NONDESTRUCTIVE EXAMINATION TECHNIQUES ON CANDU FUEL ELEMENTS

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ABSTRACT

During irradiation in nuclear reactor, fuel elements undergo dimensional and structural changes, and changes of surface conditions sheath as well, which can lead to damages and even loss of integrity. Visual examination and photography of CANDU fuel elements are among the non-destructive examination techniques, next to dimensional measurements that include profiling (diameter, bending, camber) and length, sheath integrity control with eddy currents, measurement of the oxide layer thickness by eddy current techniques. Unirradiated Zircaloy-4 tubes were used for calibration purposes, whereas irradiated Zircaloy-4 tubes were actually subjected to visual inspection and dimensional measurements. We present results of measurements done by eddy current techniques on Zircaloy- 4 tubes, unirradiated, but oxidized in an autoclave prior to examinations. The purpose of these nondestructive examination techniques is to determine those parameters that characterize the behavior and performance of nuclear fuel operation.

Key words: sheath integrity, oxide thickness, eddy current.

Introduction

One of the non-destructive examination techniques for CANDU fuel elements is represented by visual examination and photography in hot cells with the help of a periscope. Hence, macroscopic changes of the fuel element sheath (oxidation, deposits of corrosion products, corrosion effects, deformities, defects, color etc.) due to the irradiation conditions and manufacturing conditions as well are observed [1]. Dimensional changes mainly consist in increased diameter, wrinkling, stretching, bending and cambering of fuel element and are the result of swelling of the sheath and fuel-to-fuel sheath interaction induced by nuclear radiations. The method aims to determine the above mentioned changes. Visual examination and dimensional measurements of samples were performed using an universal test machine (**Figure 1**) equipped with step by step motors for vertical and rotational displacements of the fuel element, a console for diameter measurement with two displacement transducers, diametrically opposite, mounted on car, and a control-command console, equipped with digital measuring devices to display fuel element position and measurements values.

Another non-destructive technique, the control technique with eddy currents obtains information about the sheath integrity of the irradiated nuclear fuel or about the existence of defects produced by irradiation (cracks, holes, external and internal notches, changes of sheath wall thickness, inclusions, etc). The control equipment consists of a flaw detector with eddy currents, operable in the frequency range 10 Hz ÷

10 MHz, and a differential probe. The calibration of the flaw detector is done using artificial defects (longitudinal, transversal, external and internal notches, bored and unbored holes) obtained on Zircaloy-4 tubes identical to those out of which the sheath of the CANDU fuel element is manufactured (having a diameter of 13.08 mm and a wall thickness of 0.4 mm). Measuring the oxide layer thickness, by eddy currents, formed on elements sheath is useful for characterizing the behavior of fuel elements at high fuel burn-up or during a long-term storage. Eddy current technique has the advantage of allowing rapid measurement of Zirconium oxide layer thickness along the length of the fuel element, while the metallographic on the sheath allows only local measurements. To measure the thickness of the oxide layer, a high frequency electromagnetic field is generated, that induces eddy currents in the substrate conductive material. The amplitude of these eddy currents depends on the distance between the probe coil and the substrate material. The measurement signal is produced by the variation of the impedance reflected in the probe coil by the eddy currents generated in the substrate material. The changes of the coil impedance depend on the distance between the coil of the control probe and the conductive substrate material and its dimensions [2].

