Comparison of Traditional Nondestructive Analysis of RERTR Fuel Plates with Digital Radiographic Techniques

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Abstract

The current design and fabrication process for RERTR fuel plates utilizes film radiography during the nondestructive testing and characterization. Digital radiographic methods offer a potential increases in efficiency and accuracy. The traditional and digital radiographic methods are described and demonstrated on a fuel plate constructed with and average of 51% by volume fuel using the dispersion method. Fuel loading data from each method is analyzed and compared to a third baseline method to assess accuracy. The new digital method is shown to be more accurate, save hours of work, and provide additional information not easily available in the traditional method. Additional possible improvements suggested by the new digital method are also raised.

Introduction

Digital radiography offers the possibility of increased accuracy in assessing fuel loading values of research reactor fuel plates.[1] This decrease in uncertainty would result in the potential to safely increase the power of the reactor when setting up conversions of research and testing reactors by knowing the loading more precisely. Digital radiography also offers a much quicker assessment of the fuel zone and plate quality, allowing a faster turnaround time on designs and modifications. It also eliminates the need for any chemical processing and storage of film radiographs.[2] Looking forward to fuel zone loading gradients which are required for some future conversions.[3]

Digital radiography may provide important three dimensional data that would be very difficult and expensive to obtain using the traditional methods. The digital information generated can be easily integrated into computer analyses and modeling programs. Due to the exclusion of radioactive materials in the digital radiography facility, tungsten was used as a surrogate fuel. Procedures successfully developed with tungsten as the "fuel" have been found to also apply to Uranium alloy fuel.[4] The plates were made by the dispersion method which is covered in more detail elsewhere.[5]

Traditional Nondestructive Analysis

The traditional method of nondestructive analysis has consisted of taking various radiographs of fuel plates and measuring the volume through the Archimedes water displacement method. These methods along with known parameters of the materials used to construct the fuel plate allow for

numerous key attributes to be calculated, most importantly, the fuel loading density. The radiographic component of this process is the most time consuming and is the greatest potential source of uncertainty.

Two types of radiographic exposures are used for each fuel plate, a shorter duration "location" exposure (see Fig. 1) and the more extended "density" exposure (see Fig. 2). The location x-ray is used for qualitative analysis of the location of the fuel and is used to detect any fuel in the non-fuel zone areas, the rails and ends of the plate (see Fig. 3). Fuel located in these areas is referred to as fuel out of zone (FOZ). The parameters for this exposure rarely need to change even with varying fuel types and loadings. However, the density x-ray parameters are more variable. With only a trial-and-error method to determine the appropriate values this can be a time consuming setup.

Due to the dimensions of the Torexx-150 x-ray machine and the fuel plate, the fuel zone was imaged in two separate films. Once the appropriate parameters (see Table 1) for the density radiograph have been determined, both radiographs are exposed and the developed films are analyzed using an X-rite Co. Model 301 analog densitometer calibrated via a standard film density strip. A known loading step wedge standard is used to calibrate the loadings of the unkown loading fuel plate in each film radiograph. The step wedge standard used in this study was a strip of tungsten machined at thicknesses varying from 0.035 cm (0.014 in.) to 0.023 cm (0.009 in.) in 0.0025 cm (0.001 in.) steps. In each density radiograph, each step height was measured five times, and then the mean value was calculated. These mean densitometer readings and the actual thicknesses of tungsten for each step were used in a quadratic regression to obtain a function relating the densitometer readings and the thickness of tungsten for each individual film radiograph (see Fig. 4).

Along the length of the fuel zone in each film (representing half of the overall fuel zone), three rows of ten measurements each were taken. These rows of measurements were taken 1 cm (0.4 in.)above, directly on, and 1 cm (0.4 in.) below the center line of the fuel zone. The densitometer readings from the fuel zones were then converted to equivalent thicknesses of tungsten using the quadratic fit equation determined from the standard. These thicknesses were then converted to fuel loading densities by the using the average fuel zone height as calculated from the Archimedes volume measurements.

