.Non-Destructive Dimensional Analyses at INL's Hot Fuel Examination Facility

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Abstract

The BONA4INL measurement bench was installed in the Hot Fuels Examination Facility and became operational in early 2016. The measurement bench makes location-specific contact measurements set on a grid of 1, 2, 4, or 12 measurements per mm in the longitudinal direction. Measurements can be spaced along the axial direction with 0.1 degree (~0.157mm) accuracy. The bench has been tested with multiple standards and in one fuel campaign, resulting in extremely high resolution profilometry data. The first campaign to use the measurement bench following the measurement calibration and dimensional analysis was a full-size monolithic fuel element.

1. Introduction and Experiment Description

The United States Material Management and Mitigation (M^3) Fuel Development (FD) Program is tasked with advancing fuels in support of the conversion of high power research and test reactors from highly enriched uranium to low-enriched uranium fuel. [1] The FD pillar has overseen an array of plate-type-fuel experiments at both the mini-plate and commercial scale. The latest experiment in the fuel development campaign was designed to evaluate the performance of monolithic uranium-molybdenum (U–Mo) fuels in geometries which are prototypic of US high-performance research reactor (HPRR) fuel plates. [2] Four curved, commercial-scale plates were swaged into a mini-element and irradiated in the Advanced Test Reactor to moderate burnups.

A primary feature of interest in regards to qualifying fuel is the loss of coolability. This is driven by the fuel plates losing geometric stability due to excessive fuel swelling or excessive mechanical response under irradiation. This behavior can be quantified with the BONA4INL measurement bench, which was designed in a collaboration between Idaho National Laboratory and SCK-CEN. BONA4INL has been constructed, tested, and installed into the Hot Fuel Examination Facility (HFEF) for performing dimensional and eddy-current inspection of flat fuel plates, curved fuel plates, and fuel rods. [3] These measurements are performed using a motor to drive a measurement head over the surface of the plate while recording the location-specific measurement output (thickness and oxide). The measurement head is capable of moving in both longitudinal and transverse directions for measurement over a flat plate, longitudinal and rotational axis (phi) for measurement of a curved plate, and longitudinal and theta for measurement of a fuel rod. Measurements are taken using line scans down the length of the plate with transverse movement or rotation occurring between longitudinal line scans.