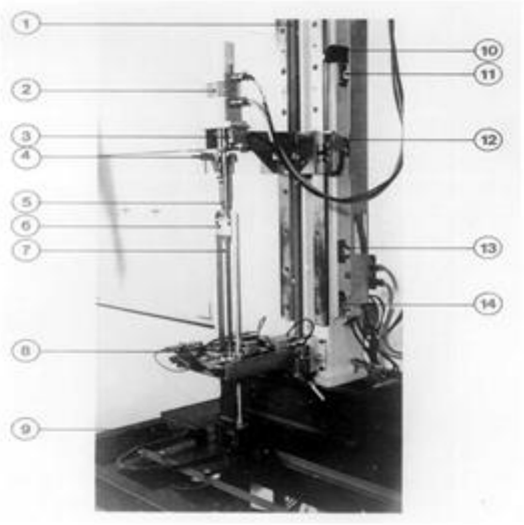


Figure 1 *Universal test machine*

1 - Screw for vertical motion “Z”
2 - Stepping motor for rotation “R”
3 - Origin limiter “R”
4 - Fastening end for the element-holder
5 - Fastening head for the element-holder
6 - (Fuel) element-holder
7 - Fuel element
8 - Device for the measurement of diameter and defects in the sheath of the fuel element
9 - Loading device
10 - Mechanical stop
11 - Origin limiter "Z"
12 - Cam driving the limiters
13 - End limiter "Z"
14 - Limiter for the fastening interval of the element-holder

The visual examination and photography

The fuel element of interest, fastened in the universal machine (**Figure 1**) was visually examined through periscope, in order to observe the corrosion products deposited, "pitting" or other forms of localized corrosion, other defects (deformation, cracks, etc.), its color etc. After visual examination, the outside appearance of the fuel element was photographed at angles 0˚, 120˚ and 240˚, as shown in **Figure 2**.

Visual inspection revealed the existence, all over the sheath, of fine, non-adherent and dark gray deposits, except the areas between the spacers and those between spacers and central skate, where the sheath has a shiny metallic look. Above the right spacer a little lack of material was observed due to a localized corrosion process. It has a circular form, has 0.7 mm in diameter and is at 2.6 mm from the spacer and 139.6 mm from the marked end. This detail is shown in **Figure 3**.

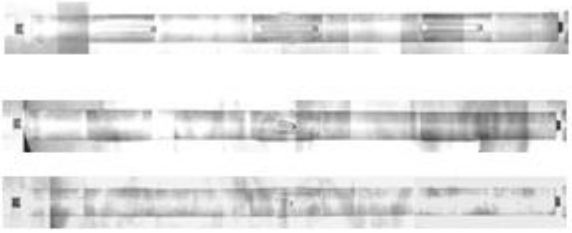


Figure 2
The outside appearance of the fuel element

Figure 3
The galvanic corrosion primed by the thermocouple and sheath contact

Dimensional measurements

The dimensional inspection machine (**Figure 1**) allows the vertical displacement, on the Z direction, of the fuel element, with the help of a screw of great precision with 4 mm step, driven by a step by step motor (400 steps/rotation), one step corresponding to a 10 µm displacement. The origin of Z motion is provided by a micro – switch. The stepper motor is controlled by an electronic module named indexer that allows the command and the control of movements and also their values display. Displacement accuracy is ± 0.05 mm on a distance of 1500 mm. Diameter measurement was performed along the fuel element (except the skates and the spacers), beginning at the marked end, with a step of 1 mm, on three longitudinal directions: 0˚, 120˚ and 240˚ (clockwise), the reference direction (0 °) being the longitudinal axis of the skates.

The arrow was measured at the same time as the diameter, being determined by the semi-difference of the values measured between those two displacement transducers which are a differential transformer type with mobile core, being disposed in opposite sides of the fuel element. They come in contact with it through the touch probes which are directly related to the cores. The fuel element moves vertically, step by step, between those two touch probes, diametrically opposed. Measurement accuracy is ± 5 µm. The arrow profile (bending) of the fuel element was also obtained. The length is measured by moving the fuel element from the "origin Z" vertically in front of the periscope until its central crosshair overlaps with the inferior stopper shoulder first and then with the superior stopper shoulder [3]. The value of each Z displacement is displayed by the indexer on the control command panel, and the difference between them is the length of the fuel element. The results of the measurements are shown in **Figure 4** and **Figure 5** and highlight the fact that the fuel element has suffered bending of the sheath.

