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Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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Abstract:
As nuclear fuel plates get irradiated, their thicknesses change. How the fuel plate changes with irradiation is a significant parameter that is an important factor in predicting fuel performance in new fuel systems. The channel gap probe (CGP) is used to indirectly infer changes in fuel plate thicknesses by measuring the gaps between the fuel plates contained within capsules after each irradiation cycle. Independent measures should be used to corroborate salient measurements such as changes in fuel thickness which help ascertain fuel performance. The use of traditional metrological tools to validate CGP measurements are not practical due to the capsule geometry. The accuracy of the CGP inserted within a capsule has not been verified. Since there is no "gold" standard measurement to verify CGP measurements, an optical profilometer has been used to corroborate the CGP measurements. The optical profilometer has been able to corroborate the capsules channel gaps to within 0.025 mm for both ends of the capsule. The optical profiler is also able to measure plate thickness that matched micrometer measurements to within 0.033 mm. The profilometer is also corroborated with the CGP measurements.

SECTION I.

Introduction

Changes in nuclear fuel thickness is a significant performance parameter for developmental fuel types [1–3]. To determine the performance of new, commercially fabricated, U-10Mo monolithic plate-type fuel, an irradiation campaign has been planned that consists of multiple mini-plate capsules. Eight mini-plates that are either fueled or "dummy" plates are contained in each capsule. The fuel thickness changes within a capsule are monitored by measuring the spacing between the plates with ultrasound. The channel gap probe (CGP) system measures the spacing between the plates.

While ultrasound time-of-flight techniques are commonly used to make spacing and thickness measurements, it can be very difficult to verify the measurements for assembled complex components. Typically, physical standards are used that are carefully fabricated and then metrologically scrutinized. For the mini-plate spacing within a capsule, it is difficult to access the spacing with typical metrological tools as shown in Fig. 1. Radiological imaging can be a useful tool for measuring, but it is not very practical on the shop floor. A measurement technique that can be automated during fabrication would be ideal.

Fig. 2 shows a fuel plate that has blistered. The blister may interfere with coolant flow in the channel gap. The channel gap probe is designed to make in situ channel gap measurements in the reactor canal between irradiation cycles [4], [5]. Blisters and other geometric distortions that may adversely affect coolant flow provide motivation for this effort. It is important to understand the resolution of the probe in the capsule because the resolution determines the threshold at which geometric distortions can be identified and tracked.

While the drawings of the capsules provide nominal dimensions, fabrication tolerance stack up and capsule sealing (welding) can shift the actual location of the plates. The channel gap probe has a resolution of < 0.0254 mm [4], but the actual accuracy of the probe within a capsule is unknown. A qualified standard capsule is not practical to fabricate. The CGP does have a carefully crafted and measured calibration block, but the block has transition sections between step gaps and the surfaces are polished. Thus, there is a chance that the behavior of the CGP within the capsule environment may influence the measurements.

Fig. 1.
Access for physical measurements is at the ends of the fully assembled capsules and is confounded by the capsule geometry. The outside width between the flat surfaces is nominally 23.4 mm.

For most applications in measurements, the hardest part of the job is to confirm/verify the measurements that are being made. Unfortunately, there is no “gold” standard measurement to compare with capsule CGP measurements. This paper focuses on using an optical profilometer to provide geometrical information from the capsule, plates, and gap geometries. Corroborative measurements have been made between the CGP, an optical profiler, caliper and a micrometer. The comparative results are then discussed.

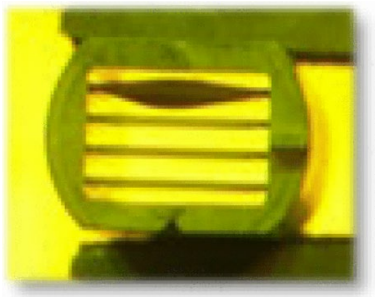

Fig. 2.
Fuel plates can blister which may interfere with coolant flow through the channel gap as seen in the photograph. The outside width between the flat surfaces is nominally 23.4 mm.

SECTION II.

Measurment Techniques Review

A. Channel Gap Probe

A comprehensive discussion of the CGP construction and application can be found in [4]. A schematic of the CGP and the measurement wand are shown in Fig. 3. The capsule is placed in a holder in the canal and the CGP is lowered onto the capsule. The wand is inserted into each channel gap and ultrasonic time-of-flight measurements are made as the wand is being extracted. The ultrasonic time-of-flight measurements are converted into temperature corrected gap width measurements down the centerline of the plates.

