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Nondestructive inspection of fresh WWER-440 fuel assemblies

M. Bastürk *, H. Tatlisu, H. Böck

Atomic Institute of the Austrian Universities – TU Wien Stadionallee 2, A-1020 Vienna, Austria

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Abstract

This paper describes the investigation of two WWER-440 fuel assemblies in order to determine the upper and lower ends of the active fuel by means of high resolution neutron radiography images. The neutron radiography measurements of the fuel assemblies with 1.6 and 3.6 wt% ^{235}U enrichment were performed in the neutron radiography working-station II at the Atomic Institute of the Austrian Universities. With this study, we prove that samples much bigger than the neutron beam size can be investigated even in small neutron radiography facilities.

1. Introduction

The unused hexagonal fuel assemblies containing 126 fuel-rods for WWER-440 reactors are kept in the unused fuel storage of the Atomic Institute of the Austrian Universities (ATI-Vienna) and are used regularly in IAEA safeguard training courses. To adapt their lengths to the storage height, the fuel assemblies had to be shortened to the total length of 210 cm. The WWER-440 fuel assembly consists of the fuel-rod bundle, cap, tailpiece and jacketed tube as shown in Fig. 1. The fuel-rods within the bundle are connected by the honeycomb-type spacing grids being mounted on the central tube and by the lower support grid mounted on the tailpiece [1,2].

In this study, we have investigated beginning and end of the active fuel positions within two WWER-440 fuel assemblies by neutron radiography (NR) at the Atomic Institute of the Austrian Universities (ATI-Wien). Moreover, the inner defects, if present, were inspected nondestructively.

2. Experimental setup

NR is currently one of the main nondestructive testing techniques, which is able to satisfy the quality-control requirements and gives both visual and quantitative information about the spatial distribution of different elements and isotopes in the investigated samples. In conventional NR, a neutron beam penetrates the sample and is attenuated by the materials within the sample. Nowadays, the most effective technique uses direct imaging with a digital image detection system. In this direct method, the converter foil is replaced by a scintillator, and instead of a film a digital CCD camera is used. In this way, measurement time is saved due to short exposure times for the digital system and a development process is not necessary.

* Corresponding author. Tel.: +43 1 58801 14169.
E-mail address: bastuerk@ati.ac.at (M. Bastürk).

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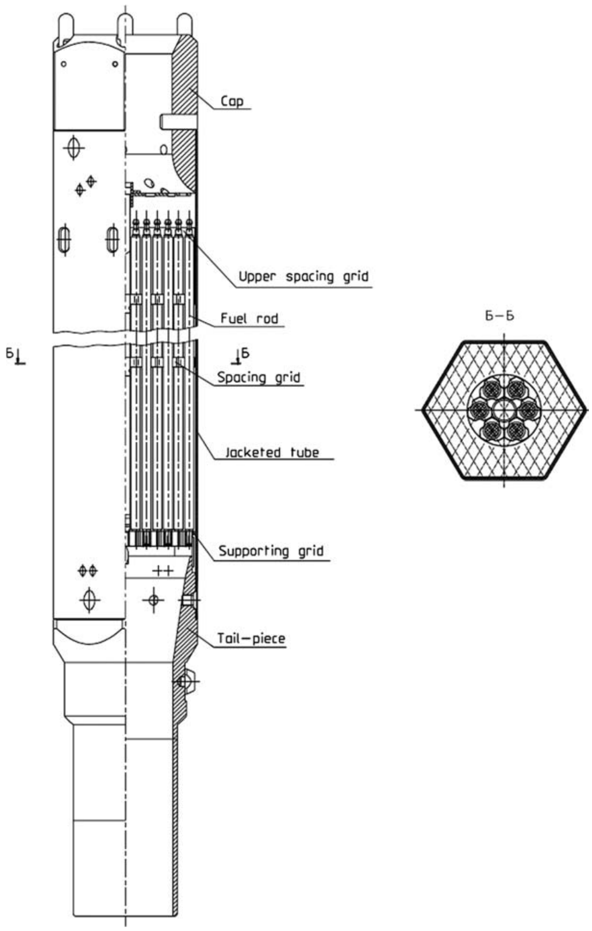

Fig. 1. The fuel assembly for a WWER-440 reactor.

