Pulsed Eddy Current Defectoscopy of Irradiated WWER Fuel Rods

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Abstract. Defectoscopy of irradiated WWER fuel rods in the RIAR hot cells is performed by means of pulsed eddy current method. Uniformity defects, local geometry anomalies can be formed during the operation of fuel rods. For failed fuel rods, appearance of secondary defects related to water ingress, oxidation and hydrogenation of ZR alloy cladding is typical. The defectoscope consists of two modules built in the industrial computer - pulse generator and analog-to-digital converter (ADC). To reveal and identify anomalies, A-, D-scans, envelope curves and hodograph curves of pulse signal are used. The EC-method makes it possible to reveal damaged fuel rods in failed WWER FAs, determine location and identify primary through defects and secondary anomalies. Totally 49 WWER FAs, including 18 failed FAs, were examined by means of this method.

1. INTRODUCTION

Eddy current (EC) defectoscopy is one of the main methods for non-destructive control of irradiated fuel elements in the hot cells of the RIAR Material Testing Complex [1]. This method is applied at one of the initial stages of PIEs for fuel elements: presence of anomalies in fuel rod claddings is revealed when passing the fuel rods discharged from the fuel assemblies through the EC-sensor. Abnormal fuel rods are then sent for further NDEs and DEs needed for evaluation of their state.

2. OBJECTS OF DEFECTOSCOPY

Fig. 2.1 presents the design of the researched WWER-440 and WWER-1000 fuel rods. Initial outer diameter of the fuel rod cladding is 9.1 mm, wall thickness – 0.69 mm, material – alloy E110 (Zr-1%Nb).

Defects typical for the irradiated WWER fuel rod claddings can be divided into two categories: uniformity defects and local changes in diameter. Among the uniformity defects of the cladding outer surface there are:

- fretting-wear resulting from interaction of the fuel rod cladding with the spacer grids of FAs;
- debris-defects – traces of interaction of the claddings with foreign objects in the coolant;
- local (nodular) corrosion;
- cracks.

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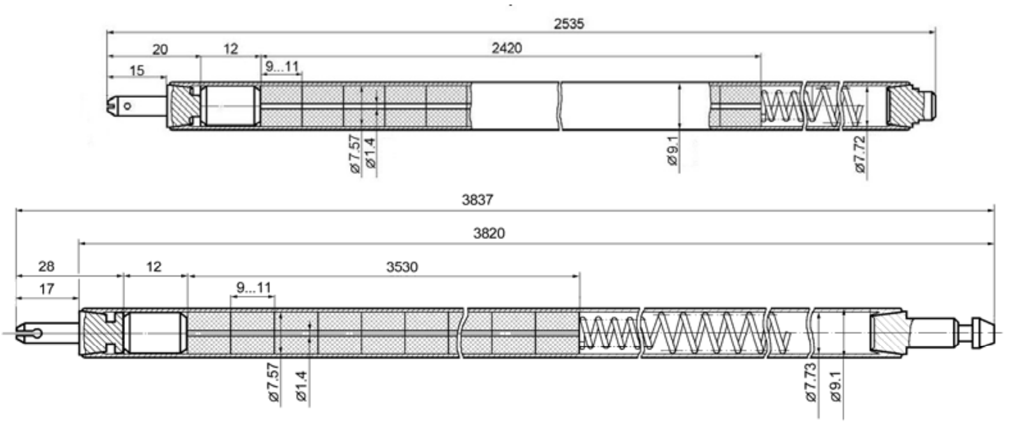


FIG. 2.1. Design of WWER-440 (top) and WWER-1000 (bottom) fuel rods.