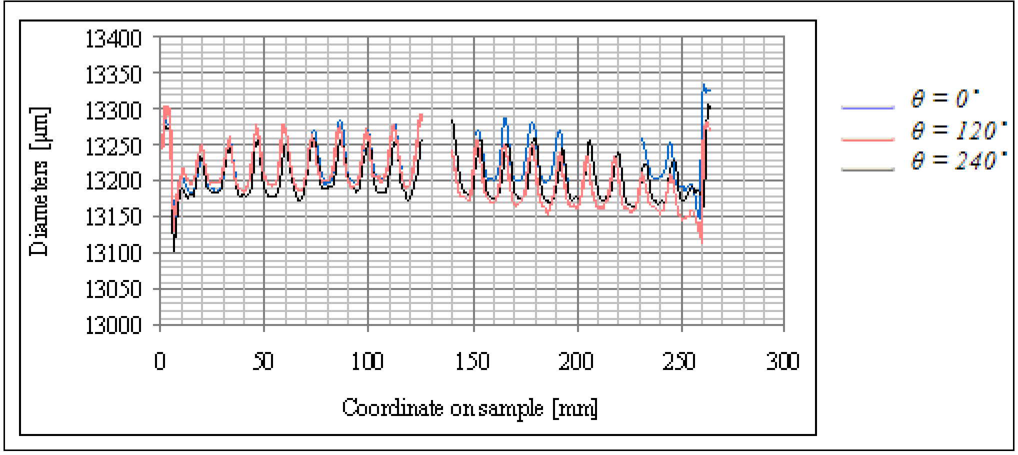


Figure 4 *Diameters profiles on three longitudinal directions*

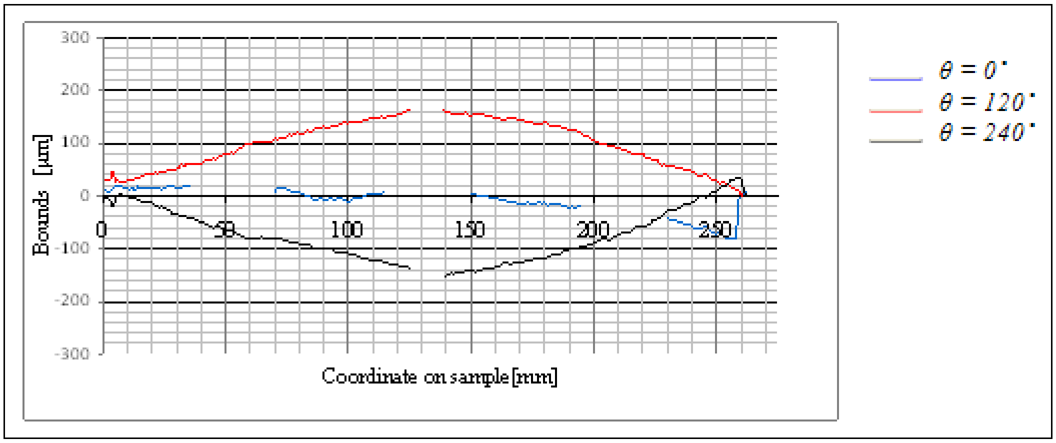


Figure 5 *Bending profiles on three longitudinal directions*

The sheath integrity control with eddy currents

The eddy current flaw detection facility consists of the following parts:
- Universal test machine (**Figure 1**);
- Control/command panel of the machine;
- Eddy current flaw detection instrument (**Figure 6**);
- Measurement console (**Figure 7**);
- Differential probe.