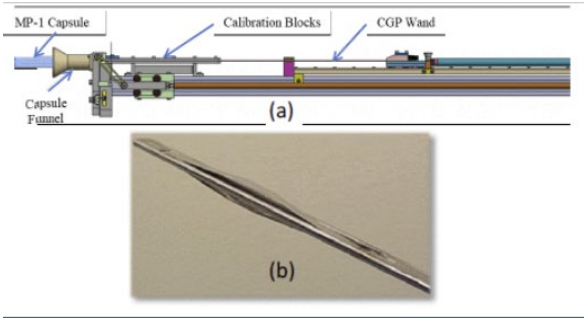

Fig. 3.
The cgp measurement system is shown and consists of the measurement frame (a) and the sensing wand that is inserted in the gaps of the capsule (b).

The CGP is calibrated by using a calibration block attached to the probe as shown in Fig. 3. The calibration block is used to both calibrate the sensor wand and check its calibration. The calibration, calibration check, and data collection occur after the wand is inserted through the calibration block and the capsule. Data collection occurs when the probe is withdrawn as the metal strip needs to be stiffened by tension to prevent buckling during the measurement. The CGP calibration check as well as the calibration [4] uses three channel gap widths of 4.7 mm, 3.96 mm, and 3.2 mm. The maximum and the minimum thicknesses are chosen to encompass the expected range of the channel gap measurements for capsules under test.

The CGP wand is calibrated at the beginning of an experiment series. The calibration is checked each time the wand is withdrawn. If any one of the block widths are off by more than 0.0254 mm, the CGP wand is recalibrated. The actual cause for the probe going out of calibration is unknown but a recalibration is occasionally needed. The CGP wand does contain a thermal couple that is located 44.45 mm above the ultrasonic crystals. The function of wave speed in water with respect to temperature is well known and temperature changes can be compensated for, but the probe can still drift off calibration.

The independent verification of the CGP measurements within the capsule will validate the calibration process and ensure that the wand is not affected by traversing it to the capsule and being inserted into the gaps between the plates. A slight twist in the wand has been shown to affect the gap measurements [4].

B. Optical Profiler

Dimensional inspection has conventionally been conducted by contacting tools like calipers, micrometers, or contact profilometers. These touch probes are not practical for measurements in an assembled capsule. Noncontact optical/laser triangulation sensors have the right characteristics to perform measurement at the capsule ends [6–8]. Optical triangulation is suited for these types of measurements because it combines non-contact inspection with the capability to measure with sub-micron resolution. Triangulation technology is useful for 2-D profiling.

Profilers that use laser triangulation calculate height by measuring light reflected off a specimen. The profiler's laser diode projects a beam of light onto the fabricated component. A small fraction of the light is reflected from the surface of the component onto a light-sensitive photodiode array built into the sensor as shown in Fig. 4. The sensor array records the location of the reflected beam that has been distorted by changing surface heights and reports a height measurement at the nominal location of the line.

A commercial laser line profiler has been used to provide geometrical measurements along a line. The measurements from the line profiler can be translated to provide three-dimensional information. For the fuel plate application, the sensor is held fixed and only provides profile measurements.