Two types of uniformity defects are observed on the inner surface of fuel claddings:

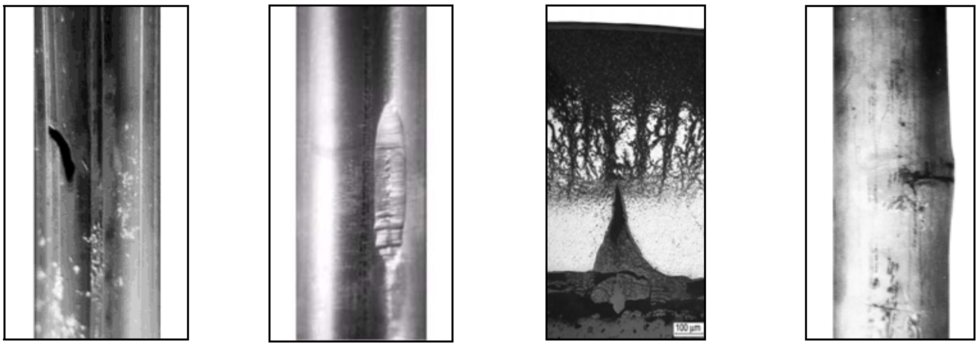
- local oxidation;
- local hydrogenation.

Development of outer and inner defects across the entire thickness of the cladding results in through defects.

As a rule, local changes in the fuel rod diameter are induced by thermal-mechanical interaction of fuel and cladding or penetration of moisture inside the fuel rod with further cladding hydrogenation.

In the claddings of failed fuel rods, super-positions of defects in various combinations are formed together with single defects.

Fig. 2.2 presents various uniformity defects observed for the irradiated WWER fuel rod claddings.



a b c d

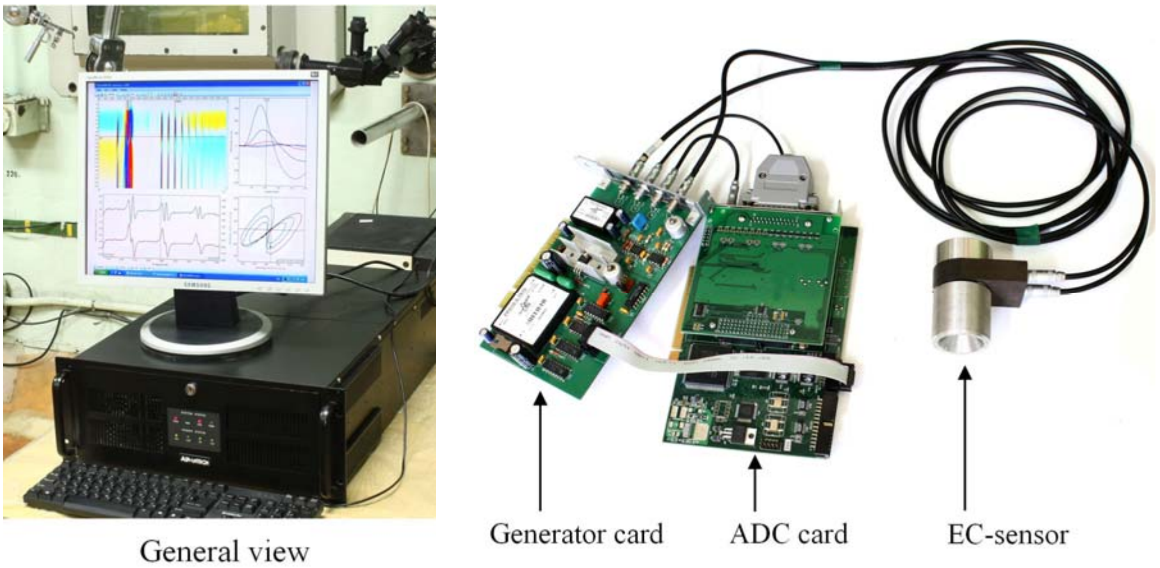
FIG. 2.2. Defects of the irradiated WWER fuel rod claddings: a – debris-defect; b – fretting-wear; c – internal hydrogenation; d – superposition of the through crack and local change in diameter.

