INL/CON-14-33069
PREPRINT

Assessment of Nuclear Fuels using Radiographic Thickness Measurement Method

2014 ANS Winter Meeting and Nuclear Technology Expo

Muhammad Abir, Fahima Islam, Hyoung Koo Lee, Daniel Wachs

November 2015

Assessment of Nuclear Fuels using Radiographic Thickness Measurement Method

Muhammad Abir[1], Fahima Islam[1], Hyoung Koo Lee[1], Daniel Wachs[2]

[1] Department of Mining and Nuclear Engineering, Missouri University of Science and Technology, 204 Fulton Hall, Rolla, MO 65409 [2] Idaho National Laboratory, 2525 N Fremont Ave, Idaho Falls, ID 83415
miafk6@mst.edu, ffiqnf@mst.edu, leehk@mst.edu, daniel.wachs@inl.gov

INTRODUCTION

The Convert branch of the National Nuclear Security Administration (NNSA) Global Threat Reduction Initiative (GTRI) focuses on the development of high uranium density fuels for research and test reactors for nonproliferation. This fuel is aimed to convert low density high enriched uranium (HEU) based fuel to high density low enriched uranium (LEU) based fuel for high performance research reactors (HPRR). There are five U.S. reactors that fall under the HPRR category, including: the Massachusetts Institute of Technology Reactor (MITR), the National Bureau of Standards Reactor (NBSR), the Missouri University Research Reactor (UMRR), the Advanced Test Reactor (ATR), and the High Flux Isotope Reactor (HFIR). U-Mo alloy fuel phase in the form of either monolithic or dispersion foil type fuels, such as ATR Full-size In center flux trap Position (AFIP) and Reduced Enrichment for Research and Test Reactor (RERTR), are being designed for this purpose. The fabrication process[1] of RERTR is susceptible to introducing a variety of fuel defects. A dependable quality control method is required during fabrication of RERTR miniplates to maintain the allowable design tolerances, therefore evaluating and analytically verifying the fabricated miniplates for maintaining quality standards as well as safety. The purpose of this work is to analyze the thickness of the fabricated RERTR-12 miniplates using non-destructive technique to meet the fuel plate specification for RERTR fuel to be used in the ATR.

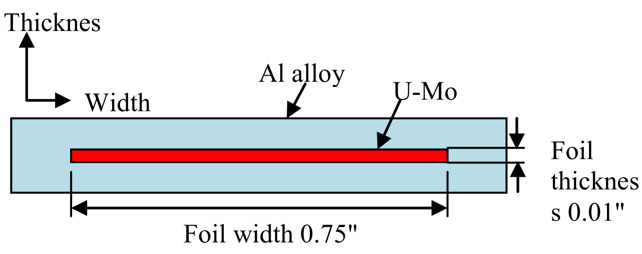

Fig.1. Schematic of as-fabricated cross section of a monolithic RERTR miniplate.

Radiographic imaging a useful technique that provides a two-dimensional image of a three dimensional object. However, the third dimension correlates the variation of the intensity of the x-ray incident on the detector or film[2]. For images of homogeneous samples consisting of a single material the variation in intensity can only be caused by variations in the sample thickness. The intensity variation can be correlated to the thickness variation of the sample utilizing a calibration specimen of known thickness imaged next to the sample[3]. If the x-ray source were monochromatic, the thickness could be estimated without the necessity of the calibration sample. For polychromatic x-ray, the differences of attenuation coefficients for different energies make the thickness calculation complicated. Combining x-ray film radiograph and digitized x-ray radiograph, a method for determining the thickness of RERTR-12 miniplates has been developed. The method utilizes an inherent property of x-ray radiographs: the brightness of a position (*P*) in a radiograph is proportional to the energy of the radiation absorbed by that pixel (*I*).

$$P \propto I \tag{1}$$

As a collection of photons traverse through a medium, a portion of them will interact with atomic electrons and attenuates before arriving to the detector or film. Attenuation varies depending on the characteristics of the medium or media being imaged. These characteristics are related to the intensity of the absorbed radiation by the Beer-Lambert law:

$$I = I_0 e^{-\mu t} \tag{2}$$

This describes how the brightness of detector pixels in an image will be different for pixels obscured by an object and those which are not. The exponential nature of attenuation characterizes the intensity of uncollided photons after traversing through a medium. The equation shows the dependence of the final intensity on the initial intensity (I_0) of the x-rays and two characteristics of the attenuating medium, the linear attenuation coefficient (μ) and thickness (t).

The optical density (OD) measures the amount of decay in a certain point through an exposed and developed x-ray film. It is a measure of the light transmittance through the film. The higher the OD, the lower the transmittance and the darker the film is. The OD of a film correlates the image pixel intensity in digitized image. The variation of OD can be correlated to the thickness variation of the sample if a calibration specimen of known thickness can be imaged next to the sample.