Figure 6 *Front panel MIZ-27SI*

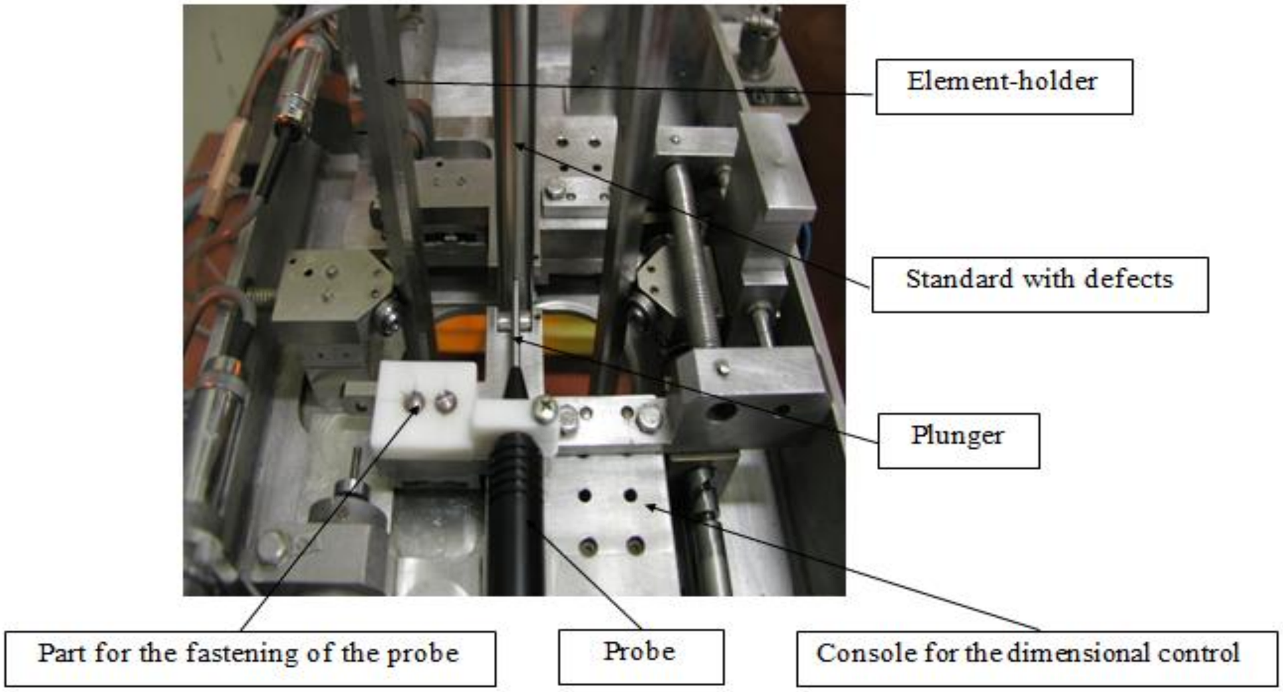


Figure 7 *Measurement console for flaw detection using eddy current*

Flaw detection using eddy current consists in determining the variations of the eddy currents produced by the alternating field of a coil inside the component to be checked. The coil, through which a sinusoidal high frequency current I is flowing, creates a magnetic field with the intensity H_i which induces eddy currents i_{CT} in the component to be checked. The eddy currents create a magnetic field of intensity H_r opposed to the initial field and therefore change the coil impedance. The currents induced in the component have the same frequency as the excitation current, but they have different phases [4].

In order to calibrate the flaw detection device, artificial defects of zircaloy-4 (from which is manufactured the CANDU fuel element sheath) tubes are used, having a diameter of 13.08 mm and a wall thickness of 0.4 mm. After calibration, the inspection of the sheath integrity of the irradiated fuel element is performed. The fuel element, fastened in the machine, is vertically moved with constant speed (10 mm/s) in front of the control coil, perpendicular to the sheath at a distance of 0.3 mm from it. Eddy current control is performed along the fuel element from the reference direction (marked with skates or the identification number of the fuel element) by rotating the fuel element with an angular step of 4.5˚, so that the entire surface is controlled. Defects having a size down to a few hundredths of a mm can be detected. The results of the control cladding integrity for an irradiated element fuel are presented in Fig. 8 and 9. The defects detected were confirmed by optical microscopy.