Data on the state of spent WWER fuel rod claddings are used for development of reference samples with artificially-applied defects simulating actual anomalies. Identification features of defects revealed by scanning of reference samples make it possible to analyze the state of irradiated fuel rod claddings.

3. DEFECTOSCOPY TECHNIQUE AND METHODS

The developed on-line EC-control system is based on the pulsed eddy current defectoscope [2]. It consists of a pulse generator and 12-bit analog-to-digital converter (ADC) built in the industrial PC (Fig. 3.1). The main advantages of the pulsed eddy current method are simple hardware design, high self-descriptiveness due to generation of a wide frequency spectrum and high sensitivity to defects. Basic parameters of the EC-equipment are as follows: length of fuel rods under inspection – up to 4 m, cladding diameter – 6–15 mm, scanning step – 1 mm, scanning rate – 35 mm/s.

Induction coils are used as sensor elements of the EC-probe. Measuring coils are switched by differential circuit. They register changes of the electromagnetic field of eddy currents induced in the fuel rod cladding with a transmitting coil to which the generator feeds current pulses. Such probes meet the requirements of the on-line EC-control of irradiated fuel rods in hot cells and inspection stands to a sufficient extent. They feature high radiation resistance, low cost, ease of fabrication, possible leak-tight execution and high sensitivity to changes of the electromagnetic field within a range of 50–1000 kHz.



a b

FIG. 3.1. EC-equipment for defectoscopy of irradiated fuel rods.

With pulse excitation of eddy currents, identification of defects is based on the evaluation of parameters of A-scan that reflects a variation with time of the amplitude of signal of the inductive EC-sensor at the place of defect location (Fig. 3.2) [3]. Response from the defect digitized at N points (strobes) at regular intervals Δt is incorporated in the defectoscope memory and further analyzed. Definite moment of time $t_i = i\Delta t$ (i = 1, N) corresponds to a strobe with number i. Duration of the response under analysis is 7 µs, time strobing pitch Δt is 33 ns. Zero-crossing time t_{ZC} is used as an identification feature of the defect.

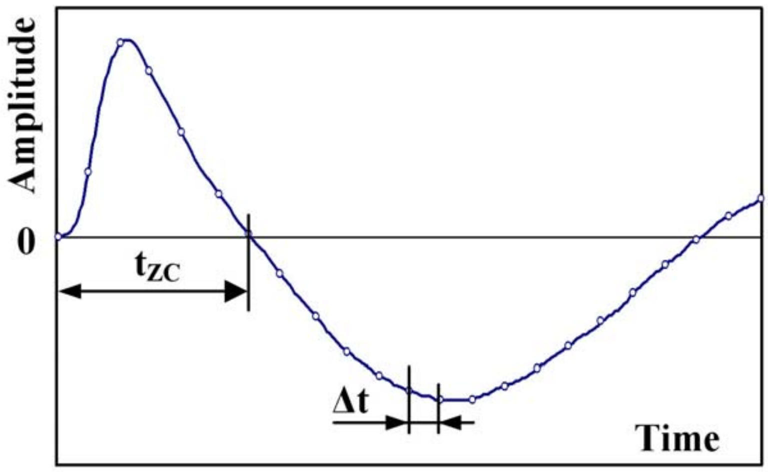


FIG. 3.2. Typical A-scan for the cladding defect.

Fig. 3.3 illustrates A-scans for various local defects of the cladding. The A-scans presented differ not only in the value of t_{ZC}, but also in their polarity. For super-positions of defects, more complicated A-scan is typical, as well as a great number of zero-crossing points within the set time interval (Fig. 3.3, b).