In the Archimedes method, the volume of the fuel plate is measured using a dry weight and then a submerged weight, subtracting the two, and dividing the resulting mass by the density of water. Since the cladding does not change density during the rolling process and its mass is known (by subtracting matrix and tungsten charge weights from the total weight of the plate in air), it can be subtracted out, leaving the volume occupied by the fuel zone only. With the volume of the fuel zone known, the mass of aluminum and tungsten in the fuel compact can be used to determine how much of the fuel zone volume is occupied by fuel and how much is void. This information allows the overall fuel loading to be calculated for the fuel zone. This is an overall average and represents a good check versus the results of the radiographic analysis. These calculations also allow the average height of the fuel zone to be calculated once the area of the zone is measured on a location radiograph.

For overall general trends the radiographs were scanned and digitized. This allows colorization of the images with photo editing software. Colorization enables easy visualization of general and gross trends in the fuel loading and improves communication between the different collaborative groups involved in design and fabrication.

Beam Characterization

Because of the method used to do the analog densitometer readings, it is very difficult to take into account the variation in the beam of the x-ray source in the traditional nondestructive analysis. For this study the beam was characterized using a sheet of tantalum film exposed at the same parameters

as the fuel plate. Tantalum was chosen because of its closeness to tungsten in density, availability and the resulting film darkness. (see Fig. 5) The area of interest where the fuel plate and step wedge standard were located in the density radiograph was mapped using the densitometer. The densitometer measurements were normalized into correction factors by taking the maximum value and dividing it by each of the individual densitometer readings. The location of each measurement from the traditional nondestructive analysis was converted into a corrected value by taking the corresponding correction factor and multiplying the raw data value by it.

Digital Radiography

The digital radiography of the fuel plate was carried out on a Phillips MG 450 system using a Phillips MCN 421 tube and a PerkinElmer RID 1620 detector. The detector consists of an area of 2048 x 2048 individual detection cells each 200 µm (0.008 in) square. This results in a photosensitive area 409.6 mm by 409.6 mm (inches). The detector can be set to take exposures varying from 1/3 second to 16 seconds. Each cell can record a gray value over a range of 16 bits or approximately 65,000 gray values. This arrangement also allowed for CT scans to be taken. While fuel plate dimensions limit CT use, pre-roll fuel compacts are good subjects.

The digital radiography method allowed for real time adjustment of beam parameters with instant feedback available on a computer monitor resulting in the parameters listed in Table 2. Images were captured within a few minutes (see Fig. 6). These images were used to carry out a similar analysis as in the traditional nondestructive analysis, using a standard of steps to compare to the fuel zone and convert to fuel zone loading values. Photoshop 7.0 was utilized in the analysis, effectively replacing the analog densitometer from the traditional method.

The standard steps were analyzed more completely in the digital method. The central 1.14 cm x 1.6 cm region of each step was analyzed to determine the mean grayscale value of all pixels in that region. This represents 71% of the step being sampled versus 14% of the step being sampled with the five measurements using the 3mm spot size of the analog densitometer. The mean grayscale value was then correlated to the actual thickness of tungsten in each step via a quadratic fit function.

Within the fuel zone itself, measurements were taken at the same locations as in the traditional method. Further mimicking the traditional method, a circular area with a diameter of 15 pixels or 3 mm was selected and analyzed to determine the mean grayscale value at that location as well as the additional information of the standard deviation. The mean grayscale values were then converted using the quadratic fit function obtained from the stepped standard into equivalent thicknesses of tungsten and then into fuel zone loading densities.

After the fuel plate was imaged, a CT scan was taken of a fuel compact. The scan worked well in the central region of the compact. However beam hardening, which occurs due to the density of the fuel and the end on angle of those exposures, obscured the ends of the compact.