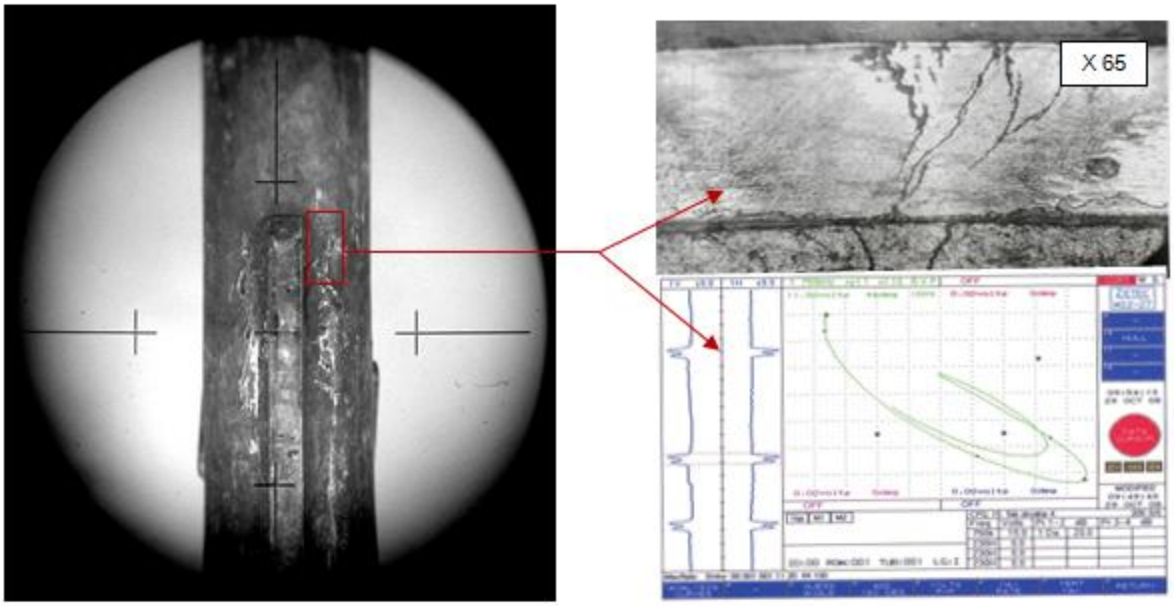


Figure 8 *Pierced longitudinal crack detected by eddy currents control in the sheath of a CANDU fuel element*