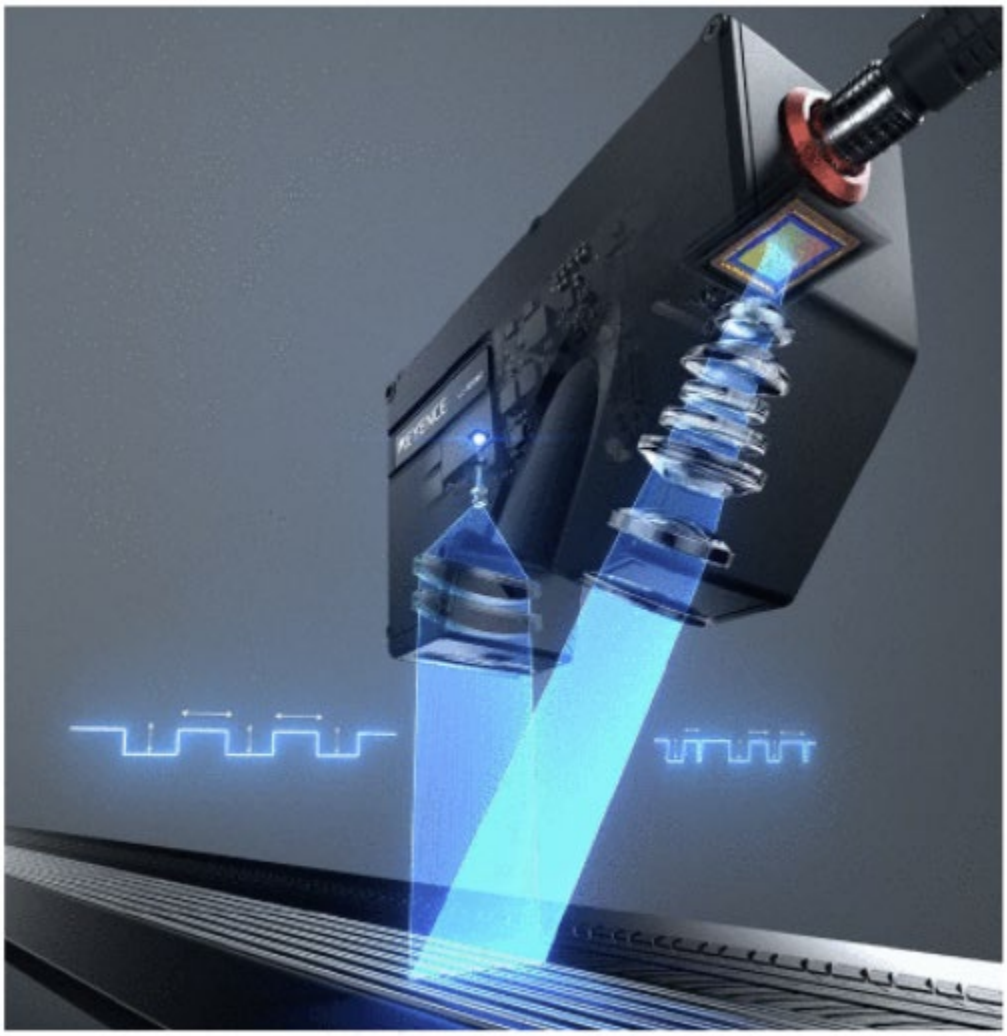

Fig. 4.
An optical profiler has been used to make geometric measurements of the capsule, plates, and gaps. Digital image from lj-x8000 series product guide used with permison from Keyence.

SECTION III.

Experiment and Discussion

A “dummy” capsule filled with eight blank (nonfueled) plates was fabricated. The nominal dimensions of the plates were 25.4 mm ×102 mm ×1.09 mm. Prior to the assembly of the plates into the capsule, the centerline of each plate was manually measured using a micrometer. Despite knowing the plate thicknesses and the capsule geometry from the drawings, uncertainty remained in the location of the plates due to fabrication tolerances.

The optical profiler has been used to find the salient dimensions of the capsules and plates. The optical profiler measurements will be compared by combining Idaho National Laboratory's measurements-CGP and micrometer-to provide equivalent information. In this manner, accuracy of the CGP will be corroborated. The schematic of the capsule is shown in Fig. 5.

Plates 1–4 can be seen by looking at End 2 of the capsule. Plates 5–8 can be seen looking at End 1. The overall inside capsule widths for the two ends have been measured by a handheld caliper and the resulting widths are given for each end.

The optical profilometer has been used to measure the following geometric dimensions at both ends: individual plate thicknesses; gaps between the channels; and gaps along the walls (left and right). To provide the equivalent mechanical measurements, the CGP and a handheld micrometer were used. The micrometer provided the plate thickness measurements prior to capsule loading. Once the capsule was fully fabricated, the CGP was used to measure the gaps between each plate. The CGP measurements for the gaps along the capsule walls were not reported. The capsule walls were rough relative to the CGP resolution (<0.0254 mm). Thus, the CGP did not provide robust measurements along the walls. The resulting data were compiled for comparison between plate thicknesses and gaps between plates as shown in Table I.