Digital X-Ray Corrections

Unlike the traditional radiographic technique, the digital method has built in corrections for both variations in beam strength and irregularities in the digital detector. These corrections are taken in the form of a hot frame, a dark frame, and a mask.

The hot frame is a blank frame of the beam taken at the same parameters as those used for the sample. This frame allows the software to take into account the variations in the beam strength across the detector. The dark frame is a frame taken when no x-rays are striking the detector. This allows the software to remove errors due to electrical noise in the system. The mask is a special set of pixels derived by selecting a narrow acceptable range of grayscale and then marking the cells outside that range for elimination from final frames. These eliminated cells are either dead or too bright due to a defect or malfunction of that individual cell. When the mask pixels are subtracted from a frame, they are replaced by an average value of the surrounding cells.

Not Addressed

Variations in x-ray film and the development process were not practical to address with this study. However, these effects would add to the uncertainty of traditional method while not affecting the digital method.

Results and Discussion

Results

Equivalent fuel fraction by volume is a measure of the amount of fuel that is present compared to the maximum amount possible if the fuel zone was solid fuel. The Archimedes method (see Table 3) is utilized to calculate the equivalent fuel fraction by volume of the plate. The known mass of the cladding and its density are used to calculate the volume of the plate that is not in the fuel zone. The plate is then weighed in air and weighed while submerged in water, allowing the volume of the entire plate to be calculated. Taking the cladding volume out of the overall volume leaves on the volume of the fuel zone. The masses and densities of the tungsten and aluminum powders allow the actual volume of the fuel material to be calculated. Dividing the volume of fuel material by the volume of the fuel zone results in a value of 51.2 volume percent tungsten.

The volume of the fuel zone from the above process can also be used along with width and length measurements of the fuel zone from location radiographs to calculate the average height of the fuel zone, using the assumption that the fuel zone is a rectangular prism. For this plate, the average height of the fuel zone was calculated to be 0.0485 cm (0.0191 in.). This height allows the equivalent fuel fraction by volume to be calculated from the density radiographs with the aid of the appropriate step wedge standard (see Table 4). It is important to note the assumption of the rectangular prism shape of the fuel zone. On the fuel plate used in this study, there appears to be some slight deviation from this ideal shape. The data in Table 4 for both methods as well as Fig. 3 and Fig. 6 reveal higher fuel fractions in the center of the fuel zone and strips of lower fuel fractions along the edges.

Traditional vs. Digital Fuel Fraction Results

Digital radiography gave average fuel volume percents of 51.3% and 51.1% with standard deviations of 2.67% and 4.34% respectively for each of the two radiographs. The traditional radiography method gave fuel volume percents of 54.8% for both radiographs with one having a standard deviation of 5.50% and the other 6.04%. These results show that the digital radiography method is a tenth of a percent off of the fuel fraction by volume, while the traditional method is off by 3.6% when both are compared to the Archimedes method results. The standard deviations reveal that the digital method gives more consistent results than the traditional method as well.

Visual inspection of Fig. 3 and Fig. 6 reveal that the digital method achieved a good range of gray values across the entire step wedge, while the traditional method only showed good variation across

the upper handful of steps. This property of the images certainly indicates that the digital method resulted better resolution and range in grayscale values. The simplest reason for this is the adjustment method for the exposure parameters. In the traditional method, each adjustment to the beam voltage or exposure time resulted in an entire set of films to be developed. Perfecting the exposure was prohibitively time consuming. With the digital method, as mentioned earlier, the image from the detector was displayed on a computer monitor and gave instant feedback as the beam voltage and integration time (the digital equivalent of exposure time) were adjusted. Another possible explanation for the differing gray ranges lies in the configurations of the two x-ray devices. The traditional method had the sample only

The traditional method shows a nonrandom shift to higher fuel fractions than determined by the other methods. This shift is most likely due to scattering from the porous, granular fuel material. The digital radiographic method utilized an integration (exposure) time of only 1/3 second. The traditional method had an exposure time of 45 seconds. The extra time for the traditional method allowed for more x-rays to be scattered and for the fuel zone to then appear lighter than the solid step wedge.