Two beam lines are dedicated to the experimental facilities of thermal NR, NR-I and NR-II in Fig. 2. The digital NR setup was installed at the NR-II beam line because of beam quality and easy handling [3]. The principle of digital NR and the detection components are shown in Fig. 2(a) and (b).

3. Measurements and results

In order to determine the true beginning and end positions of the fuel-rods, two 210 cm long WWER-440 hexagonal fuel elements containing 126 fuel-rods and 1 central rod have been investigated by means of thermal NR. Due to the small beam diameter of only 8 cm at the NR-II facility, 210 cm long and 16 cm wide (diagonal), the fuel element could not be inspected at one run. The fuel assemblies were marked and numbered at 5 cm intervals (Fig. 3). Cadmium is a strong thermal neutron absorber and can be easily detected by NR. Therefore, 8 cm long and 0.5 cm wide Cd strips were stuck on each marked line as shown in Fig. 3. With these Cd strips, we could easily determine which section of the fuel assembly we observe. The prepared fuel assemblies were moved in front of the beam position with a crane, and the level position of the fuel elements was adjusted by a water-level gauge.

A 16-bit CCD camera with 512×512 pixels and 24×24 μm pixel size with a 0.4 mm thick Levy Hill neutron scintillator (ZnS(Ag)-^{6}LiF) scintillator was used as a detection system for the NR measurements. The first measurements were performed to determine the best imaging orientation of the fuel assemblies, with the beam entering the fuel assembly either from the corner or the flat/front sides of the hexagon. NR images were taken from different sides of one element until the best imaging position was obtained for an exposure time of 40 s. In Fig. 4, a drawing showing the neutron beam entering direction for corner and front view imaging is presented.

In order to show the neutron transmission difference between corner and front views, the fuel assembly was drawn 3-dimensionally in Fig. 5(a) and (b), where the neutron beam enters orthogonally to one of the flat sides of the assembly for a front view image and at the corners for the corner view (e.g. between 2 and 3 or 5 and 6). In a corner view image, fuel-rods can be visualized separately, which is not possible in front view configuration.

In order to record front side images, where the beam is orthogonal to the flat side of the investigated assembly, the fuel assemblies were placed into the neutron beam vertically. As shown in Fig. 6, the front side NR images of the fuel assembly (middle and right NR images) could not deliver enough image contrast and information in comparison to the NR image from the corner position (left NR image), which visualizes the separate fuel-rod rows within a fuel assembly. On the other side, the frontal NR images show the center rod and spacing grids clearly.

The 150 cm long main body of fuel assemblies without considering tail-piece and cap parts marked with Cd strips were investigated with a step by step movement in horizontal and vertical directions for a complete image. Thereafter, the raw NR images were processed with special image processing software IMAGE PRO and IDL 5.6 in order to eliminate gamma-ray induced white spots, and also to enhance the image contrast. In some images, special image filters had to be used due to the high density of white spots.