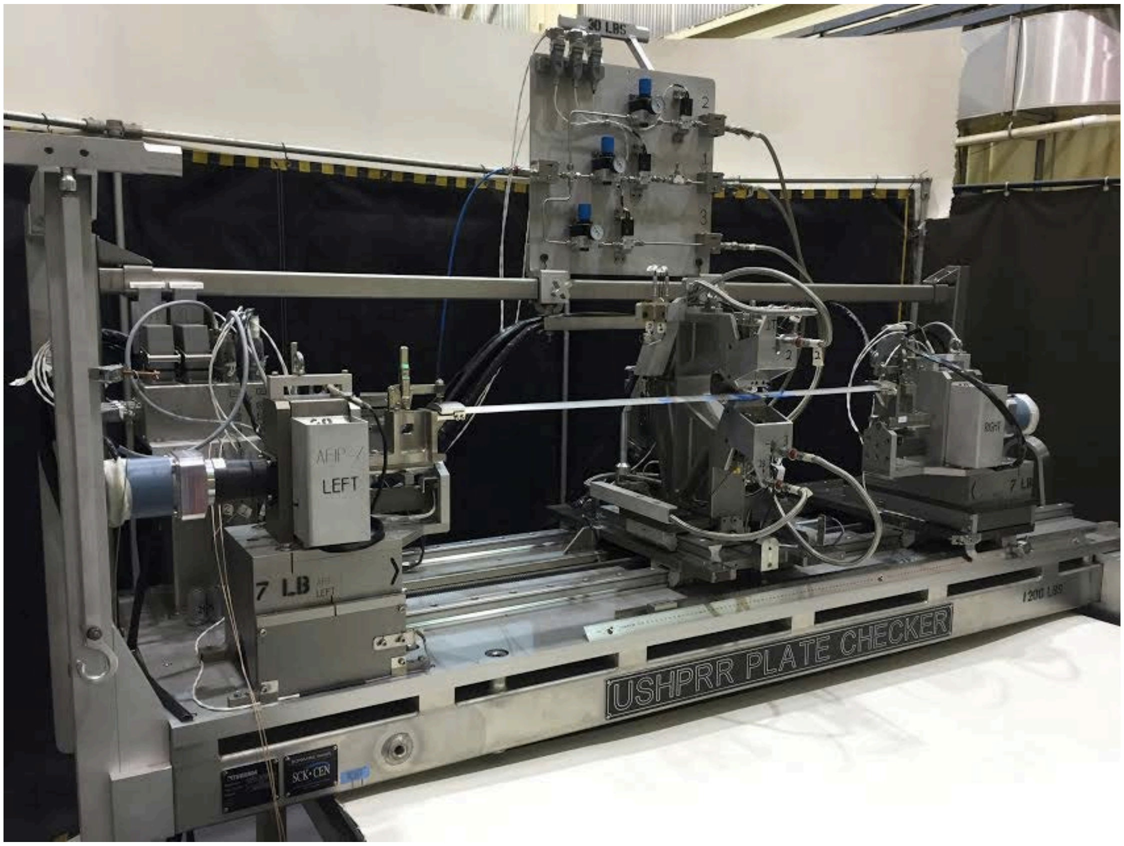

Figure 1 BONA4INL measurement bench prior to installation

Standards

In order to validate the accuracy of the location of the measurement probes after installation of the bench, which was quantified during the validation and verification phase of the bench, two standards with known geometric features were designed, fabricated and inspected at the MFC inspection laboratory. A ‘flat-plate’ standard was fabricated with evenly spaced ridges to verify longitudinal locations as well as a ramped region with a known slope, which would allow for evaluation of transverse locations. A ‘curved-plate’ standard was fabricated with evenly spaced ridges to again verify longitudinal locations as well as a ramped region with a known slope, which allows for evaluation of the rotation location.

The flat-plate standard was fabricated using aluminum alloy 6061 and is approximately 305 mm long, 57 mm wide, and 3 mm thick. Transverse ridges were machined into the top surface of the plate with nominally 25.4 mm spacing between peaks. Taking axial line scans down the length of the standard allows for verification that the output from the location encoders are providing distance-traveled values that correspond to the actual distance between the ridges. A transverse sloped region was also machined onto the surface of the standard with a known slope. Taking axial line scans down the sloped region allows for the calculation of the transverse step size using the differential thickness and known slope.

The curved-plate standard was fabricated using aluminum alloy 6061 and is approximately 305 mm long, 63 mm wide, and 3 mm thick, with an internal radius of curvature of 90.47 mm. Transverse ridges were machined into the top surface of the plate with nominally 25.4 mm spacing between peaks. A transverse sloped region was also machined into the surface of the standard with a known slope. Taking axial line scans down the sloped region allows for the calculation of the rotational step size using the differential thickness and known slope.

The flat-plate standard was loaded into the BONA4INL bench in the flat-plate configuration such that line scans could be taken axially down the plate. Ten line scans were performed down the length of the standard, with transverse spacing between scans of 5 mm (55–100 mm). Twelve measurements per millimeter were taken during the scans.

The measurement bench was then adapted to curved-plate configuration, and the curved-plate standard was loaded into the bench. Eight line scans were performed down the length of the standard with 5 degrees of rotation between scans (0–35 degrees). Twelve measurements per millimeter were taken during the scans.

The resulting data (longitudinal, transverse, or rotational location, and thickness) were recorded. A graphical representation of the resulting measurements can be seen in Figure 2 and Figure 3. The transverse ridges, as well as the sloped region, are clearly visible on both standards. Analysis of the data was also performed to identify discrepancies between the distance between measured peak values and the nominal distances from post-fabrication inspection. The average value of these discrepancies as well the standard deviation and maximum discrepancy are shown in Table 1 through Table 4.