DESCRIPTION OF THE ACTUAL WORK

Several RERTR miniplates were fabricated[1] for inspection. The miniplates are made of Zirconium co-rolled U-10 Mo foil with an average thicknesses of 0.01". 3 candidate RERTR-12 fuel plates were radiographed with 10 co-located known density standard made of U10Mo. An X-rite densitometer, configured with a 3 mm aperture was used to obtain the OD readings. Optical densities were measured on 6 density standards that bound the observed fuel meat area OD range. Five OD readings were acquired from each density standard and then averaged.

Several assumptions are made to calculate the thickness of the miniplates. The most apparent assumption is that the composition of U-Mo is assumed to be homogeneous and without impurities. This means that the attenuation coefficients of U and Mo are not a function of position through the material. Second, the contribution of scattering radiation on the image is negligible therefore the build-up factor is assumed to be 1. For photons of energy less than 1 MeV, photon interactions consist entirely of photoelectric absorptions, incoherent scatterings, and coherent scatterings. This assumption holds well for radiation that passes through the object without interaction, is absorbed via photoelectric absorption, or is scattered at an angle away from the film. Third, the resolution of the radiograph depends on the focal spot size and magnification. The x-ray source is assumed to be a point source. The experiment conducted in this paper utilized an x-ray point source of 4 mm focal spot size in diameter. The finite size of a focal spot dictates the measureable feature size in an x-ray radiograph. As the distance between the source and detector is increased, the negative effects of a large focal spot size are reduced. The ratio of source to sample distance (SSD) and sample to detector distance (SDD) is 47″ which gives a magnification of 1.0213. The distance between test specimen and image detector can be increased to obtain magnification in the image. However, geometric unsharpness or penumbra appears if the specimen is away from the detector.

$$U_g = f * \frac{b}{a} \tag{3}$$

The equation shows the dependence of the penumbra on the focal spot size (*f*), film to plate distance (*b*) and source to plate distance (*a*). The test specimen should be placed as close as possible to the detector and the source is placed some distance from the sample to reduce the penumbra. A greater distance between the source and the object will reduce penumbra. However, the intensity of the source decreases as the distance increases. Therefore, the distance should be optimized to control the penumbra. As the focal spot size (*f*) is 4 mm or 0.15748 inch and the ratio of SSD and SDD is 47 inch, therefore the penumbra is about 0.00335 inch.

RESULTS

A third order polynomial trend line is found between the optical density and the thickness of the known standards as shown in fig. 2. Optical densities were measured at 30 locations for each miniplate (3×10 grid) and the thicknesses were obtained (fig. 3) using the third order polynomial established in fig. 2. However, as thickness measurement using densitometer requires the film to be scanned at certain location and then calculate the OD on that location, it is very time consuming, tedious, and practically impossible process to acquire OD at all locations of the film. Therefore, the x-ray films were placed in a NEO S60 film digitizer[2] that scans the film by generating electrical signal proportional to OD. The images were post-processed to eliminate unwanted noise using alpha trimmed mean filtering[5]. The relation between OD and pixels intensity provides a general equation to calculate optical densities at each location on the image. A power curve is obtained between OD and pixel intensity with an R^2 value of 0.9978 which shows linear in log scale.

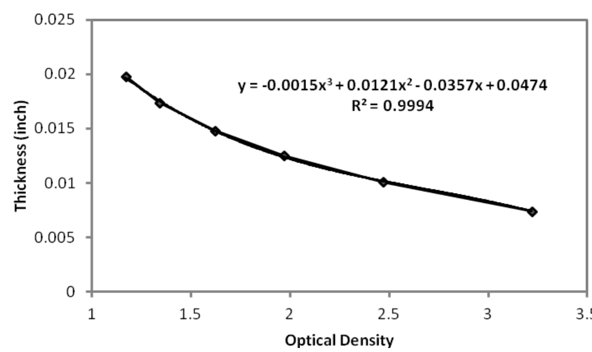

Fig. 2. Relation between thickness of the density standards and optical density

The optical densities of the miniplates were calculated using the relationship between the OD and the image pixel as obtained in fig. 4. After calculating the OD at each location, the thicknesses of the miniplates were calculated using the third order polynomial equation obtained in fig. 2.

Table 1: Relation between OD and thickness of the density standards

Thick-ness (inch)	.0074	.0101	.0125	.0148	.0175	.0198
OD	3.22	2.47	1.97	1.62	1.34	1.17

The thickness variations of the miniplate 1 along horizontal and vertical directions are displayed in fig A.1. and A.2. respectively. The average thickness of the plate 1 is found as 0.0105".

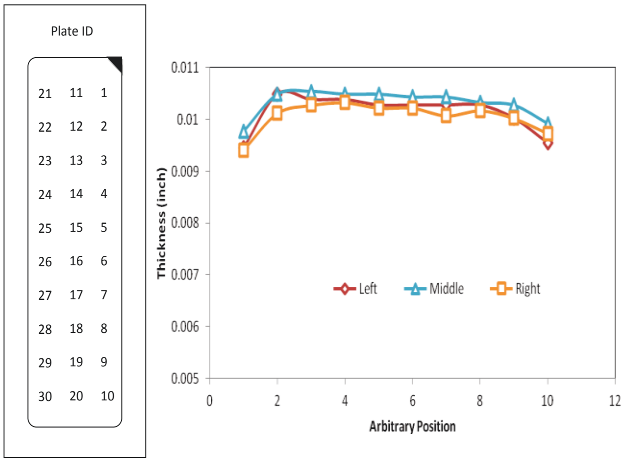

Fig. 3. Thickness map at 30 locations using densitometer.