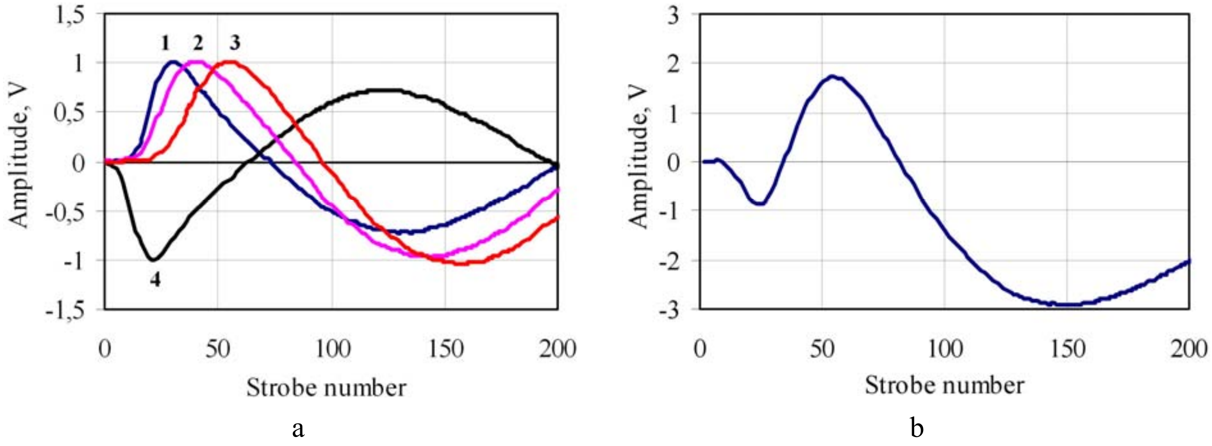


FIG. 3.3. A-scans for single defects (a): 1, 2, 3 – external, through and internal defects of uniformity, 4 – "ridge"; a superposition of a "ridge" and through defect of the cladding (b).

Type and relative dimensions of anomalies revealed during the fuel rod scanning are determined using an amplitude-time plane (Fig. 3.4). Values t_{ZC} are plotted as abscissas and values A_m (amplitude of response from defect) as ordinates. Sign of the half-plane corresponds to polarity of the first half-wave of the signal of the defect. Position of regions corresponding to this or that defect type at the amplitude-time plane is identified based on the scanning results of specimens with artificial anomalies of various type and size (for example, defects 1–6 – internal grooves 0,1; 0,2 … 0,6 mm deep).

Figure 3.5 presents the main window of the computer program used to analyze the results of the EC-control of fuel rods. For primary evaluation of the fuel rod state, D-scan is used (Fig. 3.5, a). It allows rapid revealing of the cladding regions with minor defects [2]. D-scan shows the dependence of the probe response amplitude on the axial coordinate of the fuel rod and a strobing moment of the EC-pulse (strobe number). Amplitude is reflected in bright color shades: the greater the amplitude, the more intense the brightness of the color. Precise characteristics of specific anomalies are identified with A-scans (Fig. 3.5, b). Envelope curve obtained for a specific strobe number (Fig. 3.5, c) enables express evaluation of the presence of a certain type of defects for the entire fuel rod. Two envelope curves are used for plotting hodograph curves (Fig. 3.5, d) the shape of which allows to differentiate a very deep defect from a through one [4]. The envelope curves are selected so that an angle between hodograph curves of internal and external shallow defects is equal to 90°.