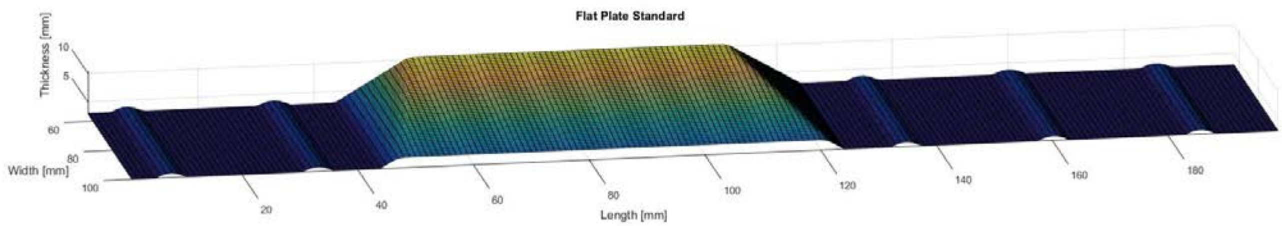

Figure 2: Flat plate standard results surface profile

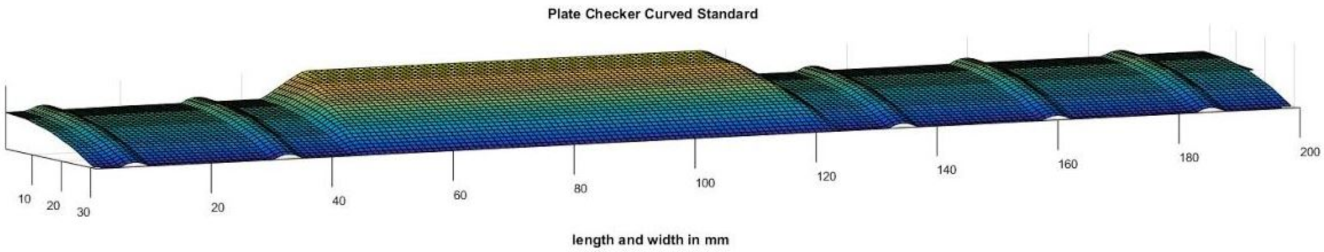

Figure 3: Curved plate standard results surface profile

Table 1 Location discrepancy for the flat plate standard

Discrepancy Average (mm)	0.0319
Discrepancy Deviation (mm)	0.0178
Discrepancy Maximum (mm)	0.0660

Table 2 Longitudinal Location discrepancy for the curved plate standard

Discrepancy Average (mm)	0.028
Discrepancy Deviation (mm)	0.017
Discrepancy Maximum (mm)	0.064

Table 3 Rotational discrepancy for the curved plate standard.

Discrepancy Average (degrees)	0.101
Discrepancy Deviation (degrees)	0.053
Discrepancy Maximum (degrees)	0.163

Table 4 Measured thickness Vs nominal discrepancy

Discrepancy Average (mm)	0.013
Discrepancy Deviation (mm)	0.010
Discrepancy Maximum (mm)	0.032

Monolithic Fuel Element

The AFIP–7 mini element was designed with four commercial-scale fuel plates in order to evaluate the performance of monolithic U–Mo fuels in geometries specific to US research reactors. Each fuel plate is approximately 1000 mm long, 63 mm wide, and 1.27 mm thick, curved, and swaged into end blocks. [4] The four AFIP–7 plates were removed from the element and, following the verification of the BONA4INL measurement bench, the MMM FD program began non-destructive examinations on irradiated fuel plates. Four AFIP–7 curved fuel plates were the first to be measured in this campaign.

Multiple longitudinal scans were performed to investigate the effects of measurement grid, data repeatability, and any systematic variations by changing from nominal orientation (measurements start at top left and end at the bottom right of the plate) to reverse orientation (plate is reversed in holder such that the measurements start at the bottom right and end at the top left of the plate.

Table 5: AFIP-7 Plate 4 Scan Data

	Orientation	**Longitudinal Resolution (mm)**	**Transverse Resolution (Degrees)**	**Data Points**	**Purpose**
Plate 4 Scan 1	Nominal	2	2	36818	Nominal Scan
Plate 4 Scan 2	Nominal	1	5	6287	Evaluate resolution based effects
Plate 4 Scan 3	Reversed	1	5	6463	Evaluate orientation effects

Scans one and two of plate four were taken, one immediately following the other, with the same orientation and unique resolutions. Scans 2 and 3 were taken at the same resolution, but int the opposite orientation. Figure 4 shows the three scan results for plate ZH4, oriented and normalized to the first scan. The features found in the first scan were verified in both succeeding scans. These features include a low-swelling region on the top and bottom of the plate and peak swelling near 650 mm down the left edge of the plate.