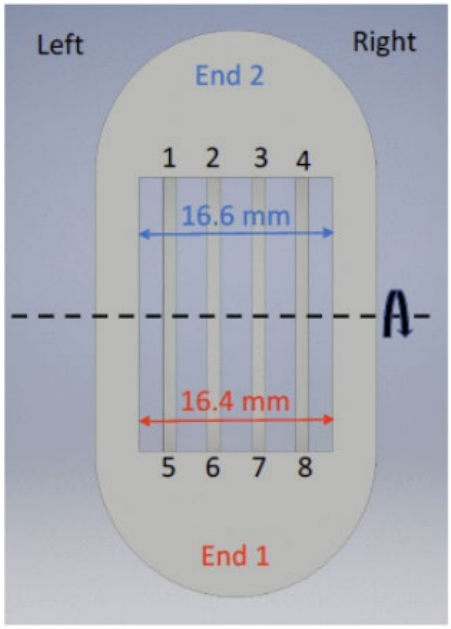

Fig. 5.
Schematic of a capsule end is shown with the plate numbers coresponding to each end along with the caliper measurements of the overall inside width of the capsule dimensions for the two ends. To switch between the ends and examine the coresponding plates, the capsule is rotated around the horizontal axis.

The channel gap widths for each channel between plates were determined by taking the average of three measurements which is the standard procedure for irradiated capsule testing. The nominal standard deviation is 0.0076 mm. The optical profilometer made three measurements of the Inside Width of the capsule wall for both ends and the resulting standard deviations are 0.0073 mm for End 1 and 0.0622 mm for End 2. Three optical measurements were used to measure the plate thicknesses, channel gaps and wall gaps for both ends. The nominal standard of deviation for the optical profilometer measuring plate thicknesses and gaps on both ends is 0.02 mm. Three caliper measurements were made to determine the Inside Width of the capsule. The resulting standard deviation is 0.043 mm for End 1 and 0.051 mm for End 2. The plate thickness measurements were made at the fabrication shop by a micrometer measuring down the centerline of the plate and a standard deviation for the measurements was not reported with the nominal thickness values.

Table I shows that the plate thickness agreements between the optical profilometer and the micrometer measurements were close to or less than 0.0254 mm for both ends. The gap width agreements between the optical profilometer and

the CGP were also precise (≈ 0.0254 mm) for both ends. Because the CGP could not accurately measure the gaps along the side walls, only the combined total of the four plates and the gaps between the plates were reported as Total Width. The differences in Total Width between the optical profiler and the INL measurements were close to the measured resolution of the CGP (0.0254 mm).

Table I tends to show a systematic bias in the differences between the optical and the mechanical measurements for End 1. The optical measurements are made at the outside edges of the plates while the micrometer and the CGP measurement are made in the interior of the plate. The Micrometer and CGP report a tight distribution of values for the plates' interior thicknesses and gaps in both Plate Spacing tables. The micrometer and CGP report a nominal value representative of the middle section in the plates. The optical profilometer reports tightly distributed values for the plate thicknesses and gaps at edges for one end of each plate. Thus, the systematic difference can be caused by measurements taken at different locations on the plates. Since the differences are near the resolution of the CGP, this is not a concern in the effort to corroborate the CGP with the optical profilometer.

The optical profilometer was used to measure the channel gaps along the capsule walls. The optical profilometer Total Width measurements were added to the wall gaps that resulted in the Inside Width measurements for the two ends. Inside Width measurements were also made by using a handheld caliper. The resulting Inside Width measurements were reported and compared in Table II for both ends.

The results in Table II are comparable. For End 1, the optical profilometer and the caliper agreed to within 0.028 mm. The differences between the two measurements were close to the resolution of the CGP which was notable given the number of plates and gaps that were individually measured by the profilometer. The plate spacing measurements (Total Width) from the physical measurements corroborated with the profilometer as shown in Table I.

Table I The plate thicknesses and channel gaps are displayed for the laser profiler and the INL measurements (CGP micrometer). The individual measurements are comparable as well as the combined sums between the measurement types.