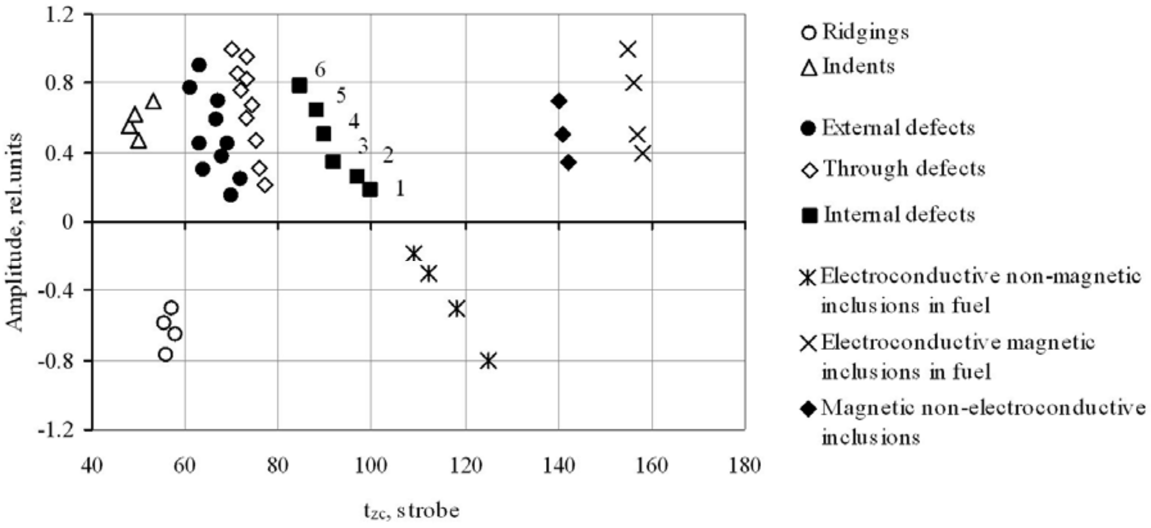


FIG. 3.4. Plane of identification of single defects for WWER fuel rods.