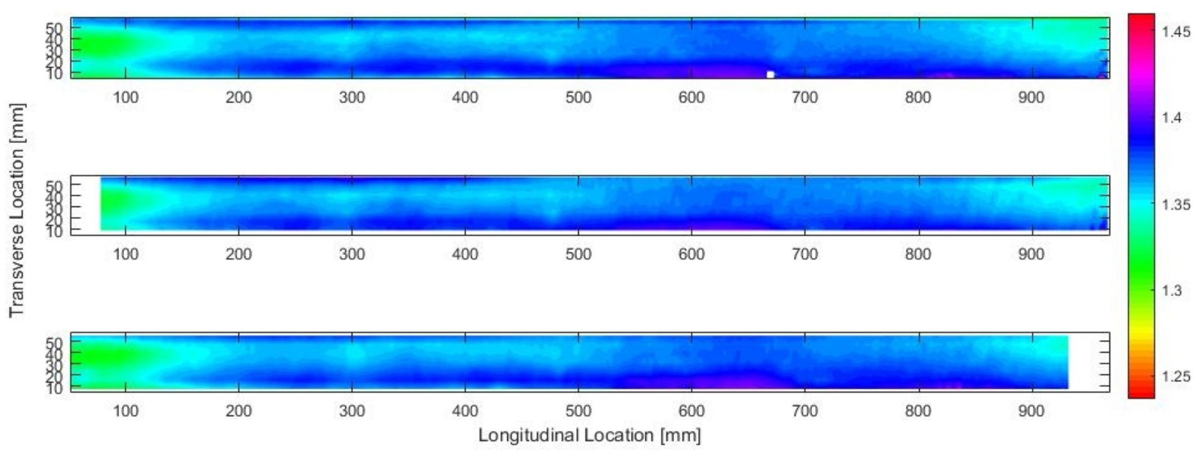

Figure 4: Contour Plot of AFIP-7 Plate 4’s Repeated Scans. (Top: Scan 1, Middle: Scan 2, Bottom: Scan 3)

The same scans were used to render the surface profiles shown in Figure 5. The higher-resolution scan 1 captures plate edges, where the two lower-resolution scans do not. The three scans do not show appreciable difference from the others. The reverse scan shows that there is not a cyclical bias from the scanning system itself, with an average absolute deviation of

~1.4 microns. The two scans with different resolution also verify that the system is not biased with reference to its resolution settings. The average absolute deviation between scan 2 and 3 was ±2 microns, showing high precision.

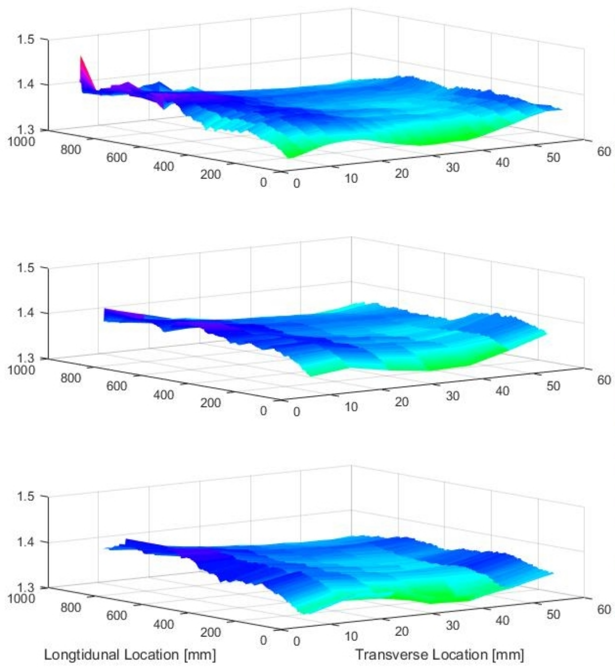

Figure 5: Surface Plot of AFIP–7 Plate 4 Repeated Scans. (Top, Scan 1; Middle, Scan 2; Bottom, Scan 3)