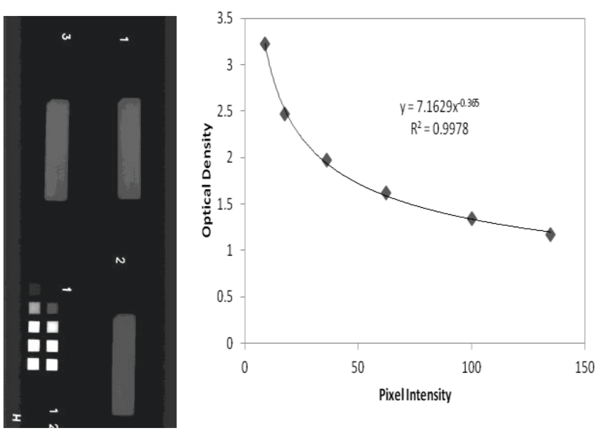

Fig. 4. Relation between optical density and pixel intensity of digitized x-ray film.

REFERENCES

1. Meyer, M., et al. "Irradiation Performance of U-Mo Monolithic Fuel." *Nuclear Engineering and Technology* 46.2 (2014).

2. Craft A., Williams W., Abir M., Wachs D., "*AFIP-7 Tomography- 2013 Status Report*," doi:10.2172/1124666 (2013). http:// www.osti.gov/scitech/servlets/purl/ 1124666.

3. Rheinländer, J. "Quantitative use of Film Density Variations for Thickness Variation Determination by Polychromatic X-Radiography." *Research in Nondestructive Evaluation* 6.1 (1994).

4. Nondestructive Testing Handbook, L.E. Bryant, and P. McIntire, 2nd ed., Vol 3, pp. 817-821, *American Society of Nondestructive Testing* (1985).

5. Abir, M., Islam F., Wachs D., Lee H., "Multiscale Based Adaptive Contrast Enhancement". *Proceedings of SPIE - The International Society for Optical Engineering* (2013).

APPENDIX A

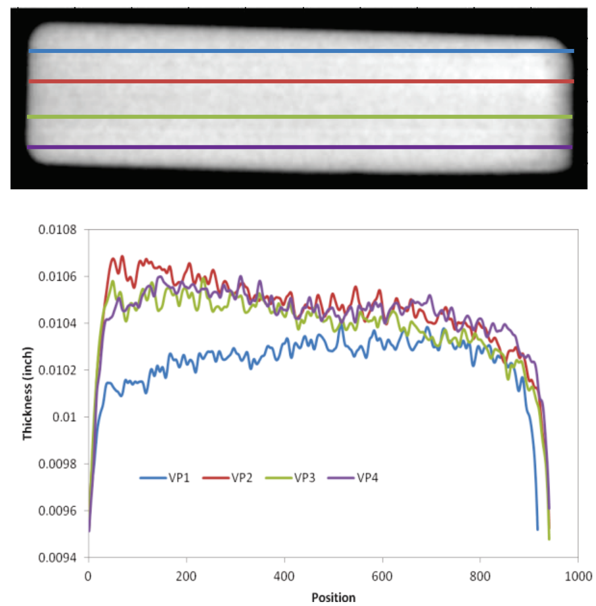

Fig. A.1. Thickness profile along horizontal direction.

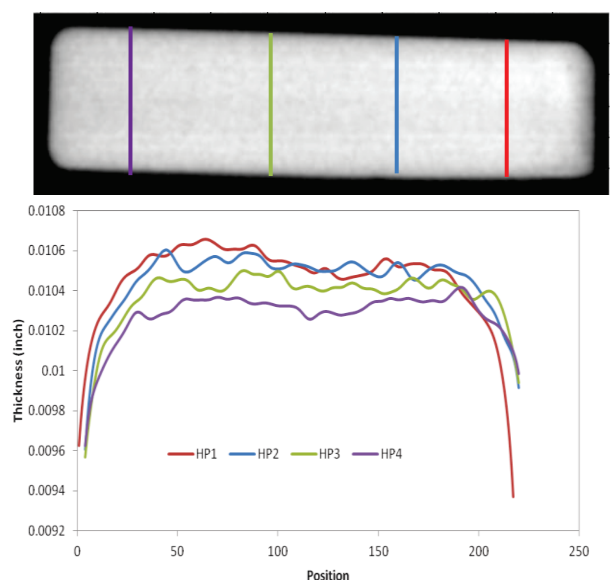

Fig. A.2. Thickness profile along vertical direction.