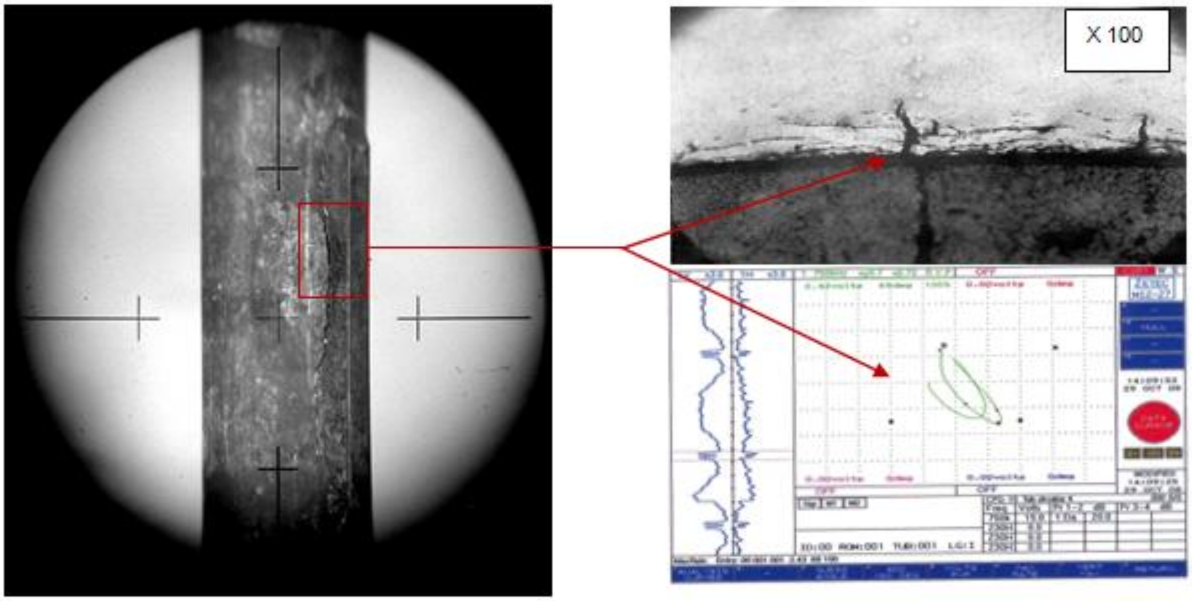


Figure 9 *Pierced internal crack detected by eddy currents control in the sheath of a CANDU fuel element*

Measuring the thickness of the oxide using the eddy current technique

The installation for measuring the oxide thickness on zircaloy-4 tubes consists of the following parts:

- Universal test machine (**Figure 1**);
- Control/command panel of the machine;
- Device for measuring the thickness of the oxide layer (**Figure 10**);
- Measurement console (**Figure 11**);
- Measuring probe.

Figure 10 *Device used to measure the thickness of the oxide*

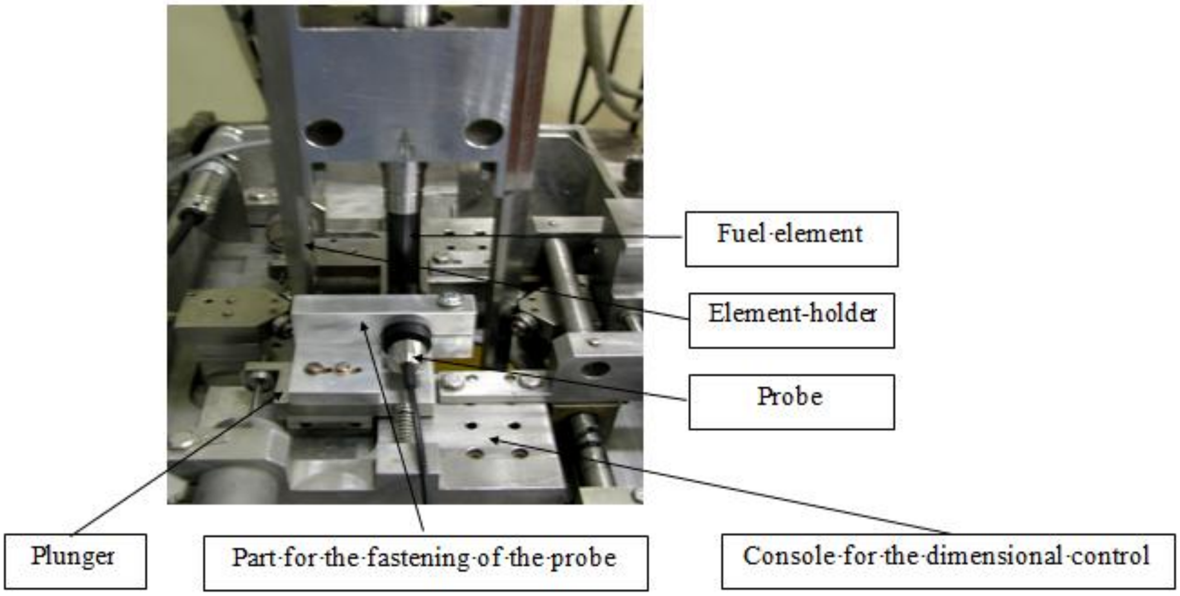
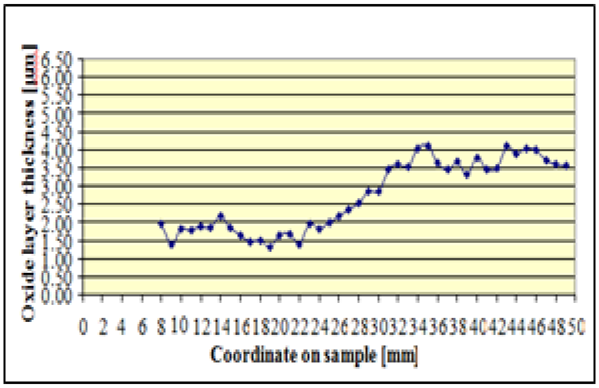