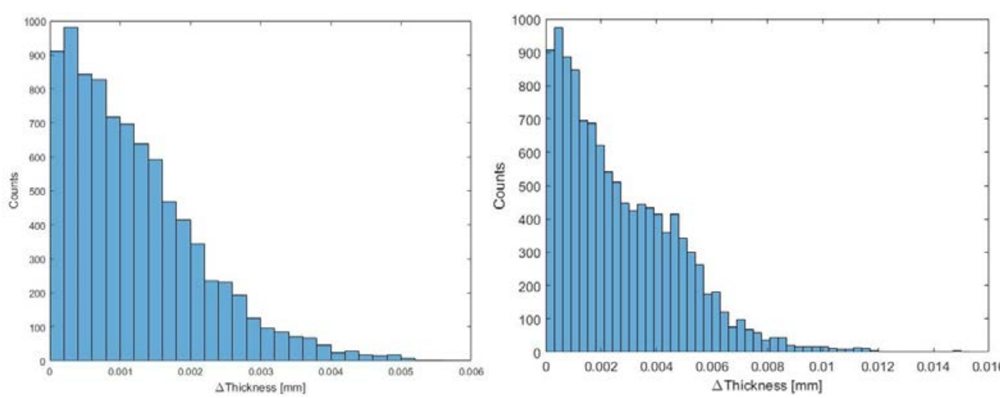

Figure 6 Figure: Thickness Variation between Scan 1 and Scan 2 (Left) & between Scan 2 and Scan 3 (Right)

AFIP–7 Plate 1 was used to investigate the repeatability of the measurement results by performing identical scanning parameters. The scanning parameters were two measurements per millimeter in the longitudinal direction and two degrees of rotation between line scans. Figure 7 and Figure 8 show the repeated-scans corrected thickness. Figure 9 shows an approximate one micron deviation between the two identical scans.

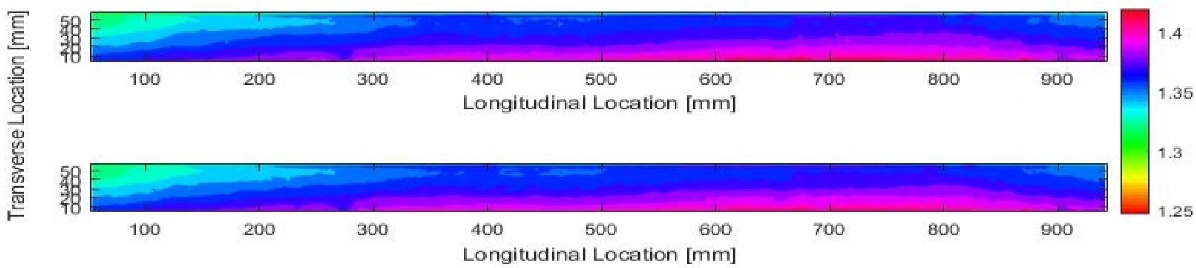

Figure 7: AFIP–7 Plate 1 Repeated Corrected thickness of Scan 1 (Top) and Scan 2(bottom)