Three Dimensional Imaging

Brief efforts were made to use the three dimensional imaging capabilities of the digital radiography setup. The results were mixed. Due to the resolution limitations of the available detector fuel plates were not viable imaging targets. In place of a finished fuel plate, a powdered fuel compact was used to test the viability of the three dimensional imaging. The trial resulted in good detail and resolution through the central regions of the fuel compact. However, beam hardening left the edge on exposures saturated and unable to be analyzed. Beam hardening is due to the relative strength of the beam and the density of the target. Funding is being sought for further investigation of these capabilities.

Conclusions

Between digital radiography and traditional radiography, digital radiography has many decided advantages. The digital radiography shows greater accuracy when compared with the traditional radiography. The process for correcting the data to account for various sources of error such as beam variation, etc. is much simpler and already automated in digital radiography. Digital radiography takes a few minutes to attain a quality image and only a few more to manually analyze those images in an image processing software program. While the actual exposure time for traditional film radiography is no more than three minutes, the film must then be processed using hazardous developer and fixer chemicals. Data then must be collected by hand using the analog densitometer. These components add up to a significant amount of time as well as overhead with chemical processing and handling and maintenance of the automatic developer machine.

Digital radiography offers many more opportunities for accuracy and additional information (such as the standard deviation of fuel fraction over an area). It also facilitates sharing of images and information that is more difficult with the traditional method. The only drawback is the necessary investment in a dedicated digital detector and x-ray source set up in a controlled radiological area.

With the digital radiographic method, there exists the opportunity to construct a computer program which would automatically analyze the images once they are taken.[1] This could further increase the speed and efficiency of the nondestructive testing of RERTR fuel plates. The three dimensional capabilities of the digital method offer an opportunity to examine compacts before they are rolled into plates. It may be possible to characterize compacts in this way, and then determine if they

will perform adequately when rolled. The ability to eliminate defective or low quality compacts through three dimensional radiography could save the time and cost of replacing an out of specification plate.

REFERENCES

1. R. SALINAS, U. RAFF, and H. CORONADO, “Computer aided quality assurance of low enriched Uranium fuel plates used in non-power nuclear reactors,” *Meas. + Control*, **36**, 305 (2003).

2. B. CACCAMISE and L. JACOBS, “Digital Radiography Now and In the Future,” *Adv. Mat. and Processes*, January, p. 46 (2007)

3. R. PRIMM, R. ELLIS, J. GEHIN, and D. MOSES, “Design Study for a Low Enriched Uranium Core of the High Flux Isotope Reactor,”

4. R. DOMAGALA, et. al., “The Status of Uranium-Silicon Alloy Fuel Development for the RERTR Program”

5. Argonne National Laboratory, “Summary Report on Fuel Development and Miniplate Fabrication for the RERTR Program 1978-1990”

Figure Captions

Figure 1. A mosaic image compiled from four digital scans of location radiographs showing the entire length of the fuel zone. The fuel zone is 49.53 cm long.

Figure 2. Approximately 1.5 cm by 1.5 cm area at the corner of the fuel zone. The white arrow indicates a small collection of fuel particles that are outside of the fuel zone area.

Figure 3. A scanned image of a traditional density radiograph. The step wedge is in the top half of the image and the fuel zone is in the bottom half.

Figure 4. Graph displaying one of the quadratic regressions used to convert from densitometer readings to thickness of solid tungsten.

Figure 5. A digital scan of a traditional radiograph of the region of interest. The black border is made up of marking tape.

Figure 6. A digital radiograph with the brightness and contrast adjusted slightly to improve visibility.