Figure 11 *Measurement console of the device for the determination of the oxide layer thickness*

In any method of nondestructive testing, the use of some references is essential to make initial settings and to ensure the reproducibility of measurements. For calibration, a tube of the same material and having the same dimensions as CANDU fuel element (zero point) and foils of calibration of plastic material of known thickness are used. The outer surface of the tube was carefully processed in order to have a roughness of 0.4 μm. Two calibration foils having the thicknesses of 11.3 μm and 24.6 μm respectively were used for calibrating the device. They were chosen so that their thicknesses were as close to the estimated oxide thickness as possible. After calibrating the device, the eddy current proof stick is oriented perpendicular to the fuel element, coming into contact with the sheath, measuring thus the thickness of the zirconium oxide layer. The fuel element fastened in the machine, is vertically moved step by step (with a step of 1 mm). Oxide layer thickness values are recorded by the device and reported. The oxide layer thickness profile is obtained along the whole length of the fuel element. In **Figures 12, 13, 14**, are shown the thickness profile of the zirconium oxide, measured by the eddy current technique, on a tube of zircaloy-4 oxidized by autoclaving. The tube was scanned longitudinally on three generators, oriented equidistant, at 120˚ between any two successive ones. A scanning on circumference was also performed on the tube, at 8 mm from the unmarked end (**Figure 15**). The measurement results were confirmed by measuring the oxide thickness of the cross-section of the tube, using an optical microscope (**Figure 16**).



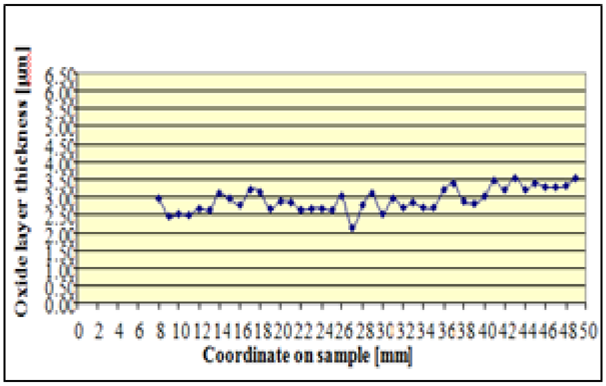
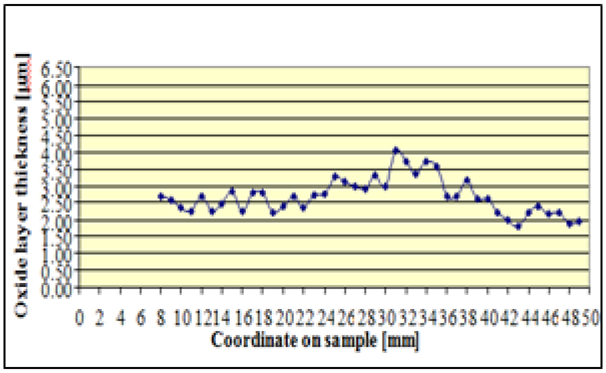