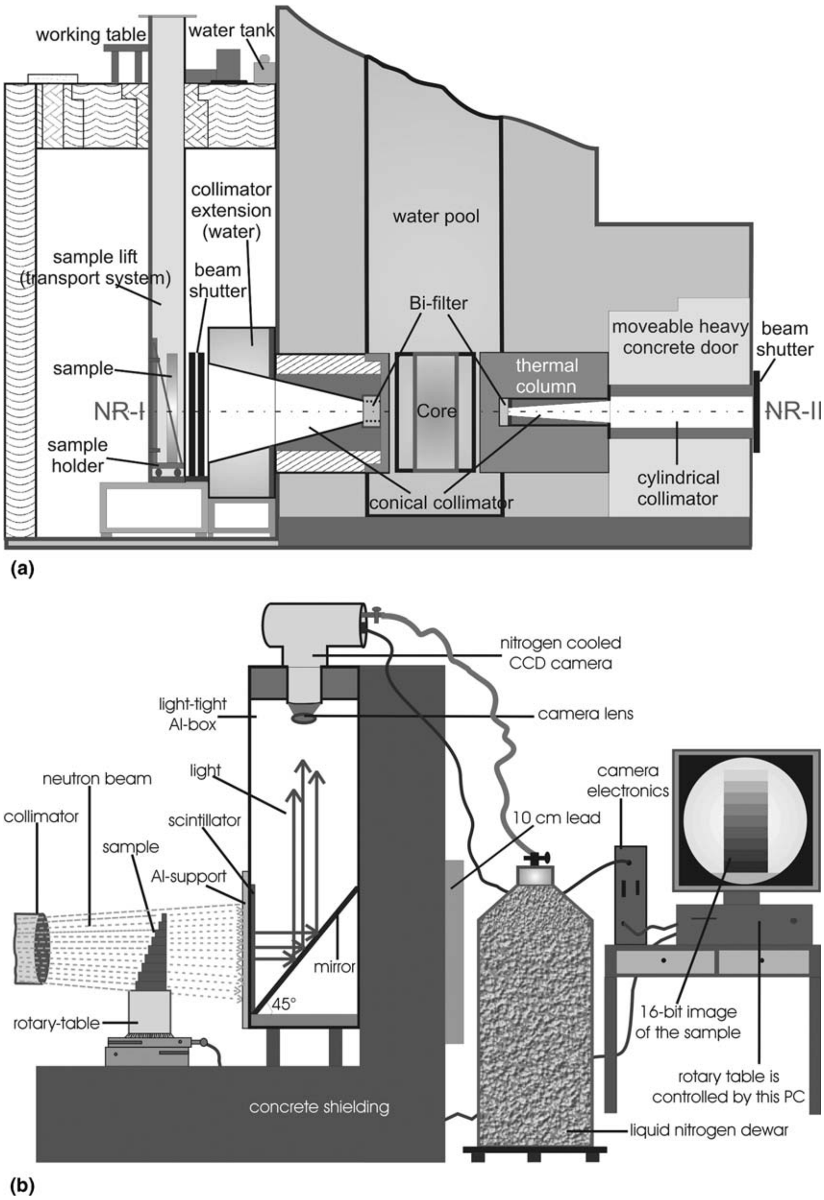

Fig. 2. (a) NR facilities and (b) the digital detection system in NR II facility installed at the TRIGA Mark II research reactor at ATI-Wien.

One of the important points was the repetition of the measurements with and without Cd strips to verify that the contrast of fuel-pellet start/end positions or defects is not masked by the strongly absorbing Cd strips. In order to extract data or pixel values from an image, an intensity profile called line profile is taken along a path defined by a line. This is an easy and efficient tool in the quantitative data analysis [4]. This procedure was exploited in our study to establish the exact start position of the fuel-pellets. In Fig. 7, neutron beam transmission through each fuel-rod row shows that the beginning positions of fuel-pellets are intermittent and not equal because of the overlapping of the neutron transmission through fuel-pellets in the same row. From the line profiles we can conclude that the beginning of the active fuel-pellets within the fuel-rods varies between 13 cm and 15.5 cm.

The fuel-pellet end positions were also determined with the same procedure described above.

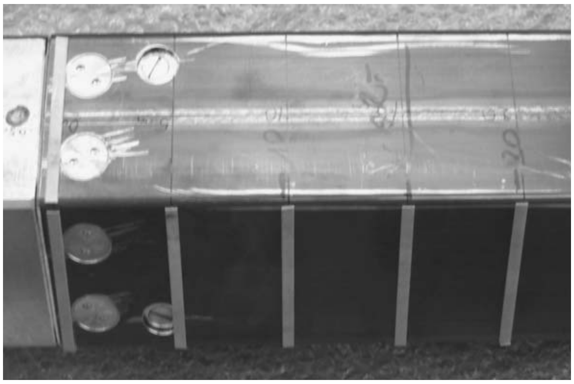

Fig. 3. A photo showing a part of one of the WWER fuel assemblies, on which 0.5 cm wide and 8 cm long Cd strips were stuck.