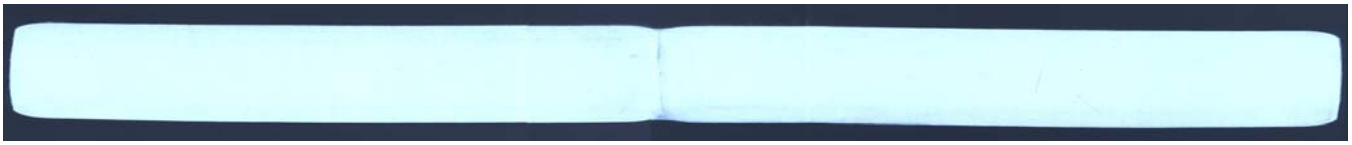

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Figure 1

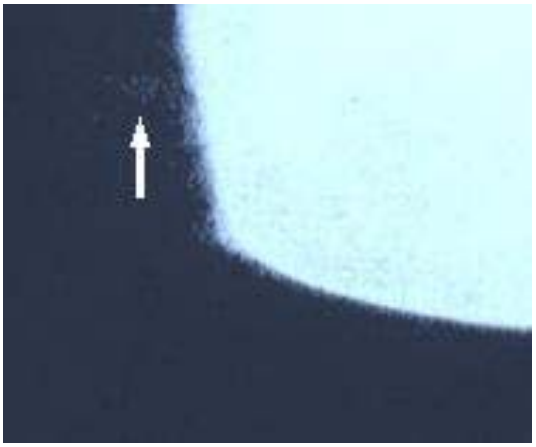

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Figure 2

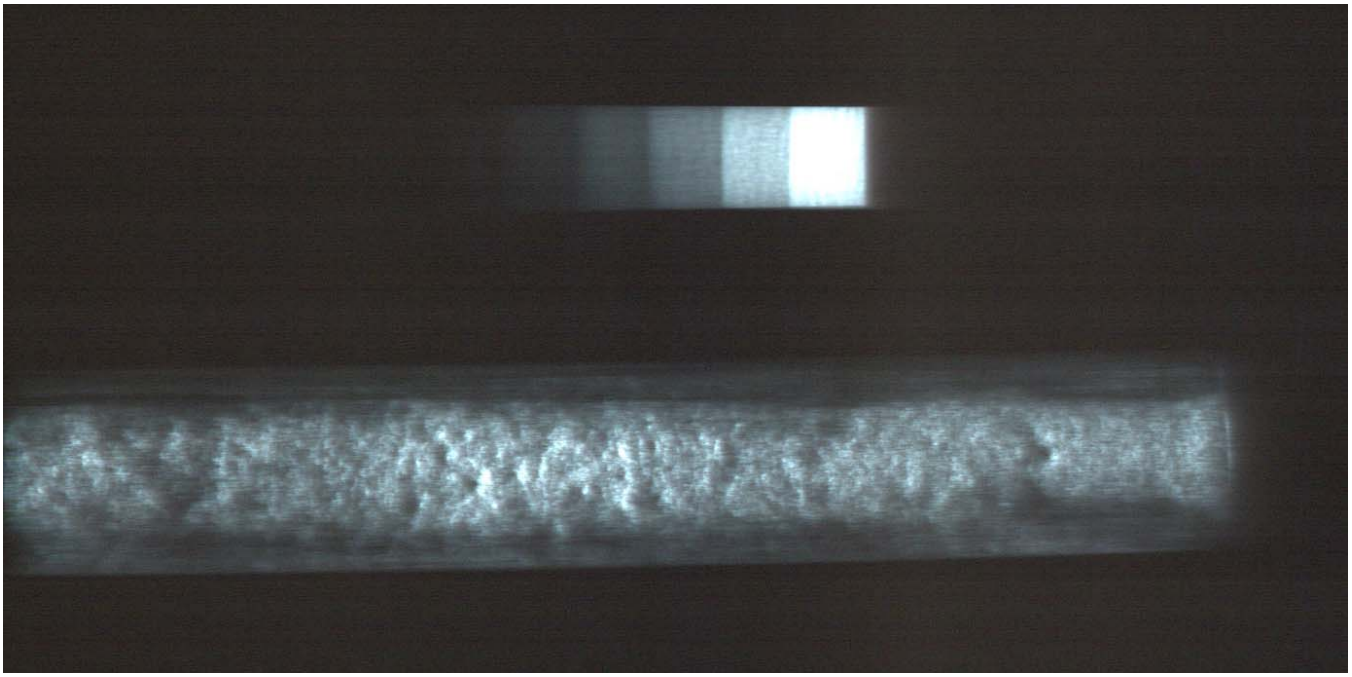

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Figure 3

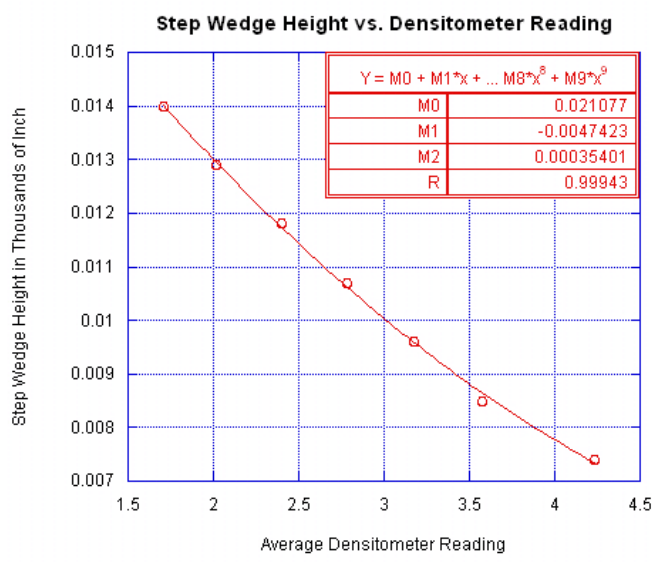

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Figure 4

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Figure 5

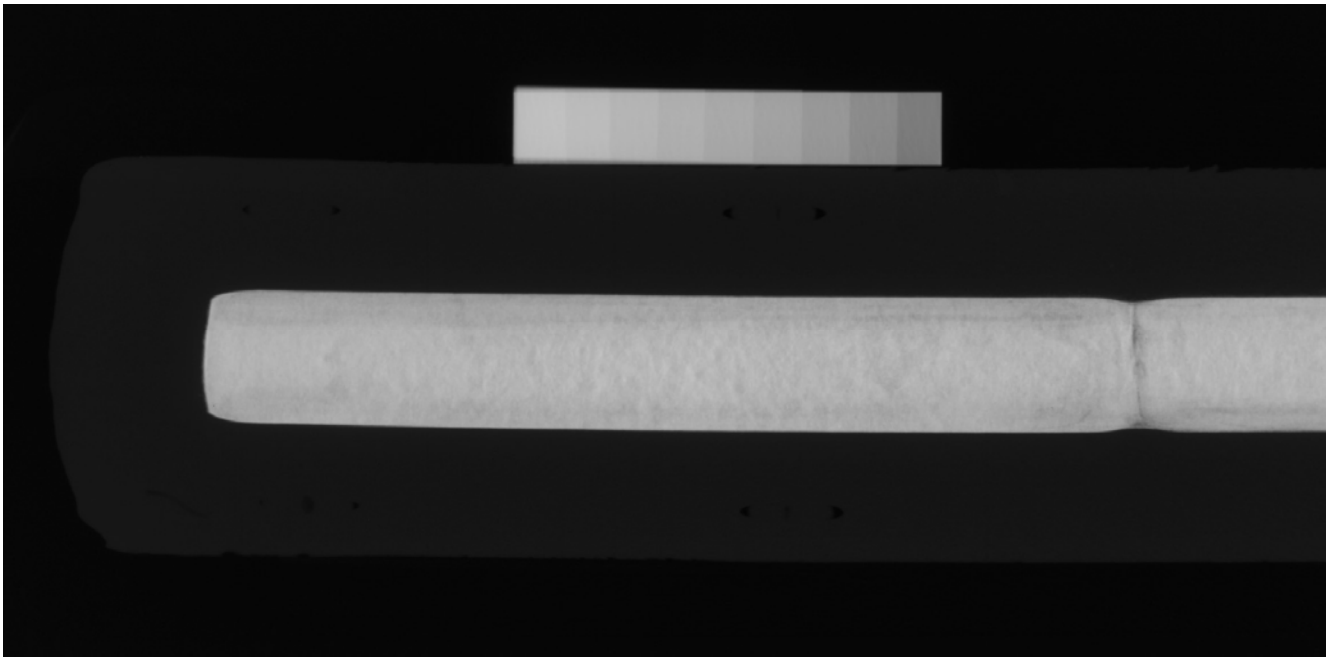

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Figure 6

Table 1. Parameters for Traditional Radiographs

Sample Distance	46 cm
Beam Voltage	140 kV
Beam Current	5 mA
Exposure Time	45 s
Detector	Kodak Industrex Film

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Table 2. Parameters for Digital Radiographs

Sample Distance	203 cm
Beam Voltage	460 kV