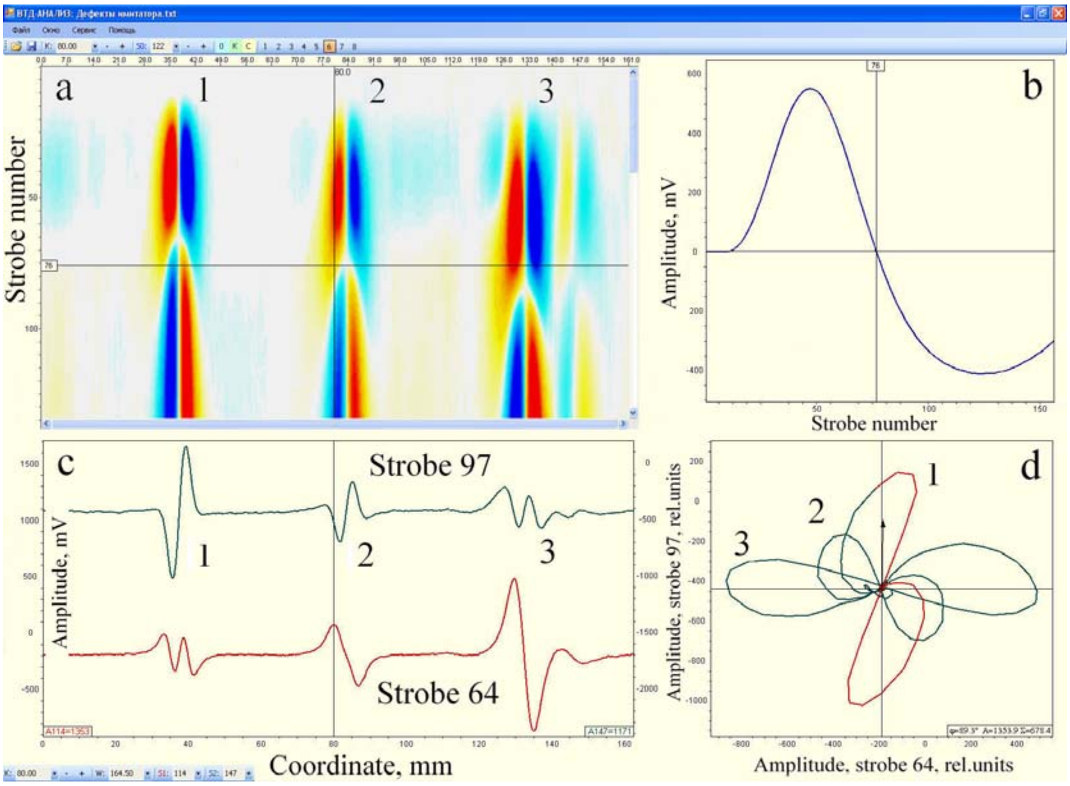


FIG. 3.5. Main window of the computer program showing the EC-control results for the imitator fragment with external (1), through (2) and internal (3) defects: a – D-scan; b – A-scan of the through defect; c – envelope curves of EC-sensor signal; d – hodograph curves

4. EXAMPLE OF EC-DIAGNOSTICS OF FUEL ROD STATE

As an example illustrating the capabilities of the developed pulsed EC control system, let's consider a procedure for detecting a damaged fuel rod as a part of failed WWER-1000 FA and diagnostics of the state of its cladding. The EC-diagrams of 311 fuel rods in this FA are typical for leak-tight fuel rods. Responses from a spring pin and lower plug were observed, background level was insignificant (Fig. 4.1a). Only one fuel rod was found to be abnormal as its EC-diagram had non-typical signals considerably exceeding the background level in the amplitude (Fig. 4.1b).

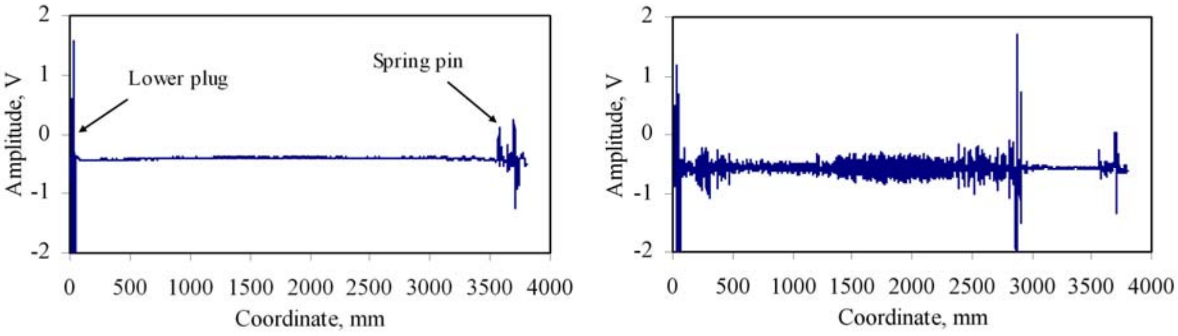


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FIG. 4.1. Typical (a) and abnormal (b) EC-diagrams of fuel rods.

The amplitude-time analysis of the EC-scans of fuel rods showed the presence of a through defect (t_{ZC} = strobe 75) at the coordinate of 34 mm (Fig. 4.2a). Visual inspection of this region revealed a through debris-defect in the cladding (Fig. 4.2b).

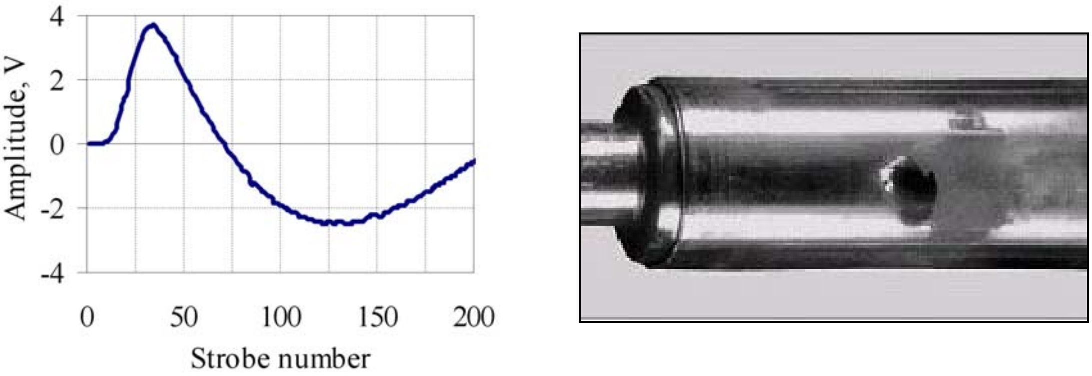

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FIG. 4.2. A-scan (a) and image of the through debris-defect (b).