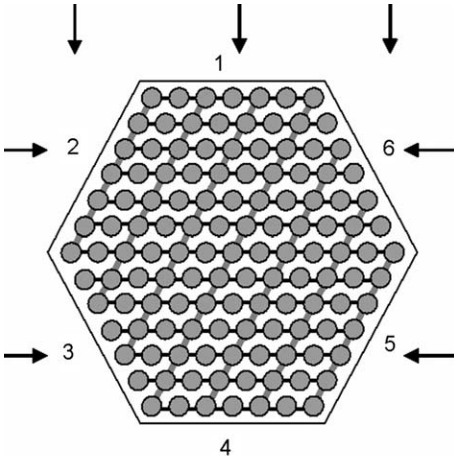

Fig. 4. A top view plot from the WWER-440 fuel assembly. The numbers on each side show the beam propagation direction into the assembly.

The only difference in Fig. 8 is that the positions of Cd strips are reversed because of the rotation of fuel assembly for the investigation of its other half. Therefore, the reversed *X*-direction is shown on the line profile diagram. The end positions for each fuel-rod row are equal and lie between 139 and 140 cm.

The same analysis was performed for the second fuel assembly of 1.6 wt% ^{235}U to localize the start and end positions of the fuel-pellets and to determine the length of the active fuel.

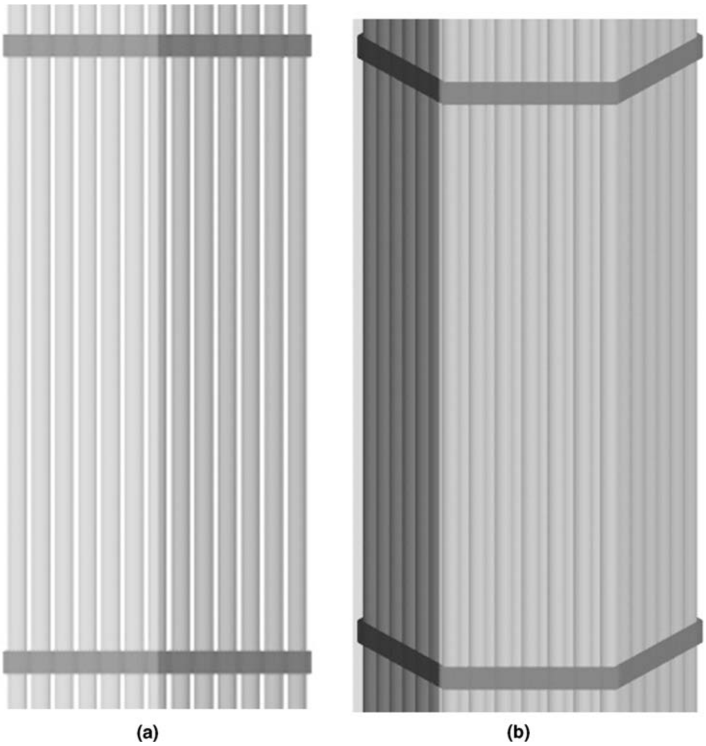

Fig. 5. 3D drawing of a hexagonal WWER-440 fuel assembly, (a) corner and (b) front view profiles. The corner side shows the fuel-rods separately.

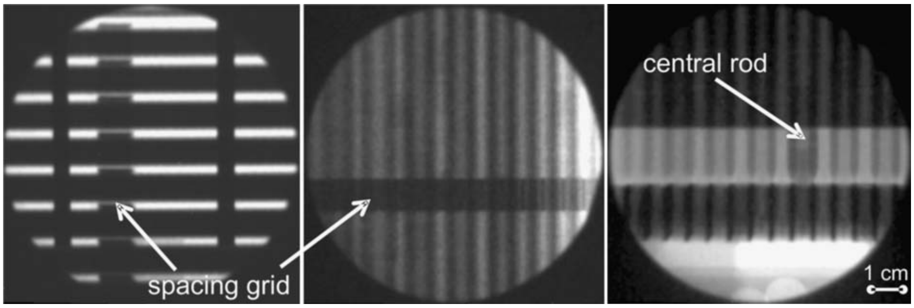

Fig. 6. The NR images of one of the fuel assemblies; corner view NR (left image) showing one of the spacing grids between two Cd-strips; front view NR (middle image), where the arrow shows the spacing grid and front view NR (right image), where the arrow shows the central fuel-rod.