Figure 12 *Longitudinal scan at θ=0º*

Figure 13 *Longitudinal scan at θ=120º*



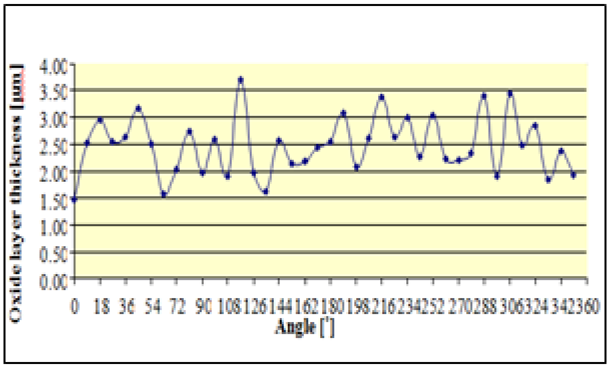


Figure 14 *Longitudinal scan at θ=240º*

Figure 15 *Circular scan (with 9 steps)*

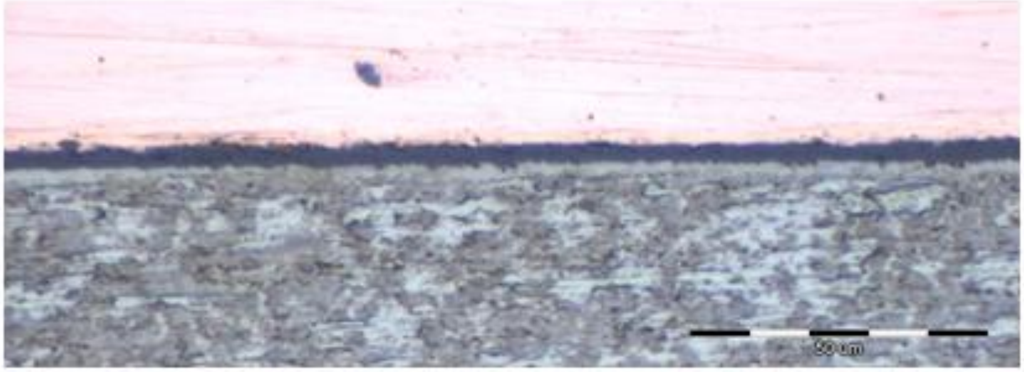


Figure 16 *Oxide layer measured by optical microscopy*

Using specialized software, minimal, maximal and average thicknesses of the oxide layer were measured:

- Minimal thickness: 1.83 μm;
- Maximal thickness: 2.96 μm;
- Average thickness is 2.29 μm.

Conclusions

The deposits were removed from the surface of the sheath prior to its visual examination. We observed in this way that the thermally affected zones are darker than the rest of the sheath, indicating a lower oxidation state. The position and the appearance of detected defect lead to the conclusion that it is the result of a galvanic corrosion process primed by the contact of the thermocouple with the sheath, the sheath's wall being not penetrated.

On dimensional control, irradiation-induced changes were observed, resulting in wrinkling of the sheath in the interface zones of the pellets. The average diameter increase is 0.35%, the highest growth was recorded in the direction 0˚, the corresponding diameter increase being 0.46%. The representation by superposition of the diametrical profiles on those three longitudinal directions (0˚, 120˚ and 240˚) has revealed that the cladding of the fuel element suffered a cambering process. It was found that the maximum camber occurred for a vertical coordinate of 261 mm and has a value of 167 μm. The fuel element bent, the maximal arrow being of 162 μm for a vertical coordinate of 125 mm.

The defects detected in the fuel element sheath by eddy current technique were confirmed by optical microscopy and also the values of the average oxide layer thickness, measured by the same technique, are close to the values measured by optical microscopy, so the measuring method by eddy currents provides a high accuracy.

References

[1] R.IN.41.100-Examens visuels-Exploitation-1980, ACB
[2] Fisherscope MMS – User manual
[3] R.IN.41.300-Metrologie cellule- Exploitation-1980, ACB
[4] Zetec MIZ - 27SI – User manual