Ingress of the water coolant inside the fuel rod though this defect leads to oxidation and hydrogenation of the inner surface of the cladding. Responses from numerous internal defects of various depth (t_{ZC} = strobe 95–103) were registered in the regions at the coordinates of 34–2400 mm. Metallography of one of such regions showed the presence of corrosion pits 40–50 μm thick on the inner surface of the cladding (Fig. 4.3a). The regions at 2400–2900 mm were found to have signals of the superposition of internal defects with local increase in the fuel rod diameter (t_{ZC1} = strobe 30–33, t_{ZC2} = strobe 101–105). Metallography of one of such regions showed significant hydrogenation of the cladding material together with internal non-uniformities, including formation of "sunburst"- type hydride layers (fig. 4.3b). As known, such hydrogenation induces the change in the WWER fuel rod cladding diameter due to the difference of molar volumes of zirconium and its hydride [5].

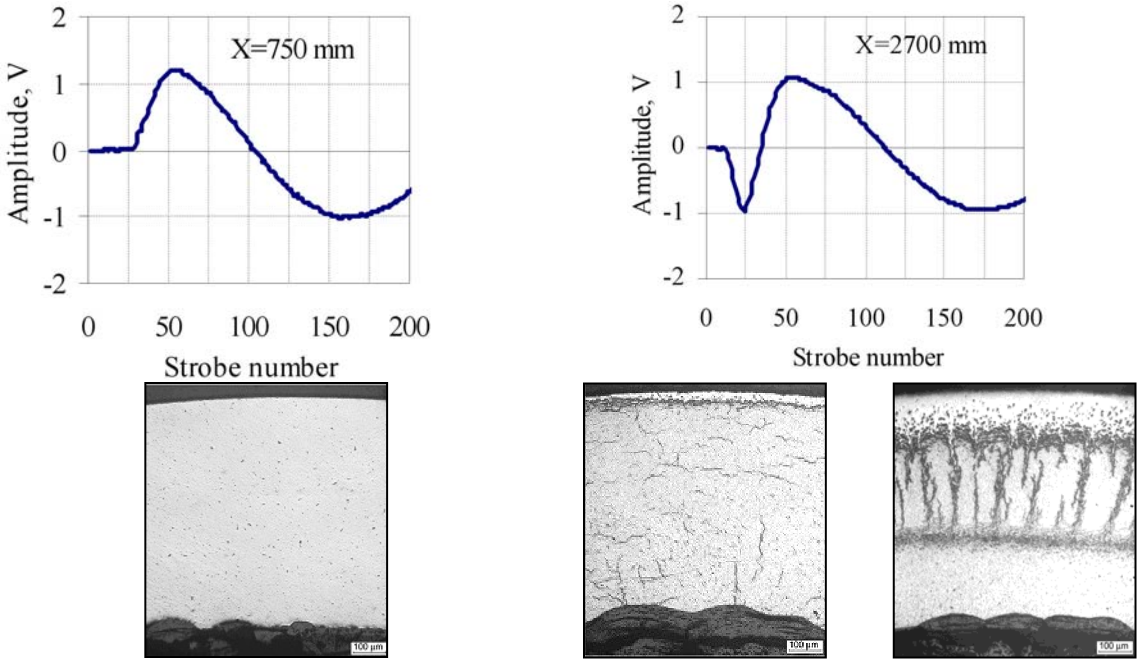

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FIG. 4.3. A-scans and images of abnormal regions at 750 mm (a) and 2700 mm (b).

