE techniques are currently used on the production plates for HEU and LEU fuel elements for reactors such as the ATR and at universities.

The radiographic examinations can produce film readings displaying the location of the fuel as well as data on the density of the fuel plate at a given area. By knowing the density of the fuel, a correlation can be created to determine fuel core thickness from which fuel loading may subsequently be determined for analysis. Additionally, the UT examination techniques are highly beneficial due to their ability to detect abnormalities and voids in the fuel plate collectively known as debonds. The UT scans also provide the data set needed to determine the minimum cladding thickness to ensure that the fuel core stays fully enclosed and that the risk of fuel leakage into reactor coolant flow is minimal as well as the information needed to determine plate thickness and create a mapped image of the fuel plate surface for in-canal AFIP experiments. Concisely, these NDEs provide the information and data on select properties that are essential for the successful irradiation of RERTR fuel experiments, without altering or damaging the fuel plate samples in the process.

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