Beam Current	3 mA
Integration Time	1/3 s
Detector	PerkinElmer RID 1620

Table 3. Archimedes Method Density Calculations

Weight of Sample in Air	279.860 g
Weight of Sample in Medium	203.895 g
Density of Medium	0.9971244 g/cm^3
Volume of Sample	76.1841 cm^3
Volume of W (from compact measurements)	4.60958 cm^3
Volume of Cladding (from mass and density)	67.1763 cm^3
Volume of Fuel Zone ($V_{sample} - V_{cladding}$)	9.00769 cm^3
Fuel Loading ($V_{tungsten}/V_{fuel\ zone}$)	0.511739

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Table 4. Comparison of Digital and Tradition Fuel Fraction Values

	Digital Radiography Method						Traditional Radiography Method					
	Fuel Fraction Side A			Fuel Fraction Side B			Fuel Fraction Side A			Fuel Fraction Side B		
	Above	Mid	Below	Above	Mid	Below	Above	Mid	Below	Above	Mid	Below
0.5 cm	0.489	0.56	0.522	0.466	0.553	0.466	0.476	0.598	0.481	0.519	0.611	0.422
2.5 cm	0.466	0.523	0.507	0.466	0.551	0.462	0.515	0.625	0.501	0.549	0.586	0.497
5.0 cm	0.497	0.552	0.501	0.489	0.536	0.519	0.557	0.631	0.578	0.562	0.575	0.471
7.5 cm	0.492	0.535	0.494	0.459	0.517	0.541	0.505	0.588	0.496	0.577	0.566	0.458
10.0 cm	0.506	0.522	0.496	0.467	0.581	0.535	0.535	0.643	0.545	0.577	0.596	0.491
12.5 cm	0.488	0.534	0.515	0.485	0.578	0.527	0.532	0.621	0.537	0.548	0.614	0.489
15.0 cm	0.517	0.512	0.490	0.472	0.575	0.533	0.538	0.598	0.524	0.547	0.623	0.540
17.5 cm	0.502	0.530	0.497	0.469	0.558	0.510	0.521	0.608	0.532	0.541	0.655	0.463
20.0 cm	0.512	0.537	0.489	0.448	0.570	0.498	0.500	0.623	0.545	0.569	0.615	0.488
22.5 cm	0.527	0.597	0.478	0.434	0.549	0.505	0.466	0.588	0.432	0.578	0.644	0.460
Mean	0.513			0.511			0.548			0.548		
Std. Dev.	0.0267			0.0434			0.0550			0.0604		

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