Plate Spacing: End 2								
Measurement Type	Plate 1 (mm)	Plate 2 (mm)	Plate 3 (mm)	Plate 4 (mm)	Gap 1-2 (mm)	Gap 2-3 (mm)	Gap 3-4 (mm)	Total Width (mm)
Optical	1.083	1.100	1.117	1.096	2.700	2.713	2.696	12.504
Micrometer, CGP	1.095	1.095	1.095	1.091	2.692	2.708	2.695	12.471
Difference	-0.012	0.005	0.002	0.005	0.008	0.005	0.000	**0.032**
Plate Spacing: End 1								
Measurement Type	Plate 5 (mm)	Plate 6 (mm)	Plate 7 (mm)	Plate 8 (mm)	Gap 5-6 (mm)	Gap 6-7 (mm)	Gap 7-8 (mm)	Total Width (mm)
Optical	1.108	1.104	1.117	1.117	2.683	2.687	2.696	12.512
Micrometer, CGP	1.087	1.090	1.093	1.084	2.692	2.720	2.708	12.474
Difference	0.021	0.014	0.024	0.033	-0.009	-0.033	-0.012	**0.038**

Table II The inside capsule width comparison between the optical profilometer and a standard hand caliper measurement. There is reasonable agreement between the measurement techniques.

Measurement Type	Plate Spacing (mm)	Wall Gap Left (mm)	Wall Gap Right (mm)	Inside Width (mm)
Optical	12.504	2.105	2.071	16.679
Caliper	—	—	—	16.624
Difference	—	—	—	0.055

Inside Capsule Width: End 1

Measurement Type	Plate Spacing (mm)	Wall Gap Left (mm)	Wall Gap Right (mm)	Inside Width (mm)
Optical	12.512	2.041	1.817	16.370
Caliper	—	—	—	16.361
Difference	—	—	—	0.009

For End 2, Inside Width, comparison results were also comparable. Despite the large standard deviation in the optical profilometer for End 2, the difference with the caliper is 0.055 mm. The difference between the optical profilometer and the caliper is slightly smaller than the standard deviation of the profilometer for End 2. One of the three measurements used for the standard deviation calculation was notably lower in value than the other two, perhaps there was a piece of foreign matter on the capsule wall for that single measurement.

Corroboration of measurements is a major reason why multiple measurement techniques are used to make similar measurements. An inconsistency between the techniques provides feedback for the technicians to further investigate the differences. This happened in the making of this paper, the original caliper values reported for End 2 in Table II were actually measurements made from End 1. This oversight was detected by noticing that the optical profilometer measurements did not agree with the caliper measurements. The conflicting measurements were investigated. The optical profilometer provided a reason to remeasure End 2 and the resulting caliper remeasurements agreed with the optical profilometer measurements.

SECTION IV.

Conclusion

The evolution of nuclear fuel thickness from irradiation is a parameter that contributes substantially to fuel performance for developmental fuel types. Changes in fuel thickness within a capsule are indirectly monitored by the CGP. The CGP is designed to make in situ channel gap measurements in the reactor canal between irradiation cycles.

Critical measurements such as channel gap width should be validated by independent methods. The complex capsule geometry can make it difficult for traditional metrological tools to verify the CGP measurements. The CGP has a known resolution but the accuracy of the probe within a capsule has not been verified.

There is no “gold standard” measurement to compare with capsule CGP measurements. In lieu of a “gold standard,” an optical profilometer has been used to corroborate the CGP measurements. The optical profilometer is also able to provide dimensional information on plate thickness as well as gap widths.

To corroborate the additional information provided by the optical profilometer, Idaho National Laboratory used mechanical measurements of plate thickness, Inside Capsule Width measurements and CGP gap widths. The optical profilometer corroborated the plate thicknesses and channel gaps to within 0.033 mm for both ends.

Because the CGP cannot make reliable measurements along the capsule walls, use of a handheld caliper was necessary to measure the Inside Capsule Width for both ends of the capsule. The Inside Width for both Ends 1 and 2 of the capsules as measured by the profilometer matched with the caliper measurements to within 0.055 mm worst case. The measured resolution of the channel gap probe is 0.0254 mm thus, even the largest difference between the optical profilometer and the CGP measurement is only twice the measured CGP resolution. The worst case measurement difference is close to the functional specification for accuracy, 0.051 mm, that the CGP needs to meet. The optical profilometer, micrometer, caliper and CGP have provided measurements that corroborated with each other to the necessary tolerance needed for measuring channel gap widths in irradiated fuel capsules.

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