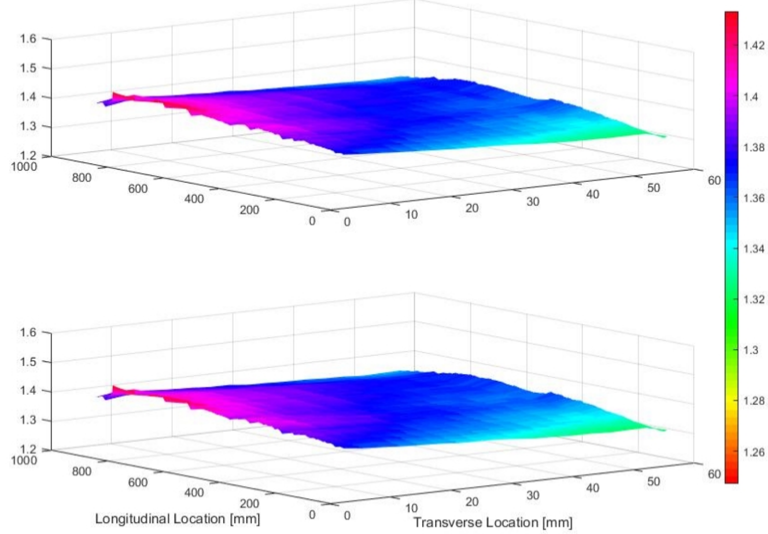

Figure 8: Surface Plot of AFIP–7 Plate 1 Repeated Scan 1 (Top) and Scan 2 (Bottom)

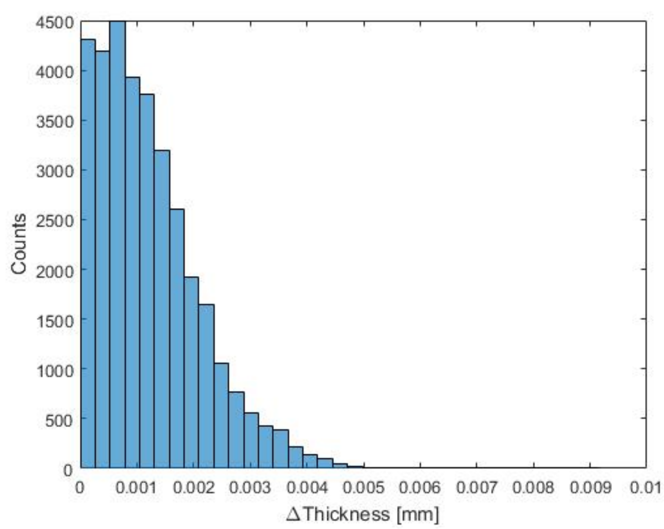

Figure 9: Thickness Variation between Plate 1 Scan 1 and Scan 2

2. Conclusions

The dimensional inspection of two location standards was completed using high-resolution axial scans of both a flat and curved standard. The resulting data analysis indicated that when inspecting a flat plate, the longitudinal location of the markers could be identified to within 0.031 mm and the transverse step size was accurate to 0.013 mm. When measuring curved plates, the longitudinal location of the markers could be identified to within 0.030 mm, and the rotation of the plate was accurate to 0.10 degrees (or ~0.1575 mm).

The measured accuracy of the measurement-head longitudinal location was determined to be an order of magnitude greater than was prescribed in the requirements document by the MMM FD program. The rotational accuracy, which was measured at 0.1 degree, was on the order of magnitude of the requested accuracy for rotation. However, this is likely due to the fabrication uncertainty of the sloped region of the curved plate (±0.31 degrees across the standard) resulting in fluctuations in the resulting data. The actual accuracy of the bench is likely greater than the value calculated due to limits of the machined parts.

Based on imperfections in the standards, such as parallelism of the ridges and fluctuations in slope, limitations exist on the ability to determine accuracy using these standards. It is likely that the measurement bench is collecting data with accuracy greater than the fabrication and quantification of the standards could realize.

The fuel-plate study, on plates with an unknown geometry, is focused on precision and repeatability. The absolute deviations between the scans is shown to near 1 micron, with the largest deviation, approximately 2 microns, coming from inverting the plates in the holder. The thickness data collected using the BONA4INL measurement bench is currently significantly higher in resolution than any other data and parameters with which the results are used in conjunction; for example, they have higher resolution than irradiation conditions, mechanical properties, etc. This will allow the user to down-sample post-irradiation thickness measurements onto the appropriate grids with statistical validity. Having high accuracy and precision will allow for a better understanding of local fuel behavior in both the AFIP–7 campaign and campaigns to come.

3. References

4.

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[3] A. Robinson, Y. Parthoens, S. VandenBerghe, R. Lind and W. James, "Design, Fabrication, Modification and Installation of the BONA4INL Measurement Bench," in *HOTLAB and Remote Handling* , Leuven, Belgium, 2015.

[4] D. M. Perez, J. W. Nielsen and e. al., *AFIP–7 Irradiation Summary Report*, INL External Report INL/EXT-12-25915, 2012.