The analysis of A-scans (Fig. 4.3) shows that the pulse EC-method can reveal local diameter variations for a failed fuel rod in the regions with maximum hydrogenation. For this purpose, the envelope curve corresponding to strobe 24 should be used. This strobe demonstrates no EC-sensor reaction to inner non-uniformities. Sensitivity to variation of diameter is maximum (Fig. 4.4a). Profilogram obtained by the contact method confirmed the results of the EC-control and showed the presence of the local increase in diameter up to 9.23 mm in the region with the coordinates of 2400–2900 (Fig. 4.4).

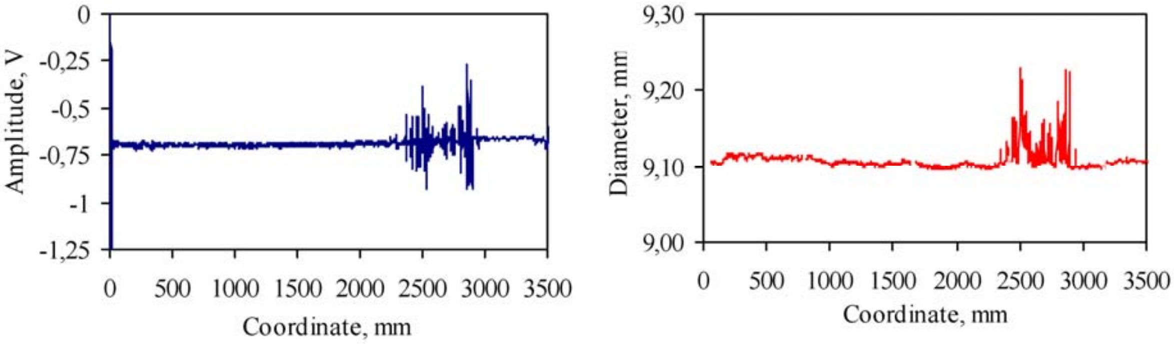

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FIG. 4.4. Envelope curve of sensor signal for strobe 24 (a) and profilogram (b) of failed fuel rod.

At 2860 mm, a signal with two zero-crossing points (one corresponds to the local change in diameter, while the other one - to the through-defect of the cladding) was registered (Fig. 3.3b). Visual inspection revealed a crack at the coordinate of the EC-signal (Fig. 4.3). The through character of the crack was confirmed by the metallography results.

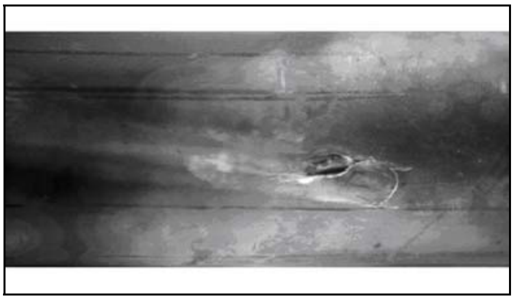

FIG. 4.5. Secondary through defect.

The time period from appearance of the primary through defect to considerable hydride damage of the cladding as a function of specific thermal load is one of the most important characteristics of the WWER fuel. For example, for LWR fuel rods with Zircaloy claddings, this characteristic is determined by Loche curve [6].

5. CONCLUSION

The developed pulsed eddy current defectoscope is used for on-line control of the state of irradiated fuel rods in the hot cells of the RIAR Material Testing Complex. Examinations of 49 WWER FAs, including 18 failed FAs, were performed using this equipment. Its capabilities enable us to detect uniformity defects and change in form of the cladding, as well as to identify location of primary and secondary anomalies in failed fuel rods. The analog of this equipment is currently installed in the inspection stand of the cooling pond at the Kalinin NPP [7].

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