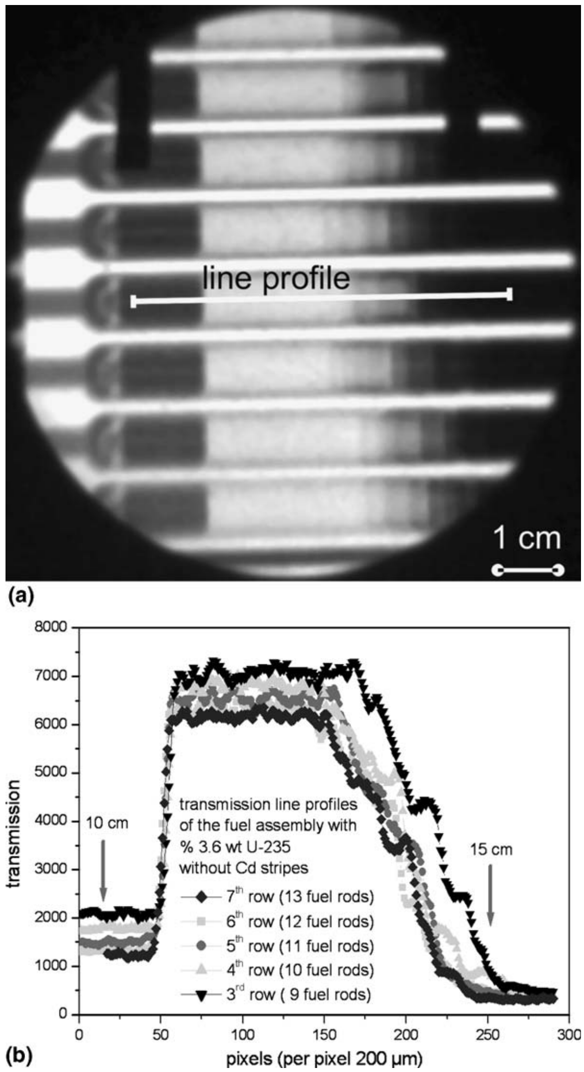

Fig. 7. (a) Corner view NR image taken at the 10–15 cm interval, where left upper Cd strip refers to 10 cm and right upper Cd strip to 15 cm positions on the image; (b) corresponding line profiles show the fuel-pellet start positions for the fuel assembly of 3.6 wt% ^{235}U.

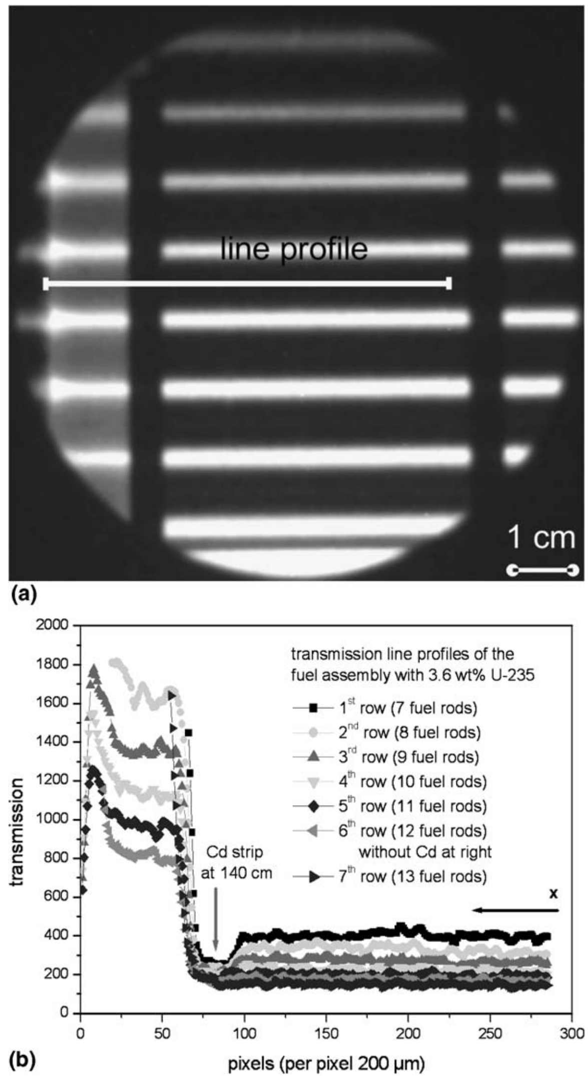

Fig. 8. (a) Corner view NR image taken at the 140–135 cm interval with Cd strips, where left Cd strip refers to 140 cm and right Cd strip to 135 cm positions on the NR image; (b) corresponding line profiles show the fuel-pellet end positions for the fuel assembly of 3.6 wt% ^{235}U.

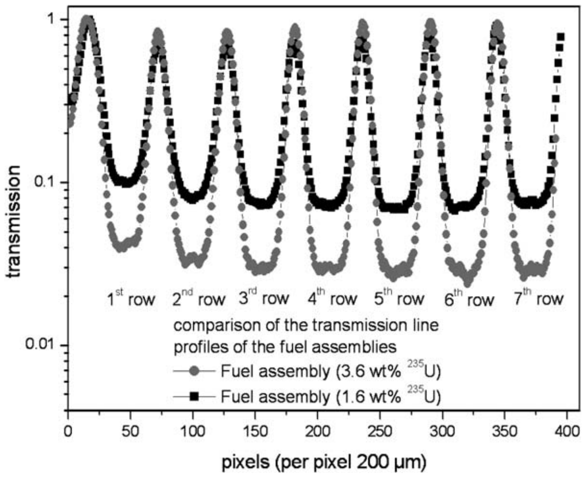

Fig. 9. Comparison of the neutron beam transmission through both fuel assemblies by means of vertical line profiles taken at the same positions (in logarithmic scaling). The neutron transmission through the 1.6 wt% ^{235}U enriched fuel assembly is higher than the 3.6 wt% ^{235}U enriched assembly because of their different ^{235}U content.

Furthermore, neutron transmission measurements were carried out for a complete inspection of both fuel assemblies, and no conspicuous defects were detected. Approximately 1 cm wide spacer grids could be detected at five different positions of both fuel elements with an interval of 24 cm; at the positions of 26 cm, 50 cm, 74 cm, 98 cm and 122 cm. One of the spacer grids is shown in Fig. 6.

Moreover, vertical line profiles for the same position (at 132 cm) of fuel assemblies with different enrichments were compared in Fig. 9. The difference in neutron transmission between the fuel assemblies is noticeable on account of their different ^{235}U contents. However, neutron transmission through fuel-rods for the same fuel assembly does not change after the fourth row (10 fuel-rods) because of strong neutron absorbing materials; these limiting factors were analyzed in detail in a previous article [5].

4. Conclusions

The unused hexagonal WWER fuel assemblies were investigated using the thermal neutron imaging method. Complete neutron radiography over the whole fuel region was performed for two fuel assemblies of 1.6 and 3.6 wt% ^{235}U. The upper and lower ends of the fuel region (start and end positions of the fuel-pellets) in two WWER fuel assemblies were determined by means of neutron transmission. The complete NR inspection of two WWER-440 fuel assemblies showed that fuel-rods are located between 9 and 142 cm of the assembly: the total length of the fuel column is approximately 133 cm. However, some pellets at the beginning and end of the fuel-rods do not contain uranium fuel. The upper and lower end of active fuel-pellets is between 15.5 cm and 139 cm; therefore the total length of the active fuel is (123.5 ± 0.7) cm as given in Table 1.

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Table 1
Measured lower and upper fuel end positions of two unused, hexagonal WWER-440 fuel assemblies

	Fuel element of 1.6 wt% ^{235}U enrichment	Fuel element of 3.6 wt% ^{235}U enrichment
Total fuel length (cm)	$142.0 \pm 1.0 - 9.0 \pm 1.0 = 133.0 \pm 1.4$	
Upper end position of *active* fuel (cm)	$15.5.0 \pm 0.5$	15.5 ± 0.5
Lower end position of *active* fuel (cm)	139.0 ± 0.5	139.0 ± 0.5
Total length of the *active* fuel (cm)	$139.0 \pm 0.5 - 15.5.0 \pm 0.5 = \mathbf{123.5 \pm 0.7}$	
Number of spacers at 26 cm intervals	5	
Positions of spacers from beginning of fuel assembly (cm)	26, 50, 74, 98,122	